PROCEEDINGS OF THE UNITED NATIONS CONFERENCE ON NEW SOURCES OF ENERGY

SOLAR ENERGY, WIND POWER AND GEOTHERMAL ENERGY

Rome, 21-31 August 1961

VOLUME 5. SOLAR ENERGY: II

ACTES OFFICIELS DE LA CONFÉRENCE DES NATIONS UNIES SUR LES SOURCES NOUVELLES D'ÉNERGIE

ÉNERGIE SOLAIRE, ÉNERGIE ÉOLIENNE ET ÉNERGIE GÉOTHERMIQUE

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INTRODUCTION

The United Nations Conference on New Sources of Energy was held in Rome from 21 to 31 August 1961. A brief review of the proceedings, of the papers submitted to the Conference and of the related discussions has been printed in *New Sources of Energy and Energy Development : Report on the United Nations Conference on New Sources of Energy.*[1] That publication also contains the agenda and the lists of participants and conference officers, as well as lists of all the papers and reports.

The Proceedings of the Conference comprise seven volumes as follows:

Volume 1. General sessions.
Volume 2. Geothermal energy : I.
Volume 3. Geothermal energy : II.
Volume 4. Solar energy : I.
Volume 5. Solar energy : II.
Volume 6. Solar energy : III.
Volume 7. Wind power.

The present volume, "Solar energy: II", contains the papers and reports relating to agenda item III.C, "Use of solar energy for heating purposes", which consists of five sub-items : III.C.1. Water heating; III.C.2. Space heating; III.C.3. Solar drying; III.C.4. Solar cooking; III.C.5. Heat storage.

The rapporteurs' general reports and their summations of the proceedings in connexion with each sub-item are given in full in both English and French, as are those individual papers that were submitted to the Conference in both languages. With a few exceptions, all the papers are summarized in both English and French.

Within each sub-item, the papers are printed in the alphabetical order of the authors' names. References supplied by the authors are listed after the text. As a rule, they are numbered consecutively throughout each paper and are indicated by arabic figures in parentheses.

The reports and papers are printed in the form in which they were presented to the Conference, and the affiliations of the participants are those in effect at that time. Corrections to the papers have been incorporated; some of the figures have been rearranged; and minor editorial changes have been made.

The views and opinions expressed are those of the individual authors and do not imply the expression of any opinion on the part of the Secretariat of the United Nations.

The symbols appearing after the titles of the papers and reports, and in references to them in the text, correspond to the symbols under which they were presented at the Conference. They have here been abbreviated by the elimination of the prefix "E/CONF.35/", which should, be included in all full references.

[1] United Nations publication, Sales No.: 62.1.21.

INTRODUCTION

La Conférence des Nations Unies sur les sources nouvelles d'énergie s'est tenue à Rome du 21 au 31 août 1961. Le document intitulé *Sources nouvelles d'énergie et production d'énergie : Rapport sur les travaux de la Conférence des Nations Unies sur les sources nouvelles d'énergie*[1] donne un aperçu des travaux, des mémoires soumis à la Conférence et des débats dont ceux-ci ont fait l'objet. Il contient en outre l'ordre du jour, la liste des membres du Bureau et des autres personnes ayant pris part à la Conférence, ainsi qu'une liste de tous les mémoires et rapports présentés.

Les Actes officiels de la Conférence comprennent les sept volumes suivants :

Volume 1. Sessions générales.
Volume 2. Énergie géothermique : I.
Volume 3. Énergie géothermique : II.
Volume 4. Énergie solaire : I.
Volume 5. Énergie solaire : II.
Volume 6. Énergie solaire : III.
Volume 7. Énergie éolienne.

Le présent volume, « Énergie solaire : II », groupe les mémoires et rapports ayant trait au point III. C. de l'ordre du jour, « Emploi de l'énergie solaire pour le chauffage », qui comprend cinq sous-points : III.C.1, Chauffage de l'eau; III.C.2, Chauffage des locaux; III.C.3, Séchage par la chaleur solaire; III.C.4, Cuisinières solaires; III.C.5, Accumulation de chaleur.

Les rapports généraux des rapporteurs et le résumé des débats sur chaque sous-point de l'ordre du jour qui a été établi par le rapporteur intéressé sont donnés intégralement, en anglais et en français, ainsi que

[1] Publication des Nations Unies, numéro de vente : 62.1.21.

les mémoires qui ont été soumis à la Conférence dans les deux langues. Sauf quelques exceptions, ils sont tous résumés en anglais et en français.

Pour chaque sous-point, les mémoires sont classés dans l'ordre alphabétique des noms d'auteurs. La liste des références fournies par les auteurs figure à la suite du texte. D'une façon générale, elles sont numérotées consécutivement pour chaque mémoire, et sont indiquées par des chiffres arabes entre parenthèses.

En règle générale, les rapports et mémoires sont publiés sous la forme dans laquelle ils ont été présentés à la Conférence, et les fonctions indiquées pour chaque participant sont celles qu'il occupait à cette époque. Toutefois, les corrections nécessaires ont été apportées et certaines figures ont été remaniées; des modifications de rédaction mineures ont de même été faites.

Les vues exprimées n'engagent que leur auteur et n'impliquent aucune prise de position de la part du Secrétariat de l'Organisation des Nations Unies.

Les cotes indiquées après les titres des mémoires et des rapports, ainsi que dans les renvois qui y sont faits dans le texte, correspondent aux cotes utilisées pour la Conférence. On les a cependant abrégées en éliminant « E/CONF.35 », qui doit être maintenu dans les cas où la référence complète est donnée.

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General report — Rapport général

Individual papers — Mémoires

* The first title refers to the original language; in most cases, it is followed by the translation in italics.

* Le premier titre est celui de la version originale; il est suivi, dans la plupart des cas, de sa traduction en caractères italiques.

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EXPLANATORY NOTE

The following symbols have been used in this volume:

A full stop (.) is used to indicate decimals; spaces are inserted to distinguish thousands and millions.

In most cases abbreviations used by the authors have been retained.

For conversion factors to be used in obtaining metric equivalents of British units, or British equivalents of metric units, see *World Weights and Measures*, prepared by the Statistical Office of the United Nations in collaboration with the Food and Agriculture Organization of the United Nations (Statistical Papers: Series M, No. 21; United Nations publication, Sales No.: 1955.XVII.2).

NOTE EXPLICATIVE

Les signes suivants ont été employés dans ce volume :

La virgule (,) indique les décimales; les espaces entre les chiffres distinguent les milliers et les millions.

Dans la plupart des cas, les abréviations utilisées par les auteurs ont été retenues.

Pour la conversion des mesures métriques en mesures anglaises et pour l'opération inverse, consulter la brochure *World Weights and Measures* que le Bureau de statistique des Nations Unies a établie avec le concours de l'Organisation des Nations Unies pour l'alimentation et l'agriculture (Études statistiques : série M, n° 21; publication de l'ONU, n° de vente: 1955.XVII.2).

Agenda item III.C

USE OF SOLAR ENERGY FOR HEATING PURPOSES

Point III.C de l'ordre du jour

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE

Chairmen — Présidents

III.C.1, III.C.2 — Roger N. Morse

III.C.3, III.C.4, III.C.5 — Freddy Ba Hli

Rapporteurs

III.C.1 : Isao Oshida

III.C.2, III.C.3, III.C.4 — George O. G. Löf

III.C.5 : Kailash N. Mathur

Agenda item III.C.1

USE OF SOLAR ENERGY FOR HEATING PURPOSES: WATER HEATING

Isao Oshida *

Solar water heaters represent the most widespread direct use of solar energy at the present time (S/38, S/31). The study of the technical problems, manufacture and installation of solar water heaters is proceeding in many areas in the solar belt (between latitudes 45°N and 45°S). These include Algeria, Australia, the Congo (Leopoldville), Burma, Chile, France, India, Iran, Israel, Italy, Japan, New Zealand, the United Arab Republic, South Africa, the United States of America, the Union of Soviet Socialist Republics, and others.[1] Eleven papers from nine countries have been contributed on this subject.

It is believed that a vast number of solar water heaters are in use in the world at present. In Japan, about 350 000 solar water heating units of various types were in use at the end of 1960, and the number is still increasing rapidly (S/68). In the United States, the former popularity of the box-type solar heaters is decreasing, but about 25 000 such units are still in use in Florida. Meanwhile, the solar heating of swimming pools is rapidly expanding (S/96). There are about 10 000 solar water heating units in use in Israel (S/26). Although the writer is not aware of the number of working solar water heaters in other countries, the figures mentioned probably represent a world-wide tendency.

The utility, the distribution, the optimum scale and design, the usage and the extent to which they help to save other fuels naturally differ from land to land. These considerations are presumably determined by the following four factors.

(*a*) The need for hot water and the objects for which it is required. This factor is important as it is the motive power in the use of water heaters. It is determined originally by the degree of development, the customs and the meteorological and geographical condition of the country concerned. These influence the quantity and the temperature of hot water needed, and the latter influence in turn the size, type and design of solar water heaters.

(*b*) The amount of solar energy available. This factor is chiefly determined by meteorological and geographical conditions, such as latitude, duration of sunshine, number of clear days in a year, mean cloudiness, transparency of the air, altitude, rainfall, mean air temperature and the temperature of the water supplied. The occurrence of freezing in winter is also an important problem because it sometimes causes damage to the solar water heaters.

(*c*) Technical attainment. Scientific and technical progress is, of course, one of the important factors. In particular, the introduction of new materials and mass production of equipment are most effective. As a result, the costs of manufacture, installation and maintenance are lowered and the life of the units becomes longer. Architectonic considerations should not be overlooked.

(*d*) Supply of other sources of energy. This last factor, which is also very important, concerns the supply and cost of other sources of energy in competition with solar energy. Oil, natural gas, coal and electricity are to be considered in many areas.

Though it is possible to list more detailed factors, these (S/38, S/58) seem to be classifiable into the four listed above. In the following discussion, the papers contributed to this agenda item are analysed and synthesized according to these four factors.

The demand for hot water

The demand for hot water, especially of water of from 40°C to 70°C, which are the temperatures most easily obtainable by solar water heating, is, of course, the first factor for widespread use of solar water heaters. This point is discussed by only a few contributors, but this by no means shows that the factor is to be ignored, but that it is a vast underlying factor difficult to measure.

A good example is represented by the active use of solar water heaters in Japan, as mentioned above, which is thought to be a natural result of the Japanese custom of taking a bath almost daily (S/68). On the other hand, in the United States, home swimming pools have increased very rapidly during the past few years, and the heating of the swimming pool water is one of the uses to be considered (S/96).

In most countries, hot water is used mostly for washing and cooking. The quantity of hot water necessary per day per person or per family (of from 2 to 4 members) is mentioned in some papers. The figures do not seem to be conflicting: 75 litre/person (S/1), 200 litre/family (S/58) and 170 litre/family (S/38).

Large-scale water heaters are and will be in use for buildings in which much hot water is demanded. The kinds of buildings mentioned in the papers

* Director, Kobayasi Institute of Physical Research, Tokyo.

[1] United Nations. Economic and Social Council. Recent developments relating to new sources of energy and recommendations regarding the agenda for an international conference. Report by the Secretary-General. 6 March 1959 (E/3218).

are as follows: public bath houses, dormitories, laundries, hospitals, schools, hotels and apartment houses.

The amount of solar energy available: meteorological conditions

Though solar energy availability is the subject of another agenda item (III. A.), this factor cannot be omitted here. However, the discussion will be confined to water heating only.

The number of fine days and of overcast days in a year is the first important consideration. Around Cairo, only 60 days are cloudy or semi-cloudy (S/50). In Israel, it is presumed to be 65 days (S/26). The data for Jerusalem show a somewhat larger value (S/31).

The duration of sunshine will be a more quantitative reference in this connection. All the regions located between latitude 45°N and 45°S and having over 2 000 hours of sunshine a year may be suitable for the use of solar water heaters (S/58). The data for New Delhi (2 844 hours) (S/102) and for Haifa, Jerusalem and Beit-Shean (S/31) were shown.

The intensity of solar radiation, I, is, of course, the most decisive element in this factor. The amount of insolation I per unit area depends on the angle between the sun's direction and the normal direction of the surface in question. Moreover, I depends on the time interval over which the instantaneous insolation is averaged. For the sake of reference to solar water heating, it is most convenient to know the value of I for a surface due south (in the northern hemisphere) or due north (in the southern hemisphere) and making any angle α, to horizontal plane, and averaged over any day of the year. Nevertheless, data for other surfaces or over other periods are, of course, also useful.

The intensity of instantaneous normal radiation in Israel (S/31), and the daily average in Cairo for $\alpha = 30°$ (equal to the latitude of Cairo) (S/50) and in Gainsville, Florida, for $\alpha = 0°$ (horizontal) (S/1) were shown. The latter two include sky radiation as well as direct solar radiation. These values vary from 810 btu/sq ft (Florida, December) to 2 400 btu/sq ft (Cairo, April).

The temperatures of the ambient air and that of the water supplied should be considered. These two temperatures are presumed to be equal or nearly equal by most authors.

Technical attainments

Most papers consider this factor in detail. Accordingly, it is thought to be reasonable to divide this factor into more detailed units.

Dimensions

As a matter of course, the size and the type of the examined solar water heaters are different. As for their size, roughly speaking, it may be divided into two groups: those of small-scale for households, and large-scale for public baths, laundries, dormitories, hospitals, etc.

The areas of the collectors of solar water heaters of the first group were, as if pre-arranged, nearly equal and about 2 sq m (or 21.5 sq ft) (S/58, S/96, S/68, S/26, S/50, S/102). This size can, therefore, be considered the standard unit of the collector area, which is a measure of the scale of solar water heaters. Heaters of double-size (S/31) or larger collectors (S/1, S/38) were recommended for household use by other contributors. Half-size collectors, being about 1 sq m, were tested only by laboratory experiment (S/72). For large-scale heaters of the second group, the collectors consist of rather small units of 1.5 sq. m. (S/26) or 3.3 sq. m. (S/68).

The water capacity is also a measure of the size of a solar water heater. This is equal to the capacity of the storage tank or, for the types without storage tank, to the capacity of the heater itself. The figures for the capacities of the storage tanks were from 120 litres to 400 litres for domestic use (S/58, S/31, S/26, S/50, S/1, S/102, S/38).

Types

Various types of heaters were discussed (S/1). Almost all can be divided into the following two categories: (*a*) absorbing and storing in the same unit; (*b*) absorbing and storing in separate units.

Pan-type heaters, simple types of category (*a*), have been improved and are widely used in the rural areas of Japan (S/68, S/1). Two box-type heaters, with capacities of 16 litres and 50 litres, respectively, were tested in Algeria (S/72).

Plastic "pillow" type solar water heaters, containing about 200 litre of water, are in mass production in Japan. About 150 000 units of this type had been sold up to the end of 1960 (S/68). The tube-in-strip type, without storage tank, is also common in Japan (S/68).

The types of category (*b*) were discussed by many contributors. These can be classified according to the construction of the absorber (S/1). Some papers were concerned with the tube-in-strip type, consisting of straight tubes, ducts with headers and a storage tank (S/68, S/1, S/38). The metal-in-strip type consists of a flat and a corrugated sheet, of equal area, riveted at several points along the lines of contact, so that the openings thus formed operate as in the case of straight tubes. Solar water heaters of this type can be made at lower costs (S/50, S/102). The sinusoidal tube type, consisting of a long tube bent back and forth sinusoidally to conserve space, is common in the United States (S/1). A new variation of this type, consisting of a long polyethylene tube bent sinusoidally and sandwiched by a pair of corrugated aluminium sheets, was tested (S/96).

Materials

Sheets and tubes of copper, aluminium and galvanized iron were the materials used for the absorbers and the water ducts mentioned in the papers (copper in S/68, S/1, S/38; aluminium in S/96, S/68; galvanized iron in S/68, S/50, S/102). To avoid corrosion of the iron plate coating by plastic film is proposed (S/68). Plastic tubes were tried (S/96), as well as glass tubes (S/38). Polyethylene sheets or polyvinylchloride sheets are among the promising materials recently introduced for solar water heaters (S/68). For storage tanks, the use of galvanized iron (S/72) or gasoline drum cans (S/68) are mentioned.

Absorbers

The main part of the absorber is in general a black surface of metal sheet, or surfaces of arranged metal tubes. A prescription of black paint is mentioned (S/102). The use of selective surfaces was tested or suggested (S/26, S/50, S/58).

The absorbers are generally put in hot boxes made of wood (S/68, S/102) or galvanized iron (S/1). As materials for back insulation, glass wool (S/96, S/50, S/1, S/102) or felt (S/1) was used in layers, 5 to 10 centimetres thick.

The number of glass covers for a hot box was discussed. The most effective number varies with the location and air temperature (S/1). Any increase in the number of glass layers reduces the heat losses but also reduces the energy transmitted (S/102). In place of a pane, a sheet of 0.005 inch (0.13 mm) thick Mylar film was tested (S/96).

Orientation of the absorber

A mechanism for making the absorber follow the sun is not practical for widespread use (S/1). It is easy to see that the best stationary orientation is due south in the northern hemisphere and due north in the southern hemisphere (S/1, S/38). In this position, the angle between the surface of the absorber and the horizontal plane is still to be determined to produce the best results. Sometimes the angle is presumed to be equal to the latitude (S/50), but most authors propose somewhat different angles, namely, 0.9 times the latitude (S/38), 10° greater than the latitude (S/31, S/1), 23.5° greater than the latitude in order to face the winter position of the sun at noon (S/26), 1.5 times the latitude (S/38), and 45° (in New Delhi) (S/102). By using larger angles, the absorber can receive nearly equal insolation at the summer and winter solstices (S/38). Of course, a mechanism for changing the inclination of the absorber will produce better results (S/58).

Circulation of water

Both natural (thermosiphon) and forced circulation were tried. The rate of flow from the absorber has an optimum value. This was a rather small value of 0.2 litre/min for a 2 sq. m. absorber (S/50). Higher rates of 0.5 litre/min or 0.7 litre/min (S/50, S/102) are more practical figures. To warm swimming pool water, a far higher flow rate, nearly 75 litre/min, was adopted to treat large amounts of water (S/96).

Temperature rise of water

Naturally, the rise of the temperature of water by solar heating varies with the weather, the area of the absorber, the flow rate, the type of heater, the air temperature, the temperature of water supplied, the wind velocity and other conditions. A test for a modified pan-type solar water heater, with a size of 0.9 m × 2.0 m and a capacity of 180 litres, showed that for a clear day in Tokyo the maximum water temperatures attained were 33°C in midwinter and 69°C in summer (S/68).

For circulation types, namely, for the types of category (*b*) mentioned above, the rise of the water temperature depends on the flow rate. For the sake of comparison, the results reported for solar water heaters with 2 sq m absorbers will be shown below. After exposure over a period of 6 hours a day, 190 litres of water were heated to 28°C, or 270 litres of water heated to 21°C for the winter months in northern India (S/102). In Cairo, a daily average temperature rise of 25°C was obtained for 270 litres as a yearly average (S/50). In most parts of Florida, on an average day in December, 250 litres of water can be heated from the air temperature to 60°C (S/1). Similar figures were obtained in Israel (S/31, S/26).

In the use of solar water heaters to warm swimming pools, the temperature of the pool increased by 4-6°F (in early spring or late autumn) or by 9-10°F (during summer) and the usual pool season was three times longer (i.e. 152 days compared to 50 days) in Princeton (S/96).

Amount of heat collected

The amount of heat collected by the solar water heater can be calculated from the daily temperature rise and the mass of water heated.

The following figures were obtained for absorbers of normal size, i.e. 2 sq m or 22 sq ft: 7 100 kcal/day, or 8.2 kWh/day (yearly average) (S/58); 5 550 kcal/day, or 6.7 kWh/day (Cairo yearly average) (S/50); 5 000-6 800 kcal/day, or 6-8 kWh/day (New Delhi) (S/102). Some other papers show figures for absorbers of other sizes (for 0.96 sq m, S/72; for 1.5 sq m, S/26; for 4 sq m, S/31).

Heat loss from the storage tank

The heat loss from the surface of the storage tank is the main factor to be considered. As an insulating material for storage tanks, a layer of glass wool 4 inches thick was proposed (S/102). In a paper, the value 6 btu/h/°F is given as the heat loss from a typical 70 gal (270 litre) tank. The loss in a day amounts to 15-20 per cent of the day's solar heat input (S/38). A value of 15 per cent loss is adopted by another author (S/31).

Efficiencies

It was noted that the efficiency of a solar water heater varies with the period over which the solar heat input and the heat loss are calculated (S/38). From the ratio of the heat collected in hot water to the integrated insolation on the surface of the absorber, the efficiency over 24 hours can be determined. The values reported for this efficiency are as follows: 50 per cent (S/72) and 35-45 per cent in summer and 50-60 per cent in winter (S/26). For a high rate of water flow, the efficiency becomes higher (S/102, S/96). The "instantaneous" efficiency, i.e. the efficiency measured in a ½-1 hour period, shows a high value in general, say, 70 per cent (S/38). A standard method of measuring the quantities in calculating the instantaneous efficiency was proposed (S/97).

The efficiency measured over a full year shows the lowest value in general. Typical values lie between 30 and 40 per cent (S/38, S/31). This is the efficiency that plays the most important role in the discussion of economic problems.

Auxiliary heating

The problem of auxiliary heating was discussed in some detail. The analysis showed that, in Israel, the amount of auxiliary heating can be reduced to 10-15 per cent of the total year-round heat. Auxiliary heating is mainly done by electricity. However, switching on or switching off the electrical resistance by hand causes a much higher use (25-30 per cent) of the auxiliary heating. In this connection, an automatic control device consisting of an electric clock and a thermostat is mentioned (S/31).

Large-scale solar water heaters

A large-scale solar water heater with a 66 sq m absorber has been constructed in Tokyo to supply hot water for more than 100 university students. Except in the winter season, it was able to supply 7 000 litres of hot water at over 50°C a day (S/68). Large solar water heaters, such as those with a capacity of 3 000 litres or 2 000 litres were reported (S/26).

Methods of preventing freezing

Some devices to prevent frost damaging solar water heaters were presented. Indentation in the upper and lower headers in the absorbers has been only partly effective (S/38). Plastic tubes were not damaged by freezing (S/96). Antifreeze mixture, such as water plus alcohol or water plus ethylene glycol, can be used for this purpose (S/58, S/1). To prevent frost damage, dual circulation systems were devised (S/1).

Cost per unit of energy

The cost per unit of energy obtained from a solar water heater is an essential factor in considering technical achievements. It is mainly determined by the initial investment and the life of the heater.

For the initial investment, the manufacturing cost or purchase price, the cost of installation and the interest on the initial cost for the period of durability should be taken into account.

A comparison of the manufacturing price or the selling price of various types of solar water heaters with various sizes of storage tanks is very difficult. The figures per square metre of absorbers were as follows: selling price, about U.S. $200 (S/58), $45 (S/50), $100 (S/31), $150, $90 (S/38), $60 (S/1); manufacturing price, about $52, $35 (S/102), $47 (S/26). These are only rough figures, and a comparison on the basis of these figures is almost meaningless because the materials, the capacity of the tank, the type and the characteristics of the heaters were very different. Nevertheless, these figures give, as a whole, the order of magnitude of the cost of solar water heaters at present.

The costs of installation are also difficult to compare for the same reason. The figures presented ranged from U.S. $30-60 (S/58) and $16 (S/26). The rate of interest per year was taken to be 5 per cent (S/26, S/31, S/38).

As for the life, or the durability, of solar water heaters, ten years (S/58, S/50, S/1) or eight years (S/31, S/26) were presumed.

Some authors ignored the maintenance expense, but others assumed 1 per cent (S/31) and 0.5-1.5 per cent (S/38) per annum of the initial cost.

Finally, the cost per unit of energy was calculated on the basis of the above figures. These were 1.5-1.9 US cents per kWh (S/58), 3 cents per kWh (S/31), 1.2 cents per kWh (S/26) and 0.37 cents per kWh (S/50). There is a wide variety, which is probably due chiefly to the different assumptions adopted by the different authors.

Supply of other sources of energy

The last factor is the existence and the price of other energy sources which compete with solar energy in heating water. Electricity and oil fuel were considered principally.

The prices of electricity per kWh shown in the papers are 4 cents (S/31), 3 cents (S/26, S/50), about 2 cents (S/102), 2.6 cents and 1.5 cents (S/38).

The prices of oil fuel per kWh of utilized energy were reported to be 0.55 cents (kerosene efficiency 33 per cent) (S/50) and 0.6 cents (S/38).

It is not easy to compare these different heat sources from the economical point of view. Calculation of the sale price, the life and the maintenance expense for different types of heaters also depends on many assumptions. Therefore, it is natural that the opinions shown by the different authors differed very much. In answer to the question "How many years does it take to cover the initial cost, if a solar water heater replaces an electric heater or an oil water heater?" the following values were given: for electricity, one year (S/50, S/102), eight years and thirteen years (S/38); for oil, three years (S/1), seven years (S/50), forty-five years (S/38).

Topics proposed for discussion

1. The present status of the use of solar water heaters.

2. The need for hot water in terms of objects, quantities and temperatures.

3. The amount of solar energy available, especially as a fundamental material for planning solar water heaters.

4. Technical problems :

Adequate size of solar water heaters for domestic use.

Adequate types of solar water heaters for domestic use.

New materials to be applied in solar water heaters,

Construction of absorbers, especially low-cost construction.

Orientation of the absorber.

Circulation of water, especially on devices concerned with the circulation system and on the rate of water flow.

The temperature of the heated water.

The amount of heat collected.

Heat loss from the storage tank, in relation to its construction.

Efficiencies and the methods of calculation.

Problems of auxiliary heating.

Large-scale water heaters, present situation and future prospects.

Methods of preventing freezing.

Cost per unit of heat quantity or per unit of energy.

Problems of standardization in construction and in methods of testing.

Problems of automation.

5. Economic problems :

Manufacturing costs.

Costs of installation.

Maintenance expense.

Life of solar water heaters.

Comparison with other sources of energy, such as electricity, oil, coal and atomic power in heating water.

6. Future developments, especially widespread use in under-developed regions.

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : CHAUFFAGE DE L'EAU

(Traduction du rapport précédent)

Isao Oshida *

Les chauffe-eau solaires représentent aujourd'hui le moyen le plus répandu d'exploiter directement l'énergie solaire (S/38, S/31). Dans un grand nombre de pays situés dans la « ceinture solaire » du globe (entre le 45e parallèle nord et le 45e parallèle sud), les problèmes techniques que posent la fabrication et l'installation des chauffe-eau solaires font l'objet d'études continues. Ces pays comprennent l'Algérie, l'Australie, le Congo (Léopoldville), la Birmanie, le Chili, les États-Unis, la France, l'Inde, l'Iran, Israël, l'Italie, le Japon, la Nouvelle-Zélande, la République arabe unie, l'Union des Républiques socialistes soviétiques, l'Afrique du Sud, et divers autres pays [1]. Onze communications provenant de neuf pays ont été préparées sur ce sujet.

Il est vraisemblable qu'il existe actuellement dans le monde un très grand nombre de chauffe-eau solaires couramment utilisés. Au Japon, près de 350 000 groupes de chauffage de l'eau par le soleil, de formules diverses, étaient utilisés à la fin de 1960; ce nombre croît rapidement (S/68). Aux États-Unis, le succès qu'avait connu le chauffe-eau solaire du type en caisson a diminué, mais il en existe encore quelque 25 000 en usage en Floride. En revanche, le procédé du chauffage des piscines par le soleil se répand rapidement (S/96). En Israël, il existe environ 10 000 chauffe-eau solaires en service (S/26). L'auteur de cette communication ne possède aucune indication précise sur le nombre de chauffe-eau solaires en usage dans les autres pays, mais les chiffres cités témoignent d'une tendance qui intéresse le monde entier.

Il est évident que d'un pays à l'autre il existe des différences considérables quant aux conditions d'utilisation de ces appareils, portant sur le service qui leur est demandé, sur les dimensions et les conceptions optimales, sur leurs applications et sur la mesure dans laquelle ils permettent d'économiser les autres combustibles. Ces considérations dépendent probablement des quatre facteurs suivants :

a) La demande d'eau chaude et les besoins pour lesquels elle a lieu. Ce facteur est important, car il est déterminant quant à la raison d'être des chauffe-eau solaires. Il dépend initialement du degré d'évolution, des coutumes, des conditions météorologiques et géographiques du pays considéré. Ces conditions influent sur la quantité d'eau chaude requise et sur sa température, ce qui d'autre part influe sur les dimensions, le type et la conception des chauffe-eau solaires.

b) L'importance de l'énergie solaire exploitable. Ce facteur dépend essentiellement des conditions météorologiques et géographiques, telles que la latitude, la durée de l'ensoleillement, le nombre de jours ensoleillés chaque année, la nébulosité moyenne, la transparence de l'atmosphère, l'altitude, le régime des pluies, la température moyenne de l'air et la température de l'eau à chauffer. Le gel pouvant se produire en hiver donne lieu également à un important problème, en considération des dégâts que peuvent subir les chauffe-eau solaires.

c) Possibilités techniques. Il est évident que le progrès scientifique et technique est l'un des facteurs importants. En particulier, l'adoption de matériaux nouveaux et la fabrication en série des éléments du matériel jouent un rôle décisif. Il en résulte une diminution des frais de fabrication, d'installation et d'entretien, en même temps que la longévité des ensembles s'allonge. Il convient de ne pas négliger les considérations relevant de l'architectonique.

d) Existence d'autres sources d'énergie. Ce dernier facteur, qui est aussi très important, est fourni par la quantité disponible et le prix des autres sources d'énergie qui peuvent concurrencer l'énergie solaire. Dans de nombreuses régions, le pétrole, le gaz naturel, le charbon et l'électricité doivent entrer en ligne de compte.

Une analyse plus complexe des facteurs peut être envisagée, mais il est possible, semble-t-il, de classer tous les facteurs sous l'une des rubriques ci-dessus (S/38, S/58), Dans l'exposé ci-après, les communications présentées seront analysées et synthétisées en fonction de ces quatre facteurs.

La demande d'eau chaude

La demande d'eau chaude, à une température comprise en particulier entre 40 °C et 70 °C, cet éventail étant celui que l'on peut obtenir le plus facilement avec l'énergie solaire, est, bien entendu, le premier des facteurs conditionnant l'extension de l'utilisation des chauffe-eau solaires. Ce point n'est abordé que dans un petit nombre des communica-

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[1] Nations Unies. Conseil économique et social. Faits nouveaux intervenus dans le domaine des sources nouvelles d'énergie et recommandations concernant l'ordre du jour d'une conférence internationale. Rapport du Secrétaire général, 6 mars 1959 (E/3218).

tions, ce qui ne signifie nullement que ce facteur ne doive pas être pris en considération, mais qu'il s'agit plutôt d'un facteur latent dont la mesure est particulièrement difficile.

En l'occurrence, un excellent exemple est fourni par l'utilisation intensive des chauffe-eau solaires au Japon, comme mentionné précédemment, ce que l'on peut attribuer naturellement à la coutume du bain quasi quotidien qui prévaut au Japon (S/68). D'un autre côté, aux États-Unis, les piscines privées se sont multipliées très rapidement au cours des dernières années, en sorte que le chauffage de l'eau des piscines apparaît comme l'un des usages à considérer (S/96).

Dans la plupart des pays, l'eau chaude est utilisée principalement pour le lavage et la cuisine. La quantité quotidienne d'eau chaude nécessaire par personne ou par famille (de 2 à 4 personnes) est mentionnée dans quelques communications. Les chiffres ne semblent pas se contredire : 75 litres par personne (S/1), 200 litres par famille (S/58) et 170 litres par famille (S/38).

Les chauffe-eau de grandes dimensions sont et seront utilisés pour les bâtiments ou immeubles où les quantités d'eau chaude requises sont importantes. En ce qui concerne les constructions de cette catégorie, les communications mentionnent les bains publics, les dortoirs, les blanchisseries, les hôpitaux, les écoles, les hôtels et les immeubles d'habitation.

L'importance de l'énergie solaire exploitable : conditions météorologiques

Encore que la question de la quantité d'énergie solaire exploitable forme le sujet d'un autre point de l'ordre du jour (III.A), ce facteur ne saurait être passé sous silence dans cet exposé. Cependant il n'y sera question que des considérations se rapportant au chauffage de l'eau.

Le nombre des journées à ciel clair et des journées à ciel couvert dans une année est la première des considérations importantes. Autour du Caire, on ne compte que 60 journées nuageuses ou partiellement nuageuses par an (S/50). En Israël, c'est sur 65 jours que l'on doit sans doute tabler (S/26), les chiffres fournis pour Jérusalem étant cependant plus importants (S/31).

La durée de l'ensoleillement sera une référence plus quantitative à ce propos. Toutes les régions s'étendant entre le 45e parallèle nord et le 45e parallèle sud et présentant plus de 2 000 heures d'ensoleillement par an peuvent remplir les conditions requises pour l'utilisation des chauffe-eau solaires (S/58). Les chiffres ont été fournis pour la Nouvelle-Delhi (2 844 heures) (S/102), pour Haïfa, Jérusalem et Beit-Shean (S/31).

L'intensité du rayonnement solaire, I, est, de toute évidence, l'élément le plus déterminant de ce facteur. La quantité d'insolation I par unité de surface dépend de l'angle formé par la direction du soleil et la direction normale de la surface considérée. En outre, I dépend de la durée de la période servant à la détermination de l'insolation moyenne instantanée. En ce qui concerne plus particulièrement le chauffage de l'eau par le rayonnement solaire, le plus commode est de connaître la valeur de I pour une surface orientée vers le sud (dans l'hémisphère nord) ou vers le nord (dans l'hémisphère sud) et faisant un angle α quelconque avec le plan horizontal, cette valeur faisant l'objet d'une moyenne pour chaque jour de l'année. Toutefois, il est évident que les chiffres correspondant à d'autres surfaces ou à d'autres périodes sont également utiles.

Les chiffres fournis concernent l'intensité du rayonnement normal instantané en Israël (S/31), la moyenne quotidienne au Caire pour un angle $\alpha = 30°$ (correspondant à la latitude du Caire) [S/50] et à Gainsville, en Floride, pour un angle $\alpha = 0°$ (surface horizontale) [S/1]. Les deux dernières valeurs tiennent compte du rayonnement du ciel (réverbération) aussi bien que du rayonnement solaire direct. Ces valeurs varient de 810 BTU/pied^2 ou 202 Kcal/0,092 m^2 (Floride, décembre), à 2 400 BTU/pied^2 ou 600 Kcal/0,092 m^2 (Le Caire, avril).

La température de l'air ambiant et celle de l'eau admise dans l'appareil doivent être prises également en considération. Ces deux températures sont par hypothèses tenues pour égales, ou presque égales, par la plupart des auteurs.

Possibilités techniques

La plus grande partie des communications traitent de ce facteur d'une manière détaillée. En conséquence, on peut admettre qu'il convient de fractionner ce facteur en divers éléments plus précis.

Dimensions

Il est bien entendu que les chauffe-eau solaires considérés diffèrent par les dimensions comme par la conception. En ce qui concerne les dimensions, il est possible de les répartir entre deux groupes — les chauffe-eau de faibles dimensions destinés aux maisons d'habitation, et les chauffe-eau de grandes dimensions conçus pour les bains publics, les blanchisseries, les dortoirs, les hôpitaux, etc.

Les chauffe-eau solaires du premier groupe possèdent des insolateurs dont la surface, dans tous les cas, est égale à 2 mètres carrés environ, comme si une entente était intervenue à ce sujet (S/58, S/96, S/68, S/26, S/50, S/102). Cette valeur peut donc être considérée comme l'unité de surface normalisée dans le cas des insolateurs, unité qui peut servir à la détermination de l'importance des chauffe-eau solaires. Des chauffe-eau correspondant à deux unités (S/31) ou des insolateurs plus grands (S/1, S/38) ont été préconisés pour les maisons d'habitation par certains autres auteurs. Des insolateurs correspondant à une demi-unité, c'est-à-dire d'une surface égale à 1 mètre carré environ, existent, mais appartiennent exclusivement au domaine des expériences de laboratoire (S/72). En ce qui concerne les chauffe-eau de grandes dimensions du deuxième groupe, leurs insolateurs sont composés de parties de dimensions relativement faibles : 1,5 mètre carré (S/26) ou 3,3 mètres carrés (S/68).

Le volume d'eau admis intervient également pour la détermination des dimensions d'un chauffe-eau solaire. Ce volume est égal à la capacité du réservoir d'emmagasinage, ou, dans le cas des modèles dépourvus de réservoir d'emmagasinage, à la capacité d'un chauffe-eau proprement dit. En ce qui concerne les ensembles destinés aux maisons d'habitation, la capacité des réservoirs d'emmagasinage varie de 120 à 400 litres (S/58, S/31, S/26, S/50, S/1, S/102, S/38).

Modèles

Divers modèles de chauffe-eau ont été présentés (S/1); ils peuvent se répartir à peu près tous entre les deux catégories suivantes : *a*) absorption et emmagasinage dans le même ensemble; *b*) absorption et emmagasinage dans des groupes séparés.

Les chauffe-eau du type en bac, qui sont les modèles les plus simples de la catégorie *a*, ont fait l'objet de perfectionnements et sont très largement répandus dans les régions rurales du Japon (S/68, S/1). Deux chauffe-eau du type en caisson, contenant respectivement 16 litres et 50 litres d'eau, ont été expérimentés en Algérie (S/72).

Les chauffe-eau du type en « vessie de plastique », qui contiennent environ 200 litres d'eau, sont fabriqués en grande série au Japon. A la fin de 1960, quelque 150 000 ensembles de ce modèle avaient été vendus (S/68). Le modèle à « série de tubes », sans réservoir d'emmagasinage, est également très répandu au Japon (S/68).

Les modèles de la catégorie *b* ont fait l'objet d'une étude de la part d'un grand nombre d'auteurs. Ils peuvent être classés selon le mode de construction de l'élément absorbant (S/1). Certaines communications traitent du modèle « série de tubes » caractérisé par des tubes rectilignes, des conduits à collecteurs et un réservoir d'emmagasinage (S/68, S/1, S/38). Le modèle à « bandes de métal » se caractérise par une tôle plate et une tôle ondulée de même surface apparente, assemblées par rivetage en plusieurs points le long des lignes de contact, les ondulations formant alors des conduits qui fonctionnent dans les mêmes conditions que des tubes rectilignes. Les chauffe-eau solaires de ce modèle se construisent à moindres frais (S/50, S/102). Le modèle à tube sinusoïdal, qui se caractérise par un long tube cintré en sinusoïde pour occuper le minimum de place, est très répandu aux États-Unis (S/1). Une variante de ce modèle a fait l'objet d'essais; elle fait intervenir un long tube de polyéthylène également cintré en sinusïode intercalé en sandwich entre deux tôles d'aluminium ondulées (S/96).

Matériaux de construction

Les matériaux mentionnés dans les communications comme servant à la fabrication des éléments absorbants et des conduites d'eau sont des tôles et tubes de cuivre, d'aluminium et de fer galvanisé (cuivre : S/68, S/1, S/38; aluminium : S/96, S/68; fer galvanisé : S/68, S/50, S/102). Pour prévenir la corrosion des tôles de fer, un revêtement constitué par une pellicule de matière plastique est préconisé (S/68). Des essais ont été effectués avec des tubes de plastique (S/96) et avec des tubes de verre (S/68). Des plaques de polyéthylène ou de chlorure de polyvinyle sont depuis peu au nombre des matériaux appelés à donner de bons résultats pour la fabrication des chauffe-eau solaires (S/68). En ce qui concerne les réservoirs d'emmagasinage, l'utilisation du fer galvanisé (S/72) ou des barils d'essence (S/68) a été mentionnée.

Éléments absorbants

La partie principale de l'élément absorbant est en général une surface noircie de tôle métallique, ou des surfaces de tubes métalliques spécialement disposées. L'usage d'une peinture noire est recommandée (S/102). L'utilisation de surfaces sélectives a fait l'objet d'essais ou a été proposée (S/26, S/50, S/58).

Les éléments absorbants sont généralement installés dans des coffres chauffants en bois (S/68, S/102) ou en fer galvanisé (S/1). En ce qui concerne le calorifugeage postérieur, les matériaux utilisés sont la laine de verre (S/96, S/50, S/1, S/102) ou le feutre (S/1), en couches de 5 à 10 centimètres d'épaisseur.

Le nombre des couches de verre requis pour un coffre chauffant a fait l'objet d'une étude détaillée. Le nombre optimal varie selon l'emplacement et la température de l'air (S/1). Toute augmentation du nombre des épaisseurs de verre réduit les pertes de chaleur mais réduit également l'énergie transmise (S/102). Pour remplacer le verre, une feuille de Mylar épaisse de 0,13 mm a été expérimentée (S/96).

Orientation de l'élément absorbant

Un mécanisme permettant à l'élément absorbant de suivre le soleil dans sa course n'est pas utilisable en usage courant (S/1). Il est facile de voir que l'orientation fixe la plus avantageuse est plein sud pour l'hémisphère nord et plein nord pour l'hémisphère sud (S/1, S/38). Avec cette orientation, l'angle que forme la surface de l'élément absorbant et le plan horizontal doit cependant être déterminé en vue des meilleurs résultats possibles. Cet angle est parfois supposé égal à la latitude (S/50), mais la plupart des auteurs préconisent des angles un peu différents, à savoir 0,9 fois la latitude (S/38), 10° de plus que la latitude (S/31, S/1), 23,5° de plus que la latitude pour obtenir que l'élément absorbant soit dirigé vers la position du soleil en hiver à midi (S/26), 1,5 fois la latitude (S/38) et 45° (à la Nouvelle-Delhi; S/102). En faisant appel à des angles plus grands, l'élément absorbant pourra recevoir des insolations pratiquement égales, aux solstices d'été et d'hiver (S/38). La présence d'un mécanisme permettant de faire varier l'inclinaison de l'élément absorbant garantira, naturellement, de meilleurs résultats (S/58).

Circulation de l'eau

La circulation naturelle (thermosiphon) et la circulation forcée ont été expérimentées toutes les deux. Le débit à la sortie de l'élément absorbant présente une valeur optimale. Cette valeur s'est révélée relativement faible, avec 0,2 litre/min. pour un élément absorbant de 2 mètres carrés (S/50). Des débits plus élevés de l'ordre de 0,5 litre/min. ou 0,7 litre/min. (S/50, S/102) correspondent à des chiffres plus acceptables. Pour le chauffage de l'eau d'une piscine, un débit considérablement plus élevé, près de 75 litres/min., a été adopté pour le traitement de grandes quantités d'eau (S/96).

Hausse de la température de l'eau

Naturellement, la hausse de la température de l'eau sous l'action du soleil varie selon les conditions atmosphériques, la surface de l'élément absorbant, le débit, le modèle du chauffe-eau, la température de l'air, la température de l'eau à l'admission, la vitesse du vent et divers autres facteurs. Une expérience faisant intervenir un chauffe-eau solaire du type à bac modifié, dont les dimensions étaient de 0,9 m × 2,0 m et la capacité de 180 litres, a fait apparaître qu'à Tokyo, le ciel étant parfaitement dégagé, la température maximum atteinte était de 33 °C au milieu de l'hiver et de 69 °C en été (S/68).

Pour les modèles à circulation d'eau, plus précisément pour les modèles de la catégorie b) mentionnée précédemment, la hausse de la température de l'eau dépend du débit. Pour permettre la comparaison, les résultats signalés pour le cas de chauffe-eau incorporant des éléments absorbants de 2 mètres carrés sont reproduits ci-après. Après une exposition d'une durée de six heures par jour, 190 litres d'eau ont été chauffés à 28 °C, ou 270 litres à 21 °C pendant les mois d'hiver dans le nord de l'Inde (S/102). Au Caire, une hausse quotidienne moyenne de température de 25 °C a été obtenue avec 270 litres d'eau, le chiffre moyen étant calculé sur une année (S/50). Dans la plus grande partie de la Floride, pour une journée moyenne de décembre, 250 litres d'eau peuvent être chauffés à 60 °C à partir de la température de l'air (S/1). Des résultats analogues ont été obtenus en Israël (S/31, S/26).

Lorsque les chauffe-eau solaires sont utilisés pour réchauffer les piscines, la température de la piscine augmente de 2-3 °C (au début du printemps ou à la fin de l'automne) ou de 5-6 °C (en été), ce qui permet de tripler la durée de la saison des bains en piscine à Princeton (152 jours contre 50; S/96).

Quantité de chaleur captée

Compte tenu de la hausse quotidienne de température et de la masse de l'eau chauffée, il est possible de calculer la quantité de chaleur captée par le chauffe-eau solaire.

Les chiffres suivants ont été obtenus avec des éléments absorbants de dimensions normales, c'est-à-dire de 2 mètres carrés : 7 100 Kcal/jour ou 8,2 kWh/jour (moyenne calculée sur une année; S/58), 5 550 Kcal/jour ou 6,7 kWh/jour (moyenne calculée sur une année au Caire; S/50), 5 000-6 800 Kcal/jour ou 6-8 kWh/jour (Nouvelle-Delhi; S/102). Quelques autres communications indiquent des chiffres correspondant à des éléments absorbants d'autres dimensions (0,96 m², S/72; 1,5 m², S/26; 4 m², S/31).

Pertes de chaleur imputables au réservoir d'emmagasinage

Les pertes de chaleur se produisant à la surface du réservoir d'emmagasinage sont le facteur essentiel dont il faut tenir compte. Pour le calorifugeage des réservoirs d'emmagasinage, un matelas de laine de verre de 10 cm d'épaisseur a été proposé (S/102). Une communication donne le chiffre de 6 BTU/heure/°F (1,5 Kcal/heure/½ °C) comme étant la perte de chaleur produite par un réservoir typique de 70 gallons (270 litres). La perte quotidienne correspond à 15-20 p. 100 de l'absorption quotidienne de chaleur solaire (S/38). Le chiffre de 15 p. 100 est adopté par un autre auteur (S/31).

Rendements

Il a été constaté que le rendement d'un chauffe-eau solaire varie selon la durée de la période pendant laquelle l'absorption de chaleur solaire et les pertes de chaleur sont calculées (S/38). Il est possible de déterminer le rendement en 24 heures en partant du rapport de la chaleur emmagasinée dans l'eau chaude à la somme du calorifugeage que porte la surface de l'élément absorbant. Les chiffres signalés pour ce rendement sont les suivants : 50 p. 100 (S/72); 35-45 p. 100 en été et 50-60 p. 100 en hiver (S/26). Lorsque le débit de la circulation d'eau augmente, le rendement s'élève (S/102, S/96). Le rendement « instantané », c'est-à-dire le rendement mesuré sur une période d'une demi-heure à une heure, est généralement élevé, de l'ordre de 70 p. 100 par exemple (S/38). Une méthode unifiée de détermination des quantités intervenant dans le calcul du rendement instantané a été proposée (S/97).

Le rendement mesuré sur toute une année accuse les chiffres en général les plus bas. Les valeurs typiques se situent entre 30 et 40 p. 100 (S/38, S/31). C'est là le rendement qui joue le rôle le plus important dans l'étude des problèmes de rentabilité.

Chauffage d'appoint

Le problème du chauffage d'appoint a été exposé d'une manière assez détaillée. L'analyse ainsi établie fait apparaître qu'en Israël, l'importance quantitative du chauffage d'appoint peut être ramenée à 10-15 p. 100 de la chaleur totale utilisée pendant l'année. Le chauffage d'appoint est obtenu principalement par l'électricité. Cependant, l'interruption ou la mise en marche manuelle de la résistance électrique se traduit par une utilisation beaucoup plus forte, 25 à 30 p. 100 du chauffage d'appoint. A ce propos, un dispositif automatique de commande, composé d'une minuterie électrique et d'un thermostat, est mentionné (S/31).

Chauffe-eau solaires de grandes dimensions

Un chauffe-eau solaire de grande capacité, incorporant un élément absorbant de 66 mètres carrés, a été construit à Tokyo pour fournir de l'eau chaude à plus d'une centaine d'étudiants d'université. Sauf pendant l'hiver, l'installation a pu débiter 7 000 litres d'eau à plus de 50 °C par jour (S/68). Des chauffe-eau de grandes dimensions, d'une capacité de 3 000 litres ou de 2 000 litres, ont été signalés (S/26).

Méthodes de protection contre le gel

Un certain nombre de dispositifs destinés à prévenir la détérioration par le gel des chauffe-eau solaires ont été présentés. Le procédé consistant à pratiquer des échancrures dans les collecteurs supérieurs et inférieurs des éléments absorbants ne s'est révélé que partiellement efficace (S/38). Les tubes de plastique n'ont pas été détériorés par le gel (S/96). L'adjonction à l'eau d'un produit antigel, comme l'alcool ou l'éthyl-glycol, peut être adoptée (S/58, S/1). Pour prévenir les détériorations dues au gel, des systèmes à double circulation ont été conçus (S/1).

Prix de revient de l'unité d'énergie

Le prix de revient de l'unité d'énergie obtenue avec un chauffe-eau solaire est un élément essentiel à considérer lorsqu'il est question d'étudier les résultats techniques à prévoir. Ce prix de revient dépend principalement de l'investissement initial et de la durée du chauffe-eau.

En ce qui concerne les dépenses initiales, il convient de prendre en considération les frais de construction ou le prix d'achat, les frais d'installation et l'amortissement des dépenses initiales sur la période correspondant à la longévité du chauffe-eau.

Il est extrêmement difficile d'établir une comparaison des frais de construction ou des prix d'achat des divers modèles de chauffe-eau solaires incorporant des réservoirs d'emmagasinage de capacités différentes. Par mètre carré de surface des éléments absorbants, les chiffres sont les suivants : prix d'achat, environ 200 dollars des États-Unis (S/58), 45 dollars (S/50), 100 dollars (S/31), 150 dollars, 90 dollars (S/38), 60 dollars (S/1); frais de construction, environ 52 dollars, 35 dollars (S/102), 47 dollars (S/26). Il ne s'agit que d'approximations, en sorte qu'une comparaison fondée sur ces chiffres est pratiquement dépourvue d'intérêt, étant donné que les matériaux, la capacité des réservoirs, les modèles et les caractéristiques des chauffe-eau sont extrêmement différents. Quoi qu'il en soit, ces chiffres donnent en gros une idée de l'ordre de grandeur du prix des chauffe-eau solaires à l'heure actuelle.

Les frais d'installation ne peuvent guère se comparer, pour les mêmes raisons. Les chiffres signalés s'échelonnent de 30-60 dollars des États-Unis (S/58) à 16 dollars (S/26). En ce qui concerne le taux d'amortissement, il est donné comme étant de 5 p. 100 (S/26, S/31, S/38).

En ce qui concerne la durée des chauffe-eau solaires, on admet qu'elle peut s'établir autour de dix ans (S/58, S/50, S/1) ou de huit ans (S/31, S/26).

Certains auteurs ne tiennent pas compte des frais d'entretien, alors que d'autres les chiffrent pour une année à 1 p. 100 (S/31) et à 0,5-1,5 p. 100 des dépenses initiales.

Enfin, le prix de revient de l'unité d'énergie a été calculé sur la base des chiffres précédents. Il s'est établi à 1,5-1,9 cent par kWh (S/58), 3 cents par kWh (S/31), 1,2 cent par kWh (S/26) et 0,37 cent par kWh (S/50). Les écarts sont extrêmement marqués, ce qui s'explique surtout par les hypothèses différentes adoptées par les auteurs.

Existence d'autres sources d'énergie

Le dernier facteur entrant en ligne de compte, c'est l'existence et le prix des autres sources d'énergie pouvant être utilisées pour le chauffage de l'eau, en concurrence avec l'énergie solaire. L'électricité et les combustibles extraits du pétrole ont été particulièrement pris en considération.

En ce qui concerne l'électricité, les prix par kWh cités dans les communications sont les suivants : 4 cents (S/31), 3 cents (S/26, S/50), 2 cents environ (S/102), 2,6 cents et 1,5 cent (S/38).

Par kWh d'énergie utilisée, les prix mentionnés pour les combustibles dérivés du pétrole sont 0,55 cent (kérosène, rendement 33 p. 100; S/50) et 0,6 cent (S/38).

Il n'est pas facile de comparer ces diverses sources de chaleur du point de vue économique. Le calcul du prix d'achat, de la durée et des frais d'entretien, dans le cas des différents modèles de chauffe-eau, est aussi subordonné à un grand nombre d'hypothèses. Il est donc naturel que les opinions exprimées par les divers auteurs puissent différer considérablement. En réponse à la question suivante : « Combien d'années faut-il pour amortir les dépenses initiales, dans le cas où un chauffe-eau solaire remplace un chauffe-eau électrique ou un chauffe-eau à combustible liquide? », les chiffres suivants ont été cités. Électricité : un an (S/50, S/102), huit ans et treize ans (S/38); combustible dérivé du pétrole : trois ans (S/1), sept ans (S/50), quarante-cinq ans (S/38).

Sujets de discussion proposés

1. L'utilisation des chauffe-eau solaires; situation actuelle.
2. La demande d'eau chaude considérée du point de vue des besoins et des quantités et températures requises.
3. Le volume de l'énergie solaire disponible, notamment en tant qu'élément de base servant à la conception des chauffe-eau solaires.

4. Problèmes techniques :
   - Dimension optimale des chauffe-eau solaires à usage domestique.
   - Types optimaux de chauffe-eau solaires à usage domestique.
   - Nouvelles matières que l'on peut utiliser dans les chauffe-eau solaires.
   - Construction des éléments absorbants envisagée particulièrement sous l'angle des réductions de frais.
   - Orientation de l'élément absorbant.
   - Circulation de l'eau, notamment examen des appareils réglant la circulation et le débit de l'eau.
   - Température de l'eau chauffée.
   - Volume de chaleur capté.
   - Perte de chaleur du réservoir d'accumulation, envisagée sous l'angle de la construction.
   - Rendement et méthodes de calcul du rendement.
   - Problèmes du chauffage d'appoint.
   - Chauffe-eau solaires de grandes dimensions : situation actuelle et perspectives d'avenir.
   - Procédés utilisés pour empêcher le gel.
   - Coût par unité de volume de chaleur ou par unité d'énergie.
   - Problèmes de normalisation de la construction et des méthodes d'essai.
   - Problèmes de l'automatisation.
5. Problèmes économiques :
   - Coûts de fabrication.
   - Coûts d'installation.
   - Frais d'entretien.
   - Longévité des chauffe-eau solaires.
   - Comparaison des autres sources d'énergie qui peuvent servir au chauffage de l'eau, telles que l'électricité, le pétrole, le charbon et l'énergie atomique.
6. Perspectives d'avenir, notamment utilisation à une large échelle dans les régions sous-développées.

USE OF SOLAR ENERGY FOR HEATING PURPOSES: WATER HEATING

Rapporteur's summation

The session concerned with solar water heating —that is, agenda item III.C.1—had before it eleven papers contributed by authors from nine countries.

The first point of importance that was discussed was the widespread use of solar water heaters in favourable localities, such as occur in Israel and Japan, and in many other countries as well. It was stressed that hundreds of thousands of solar water heaters are actually saving fuel amounting to hundreds of thousands of tons per year. At present, no other direct use of solar energy competes with solar heating in the amount of energy used.

The second point of importance related to the problem of efficiency. Two types of efficiency were considered: physical efficiency and economic efficiency.

Efficiency in its physical sense is measured by the ratio of heat collected in hot water to the integrated insulation on the surface of the absorber. This efficiency varies with the time period over which the quantities are calculated. Efficiency for a few hours near noon of a fine day is generally high, and a figure of over 70 per cent can be obtained easily. Efficiency over a day or a full year is naturally lower than this, because of the inclusion of nights or cloudy days, in which the absorber does not operate or operates incompletely.

With this fact taken into consideration, the figures on reported efficiencies may be said to be near one another. A typical value of efficiency over an entire year for a solar water heater with a storage tank lies between 30 and 40 per cent. These values appear high if compared with the efficiency of solar batteries or other solar energy converters. Efforts to enhance efficiency are of course necessary, but they have to be made without greatly increasing the expense. In most cases it is deemed satisfactory if a solar water heater with an efficiency rating of 40 per cent is reduced to 30 per cent efficiency and if, at the same time, the price is reduced by half.

This leads to the question of efficiency in an economic sense. This is measured by the quantity of heat energy obtainable for a unit investment in a solar water heater. The opinion of different contributors at the Conference differed very much. Regarding efficiency in the economic sense, my own opinion is that more careful calculations led to lower values. The figure given by one of the most careful authors was 0.3 kWh of heat energy for one US cent. This figure cannot be considered high, even if it is compared with that for electricity. Efforts to reduce the cost of solar water heater units are required. Reductions will be accomplished by the introduction of new materials, such as synthetic plastics and selective surfaces, by improvement in design, and by mass production.

One speaker stressed the need of standardized testing methods for solar water heaters. This is no doubt an important matter. Some standardization, however, of the solar water heater itself would be useful in mass production and, accordingly, in lowering costs.

Most speakers were concerned with installations, improvement in design and performance, and future plans for development. They submitted useful suggestions for the solar water heaters of the future.

Another problem that was earnestly discussed was the need for solar water heaters that were simpler in design and lower in cost, especially for use in under-developed countries. There seemed to be a gap between solar water heaters being studied or used in economically developed countries and those warmly welcomed by the people of under-developed countries.

There appears to be a promising future course for solar water heating. A great number of solar water heaters are already in use in some countries, and the number is still increasing rapidly. Technological improvements are being made; costs are gradually being lowered. Although some problems remain to be solved, the facts indicate that the use of solar water heaters in under-developed countries will become popular.

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : CHAUFFAGE DE L'EAU

Résumé du rapporteur

A la séance consacrée au chauffage de l'eau par l'énergie solaire — point III.C.1. de l'ordre du jour — onze mémoires présentés par des auteurs originaires de neuf pays ont été examinés.

Le premier point important examiné a été l'usage très répandu de chauffe-eau solaires dans des pays situés à une latitude favorable, comme Israël, le Japon et bien d'autres. On a souligné que des centaines de milliers de chauffe-eau solaires permettent actuellement d'économiser des quantités de combustibles équivalant à des centaines de milliers de tonnes par an. Pour le moment, aucune autre utilisation directe de l'énergie solaire ne peut se comparer au chauffage solaire pour ce qui est de la quantité d'énergie employée.

Le deuxième point important avait trait au problème du rendement. Deux aspects ont été considérés: le rendement physique et la rentabilité.

Le rendement est le rapport de la chaleur recueillie dans l'eau chaude à l'énergie solaire intégrée recueillie à la surface de l'absorbeur. Ce rapport varie en fonction du temps pendant lequel on calcule les quantités. Pendant quelques heures vers midi, par une belle journée, il est généralement élevé et on peut obtenir facilement un rapport supérieur à 70 p. 100. Le rendement quotidien ou annuel est naturellement moins élevé car il faut tenir compte des nuits, des jours non ensoleillés pendant lesquels l'absorbeur ne fonctionne pas du tout ou fonctionne partiellement.

Compte tenu de cela, on peut dire que les rendements signalés sont assez proches les uns des autres. Un rendement normal pendant une année entière pour un chauffe-eau solaire équipé d'un réservoir d'accumulation s'établit aux environs de 30 à 40 p. 100. Il paraît élevé si on le compare à celui des batteries solaires ou autres convertisseurs solaires d'énergie. Il faut bien entendu s'efforcer de l'accroître, mais sans augmenter considérablement la dépense. En général, le résultat est jugé satisfaisant si le rendement d'un chauffe-eau solaire ne tombe que de 40 p. 100 à 30 p. 100 lorsqu'on réduit de moitié le prix de l'appareil.

Cela nous amène à la question de l'efficacité au sens économique. C'est la quantité d'énergie calorique obtenue pour un investissement donné dans un chauffe-eau solaire. Sur ce point, les divergences d'opinion des participants ont été très grandes. Plus les calculs ont été poussés, plus les valeurs obtenues ont été petites. Un des auteurs les plus prudents a avancé le chiffre de 0,3 kWh d'énergie thermique pour 1 cent (États-Unis). On ne peut pas considérer que ce chiffre soit élevé, même si on le compare au prix de l'électricité. Il faut donc s'efforcer d'abaisser le prix des chauffe-eau solaires. On y parviendra en utilisant des matières nouvelles comme les matières plastiques synthétiques et des surfaces sélectives, en perfectionnant les modèles et en organisant la production de masse.

Un orateur a souligné la nécessité de normaliser les méthodes d'expérimentation des chauffe-eau solaires. La question est assurément importante. Mais une certaine normalisation des appareils mêmes serait utile pour la production en série et, par conséquent, pour abaisser les prix.

La plupart des orateurs ont traité des installations, de l'amélioration des modèles et de leur fonctionnement et des perspectives d'avenir. Ils ont fait des suggestions intéressantes en ce qui concerne les chauffe-eau solaires de l'avenir.

On a aussi longuement discuté de la nécessité de construire des chauffe-eau solaires plus simples et moins chers destinés en particulier à être utilisés dans les pays sous-développés. Il semble qu'il y ait une grande différence de conception entre les appareils qui sont mis au point ou utilisés actuellement dans les pays développés et ceux qui sont accueillis avec satisfaction par les populations des pays sous-développés.

L'avenir des chauffe-eau solaires paraît intéressant. Ces appareils sont déjà utilisés en grand nombre dans quelques pays et leur nombre va rapidement croissant. La technique progresse et les prix baissent peu à peu. S'il reste bien des problèmes à résoudre, tout indique que l'emploi des chauffe-eau solaires va se répandre dans les pays sous-développés.

TEN YEARS' EXPERIENCE WITH SOLAR WATER HEATERS IN THE UNITED ARAB REPUBLIC

M. S. M. Abou-Hussein *

The southern province (Egypt) of the UAR has a limitless amount of sunshine compared with other countries. On the average, only sixty days per annum are cloudy or semi-cloudy around Cairo. The daily total direct and sky radiation incident upon a south-facing surface tilted 30° from horizontal at Cairo latitude (30° north) during cloudless days varies from a maximum of about 2 400 btu/sq ft/day during April to a minimum of about 2 000 btu/sq ft/day during January. A one sq meter solar water heater of an over-all efficiency of 70 per cent may heat, therefore, about 110 litres of water per day from the April average temperature of 21°C to 55°C, or about 80 litres of water per day from the January average temperature of 13.8°C to 55°C. The solar heater may also heat about 132 litres of water per day during August having a maximum incident radiation of about 2 200 btu/sq ft/day from the average temperature of 28.6 to 55°C.

In other words, a heater of one square meter area may heat annually a quantity of water to 55° ranging from a minimum of about 80 litres/day to a maximum of about 132 litres/day.

The importance of these figures is apparent when the continuity of the sunshine during at least 10 months per year, and the relatively high cost of fuel (other than solar) used at present for water heating, are pronounced.

During the past ten years, different types of solar water heaters were made and their use was confined to laboratory experiments. The basin open cycle type, characterised by its low cost, was found suitable for rural use, and the unit was standardized to be of one square meter area and multiples. The metal-in-strip closed cycle type, found suitable to heat water for city and country services, e.g., hospitals, hotels, schools, private and public houses and for country public washing units, is standardized to have two square meters area and multiples. For big installations, e.g., the university city and the like, any size, other than the standard size mentioned, may be made in metal-in-strips. With the two square meter metal-in-strip heater, the storage tank has a capacity of about 150 litres. The natural circulation (thermosiphon) system or the forced circulation system with a pump controlled either thermostatically or by radiation may be used. The plastic "pillow" or "dish" type of solar water heater is in its early stage of laboratory testing.

In tables 1 and 2, tests made on a metal-in-strip heater, 2 square meters area, with forced water circulation, are given, but preceded by the solar radiation and average ambient yearly temperatures at the place of testing.

Table 1. Daily total direct and sky radiation incident upon a south facing surface tilted 30° from horizontal at Cairo (30° north) during cloudless days

First day of	*Incident radiation btu/sq ft day*
January	1 970
February	2 100
March	2 280
April	2 390
May	2 400
June	2 300
July	2 280
August	2 350
September	2 400
October	2 300
November	2 200
December	2 000

Table 2. Average air temperature °C at Cairo-South during the years 1951-1956

Year	*1951*	*1952*	*1953*	*1954*	*1955*	*1956*
January	14.3	13.9	13.0	12.4	14.9	14.4
February	15.1	15.5	15.3	14.4	18.0	16.5
March	19.2	17.4	14.7	18.4	18.4	16.0
April	21.4	21.7	21.3	19.9	21.8	21.0
May	26.2	24.9	26.1	26.3	24.6	23.4
June	27.1	26.9	27.7	27.3	28.1	27.7
July	28.1	27.8	29.5	28.6	28.7	28.8
August	28.8	29.5	28.2	28.8	27.4	29.1
September	27.7	28.2	25.6	25.4	26.9	28.0
October	24.9	25.0	23.7	23.5	25.1	22.2
November	19.1	19.6	17.4	19.4	19.6	19.4
December	12.2	16.6	13.7	14.2	15.1	14.3
Average	22.1	22.2	21.4	21.6	22.4	21.8

Performance

The heater is made of one corrugated galvanised iron sheet and a plane sheet. The two sheets are riveted at several points along the lines of contact. The end edges are soldered to square headers made

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Table 3. Variable discharge test at maximum incident radiation: heater area 2 sq m; tilt 30° with horizontal; latitude 30° north; date: 13/4/60; sky: sunshine; duration of test: 12.30-13.30; inlet water temp. = 22°C

Discharge litres/min	*Temp. rise °C*	*Discharge litres/min*	*Temp. rise °C*
0.2	62	1	25
0.3	50	2	17
0.4	41	3	13
0.5	35	4	12
0.75	30	5	11
		6	10

also of galvanised iron of thicker gauge. Cold water is let in at the lower end and flows up the channels (eight per meter) into the upper header. The plane sheet is 1 × 2 meters and about 0.50 mm thickness. Two 3 mm thickness glass covers are used with about 2 cm spacing. About 5 cms space exists between the lower glass cover and the plane iron sheet. The back insulation is glass wool of about 5 cms thickness. The iron surface was blackened by a suitable method.

In one test water at 22°C, was pumped through the heater at different rates obtaining results in Table 3.

Similar tests were made with heaters of areas of 4, 6 and 8 square meters and the results are given in Table 4.

The temperature-hour curves of the heaters of the mentioned areas are given in Table 5.

Some economic aspects

A 2 sq meter solar heater may heat yearly a daily average of 270 litres with a daily average temperature rise of 25°C. Thus the useful daily heat energy obtainable from such a heater will be 6 750 Kcal/day. A yearly figure corresponding to 300 days of sunshine in the Cairo area will be 2 025 000 Kcal/annum.

The three sources of fuel mainly in use for water heating are kerosene, butane gas and electricity. The fuel weight equivalent to the annual K calories usefully obtained from the heater are respectively: 607 kgm of kerosene, 200 kgm of butane gas and 2 600 kW hr. (The calorific values of kerosene and butane gas are assumed to be 10 000 and 12 000 K cal/kgm respectively. The over-all efficiencies of the heaters, including combustion efficiency, were taken as 33 per cent, 80 per cent and 92 per cent for the cases of heating by kerosene, butane gas and electricity respectively.)

The corresponding price of the fuel saved by using a 2 sq meter solar heater for one year will thus amount to the following, based on the existing market prices:

£Egyptian 6.07 or $US 13.50 of kerosene
£Egyptian 6.20 ($US 13.73) of butane gas
£Egyptian 32.40 ($US 72.00) of electricity

The manufacturing cost of the solar heater with the tank amounts to £Egyptian 32 or $US 71.1 and its sale price is about £Egyptian 40 or $US 90.

Table 4. Variable discharge tests at maximum incident radiation (under all conditions of Table 3)

Discharge litres/min	*4 m²*	*6 m²*	*8 m²*
	Temperature rise °C		
0.2	70	74	
0.3	60	67	72
0.4	56	60	66
0.5	53	57	61
0.75	42	51	55
1	36	44	51
2	24	33	42
3	22	29	36
4	21	26	33
5	19	24	30
6	17	21	27

Table 5. Constant discharge test (all conditions of Table 3 except: inlet water temperature: 22.1°C; test duration: 7-17 hours; date: 27/4/60; constant discharge of 0.50 litre/min.)

Hour	*2 m²*	*4 m²*	*6 m²*	*8 m²*
	Water outlet temperature °C			
7	28	34	38	41
8	33	41	46	49
9	40	49	55	59
10	45	57	64	70
11	52	64	71	76
12	55	71	76	81
13	57	73	79	84
14	51	71	78	83
15	44	66	74	77
16	37	56	63	68
17	32	45	54	59

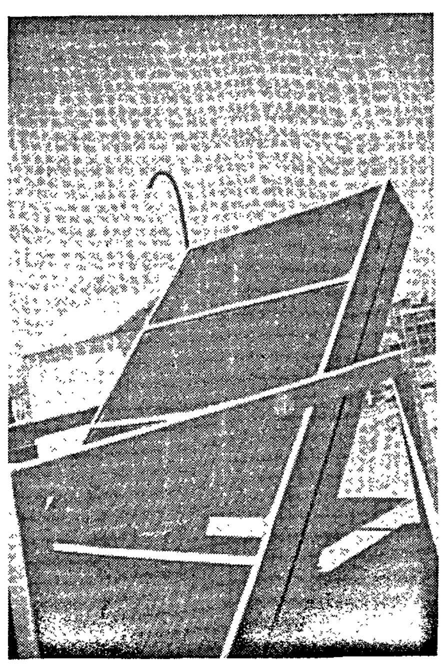

Table 6. Average yearly expenses for the different types of heaters*

Type	*Kerosene*	*Butane gas*	*Electricity*	*Solar*
Sale price ($US) . . .	3.3	90	111	90
Life (years)	3	10	10	10
Fuel cost, $US/year . .	13.5	13.73	72.00	0
Depreciation, $US/year	1.1	9.00	11.10	9.0
Total yearly expenses, $US/year	14.6	22.73	83.10	9.00

* Neglecting maintenance expenses in each case.

The average yearly consumer expenses for the existing and solar water heaters are mentioned in Table 6.

This shows that heating water by solar energy is the cheapest method, and it covers its initial cost in not more than 7 years if it replaces the non-efficient kerosene water heaters, and in one year if it replaces the most expensive electric heaters.

Suggested technical improvements

The following proposals are suggested in this respect:

Changing the bulky shape of the heater.

Producing an efficient water pump to enable the use of the tank indoors below the heater.

Introducing a selective paint instead of using the electroplating method. The paint should be cheap in cost and easy to apply by brush. At the same time, it should not be oxidized or change its colour through prolonged exposure to sunlight.

Reducing the cost by introducing new cheap materials which are absorptive to solar radiation and non-emissive to heat energy.

Summary

The paper shows the present status of solar water heaters in the UAR, and a review of their development from the early open-cycle basin type to the recent metal-in-strip closed-cycle type with storage tank.

It is shown that a one square meter solar heater may heat annually a quantity of water to 55°C ranging from a minimum of about 80 litres per day in January to a maximum of about 132 litres per day in August. The heater has a 30° tilt with the horizontal at 30° north latitude.

Tables of the monthly total incident solar radiation in btu/sq ft/day upon a south facing surface tilted by 30° from horizontal at Cairo latitude and of the average monthly air temperatures in degrees centigrade at Cairo-south during the years 1951-1956 are given.

Test results of solar water heaters showing the variation in the temperature rise with the water discharge for a fixed heater area, and in the water outlet temperature with the hours of the day for a constant discharge and a specified heater area are included. Also similar results obtained with different heater areas are added. The heater areas used are 2, 4, 6, 8 square meters.

It is shown that at constant discharge rate of 0.2 litres per min, the optimum temperature rises reached under test conditions were 62, 70, 74°C, for the 2, 4, and 6 square-meter heater areas respectively. At 0.5 litres/min discharge the corresponding water temperatures for the four areas at 13.00 hours were 57, 73, 79, 84°C.

The economic value of the solar water heating in comparison with water heating by kerosene, butane gas and electricity was expressed as "the average yearly consumer total expenses". The comparison was based on equal useful heat output from each heater and the figures were found to be:

The average yearly consumer total expenses

Kerosene	*Butane gas*	*Electricity*	*Solar*
14.6	22.73	83.10	9.0

The figures are in $ US and the maintenance expenses are ignored for each case.

The comparison shows that water heating by solar energy is the cheapest method.

Several technical suggestions are mentioned, dealing with reducing the heater cost and improving the efficiency of operation.

DIX ANS D'EXPÉRIENCE DES CHAUFFE-EAU SOLAIRES DANS LA RÉPUBLIQUE ARABE UNIE

Résumé

Ce mémoire présente une étude du développement actuel des chauffe-eau solaires dans la République arabe unie, ainsi qu'une revue de leur évolution, depuis le modèle à bassin et à cycle ouvert des premiers jours jusqu'aux modèles récents à bandes de métal et à cycle fermé, avec réservoir d'énergie.

L'auteur montre comment un dispositif de chauffage solaire d'un mètre carré peut annuellement porter à 55 °C une quantité d'eau allant d'un minimum de 80 l par jour en janvier à un maximum de 132 l environ en août. Sous 30° de latitude nord, le collecteur est incliné à 30° sur l'horizontale.

Le mémoire donne des tables indiquant les totaux mensuels d'énergie solaire incidente sur une surface orientée au sud et inclinée à 30° sur l'horizontale à la latitude du Caire, ainsi que la température moyenne de l'air en degrés centésimaux à la station du Caire-Sud au cours des années 1951-1956.

L'auteur reproduit les résultats d'essais exécutés avec les chauffe-eau solaires indiquant la variation de la montée de température avec le débit d'eau pour une surface fixe de collecteur, ainsi que la variation de température au robinet d'eau suivant les heures du jour et une surface de collecteur également donnée, à débit constant. Il ajoute à ces statistiques les résultats qu'ont donné des éléments chauffant de surfaces différentes. Les surfaces utilisées furent de 2, 4, 6 et 8 m².

Le mémoire montre que, pour un débit constant de 0,2 litre à la minute, la montée de température idéale réalisée dans des conditions d'essai s'est établie à 62,7 et 74 °C respectivement pour les surfaces de collecteur indiquées. Quand le débit moyen à la minute est de 0,5 litre, les températures d'eau correspondantes à 13 h sont de 57, 73, 79 et 84 °C.

L'auteur exprime la valeur économique du chauffe-eau solaire, pour la comparer à celle des méthodes qui font appel au pétrole, au butane et à l'électricité, sous forme de « frais annuels totaux moyens de l'usager ». La comparaison repose sur l'hypothèse que chaque chauffe-eau donne un débit de chaleur utile égal à celui des autres. En se basant sur les prix locaux, on trouve les chiffres suivants :

Frais annuels totaux de l'usager

Type de chauffage

Au pétrole	*Au butane*	*A l'électricité*	*Solaire*
14,6	22,73	83,10	9,0

Les chiffres sont donnés en dollars des États-Unis et on a laissé de côté dans chaque cas les frais d'entretien.

La comparaison indique que le chauffage solaire est le plus économique.

L'auteur présente plusieurs suggestions d'ordre technique, lesquelles portent essentiellement sur la réduction des frais de premier établissement et les moyens d'améliorer le rendement du système.

SOLAR WATER HEATERS

Stella Andrassy *

Solar water heaters are probably the best known and most widely established solar devices. The "classical" design consists of an insulated box, covered with transparent panes. A black-coated metal heat absorber is inside the box, with metal coils soldered to it for the circulation of water.

For heating domestic hot water the former popularity of box-type solar heaters is decreasing in the United States, only about 25 000 units are still in use in Florida. During the past years, however, interest in solar water heaters has been revived in a new field: for heating swimming pools (1). The expansion of swimming pool construction has been rapid during the past few years and in 1960 more than 311 000 pools were in use (2).

In countries where natural fuel is scarce and expensive, solar water heaters are becoming increasingly important for domestic use. This is indicated by previous articles by scientists who are present at this Conference (3,4,5,6).

Characteristics of a new design

The writer has developed and tested an inexpensive new solar water heater which combines sheet metal with durable plastic tubing. The solar heater is made of panels of modular sizes. Black-coated light gauge sheet metal is corrugated in a special way to form tubular openings. Plastic pipe is inserted into the tubular openings forming a continuous coil. Sheet aluminum 0.019 inch thick has been used, the corrugations being spaced 2 to 3 inches on center. Flexible polyethylene has been used successfully for moderately warm temperatures, while other plastics for higher temperatures areb eing tested.

Copper powder has been mixed with polyethylene to increase the heat conductivity of the tubing and to improve heat transfer through the tube wall. The natural color of this tubing is gold-yellow and the exposed parts are coated with dull black for protection against damage by solar radiation. Typical panels used experimentally were 2-ft wide by 10-ft long (20 sq ft), with 9 grooves containing about 100-ft plastic tubing, inserted into the grooves. The outside diameter of this tubing was 7/16 inches, wall thickness 1/16 inch and at 120°F a pressure of 52 psi could be used. It is essential that the tubing should adhere tightly to the metal casing for good heat transfer.

* Research Consultant, Princeton, United States.

Comparative tests

Comparative tests have been made between two solar water heaters, both of equal area (20 sq ft). One of these was the type of panel described above; the other was made of 0.019 inch thick copper "Tube-in-Strip"[1] with metal headers soldered to the bottom and top ends of parallel vertical tubes. Both panels were blackened and placed into well-insulated boxes, tightly covered with 0.005 inch thick Mylar film. Equal amount of water was circulated through both panels; the flow rate and inlet and outlet temperature of the water was measured. The test results (figure 1) show no difference in performance between the two panels, within the limit of experimental errors.

Advantages

The new design and its performance shows the advantages of an all-metal panel, without any of its disadvantages.

(*a*) It is not damaged by below-freezing temperatures, nor by heat (when heat resistant plastic tubing is used).

(*b*) It is lighter in weight and, therefore, easier to install.

(*c*) It is less expensive.

(*d*) It eliminates the need for soldered or welded pipe connection which may develop leaks due to corrosion. It is, therefore, leakproof.

The new design used for heating swimming pools

A substantial number of the 311 000 swimming pools in the United States are heated with fuel burning heaters to extend the season of their use. The initial cost of such heaters and their installation is rather high and the fuel cost is exorbitant, therefore the interest in inexpensive solar water heaters is considerable.

Two larger type solar heated swimming pools have been installed in Princeton, New Jersey (latitude 40°N on the east coast of the United States).

	Heater area sq ft	*Pool surface sq ft*	*Water flow rate pounds/hour*
Pool A.	1 140	716	10 700
Pool B.	300	512	9 750

[1] A product of Revere Copper and Brass Co.

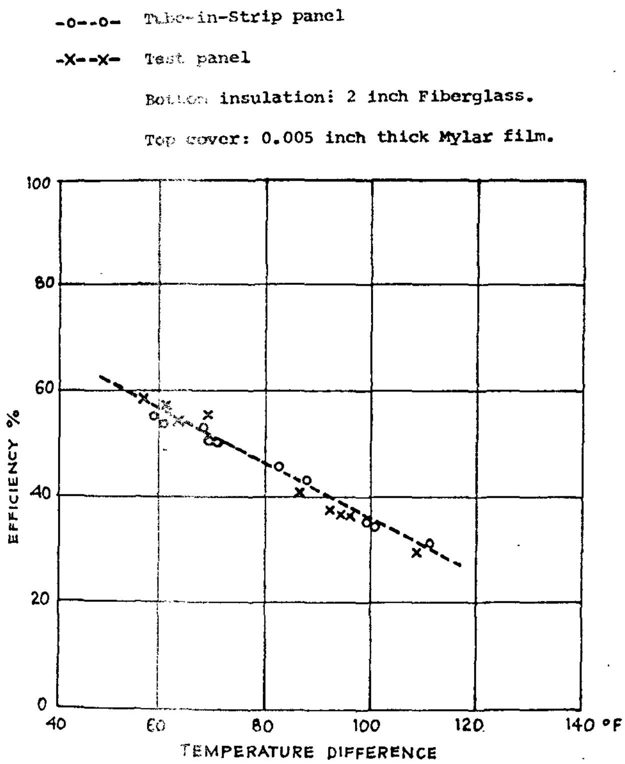

Figure 1. Solar water heater tests

Both heaters were made of panels as described above. They were not covered with glass or plastic panes. The panels were installed on the roof of buildings, with a slight tilt from the horizontal. The inlet and outlet tubes of the panels were connected to headers made of 1.5 inch diameter black polyethylene pipes. Water was circulated through the heaters at a rapid rate with the aim of removing solar heat from the panels without large temperature increase. The heat loss from the surface of the panels was rather small and, therefore, the efficiency of solar heat collection was quite high.

For control purposes some panels of heater A were constructed with aluminium tubes instead of polyethylene tubing. After a period of operation the aluminium tubes burst because the water in them froze during a clear night. Although the air temperature was 41°F, the sheet metal temperature dropped below 32°F due to the cooling effect of night-sky radiation. (This damage occurred in early September.)

The solar heater of pool B consists of 15 panels 20 sq ft each, forming the entire roof of a small building (figure 2). The panels were made of sheet aluminum with polyethylene-copper-powder tubing as described above. The water from the pool was pumped through the heater by the filter pump, which must be used in all swimming pools in the United States. For this reason the circulation of the water involved no extra cost.

Test results of pool B

The temperature of the water was measured daily from May to December. The data indicate that

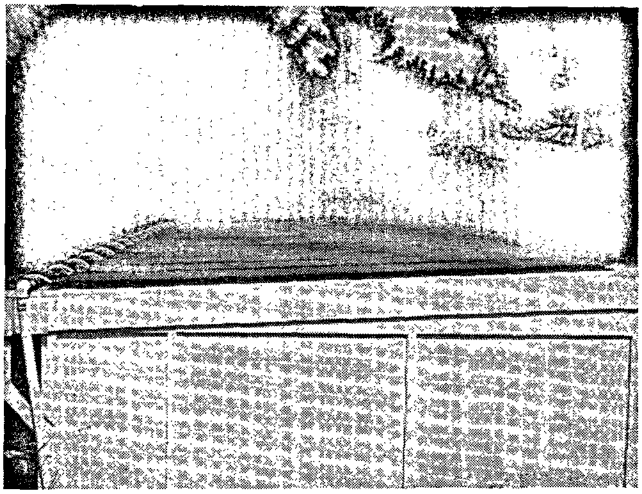

Figure 2. Solar water heater of pool B

300 sq ft area, forming the roof of a building

the temperature of the pool increased by 4 to 6°F on clear days during the early spring or late autumn. During the summer months the temperature of the water increased by 9 to 10°F on its passage through the heater. For this reason the heater was operated rather infrequently and only to maintain the temperature evenly around 80°F.

The temperature of the pool drops every night depending upon night-sky radiation, wind and other climatic influences. On clear days, however, the solar heater quickly replaces the night loss. The following Table 1 shows temperature variations in the

Table 1. Heating of the pool in early spring

Date	*Time*	*Temperature of water in pool*	*Water returning from roof to pool*	*Ambient*	*Weather*
		Heater B			
April 1961					
23	9 am	62	62	62	Haze
	noon	64	67	67	Clear
	5 pm	67	67	68	Clear
24	9 am	63	64	62	Haze
	noon	66	69	71	Rain
	5 pm	68	68	71	Haze
25	9 : 30 am	64	66	64	Haze
	1 pm	67	70	82	Clear
	5 pm	69	69	79	Clear
26	9 : 30 am	67	69	70	Clear
	noon	68	70	68	
	5 pm	69.5	69	66	Cold N. wind
May					
9	9 am	64	64	70	Fog
	noon	67	70	78	Fog lifting
	5 pm	71	73	82	Clear
10	9 am	68	69	68	Light Clouds
	noon	68	71	60	Cloudy
	5 pm	70	71	60	

early spring of 1961, which was unusually cold and foggy.

The actual number of days of swimming pool use at Princeton is limited to an average of only 50 days during the season, which lasts from the middle of June to the end of August. The question has often been debated as to what temperature can be considered most comfortable for swimming. Opinions differ widely. The temperature of pools for Olympic athletes is kept at 65°F. This may seem too chilly for most people, who prefer a minimum of 70°F. The following table 2 shows the number of days when the temperature of the pool was above 70°F.

Table 2

Date, 1960	*Days when pool water temperature was in excess of 70°F*
May	19 days
June 1 to 15	15 days
June 15 to Aug. 31	All days (this is the usual pool season)
September	30 days
October	11 days
TOTAL extra days	75 days

The usual pool season was three times longer when using the solar heater. Swimming was possible during the 77 days of the usual season and during 75 extra days, for a total of 152 days, while the usual number of days is only 50 in an unheated pool. Results obtained during the last week of September 1960 are shown in table 3.

Cooling effect of pool panels

During nights with clear skies and low humidities the collector plate temperature often dropped as much as 20°F below the ambient air temperature. This cooling effect can be used to decrease the temperature of the water in the pool, by circulating water during the night and not during the day. In Southern arid regions of the United States it is often desirable to cool the swimming pool during a considerable part of the summer. This can be easily accomplished with the panels.

During the operation of pool A in June the pump was operated at night to determine the performance of the cooling effect of the panels. The water flow was 10 700 pounds per hour, the temperature of the water dropped by 6 to 9°F during its passage through the panel. The temperature of the panels was generally equal to the ambient within a few degrees. A drop of seven degrees corresponds to the removal of 75 000 btu/hour or 66 btu/hour per sq ft collector panel. During clear nights, with 8 hour operation, the heat removed by the panel was about 500 btu/sq ft.

It is obvious that both heating and cooling obtainable with these panels can be used for house heating or cooling, using a tank for storing heat or coolness.

Table 3. Agreeable temperatures for swimming in late autumn 1960

Date Sept. 1960	*Time P.M.*	*Water*		*Ambient °F*	*Weather*
		In pool	*To pool*		
		Heater B			
24	4	73	75	66	Haze, clear
26	5	71	73	67	Cloudy, clear
27	5	72	73	71	Fog, haze, clear
28	4	70	71	68	Fog, haze, rain
29	4	69.5	69.5	64	Cloudy, haze
30	5	69.5	71	71	Cloudy, haze, clear

Cost estimates

The material costs of the solar heater can be easily determined as follows:

For one 20 sq ft panel	$
Cost of 30 sq ft black sheet aluminum required to produce a 20 sq ft corrugated sheet	4.30
100 foot plastic pipe	1.50
TOTAL MATERIAL	5.80
Material cost per sq ft	0.29

The labor required for mass producing corrugated sheets and for inserting the pipe has been estimated as an additional cost of $0.06 per sq ft resulting in material and labor cost of $0.35 per sq ft of collector. This is substantially lower than the "classical" copper sheet with soldered coils ($1.25 per sq ft) and the new panel represents a rigid, durable, reliable device which can be employed for many applications in the heating and cooling field.

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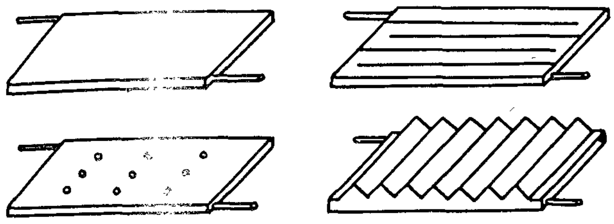

Figure 6. Flat-plate-type solar absorbers

Orientation of the absorber

The question of how much solar energy can be intercepted is of utmost importance in evaluating the heating of water. From figure 1, the amount of solar energy falling upon a flat, horizontal surface is obtained. It is easy to see that a surface which always points at the sun receives considerably more sunshine. However, the mechanism to make the absorber follow the sun is very expensive and therefore not practical for widespread use.

Thus the best stationary arrangement will be considered. Since the sun is in a southerly direction (in the northern hemisphere at moderate latitudes) most of the day, it is best for the absorber to face south. Since the days are shorter and the air temperature lower in winter, it is more difficult for the absorber to deliver the required amount of hot water during this season, while in the summer it is usually capable of delivering a considerable excess. For this reason, it is found that the best all year round performance is obtained with a stationary absorber facing due south, when it is inclined with the horizontal approximately 10 degrees more than the local geographic latitude. This greater inclination has the added advantage of preventing dust and dirt from clinging to the glass and reducing its transmission.

The amount of energy falling upon a surface oriented in this manner can be obtained from figure 8, giving a multiplication factor by which the values in figure 1 have to be multiplied. This figure thus gives the relationship of energy falling upon the surface as compared to that on a horizontal surface. Data for different latitudes and different times of the year are given.

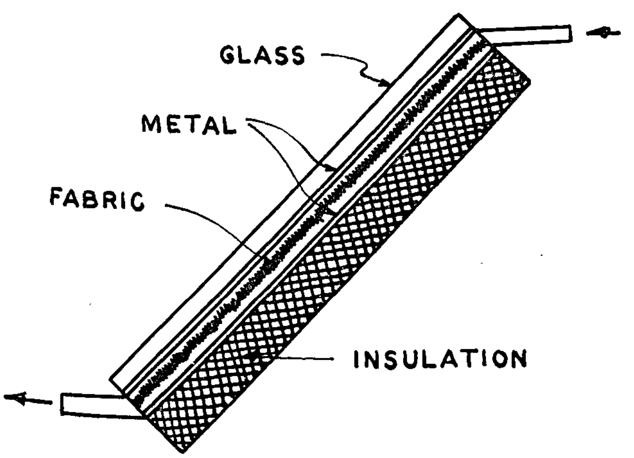

Figure 7. Kawai solar absorber

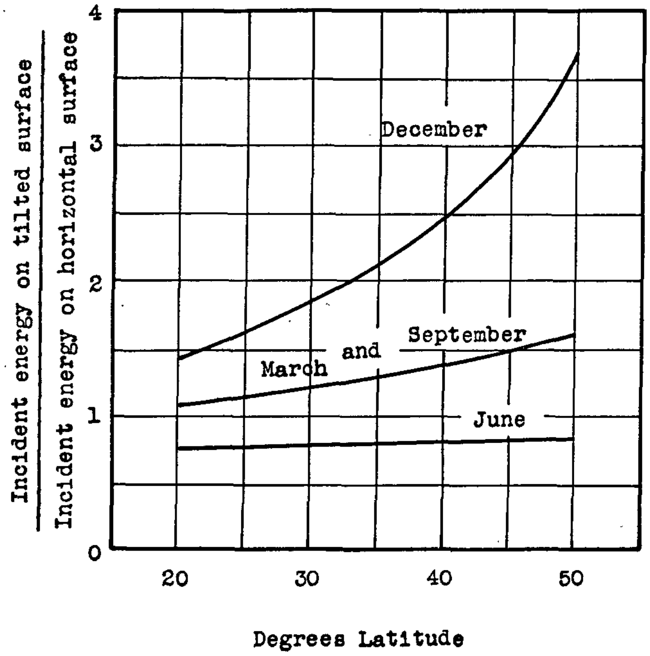

Figure 8. Conversion factor to determine the amount of solar energy falling upon a surface facing due south and inclined 10 degrees more than the local geographic latitude for different times of the year

Effect of number of glass covers

Glass covers on the solar absorber transmit a considerable portion of the short wave radiation from the sun but reflect some, especially at the small angles between sun-ray and glass. The long wave radiation from the hot surfaces of the absorber is transmitted only to a small degree. Clear, untinted glass is best, since constituents like iron (greenish tinge on the breaking edge) reduce the transmission of short-wave radiation.

The amount of solar energy transmitted depends greatly upon the angle at which the sun-rays hit the glass which varies continuously all day. The closer to 90 degrees the angle between the glass and the sun-rays, the better. When more than one glass plate is used, the amount of energy transmitted is further reduced, but at the same time the heat losses from the top of the absorber box are reduced since the air layers between the glass plates have good insulating qualities.

Table 1 shows how the number of glass covers affects the energy transmitted as a fraction of the amount falling upon the glass per day (transmission coefficient).

Taking these transmission coefficients and the insulating qualities of the number of glass layers into account, it can be seen that there exists an optimum number of glass plates for each location.

Table 1. Daily solar energy transmission
(As a function of the number of glass covers)

Number of glass plates	*Transmission coefficient*
0	1.0
1	0.748
2	0.625
3	0.542
4	0.474

The standard absorber for which the data is presented here delivers water at about 140°F with an average temperature difference between the heated water and the air of about 80°F. Figure 9 clearly points out this optimum number of glass plates which will collect the maximum amount of solar energy as a function of location.

Absorber size and design

It is not always possible to choose the best technical design, and often it is necessary to compromise. A compromise between costs, convenience and available space for a unit will determine the actual final design. The available materials, geographic location, and weather conditions also play an important role. Many times a poor system is chosen (as less expensive) as long as it still delivers the amount of hot water required. The most common design in the United States uses only one glass cover and for an average family of four measures 4 × 14 ft.

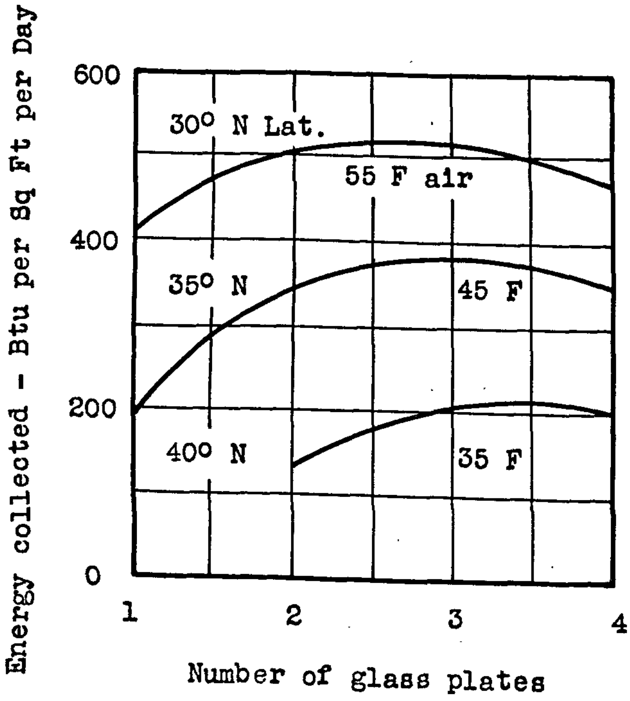

Figure 9. Solar energy collected by a typical collector for a typical day showing the effects of number of glass plates, latitude and air temperature

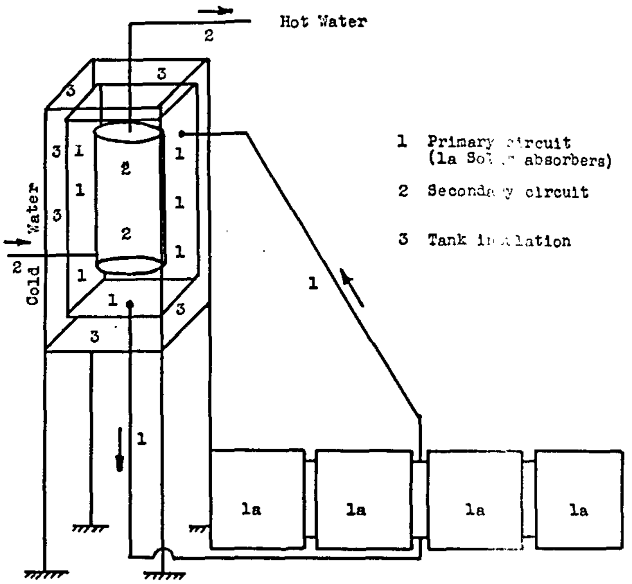

Figure 10. Dual-circulation hot water system

For larger families, apartment buildings, and restaurants, several of these fundamental units are connected together.

Storage tank, size and location

The most common fault of solar hot water installations is inadequate storage. If the hot water stored is used up during the night, no more can be obtained until the sun shines again. If the tank is too small, once the water is hot, circulation between the absorber and tank will stop and the system becomes inoperative even though the sun shines, until some of the hot water is used.

Data indicate that the average person uses about 20 gallons of hot water per day. Thus, for a family of four, 80 gallons of hot water should be stored for a twenty-four hour period, requiring an 80 gallon tank. If bad weather is expected often, this storage capacity should be increased or a fuel booster added. Even on cloudy days, a considerable amount of solar energy is collected; thus, too large a reserve is not required.

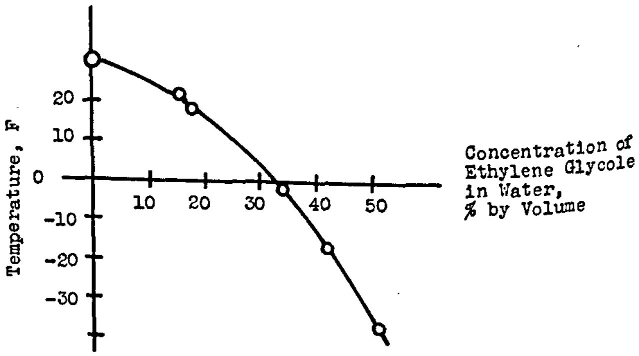

Figure 11. Freezing temperature protection in the primary circuit of a solar dual-circulation hot water system

chaude, l'auteur présente les constatations faites au cours d'une étude de la question, ainsi que certains résultats d'expériences. Ces données indiquent qu'on aurait besoin d'une vingtaine de gallons d'eau chaude par personne et par jour.

Ce mémoire examine plusieurs emplacements possibles du collecteur et du réservoir, et passe en revue leurs avantages et inconvénients respectifs.

Il considère également le choix des matériaux et des types de verre à employer, ainsi que ceux qui sont à rejeter.

Dans la section consacrée à la réalisation de ces systèmes, l'auteur examine les sujets suivants :

a) Orientation du collecteur : Pour fonctionner dans les meilleures conditions possibles, il doit être orienté vers le sud (dans l'hémisphère nord) et incliné sur l'horizontale d'un angle sensiblement égal à la latitude du lieu plus dix degrés.

b) Effet du nombre de couvercles en verre : L'auteur pose ce problème et en résume les données par des graphiques de manière à pouvoir trouver une solution pour chaque position possible.

c) Dimensions et réalisation du collecteur : Ce mémoire passe la question en revue dans ses détails.

d) Dimensions et emplacement du réservoir : L'auteur souligne que l'erreur la plus courante, dans la réalisation des systèmes solaires de production d'eau chaude réside dans une insuffisance de capacité de l'accumulateur.

Ce mémoire examine les modes de réalisation et les agencements spéciaux susceptibles de présenter des avantages dans certaines situations.

Le système de production d'eau chaude à double circulation est décrit et ses avantages sont indiqués.

L'auteur décrit nombre d'installations type de chauffe-eau à énergie solaire en service dans l'état de Floride et présente des photographies de ces installations.

La section consacrée à une analyse économique et à une comparaison des frais d'exploitation prend en considération les éléments suivants :

a) Insolation;

b) Disponibilité et prix des combustibles d'origine fossile;

c) Frais de premier établissement et mode de réalisation des installations de chauffage de l'eau par l'énergie solaire;

d) Durée de service envisagée.

L'auteur termine par une comparaison entre le système solaire de chauffage de l'eau, avec et sans dispositif auxiliaire manuel ou automatique, et les chauffe-eau classiques à combustible d'origine fossile. (La comparaison est rapportée à 100 gallons d'eau chaude.)

Avec les 25 figures qui l'accompagnent, dont nombre de photographies de systèmes en service, des graphiques et une table, le mémoire se prête à l'étude de tout système ou installation actuellement en service ou à l'état de projet.

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE DE L'EAU

J. Geoffroy *

Si théoriquement la zone idéale pour l'emploi de l'énergie solaire est la zone où le nombre de jours ensoleillés par an est maximale, la durée de l'ensoleillement quotidien est constant, et les énergies classiques sont rares et par suite chères, l'expérience commerciale prouve que *toutes les régions* comprises entre le 45e degré de latitude nord et le 45e degré de latitude sud et disposant de plus de 2 000 heures d'ensoleillement annuel peuvent prétendre à un emploi rationnel de l'énergie solaire pour le chauffage de l'eau sanitaire, sans craindre la concurrence des énergies classiques.

Il est connu que la captation de l'énergie solaire peut être effectuée *avec ou sans concentration*, et les deux procédés peuvent être utilisés pour le chauffage de l'eau.

La concentration peut être réalisée soit par un miroir parabolique, soit par un miroir cylindro-parabolique.

Le miroir parabolique exige un mécanisme fragile et coûteux permettant de suivre le soleil dans sa course, et il est encombrant. En contre-partie, il permet de recueillir pendant toute la durée de l'ensoleillement le maximum d'énergie à des températures de l'ordre de plusieurs centaines de degrés centigrades.

Le miroir cylindro-parabolique exige un réglage périodique de son inclinaison; il est fragile, coûteux et encombrant. Il ne permet pas de capter plus d'énergie qu'un récepteur plan, mais il permet d'obtenir des températures de travail supérieures à 100° [1].

Le récepteur plan n'est ni fragile, ni très coûteux. Orienté et incliné convenablement, en fonction du lieu d'utilisation, il capte autant d'énergie que le récepteur cylindro-parabolique, mais la température de travail assurée reste inférieure à 100°.

Conditions auxquelles doit satisfaire le chauffe-eau solaire

Il doit pouvoir assurer un service continu. Le chauffe-eau solaire doit donc être un chauffe-eau à accumulation dont la capacité doit être suffisante pour assurer les besoins de 24 heures de l'utilisateur. Il doit en outre disposer d'un chauffage d'appoint dans la mesure où les pannes de soleil existent au lieu d'utilisation.

Il ne doit pas poser de problème d'architecture.

Par son volume : son accumulateur doit pouvoir éventuellement être installé dans une pièce de l'habitation, le récepteur étant fixé sur la façade de l'immeuble;

Par son poids, qui ne doit pas excéder les charges admises par les toitures, terrasses et planchers;

Par son aspect inesthétique : le chauffe-eau installé doit avoir un aspect ramassé, permettant un habillage dans le style de l'immeuble.

Il doit pouvoir être mis en place sans qu'il soit besoin de faire appel à un spécialiste et, comme tout appareil ménager, le chauffe-eau solaire doit pouvoir être mis en œuvre sur simple lecture d'une notice détaillée.

Il ne doit pas être plus sensible à l'entartrage qu'un chauffe-eau à énergie classique. Les eaux distribuées étant ce qu'elles sont, le chauffe-eau solaire devra être calculé pour que la température obtenue ne dépasse pas 70°, température à partir de laquelle l'entartrage s'effectue plus rapidement. L'emploi d'un circuit de chauffe et d'un échangeur supprime le risque d'entartrage des parties sensibles du chauffe-eau.

Il ne doit pas être sensible au gel. L'emploi du circuit de chauffe indépendant du circuit de distribution permettra de protéger les parties sensibles de l'appareil en utilisant un fluide incongelable (eau + alcool ou eau + antigel en proportion convenable). L'accumulateur et le circuit de distribution seront fortement calorifugés.

Il doit être robuste et ne demander ni entretien, ni surveillance. Le chauffe-eau solaire est le plus souvent installé sur la toiture ou la terrasse des bâtiments, pour y avoir la meilleure exposition. Son accès est par conséquent malaisé. Sa construction ne doit comporter aucune pièce mobile qui pourrait se dérégler ou exiger un graissage, et les matériaux utilisés doivent être insensibles à l'attaque des éléments naturels (vent, pluie, sable, air marin).

Enfin, son prix doit être compétitif avec ceux des autres chauffe-eau utilisant une énergie classique. Mais, par prix des autres chauffe-eau, il faut entendre le total des dépenses d'investissement et des dépenses d'énergie pendant une période de trois ans minimum.

Solutions présentées par la Société Radiasol

La Société Radiasol présente le chauffe-eau standard 200 l/2 m², qui correspond aux besoins d'une famille de 2 à 4 personnes; c'est un ensemble

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* Société anonyme Radiasol, Paris et Casablanca.

[1] Toutes les températures citées dans le mémoire sont exprimées en degrés centésimaux.

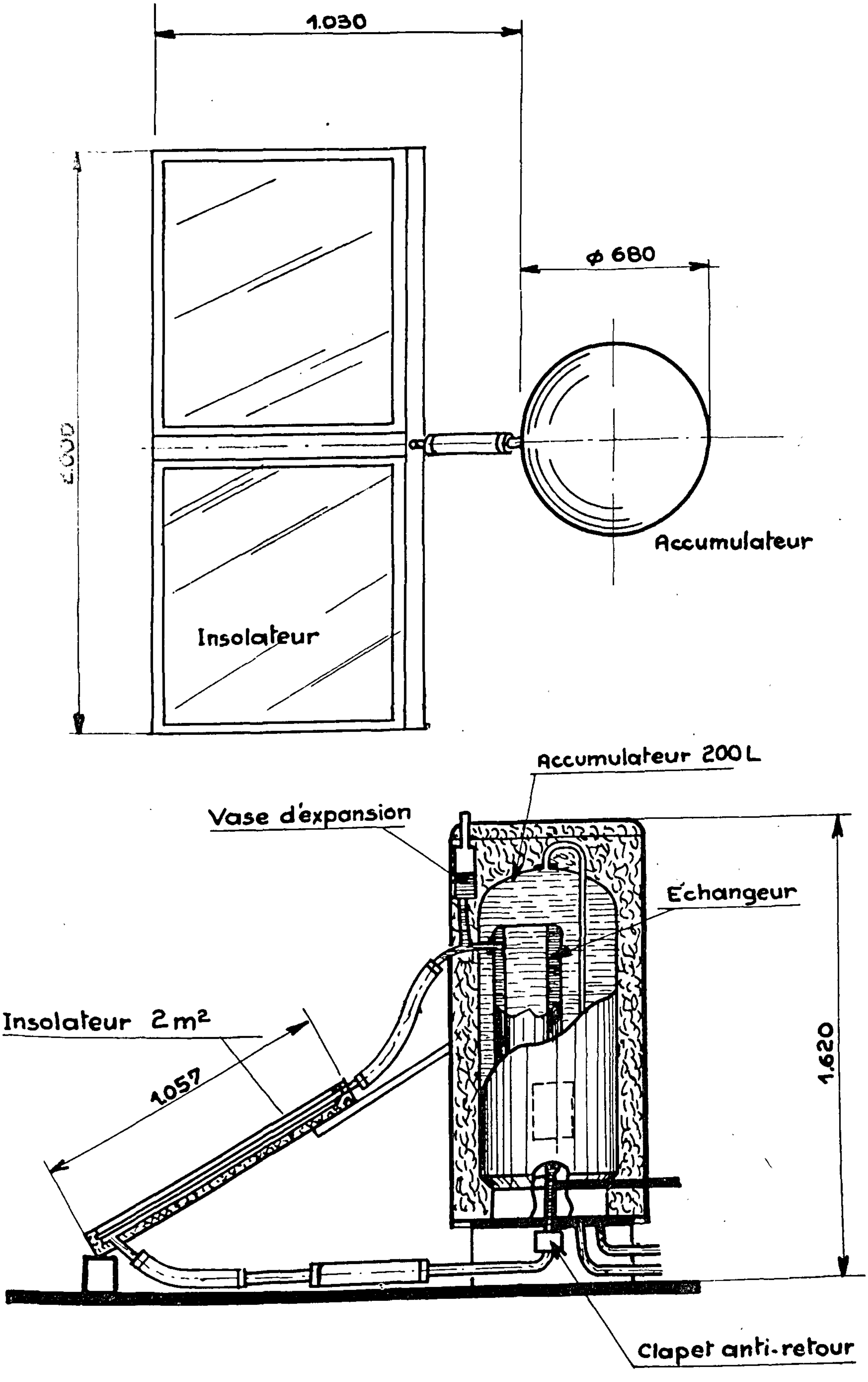

Figure 1. Schéma descriptif du chauffe-eau Radiasol (200 l/m²)

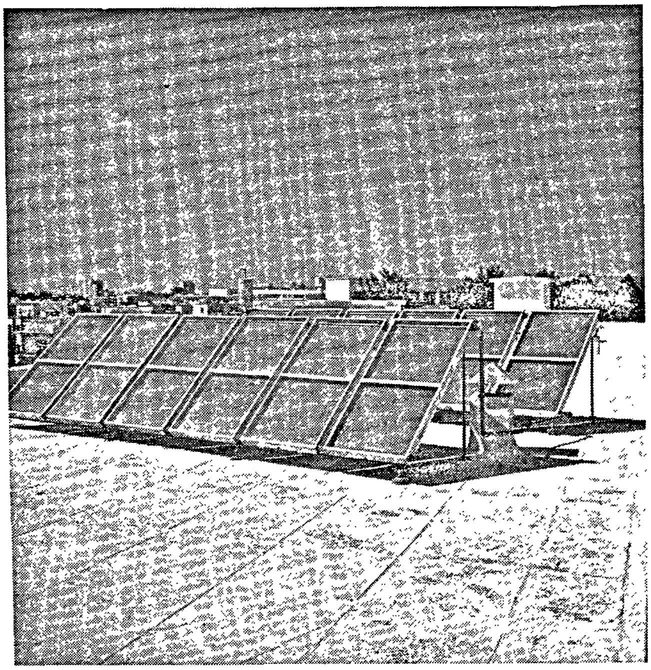

Figure 2. Batteries d'insolateurs Radiasol

complet, expédié d'usine en deux caisses et pouvant être mis en œuvre instantanément, à la condition de disposer d'une tuyauterie d'amenée d'eau froide et d'une tuyauterie de distribution d'eau chaude (voir figure 1).

Radiasol présente également les matériels pour installations de service d'eau chaude de grandes capacités (plusieurs mètres cubes), comprenant :

a) L'insolateur élémentaire de 2 m² permettant la constitution de batteries, par assemblage du nombre nécessaire d'insolateurs élémentaires (voir figure 2);

b) Des réservoirs de capacités diverses (500 l, 750 l, 1 000 l, 1 500 l et 2 000 l) à simple ou double échangeur permettant de chauffer les quantités d'eau demandées, avec ou sans chauffage d'appoint (voir figure 3).

Pour le captage des calories, les appareils Radiasol utilisent « l'effet de serre » : les insolateurs de 2 m² sont constitués par un réservoir très plat, appelé absorbeur, placé dans un coffrage calorifugé et fermé par une vitre exposée au soleil. L'absorbeur est relié à un échangeur de température placé dans l'eau sous pression d'un réservoir calorifugé. Les insolateurs sont toujours disposés de façon à recevoir à midi le maximum de radiation solaire. Pour la transmission des calories à l'eau de consommation, la Société Radiasol utilise soit une circulation par thermosiphon, soit une circulation forcée.

Dans l'appareil standard (200 l), dès que la radiation solaire frappe la vitre, l'eau s'échauffe dans l'absorbeur, le circuit s'anime par thermosiphon et les calories sont livrées à l'eau de consommation par l'échangeur de calories. Dès que le soleil disparaît, la circulation s'arrête et le circuit est irréversible, soit par suite de la disposition de l'insolateur (régions tropicales), soit par l'effet d'un clapet Radiasol breveté (régions méditerranéennes) qui permet de réduire la hauteur de l'appareil à la hauteur de l'accumulateur (voir figure 1).

Dans les installations plus importantes, pouvant aller jusqu'à plusieurs dizaines de mètres cubes de capacité, les accumulateurs sont placés dans les sous-sols de l'immeuble. La circulation, qui ne peut alors se faire par thermosiphon, est animée par une pompe commandée par un régulateur Radiasol breveté (voir figure 4). Le régulateur détermine automatiquement les périodes de la journée où un gain de calories peut être apporté au volume d'eau à chauffer.

Cette circulation forcée améliore considérablement le rendement du procédé. Le fait, en outre, de pouvoir placer les réservoirs à l'abri du gros-œuvre permet de réduire de façon très sensible les pertes calorifiques subies lorsque ceux-ci sont placés à l'extérieur (voir figure 3).

Par ailleurs, les charges sur terrasse ou toiture sont considérablement réduites, et l'installation, dont la hauteur ne dépasse pas 1,60 m en région méditerranéenne, est pratiquement invisible du sol (voir figure 2).

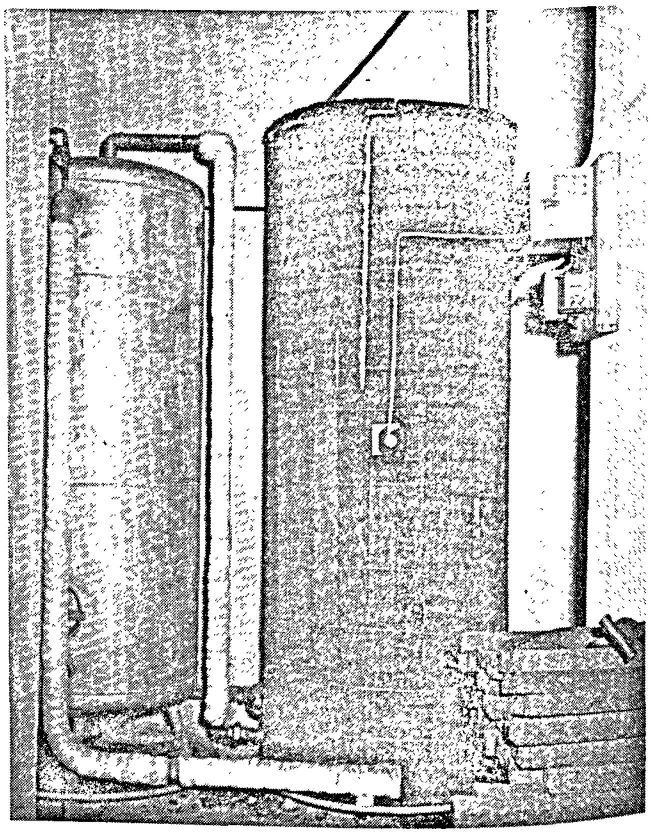

Figure 3. Réservoirs à échangeurs en cours de calorifugation

NOTER : 1) le tableau de commande de l'installation; 2) la sonde sur le réservoir de droite; 3) la pompe apparaissant derrière le réservoir de droite.

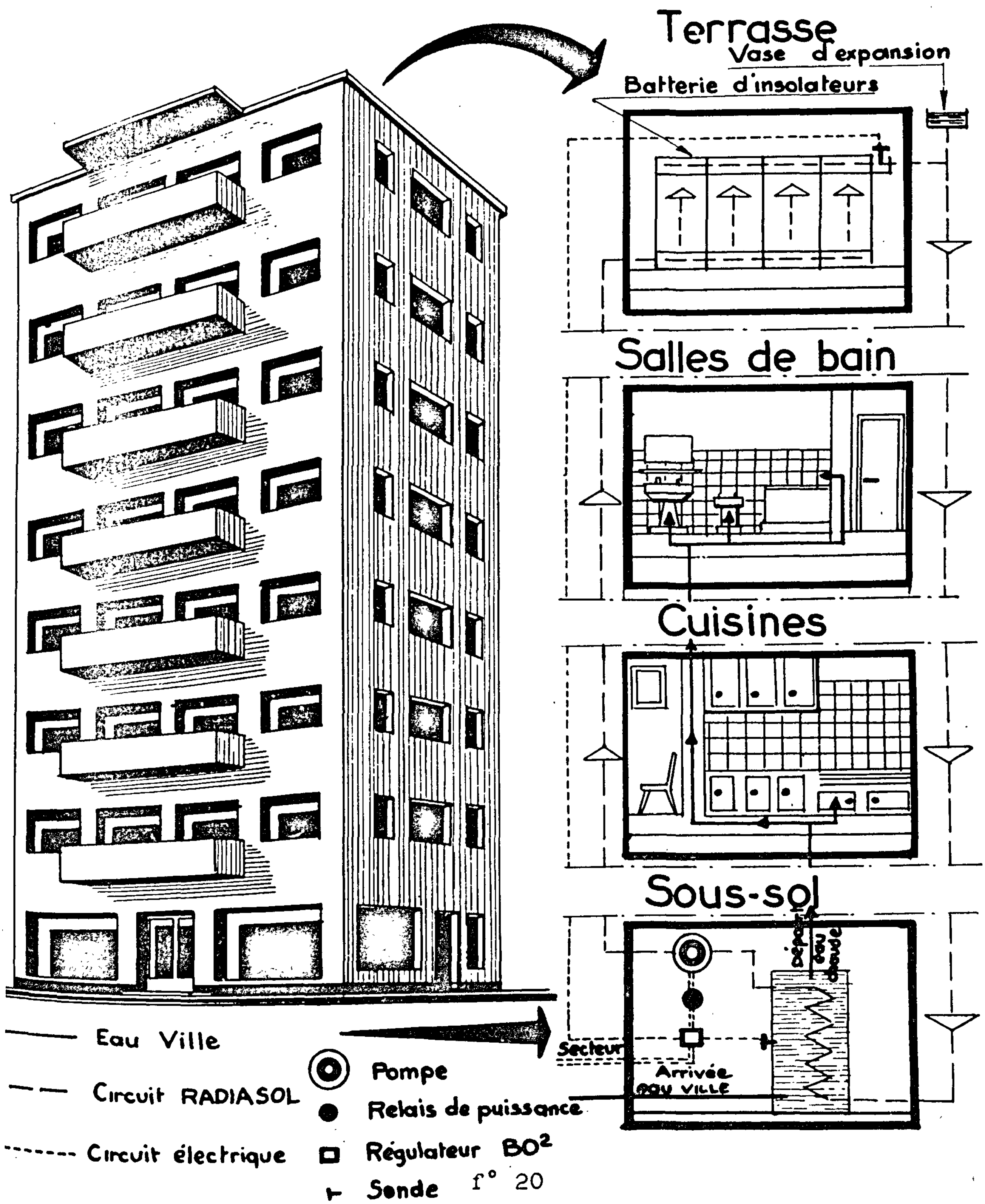

Figure 4. Schéma de principe d'un service d'eau chaude Radiasol

Enfin, ce procédé permet de réaliser des installations répondant exactement aux besoins exprimés; grâce aux éléments standard utilisés, il suffit, en cas d'extension des besoins, d'augmenter les surfaces de chauffe et le nombre ou la capacité des accumulateurs.

Derniers perfectionnements des procédés Radiasol

Inclinaison saisonnière de l'insolateur

Le nouveau mode de fixation de l'insolateur au bloc accumulateur permet, en cours d'année, de modifier l'inclinaison de l'insolateur. La fixation comporte, en effet, un collier coulissant sur l'accumulateur et un jeu de durits qui rend possibles toutes les inclinaisons entre 15 et 45°.

Le clapet antiretour sensible aux charges motrices infinitésimales

Les chauffe-eau solaires, à échangeur de calories et fonctionnant par effet de thermo-siphon sont de deux types.

Les uns ont leur échangeur placé dans une petite cuve fixée à la base du réservoir contenant l'eau à chauffer, et leur insolateur est installé en contre-bas. La hauteur totale de l'appareil est la somme des hauteurs totales ou partielles de ces trois éléments : réservoirs, échangeurs et insolateur. Une telle disposition évite, de nuit, la circulation inversée du thermosiphon, mais la hauteur totale de l'appareil présente de nombreux inconvénients sur les plans de l'esthétique, de la facilité de pose, de la prise au vent, etc.

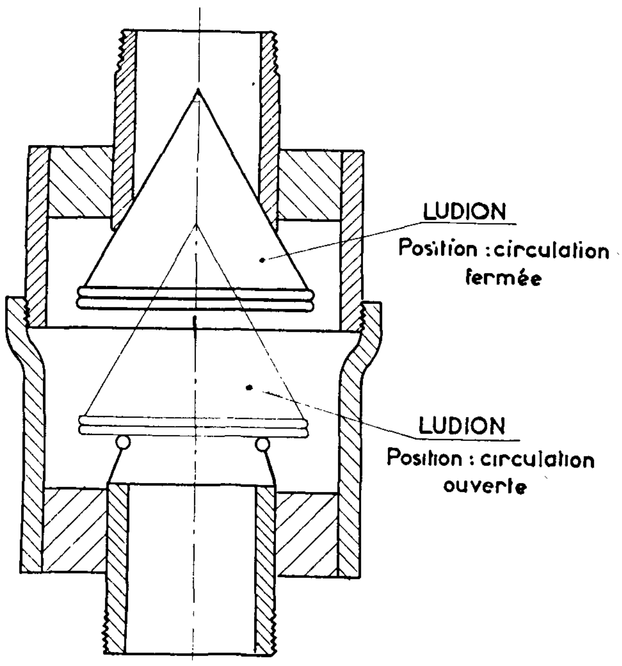

Figure 5. Schéma de principe du clapet antiretour Radiasol sensible aux charges infinitésimales

Les autres ont leur échangeur placé à l'intérieur du réservoir, et l'insolateur est installé à même hauteur que l'échangeur. L'appareil a alors une hauteur totale très inférieure à celle des appareils du premier type, mais dans ces conditions de construction, on observe de nuit une inversion de l'effet de thermosiphon qui fait perdre à l'accumulateur une partie des calories emmagasinées de jour.

Le clapet antiretour Radiasol empêche cette inversion et, contrairement aux clapets connus jusqu'à ce jour, il est sensible aux charges motrices infinitésimales et ne réduit pas celles-ci de façon notable.

Ce clapet est constitué par un ludion mobile dans un boîtier muni de deux ouvertures, l'une à sa partie supérieure, l'autre à sa partie inférieure (voir figure 5). Le ludion a la forme d'un tronc de cône. Il est réalisé en un matériau plastique insensible à la corrosion et dont le coefficient de dilatation cubique est faible par rapport à celui de l'eau. Il est lesté de telle sorte qu'il soit en équilibre indifférent lorsqu'il est plongé dans le liquide utilisé pour le circuit de chauffe. Il est enfin dimensionné de telle sorte que sa pointe ne puisse se dégager de l'ouverture qu'il doit obturer.

La régulation électronique du circuit de chauffe des installations de grande capacité

Lorsque le réservoir et son échangeur sont placés à un niveau égal ou inférieur à celui des absorbeurs, la circulation se fait grâce à une pompe. Mais cette pompe ne doit fonctionner que lorsque la température du fluide contenu dans les absorbeurs est supérieure à la température moyenne de l'eau contenue dans le réservoir.

Le régulateur Radiasol est un dispositif électronique sensible à une différence de température (voir figures 6 et 7). Il comporte un générateur de courant constant qui alimente un pont de Wheatstone dans les branches duquel sont placées la sonde prenant la température des insolateurs (dite sonde chaude) et celle prenant la température du réservoir (dite sonde froide). Sur la diagonale du pont est placé un détecteur d'écarts de température, dont les différentiels de déclenchement sont réglables en fonction des pertes calorifiques de l'installation et de son circuit. Il permet de mettre en marche ou d'arrêter, par l'intermédiaire d'un relais de puissance, la pompe animatrice du circuit.

La loi générale de fonctionnement du régulateur est de la forme

$$\frac{K\,\Delta\theta}{1+\alpha\,\theta_2} \qquad \text{ou} \qquad \Delta\theta = \theta_2 - \theta_1$$

$\Delta\theta$ étant la différence de température entre les sondes,
θ_1 la température de la sonde froide, et
θ_2 celle de la sonde chaude.

L'identification du terme α au coefficient thermodynamique $\beta = 1/273$ permet, une fois les différentiels de déclenchement réglés, de maintenir le rendement thermodynamique constant quelle que soit la température des sondes.

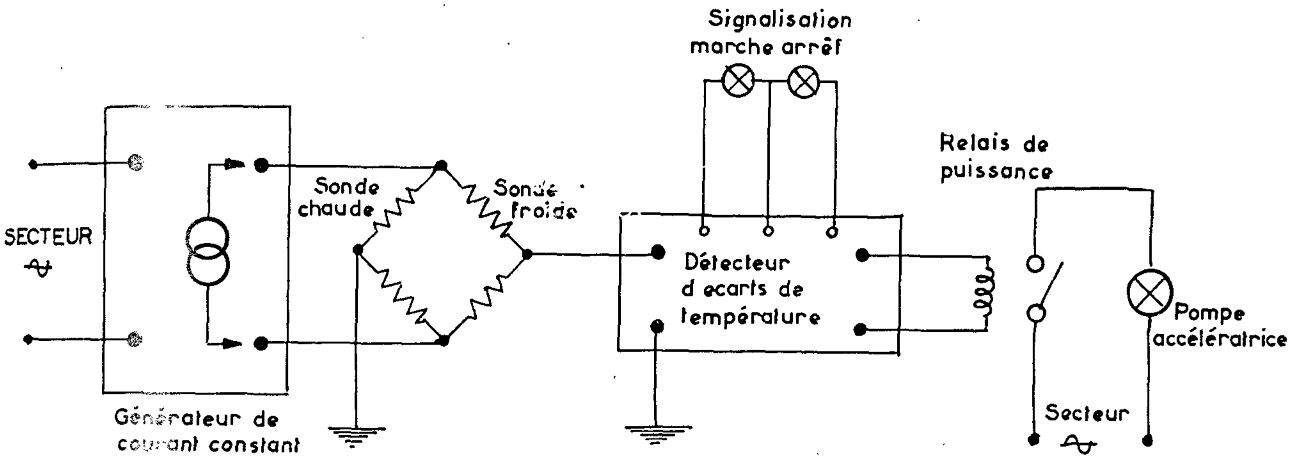

Figure 6. Schéma de principe du régulateur Radiasol BO²

Le chauffage d'appoint

Pendant les jours de pluie ou de très faible ensoleillement, la radiation solaire peut être insuffisante pour obtenir la température minimale requise dans le réservoir. Bien que ces périodes soient très rares en climat désertique, discontinues en climat tropical et n'excèdent pas quelques dizaines de jours en climat méditerranéen, Radiasol a prévu un chauffage d'appoint chaque fois qu'un service d'eau chaude sans défaillance est nécessaire. Ce chauffage pose deux problèmes essentiels :

1) Pour conserver tout le bénéfice possible de l'énergie, toute installation utilisant une énergie d'appoint doit tenir compte de ce que l'énergie solaire travaille à une température inférieure à celle de l'énergie classique. Par conséquent, pour que l'énergie classique ne contrarie pas le travail de l'énergie solaire, il faut que les deux énergies travaillent en série : soit dans deux réservoirs, l'énergie solaire travaillant en préchauffage dans le réservoir amont, l'énergie classique travaillant dans le réservoir aval recevant l'eau préchauffée; soit dans le temps, l'énergie *d'appoint n'étant utilisée* que lorsque l'énergie solaire a donné son potentiel calorifique.

2) Le coût d'investissement nécessaire pour le chauffage d'appoint doit être le plus faible possible et par conséquent tenir compte de l'équipement énergétique de l'endroit considéré.

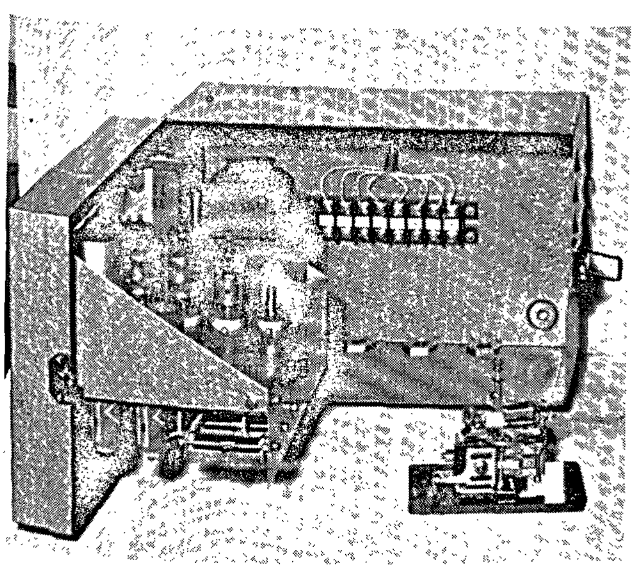

Figure 7. Le régulateur Radiasol BO² et son relais de puissance

Chauffage d'appoint du chauffe-eau Radiasol standard 200 l/2 m². On utilise en principe une résistance électrique de 1 kW commandée par un thermostat, pour laquelle un logement est prévu, et une horloge ne permettant la fermeture du circuit électrique que *a*) lorsque l'eau du réservoir a une température inférieure à 50° (par exemple), et *b*) de nuit, pour profiter du tarif d'électricité de nuit, lorsqu'il existe.

Chauffage d'appoint des chauffe-eau solaires de grande capacité à circulation forcée. Il existe plusieurs solutions. On peut :

a) Comme pour le chauffe-eau standard 200 l/2 m², placer une résistance électrique de puissance convenable sur le dernier réservoir (aval) de l'installation;

b) Lorsqu'il existe un chauffage central dans l'immeuble considéré, utiliser comme réservoir aval de l'installation un réservoir à deux échangeurs, un à grande surface de chauffe pour le circuit de chauffe solaire, l'autre à surface normale de chauffe qui sera branché sur le circuit chauffage central comme un simple radiateur;

c) Placer un générateur d'eau chaude à gaz à la sortie de l'installation solaire dont le brûleur ne s'allumera que si l'eau préchauffée par l'énergie solaire n'a pas atteint la température désirée.

Essais et rendement

Cette section vise plus à définir un programme qu'à relater un processus déjà appliqué. En effet, des essais et des calculs de rendement rigoureux nécessitent des appareils de mesure et d'enregistrement très coûteux, et surtout des permanences d'observation qu'une entreprise peut difficilement assurer par ses propres moyens.

Pour ces raisons, il serait souhaitable que les stations officielles de météorologie et de l'Institut de physique du globe puissent participer activement à l'expérimentation des appareils utilisant les sources nouvelles d'énergie telles que l'énergie solaire.

Pour que soient significatifs les essais portant sur les perfectionnements, les mesures de production doivent porter simultanément sur deux chauffe-eau ne se différenciant que par le perfectionnement que l'on veut tester.

La *mesure de l'énergie incidente* est réalisée par un solarigraphe orienté et incliné comme les insolateurs des chauffe-eau.

La *mesure de la production* porte sur la quantité d'eau fournie à une température T constante pour la durée de l'essai (période d'ensoleillement). La mesure de production est répétée en modifiant la valeur de T.

Le *rendement* est établi sous la forme « Rendement moyen journalier pour la température Tx de l'eau chaude produite ».

Auscultation du chauffe-eau : pour faciliter l'explication des résultats observés, on relève les températures des points les plus intéressants du chauffe-eau.

Coûts d'investissements et coûts de production

Les coûts d'investissement comprennent *a*) le coût de fabrication usine, *b*) le coût de l'emballage et du transport, *c*) le coût du montage, *d*) le coût des interventions commerciales.

En France, le coût de fabrication usine du chauffe-eau 200 l/2 m^2 revient en série industrielle à environ 900 NF, le coût emballage et transport évolue entre 100 NF pour une destination métropolitaine et 400 NF pour une destination outre-mer lointaine, le coût montage évolue entre 100 et 200 NF selon la difficulté présentée, et le coût des interventions commerciales est de l'ordre de 50 p. 100 du prix usine, soit 450 NF.

Pour l'utilisateur, sans tenir compte des taxes et des frais de douane éventuels, le chauffe-eau coûte, selon le lieu d'emploi entre 1 550 et 1 950 NF.

Les coûts de production d'eau chaude se réduisent à l'entretien du matériel, qui est négligeable, et l'amortissement sur 10 ans (des appareils Radiasol fonctionnent depuis 14 ans). L'amortissement sur 10 ans est donc compris entre 155 et 195 NF par an.

Le chauffe-eau apportant à l'utilisateur l'équivalence de 3 000 kW électriques par an en moyenne, et le prix du kW évoluant de 0,05 NF à 0,5 NF (environ) selon les régions, la formule

$$x = \frac{I}{3\,000 \text{ PkW}}$$

donne le nombre d'années nécessaires (x) pour couvrir la dépense d'investissement (I) par l'économie d'énergie (PkW étant le prix du kW électrique au lieu considéré).

Mesure dans laquelle les systèmes de chauffe-eau solaires répondent aux besoins sociaux des consommateurs

Quelle que soit la latitude où la question se pose, on constate que l'eau chaude est un besoin pour l'individu. Le chauffe-eau solaire répond donc à une nécessité dans la mesure où il peut fournir aux consommateurs une eau chaude à un prix de revient inférieur à celui de toute autre énergie classique.

Il a été démontré précédemment, en prenant l'électricité pour énergie de comparaison, que le chauffe-eau solaire était parfaitement compétitif, même dans les régions à équipement énergétique développé.

L'analyse de la clientèle des chauffe-eau solaires montre que, dans le cas de prix de revient sensiblement équivalents, d'autres facteurs sont déterminants pour le choix du chauffe-eau solaire : l'absence d'entretien technique, l'absence de risques, et enfin la robustesse du matériel.

On constate en effet que 70 p. 100 du chiffre d'affaires de la Société Radiasol est représenté par des installations intéressant des communautés : hôtels, cliniques — maternités — dispensaires, clubs sportifs, casernements militaires, internats, communautés religieuses.

Suggestions

Le succès des chauffe-eau solaires reste pour l'avenir essentiellement tributaire de deux facteurs fondamentaux : les perfectionnements d'ordre technique, et l'éducation du public.

Perfectionnements d'ordre technique

Les efforts de recherche doivent porter sur :

Les surfaces sélectives en vue d'augmenter la proportion d'énergie captée;

Les calorifuges en vue de diminuer les pertes calorifiques sur l'énergie accumulée;

Les revêtements anti-corrosifs en vue d'augmenter la durée d'usage des appareils;

L'adoption de matériaux légers en vue de diminuer le poids des appareils.

L'aboutissement de ces recherches doit permettre une amélioration du rendement des chauffe-eau se traduisant par un abaissement du prix de revient de la calorie.

Il est grandement souhaitable de mettre à la disposition des constructeurs des instruments de mesure simplifiés et normalisés, tant pour la mesure de l'énergie incidente que pour celle des températures.

Une excellente mesure serait celle qui consisterait à pouvoir utiliser comme stations d'essais, les stations de la Météorologie et celles de l'Institut de physique du globe.

Enfin, il est suggéré de constituer un organisme international qui définirait les normes auxquelles les chauffe-eau solaires devraient satisfaire pour obtenir un label de qualité.

L'éducation du public

Malgré les efforts de vulgarisation entrepris depuis quelques années, l'énergie solaire n'est encore pour le grand public qu'une vue de l'esprit sans application pratique possible.

Pour faire connaître les possibilités de l'énergie solaire, l'intervention des pouvoirs publics est indispensable, car la seule publicité des constructeurs de chauffe-eau solaires est insuffisante pour faire entrer dans les mœurs ces procédés nouveaux.

Il est indispensable que des notions de base sur l'énergie solaire soient incorporées dans le programme des études de l'enseignement secondaire scientifique et technique et dans celui des écoles professionnelles du bâtiment, et des écoles d'architecture et d'urbanisme.

Résumé

Le développement de l'emploi de l'énergie solaire en un lieu considéré pour le chauffage de l'eau est directement fonction du nombre de jours ensoleillés par an, de la constance de la durée d'ensoleillement quotidien, et du coût des énergies classiques.

La captation et la retenue du maximum possible d'énergie thermique peuvent être effectuées soit *avec* concentration de l'énergie solaire, soit *sans* concentration de l'énergie solaire.

Pour le chauffage de l'eau, le récepteur plan présente le maximum d'avantages.

Conditions auxquelles doit satisfaire le chauffe-eau solaire

Il doit pouvoir assurer un service continu. Par suite, sa capacité doit être suffisante, et il doit disposer d'un chauffage d'appoint si les journées d'ensoleillement sont discontinues.

Il ne doit pas poser de problème d'architecture par son volume, par son poids, ni par un aspect inesthétique.

Il doit pouvoir être mis en place sans qu'il soit besoin de faire appel à un spécialiste.

Il ne doit pas être sensible à l'entartrage : l'eau fournie ne doit pas être à une température supérieure à 70 °C.

Il ne doit pas être sensible au gel.

Par suite, obligation du chauffage indirect et d'un calorifugeage très soigné.

Il doit être robuste et ne demander ni entretien ni surveillance. Par suite, il ne doit comporter aucune pièce mobile, et ses différents éléments ne doivent pas être sensibles à la corrosion.

Son prix doit être compétitif avec ceux des autres chauffe-eau.

L'économie réalisée par l'énergie gratuite doit permettre son amortissement en trois ans.

Solutions présentées par la Société Radiasol

Radiasol fabrique les matériels suivants en série industrielle :

a) *Le chauffe-eau standard 200 l/2 m²* correspondant aux besoins d'une famille. Le circuit de chauffe fonctionne par thermosiphon. Variante : 200 l/4 m², pour satisfaction de besoins d'eau chaude plus importants pendant la période d'ensoleillement;

b) *Les installations de grande capacité* (plusieurs mètres cubes) pour collectivités (hôpitaux, internats, etc.). Le circuit de chauffe est animé par une pompe commandée par un régulateur spécialement adapté.

Derniers perfectionnements des procédés Radiasol

a) Variation saisonnière de l'inclinaison de l'insolateur.

b) Irréversibilité du thermosiphon : clapet adapté aux pressions infinitésimales.

c) Régulation électronique du circuit de chauffe des installations de grande capacité, par application du pont de Wheatstone.

d) Chauffage d'appoint. En aucun cas celui-ci ne doit contrarier le chauffage solaire.

Essais et rendement

Pour que soient significatifs les essais portant sur les perfectionnements, les mesures de production doivent porter simultanément sur deux chauffe-eau ne se différenciant que par le perfectionnement que l'on veut tester.

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Coûts d'investissement et coûts de production

Les coûts d'investissement comprennent *a*) le coût de fabrication usine, *b*) le coût emballage et transport, *c*) le coût montage, *d*) le coût des interventions commerciales.

Les coûts de production se réduisent à l'entretien du matériel et l'amortissement du matériel.

Mesure dans laquelle les systèmes de chauffe-eau solaires répondent aux besoins sociaux des consommateurs

L'analyse de la clientèle des chauffe-eau solaires montre que, même dans les régions où les énergies classiques sont peu chères, le chauffe-eau solaire concurrence les chauffe-eau à énergie classique, et ceci grâce à la gratuité de l'énergie, la simplicité et la robustesse du matériel, l'absence d'entretien technique et l'absence de risques.

Suggestions

Le succès des chauffe-eau solaires repose, pour l'avenir, sur les facteurs fondamentaux suivants :

a) Les perfectionnements techniques permettant d'espérer une amélioration du rendement et un abaissement du prix de revient;

b) L'éducation du public, grâce à l'intervention des pouvoirs publics.

USE OF SOLAR ENERGY FOR WATER HEATING

(Translation of the foregoing paper)

J. Geoffroy *

Theoretically, the ideal zone for the use of solar energy is the zone with the maximum annual number of days of sunshine and where the daily duration of sunshine is constant and the conventional forms of energy scarce and therefore expensive. Commercial experience, however, proves that *all the regions* located between 45° N. lat. and 45° S. lat. and having over 2 000 hours of sunshine a year may be regarded as suitable for the rational use of solar energy to heat water for domestic purposes, without fearing the competition of the conventional forms of energy.

It is well known that solar energy may be collected *with or without concentration*, and that either of these methods may be used for water heating.

Concentration may be accomplished either by a parabolic mirror or by a cylindro-parabolic mirror.

The parabolic mirror requires a delicate and expensive mechanism to follow the sun during the day, and it takes a good deal of space. On the other hand, it does collect the maximum energy during the entire period of sunshine, at temperatures of the order of several hundred degrees centigrade.

The cylindro-parabolic mirror requires periodic adjustment of its inclination and is delicate, expensive and bulky. It collects no more energy than a plane collector, but it gives working temperatures over 100°C.

The flat collector is neither delicate nor very expensive. When properly oriented and tilted, according to the site, it collects as much energy as the cylindro-parabolic collector, but the operating temperature is below 100°C.

Conditions to be met by a solar water-heater

It must provide continuous service. Consequently, it must be a storage water-heater of capacity sufficient to meet the 24-hour needs of the consumer. It must also be provided with a stand-by heating system to take care of any interruptions of sunlight at the site.

It must not raise architectural problems:

Because of its bulk: its storage tank must, if required, fit into a single room, while the collector is installed on the front of the building;

Because of its weight, which must not exceed the permissible loads on roof, balconies and floors;

Because of its unaesthetic appearance: the water heater installed must be compact in appearance and compatible with the general style of the building.

Its installation must not require a specialist, and, like any other household equipment, the solar water-heater must be simple enough to operate after simply reading detailed instructions.

It must not be more liable to scaling than a water-heater using a conventional form of energy. The water supply being what it is, the solar water-heater must deliver water no hotter than 70°C, since scaling is more rapid above this temperature. The use of a heating circuit and a heat-exchanger eliminates the danger of scaling in the sensitive parts of the equipment.

It must not be liable to freeze. The use of a heating circuit independent of the distribution circuit makes it possible to protect the sensitive parts of the equipment by using an antifreeze mixture (water + alcohol or water + antifreeze in proper proportions). The storage tank and the distribution circuit must be very thoroughly heat-insulated.

It must be sturdy and require neither maintenance nor inspection. A solar water-heater is usually installed on the roof or balcony for optimum exposure. Access is thus inconvenient. The heater should have no moving parts, which might get out of order or need lubrication, and the materials must be resistant to weather conditions (wind, rain, sand, sea air).

Finally, it must be competitive in cost with water heaters using conventional forms of energy. But the cost of conventional water heaters should include not only the total capital investment but also the cost of energy for a least three years.

Solutions offered by the Radiasol Company

The Radiasol Company offers a standard 200 1/2 sq m water heater, serving a family of 2 to 4. It is a complete set, shipped from the factory in two cases. It can be put into service immediately, provided there is a cold-water header and a hot-water distribution system (see figure 1).

* Société anonyme Radiasol, Paris and Casablanca.

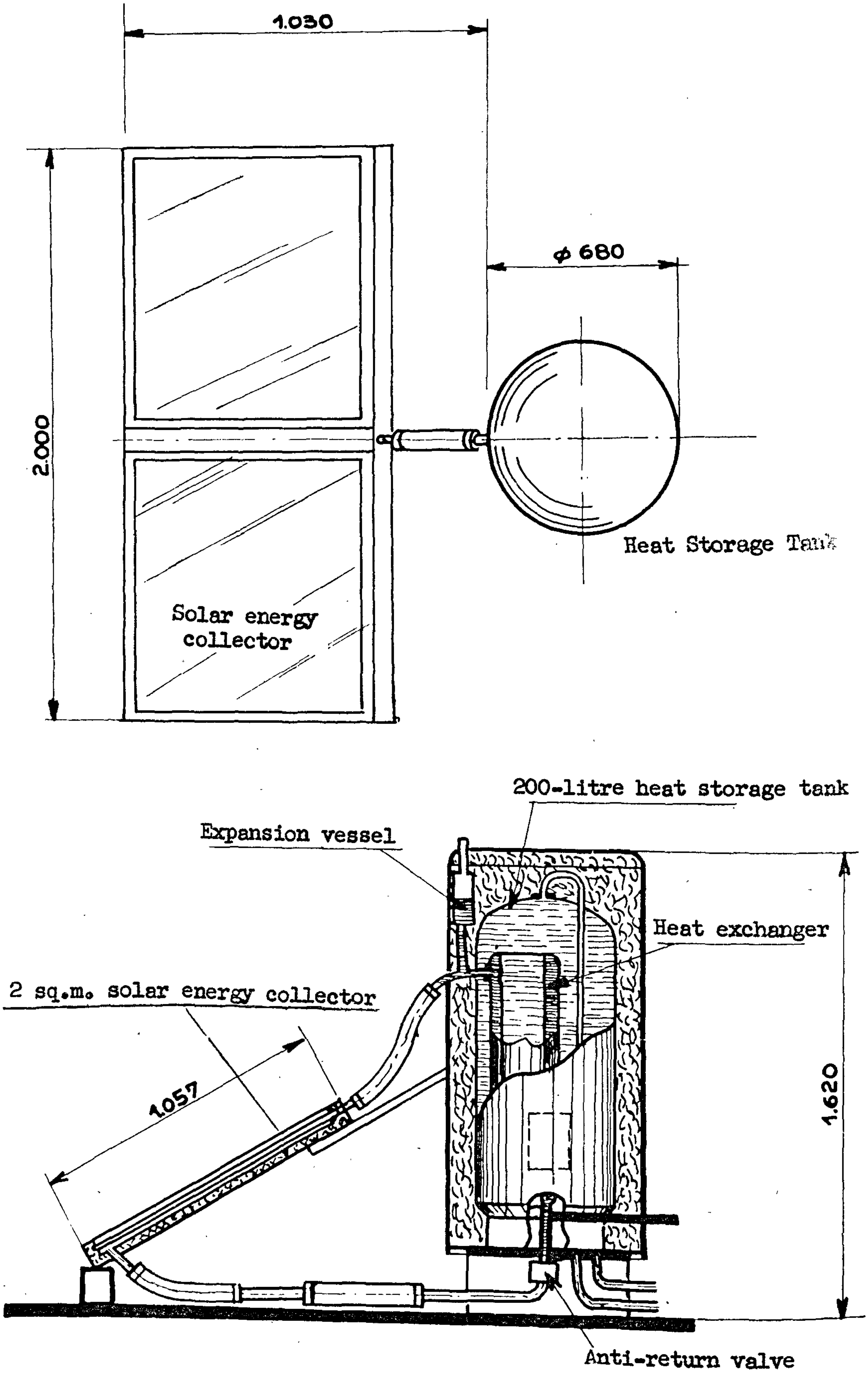

Figure 1. Descriptive schematic diagram of Radiasol water heater (200 l/2 m²)

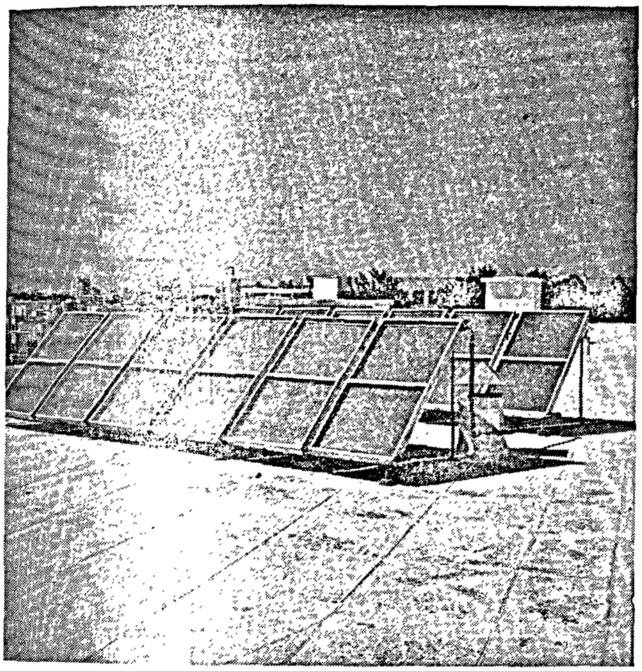

Figure 2. **Batteries of Radiasol solar energy collectors**

Radiasol also offers the equipment for large hot-water plants (several cubic metres), comprising:

(*a*) Unit collectors of 2 sq m for assembly into batteries (using the required number of units) see (figure 2);

(*b*) Storage tanks of various sizes (500 l, 750 l, 1 000 l, 1 500 l and 2 000 l) with a single or double heat-exchanger, permitting the heating of the required amount of water, with or without a stand-by heating system (see figure 3).

Radiasol heaters use the "glass-house effect" for collecting the heat. The 2 sq m solar collectors consist of a very flat reservoir, termed the absorber, placed in an insulated box and glazed with a glass pane exposed to the sun. The absorber is connected to a heat exchanger placed in the pressurized water contained in an insulated storage tank. The collectors are always so arranged as to receive the maximum solar radiation at noon. To transfer the heat to the water supply, the Radiasol Company uses thermosiphon circulation or forced circulation.

In the standard water heater (200 l), as soon as the sunlight strikes the glass, the water becomes heated in the absorber, the circulation starts by the thermosiphon effect, and the heat is delivered to the supply water through the heat exchanger. As soon as the sun disappears, the circulation stops and is irreversible, owing to the location of the collector (in tropical regions), or else by the action of a patented Radiasol valve (in Mediterranean regions), which permits reducing the height of the equipment to the height of the storage tank (see figure 1).

In the larger plants, with a capacity up to several tens of cubic meters, the storage tanks are placed in the basement of the building. In such cases, the thermosiphon principle can no longer be used to circulate the water, and a pump controlled by a patented Radiasol regulator is used instead (see figure 4). The regulator automatically determines the period of the day when heat can be supplied to the volume of water to be heated.

This forced circulation considerably improves the output of the process. Moreover, the fact that the storage tanks may be placed in the shelter of the building foundations, rather than in the open air, markedly diminishes the heat losses (see figure 3).

The loads on the balconies or roof are also considerably reduced in this way, and the installation, the height of which is no more than 1.60 m in the Mediterranean region, is practically invisible from the ground (see figure 2).

Finally, this method makes it possible to fit the plant exactly to the requirements. Since standard components are used, it is sufficient, if the consumption increases, to increase the heating surfaces and the number or capacity of the storage tanks.

Recent improvements in Radiasol methods

Seasonal inclination of the collector

The new method of attaching the collector to the storage tank unit allows the inclination of the collec-

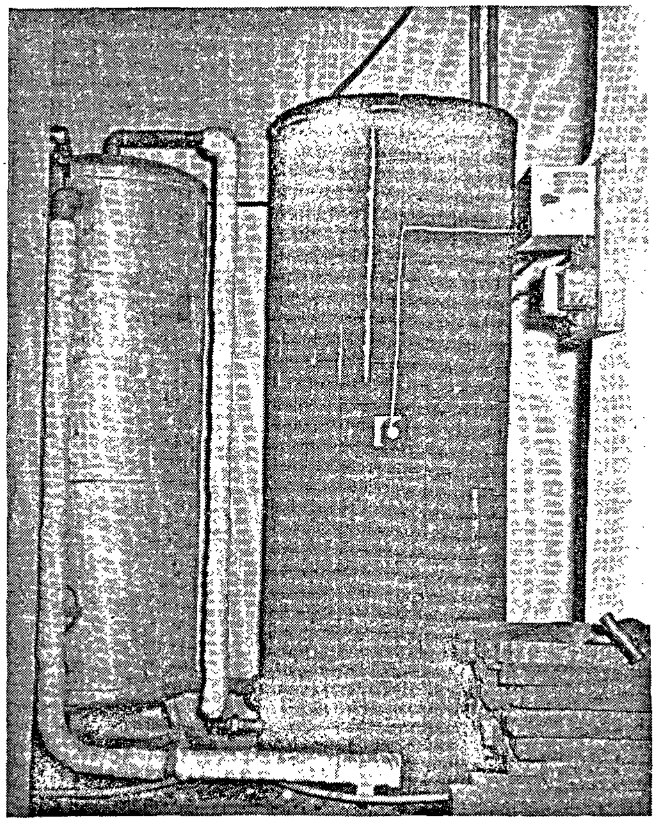

Figure 3. Reservoirs with heat exchangers during insulation work

Note: 1, the control desk of the installation; 2, the probe on the reservoir at the right; 3, the pump that can be seen behind the reservoir at the right.

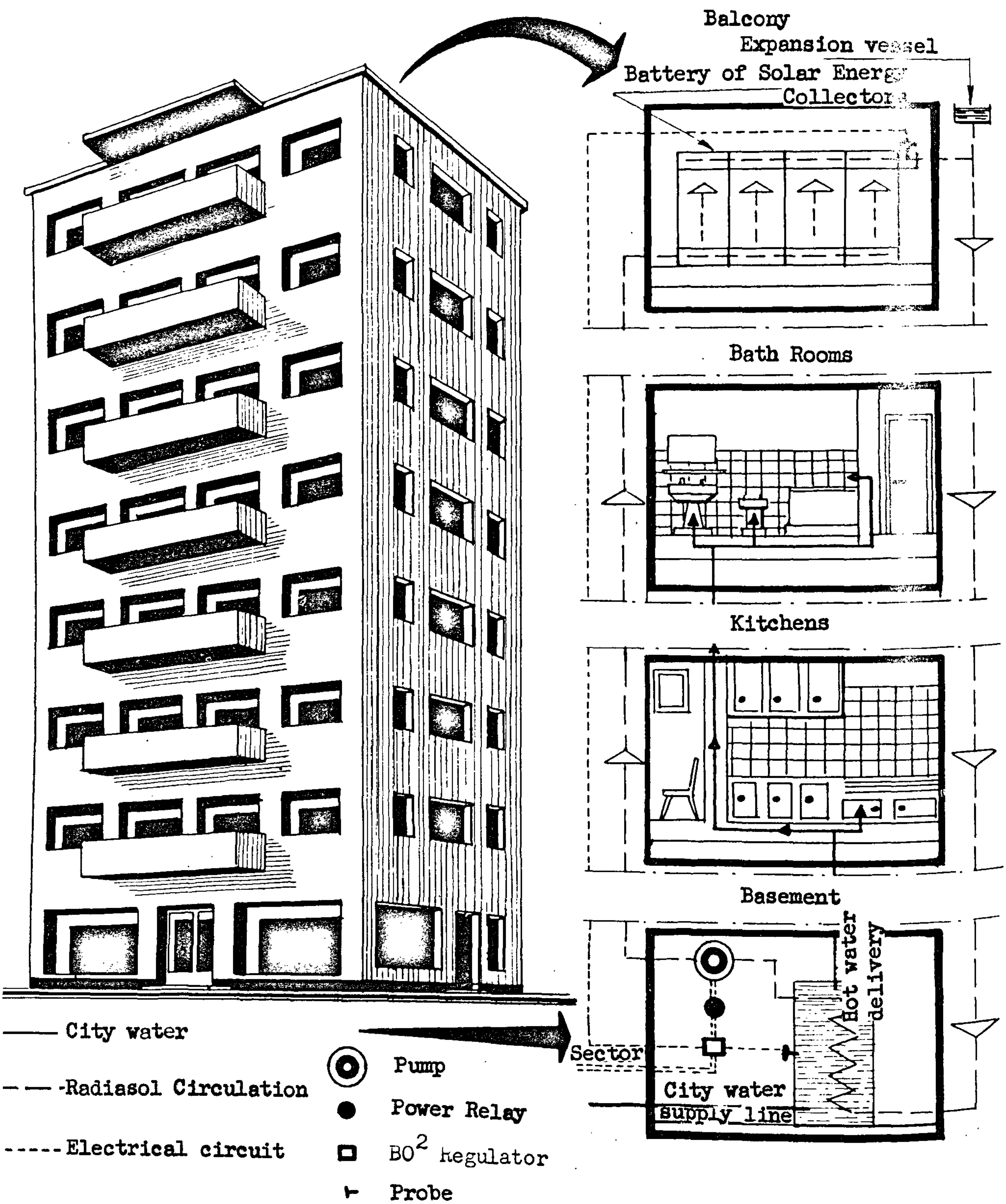

Figure 4. Schematic diagram of a Radiasol hot-water service

tor to be changed during the course of the year. This attachment is accomplished by means of a collar sliding along the surface of the storage tank and a set of flexible connecting piping permitting all inclinations between 15 and 45°.

The anti-return valve sensitive to extremely small pressures

Solar water heaters with heat-exchanger, operating by the thermosiphon principle, are of two types.

One type has the heat exchanger in a small tank attached to the bottom of the reservoir containing the water to be heated, with the collector installed below. The total height of the plant is the sum of the total or partial heights of these three elements: tanks, heat exchanger and collector. This arrangement prevents return flow on the thermosiphon principle at night, but the total height of the plant involves many disadvantages — aesthetic considerations, ease of installation, ventilation, etc.

The others have their heat-exchanger inside the reservoir, and the collector is installed at the same height as the exchanger. In these cases, the total height of the plant is much less than with plants of the former type, but, under these design conditions, there is a return thermosiphon effect at night, thus causing the storage tank to lose part of the heat stored in it during the day.

The Radiasol anti-return valve prevents this reversal. In contrast to the valves in use up to now, it is sensitive to extremely low actuating pressures and does not substantially reduce them.

The valve comprises a moving mushroom in a shell with two apertures, one at the top and the other at the bottom (see figure 5). The mushroom is conical and is made of corrosion-resistant plastic with a coefficient of cubical expansion low by comparison with that of water. It is so weighted as to be in indifferent equilibrium when placed in the liquid used for the heating circulation. Finally, it is so dimensioned that its point cannot leave the orifice it must close.

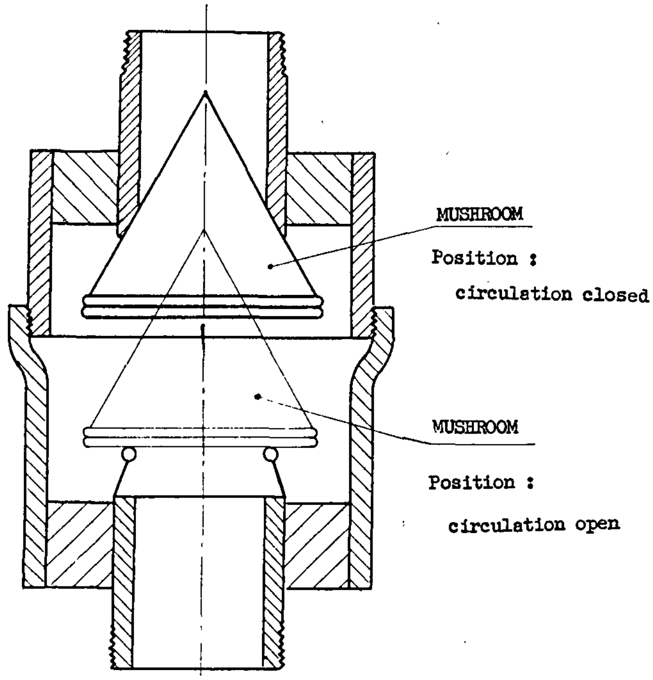

Figure 5. Schematic diagram of Radiasol anti-return valve sensitive to very low pressures

Electronic regulation of the heating circulation of high-capacity plants

When the reservoir and its exchanger are placed at the same level as the absorber, or below it, the circulation is accomplished by a pump. But this pump must operate only when the temperature of the fluid in the absorber is higher than the mean temperature of the water in the reservoir.

The Radiasol regulator is a temperature-sensitive electronic device (see figures 6 and 7). It consists of a D.C. generator feeding a Wheatstone bridge with one probe in its branches to take the temperature of the solar collectors (termed the hot probe) and another to take the temperature of the reservoir (termed the cold probe). A temperature-difference detector is placed on the diagonal of the bridge.

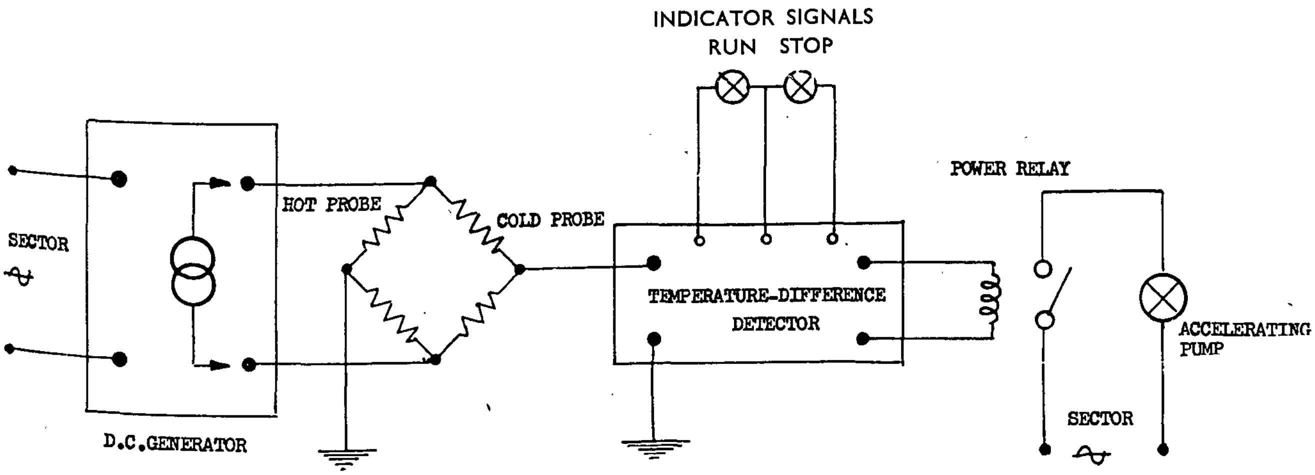

Figure 6. Schematic diagram of Radiasol BO^2 regulator

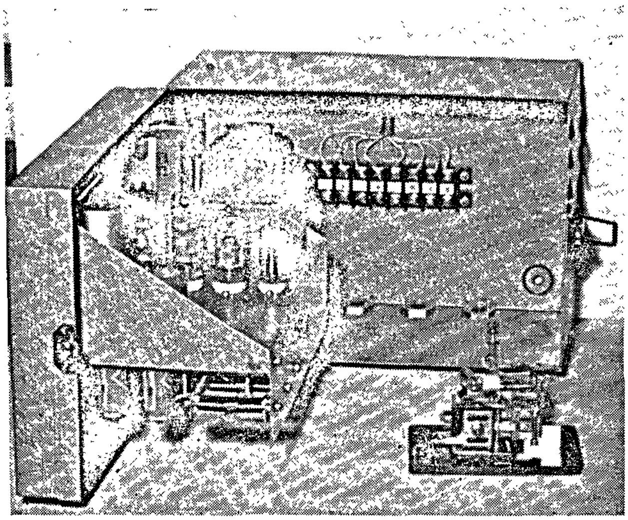

Figure 7. BO² Radiasol regulator with its power relay

The differentials operating it may be regulated according to the heat losses of the plant and its circulation. Through a power relay, it will start and stop the pump forcing the circulation.

The general law of operation of the regulator is of the form:

$$\frac{K\,\Delta\theta}{1+\alpha\theta_2} \quad \text{where } \Delta\theta = \theta_2 - \theta_1$$

$\Delta\theta$ being the temperature difference between the probes,
θ_1 the temperature of the cold probe, and
θ_2 that of the hot probe.

The identification of the quantity α with the thermodynamic coefficient $\beta = 1/273$ allows the thermodynamic output to be held constant, whatever the temperature of the probes, when the actuating differentials have once been set.

The stand-by heating system

During rainy days, or days with very little sunshine, the solar radiation may be insufficient to obtain the minimum temperature required in the reservoir. While such periods are very infrequent in a desert climate, are discontinuous in a tropical climate, and do not exceed several tens of days per year in the Mediterranean climate, Radiasol has provided a stand-by heating system in all cases where uninterrupted hot water service is essential. The stand-by heating system raises two essential problems.

(1) To retain all the possible advantages of energy, every plant making use of stand-by energy must take account of the fact that solar energy operates at a lower temperature than the conventional forms of energy. Consequently, to prevent the conventional energy from interfering with the work of the solar energy, both energies must operate in series: either in two reservoirs, the solar energy being used for pre-heating in the first reservoir, and the conventional energy operating in the second reservoir, which receives the pre-heated water; or in time, the stand-by energy being used only after the solar energy has already given up its calorific potential.

(2) The cost of the investment necessary to provide stand-by heating must be as low as possible, and it must consequently take account of the power equipment of the place under consideration.

Stand-by heating system for the standard Radiasol water heater of 200 l/2 sq m. In principle, an electrical resistance passing 1 kW is used. It is controlled by a thermostat, for which a place is provided, and a clock, which will permit the electric circuit to be closed only (*a*) when the temperature of the water in the reservoir is below, say, 50°C, and (*b*) at night, to gain the benefit of the night electric rates, where they exist.

Stand-by heating system for the large forced-circulation solar water-heaters. There are several solutions:

(*a*) As with the standard 200 l/2 sq m water-heater, an appropriate electrical resistance may be placed on the last reservoir of the plant;

(*b*) When the house has central heating, the last reservoir of the water-heating plant may have two heat-exchangers, one with a large heating surface for the solar heating circulation, the other with a normal heating surface branching onto the central heating system like a simple radiator;

(*c*) A gas water-heater may be placed at the delivery of the solar heating plant. The burner of this gas heater will light only if the water preheated by solar energy fails to reach the desired temperature.

Tests and output

This section is intended more for the purpose of defining a programme than of describing a procedure already applied. For rigorous output, tests and calculations require very costly measuring and recording instruments, and, above all, long periods of observations, which a private firm could afford only with difficulty.

For these reasons, it would be desirable to have the official meteorological stations and physical institutes of the world participate actively in experiments on equipment utilizing new sources of energy, such as solar energy.

For tests of improvements to be significant, the measurements of production would have to be made simultaneously on two water-heaters, differing only in the improvement to be tested.

Incident energy is measured by a solar graph oriented and inclined like the collectors of the water heaters.

Production measurements relate to the quantity of hot water delivered at the temperature T, constant throughout the test (period of sunshine). The production is measured at various values of T.

Output is found in the form "Mean daily output for the temperature Tx of the hot water produced."

Probe-measurement of water heaters: to facilitate the explanation of the observed results, the temperatures are taken at the points of greatest interest in the water heater.

Capital costs and operating costs

The capital costs comprise: (*a*) the cost of production at the factory; (*b*) the cost of packing and shipping; (*c*) the cost of installation; (*d*) the commercial or selling costs.

In France, the cost of production at the factory of the 200 1/2 sq m water-heater comes to about 900 NF for production in series; packing and shipping costs range from 100 NF for a destination in France to 400 NF for a distant overseas destination; the installation cost ranges from 100 to 200 NF, according to the difficulty of the job; and the commercial or selling cost is of the order of 50 per cent of the factory price, or 450 NF. For the consumer, without taking account of the possible charges and customs duties, the water-heater costs, according to the place of installation from 1 550 to 1 950 NF.

The operating costs, or costs of producing hot water, reduce down to cost of maintenance of the equipment, which is negligible, and amortization on a 10-year basis (Radiasol heaters have been operating for 14 years). The amortization in 10 years is thus between 155 and 195 NF annually.

Since the water-heater gives the consumer the equivalent of 3 000 kW per year, on the average, at electric rates ranging from about 0.05 to 0.5 NF per kW, according to the region, the formula

$$x = \frac{I}{3\ 000\ \text{PkW}}$$

giving the number of years required (x) for the saving in energy cost to pay for the capital investment (I) PkW being the cost of 1 kW at the place of operation.

Extent to which solar water-heating systems meet the social needs of the consumers

Whatever the breadth of this question, it will still be noted that hot water is a necessity for the individual. The solar water-heater therefore meets a need to the extent to which it can provide consumers with hot water at a unit cost lower than for any conventional form of energy.

We have demonstrated above, taking electricity as the energy for comparison, that the solar water-heater is fully competitive, even in regions with a highly developed electric power system.

The analysis of the customers for solar water-heaters shows that, in cases where the equipment cost is substantially the same, other factors are decisive for the choice of solar heaters: no technical maintenance required; no hazard; and, finally, the sturdiness of the equipment.

Seventy per cent of the total business of the Radiasol Company is for plants serving public buildings: hotels, clinics, maternity hospitals, dispensaries, athletic clubs, military barracks, boarding schools, religious communities.

Suggestions

The future success of solar water-heaters will depend essentially on two basic factors: technological improvements and the education of the public.

Technological improvements

Research should be directed towards: selective surfaces, to increase the proportion of energy captured; thermal insulation, to reduce the losses of stored heat; anticorrosive coatings, to prolong the service life of the equipment; and use of light materials to decrease the weight of the equipment.

The results of such research should permit an improved output from the water-heaters, which would reduce the cost per calorie.

It would be extremely desirable if designers made available to constructors simplified and standardized instruments for measuring incident energy and for measuring temperature.

It would be excellent if the stations of the Meteorological Service and those of the Institute of Geophysics could be used as test stations.

Finally, it is suggested that an international agency be organized to establish standards for solar water-heaters in connection with a label of quality.

Education of the public

In spite of the efforts at popularization that have been going on for several years, the public still sees solar energy as a mere hope, without possible practical applications.

To make the possibilities of solar energy known, the intervention of the authorities is indispensable, for the new items about designers of solar water-heaters are insufficient to incorporate these new methods in the way of the life of the people.

The basic ideas about solar energy should be included in the curricula of scientific and technical secondary education, of vocational building-trades schools, and of schools of architecture and town-planning.

Summary

The development of solar water-heating in a given place depends directly on the number of days of sunshine in the year, the constant value of the daily duration of sunshine and the cost of conventional forms of energy.

The maximum possible amount of thermal energy may be captured and retained either with or without concentration of solar energy.

The flat solar collector is the most advantageous system for water heating.

Conditions that a solar water-heater must meet

It must be able to ensure continuous service. Consequently, its capacity must be adequate, and it must also have means for stand-by heating if the sequence of days with sunshine is not continuous.

It must not raise architectural problems by reason of its volume, its weight, or its unaesthetic appearance.

Its installation must not require the services of a specialist.

It must not cause scaling of the boiler: the water must be delivered at a temperature not over 70°C.

It must not be liable to freeze. Heating must thus be indirect, with very careful thermal insulation.

It must be sturdy, and require neither maintenance nor inspection. Consequently, it must have no moving parts, and its components must not be liable to corrosion.

Its price must be competitive with those of other water-heaters. The saving due to the fact there is nothing to pay for the energy must pay for the equipment in three years.

Solutions offered by the Radiasol Company

Radiasol produces the following materials in its industrial series:

(*a*) Standard water heater (200 l/2 sq m) to meet the needs of a single family. The heating circulation operates on the thermosiphon principle. Another version (200 l/4 sq m) for a larger supply of hot water during sunshine hours;

(*b*) Large-capacity plants (several cubic metres) for hospitals, boarding schools, etc. The water is circulated by a pump with a specially designed regulator.

Recent improvements in Radiasol methods

(*a*) Seasonal variation of the angle of inclination of the collector;

(*b*) Irreversibility of the thermosiphon: the valve acting at extremely low pressures;

(*c*) Electronic regulation of the water circulation in large-scale units, by application of Wheatstone bridge;

(*d*) The stand-by heating system. In all cases, the stand-by heating must not interfere with the solar heating.

Tests and output

For tests on improvements to be significant, the output must be measured simultaneously on two water heaters differing only in the improvement to be tested.

Incident energy is measured by a solarigraph with the same orientation and inclination as the collectors of the water heater.

Production measurements relate to the quantity of water delivered at a temperature *T*, constant during the test (period of exposure to sunshine). The production is measured at various values of *T*.

Output is found in the form "Mean daily output for temperature *Tx* of the hot water produced".

Measurement of temperatures at various points: to facilitate explanation of the observed results, the temperatures are recorded at the most important points of the water heater.

Capital investment and production costs

The capital investment costs comprise : (*a*) manufacturing cost at factory; (*b*) packing and shipping costs; (*c*) installation cost; (*d*) selling cost.

The production cost reduces down to maintenance of plant and amortization of plant.

Extent to which solar water-heating systems meet the social needs of the consumers

Marketing research on solar water-heaters indicates that, even in areas where conventional forms of power are inexpensive, such heaters are competitive with conventional water-heaters because the energy is free of cost, the equipment is simple and sturdy, no technical maintenance is required, and no hazard is involved.

Suggestions

The future success of solar water heaters is based on the following basic factors:

(*a*) Technical improvements promising increased output and reduced cost;

(*b*) Education of the public by the intervention of the authorities.

SOLAR WATER HEATERS

*K. N. Mathur * and M. L. Khanna ***

The developments in the direct utilisation of solar energy for human needs have taken place along two different lines. In one, use is made of concentrators like lenses or mirrors to bring to focus solar energy falling over a large area and thereby producing very high temperatures over small areas; in the other, heat collectors in the form of flat surfaces are used to receive solar energy and then transfer it to a fluid medium in close contact with the surface. In general, concentration of solar radiations is called for where attainment of high temperatures is the objective as in cooking or for purposes of power development; on the other hand, the flat plate collectors are most useful where large quantities of fluids have to be heated through a limited range of temperature. A very important advantage here is that the flat plate collectors are comparatively cheap, and require practically no attention once they have been installed. For this reason, they have found extensive use in the experimental projects on solar heating of houses.

In this paper a more modest use has been investigated, namely, hot water supply for domestic requirements like bath, kitchen use, etc. For this purpose the equipment designed and described here has proved economical and satisfies all the demands of an average family for its needs of daily hot water supply.

The success of any method of utilising solar energy inevitably depends upon the number of sun hours available. The Indian winter months offer the most favourable time to make the best use of solar radiations. This is also the time when it is most desirable to have a domestic hot water supply. Hot water installations have been in use for some time in the U.S.A., Japan and elsewhere, but the aim of the present investigation was to gather performance data for an economical unit, the cost of which would be within the means of an average income group family.

The main characteristics of the North Indian winter months are as follows. Beginning with October the day temperature starts going down and by about the middle of the month the maximum falls to 90°F. By the end of November, the maximum goes down to 80°F. and the minimum to 45°F. During December and January, the minimum night temperatures are around 35°-38°F and the maximum stands between 65°-70°F. Through February the temperatures show a tendency to rise and March shows a distinct rise. Towards the end of March, the hot season begins to set in and the equinox is in fact a herald of the summer season. An average Indian household needs a domestic supply of hot water for bathing and washing purposes from, say, the middle of October to the end of March, i.e., for a period of about five and a half months, and for washing purposes alone for the rest of the year. Table 1 shows that the period from October to May is about the most favourable for utilizing solar energy and also synchronises with the maximum demand.

In most of the common types of flat plate collectors tried in the U.S.A. and other countries, the heat transfer is effected by water flowing through copper pipes soldered to a blackened copper absorber plate (1, 2, 3, 4, 5). The surface facing the sun has one or more layers of glass plates a little above the absorber surface, while the underside and the edges are protected with insulation to prevent undue heat losses. In this pattern of the collector, the heat absorbed by the copper plate, when exposed to the sun, goes to heat the circulating water via the copper pipe. This method suffers from certain obvious disadvantages, which go to reduce the efficiency of heat transfer. In the first place, the copper pipes fixed to the absorber are usually spaced about 4 to 6 in. apart and it is found that midway between two adjacent pipes the temperature is considerably higher than the temperature of the water-carrying pipes. The effect of this on absorber efficiency, according to Hottel and co-workers (6), depends upon a number of factors, such as the material and thickness of the absorber sheet, the number of glass plates and the spacing between consecutive copper pipes. The second factor which reduces efficiency is the very limited area of contact between the circular pipe and the flat surface of the plate, where the pipe is soldered to the plate with soft solder. It is through this narrow region of contact that all the heat exchange between the flowing water and the collector plate takes place.

In view of the above disadvantages it was decided to do away with copper pipes altogether and to use instead corrugated metal sheets as heat collectors and to back them up with a plane metal sheet to form a sandwich with parallel water channels running the entire length of the corrugated sheet. Galvanised iron corrugated sheets form one of the cheapest roofing materials in India and are usually available in widths of 2-10 in., varying in length from 6 ft to 10 ft. These sheets are available in several thicknesses

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Table 1. Total number of bright sunshine hours at New Delhi, latitude 28°35′ N; longitude 77°12′ E, for the years 1955-1960 (courtesy Indian Meteorological Department)

Months	*1955*	*1956*	*1957*	*1958*	*1959*	*1960*	*Average*
January . .	189.0	235.5	181.6	241.2	221.1	247.3	219.3
February . .	259.9	279.2	265.8	248.7	247.2	279.0	263.3
March . . .	262.9	259.2	255.5	274.8	271.0	232.1	259.3
April	268.9	307.9	276.5	191.0	269.3	276.5	265.0
May	284.9	283.7	308.9	185.5	309.3	309.3	280.3
June	101.1	207.4	251.8	166.2	251.0	237.5	202.5
July	167.4	200.6	153.8	140.4	199.1	153.8	169.2
August . . .	161.5	205.8	211.8	189.5	190.2	123.7	180.4
September. .	208.2	266.4	209.8	164.3	203.8	244.4	216.2
October. . .	246.9	236.7	296.5	275.8	276.8	264.0	266.1
November. .	298.2	279.0	276.9	285.3	273.4	288.9	283.5
December . .	261.4	210.1	216.1	242.6	266.4	246.3	240.5

but we have found 26 gauge (0.019 6 in. thickness) most convenient to handle.

Details of construction

A sandwich is formed with a corrugated sheet backed with a plane sheet of the same gauge, the two being secured by rivets at points along the lines of contacts. The edges along the length are hammered together with an overlap and then sealed with soft solder as shown in figure 1. The openings along the width are carefully soldered to circular header pipes formed from galvanised sheet of a thicker gauge cut carefully along one edge to follow the crests and troughs of the corrugated sheet. One end of the header pipes is closed. To the other end are soldered galvanised iron threaded reducers to take 1½ in. standard G.I. pipe. These are soldered to diagonally opposite corners, so that water entering through one side flows through the header pipes, then through the channels of the corrugated sheet and out into the upper header pipe. To complete the heating unit, the corrugated face is given a coating of carbon black dispersed in a dilute solution of shellac in methylated spirit of wine. The completed assembly is encased in a wooden box large enough to allow 4 in. of rock wool insulation at the back and a similar thickness around the sides. In order to prevent shadows an extra space of 4 in. is allowed on the two long sides and wooden planks painted white are fixed at a small angle with the sides. The upper face of the box is glazed with sheets of 1/8 in. thick window glass with an air gap of about 2 in. between the glass sheets and the metal heater surface.

The heater units thus formed had a glazed surface area of 22.4 sq ft and blackened sun collecting area of 19.0 sq ft. Arrangement was provided for inserting thermometers in the inlet and outlet pipes. For the purpose of taking observations as described in this paper, a constant head arrangement was adopted to enable a constant water flow to be maintained and a bib cock on the outlet side (not shown in the figures) enabled the rate of discharge to be controlled. This arrangement was used only to find out the over-all thermal efficiency of the system. The system as installed for domestic hot water supply is shown in figure 2, and its details of construction are given, in figure 3.

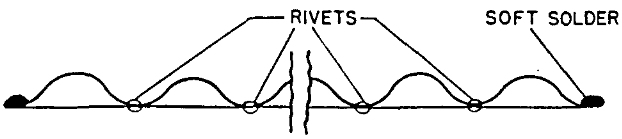

Figure 1. Section through heat collector units with one corrugated and one plane sheet

In order to get maximum advantage of sunlight an adjustable arrangement is necessary by which the collector can be made to face the sun so that at any instant the rays of the sun strike the surface at normal incidence. An elaborate arrangement of this type will be cumbersome and expensive and, therefore, a compromise had to be made to fix the collector in a position that gave maximum advantage. This can be secured in the northern hemisphere by facing the collector due south and inclining the surface by the same angle to the horizontal as the latitude of the place. This will ensure normal incidence at noon time at the periods of the equinoxes, when the sun is too low in winter and too high in summer. However, in order to make the best use of the winter sun, when the length of the day is short and the hot water requirements are large, it was decided to set up the collector at an angle of inclination of 45° to the horizontal (latitude of Delhi, 28° 35′). This ensures a larger measure of solar intensity during the winter months.

Observations

Observations using a heat-collector unit with a single layer of glass were recorded on a number of days and are presented in table 2. The observations were made at intervals of one hour during 6 hours of sunshine from 10.30 hrs. to 16.30 hrs. IST. To determine the heating capacity of the system, the quantity of water passed through the unit was varied from a maximum rate of 21 gallons per hour to

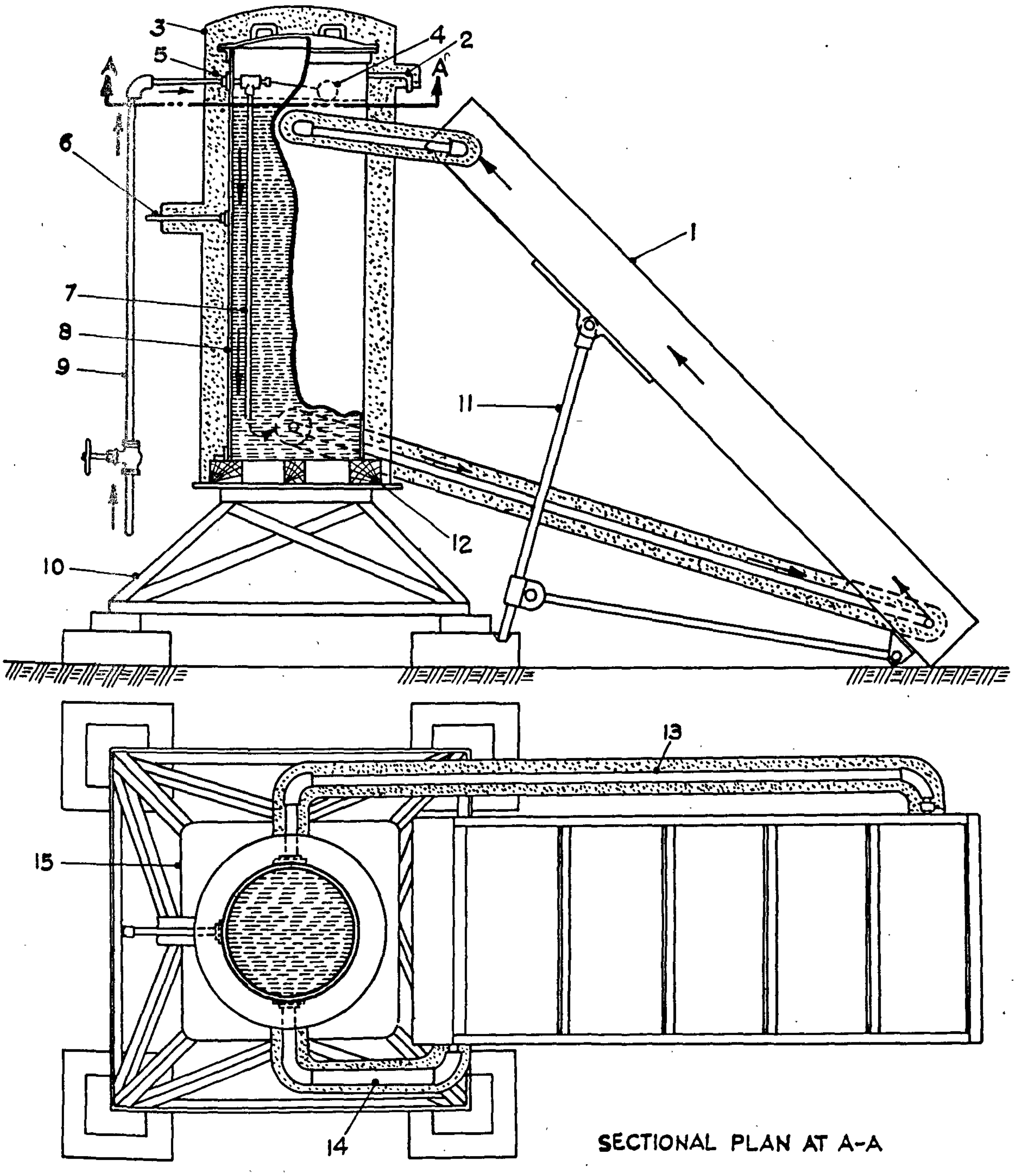

Figure 2. Complete set-up of the single solar water heater unit

(1, glass cover; 2, overflow; 3, outer cover of water reservoir; 4, float; 5, rockwool insulation; 6, hot water outlet; 7, cold water inlet; 8, wall of water reservoir; 9, connection to water supply; 10, angle iron stand; 11, support for water heater; 12, wooden base for reservoir; 13, cold water inlet pipe; 14, hot water outlet pipe; and 15, outer frame of the reservoir)

4.0 gallons per hour, which corresponds to a flow rate of 9.4 lb. to 1.8 lb. per hour per sq ft of the effective glazed area.

The values for intensity of solar radiation have been calculated from measurements of the total intensity of incident solar radiation and of the scattered sky radiation made with a simplified type of pyrheliometer. Measurements were made at intervals of one hour and the average of these readings was taken as the intensity during the period. Readings were, however, subject to a certain amount of fluctuation due to passing light clouds or gusts of wind.

From the measured rate of flow of water and the rise in temperature, the quantity of heat, Q_w, absorbed by water per hour per sq ft of the exposed

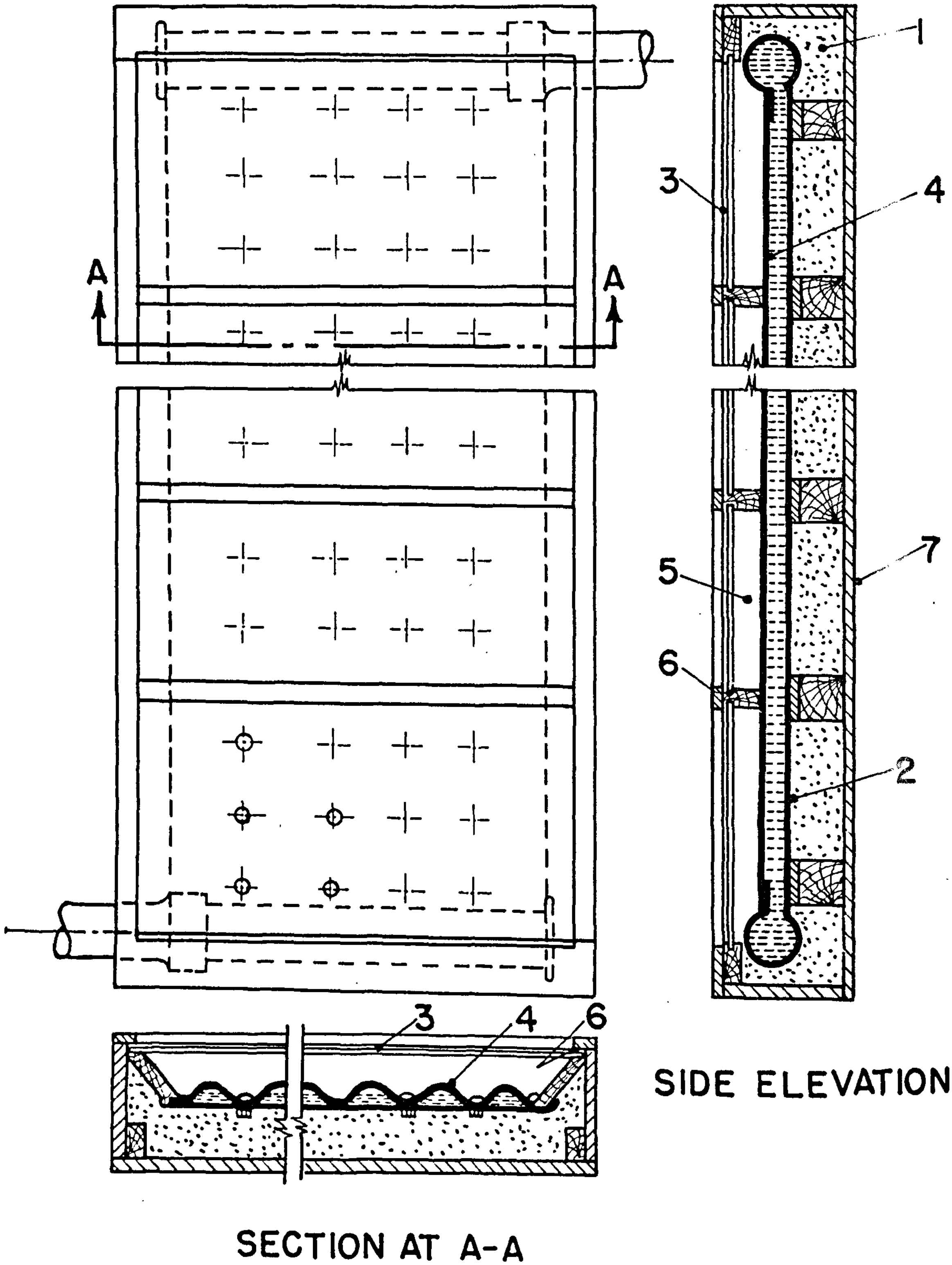

Figure 3. Details of construction of the single solar water heater unit

(1, rockwool insulation; 2, bottom plane G.I. sheet; 3, glass sheet cover; 4, top G.I. corrugated sheet; 5, air gap; 6, felt padding; and 7, wooden casing)

Table 2. Working efficiency of solar water heater with a single corrugated sheet with different rates of flow of water

Av. rate of water flow, gal/hr	$\Sigma I_{av.}$ btu/sq ft for 6 hrs	$I_{av.}$ btu/sq ft/hr	$\Delta\,\theta_{av.}$ °F	ΣQ_w btu/sq ft for 6 hrs	Q_w btu/sq ft/hr	Eff., %	$K_{av.}$*
21.0	1 419	236.5	20.8	1 186	197.7	83.6	1.9
19.0	1 433	238.8	22.6	1 148	191.3	80.1	2.1
13.0	1 517	252.8	31.2	1 069	178.1	70.4	2.4
10.0	1 353	225.5	38.1	1 045	174.1	77.2	1.35
7.0	1 361	226.8	50.0	975	162.5	76.6	1.28
7.0	1 407	234.5	52.8	1 004	167.3	71.3	1.27
6.0	1 193	198.8	52.4	824	137.3	69.1	1.1
4.0	1 120	186.6	57.4	564	94.0	50.4	1.6

* $K_{av.}$ has been calculated from equation [2] using average values, $\Sigma I_{av.}$, ΣQ_w and $\Delta\theta_{av.}$ as given in this table.

glass surface of the heater was calculated. (Specific heat of water was taken as unity in all calculation.)

The ratio of Q_w to the amount of total solar radiation, I, falling on the exposed glass surface, gives the over-all efficiency of the flat plate absorber. The total solar radiation I, was obtained from the observed value of I_s, the intensity of scattered radiations, and the normal component, I_c, of direct solar radiation, I_d falling on the surface. Thus $I = I_c + I_s$. The value of I_c is calculated from the observed value of I_d making use of the well-known equations involving the hour angle, the solar declination, the solar altitude and the angle of the absorbing surfaces with the horizontal.

As a result of the incidence of the quantity I of solar energy, the water in the heater will be heated up and there will be a difference in temperature of incoming and out-flowing water. Let θ_i be the temperature of incoming and θ_o the temperature of out-flowing water. Then if W is the mass of water flowing through the absorber per hour per sq ft of the glazed (i.e. exposed) surface, then $Q_w = W(\theta_o - \theta_i)$ (specific heat being unity) will give the amount of heat absorbed by water. This should be equal to the amount of total solar radiation, I, falling on the exposed glass surface of the collector provided there is no loss of heat due to any cause. However, there is loss of heat not only due to radiation from surface of the top glasses as well as from the blackened surface of the collector, but also by conduction through the back surface of the heater plate in contact with the insulating material, and by convection through air blowing over the glass surfaces. These losses depend upon factors, like ambient temperature, wind velocity, presence of clouds, etc. If the over-all heat transfer coefficient, k, is expressed in btu/hr/sq ft/°F, then the total quantity of heat lost to the surroundings, to a first approximation, will be given by :

$$k\left[\left(\frac{\theta_o + \theta_i}{2}\right) - \theta_A\right]$$

where θ_A is the temperature of the surrounding air. If we take the temperature of incoming water θ_i to be the same as the ambient air temperature θ_A, then the heat balance equation can be expressed as :

$$I = k\left(\frac{\theta_o + \theta_i}{2} - \theta_A\right) + W(\theta_o - \theta_i)$$

or

$$I = (K + W)\,\Delta\theta \qquad [1]$$

where $K = k/2$ and $\Delta\theta = (\theta_o - \theta_i)$, the rise in temperature of water. It is apparent from the above that heat utilization will be maximum when $K = 0$.

The efficiency of solar heat utilization as given in table 2 is calculated from the following relation :

$$\text{Percentage efficiency (Eff. per cent)} = \frac{Q_W}{I} \times 100 = \frac{100\,W}{(K + W)} \qquad [2]$$

Experiments were also carried out with two and three layers of glass sheets to see if there was any improvement in heat utilisation. The results have been discussed later.

Discussion

The performance of flat plate collectors has been the subject of much detailed theoretical and experimental study by several workers (1, 2, 3, 4, 5, 7). Ward (5) has distinguished between four possible conditions of heat flow in a flat plate collector, i.e., (1) steady state condition with no fluid flow, (2) unsteady state with no fluid flow, (3) steady state with fluid flow and (4) unsteady state with constant rate of fluid flow. Of these, (3) and (4) are the most important conditions from a practical standpoint.

In the present set of experiments we have tried to approximate to condition (3), namely, steady state with fluid flow. It is apparent that during the early hours of morning this is far from the case and it takes some time for the system to reach a somewhat steady condition of working. In the experiments the rate of water flow through the collector has been varied from 21 gal/hr to 4 gal/hr. At the higher rates of flow, it is obvious that the rise in the water temperature, $\Delta\theta$, will be less, and reference to the data in column 4 of table 2 shows that the maximum increase in temperature with a flow of 21 gal/hr is 20.8°F only. With the flow rate of 13 gal/hr, this goes up to 31.2°F, with 7 gal to 52.8°F and with 4 gal to 57.4°F. When the rise in temperature is large, i.e., with slower rates of water flow, the losses due to radiation, conduction and convection increase considerably. On the other hand, with higher rates of flow, the temperature rise is less and the losses are correspondingly reduced. This aspect is brought out clearly in table 2 where the total quantity of heat absorbed by water, i.e., ΣQ_w over a 6 hr period of sunshine during the day, is given along with the rate of flow of water and the average rise in temperature over the ambient temperature — the average rise $\Delta\theta_{av}$ being the mean of the readings $\Delta\theta$ obtained at hourly intervals.

It will be seen from the results presented in table 2 that as the rate of flow is reduced the rise in temperature is greater, while the total amount of heat actually absorbed by the water during a day is reduced, the reduction being due to increased heat losses. Part of these losses can be reduced by (1) reducing radiation, conduction and convection losses from the glass surface by using two or more layers of glass and (2) increasing the thickness of insulating material. The effect of increasing the number of glass layers was investigated for 7 and 10 gallon flow rates and is given in table 3.

The results show that for both rates of flow the total amount of heat absorbed, as also the increase in temperature, is significantly less compared with one layer of glass. This agrees with the observations made by Trombe at Mont Louis, (8) that while the multiple layers of glass undoubtedly help to reduce the heat losses, they also reduce the amount of heat energy reaching the heating surface because of absorption in the glass. However, if the ambient temperature is very low, as may happen in the colder climates, where both low temperature and cold winds may be present, there may be some advantage in using two or three layers of glass. It will be seen from equation [2] that the heat transferred to water will be maximum when $K = 0$. In figure 4 the variation in the value of K calculated from individual hourly readings has been plotted against the time of day. It is observed that for both: the higher rate of 19 gal/hr and the lower rate of 6 gal/hr, the K values show large variations reaching a figure as high as 4.1. On the other hand, for the rate of 7 gal/hr observed on two different days the variation in value of K is much less and lies between 0.79 and 1.4.

Table 3. Effect of glass layers

Av. rate of flow of water, gal/hr	*ΣQ_w btu/sq ft for 6 hrs*		*$\Delta\theta_{av}$ rise in temp. over ambient temp. (°F) with*	
	2 layers	*3 layers*	*2 glass layers*	*3 glass layers*
7	830	785	50.7	47.3
10	924	882	34.4	33.8
10	907	880	32.7	31.4

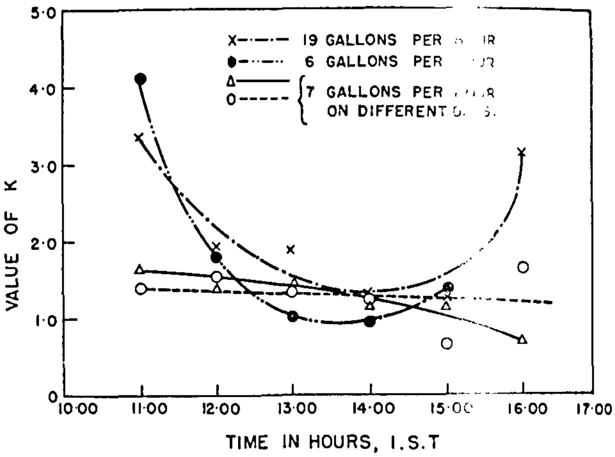

Figure 4. Variation of over-all coefficient of heat transfer (K) on different days employing different flow rates of water

This is found to be the case, more or less, for the rates of 9 and 10 gal/hr also. It may be concluded from this that for the size of water heater described in this paper the flow rate of 7 to 10 gal/hr appears to be optimum; the rate of 7 gal/hr being preferable if the water is to be heated to higher temperatures.

Conclusion

From the results summarised in this paper it is clear that the design of the Solar Water Heater described here is a practical proposition for obtaining a supply of hot water. In the size investigated, i.e., an insolation area of 22 sq ft, an optimum supply rate of 7 to 10 gallons per hour could be maintained with a rise in temperature of 38° to 50°F for a period of 6 hours a day during the winter months in North India (leaving out a few cloudy days during late December and early January). Over a 6-hour

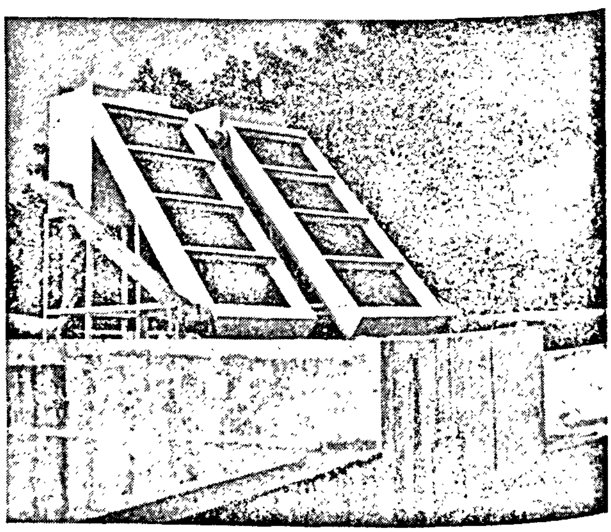

Figure 5. An installation consisting of two solar water heater units

period the energy absorbed for 22 sq ft insolation area averages between 20 000 and 26 000 btu per day, corresponding to slightly over 6 kW hr of electrical energy. Electricity for domestic power is supplied in the Delhi area at the rate of 10 *naye paise* per unit or one rupee for 10 units. This works out to about 60 *naye paise* per day or 18 rupees per month. A heater assembly comprising one 100-gallon insulated storage tank coupled to two heating units each of 22 sq ft insolation area appears to be a suitable unit for domestic purposes. Such units have been under observation in Delhi for the last five years and the results have been very satisfactory. In actual use a constant stream of water is not drawn from these units but water is drawn as and when needed. On a clear winter day in Delhi the number of bright sunshine hours average to more than 250 during November to April which works out to about 8 hours a day. During the first morning hour and the last afternoon hour the sun is too low for much effective heating but the remaining 6 hours contribute between 20 000 to 25 000 btu/22 sq ft heating area to the heating of water. In the arrangement adopted (figure 5) thermosiphon action keeps the water circulating between the heater and the storage tank and the temperature of water in the reservoir attains a temperature between 120° to 140°F. Most of the demand for hot water occurs during the earlier morning hours and so it is most essential that the storage tank is properly insulated. Rock wool insulation 4 in thick was provided for the storage tank and the fall of temperature after a night of storage (minimum night temperature being 34° to 36°F) did not exceed 20°F. Thus a supply of water, heated the previous day, was available for use in the morning at a temperature around 120°F which was found to be adequate for most purposes. The heating system has been installed on the roof of several houses and care was taken to see that sufficient pressure exists in the pipe line to refill the storage tank as hot water is drawn out. If due to low supply pressure during the day the storage tank does not fill, then the thermosiphon action stops and no heating takes place. In such cases a cold water tank at a somewhat higher level was found necessary to keep the storage tank full all the time.

The main point about the arrangement adopted here is the low cost of the system. In the conventional heaters used elsewhere copper pipes fixed over copper sheet have been used. These offer no particular advantage over the system adopted by us. On the other hand their efficiency is somewhat lower for the reasons discussed earlier in this paper. Our figure for efficiency averages to 80 per cent under certain conditions. This figure compares favourably with the recent observations reported by Thomason for heating cold city water for a swimming pool using corrugated sheet metal as the heating surface (9).

In the arrangement adopted here an effort has been made to keep the cost as low as possible. The cost of materials and labour for a unit using two 22 sq ft insolation cabinets and an insulated storage tank of 100 gallon capacity works out at 500 rupees ($110). To this must be added the cost of pipe line and its insulation from the storage tank to the points of consumption.

If the demand for hot water is not large, then only one heating unit of 22 sq ft area need be used with a 60-gallon storage tank. This will bring down the first cost to about 350 rupees which is about two-thirds the cost of a comparable electric heater with the added advantage that there is no recurring cost of energy.

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Summary

An arrangement for heating water from solar energy has been described using a flat plate collector. The usual flat plate construction using a copper sheet with a length of copper pipe soldered on it has been replaced by a comparatively inexpensive arrangement consisting of a corrugated galvanised iron sheet blackened on top and backed by a plain galvanised iron sheet forming a compact sandwich in which water could flow through the channels between the plane sheet and the corrugations. Two header pipes soldered on either side along the width served as inlet and outlet for circulating water and completed

the heating unit. The unit was enclosed in wooden casing with glazed top and was provided with adequate insulation on the back and sides to prevent undue heat losses. The unit was set up facing due south at an angle of 45° to the horizontal.

Experiments were conducted to test the efficiency of the heating unit by passing a constant stream of water at rates of flow varying from 6 gallons per hour to 21 gallons per hour. Observations show that for a heating unit with an insolation area of 22 sq ft, the optimum rate of flow lies between 7 to 10 gallons per hour with a rise of temperature of 50°F for 7 gallons rate and 38°F for 10 gallons rate. Over a 6-hour day of sunshine the heat gain comes to between 20 000 and 26 000 btu per day or over 165 btu per hour per sq ft of insolation area with an efficiency better than 70 per cent. In Delhi (lat. 28° 35′, long. 77° 12′ E) and in most parts of North India the winter months from October to March give an average of about 8 hours of sunshine per day. Only a few days of clouds and rain are encountered during this period but even on these days appreciable heating takes place due to scattered sky radiations.

For practical use as a household hot water supply system the heater was connected to an insulated storage tank provided with a float valve and an inlet pipe from town water supply. The header pipes of the heating unit were connected to the storage tank to form a thermosiphon system so that an entire day's insolation energy could be utilised to heat the water in the storage tank during the night and the following morning. Water temperature after the day's insolation rises to about 120° to 140°F and allowing for a fall of about 20°F during the night's storage could give water at 100° to 120°F the following morning.

For obtaining larger supplies, two units each of 22 sq ft area could be connected together to a 100-gallon storage tank from which up to [illegible]0 gallons of water could be usefully withdrawn.

The arrangement is cheap and makes use of easily available materials and in the larger size costs about 500 rupees ($110) giving a saving of up to 36 rupees per month. Several of these units have been under experimental use for several years and have proved entirely satisfactory.

CHAUFFE-EAU SOLAIRES

Résumé

Ce mémoire décrit un dispositif pour le chauffage de l'eau par l'énergie solaire, qui fait usage d'un collecteur à plaque plate. Le mode de construction usuel de ce genre de matériel, qui fait usage d'une feuille de cuivre à laquelle on soude une longueur de tuyau de cuivre, a été remplacé par un dispositif relativement peu coûteux constitué par une feuille de tôle ondulée en fer galvanisé, noircie en sa surface supérieure et doublée d'une tôle ordinaire en fer galvanisé de manière à former un « sandwich » compact où l'eau peut s'écouler par les rigoles formées entre la tôle plate et les creux des parties ondulées. Deux collecteurs soudés de chaque côté et sur la largeur du dispositif servent d'admission et de sortie à l'eau circulante et complètent le dispositif de chauffage. Il est contenu dans une caisse en bois avec partie supérieure en verre et protégé par un isolant satisfaisant sur l'arrière et les côtés, pour éviter les pertes de chaleur excessives. Le dispositif est monté de manière à être orienté exactement vers le sud, à 45° sur l'horizontale.

On a mené des expériences pour vérifier le rendement du système en se servant d'un courant d'eau continu à des régimes de 6 à 21 gallons d'eau à l'heure (27 à 95 litres). Les observations faites indiquent que, pour un élément chauffant ayant une surface exposée au soleil de 22 pieds carrés (2,04 m²), le régime d'écoulement idéal est compris entre 7 et 10 gallons à l'heure (32 et 45 litres) avec une montée de température de 50 °F (26 °C environ) pour le débit de 7 gallons et 38 °F (21 °C) pour le débit de 10 gallons. Pour une journée avec 6 heures de soleil, le gain de chaleur s'établit à une valeur comprise entre 20 000 et 26 000 BTU (5 000 et 6 500 grandes calories) par jour, soit plus de 165 BTU par heure et par pied carré de surface exposée au soleil, avec un rendement dépassant 70 p. 100. A Delhi (latitude 28°35, longitude 77°12′E) et dans la majeure partie de l'Inde du nord, les mois d'hiver, d'octobre à mars, donnent une moyenne d'environ 8 heures de soleil par jour. On ne trouve que quelques jours ennuagés et pluvieux pendant cette période, et, même au cours de ces jours, un chauffage appréciable se produit en raison du rayonnement céleste diffus.

En vue de son application pratique comme dispositif ménager de chauffage de l'eau, le chauffe-eau a été relié à un réservoir calorifugé doté d'une soupape à flotteur et d'une tubulure d'admission d'eau de la ville. Les collecteurs du dispositif de chauffage furent reliés au réservoir pour constituer un thermo-siphon, de telle sorte que l'énergie solaire d'une journée entière puisse être utilisée au chauffage de l'eau du réservoir, qui pourrait être utilisée pendant la nuit et la matinée suivante. La température de l'eau, après exposition au soleil pendant la journée, monte à 120 ou 140 °F (48 ou 59 °C) et, compte tenu d'une chute de 20 °F environ (11 °C) pendant la nuit d'emmagasinage ou accumulation, on pouvait en tirer de l'eau à 110 ou 130° F (43 ou 54 °C) le matin suivant.

Pour ob[illegible]r une plus grande quantité d'eau chaude, d[illegible]éléments de 22 pieds carrés chacun pourraient [illegible]e branchés ensemble sur un réservoir de 100 gal[illegible] (454 litres), duquel on pourrait tirer utilement [illegible]qu'à 60 gallons d'eau (270 litres).

Le dispo[illegible]f est peu coûteux et fait usage de matériaux faciles à se procurer. Le grand modèle coûte environ 500 roupies (110 dollars), et permet de réaliser une économie qui peut atteindre 36 roupies par mois. Plusieurs de ces appareils ont été soumis à des expériences pendant des années et se sont montrés entièrement satisfaisants.

WATER HEATING BY SOLAR ENERGY

R. N. Morse *

General

Water heating probably represents the most widespread engineering use of solar energy at the present time. There is extensive literature on the subject which is being studied throughout the world. Some indication of the scope of this work may be obtained from the Bibliography published in 1959 by the A.F.A.S.E., which, under the heading of solar water heaters, lists 191 references, ranging from scientific papers to patents (1).

Units are in commercial production in many countries and are competing more or less successfully with fuel operated systems. However, the economic advantages are often marginal due to high first costs, and research is continuing in order to develop designs which are both cheap to produce and easy to install.

Economic considerations

Since the energy is free, the annual operating cost of any solar device comprises interest on investment, depreciation and maintenance. Interest rates vary but for the present purpose may be taken at 5 per cent per annum, whilst depreciation depends on the life of the equipment. Maintenance depends on the design and the materials used for construction and might be taken as varying between ½ and 1½ per cent per annum of the first cost. The unit energy cost is then

$$\frac{\text{Total annual cost}}{\text{Number of energy units utilized per annum}}$$

If this unit energy cost is greater than the cost of alternative sources of heating, the system will never pay for itself. However, if it is less, the first cost will be recovered in a way which may be seen from figure 1.

This diagram has been prepared in a generalized form so that any currency and area units may be used. Knowing the installed cost per unit area of the absorber and the annual energy utilized by this area in the particular installation, the time in years to pay off the first cost may be determined for any alternative fuel cost expressed in £, $, etc. for 100 kWh.

Two illustrations are as follows:

A solar water heating installation in Darwin costing £5/sq ft will utilize 2.17×10^5 btu/annum/sq ft and is paid off in eight years when compared with electric power [θ]3d/kWh. In Melbourne it might cost £3/sq ft, utilize 2.06×10^5 btu/annum/sq ft and would take 13 years to be paid off in relation to power at 1.5d/kWh. If, however, it were compared with oil fuel [θ] the equivalent of 0.7d/kWh, it would take 45 years.

It is largely a matter of opinion where this becomes "uneconomic". Solar water heaters are being built which might last 45 years, but most people would not be prepared to wait so long to recover their investment. On the other hand, most people would regard it as an attractive proposition if they got their money back in less than five years. It is the intermediate period of 10-20 years which is more difficult to assess. In Australia, practically all new houses built have a hot water service of some sort, so if this may be financed as an integral part of the house there would appear to be good reasons for regarding the return of the investment in 20 years or so, as being economically sound. This is the justification for the decision to provide solar water heaters in new government houses in the Australian Northern Territory and New Guinea.

On the other hand, long-term finance is difficult to attract, so it is unlikely that on this basis the chain reaction of increased production leading to reduced cost, which in turn leads to increased production, would be likely to start. For this it

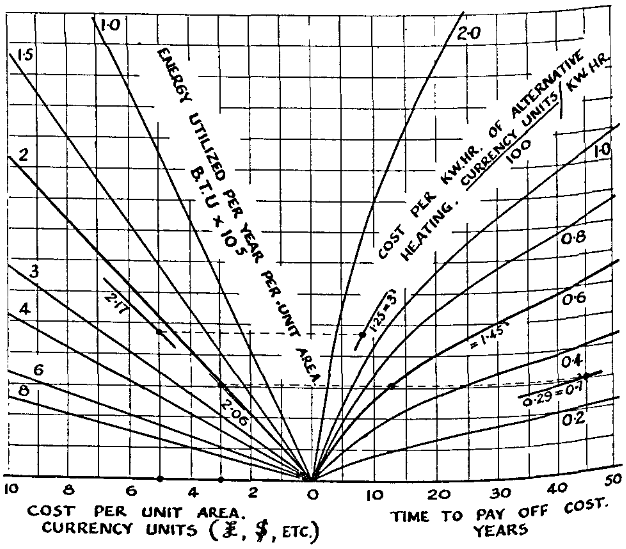

Figure 1. Solar energy economics. Ineterest 5 per cent per annum, maintenance 1½ per cent per annum

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may be necessary to recover the first cost in about three years, so that short-term hire-purchase finance can be used. Under these conditions, a much shorter life could be tolerated. A solar water heater with a life of say 10 years, the first cost of which was recovered in three years, would be a very attractive proposition if installation were very simple.

Two important principles are illustrated in figure 1. The first is that the efficiency of the absorber is only important in relation to its cost. If the cost of an absorber could be halved and its efficiency also halved, it would not change the over-all economic situation. When seeking to improve absorber performance, a reduction in efficiency would be justified provided it were more than offset by reduced costs. The second point is that it is annual energy *utilized* as distinct from annual energy collected which must be considered. During months of high insolation it is often impossible to utilize all the energy collected and care should be taken not to include this wasted heat in the annual figure. A similar situation arises where solar energy is used for seasonal applications. A false picture will be presented if annual figures are used under these conditions. Methods of estimating the annual energy utilized in water heating installations will be discussed later.

Influence of local conditions

It will be clear that due to wide variation in solar radiation, ambient temperature, interest rates, material, labour, and fuel costs, availability of finance, and hot water demands, all of which influence the design of a solar water heater, it is not surprising that different designs are emerging in different countries. Mathur *et al* have described a domestic solar water heater which, under Indian conditions, will recover its initial cost in less than one year (2). The same design, however, used in Australia would not be an attractive proposition due to the different labour, material, and power costs.

This illustrates the way local conditions can influence the design of solar collecting devices and shows how unlikely it is that one design would find wide acceptance in different countries. It will be quite impossible in this paper to cover adequately the developments in the various countries at present using solar water heaters. Accordingly, the aim will be to describe some of the factors which are influencing developments in Australia, in the hope that they may have a wider application.

System design

Design variables

Although concentrating devices have been used for water heating, the flat plate absorber can operate at a high collection efficiency and is inherently simpler, easier to install, and requires less maintenance than collectors using parabolic or other types of reflectors. Accordingly, it is only the flat plate absorber that will be described in detail.

The important design variables are:

1. Materials of construction and their durability;
2. Size — length, width, and depth;
3. Number of transparent cover sheets;
4. Rear and edge insulation;
5. The absorber plate itself;
6. Mass flow of water through the absorber.

In describing in some detail the design which is now in commercial production throughout Australia (3), it is proposed to show how this has emerged and give reasons for the decisions which have been progressively taken.

Absorber losses

When this design was first introduced about six years ago, there seemed no prospect of finding materials even with a short life which would enable a design to be developed, the cost of which could be recovered in, say, three years. Accordingly, it was decided to aim for a life in excess of 25 years, the cost of which could be recovered in less than 20 years. The basic materials chosen were asbestos cement sheet for the case, glass covers and copper absorber plate with mineral wool for the rear insulation.

It is clear that edge losses will be proportionately reduced the larger the unit becomes. There is, moreover, considerable advantage in selecting a design in which the glass is held only at its outside edges. The largest sheet which could be supported in this way without using heavy and expensive glass is about 4 ft, which led to the choice of a nominal 16 sq ft absorber, 49 in. square when measured over the outside edges. The asbestos cement absorber case is moulded in one piece with an internal ledge to support the inner glass and another ledge to support the absorber plate. The outer glass which has to withstand weather conditions is 32 oz/sq ft whilst the inner glass is 26 oz/sq ft (figure 2).

The choice of the optimum number of glass cover sheets and the extent to which the rear and edges should be insulated is a much more complex problem. A comprehensive study of this has been undertaken by Tabor who suggests new heat transfer coefficients for flat plate absorbers to improve the accuracy of performance calculations (4).

The choice of the optimum rear and edge insulation presents some interesting problems. Tabor suggests that the thickness of the edge insulation should equal that of the rear insulation based on optimizing the design from the point of view of losses. However, for a given size external case the edge insulation reduces the area of plate which can be exposed to radiation, and, under certain circumstances, it can be shown that the increased energy absorbed is more than the extra losses which would take place if the insulation were not present.

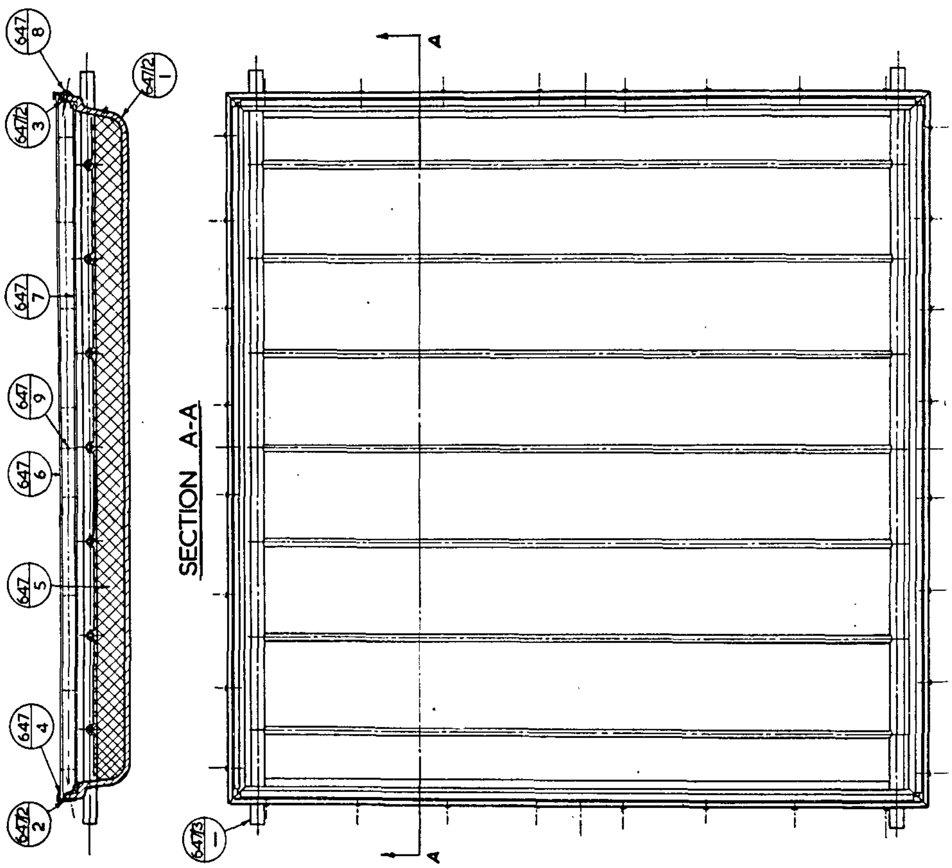


Figure 2. General arrangement of typical absorber. Asbestos cement base, glass cover sheets, copper absorber plate

The designer has the choice between (1) and (2) in figure 3. The two designs may be compared under the following typical installation conditions:

1. Absorber inclination 0.9 times the latitude;
2. Main daily insolation over a year 1 610 btu/sq ft/day;
3. Annual efficiency of collection 35 per cent;

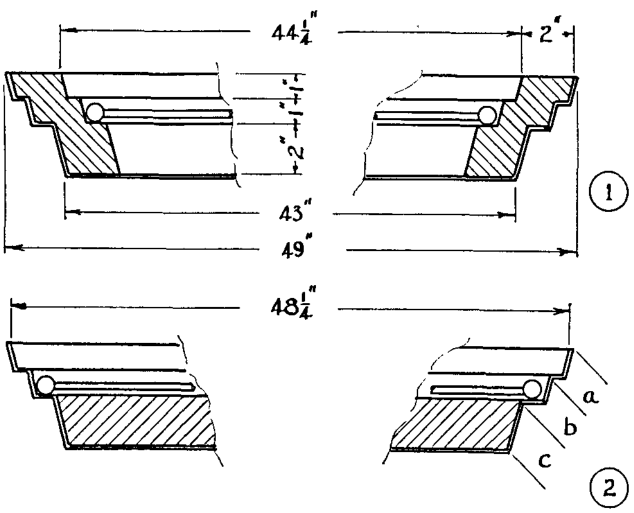


Figure 3. Absorber edge losses

4. Average daily operating period 6½ hr/day;
5. Conductivity of insulation 0.4 btu/sq ft/in./°F.

Since under operating conditions water is heated daily from mains temperature up to the operating temperature of 135°F, the effective temperature characteristic of the daily losses will be a weighted mean. For a water inlet temperature of 60°F this has been found to be 105°F, and assuming that the ambient temperature is not substantially different from the water inlet temperature, the mean temperature difference ΔT between the plate and ambient is 45°F.

Case 1

Using Tabor's edge correction factor, the rear and edge loss

$$H_{RE1} = 1.075 \times 6.5 \times \frac{43^2}{144} \times \frac{0.4}{2} \times 45 = 810 \text{ btu/day}$$

Case 2

For zone (*a*), ΔT = 22.5°F, edge area = 2½ sq ft, over-all heat transfer coefficient h = 0.68 btu/hr/sq ft/in./°F.

$$H_{Ea} = 0.68 \times 2.5 \times 22.5 \times 6.5 = 249 \text{ btu/day}$$

For zone (*b*), ΔT = 45°F, edge area 2½ sq ft

$$H_{Eb} = 498 \text{ btu/day}$$

For zone (c), area $2\frac{1}{2}$ sq ft. Assume same as (a)

$$H_{Ec} = 249 \text{ btu/day}$$

$$H_E = H_{Ea} + H_{Eb} + H_{Ec} = 996 \text{ btu/day}$$

Rear loss H_R is difficult to calculate accurately. A generous estimate is to assume it is the same as H_{RE1}.

i.e. $H_R = 810$ btu/day.

$\therefore H_{RE2} = H_R + H_E = 1\,806$ btu/day.

This is 996 btu/day more than H_{RE1}.

However, the glass area in Case (2) is 2.5 sq ft more than in Case (1) and this will collect 4 030 btu/day and utilize at least 35 per cent of this, i.e., 1 410 btu/day. Thus there is an over-all gain of 414 btu/day for (2) as compared with (1). Moreover (2) is simpler to build and no more expensive, even allowing for extra absorber plate area.

The above analysis is not meant to be a rigorous justification for omitting edge insulation as a general rule, rather is it given to illustrate one of the factors which should be considered in designing an absorber. Clearly for a higher operating temperature, the position could be quite different.

Absorber plate

Tube-in-strip copper is an attractive material for the absorber plate and is now being used to supersede the design illustrated. By reference to the plate efficiency factors developed by Bliss (5), it can be shown that for 0.028 in. sheet having tubes 5.6 in. apart, the efficiency is 91 per cent.

Number of glass cover sheets

For water heating (mean annual absorber temperature 105°F) it will be found that the choice lies between:

1. Non selective plate and one glass cover;
2. Non selective plate and two glass covers;
3. Selective plate and one glass cover.

Using Hottel and Woertz (6) expression for losses and Tabor's coefficients both for hemispherical emissivity of the glass ε_g and for the convection term, when the plate temperature $T_p = 105$°F, mean ambient $T_a = 59$°F, mean maximum ambient 67°F, $\varepsilon_g = 0.88$, assuming outer glass is radiating to a temperature $= (T_a - 20)$°F and daytime convection is calculated for ambient 63°F.

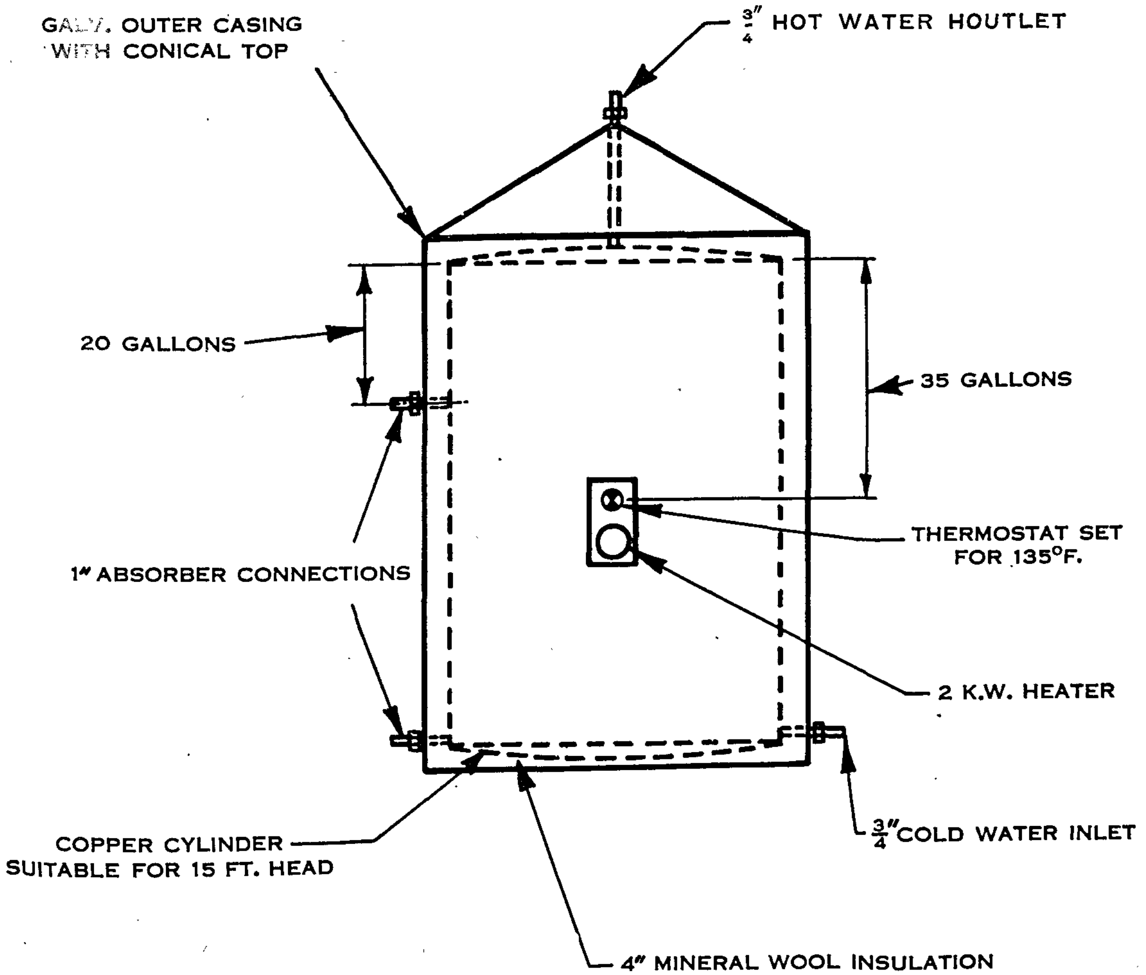


Figure 4. 70 gallon outdoor hot water storage tank

Case (1) $\varepsilon_p = 0.95$.

It will be found that the convection and radiation loss from glass

$H_{CRG} = 27 + 22 = 49$ btu/hr/sq ft where the first term is the convection and the second the radiation loss. From the plate to the glass

$$H_{CRP} = 16 + 33 = 49 \text{ btu/hr/sq ft}$$

Case (2) $\varepsilon_p = 0.95$.

$$H_{CR} = 25 \text{ btu/hr/sq ft}$$

Case (3) $\varepsilon_p = 0.1$

$$H_{CRG} = 12 + 11 = 23 \text{ btu/hr/sq ft}$$
$$H_{CRP} = 18 + 5 = 23 \text{ btu/hr/sq ft}$$

In each of the above expressions for H, the first term is the convection and the second the radiation loss. Comparing H_{CRG} and H_{CRP} for Case (1) and (3) it may be seen how the selective surface operates to reduce the radiation term in H_{CRP}.

The absorber with the selective surface, Case (3), is clearly the best proposition from a thermal point of view since not only are the losses minimized but with only one glass cover more energy will reach the plate.

Storage

A common practice which has been followed for a number of years is to provide 1½-2 days' supply in an insulated storage tank. A typical 70 gal tank suitable for a small family is shown in figure 4. The upper absorber connection is arranged so that relatively cool water coming from the absorber during periods of low insolation will not mix with hot water in the top of the tank. A booster, if provided, is placed about half way up the tank so that only water for the current day's use is heated.

Losses from a tank of this design amount to about 6 btu/hr/°F mean temperature difference from water to ambient. In a day this is usually about 15-20 per cent of the day's solar heat input. Additional insulation is not usually justified since it costs about the same as providing the same amount of energy by extra absorber area.

Circulation rate through absorber

There seems to be some difference of opinion as to whether it is better to have a high or low circulation rate through the absorber. A low rate with its consequent high temperature rise will give some hot water available sooner from a cold start, but a high flow rate, in which the contents of the tank pass through the absorber several times a day, gives lower losses in the morning. It is probably not very critical but more experimental work is necessary to confirm this. The low impedance high flow absorber described herein does have the advantage that it can be used on either small or large systems.

System efficiency

The collecting efficiency of a flat plate absorber is

$$\eta = \frac{H_w}{E}$$

where H_w is the heat removed from the absorber by the water and E is the radiation incident on the absorber.

Since there may be appreciable time lags in the system these values must be measured over some period of time to be meaningful. Values integrated over a ½-1 hour period are often taken to determine the "instantaneous" efficiency η_{inst}. For absorbers such as those described, η_{inst} may be as high as 70 per cent under certain conditions, but this gives a misleading picture of the efficiency of a water heating system operating over long periods. As a measure of this it is better to express the system efficiency in terms of values integrated over a full year

$$\eta_{YR} = \frac{H_{YR}}{E_{YR}}$$

where H_{YR} is the heat transported by the water to the storage tank per annum and E_{YR} is the insolation on a plane of the same external dimensions, inclination and orientation as the absorber, assuming no shading at any time.

Values of system efficiency measured over 24 hours η_{DY} are also useful. However, the yearly system efficiency η_{YR} is the most useful characteristic for the designer to use. It enables system performance and economic value to be predicted from published radiation data for a locality. Typical values of η_{YR} lie between 30-40 per cent.

Observations by Czarnecki (7) together with published Australian radiation records, (8) enable various system efficiencies to be determined for a solar water heater comprising two 24 sq ft absorbers and a 70 gal tank from which 45 gal of hot water was withdrawn each day for 12 months.

From table 1 it will be seen that monthly efficiencies vary from about 30 per cent in the winter to 40 per cent in the summer months, with a yearly average of 35 per cent. Note the low value for February which had unusually high insolation much of which could not be utilized.

In order to devise ways of improving efficiency it is necessary to examine the losses in detail. On an annual basis a typical absorber may be represented by figure 5. This may be considered as the sum of all the instantaneous heat balances throughout the year. For a single day, the system behaviour may conveniently be represented by figure 6, which is typical of a clear day near an equinox.

It shows a daily system efficiency of 48 per cent. The total energy reaching the absorber during the day is the area under curve (1). The losses are made up as follows:

(2) Early morning shading and late afternoon cut off 5 per cent.

Table [illegible] Solar water heater system efficiency

Yearly and monthly values; Melbourne latitude 37° 50′

Month	*Mean insolation absorber sq ft/day*	*Mean daily supplementary heating kWh*	*Mean daily solar contribution*		*System efficiency per cent*
			per cent	*kWh*	
January . .	1 630	2.9	75	8.7	40
February . .	2 220	0.5	95	9.5	32
March . . .	1 690	2.6	74	7.4	33
April	1 240	5.2	52	5.6	34
May	1 290	6.2	47	5.5	32
June	1 220	7.7	39	4.9	30
July	1 290	8.1	38	5.0	29
August . . .	1 530	6.1	50	6.1	30
September .	1 600	4.9	59	7.1	33
October . .	1 860	3.9	67	7.9	32
November .	1 880	3.7	68	7.9	32
December .	1 790	3.5	72	9.0	38
Year	1 610	4.6	61	7.2	35

(3) Reflection and absorption by two glass cover sheets 30 per cent.

(4) Reflection by the plate and miscellaneous 6 per cent.

(5) Rear, edge, and top losses due to conduction, convection, and radiation, 11 per cent.

From these figures it will be seen that considerable improvement in performance would result if the reflection and absorption losses due to the glass were reduced. For this reason, a single glass cover sheet will often give a better over-all performance than two. Designs at present employing two cover sheets, where not exposed to heavy frosts, might well be examined critically in this light.

Installation

General

The problems associated with the installation of a complete solar water heating system are as follows:

1. Location of absorbers and determination of area;
2. Location of storage tank;
3. Choice of thermosiphon or forced circulation.

Location of the absorbers is often dictated by architectural and aesthetic considerations, but because they are sometimes unsightly there is a tendency merely to put them out of sight. Even where the installation is planned in advance there seems to be a marked reluctance on the part of architects to let the building design be influenced in any way, to provide simple mountings or logical placing of absorbers. Yet this could have a profound effect on their wider acceptance.

When positioning absorbers, the most important consideration is the avoidance of shading by nearby objects, especially during winter when the sun's elevation is low. Inclination and orientation are not as critical as was once thought.

Inclination and orientation

It will be evident that there is an optimum angle of inclination for a surface facing north (in the southern hemisphere) which will collect more energy per unit area than either a horizontal or a vertical surface. This angle of inclination will vary throughout the year as the sun's declination changes, but there is, nevertheless, an optimum angle of elevation for which the annual energy collected will be a maximum.

The calculations to determine this, together with the variations from month to month, are extremely laborious, especially for surfaces which are inclined to the horizontal and are oriented in azimuth away from the due north position. Curves plotted from calculated values showing the effect on incident radiation of inclination and orientation have been published by Morse and Czarnecki (9). These are based on typical values of insolation for a particular latitude but may be corrected for the solar radiation characteristics of a particular locality, if this is knnow on a horizontal surface.

In this report, curves are plotted for the monthly mean values of daily radiation on surfaces inclined at 0.9 φ, 1.2 φ, 1.5 φ, to the horizontal, for latitudes φ, 15°S, 30°S, and 45°S, and deviations in azimuth of 0°, 22½°, and 45°, measured from the due north position.

It is shown that for a surface facing due north the maximum insolation received in a year occurs for an inclination of 0.9 φ, to the horizontal, for latitudes from 15-45°. In addition, a surface inclined at 1.5 φ will receive equal insolation at the summer

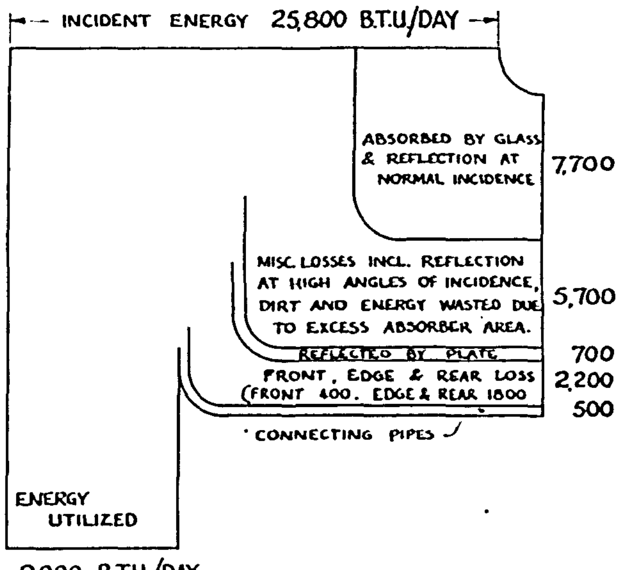


Figure 5. Diagrammatic representation of the daily losses from a 16 sq ft absorber in a thermosiphon solar water heater averaged over a year

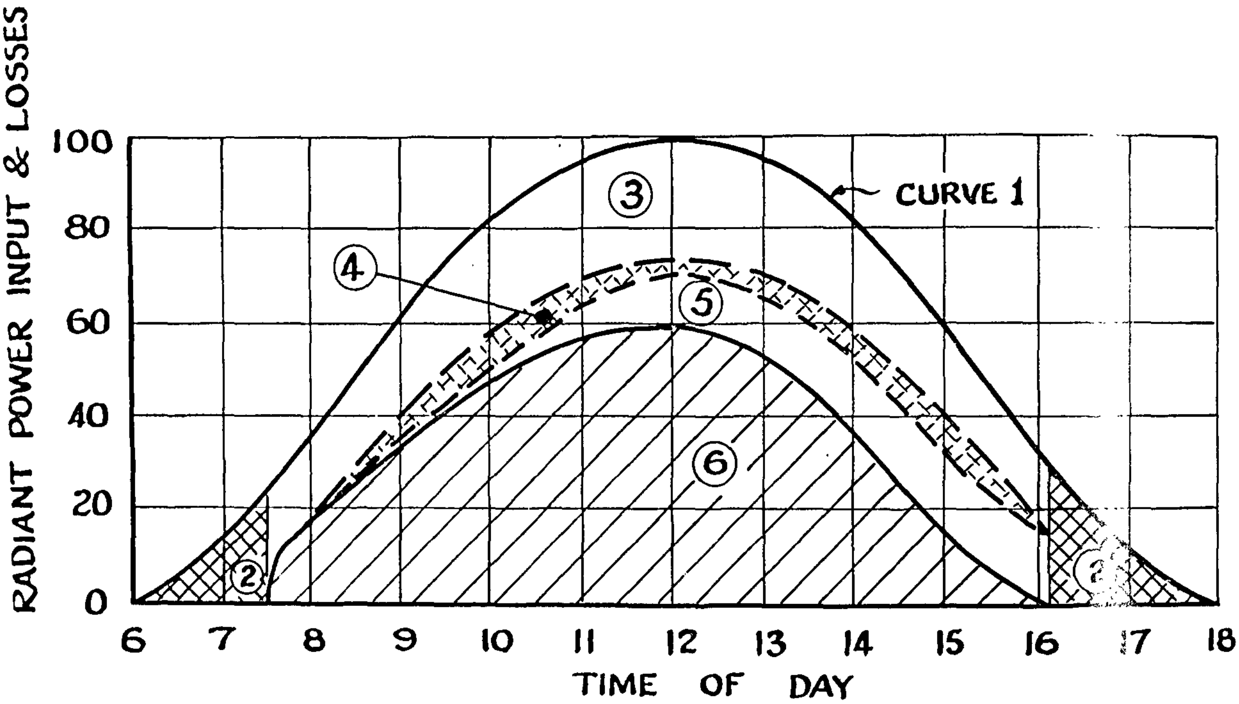


Figure 6. Typical daily absorber performance

Absorber area 48 sq ft, two glass cover sheets, 70 gal tank thermosiphon flow
Area under curve 1 is the total insolation on the absorber during the day.
Area (2) amounting to 5 per cent of the total is due to morning shading and afternoon cut off.
Area (3) amounting to 30 per cent of the total is due to reflection and absorption by the glass cover sheets.
Area (4) amounting to 6 per cent of the total is due to reflection from the plate and miscellaneous.
Area (5) amounting to 11 per cent of the total is due to convection and radiation losses.
Area (6) amounting to 48 per cent of the total is the energy utilized.

and winter solstices. This has important practical applications. A solar water heater which is fitted with an auxiliary booster will use minimum power from the booster when the absorber is inclined at 0.9 times the latitude, if the load on the system is uniform throughout the year.

A useful compromise where boosting is not used is an inclination of 1.2 φ which gives good uniformity throughout the year and collects about 97 per cent of that for 0.9 φ for latitudes up to 45°.

It is important to appreciate the significance of departures from the optimum both in inclination and orientation since in practice the ideal is frequently unattainable. Figures 7 and 8 show the annual loss due to these departures. For latitudes less than 30°, the loss is quite small for relatively large departures from the optimum. For instance, at latitude 15°S, an absorber inclined at 13½° to the horizontal facing 45° from north (i.e. north-east or north-west) will collect in a year only 1½ per cent less energy than one facing due north. It should be pointed out at this stage that this makes no allowance for the increased reflection losses from the absorber glass cover sheets so the actual situation may be somewhat worse. However, it does indicate that expensive and ugly mountings to correct an apparently unsuitable roof alignment can rarely be justified. It is usually cheaper and nearly always tidier to use a simple and neat mounting on a roof or building not ideally oriented and correct if necessary by providing a little extra absorber area determined from figures 7 and 8.

Absorber area

It is now possible to determine the absorber area knowing the daily demand for hot water and the average daily insolation at the site for the inclination and orientation chosen.

Two examples will be considered :

Installation in Melbourne, latitude 37° 50′

Inclination 34°. Efficiency 35 per cent. Demand 45 gal/day at 135°F.

	Yearly average	*Best month*	*Worst month*
Insolation btu/sq ft/day	1 610	2 165	1 000
Cold water temperature °F . . .	64	67	53
Daily energy required btu/day . .	32 000	30 600	36 900
Add 20 per cent for tank losses btu/day	38 400	36 700	44 400
Absorber area required sq ft . . .	68	48	127

Due to the large difference between the best and worst months, supplementary heating should be used, the area being based on the best month so that no absorber area is wasted at any time of the year. Therefore, choose 48 sq ft and supply about one-third the annual heating by boosting.

Installation in Darwin, latitude 12°

Inclination 15°. Efficiency 35 per cent. Demand 45 gal/day at 135°F.

	Yearly average	*Best month*	*Worst month*
Insolation btu/sq ft/day	1 900	2 240	1 630
Cold water temperature °F	80	80	80
Daily energy required btu/day	24 800	24 800	24 800
Add 15 per cent for tank losses btu/day	28 500	28 500	28 500
Absorber area required sq ft	43	36	50

Since the values for the best and worst months are so close together, choose 48 sq ft, i.e., three absorbers each 16 sq ft without any supplementary heating.

Method of circulation

Thermosiphon is the simplest and best for small systems but requires the tank to be close to and above the absorber. In order to prevent reverse flow at night, the lower tank connection must be about 6 in. above the upper absorber header and the connections to the tank well insulated. This is rather less than is sometimes recommended but has been found experimentally to be adequate. However, it is particularly important to insulate the line from the upper tank connection to the top of the absorber with at least 1 in. thickness of good quality insulating material and waterproof it.

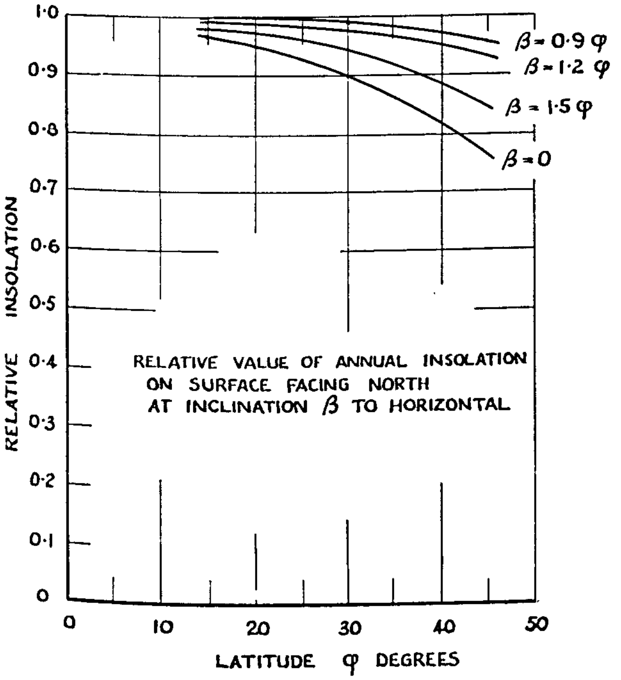


Figure 7. Effect of inclination on absorber performance

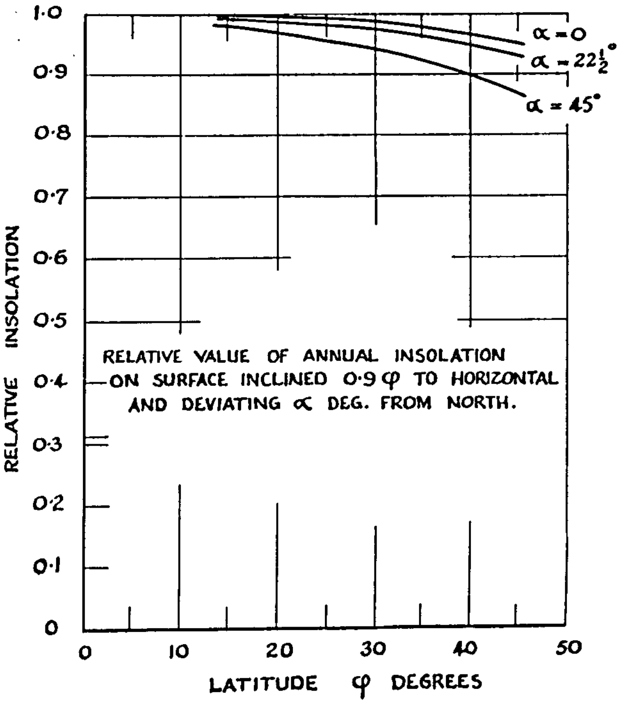


Figure 8. Effect of orientation on absorber performance

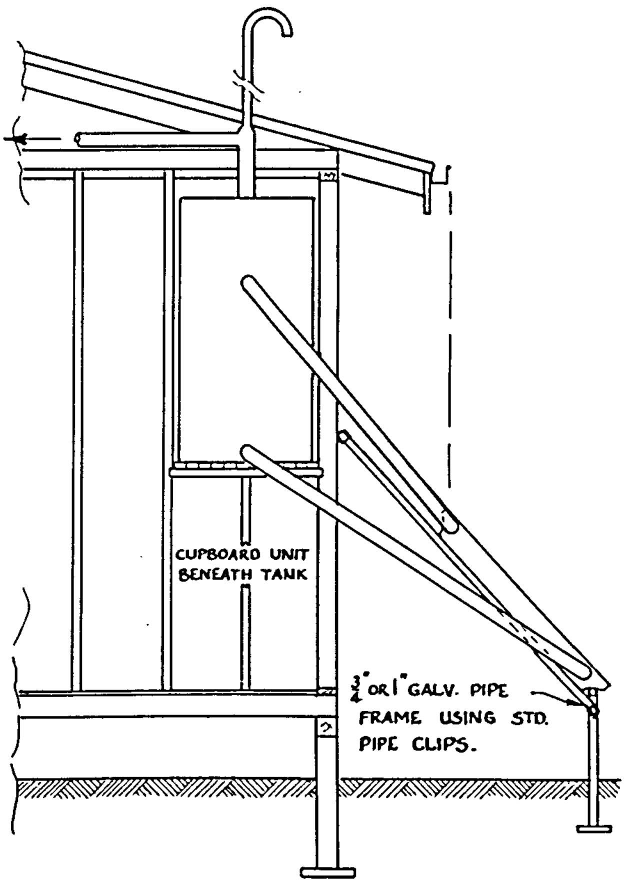


Figure 9. Installation showing storage tank supported on partition wall between two rooms

The design of connecting piping for thermosiphon systems has been discussed elsewhere (10).

A typical domestic installation is shown in figure 9 whilst figures 10, 11 and 12 illustrate various outdoor arrangements. To meet the popular demand in Australia for information on domestic installations, a circular (11) has been published summarizing the recommended practice. Large installations require forced circulation. Figure 13 shows a diagrammatic arrangement of a unit at present under construction in Canberra. The time switch ensures that (*a*), the booster is off during the day and (*b*), the absorber pump which is controlled through a differential thermostat, is off at night.

Research problems

Although some progress has been made, it will be clear that a considerable research effort is still necessary before solar energy is utilized as extensively as it could be for even such a simple process as water heating. Different aspects of the problem will assume different degrees of importance in different countries. Water heating in Australia is an important fuel consumer and in this respect, solar energy could make an important national contribution, but it must compete on economic grounds. The key to this is a cheap absorber.

It is suggested that the objective ought to be an absorber which would recover its capital cost in three years, when compared with oil at 0.7d/kWh, and must be very cheap and easy to install. From figure 1 it will be seen that the cost of this must not exceed 10/- per sq ft. Materials such as copper seem to be out of the question since tube-in-strip without any processing costs about 8/– per sq ft. Other metals such as galvanized iron or even black iron are possibilities but it is doubtful whether they would have sufficient life under operating conditions. Plastics seem to offer the most attractive possibilities, particularly the polyvinyl fluorides which appear to have the necessary durability both to solar radiation and high temperature.

In developing these cheap absorbers, efficiency will be unimportant provided the above requirements are met. Extreme simplicity of installation is necessary to reduce expensive plumbing to an absolute minimum.

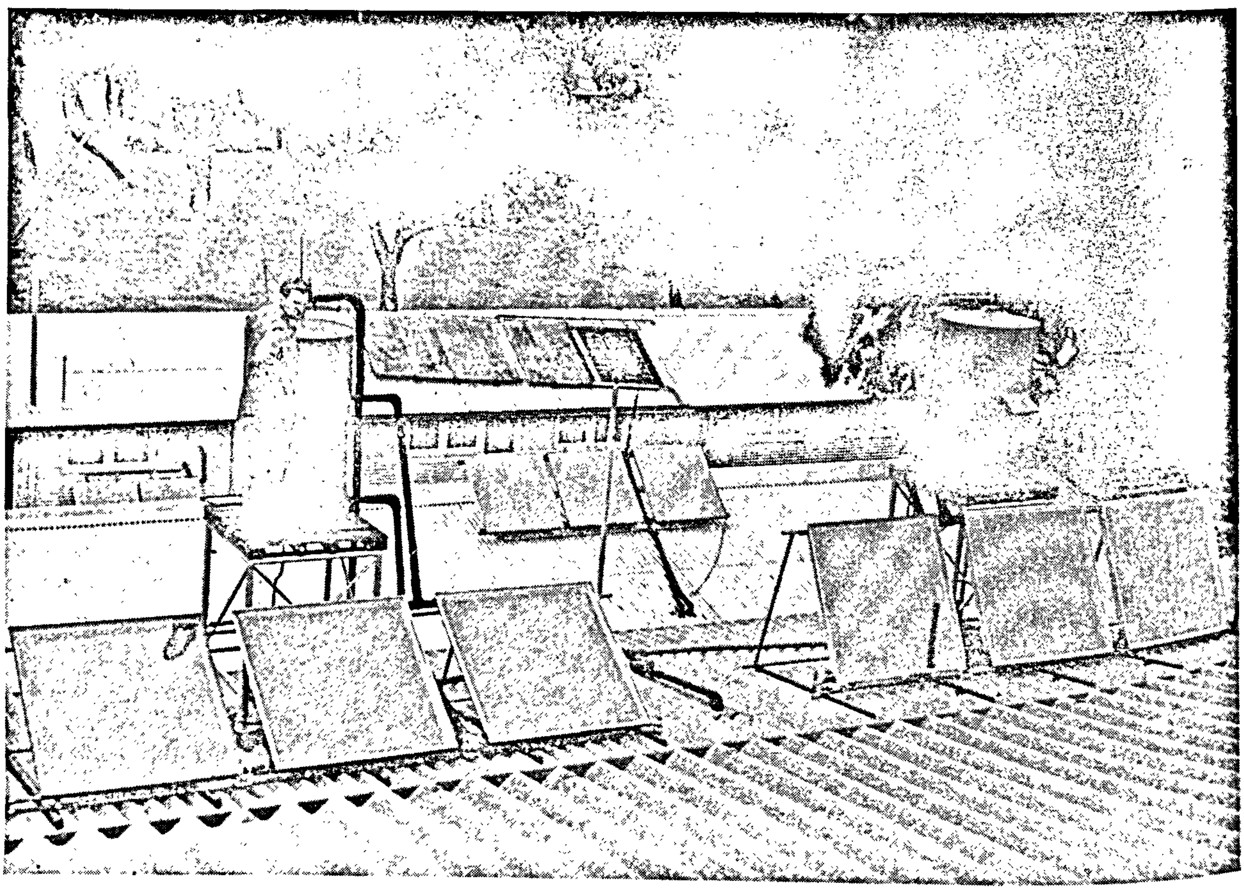
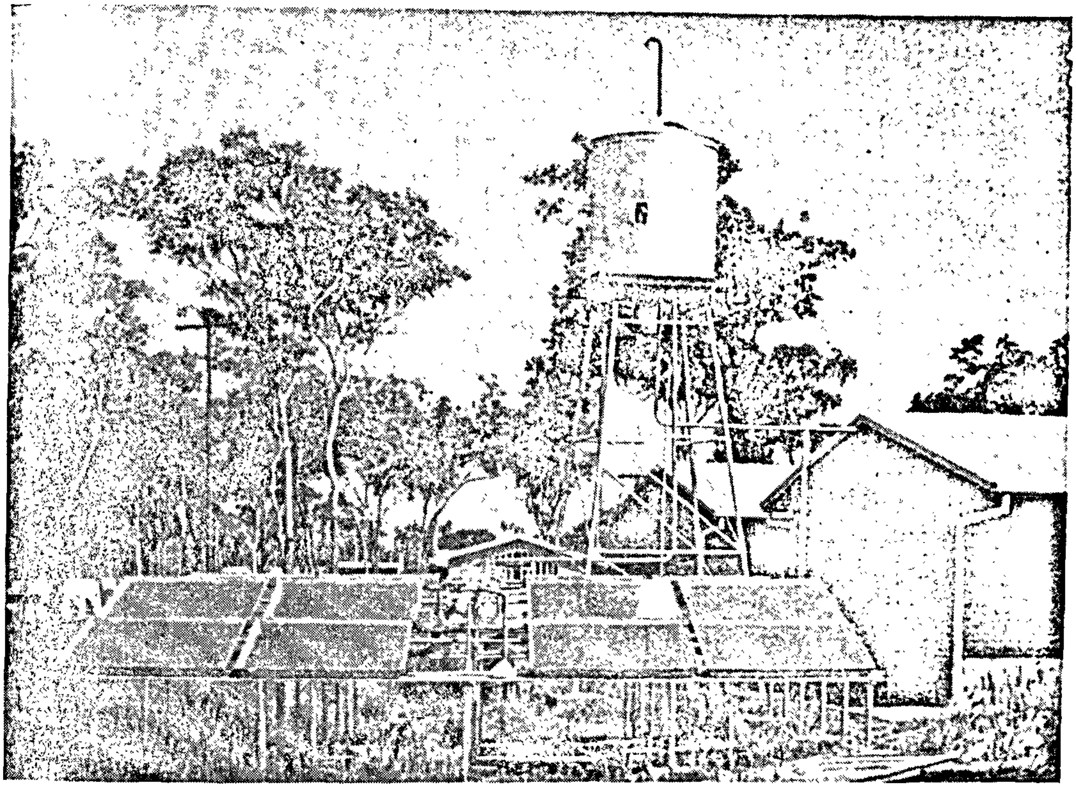
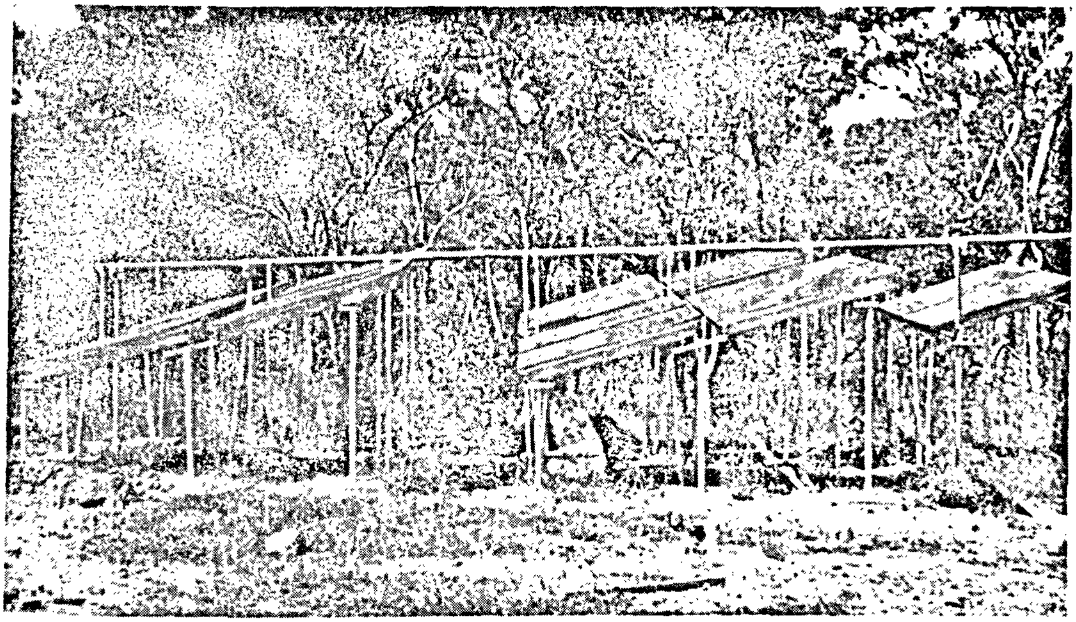


Figure 10. Three solar water heater installations: (*a*) Left hand unit — absorber inclination 0.9 times the latitude for maximum year round output; (*b*) Right hand unit — inclination 1.5 times the latitude for equal output winter and summer solstices; (*c*) Centre installation — unit arranged for pump circulation with storage tank inside the building





Figures 11 and 12. Front and side views of a large unit at Darwin installed by Commonwealth Department of Works. 300 sq ft absorber 600 gal tank

In many localities freezing of the absorbers is a problem. Attempts to overcome this by means of indentations in the upper and lower headers in the absorbers have only been partly successful (12). These indentations trap air pockets which prevent the pressure in the pipe building up to a dangerous value on freezing, and are quite successful whilst the air is present. It is not difficult to maintain the pockets in the upper header due to the air coming out of solution in the water as it is heated on passing through the absorber. In the lower header, however, water returning from the storage tank is below

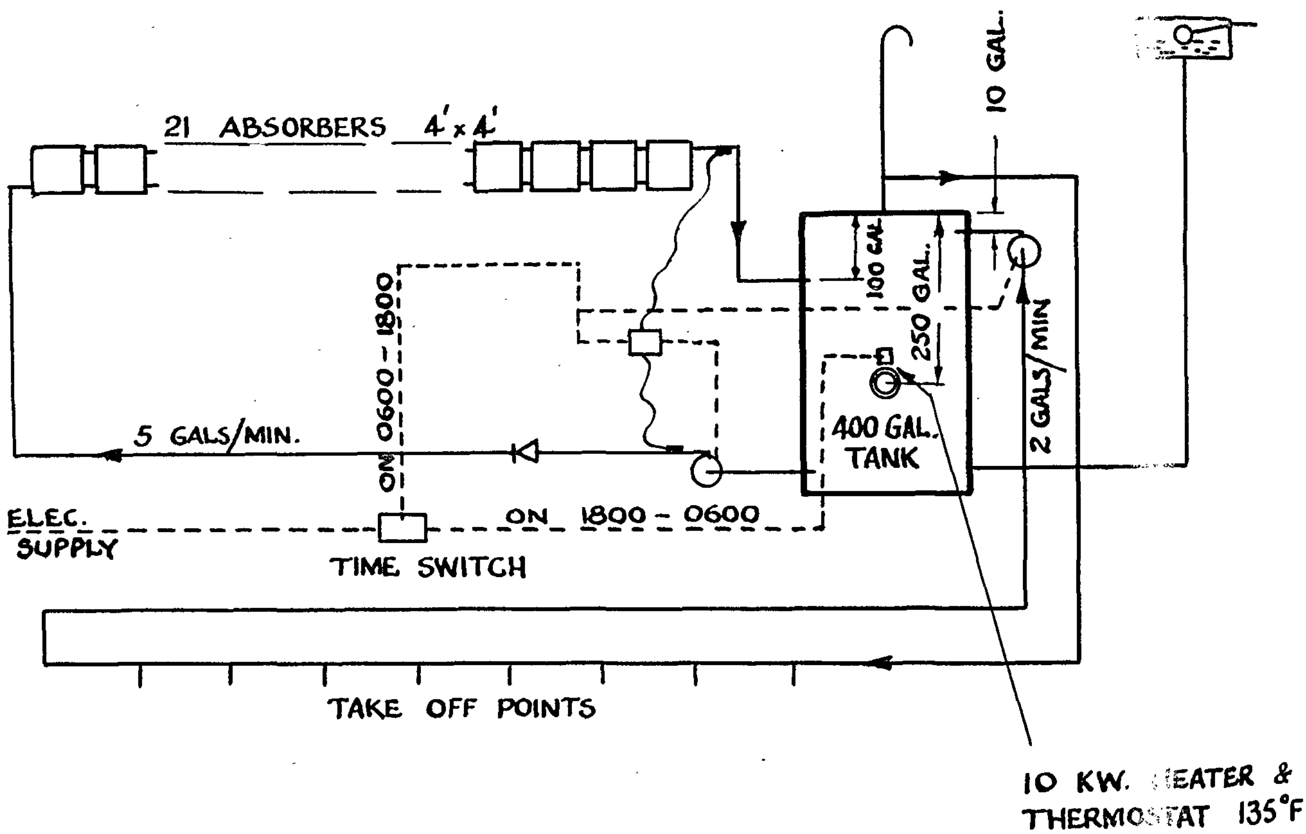


Figure 13. Diagrammatic arrangement of large solar water heater for a laboratory being erected in Canberra

its saturation point as far as solubility of air is concerned, and any air present here tends to go into solution. Field experiments have shown that whilst no damage occurs to the upper header in this way, the lower one will be fractured under severe frost conditions. Experiments are continuing using internal air cushions in plastic containers.

Wider use of selective surfaces which are potentially useful for higher temperature applications, appear to be imminent. In Israel, for example, small scale production is already taking place for absorbers for water heating. In other parts of the world, work is proceeding to find cheaper ways of producing the selective surface coating.

Radiation data

There is a dearth of radiation data in the equatorial belt where solar energy is potentially so useful. Since one of the characteristics of the tropics is the consistency of its conditions, it could be that an extensive network of radiation stations is not necessary. However, it would be extremely valuable if more information were available on the radiation pattern in different localities.

Conclusion

Although work is proceeding in a number of countries, there are many unsolved problems and an even greater effort could be justified. Water heating is such a basic problem that advances in this field could lead to advances in other fields involving the heating of fluids, e.g., refrigeration, air conditioning, and water desalting.

The flat plate absorber which is widely used is now better understood and rational design procedures are emerging which will enable performance of complete installations to be more accurately predicted. This is particularly important for any installation for which the operating cost is proportional to the first cost. The penalty for over design is an increase in operating cost in direct proportion to the amount by which it exceeds requirements. Solar water heaters are proving to be operationally satisfactory and economically sound in many areas where the climatic conditions are suitable and alternative fuels are expensive. However, in other places where they could be used, their widespread acceptance is being impeded by their cost. In Australia, a reduction to half the present cost would very greatly increase the numbers installed, whilst a reduction to one quarter of the present cost would probably mean that none of the existing alternative water heaters would be able to compete with the solar unit. Using some of the new materials and manufacturing techniques now available, this is by no means impossible.

Acknowledgement

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Summary

Solar water heaters are in commercial production in many countries and whilst they are operationally satisfactory, their economic justification is often marginal. A clear understanding of the factors influencing their operating costs is essential if this situation is to be improved. Curves are presented which show the time in years it takes for an installation to pay for itself, knowing the installed cost and the energy utilized per annum.

The emphasis is on energy utilized as distinct from energy collected per annum, since there are periods of the year when all the energy collected cannot be utilized. Efficiency of collection is important only in relation to cost. Other things being equal, the absorber which has the lowest first cost is the best proposition irrespective of collection efficiency.

The factors which influence the design of a solar water heating system are considered in detail and are related to a unit in production in Australia. It is shown that edge insulation in absorbers is sometimes undesirable. The additional plate area which can be provided if it is omitted can collect energy which more than offsets the reduced losses due to the insulation.

Attention is drawn to the value of measuring system efficiency in terms of the heat transferred to the system per annum and the annual insolation on a plane of the same external dimensions, inclination and orientation, as the absorbers. This for actual installations has been found to be about 35 per cent.

The significance of inclination and orientation of absorbers is discussed. Although maximum year round insolation occurs on a surface facing north with an angle of inclination 0.9 times the latitude, wide departures from the optimum are acceptable both in inclination and orientation especially for latitudes less than about 30°. In practice, it is usually cheaper and nearly always tidier to use a simple and neat mounting on a roof or building not ideally oriented and correct by increasing the absorber area if necessary. Rational design procedures are emerging which enable the performance of complete systems to be predicted with some confidence.

Although a good deal of progress has been made, there is much remaining to be done, both from the point of view of research into cheaper and better ways of collecting solar energy and also into improving methods of manufacture. There are many areas where solar water heaters would be quite satisfactory from a functional point of view, the chief impediment to their widespread use being their cost. In Australia, if the cost could be reduced to one quarter of its present value, the solar unit would probably become the most widely used system for domestic water heating.

CHAUFFAGE DE L'EAU AU MOYEN DE L'ÉNERGIE SOLAIRE

Résumé

Les chauffe-eau solaires sont actuellement en production commerciale dans nombre de pays, mais, bien qu'ils soient satisfaisants quant à leur fonctionnement, leur justification économique peut parfois être mise en doute. Une bonne compréhension des éléments qui se répercutent sur leur coût de fonctionnement s'impose si l'on doit améliorer cet état de choses. L'auteur présente des courbes qui indiquent le temps, en années, nécessaire pour qu'une installation soit amortie, compte tenu de ses frais

d'installation et de la consommation annuelle d'énergie.

Ce mémoire fait ressortir l'énergie utilisée, plutôt que l'énergie recueillie, car il y a des périodes de l'année pendant lesquelles la totalité ainsi recueillie ne peut pas être utilisée. Le rendement du système de captation d'énergie n'est important que dans ses rapports avec les frais. Toutes choses égales d'ailleurs, l'absorbeur qui coûte le moins à installer est le meilleur, quel que soit le rendement de la captation de l'énergie solaire.

Les éléments qui influent sur les caractéristiques à donner au système de chauffage de l'eau par le soleil sont étudiés en détail, et sont rapportés à un appareil fabriqué en série en Australie. L'auteur montre que le calorifugeage des bords des absorbeurs n'est parfois pas désirable. La surface supplémentaire de plaque que l'on peut mettre en œuvre en n'ayant pas recours à cet isolement thermique peut récupérer de l'énergie qui fait plus que compenser les pertes dues à l'isolement.

Ce mémoire attire l'attention sur la valeur des mesures du rendement du système en fonction de la quantité de chaleur qui lui est fournie annuellement et de l'insolation annuelle d'un plan ayant mêmes dimensions hors-tout, même inclinaison et même orientation que les absorbeurs. Pour des installations effectivement en service, ce rendement s'établit à environ 35 p. 100.

L'auteur examine l'importance de l'inclinaison et de l'orientation des absorbeurs. Bien que l'insolation maximale, pour l'année entière, se produise sur une surface qui fait face au nord, inclinée d'un angle égal à 0,9 fois la latitude, de grands écarts par rapport à l'optimum sont acceptables, tant pour l'inclinaison que pour l'orientation, particulièrement aux latitudes inférieures à 30°. En pratique, il est généralement moins coûteux et presque toujours moins compliqué de se servir d'un montage simple sur un toit ou un bâtiment qui n'est pas orienté idéalement et de corriger ceci en augmentant au besoin la surface de l'absorbeur. On commence à mettre au point des techniques rationnelles pour l'établissement de ces projets, ce qui permet de prévoir le fonctionnement du système complet avec quelque confiance.

Bien que des progrès importants aient été réalisés, il reste beaucoup à faire tant au point de vue des recherches visant à mettre au point des moyens plus économiques plus et efficaces de récupérer l'énergie solaire, que sur le plan de l'amélioration des méthodes de fabrication. Il existe nombre de régions où des chauffe-eau solaires seraient tout à fait satisfaisants au point de vue fonctionnel, le principal obstacle à leur utilisation généralisée étant leur prix. En Australie, si on pouvait ramener ce prix au quart du chiffre actuel, l'appareil solaire deviendrait très probablement le système le plus communément utilisé pour le chauffage de l'eau destinée à des emplois ménagers.

THE SOLAR SWITCH — AN AUTOMATIC DEVICE FOR ECONOMIZING AUXILIARY HEATING OF SOLAR WATER HEATERS

Natan Robinson and Eliyahu Neeman *

The idea of exploiting the vast amounts of energy reaching us from the sun has fired the imagination of man for many generations. Unfortunately, practical difficulties due to its comparatively low intensity have hitherto prevented direct conversion of solar radiation into heat and power.

The development of the flat plate collector, converting solar radiation into low-intensity heat energy (up to temperatures of 70-100°C) has for the first time made possible the widespread use of solar energy. The simplicity of its construction and maintenance renders its application practicable in many regions all over the world. By adding a thermally insulated storage tank, hot water can be stored for periods of darkness or overcast (see figure 1).

The data proposed in this paper refer to conditions in Israel, located as it is in the eastern Mediterranean region, between the 30th and 33rd parallels. In order to adapt this for other regions, it is essential to correlate the climatic conditions with those presented in this paper.

The need for auxiliary heating

Two factors determine the practical use obtained from a solar heater. The first is directly dependent on local climatic conditions, hence beyond human control; the second is the total efficiency of the heater. These factors will determine the profitability of the installation. It is obvious that in countries lacking sufficient sources of energy, the solar heater, even though its operation is intermittent and governed by climatic factors, may prove a long step forward. On the other hand, in countries with a higher standard of living, where the consumer makes his choice between solar, electrical, fuel-oil and gas heating, the method must be capable of competing with the others, both from the economic viewpoint and from that of providing heating in all weathers.

Many scientists in several countries, including Israel, have done a great deal of work on the theoretical analysis (1) and practical development of the flat plate collector, with a view to reducing losses by improving insulation (2-5) and increasing absorption by using selective black (6). With several additional refinements in the manufacturing process, quite efficient collectors may be produced. Israeli manufacturers claim that locally produced solar heaters achieve a 40 per cent efficiency in converting solar energy (7).

While extensive research has been devoted to the development of the heater and especially the flat plate collector, it is felt that not enough attention has been focused on problems of auxiliary heating. The latter, if not kept to the lowest possible minimum, may increase the cost of the solar heating above the level of economic feasibility. Experience shows that the consumer seeking a regular supply of hot water tends to use auxiliary heating more than strictly necessary, resorting to it whenever solar heating seems undependable owing to cloudy weather. He does not consider the amount of energy consumed for auxiliary heating and is thus unaware of the actual cost of this method of heating.

Auxiliary heating is mostly effected by means of electric power. This source of energy, while not always cheap, is simple to use and does not unduly complicate the construction of the heater. An electric heater and thermostat are installed in the storage tank. Analysis of this type of auxiliary heater will immediately show that the thermostat does not

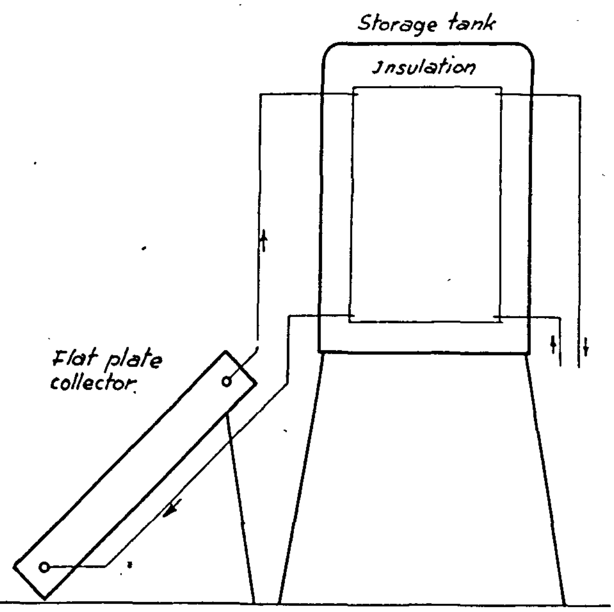

Figure 1. Solar water heater with flat plate collector

* Technion, Israel Institute of Technology, Haifa. (Based on second author's M.Sc. thesis, carried out at the Technion, Faculty of Electrical Engineering, under the supervision of the first author, Head of the Solar Physics Laboratories of the Technion.)

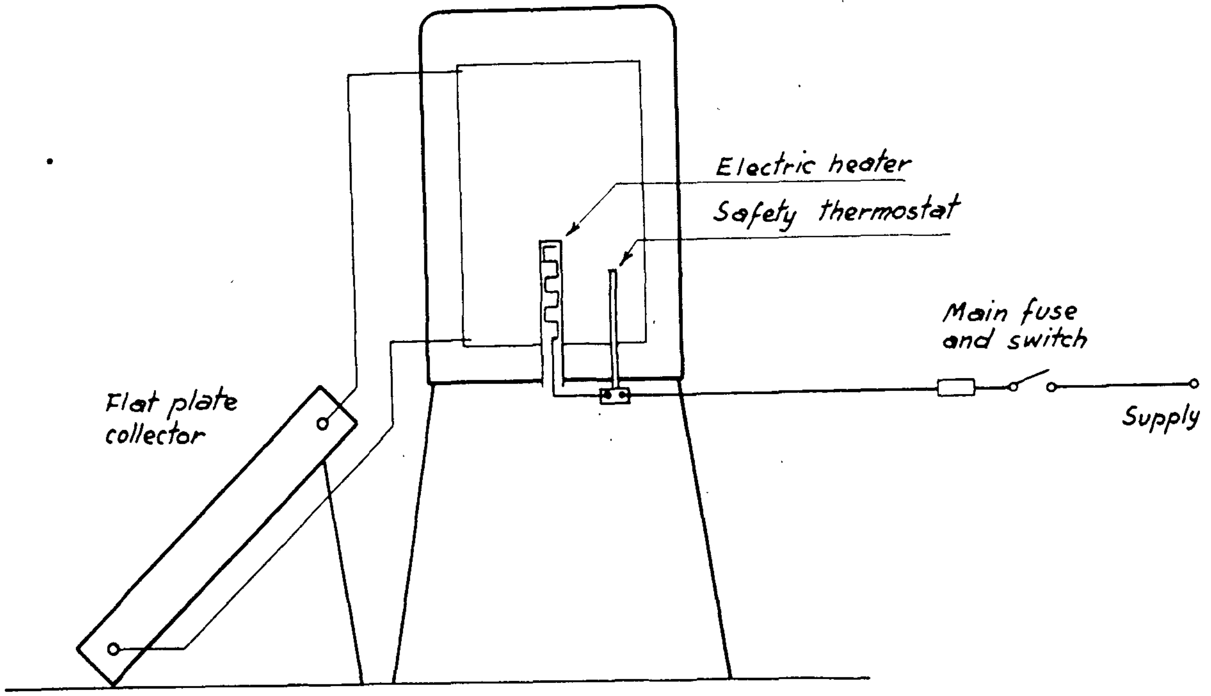

Figure 2. The circuit of the auxiliary electric heater

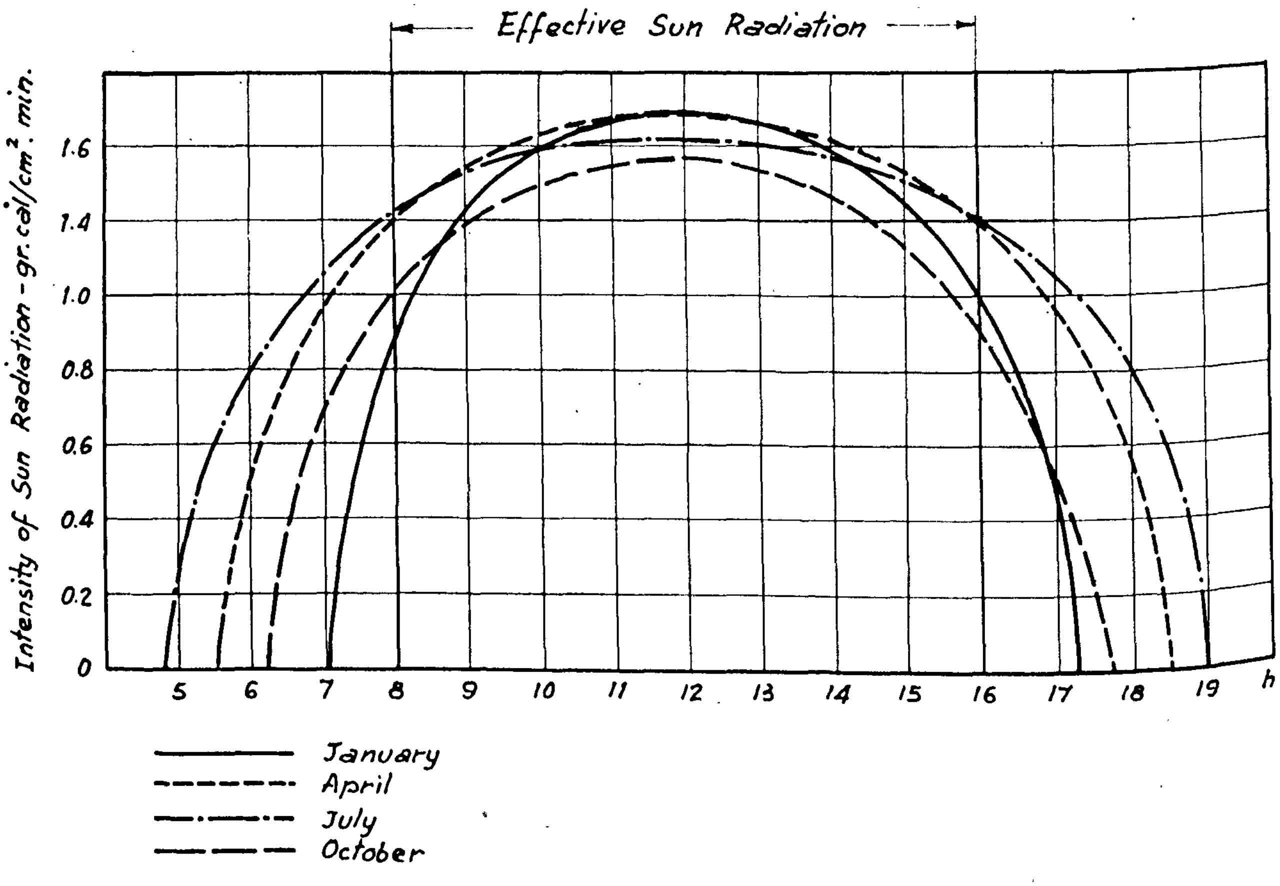

Figure 3. Intensity of solar radiation on a normal surface

regulate the consumption of power and only serves as a safety device. The electric circuit of the heater is shown in figure 2.

Estimating the amount of energy required for auxiliary heating entails analysis of the operation of solar heaters as a direct function of solar radiation and climatic conditions.

Intensity of solar radiation and duration of sunshine periods

The main factor influencing the operation of the solar heater is the diurnal and seasonal variation of the intensity of solar radiation. Figure 3 shows the intensity of normal radiation in Israel (latitude 30-33°N) for several months of the year.

It is apparent that between 8 a.m. and 4 p.m., the crucial hours for solar heating, there is no extreme seasonal variation in solar radiation. The intensity of solar radiation incident on the surface of a flat plate collector, inclined at a certain fixed angle, will be smaller than that on a surface invariably normal to the rays. If direct radiation on a normal surface is denoted by I and that on the flat plate collector by I_i, the relation between them is : $I_i = I \cos i$, with the angle i dependent on diurnal and seasonal courses. During early morning hours and in the late afternoon, the angle i is larger and therefore the energy incident on the flat plate collector decreases considerably. Because of this, we shall define the effective radiations as the annual average, over the interval between 8 a.m. and 4 p.m. approximately. The flat plate collector should be facing the equator for optimum efficiency and, to ensure stable year-round operation, should be tilted at an angle (from the horizontal) equal to the latitude plus about 10°. The conclusion derived from figure 3 is that, barring unfavourable meteorological conditions such as clouds, haze, drop in ambient temperature, etc., fairly stable operation would be possible; such unfavourable conditions, however, have to be allowed for. The average real duration of sunshine (expressed as tenths of the possible maximum sunshine hours) is usually taken as the measure.

Figure 4 shows that during the colder winter months, when more heating becomes necessary, the day becomes shorter and the sun shines only 50-70 per cent of the maximum possible time.

In the average household, hot-water consumption in considerable quantities starts about midday; for this reason the "main heating cycle" is defined as covering the hours of 8 a.m. to 12-1 p.m. Solar heaters are actually so constructed as to bring the

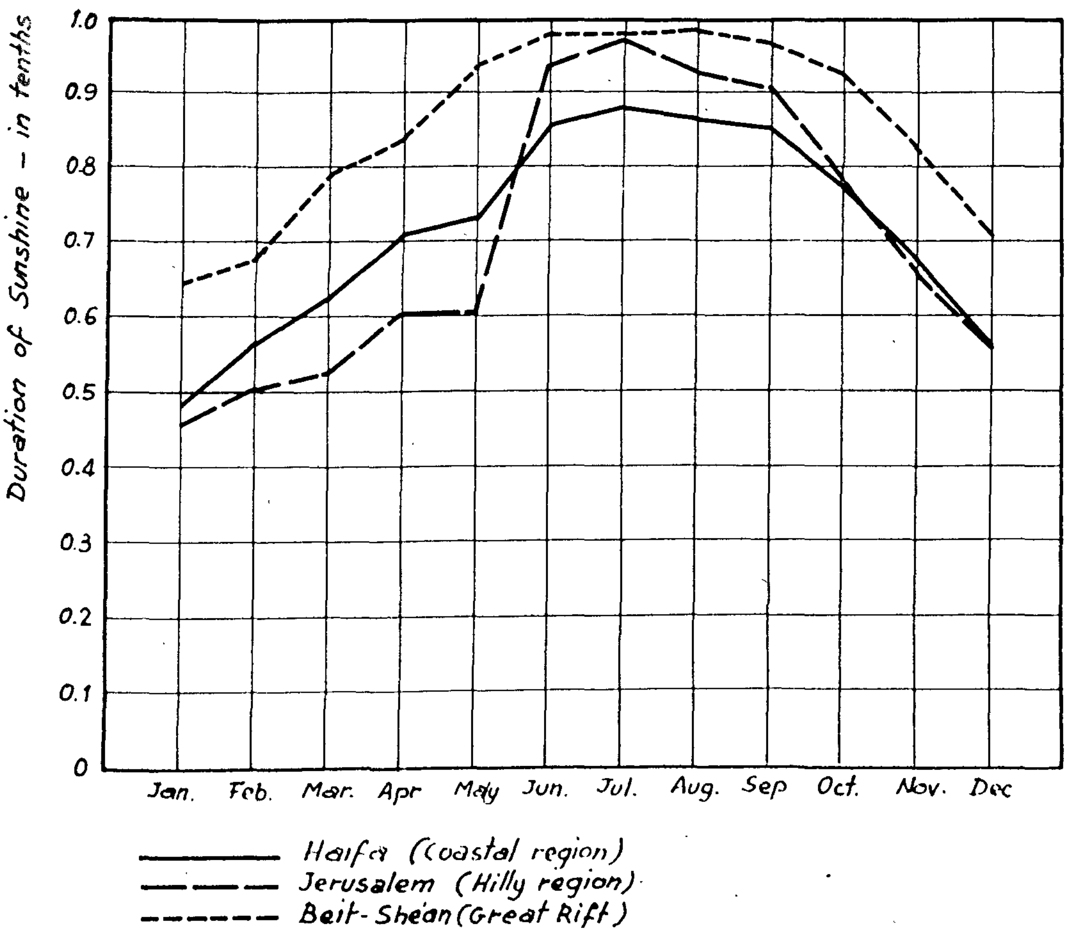

Figure 4. Duration of sunshine in tenths of the possible maximum

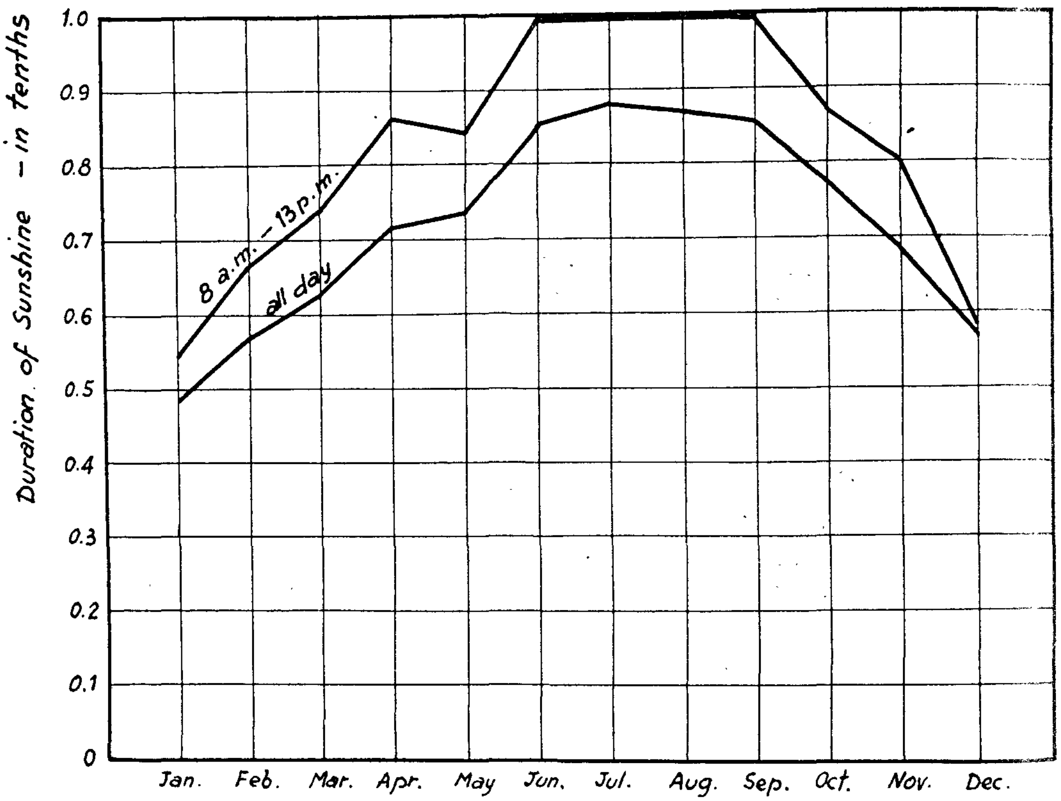

Figure 5. Duration of sunshine in Haifa between 8 a.m. to 1 p.m. in tenths of the possible maximum

water to the required temperature level during these hours. From the viewpoint of consumption, it is highly desirable that this temperature should be the highest possible, but from that of efficiency of operation (especially of the collector) temperatures exceeding 70° are undesirable owing to intensified scale formation. From this it is evident that on a bright summer day the solar heater should raise the water to the above temperature level within 4-5 hours. The same heater will reach a temperature of 50-55°C on a cloudless winter day.

If hot water from the storage tank is used up during midday hours — weather conditions permitting — heating will continue till about 4 p.m. Hot water will then be available in the evening and at night. The remainder serves as reserve for the following day, but during the night there is a certain amount of heat lost, depending on the thermal insulation and the prevailing weather. This reserve, however, does not guarantee an actual gain in the amount of heat utilized. If the following day is cloudless, radiation would not be fully utilized, considering the limits of the available range of temperatures. On the other hand, if the following day is cloudy, the reserve from the preceding day would prove extremely useful.

As heating between 8 a.m. and 1 p.m. seems to be of such crucial importance, it is advisable to consider the duration of sunshine during those hours (see figure 5).

From figure 5 it is apparent that in those hours the duration of sunshine is longer than the diurnal average, i.e. in the most essential hours cloudiness decreases from the diurnal average. For further clarification, table 1 shows the number of clear days in the month, the number of completely overcast days — on which there is no direct radiation — and the partly cloudy days on which cloudy and bright periods alternate.

Table 1 shows that at least 6-7 per cent, i.e. 20-25 days, are completely overcast and no solar heating by direct radiation would be possible. On such days, diffused radiation is hardly noticeable (1). It should

Table 1. Monthly percentage of clear and cloudy days (8)

Month	*Jerusalem (Mountainous area)*			*Tirat-Zvi (Valley of Jordan)*		
	All day clear	*All day cloudy*	*Partially cloudy*	*All day clear*	*All day cloudy*	*Partially cloudy*
January	19	16	65	31	16	53
February	19	10	71	31	10	59
March	28	10	62	28	10	62
April	31	7	62	39	4	57
May	42	2	56	54	2	44
June	74	0	26	63	0	37
July	78	0	22	64	0	36
August	62	0	38	55	0	45
September	62	0	38	74	0	26
October	43	4	53	51	4	45
November	35	16	49	47	9	44
December	31	15	54	23	15	62
Annual average	44	7	49	47	6	47

Table 2. Yearly percentage estimate of auxiliary heating *vs.* cloudiness

Cloudiness	*Number of days*	*Auxiliary heating in % of daily heating*	
		Essential minimum	*Actual consumption*
Completely overcast .	25	100	100
Heavily overcast . .	25	75	100
Moderately overcast .	30	50	100
Slightly overcast. . .	20	25	50

be noted, however, that under partial cloudiness, there will be days on which solar heating by direct radiation will be of little or practically negligible value. According to D. Ashbel (8) diffuse radiation on partly cloudy days is relatively strong and may reach 25 per cent of the total radiation in the morning and evening, decreasing to 9 per cent at midday. It may be estimated that, at best, diffuse radiation from 8 a.m. to 4 p.m. will reach 10-15 per cent. On "Sharav" (sirocco) days, characterized by marked haziness, diffuse radiation reaches 40 per cent when the sun is low and up to 25-30 per cent at midday. On such days, the maximum water temperature of the solar heater drops by 10-20 per cent.

Considering the above data and allowing for diffuse radiation, the amount of auxiliary heating necessary for stable year-round operation may be estimated. Table 1 shows that the average number of partially cloudy days is higher than 150 per annum. A conservative estimate shows that on about half of these days, solar heating is definitely impracticable. The minimum auxiliary heating required on partially cloudy days, classified in three groups, according to level of cloudiness, is given in table 2.

Summing up the data, it becomes evident that minimum auxiliary heating will be about 17.5 per cent of the year-round total. This number is in good agreement with annual sunshine data between 8 a.m. and 1 p.m. according to figure 5, which shows that solar radiation is obstructed during 18 per cent of its total possible duration.

In conclusion it can be seen that under local conditions, the required auxiliary heating amounts to about 10-20 per cent of the year-round total; figure 5 shows the months on which auxiliary heating is needed. As stated above, the average consumer tends to exaggerate the use of auxiliary heating for ensuring a constant supply of hot water. An estimate of the average actual consumption is given in the last column of table 2. Wasted consumption accounts for at least 10-15 additional per cent of total heating, resulting in excessive increase in the cost of solar heating.

The economy of water heating

Up to this point, auxiliary heating has been estimated in per cent of the yearly total without stating its quantitative value. In order to calculate the economic feasibility of the installation, the cost and necessary heat required have to be estimated. To do so, some preliminary assumptions will be made.

Water consumption

It can be stated that water consumption in considerable quantities starts at midday, continuing into the evening. If some hot water remains from one day's use, it will serve as reserve for the following day.

Heat consumption

Energy used for water heating has to cover hot water consumption as well as losses from the storage tank (in solar as well as in electric heating). Figures supplied by Israeli manufacturers of sun heaters exported to many countries will be used. According to one source (7), the requirements of an average household are 2.4 million kcal per annum. For the purpose of our calculation, the year divided by 365 days will give 6 600 kcal per day as a yearly average, equivalent to 7.65 kWh. Assuming the average yearly temperature increment obtained by using solar heating (approximately 40-45°C), it becomes apparent that a solar heater with a capacity of 150 litres and collector having 4 sq m of collecting surface have to be used; the cost of such a heater is U.S. $400. The cost of a comparable electric heater will be $150 at most.

Electric power

The cost of electric power varies from country to country and will therefore be taken as an average of 4 cents per kWh. The power supply companies encourage the use of power for heating during off-peak hours, in which power is cheaper, and will be taken to be at an average of 2.5 cents per kWh. Power consumed by an electric heater will be of the order of 2 800 kWh at the cost of $110 by the higher rate and $70 by the lower one. Auxiliary heating is undesirable for the solar heater at night; therefore its cost will be at the higher day rate of 4 cents per kWh.

Service life

It is usual to calculate the service life of solar heaters as being about eight years. For simplification, we shall assume that the electric heater will run for the same length of time.

Miscellaneous expenses

Other expenses to be considered are: cost of installation, including piping and wiring; maintenance; and interest on the investment. All these data are given in table 3.

Graphs based on these data are given in figure 6. These graphs indicate the costs of solar and electric heating, giving the primary investment plus the cost of installation and yearly running expenditure

Table 3. Comparison of solar and electric water heating costs (calculated for 8 years; in U.S.$)

	Electric		Solar			
Initial costs	$		$			
purchase price . . .	150		400			
installation (including piping and wiring .	20		40			
Total . .	170		440			
Annual charges						
5 % interest on initial costs (for 8 years) .	68		176			
Maintenance 1% per annum (for 8 years)	12		32			
	2,5 cents per kWh	*4 cents per kWh*	*4 cents per kWh*			
			% auxiliary heating			
			0	*10*	*20*	*30*
Electricity	$560	$880	$0	$88	$176	$264
TOTAL COST FOR 8 YEARS	$810	$1 130	$648	$736	$824	$912

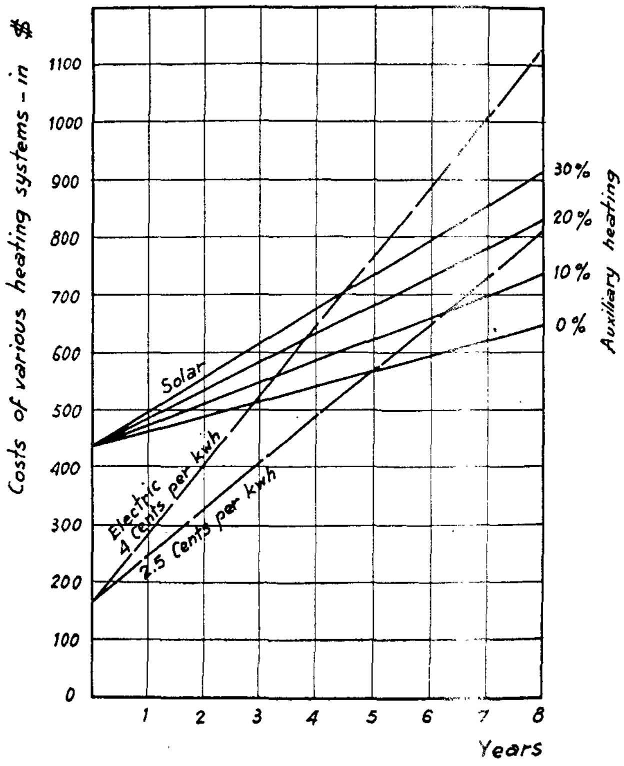

Figure 6. Cost of solar and electric heating (for 8 years)

for the 8 years taken as the average service life of the heaters.

From this figure, it can be concluded under the above conditions that solar heating is cheaper when the cost of power is above 3 cents per kWh. As the cost of power drops, it becomes necessary to save as much as possible on auxiliary heating. Only the essential minimum of power ensuring a constant supply of hot water will permit economic feasibility of solar heating. It will be seen that if the auxiliary heater is used for more than 15 per cent of the total heating, the cost of solar heating will be higher than electric heating (at the cheaper night rate).

It follows that means should be found for automatic control of auxiliary heating. This control will provide for the maximum utilization of solar energy and reduce to a minimum the use of power for auxiliary purposes. A device to make this operation automatic has been developed by E. Neeman and called a "solar switch". Obviously, this device will increase the cost of the solar heater. Provided the cost of this device can be kept down to within 3 per cent of the total cost of the solar heater, the additional cost will be recovered within about a year, through economy in power.

Design of the solar switch

Bearing in mind the requirements for the maximum possible utilization of solar heating as a condition for its economical operation, it should be considered that on any sunny day, summer or winter, heating will be effected by solar radiation, i.e. auxiliary heating will become necessary only under overcast conditions. The heating element of the electric heater will be designed to deliver, on the average, an amount of heat equal to that of the solar heater (see figure 7). In this way, we shall obtain, on an overcast day the same heating, but it will be effected by the auxiliary heater.

The purpose of the solar switch can now be precisely defined : (*a*) to prevent the electric heater operating between 1 p.m. and 8 a.m. of the following morning; (*b*) to ensure electric heating between 8 a.m. and 1 p.m. during cloudy periods.

The electrical circuit of the solar heater with the solar switch is shown in figure 8.

The cycle starts with the electric clock disconnecting the power between 1 p.m. and 8 a.m. of the following day. Between 8 a.m. and 1 p.m. the clock will reconnect its contacts. Electric heating will now be governed by the solar switch. When solar radiation is available, the solar switch will disconnect the electric circuit, while during cloudy periods it will switch it on.

Figure 7 permits calculation of the output of the electric heater. The rate of heating per unit time is expressed by :

$$H = \frac{d\theta}{dt} \cdot C \left[\frac{\text{kcal}}{h}\right] \quad [1]$$

where H = the rate of heating in kcal per hour
θ = temperature in °C
t = the time in hours
C = heat capacity of the storage tank ($C = c.V$)

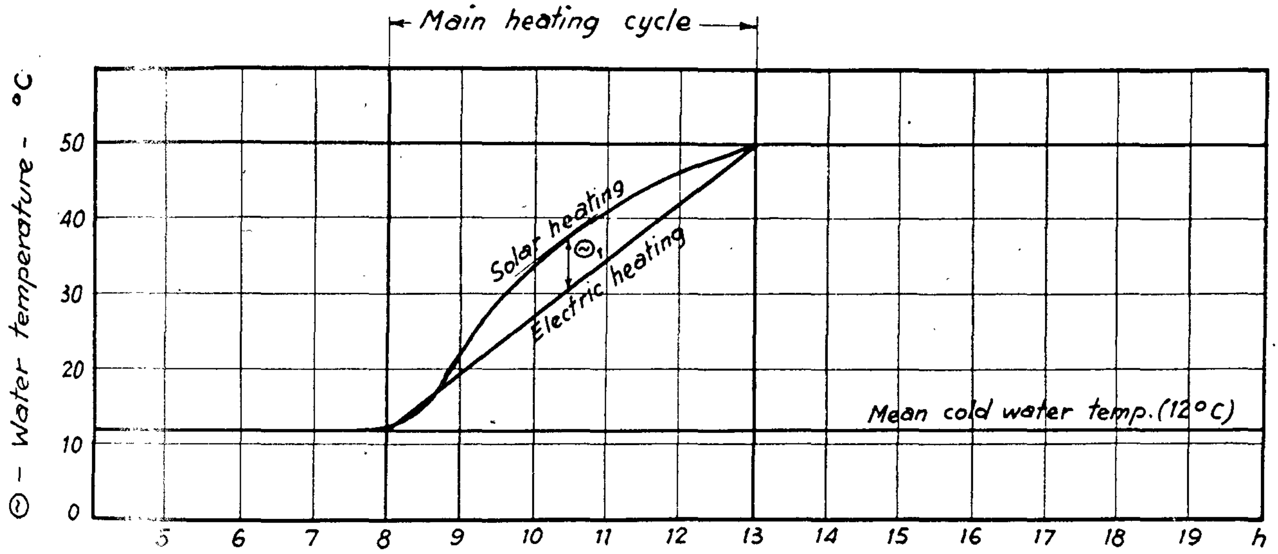

Figure 7. Water temperature during the main heating cycle in winter (solar and electric)

The expression $\frac{d\theta}{dt}$ represents the instantaneous slope of the heating curve.

While we do not have an analytic expression for the solar heating curve, the rate of electric heating will be constant; therefore:

$$H \text{ electric} = \frac{d\theta}{dt} \cdot C = \text{const} = \frac{\Delta\theta}{\Delta t} \cdot C \qquad [2]$$

when $\Delta\theta$ = the temperature difference of the cold water supplied to the heater and the hot water; Δt = duration of heating interval.

Under local winter conditions, the average cold water temperature will be 12°C, and solar heating will raise it to 50°C in 4-5 hours. Thus, it is possible to assume $\Delta t = 5$ hours, $\Delta\theta = 38$°C. From this, the electric output can be calculated:

$$N = \frac{c \cdot V}{860} \cdot \frac{\Delta\theta}{\Delta t} \text{ [kW]} \qquad [3]$$

where N = power in kW

c = specific heat of the water in $\frac{\text{kcal}}{1°\text{C}}$

V = storage tank capacity in litres.

A capacity of 100 litres will require:

$$N = 0.89 \left[\frac{\text{kW}}{100 \text{ l}}\right] \qquad [4]$$

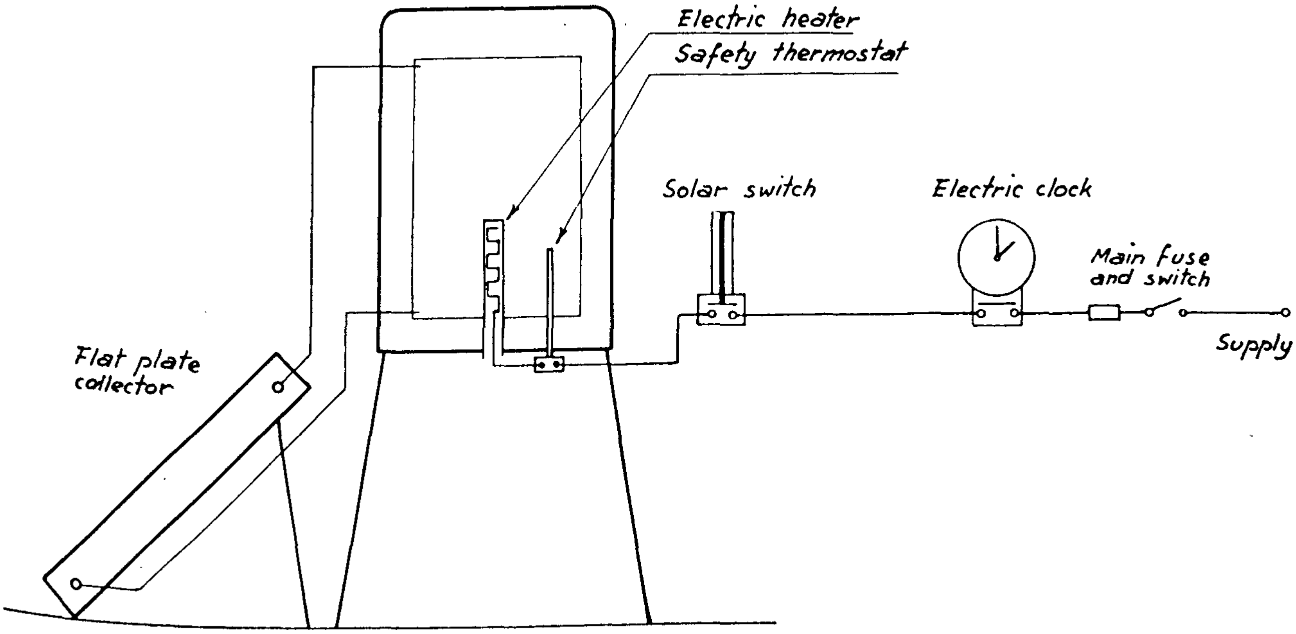

Figure 8. Circuit of auxiliary electric heater with solar switch

Assuming that thermal insulation of the storage tank will be of a high quality and that afternoon and evening consumption will make use of water heated until midday, heat losses from the tank can be expected to be small. Considering this, its thermal utilization may be of the order of 85 per cent approximately. In view of the thermal losses, the auxiliary will have to provide

$$N = 1.05 \left[\frac{\text{kW}}{100\ \text{l}}\right] \quad [5]$$

For a solar heater of 150 litres capacity, a 1.6 kW electric heating element will be required, consuming about 8 kWh during the 5 hours of the heating cycle. This figure is approximately the same as the average daily output previously calculated.

Using the typical heating curves given in figure 7, the co-operation between the two sources of heat may be analyzed. The derivative $\frac{d\theta}{dt}$ defining the slope of the curves determines intensity of radiation per unit time. From the graphs it is obvious that while the electrical heating graph is a straight line, indicating constant and stable heating, the slope of the solar heating curve is variable. This fact stresses the point that the solar heating rate will be higher than electric heating in certain hours and lower in others. If cloudiness sets in during that part of the heating cycle where the rate of solar heating is higher than the electric, the auxiliary heating will lag somewhat behind the planned heating rate. Conversely, cloudiness during the second part of the heating cycle will bring about a higher rate of auxiliary heating. Provided cloudiness is fairly evenly distributed throughout all heating hours, the required average temperature will be reached. The least favourable conditions may occur on a day, when cloudiness prevails mainly during lag hours of the auxiliary heating. The maximum possible difference is denoted by 1 (degrees centigrade) as measured by the vertical at the point in which the two curves are parallel. This will result in the water temperature at 1 p.m. being several degrees lower than the possible maximum for that day. This temperature will be reached slightly later.

Figure 9 illustrates the combined operation of solar and electrical heating, assuming cloudiness between 9-9.30 a.m. and 10.30-11.30 a.m.

The thermostat inside the storage tank is a safety device. Its purpose is to prevent an undue rise of water temperature, in the event of electrical circuit breakdown not taken care of by other safety devices. The thermostat will serve as a consumption limiter only on those rare occasions when the water temperature is brought to cut-off level by means of the auxiliary heating. This could happen if a large

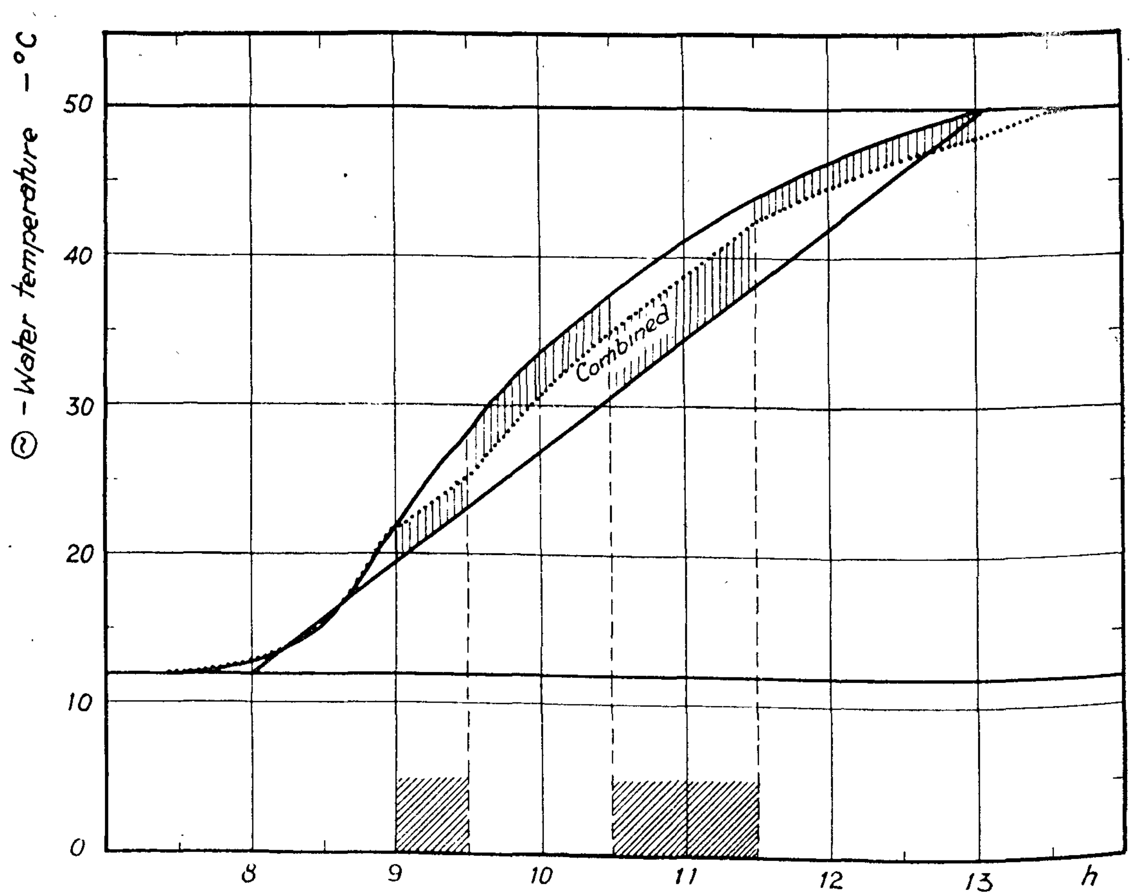

Figure 9. Combined operation of solar heater with auxiliary electric heater (cloudiness between 9-9.30 and 10.30-11.30 a.m.)

amount of hot water is left unused overnight, so that less heating is required to bring it to the required temperature. The thermostat should be adjusted to a cut-off temperature of 60°C.

Construction of the solar switch

The solar switch itself will now be described. Having defined the required conditions of operation, means of construction may be proposed. Several possible designs have been considered. A device of simple design, requiring the least possible maintenance and cheaply manufactured is preferable. Of all the designs examined, the three main ones will be discussed in this paper.

Photo-electric cell

The most obvious device that immediately comes to mind is a photo-electric cell. Such a cell can be installed with the collector adjusted so as to actuate a contactor in accordance with radiation conditions. When direct radiation is obstructed, the contactor will close, switching on the auxiliary heater. With radiation available again, the contactor opens and auxiliary heating is switched off.

Even a superficial examination of this device will show that besides the complicated problem of adjusting the device to the required radiation levels for the open and closed positions, the efficiency of the photo-electric cell will be considerably reduced by accumulating dust. Furthermore, an amplifier is required, making the device more expensive and complicating maintenance and adjustment.

A simpler and cheaper device will therefore have to be considered.

Thermostat inside the flat plate collector

There is a possibility of installing a thermostat inside the outlet of the flat plate collector. The thermostat will operate according to the temperature of the hot water leaving the collector. The advantage of the thermostat is that it is fitted with contacts able to pass the full power load, so that the operation is direct, without need for amplification.

The thermostat will operate as follows: with the appearance of radiation, water in the flat plate collector will heat up within several minutes. The thermostat will respond by opening the contacts and switching off power. Contacts will remain open for the entire period of heating by radiation. In case of overcast, direct radiation ceasing, solar heating will be reduced and hot water flow to the storage tank will stop. The flat plate collector with the thermostat will cool to the point where contacts close, switching on the auxiliary heater.

The main disadvantage of this device lies in the dependence of a solar switch of this kind on the thermal inertia of the flat plate collector. For obvious reasons, everything is done to reduce losses from the collector. If we succeed in this, cooling will be reduced and more time will elapse until the thermostat will switch on auxiliary heating.

It is argued by Hottel and Woertz (1) that obstruction of direct radiation by clouds will indeed stop water heating, but diffuse radiation during cloudy periods may be sufficient to prevent the collector temperature from dropping. Under these conditions, operation of the auxiliary heating will be undependable. It should be noted that the thermostat itself, being sensitive and operating the electric circuit directly, may be used for our own purposes in a more efficient manner.

Thermostatic solar switch

This device will utilize the advantages of the thermostat by means of an independent small flat plate collector operating in conjunction with it. This will make it independent of the inertia of the main collector. The design of the prototype is described below. This device enables us to make direct solar radiation control the electric circuit, thereby regulating auxiliary heating according to requirements.

To an ordinary thermostat, used for temperature regulating purposes in electric heaters, a small solar collector is added. The collector is made of sheet copper, 0.2 mm gauge, its area being 200 cm² (10 × 20 cm). The collector is soldered to the rod of the thermostat, the surface facing the sun painted dull black. The thermostat with its collector is installed inside a wooden box, without additional thermal insulation. The upper face of this box will be of plate glass (see figure 10). The purpose of the box is to keep the solar switch clean and dry.

The solar switch is installed near the main flat plate collector, within reasonable distance of the electric heater, to keep wiring short. The electric circuit is described in figure 8.

This prototype has been tested for a fairly long period and its operation recorded. A Campbell-Stokes instrument was installed close to the solar switch, recording sunshine periods. Figure 11 illustrates the operation of the solar switch. The diurnal recording of the solar switch operation is shown side by side with the recording of the Campbell-Stokes instrument. The recording instrument shows the positions of connected and disconnected load. Fluctuations in recording of the connected load are due to supply voltage variations and have nothing to do with the operation of the solar switch itself.

Experiments with the prototype during two winter seasons have shown its operation to be stable in all weathers. It became apparent that the apparatus is even more sensitive than necessary. Recordings show that even a passing cloud makes the thermostat contacts open and close within 2-3 minutes, which results in excessive wear (the electric circuit as a whole is not unduly affected).

Consequently, this was modified to make the time lag necessary for operating the contacts of the order of 4-6 minutes. The resulting losses in total daily amount of auxiliary heating were small. It is esti-

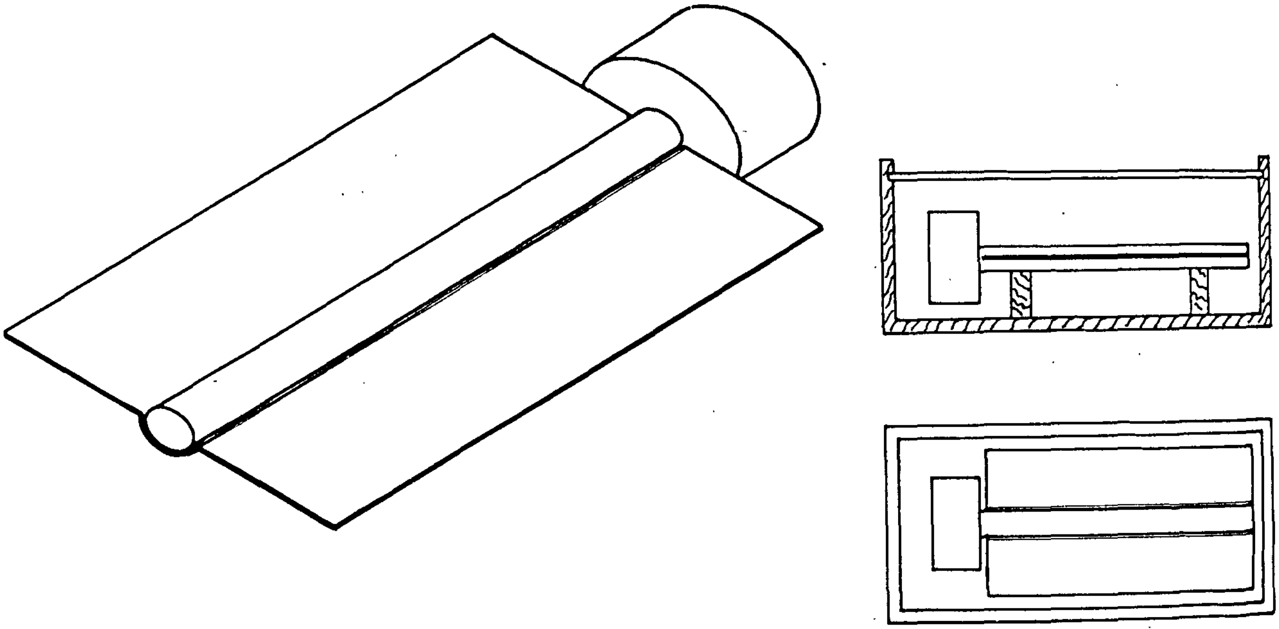

Figure 10. The thermostatic solar switch

mated that the cost of producing the solar switch with the electric clock will not be higher than assumed above.

Further improvements of the solar switch

The experiments demonstrating the high sensitivity of the solar switch make further improvement possible. Up to now, this high sensitivity was not utilized to reduce the wear on the thermostat contacts. Sensitivity is governed by the setting of the thermostat and its design: increasing the collecting area, reducing heat capacity and preventing ventilation will advance the disconnection of the contacts by solar radiation; reducing the collecting area and increasing ventilation will tend to reduce the thermal inertia of the device and so advance the closing of contacts when solar radiation ceases.

We shall now define two time constants with regard to the solar switch: (*a*) disconnecting time constant — k_1, representing the time from the instant when direct radiation appears to the instant when the thermostat switches off the electric circuit; (*b*) connecting time constant — k_2, representing the time from the instant of the sun becoming obstructed to the instant when the thermostat switches on the auxiliary heater.

These constants k_1 and k_2 are not fixed; they vary according to the angle of incidence of the radiation on the solar switch collector, cooling conditions being determined by air temperature, wind speed, etc. With the aid of interrelated planning of all design factors, it is possible to arrive at average constants, taking into consideration the actual operating conditions of the flat plate collector. For the collector itself, two parallel expressions will be defined.

(a) *Time constant for the start of hot water circulation to the storage tank* — k_1. As mentioned before, hot water flow from the collector lags behind solar heating; k_1 represents the time necessary to heat the collector up to the temperature where hot water circulation starts (free circulation in a heater based on thermosiphonic circulation, or for starting the circulating pump in a heater with forced circulation). This constant is also not fixed, being dependent on two groups of factors. The first group consists of external factors, i.e. intensity of direct and diffuse radiation, according to the time of day and the season, cloudiness, air temperature, wind speed, etc. The second group consists of factors concerning collector design and the hot water temperature in the storage tank. It has to be stressed that the constant k_1 will increase with storage temperature, i.e. the appearance of the sun after a fairly long overcast interval at midday will necessitate more prolonged heating of the collector for starting of circulation than during morning hours.

(b) *The disconnecting time constant* — k_2, *representing residual time of water flow to the tank after cessation of direct radiation.* Under overcast conditions, diffuse radiation only will reach the collector. Its intensity will mostly be lower than that necessary for heating the water up to the circulation point. H. Tabor (5) defined the cut-off solar intensity, below which the efficiency will drop to zero, i.e. no useful heating will be effected. On the whole, the time constant k_2 will be very small. During this period, hot water circulation will continue at the expense of the heat capacity of the collector. The rate of cooling of the collector, i.e. the reduction in its heat capacity, depends on weather conditions, especially on diffuse radiation. In certain cases, the diffuse radiation will offset the losses from the collectors and cooling will

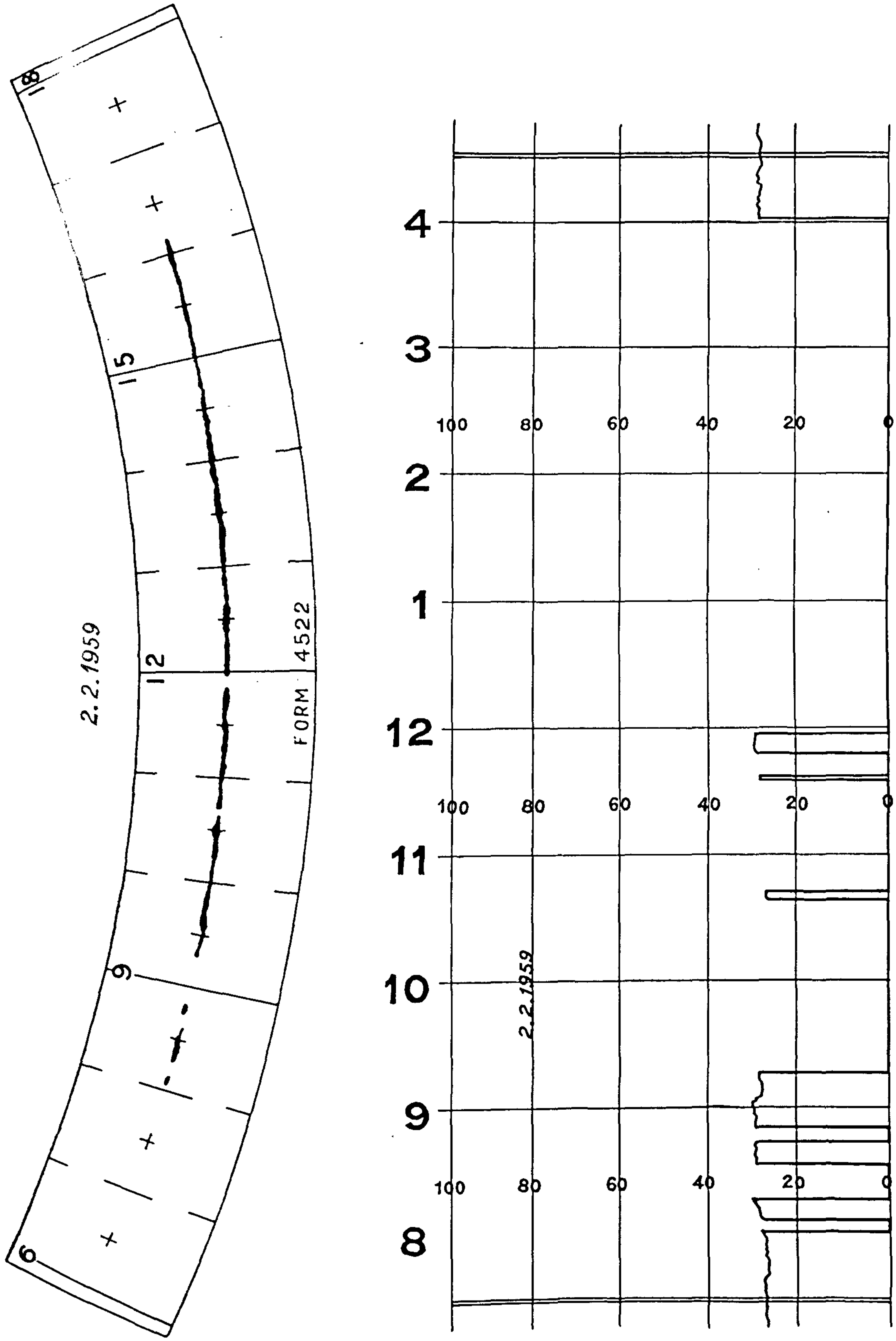

Figure 11 (a and b). Recording of the operation of the solar switch. (Fluctuations on the recorded line due to supply voltage variations)

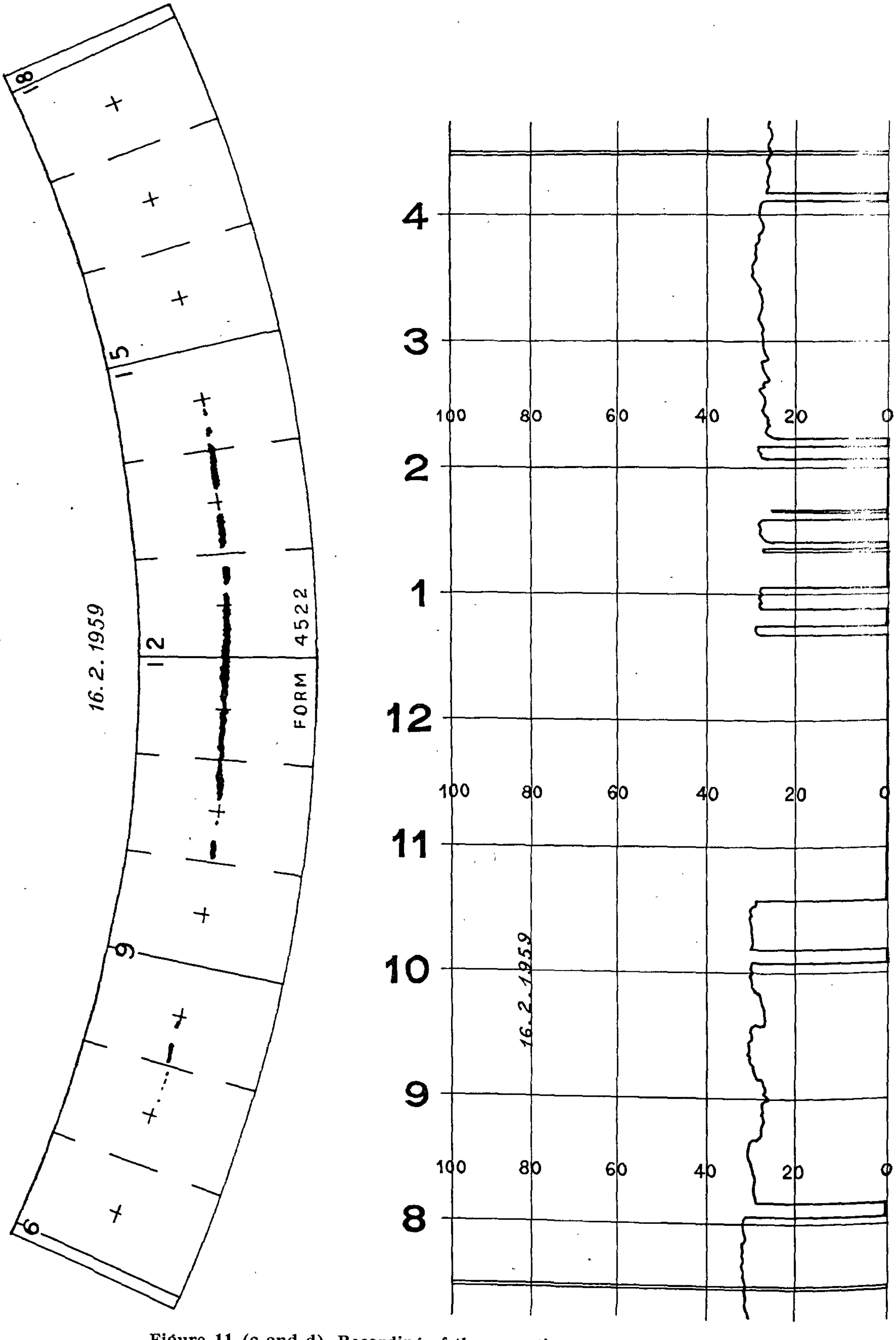

Figure 11 (c and d). Recording of the operation of the solar switch. (Fluctuations in the recorded line due to supply voltage variations) be low. This will reduce constant k_1 when the sun reappears. It may be assumed, as a first estimate, that $k_2 = 0$, meaning that hot water circulation will stop instantly when the sun becomes overcast.

After defining these four constants, we can express the desired improvement. We shall try to adapt the constants of the solar switch to those of the collector, so that the equalities $k_1 = K_1$ and $k_2 = K_2$ will be established.

Such ideal agreement will make perfect co-operation possible between the solar heater and the auxiliary heating by means of the solar switch. It should be noted again that these constants are not fixed. They depend on numerous factors, mostly impossible to define mathematically, such as meteorological data. We shall thus have to confine ourselves to a close estimate, based to some extent on experimental data, which will have to be verified again when examining different models of solar heaters.

This stage of the study, to be carried out in collaboration with the Solar Physics Laboratories and the Electric Power Division of the Technion, will consist in calculating the performance of the solar heater by means of an electronic computer, in the course of which the required time constants will also be determined.

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Summary

In many parts of the world, solar water heaters fitted with the low-temperature flat plate collector are used in order to reduce fuel costs. In regions where solar radiation is particularly intense and the climate appropriate, water is sun-heated during most days of the year. The need for auxiliary heating on overcast days, resulting in increased total cost, raises the problem of the economic feasibility of the system. Where conventional sources of heating are available, the combination of solar and auxiliary heating must be capable of competing economically with the other systems. Among the factors governing the actual cost of solar heating, the expenses for auxiliary heating are thus of the greatest importance.

In order to estimate the essential proportion of auxiliary heating, local climatic conditions and their influence on the efficiency of the solar heater should be examined. With the aid of such data, it will be possible to calculate the minimum amount of auxiliary heating required to provide for year-round hot water consumption.

Close examination of the actual proportion of auxiliary heating shows that the average consumer tends to excessive use of it. For example, in case of doubt about sunshine conditions on the following day, auxiliary heating (mainly electric) is switched on, in which case, if the following day turns out to be clear or almost clear, solar radiation remains unutilized.

Figures based on these considerations show that under local conditions, the minimum amount of auxiliary heating reaches 10-15 per cent of the total year-round heat. On the other hand, the actual use by the average consumer is much higher and reaches 28-30 per cent of the total heating.

In order to exploit the maximum solar radiation while reducing auxiliary power consumption to a minimum, as well as make sure of the amount and temperature of the heated water, a special device named by the authors a "solar switch" has been designed, constructed, checked and used. This switch permits automatic control of the supply of electric energy and operates only during sunshine hours.

The power of the electric auxiliary heater is so calculated as to give, on the average, the same rate of heating as obtained from unobstructed solar radiation. Combining their operation during the "main heating cycle", i.e., from 8 a.m. to 1 p.m., water heated to the desired temperature is obtained.

An electric clock, installed in series with the solar switch, keeps the auxiliary system switched off during the undesired period, i.e., from 1 p.m. to 8 a.m. of the following day.

The solar switch, which is sensitive to direct solar radiation, is responsible for keeping the electric heater switched on during the overcast periods in the course of the heating cycle, from 8 a.m. to 1 p.m.

Of various possible designs, the "thermostatic" solar switch was adapted. It comprises a thermostat to which a small solar black collector is soldered. This device is contained in a wooden box with a glass plate on the upper side, without thermal insulation. The switch is actuated by direct solar radiation, and switches the electrical device on directly.

The sensitivity of the solar switch has to be adapted to the working conditions of the main collector: circulation between the collector and storage tank sets in, once solar radiation is no longer available, only when the temperature of the water in the collector is higher than that in the tank. The switch must also not be so sensitive as to switch on when the clouds are too light.

LE CONJONCTEUR SOLAIRE, MOYEN AUTOMATIQUE DE SOULAGER LES DISPOSITIFS AUXILIAIRES DES CHAUFFE-EAU SOLAIRES

Résumé

Dans nombre de régions du monde, on a recours aux chauffe-eau solaires dotés d'un collecteur à basse température constitué par une plaque plate, pour réduire les frais de combustible. Dans les zones où le rayonnement solaire est particulièrement intense et le climat approprié, c'est le soleil qui sert à chauffer l'eau pendant la majorité des jours de l'année. Le besoin d'un dispositif auxiliaire pour les jours couverts, avec l'augmentation de frais globaux qu'il comporte, soulève un problème quant à la validité économique du système. Là où l'on dispose de moyens de chauffage classiques, la combinaison chauffage solaire-chauffage auxiliaire doit être capable de faire concurrence aux autres systèmes sur le plan économique. Parmi les éléments qui déterminent le coût véritable du chauffage solaire, les dépenses afférentes aux dispositifs auxiliaires sont donc de la plus haute importance.

Pour juger de la fraction indispensable des besoins de calories que le chauffage auxiliaire doit servir à combler, il faut examiner les conditions météorologiques locales et leur influence sur le rendement du chauffe-eau solaire. A partir de ces données, on pourra calculer le minimum de chauffage auxiliaire dont on aura besoin pour faire face à la consommation d'eau chaude de l'année.

L'étude détaillée de la proportion dans laquelle le chauffage auxiliaire doit effectivement intervenir démontre que le consommateur moyen a tendance à en abuser. Par exemple, quand il a des doutes au sujet de l'ensoleillement du lendemain, il met en route un dispositif de chauffage auxiliaire (généralement électrique) si bien que, si cette journée est claire ou presque claire, son apport de rayonnement reste inutilisé.

Des chiffres basés sur ces considérations démontrent que, pour les conditions locales qui nous intéressent, la proportion minimale des besoins à couvrir par le chauffage auxiliaire atteint 10 à 15 p. 100 du total annuel. L'utilisation que le consommateur moyen fait de ces ressources auxiliaires est beaucoup plus importante : elle atteint 25 à 30 p. 100 du total.

Pour exploiter le rayonnement solaire au maximum, tout en réduisant le plus possible la consommation d'énergie auxiliaire, ainsi que pour garantir que la quantité et la température de l'eau chaude sont bien ce que l'on veut, un dispositif spécial que les auteurs appellent le conjoncteur solaire a été mis au point,

fabriqué, essayé et mis en service. Il permet de régler automatiquement la fourniture d'énergie électrique et ne fonctionne que pendant les heures de soleil.

La puissance du chauffe-eau auxiliaire électrique est calculée de telle façon qu'elle assure, en moyenne, le même régime de chauffage que celui qui correspond au rayonnement solaire en l'absence de nuages ou autres obstacles. En combinant le fonctionnement de ces deux dispositifs pendant le cycle principal de chauffage, c'est-à-dire de 8 heures du matin à 1 heure de l'après-midi, on obtient de l'eau à la température voulue.

Une pendule électrique, montée en série avec le conjoncteur solaire, coupe le courant destiné au système auxiliaire pendant la période où on ne veut pas s'en servir, c'est-à-dire de 1 heure de l'après-midi à 8 heures du matin le jour suivant.

Le conjoncteur solaire, sensible au rayonnement solaire direct, assure le fonctionnement du dispositif électrique pendant les périodes nuageuses qui se présentent au cours du cycle de chauffage, c'est-à-dire de 8 heures du matin à 1 heure de l'après-midi.

On s'est rallié, parmi les diverses conceptions possibles, au conjoncteur solaire à thermostat. Il comporte donc un thermostat, auquel est soudé un petit collecteur solaire noir. Ce dispositif est logé dans une caisse en bois dont la partie supérieure est recouverte de verre, sans isolement thermique. Le conjoncteur est commandé par le rayonnement solaire direct, et il déclenche le fonctionnement du dispositif électrique.

On doit adapter la sensibilité du conjoncteur solaire aux conditions de travail applicables au collecteur principal : la circulation entre ce collecteur et le réservoir ne s'établit, au moment où l'on ne dispose plus de rayonnement solaire, que lorsque la température de l'eau dans le collecteur est plus élevée que celle qui règne dans le réservoir. Le conjoncteur doit également être assez peu sensible pour n'agir que lorsque les nuages sont assez épais.

ÉTUDE SUR LE CHAUFFAGE SOLAIRE DE L'EAU EN ALGÉRIE

J. Savornin *

Nous avons construit et expérimenté des appareils économiques destinés au chauffage de l'eau dans les régions déshéritées de l'Algérie, ce chauffage solaire étant destiné à suppléer au manque ou à la cherté du combustible : l'eau est destinée aux usages domestiques (cuisine, lavage).

Un premier type d'appareil comporte des dimensions réduites (70 cm dans sa plus grande dimension) et un volume d'eau restreint : 15 litres (figure 1). Un second type, analogue, est plus important (135 cm de dimension maximale), avec une capacité de 50 litres (figure 2). Pour réduire le plus possible le prix de revient, on a renoncé à l'alimentation automatique en eau froide : ces appareils doivent être remplis le matin, et on recueille l'eau chaude au milieu de la journée et le soir, soit entre 11 h 30 et 13 h 30, et entre 17 h et 18 h.

Construction

Les appareils comportent essentiellement une caisse plate dont le fond et les côtés sont calorifugés, soit par des copeaux de bois disposés entre deux feuilles d'isorel ou de contreplaqué (petit modèle), soit par des panneaux de liège aggloméré placés entre deux épaisseurs de planches (grand modèle). Dans cette caisse est placé un réservoir à eau métallique, plat, dont la face avant est noircie. Enfin, la caisse est fermée par un châssis vitré qui laisse passer les rayons solaires. La caisse est portée par trois pieds, deux à l'avant et un à l'arrière; elle est inclinée pour recevoir les rayons solaires normalement à midi, aux équinoxes : l'inclinaison est réglable grâce au pied arrière, constitué par un tube qui peut coulisser dans un manchon.

Pour le grand modèle, le réservoir est construit en tôle ondulée galvanisée du commerce : les ondulations ont une période de 75 mm, une profondeur de 18 mm entre un sommet et un creux. Les ondulations rendent plus rigides les parois, qui ont tendance à se déformer sous l'effet de l'élévation de température. Quatre tiges munies d'écrous maintiennent l'écartement, dans les parties centrale et inférieure. Les feuilles de tôle sont soudées à leur extrémité sur une paroi plane en fer galvanisé; elles sont disposées de telle façon que les creux d'une paroi sont vis-à-vis des creux de l'autre.

Pour le petit modèle, le réservoir est en tôle de zinc, l'écartement, ici encore, est maintenu par des traverses.

Le remplissage se fait par un tube court situé à la partie supérieure, un second tube au même niveau permet l'évacuation de l'air.

Dimensions

Le petit modèle comporte à l'avant une vitre unique, de 50 × 70 cm; le réservoir plat de même surface a pour épaisseur intérieure 45 mm, d'où une capacité de 16 litres environ. La caisse vitrée a pour dimensions extérieures 56 × 75 × 11 cm; elle repose comme on l'a dit sur trois pieds, celui de l'arrière étant réglable. Le poids de l'appareil plein est de 21 kg (sans eau).

Le grand modèle est muni d'un châssis portant quatre vitres mesurant chacune 40 × 60 cm. La surface insolée est 9 600 cm², le volume de l'eau 53 litres, et la caisse vitrée a pour dimensions extérieures 92 × 133 × 20 cm. Le poids total de l'appareil plein est de 72 kg (sans eau).

Le rapport entre la surface insolée et le volume d'eau est de 48 l/m² pour le petit, 52 l/m² pour le grand modèle.

Le chauffage de l'eau se produit graduellement depuis le matin. Sa température s'élève d'abord à la partie supérieure du réservoir; elle atteint peu à peu un maximum, vers 15 h ou 17 h, suivant les saisons, et diminue ensuite lentement.

La température de l'eau présente constamment un gradient vertical, l'eau de la base du réservoir étant naturellement à la température la plus basse. On

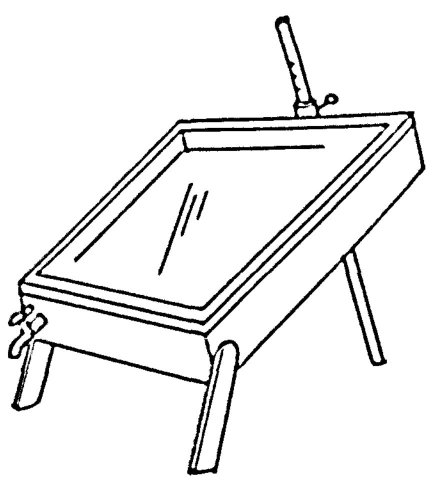

Figure 1

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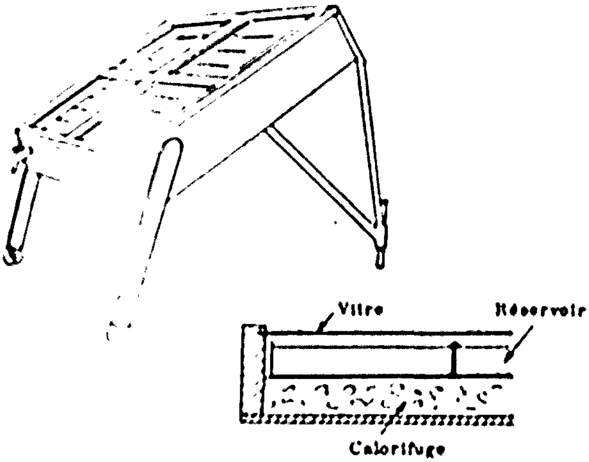

Figure 2

soutire l'eau à un niveau correspondant approximativement au quart de la hauteur : un tube intérieur part de ce niveau et débouche sur un robinet placé à la base de l'appareil.

Prix de revient

Le coût de ces appareils est difficile à évaluer, puisqu'il s'agit de prototypes de fabrication artisanale. Pour le gros modèle, le prix des matières premières (1961) est de l'ordre de 80 à 100 NF ; il est de 40 à [illegible] NF pour le petit. A ces chiffres doit s'ajouter le prix de la main-d'œuvre.

Performances

Selon la saison et l'état du ciel, la température de l'eau chaude obtenue est plus ou moins élevée : elle dépasse le plus souvent 60 °C. C'est ainsi que la figure 3 montre les températures atteintes certains jours de février, d'avril, de mai ou de juin pour le

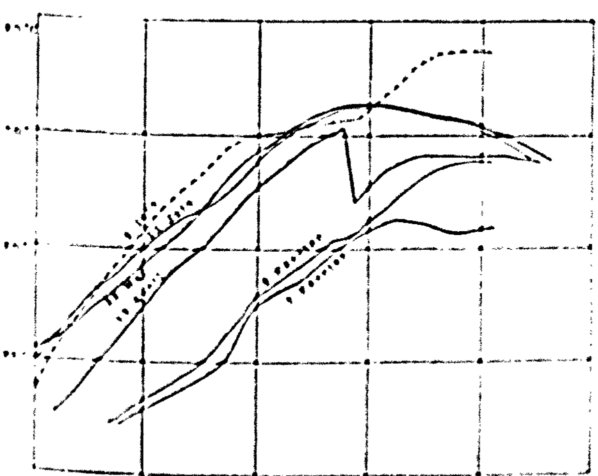

Figure 3

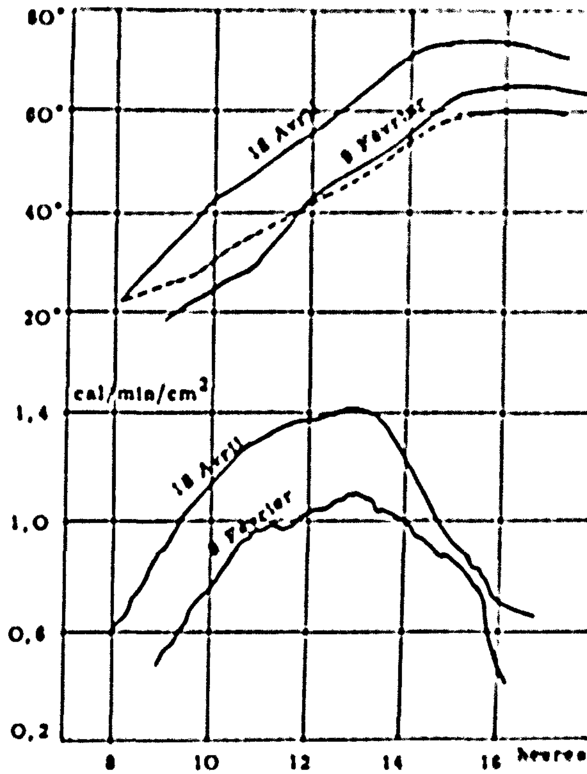

Figure 4

grand modèle. Les températures pour le petit modèle sont remarquablement les mêmes, à 1 ou 2° près. Ces courbes ont été obtenues à Alger (36° Lat. N) en plaçant l'appareil dans une position fixe (vitre normale au plan méridien et sensiblement normale aux rayons solaires à midi); seule la courbe du 2 juin correspond à une orientation corrigée à la main, environ toutes les heures (sauf de 12 h à 13 h 45) : on voit qu'il est alors possible d'augmenter très sensiblement la température de l'eau. Le 13 avril, on a soutiré 25 l d'eau à 13 h 30 ; cette eau était en moyenne à 53°, ce qui montre que les températures de la figure 3, prises à 5 cm du niveau supérieur de l'eau dans le réservoir, ne donnent pas la température de toute l'eau disponible. On a ensuite remis dans l'appareil 25 litres d'eau froide, et la température s'est encore élevée de 9° au cours des deux heures suivantes.

On a indiqué sur la figure 4 des mesures relatives aux 9 février et 18 avril, qui donnent (courbes en trait plein) la température de l'eau au sommet du réservoir (comme sur la figure 3). La courbe en trait pointillé indique la température des premiers décilitres puisés *au robinet* le 18 avril (température de l'air ambiant 20 à 23°). La température de la masse totale d'eau disponible est intermédiaire : on a soutiré de l'appareil 40 litres d'eau à 66 °C à 17 heures. En moyenne, la température de l'eau disponible est de 5 à 6° inférieure à la température donnée par les courbes de la figure 3. La figure 4 donne aussi la mesure de la chaleur solaire prise sur un solarigraphe dont la surface réceptrice était paralèlle à la vitre des capteurs. On peut en déduire le rendement des appareils de la façon suivante : la quantité de chaleur reçue par la vitre de 8 h à 15 h le 18 avril était de 4 460 kcal, et le chauffage de 50 litres d'eau de 21 à 66° a nécessité 50 × 45 = 2 250 kcal. Le rendement est donc d'environ 50 p. 100.

Conclusion

La construction et la mise en place de chauffe-eau solaires portatifs et de prix de revient peu élevé est possible en Algérie, où la climatologie se prête particulièrement à ce mode de récupération de la chaleur solaire.

Résumé

Le chauffage de l'eau pour les besoins domestiques peut se faire économiquement en Algérie, où les journées d'insolation sont nombreuses. Des réalisations commerciales comportant capteur solaire, réservoir à accumulation, et parfois chauffage électrique d'appoint, existent mais sont d'un prix de revient assez élevé.

On a cherché la construction de petits appareils simples et peu coûteux, dont plusieurs prototypes ont été étudiés. Le rendement en eau chaude de ces appareils a été déterminé suivant les saisons. On montre qu'une installation relativement peu coûteuse permet de fournir une quantité d'eau intéressante, pour les besoins du lavage et de la cuisine.

STUDY OF SOLAR WATER HEATING IN ALGERIA

(Translation of the foregoing paper)

J. Savornin *

We have constructed and tested economical solar water heaters for the undeveloped regions of Algeria, to compensate for the lack or high cost of fuel; the water is intended for domestic uses (cooking, laundry, etc.).

The first type of heater is small (70 cm in its largest dimension) and provides a limited amount of water — 15 litres (figure 1). A second type is similar but larger (135 cm in largest dimension), and has a capacity of 50 litres (figure 2). To make the heaters as cheap as possible, no automatic cold-water feed is provided. The heaters must be filled in the morning, and hot water is drawn at midday and in the evening : from 11.30 a.m. to 1.30 p.m. and from 5 to 6 p.m.

Design

These heaters consist essentially of a flat chest with bottom and sides insulated either by wood shavings between two sheets of isoral (small model) or by cork panels between two thicknesses of boards (large model). The shallow metal water tank with blackened face is placed in this chest. The chest is closed by a glazed frame that transmits the sunlight. It is supported on three feet, two in front and one in back, and is so inclined that the incidence of sunlight is normal at the time of the equinoxes; the angle of inclination may be varied by adjusting the rear foot, which consists of a tube sliding in a casing.

The storage tank in the large model is made of commercial corrugated galvanized iron. The corrugations are spaced 75 mm apart, with depth of 18 mm between crest and trough. The corrugations impart additional rigidity to the walls, which tend to deform under the action of the temperature rise. Four threaded rods with nuts maintain the distance between walls in the central and lower portions. The metal sheets are welded at their ends to a flat galvanized iron wall, and are so arranged that the troughs of the corrugation of one wall are directly opposite those of the other.

The storage tank in the small model is made of sheet zinc and the separation in this case is also maintained by cross-pieces.

A short header for filling is provided at the upper part of the tank, and a second header at the same level lets out the air.

Dimensions

The small model has a single glass pane, 50 × 70 cm, in front. The flat heating tank has the same surface area and an inside thickness of 45 mm, giving a capacity of about 16 litres. The glazed box is 56 × 75 × 11 cm, in outside dimensions. As already mentioned, it is supported on three legs. The rear leg is adjustable. The complete heater weight 21 kg (empty).

The large model is mounted on a frame with four glass panes, each 40 × 60 cm. The insulated surface is 9 600 cm², the water volume 53 litres, and the glazed box is 92 × 133 × 20 cm in outside dimensions. The total weight of the heater is 72 kg (empty).

The relation between exposed area and volume of water heated is 48 l/m² for the small model, and 52 l/m² for the large.

The water is heated gradually, beginning in the morning. Its temperature rises at first in the upper part of the tank, gradually reaching its maximum towards 3 or 5 p.m., according to the season, and then slowly declines.

At all times, there is a vertical gradient of water temperature, since the water is naturally at the

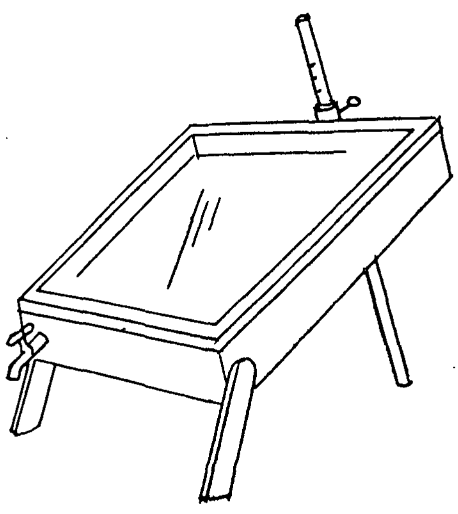

Figure 1

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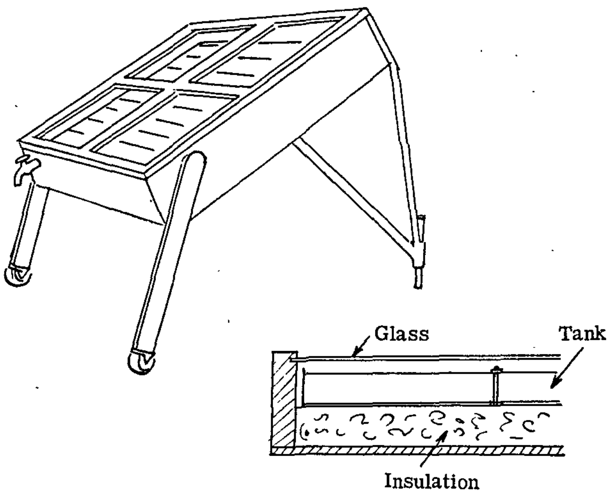

Figure 2

lowest temperature near the base. The water is withdrawn for use at a level about quarter of the way up. From this level, an inside tube conducts the water to a faucet at the base of the heater.

Cost

It is difficult to estimate the production cost of these heaters, since the prototypes were built by hand by artisans. For the large model, the material (in 1961) costs about 80 to 100 NF, and for the small model, 40 to 50 NF. The labour cost must be added to this figure.

Performance

According to the season and the state of the sky, the temperature of the hot water varies. It is usually over 60°C. Figure 3 shows the water temperatures attained by the large model on certain days of February, April, May and June. The water tem-

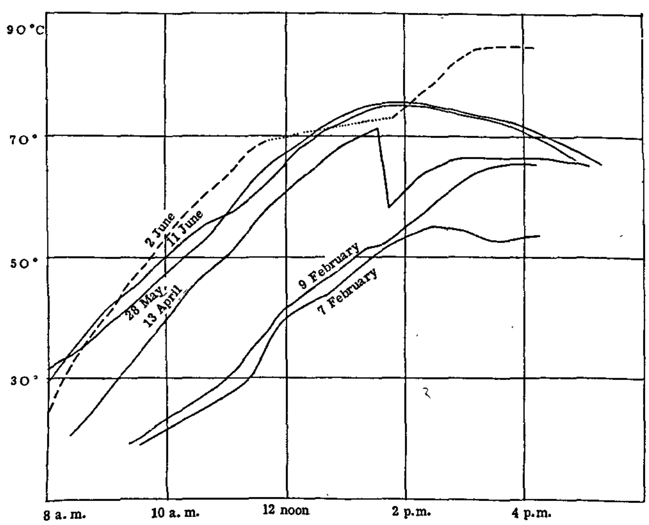

Figure 3

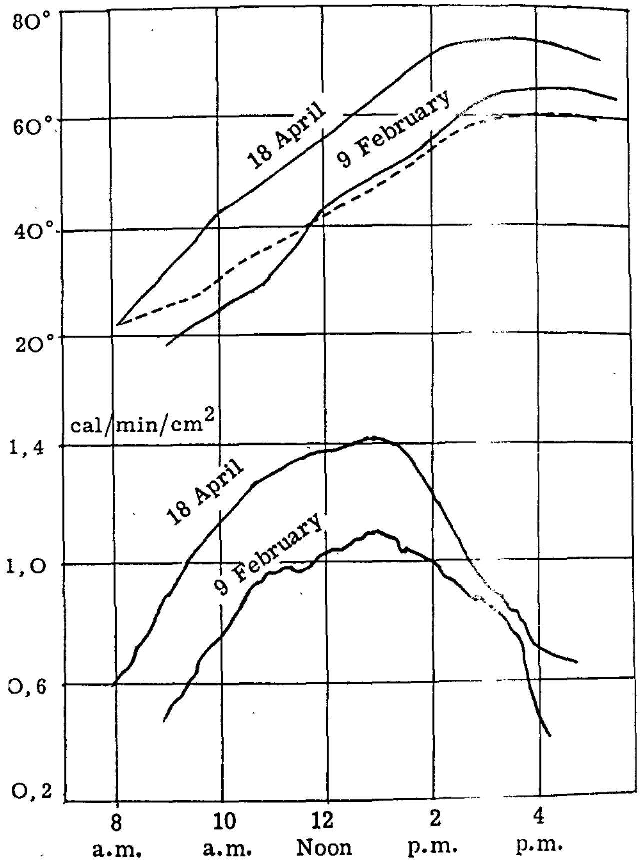

Figure 4

peratures for the small model are remarkably close to these values, within 1 or 2°. These curves were obtained at Algiers (36° N lat.) with the heater in fixed position (glass pane normal to the meridian plane and substantially normal to the direction of the solar radiation at noon). The curve of 2 June, however, corresponds to an orientation adjusted by hand about every hour (except from 12 to 1.45 p.m.). It will be seen that the water temperature can be very appreciably increased by this procedure. On 13 April, 25 litres of water were drawn at 1.30 p.m. at a mean temperature of 53°C, showing that the temperatures of figure 3, taken 5 cm below the upper level of the water in the tank, do not give the temperatures of all the hot water available. Twenty-five litres of cold water were then filled in. During the next two hours the temperature rose another 9°.

Figure 4 gives the measurements on 9 February and 18 April. The solid lines for these days show the temperature at the top of the tank (as also in figure 3). The dashed curve shows the temperature of the first decilitres drawn from the faucet on 18 April (atmospheric temperature 20 to 23°C). The temperature of the entire amount of hot water available is intermediate. At 5 p.m. 40 litres of water at 66°C were drawn. On the average, the temperature of the available water is 5 to 6° lower than that of the curves of figure 3. Figure 4 also gives the measurements of the solar heat, taken on a solarigraph with its receiving surface parallel to the glass panes of the collectors. The efficiency of the heaters may be calculated as follows. The heat received by the collector glass from 8 a.m. to 3 p.m. on 18 April was 4 460 kcal. To heat 50 litres of water from 21 to 66°C took 50 × 45 = 2 250 kcal. The efficiency is thus about 50 per cent.

Conclusion

Portable low-cost water heaters can be built and installed in Algeria, where climatological conditions are especially appropriate for this method of harnessing solar energy.

Summary

Solar water heating for domestic purposes is economical in Algeria, where there are many sunny days. Commercial models comprising a solar collector, a tank, and sometimes electrical stand-by heating facilities are on the market, but at high prices.

The design of small, simple and cheap heaters is investigated, and several prototypes studied. The hot-water output of these heaters is determined for various seasons. The author shows that a relatively inexpensive installation will provide a reasonable amount of water for laundry and cooking.

SOLAR WATER HEATERS

R. Sobotka *

Solar water heaters were first offered for sale in Israel (by Miromit) only six years ago. During the short period since then, the solar water heater has become a widely used and very popular means of heating water for homes, hospitals and industry. There are many thousands of solar water heaters in use in Israel (the writer estimated that there are 10 000).

In analysing the advantages and attractions of the solar water heater, the first consideration is the fact that of all our primary sources of energy — coal, oil, gas, wood and nuclear energy — solar energy is the only one which need not be produced, mined or processed. Solar energy flows in an unending stream for millions of years towards the earth. Though its concentration is low, the total amount is immense. The fact that there is no investment necessary for its production, processing and transport to the site of its use reduces the cost of the investment necessary for exploitation and conversion.

By comparison, in the use of coal or oil the cost starts with prospecting, test drilling, buying the land, or obtaining a concession, followed by drilling, mining and pumping, transport, refining, and finally distribution to all parts of the world by pipelines, tankers, trucks and rail.

Only the enormous quantities and the subsequent streamlining and mechanization of all stages of production processing and distribution have brought the price of oil, coal and gas within reasonable limits. It is quite obvious that the production of mass-produced solar collectors can be just as cheap and efficient as that of other modern appliances, such as radios or refrigerators. The stress is on the word "mass-production", as this has never taken place.

Cost

At present, the relative figures for the cost (in U.S. $) of a kWh produced by oil (generated electricity) or solar collectors (Miromit with selective black) are as follows:

Average cost per kWh of electricity	$0.03
Cost of installed solar collector 1.5 m² net surface	$
(retail price)	70
Interest (5 per cent) for 8 years	28
Maintenance	16
TOTAL	114

The assumed operation of the solar collector is for 300 days per year at 4 kWh per day = 1 200 kWh per year or 9 600 kWh in eight years.

$$\text{Cost per kWh} = \frac{\$114}{9\,600} = \text{aproximately } \$0.012, \text{ i.e. } 1.2 \text{ cents}$$

The comparison ($0.03 to $0.012) shows that even at the present high cost ($70) of a solar collector, the break-even point is reached after 3 1/4 years. If the cost of electricity is more than $0.03, which is the case in many of the less developed countries, the cost of the solar heater will be recovered within one to two years.

The present cost of a solar collector can be itemized as follows, and it can be shown that methods can be applied that will reduce the price drastically. The approximate figures are based on an Israel-made (Miromit) collector and do not include local purchase taxes.

	$
Material for 1 collector (1.75 m × 1.00 m), including glass	26
Labour (manufacture)	18
Transport and handling	8
Overhead, distribution, installation, and promotion and profit	18
	70

The above shows that the cost of manufacture is approximately 63 per cent of the retail price. The production cost can be reduced to approximately $20 for material and $10 for labour if modern mass-production methods are used. The transport, sale, distribution and installation will be much cheaper as well, if the number of units produced and sold is increased.

With $30 as the manufacturing cost, a unit (collector) can be sold (including installation) for $40, with a retail margin of 33 per cent that will cover overheads and distribution. The results will be even more favourable if better production methods and better materials are used, ensuring a longer life-span of approximately twelve years. This is not too optimistic when compared to the success of similar products like cars, refrigerators, air-conditioning units, or gas ranges.

Consequently, the costs can be adjusted as follows:

	$
Cost of collector	40
5 per cent interest on investment (12 years)	24
Maintenance for 12 years	24
	88

* Managing Director, Miromit Sun Heaters, Ltd., Tel-Aviv.

Output in twelve years will be 12 × 1 200 = 14 400 kWh.

$$\text{Cost per kWh} = \frac{\$88}{14\,400} = \quad \text{approximately} \ldots \quad \$0.006$$

At $0.03 per kWh electricity, this would be a saving of $36 per year, on an initial investment of $40. In other words, mass-production would very probably reduce the price of solar energy to *one-fifth* of that of electrical energy.

At the present stage, the reduction of the price of solar water heaters is not a scientific problem, but rather a technological, promotional and organizational problem.

Testing

An industry in its early stage has to reinvest large sums in development. It was necessary to measure the output efficiency of the solar collector and to register its performance over a period of several years. The effect of minerals contained in the water had to be observed and the problem of clogging-up of pipes solved.

The method of testing the performance of the solar water heater should, as nearly as possible, duplicate normal working conditions.

We connected one Miromit solar collector of 1.5 m² net collectors plate surface to a storage tank of 120 litres (32 U.S. gal). The storage tank, being in excess of the optimum output of the collector (approx. 5 000 kcal/day), will store almost 100 per cent of the heat output of the latter. Connections between collector and tank are as short as possible and well lagged. The flow of the thermosyphon is adjusted to a maximum temperature of 65°C (150°F) by a hand-regulated valve in the hot water return pipe.

At the end of the day (5 p.m.), all the water is drained from the insulated tank and for each 5 or 10 litres, the temperature is registered. The difference between the temperature of the cold water in the supply line, and the registered temperature will give the heat gain in kcal for each 5 or 10 litres. The total daily heat output of the unit will be the total of all sums.

Such tests have been performed by us during 14 months on two or three parallel and identical units. The results showed an interesting pattern. In summer (June-September) with solar radiation of 5 000-7 000 kcal/m² and water output temperature of 60 to 65°C (150°F), the efficiency of conversion is approximately 35-45 per cent, while in winter (December-March) with lower insolation (3 000-4 000 kcal/m²) and slightly lower water output temperatures (50-60°C, 135°F), the conversion efficiency was 50-60 per cent.

This results in a levelling out of the annual collector output in relation to available insolation, which in Israel is approximately, in December, one-third of the maximum (July) insolation. Thus, to ensure an even level of performance, the unit must be built in such a way that it can adjust its operation automatically to higher temperatures in the summer. Another means of compensating for differences in insolation is the angle of inclination of the collector, which should be nearer to an angle of 90° in relation to the rays of the lowest winter position of the sun. A third factor which became apparent in Istrael during several years of experience is the function of the dust cover, in the summer months, as a filter. This is particularly important in countries, like Israel, without summer rains, where the first few rains at the beginning of winter will wash off the dust and therefore raise the output during the shorter and colder winter days.

Use of selective black

The introduction and use of selective blackened surface for our collectors in 1959 improved the performance and solved some of our problems.

We know now that selective blackened collector plates are superior not only in their optical properties,

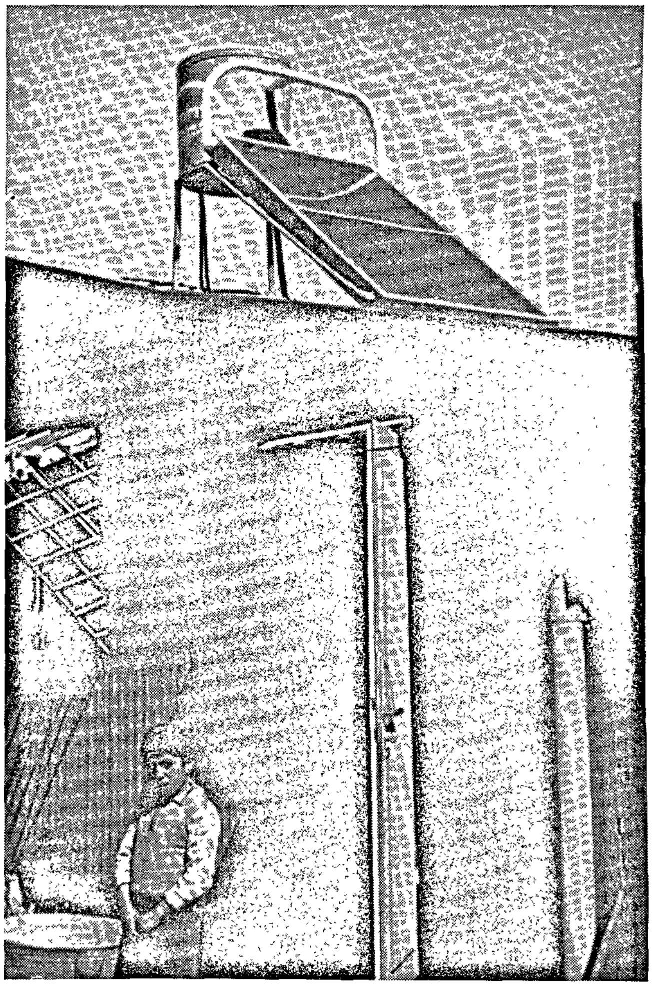

Figure 1. The smallest solar water heater unit used in Israel — a 120-litre storage tank with one collector. This unit is used for homes without bathtubs; hot water is used only for dishwashing and showers

but in many other respects as well, which originally were not thought of, for example, the stability of colour, the possibility of cleaning such surfaces, and their resistance to high temperatures.

We originally had the problem of blackboard paint cracking, peeling, and flaking off after a few years, especially at higher temperatures on materials such as copper, aluminium, or galvanized sheets. In addition, ordinary black metal sheets showed rust from condensed humidity in the collector. The colour of blackboard paint became grey and lost a great deal of its absorptive properties. Since dull, sprayed, black paint does not yield a smooth surface, it is difficult to clean the dust which penetrates into the paint coat.

Other aspects

The complete absence of any waste products (smoke, ashes, gas), fire hazards or personal danger is an advantage and makes the use of solar water heaters possible where electricity, gas or oil could not be safety employed.

In homes with children or in wooden buildings or primitive dwellings, the absence of fire, gas or electricity eliminates many hazards.

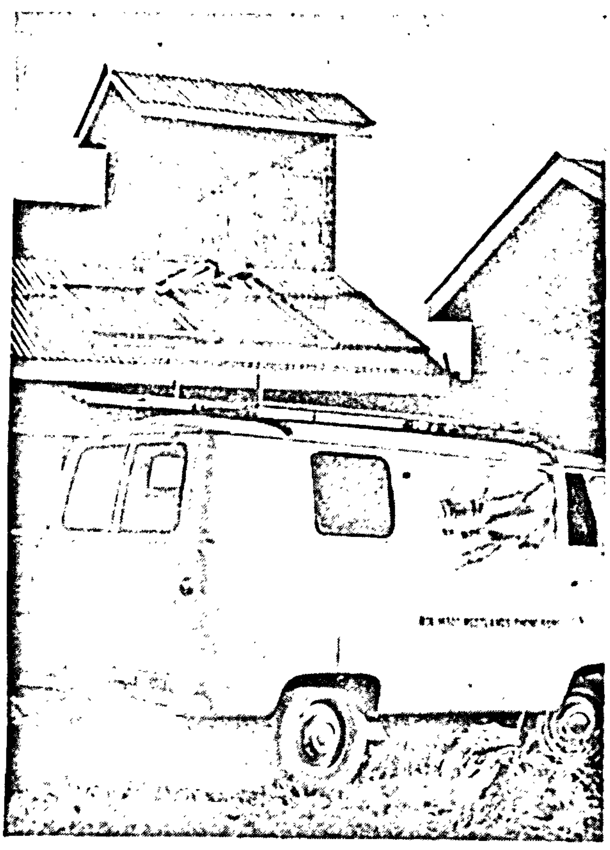

Figure 2. A solar water heater installed at the building of the Ministry of Works in Isolio, Kenya. The storage tank is in the tower. Capacity is 200 litres

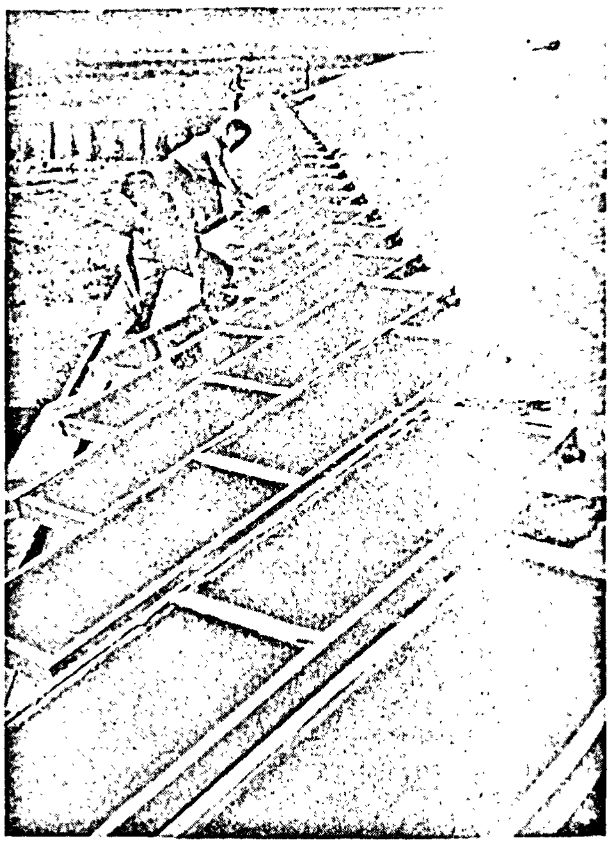

Figure 3. Roof of a hospital building, on which 40 collectors are installed. The collectors are not yet connected. Each group of 10 is connected to one 500 litre boiler. The four boilers are distributed over the whole length of the building, in order to shorten the hot water pipes

There are countries where the fire hazard during dry seasons is so great that open fires are forbidden by law. In other countries, primitive dwellings are not connected to the electric system because of distance or of danger to a primitive population. Apart from complicated and expensive automatic oil burners, there is no way to heat water for homes, without the need for constant care, maintenance, and supply of gas, coal, oil or wood. Even the use of electric boilers, which is today probably the most widely used method of heating water, is limited in most countries to certain hours of use.

Foreign experience

Much data and information has been collected by us during the last two years about the habits and demands of people in many countries. The writer has visited fifteen countries in southern Europe and Africa in order to sell and promote the use of solar water heaters. Moreover, it was then possible to study the specific problem in each of these new, mostly under-developed, countries.

While the standard size electric boiler in Israel is 120 litres (figure 1), only an 80-litre boiler is used

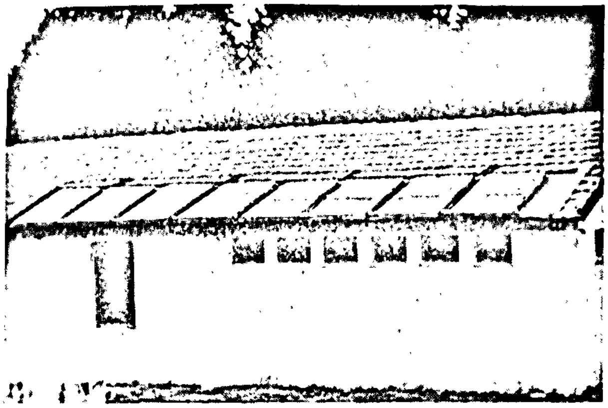

Figure 4. Installation of eight collectors which are connected to two 300-litre boilers. This section of the roof is part of an installation of six such units, each installed over the washroom of an agricultural college. The whole unit has a capacity of 10 × 300 litres, or a total of 3 000 litres with forty collectors

in Cyprus, Greece, Portugal or Spain. On the other hand, the hours of the day in which hot water is in use varies, and it is therefore important to know these hours for the planning of a hot-water system. In some countries, it is customary to bathe in the afternoon (Israel, Italy, Nigeria, Ghana), while in other countries, because of different working hours, hot water is mainly in use during the mornings (Portugal, Spain, Kenya, South Africa) (figure 2).

For the planning of the storage capacity, such habits and local demands must be considered. Another important factor is the local meteorological condition, such as the morning cloud cover in many African cities like Leopoldville, Luanda or Lagos. Little exact data is available at the moment about solar radiation and clouds. For Congo (Leopoldville, Stanleyville and Elisabethville), such records exist and were published by the Congo Meteorological Service.

For many new nations, the use of solar water heaters will not only relieve the need to import coal, oil, or gas, but it will change the way of life and hygienic habits of millions of people. All new Governments in so-called solar regions must recognize the great possibilities for their countries and economy.

The writer believes that solar water heaters have reached a new and possibly critical stage. A full and correct recognition of its potentialities, particularly by Governments and people in solar countries will inaugurate the following stage. They will then be mass-produced and popularized in all countries that have favourable climates and in countries that import gas and use oil for electric generation. In a modern community, the electricity or gas consumption for water-heating represents at least 50 per cent of the domestic energy consumption, and by saving this, it can be made available for industry and agriculture (pumping at night). In Israel, solar water heaters will supply 90-95 per cent of the domestic hot water requirements of a normal household, and the additional 5 or 10 per cent for electricity will represent an *annual* expense of only $10. In somewhat less sunny countries like

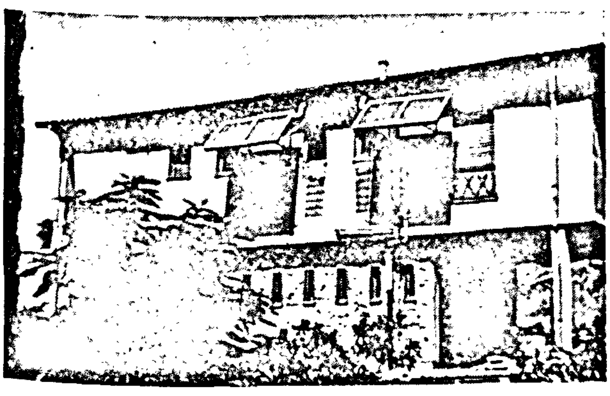

Figure 5. Two solar collectors mounted on the southern front wall of a villa. The storage tank is under the roof. Capacity is 200 litres

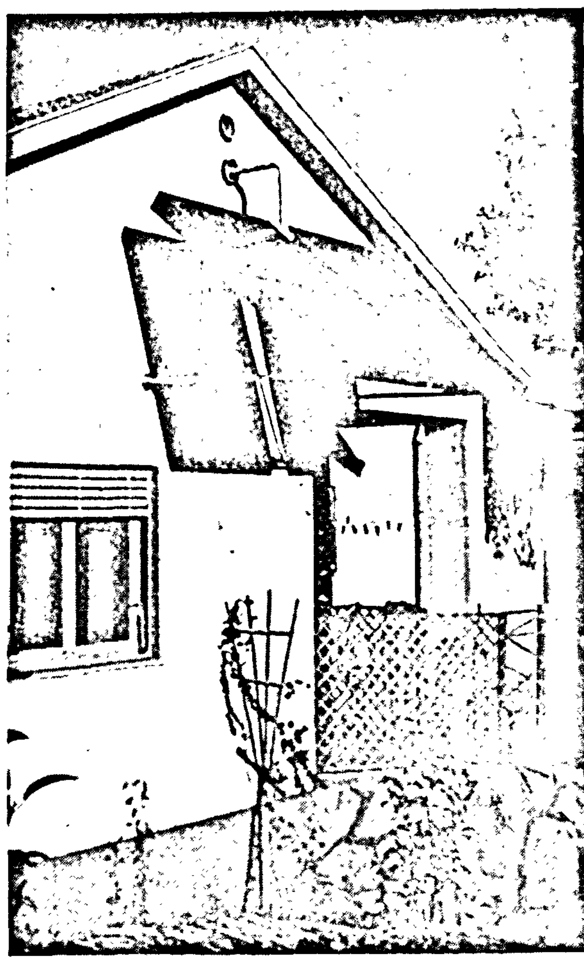

Figure 6. Two collectors installed on the wall of a house. The storage tank is behind the wall, inside the roof

Italy, Spain or Portugal, 70-80 per cent of requirements will be supplied by solar energy — still an economic proposition.

There are certain uses for solar water heaters in which efficiency is particularly high, for example in institutions or factories where the total quantity of hot water is needed and used at the end of the day. In such cases, the solar water heaters will operate during the whole day at their best, without any heat losses during prolonged periods of storage (at night). Since the period of insolation is shorter than the period without sun, losses during the time of storage are considerable, usually 20-25 per cent during 10-15 hours. Solar water heaters were installed at service stations, factories and at an agricultural school for showering after work (4 to 6 p.m.), with excellent results and at a relative low initial investment. The same can apply to army camps where the hours of use can be controlled.

Large installations

The writer's firm has planned and installed many large solar water units, such as a 2 000 litre (500 gal) unit with 40 collectors for a hospital (figure 3) and a 3 000 litre (750 gal) unit with 50 collectors for the washrooms and showers of an agricultural school (figure 4).

The possibilities of planned, integrated solar roofs of 100 sq m or more, open up architectural and engineering possibilities and further the reduction of cost. In such cases, the collector plate and pipe system can be mass-produced, but the costlier elements — box, insulation and glass cover — can be planned to be part of the roof. For such installations, the use of pre-fabricated components of asbestos cement might be suggested.

This report would be incomplete without discussing the cost and problems of installation of solar water heaters. Four years ago, when the first solar water heaters were installed in Israel, it took two to three workers 8-10 hours to install and connect a unit with two collectors on a flat roof. The installation

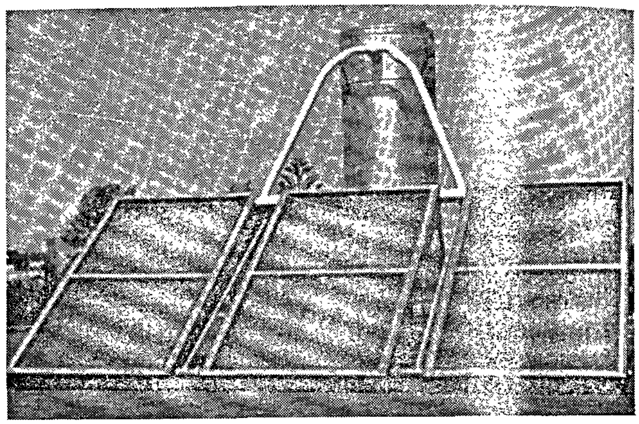

Figure 7. Unit with three solar collectors and storage tank of 300-litre capacity. The unit stands on a flat roof

on a tiled sloped roof took even longer. In the meantime, many thousands of units have been installed, and today the installation of such a unit will take two workers 4 hours: 8 man-hours compared to 15-25. An installation on a tiled roof will take 12 man-hours. This shows how an operation that is not standard and repetitive can still be improved and made less expensive by better trained workers and better methods.

If solar water heaters were included in the original building plans and installed before the house is finished, the time for installation could be further reduced. At present, most solar water heaters are installed after the building is finished, which involves separate transport, lifting and connecting of the units.

Further efforts will be directed towards designing a solar collector for the lowest price and longest life-span. The writer is certain that a price of \$30 per m² and a life-span of 12 years and more will be reached within 3 years. The shortest and most realistic approach towards this aim is to sell more and to produce a less-expensive product, which, in turn, will lead to even wider distribution.

Summary

Ten years of experience in the practical and commercial use of solar water heaters have shown the many advantages over other systems of water heating. Means of transportation, pipelines or wires are not necessary to bring solar energy to the place of use.

The cost of solar energy already compares favourably with electricity or gas, and mass-production will reduce the price further. Cheaper and more modern ways of manufacture will be possible if the sale and promotion of the use of solar energy is accelerated in all countries within the solar belt.

Tests have been made under actual working conditions, and the operation of solar water heaters in Tel-Aviv, Johannesburg, Nairobi, Lisbon, and many other places, has been observed. Various improvements that balance the output from season to season have been introduced.

Several thousand selective blackened collector plates have been installed and tested under various conditions in several countries and greatly different climatic conditions. The results have been excellent and most promising.

Solar water heaters (manufactured by Miromit Sun Heaters Ltd.) have been manufactured under licence or exported to more than twenty countries. The local customs and habits of the population have been considered in planning the size of storage tanks

and in the installation of the collecters. The solar water heater will influence the way of life in many under-developed areas where the use of hot water for domestic purposes is at the moment very limited or unknown. The introduction into such markets, by the gradual importation, assembly, and, eventually, the local manufacture of licensed solar water heaters will be the aim for the next few years.

The experience gained in the planning, manufacture and installation of solar water heaters in Israel and many other countries enables us to be very optimistic about the future expansion of markets.

The volume of future sales will be the main factor in the decision to use mass-production methods, and if used, they should lower the price of solar water heaters by half.

LES CHAUFFE-EAU SOLAIRES

Résumé

Dix ans d'expérience des applications pratiques et commerciales des chauffe-eau solaires ont montré que ces appareils présentaient nombre d'avantages par rapport aux autres systèmes de chauffage de l'eau. Ils permettent de se passer de systèmes de transport, de pipelines ou de réseaux de câbles et fournissent l'énergie solaire à pied d'œuvre.

Le prix de revient de cette énergie solaire peut déjà soutenir une comparaison favorable avec l'électricité ou le gaz, et il sera encore moindre quand les appareils nécessaires seront produits en grande série. On pourra mettre en œuvre des moyens de fabrication plus économiques et plus modernes si la vente et les campagnes en faveur de l'utilisation de l'énergie solaire sont intensifiées dans tous les pays de la zone ensoleillée du monde.

On a procédé à des essais dans des conditions de travail réelles et on a observé le fonctionnement de chauffe-eau solaires à Tel-Aviv, Johannesburg, Nairobi, Lisbonne et nombre d'autres lieux. On a adopté diverses améliorations visant à égaliser le débit d'une saison à l'autre.

On a installé plusieurs milliers de plaques de collecteur sélectives et on les a soumises à des essais dans des conditions diverses, dans plusieurs pays et sous des conditions climatologiques très variées. Les résultats ont été excellents et sont riches en promesses.

Des chauffe-eau solaires (fabriqués par Miromit Sun Heaters, Ltd.) ont été construits sous licence ou exportés vers plus de vingt pays. Il faut tenir compte des coutumes locales et des habitudes de la population quand on étudie les dimensions des réservoirs et le mode d'installation des collecteurs. Le chauffe-eau solaire aura des répercussions sur la manière de vivre de la population dans nombre de pays sous-développés où l'emploi de l'eau chaude à des fins ménagères est actuellement très limité ou inconnu. L'introduction de chauffe-eau solaires sur ces marchés qui se fera par leur importation progressive, leur montage et, enfin leur fabrication sur place sous licence, représente l'objectif des quelques années à venir.

L'expérience acquise dans la création, la fabrication et l'installation de chauffe-eau solaires, en Israël et dans nombre d'autres pays, nous donne lieu d'être très optimistes quant aux possibilités d'avenir des marchés.

Le volume des ventes à venir sera le facteur principal qui motivera la décision d'avoir recours aux méthodes de la production en série et de ramener le prix du chauffe-eau solaire à la moitié de ce qu'il est aujourd'hui.

RECENT DEVELOPMENT OF SOLAR WATER HEATERS IN JAPAN

Ichimatsu Tanishita *

The major part of Japan, except Hokkaido, lies between 30° and 40° N lat. The climate, therefore, is very temperate and the amount of sunshine yearly is great enough throughout most of the country to permit its utilization. In this respect, Japan, like the southern part of Italy, the Soviet Union and the United States, is one of the most favoured places among the industrialized countries for the utilization of solar energy.

Because the climate of Japan is very wet, especially in summer, Japanese people like to take baths, and this requires the use of a rather large quantity of fuel, the cost of which is comparatively high. In general, the homes of ordinary Japanese people do not have the apparatus to supply hot water; they do have bath tubs with furnaces, however, or else they go to the public baths. These conditions make it evident that Japan is most suited to spread the use of solar water heaters to homes throughout most of the country. In fact, the total number of solar water heaters used in Japan recently increased beyond expectation.

It was found, through an investigation by the agricultural authority of the Japanese Government, that the number of solar water heaters used in farmers' houses alone amounted to about 180 000 in August 1958. The total number of solar water heaters in use in Japan is believed to have amounted to about 200 000 at the end of 1958, about 250 000 at the end of 1959 and about 350 000 at the end of 1960. At the same time, it is estimated that about 80 000 solar water heaters were produced in 1959 and about 150 000 in 1960. Formerly, most of the makers of solar water heaters in Japan were small factories in the towns, but recently some big companies, have been considering producing solar water heaters in their factories. Thus, it is not an exaggeration to say that the total number of solar water heaters will increase to one million, with the result that more than one million tons of fuel will be saved yearly within 3 or 4 years.

The various kinds of solar water heaters now used in Japan are the open type, closed type, closed-membrane type, natural-circulation type, and once-through type, of which the closed-membrane type is the cheapest and the one used in largest number, followed by the open type and the closed. The natural-circulation type is not used in large numbers now, but the writer believes that its use will increase in the future.

As there are a large number of public baths in Japan, it is hoped to use solar water heaters in this field too.

Open type

The principle of the open-type solar water heater lies in the fact that if water is poured into a basin and put in the sunshine, the water is warmed. This type of solar water heater was first used in a farmer's house in Japan about 15 years ago; its use has now spread throughout most of the country.

Figure 1 shows the open-type solar water heater formerly used; the width is about 0.9 m, the length, about 2 m, and the depth, about 0.15 m. The inside of the bottom and side surfaces is covered with black vinyl membrane and the upper surface is covered with glass plate; it is filled partially with water, to a depth of about 0.11 m. Because this type of solar water heater is simple in construction, being very easy to make and to repair, and is low in price (about $20), its use spread widely, especially in agricultural districts. The total number of these solar water heaters now in use appears to be about 150 000. The life-span of this type of heater is about ten years.

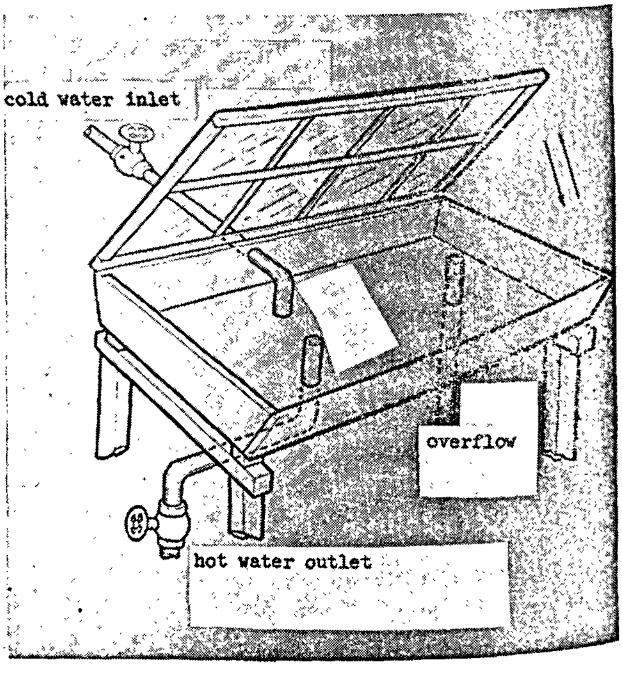

Figure 1

* Keio University, Tokyo.

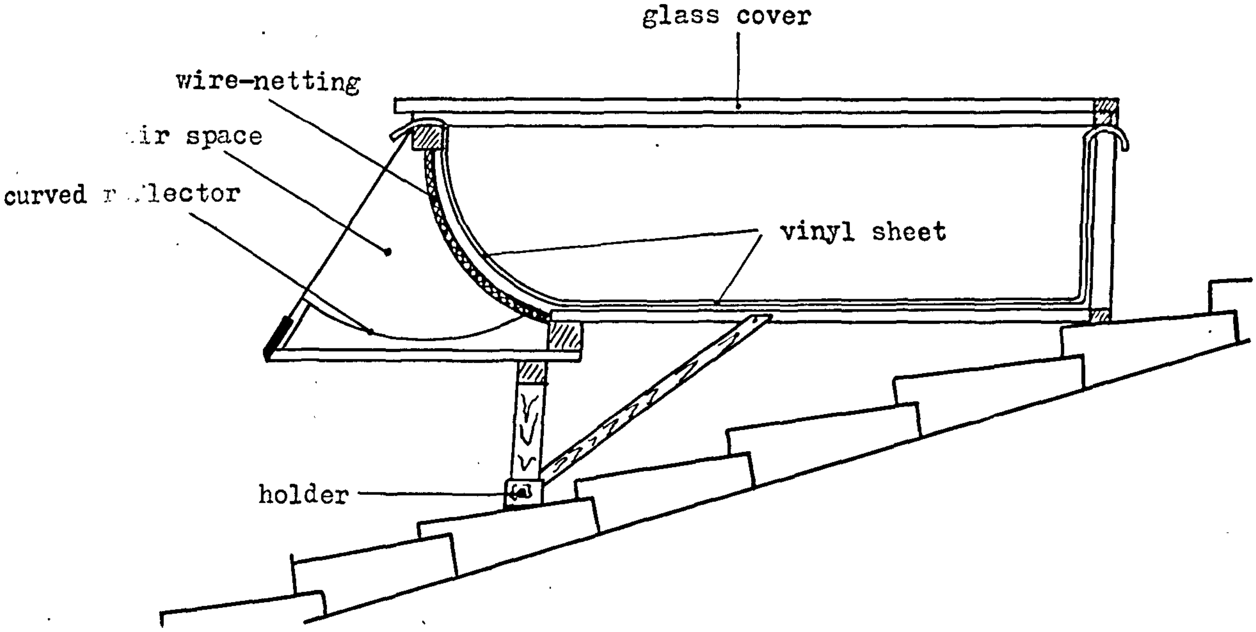

Figure 2

Figure 2 shows a new type of solar water heater which was an improvement over that shown in figure 1. These heaters are usually placed on an inclined roof surface facing south. The southern side face of the heater box is made of wire netting and a reflecting surface made of aluminium foil is placed in front of it. The inside face of the heater box is covered by black vinyl membrane to hold water, and the reflected rays pass through the wire netting to the vinyl membrane and heat the water. Thus the new open-type solar water heater utilizes more solar energy than the ordinary open-type heater. The test results of this new open-type heater on fine days are as follows :

Month	*Maximum temperature attained*
January	33°C
February	38°C
March	45°C
April	62°C
May-August	69°C
September	62°C
October	45°C
November	38°C
December	33°C

The area of this water heater is 0.9 m × 2.0 m and the water capacity is about 180 litres.

Figure 3 illustrates another open-type solar water heater produced by a different firm in Tokyo. It is the same in principle as the one shown in figure 1, but differs in detail. It is constructed of wood and plastics without using any metallic part. The inside face of the heater box, the dimensions of which are 0.74 m × 2.7 m × 0.15 m, is covered by a polyethylene film about 1 mm thick. Water is let into this box to a depth of 0.11 m, and it is covered by a thin transparent polyethylene film above the water surface. The life-span of this solar water heater is considered to be very long, because the 1 mm thick polyethylene film is very strong and hardly ever breaks. All the material is packed in one package and is sold for $17.5. It is very easy

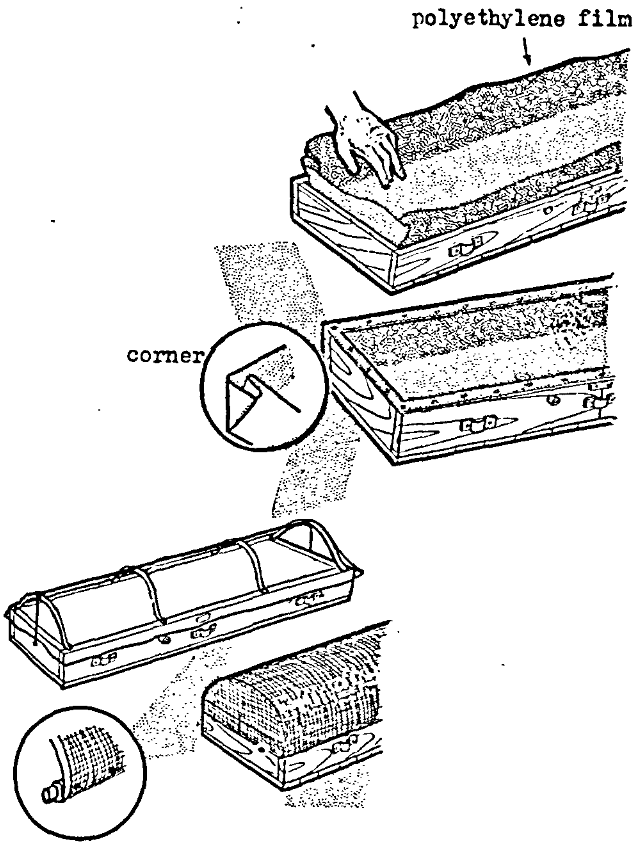

Figure 3

to assemble with simple tools. A total of 1 650 of this type of solar water heater was produced in 1960, but its production will probably be increased in 1961.

Closed-membrane type

A simple closed solar water heater made of vinyl film in the form of a water pillow appeared as early as 1955, but at that time, solar water heaters were not yet appreciated, so that it was not much used and it disappeared for a time. But, recently, solar water heaters have reappeared and become more popular and have spread rapidly over almost the whole country. This is due mainly to their low price and also to a good system of selling them. More than half of the solar water heaters now in use in Japan are of this type.

The standard size of the closed-membrane type heater is 0.9 m in width, 1.8 m in length and 0.12 m in depth; it has the shape of a water pillow, and it holds about 200 litres of water. Both smaller and larger types than this are also used. Usually, the bottom surface is made of black vinyl membrane and the top surface of transparent vinyl membrane, but sometimes both the bottom and the upper surfaces are made of black vinyl membrane. The heat-absorbing effect is approximately the same in both cases, the former being somewhat superior. In the summer season, from April to October, it can be used, as indicated in figure 4, without covering; but it can be used in both summer and winter if it is covered by glass plate or transparent vinyl membrane (figure 5). Figure 6 shows the actual appearance of this type of solar water heater. It is sometimes given a corrugated top surface (figure 7), but in this case the price becomes higher than for an ordinary heater.

The price of the ordinary closed-membrane type heater is about $6 to $10 and it can usually last two years. Fuel many times this cost per year can be saved, and also the labour to burn the fuel.

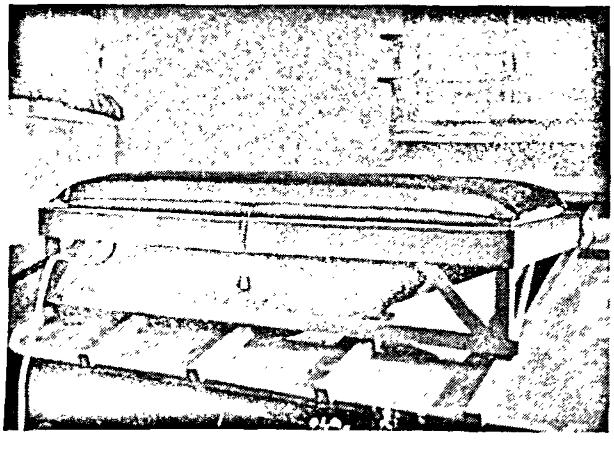

Figure 4

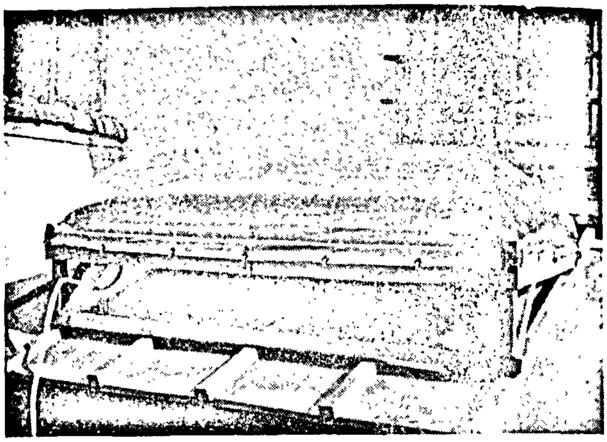

Figure 5

About 20 000 closed-membrane type heaters were produced in 1958, about 70 000 in 1959 and about 150 000 in 1960, of which about 100 000 were produced by one firm in 1960. The reasons for the rapid increase in number of this type of solar water heater are its low price and the ease of use and installation in individual homes.

Closed type

Open and closed-membrane type heaters must be placed horizontally, with the result that the heating effect in winter is very weak because the sun's rays decline in this season. By contrast, the closed-type heater is constructed so as to incline the heat-receiving surface to the south, to receive the strong sun rays. If this type of solar water heater were made of a thin, flat sheet of metal, the lower part of the heater surface would swell and break the glass plate which covers the heater surface. For this reason, the closed-type heater is usually made of pipes with a diameter of about 0.12 m. Figure 8 shows the popular closed-type heater of simple construction. Six circular pipes, made of thin sheets of aluminium or copper, with a diameter of 0.12 m and a length of 1.1 m, are arranged in a wooden box, 0.9 m × 1.2 m × 0.20 m. This box is covered by a glass plate. The lower part of the pipes is connected to the city water pipe through a valve, and a small bent pipe *b* is attached to the upper part of each pipe to overflow the water and wash the glass surface when water fills the pipes in the morning. As the quantity of water filling one box is about 80 litres, two or three boxes are jointly used for domestic bath use. In the morning, if valve *d* is closed and valve *c* is opened, cold water flows into the pipes from pipe *a*. Water flows out from bent pipe *b* and washes the glass plate clean after the pipes are filled with water. Then valve *c* is closed. The water in the pipes receives heat from the sun and attains maximum temperature at about 2:30 to 3:00 in the afternoon. The hot water is let down into the bath-tub in the evening. Figure 9 is a photograph of the solar water heater sketched

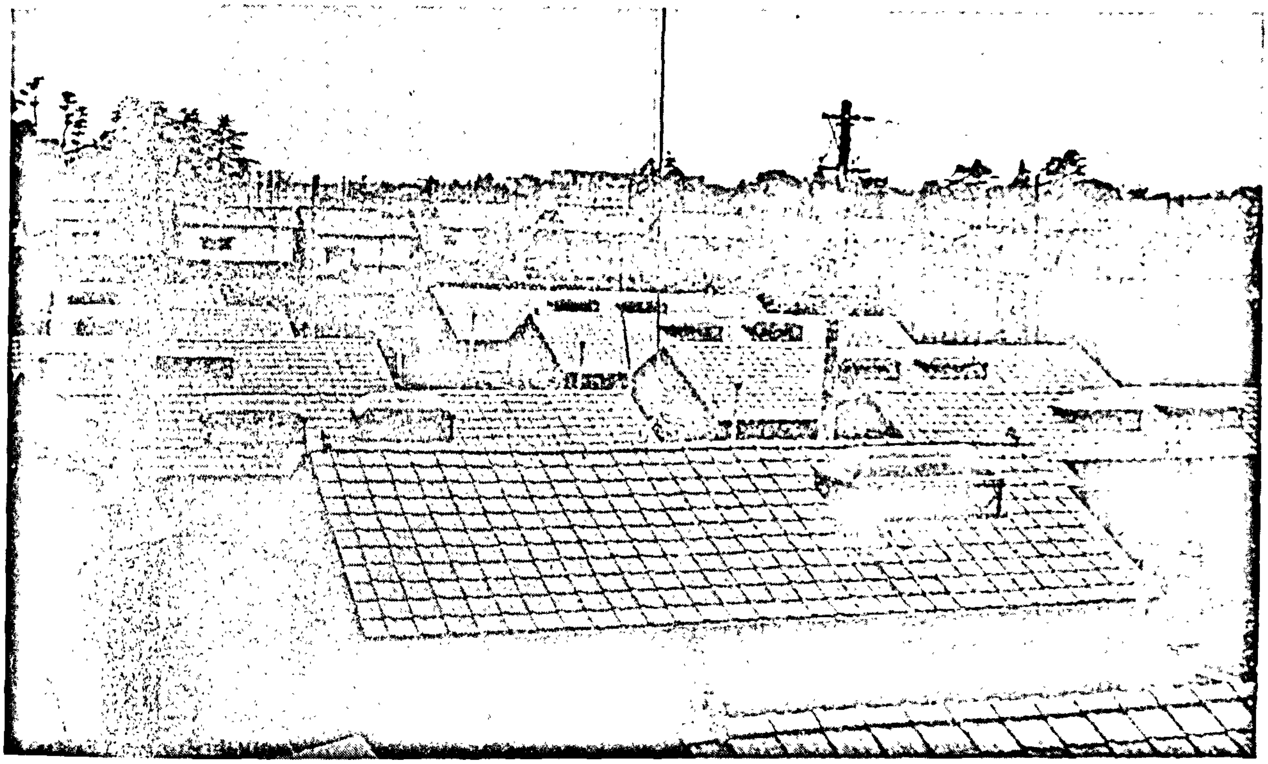

Figure 6

in figure 8. The price of this solar water heater is about $50 per box; thus that of 2-box heaters (water capacity, 160 litres) is $100 and that of 3-box heaters (water capacity, 240 litres) is $150.

Figure 10 is a modification of the heater shown in figure 9. A long pipe of comparatively small diameter is arranged zigzag in the lower part. This is suited to use for the washstand where the hot water is let out at times. Figure 11 illustrates the larger type of heater which is composed of four units of figure 10.

If the pipes are made of aluminium, the material sometimes corrodes and the water leaks out. The heater can be corrosion-proof if copper pipes are used; however, the price becomes high. Thus, recently, closed-type heaters made of glass pipes or plastic pipes have been tried. Figure 12 shows a special type of closed heater which is made of two galvanized iron plates of undulatory form and soldered to each other. To avoid corrosion, a plastic film is coated inside the iron plates. This heater has comparatively long life and low cost. Its dimensions are 0.915 m × 1.85 m × 0.27, it holds 175 litres of water, and it costs about $50. Its life-span is believed to be about 10 years.

The closed-type heaters do not have any tank and connecting pipe; they therefore have a minimum surface area and probably are most effective in the heating period until about 2:30 or 3:00 p.m. But, the whole mass of hot water is contained beneath the glass plate, from where the heat is radiated, and the hot water cools down quickly in the evening.

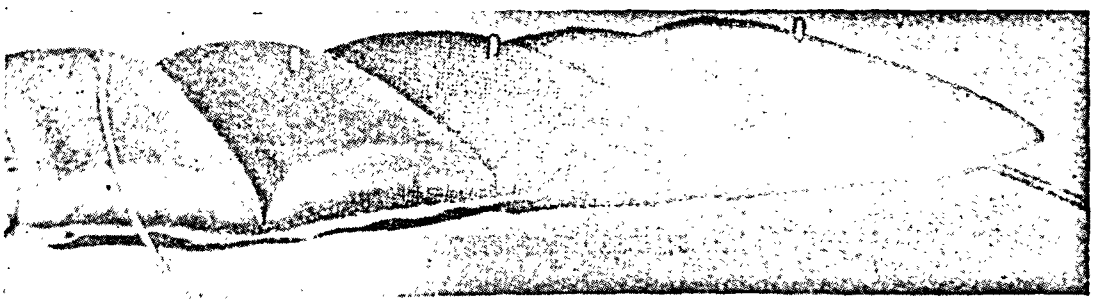

Figure 7

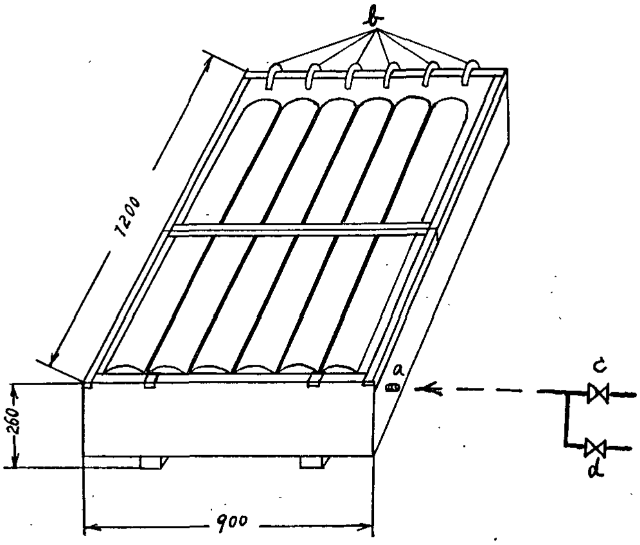

Figure 8

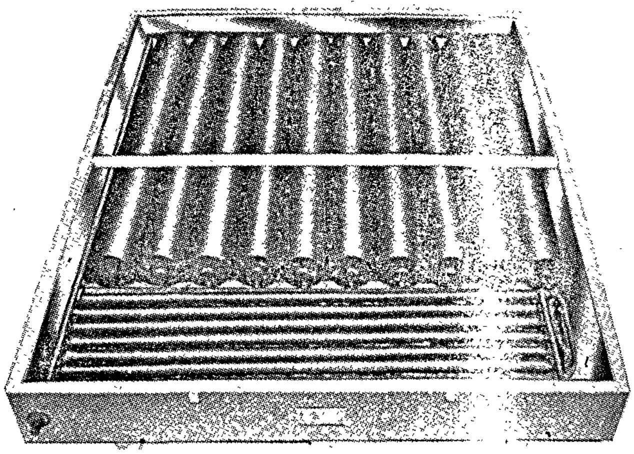

Figure 10

Therefore, the hot water must be let down into the bath-tub early in the evening and care must be taken not to let it cool quickly. Sometimes, a well-insulated separate tank is prepared and the hot water is let into this tank from the heater at about 3:00 p.m. Then the hot water from the tank can be used at any time.

About 50 000 closed-type solar water heaters are now used in Japan.

Natural-circulation type

The writer has constructed and has been testing the natural-circulation type of solar water heater since 1948, and some of the results have been previously reported (1). This type of solar water heater

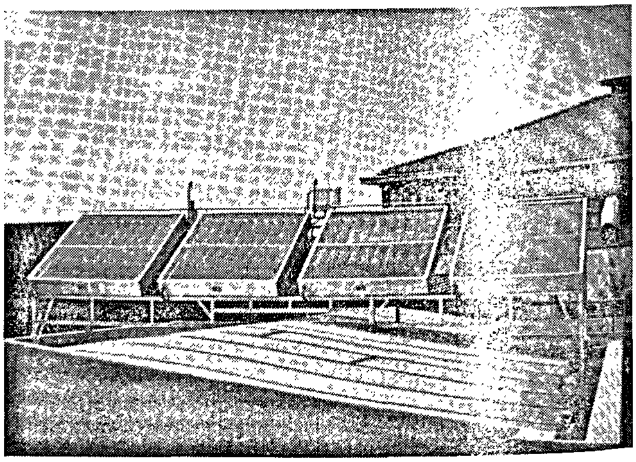

Figure 11

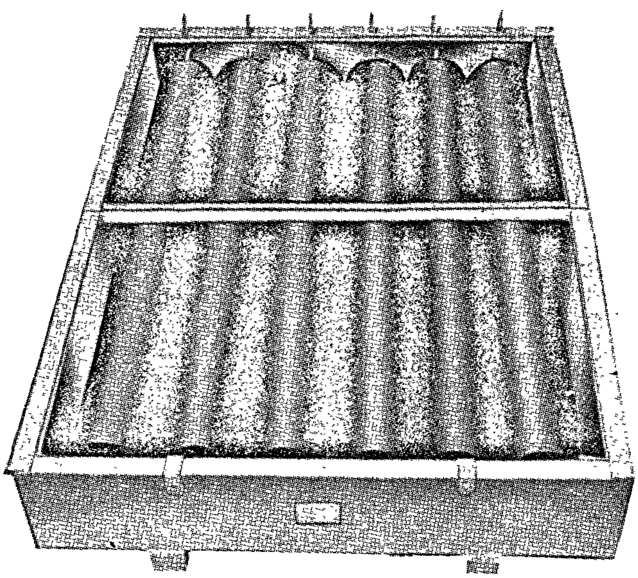

Figure 9

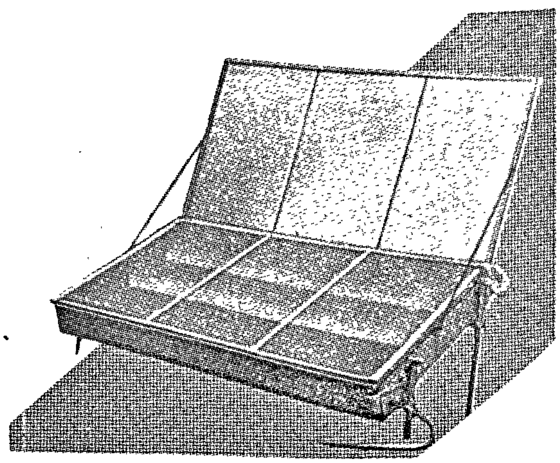

Figure 12

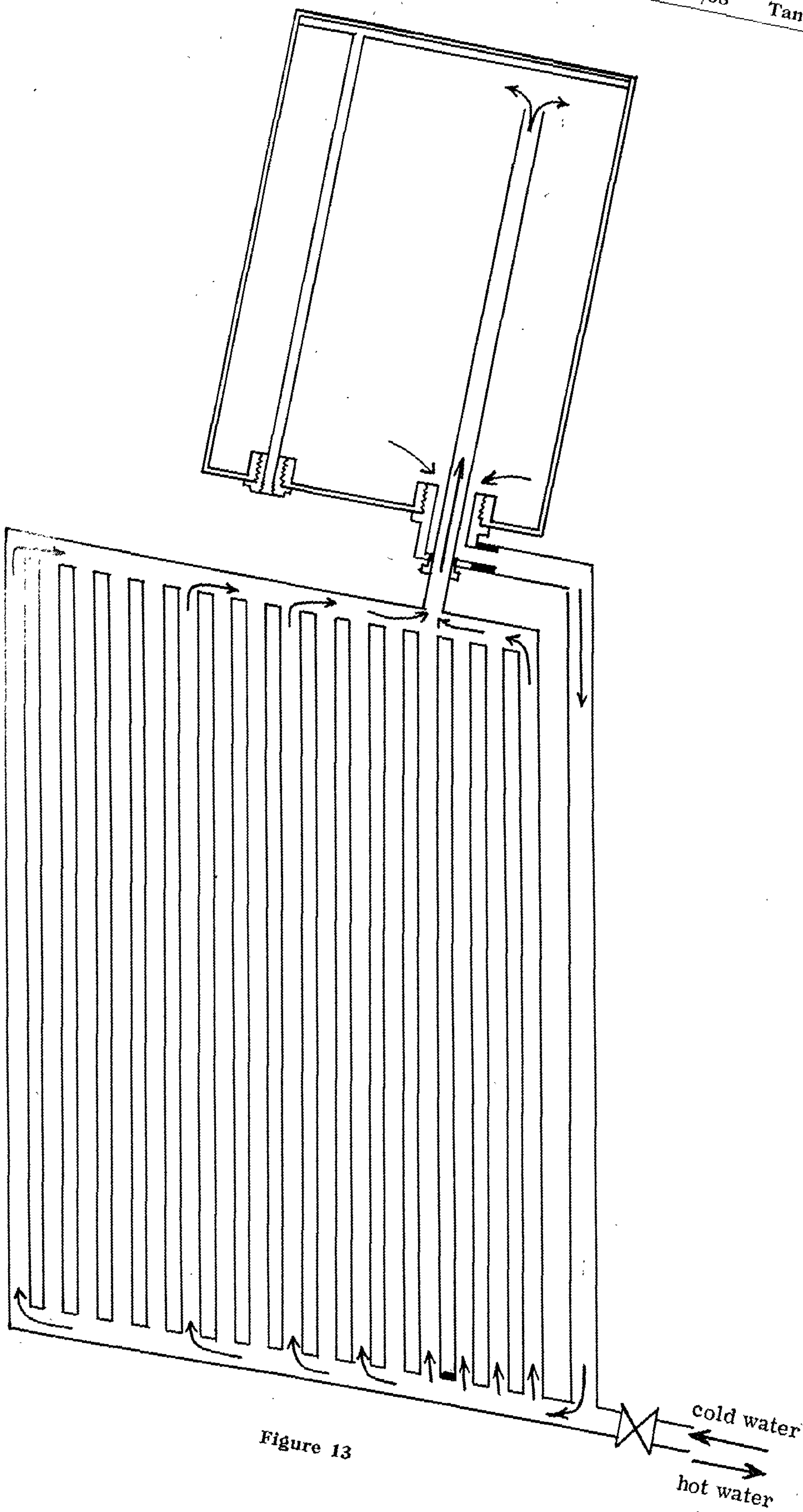

Figure 13

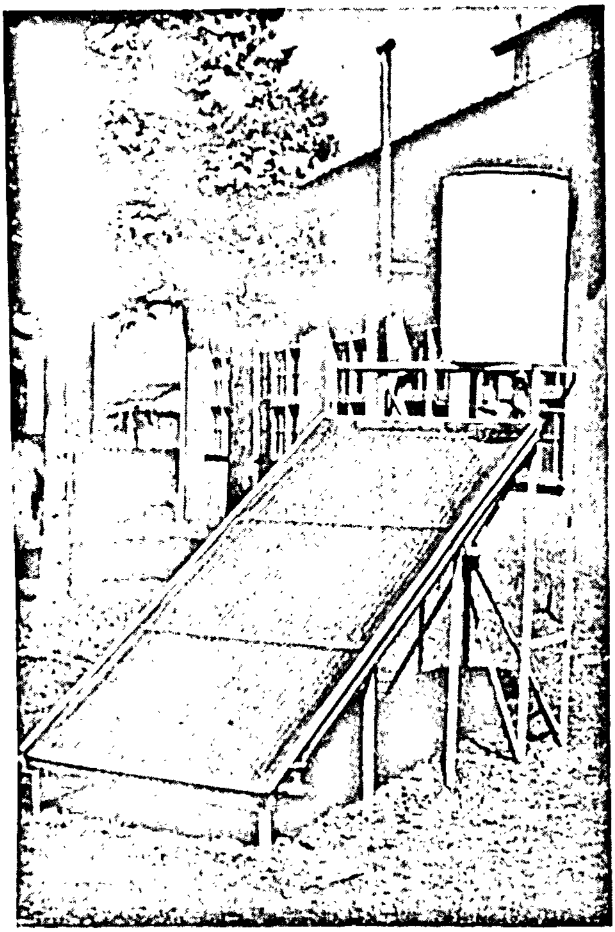

Figure 14

is not commonly used as yet in Japan, owing, among other reasons, to the fact that the price is comparatively high and that it is not easy to place the hot water tank on the roof. It is reported that, in Florida, in the United States, the hot water tank of the solar water heater on the roof was made to take on the appearance of a chimney. The appearance of the building is very important and the co-operation of the architects must be enlisted.

The writer has recently constructed a natural-circulation type heater (figure 13), with the hope of developing one that is simple and cheap, suited for common use.

It is not easy to connect upriser pipe and downcomer pipe between the hot water tank and the heater. The writer devised a method of pipe connection for this purpose (see figure 13). Usually, a drum is used as the hot water tank for a solar water heater of this type. The drum has two screwed holes, one large and the other small. A small joint *a* was screwed into the small hole, and a small pipe *b* was connected to it upward for air vent. A large joint *c* was screwed into the large hole, and pipe *d* was connected to it upward to take the role of the upriser of the hot water from the heater. The downcomer pipe *e* is also attached to the joint *c*. It may be said that the construction of the hot water tank and the piping between the tank and the heater is greatly simplified. But the circulation flow in this case is somewhat weakened by the heat transmission between the hot water in the pipe *d* and the cold water outside of it.

The heat-receiving pipes are made of iron and have an outer diameter of 20 mm and a thickness of 1.6 mm; the pitch of the pipe is 35 mm and both ends are welded to heater pipes with an outer diameter of 40 mm. After the welding, both the inside and the outside surfaces were galvanized. Figures 14 and 15 show two kinds of this solar water heater, a small one and a large one. The heat-receiving area of the large one is 1.2 m × 2.7 m, and that of the small one, 1.2 m × 1.8 m. The water capacities of both are almost the same. The price of the large one is about $120, and that of the small one, about $100, which is almost the same as that of the closed-type heater shown in figures 8 and 9. The life-span is considered to be about 15 years. From these conditions, it seems that the use of the natural-circulation type of solar water heater will spread to some extent for domestic use in the future.

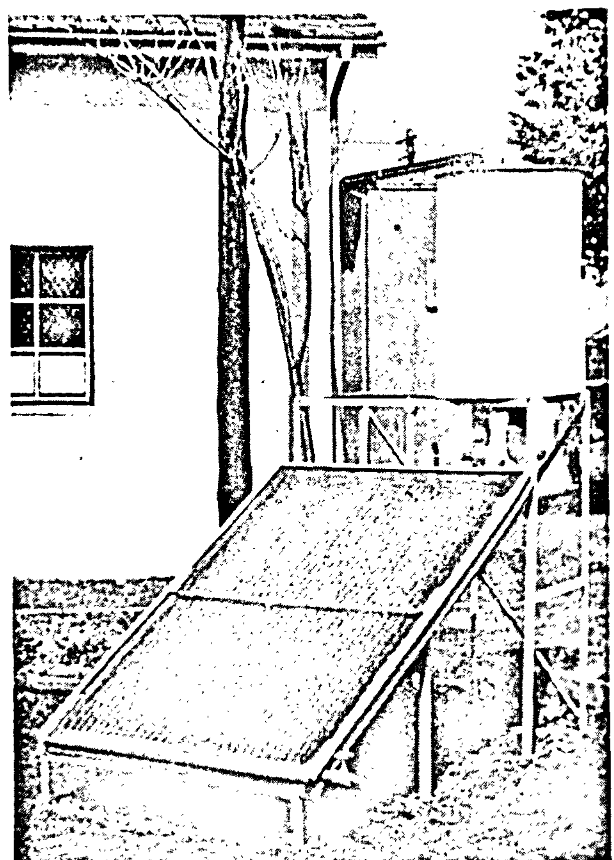

Figure 15

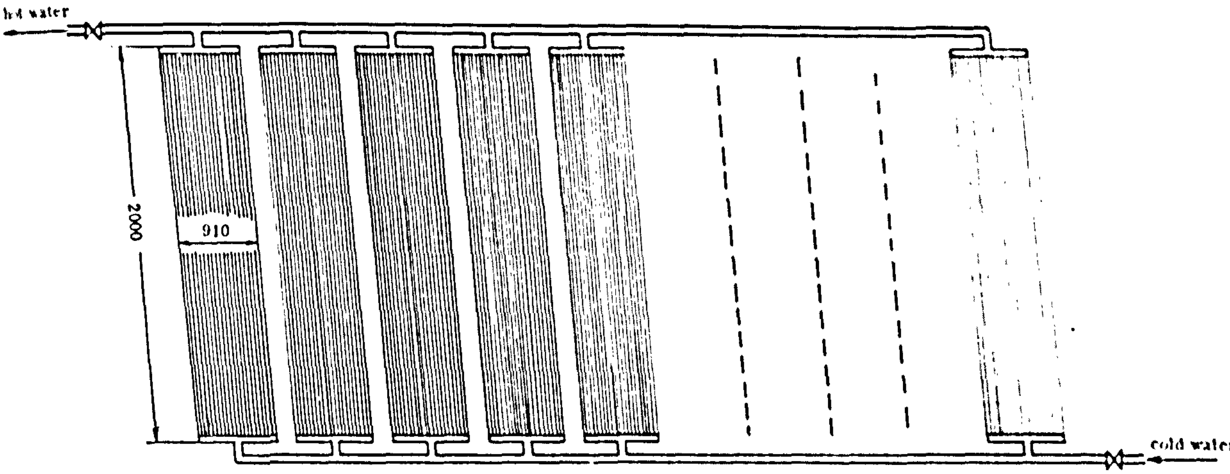

Figure 16

Once-through type

There is much possibility of using solar water heaters of larger size in Japan because there are many public baths. For this purpose, the writer has constructed and tested a once-through type heater, with a heat-receiving area of 66 m², at one of the dormitories of Keio University. The main purpose of this heater is to supply hot water for baths for more than 100 students.

It was not practicable to adopt the natural-circulation type heater in this case because it was difficult to place a large water tank on the roof. The once-through type heater was therefore adopted. In this type, the cold water passes through the heating pipe only once, and flows out as hot water, which is usually stored in a hot water tank. Figure 16 shows the construction of this solar water heater diagramatically, and figure 17 is a photograph of it. The heating pipes are iron pipes having an outer diameter of 20 mm, a thickness of 1.6 mm and a length of 4 m. Twenty groups of pipes were adopted, each group composed of 23 pipes arranged with a pitch distance of 35 mm. The inside and outside surface of the pipes was galvanized after the group of pipes was welded in one block. When the water valve *a* is opened, cold water from the city water main flows into the heating pipes at a proper speed, which is regulated by the opening of the valve, and flows out from the heating pipes as hot water, which is stored in a hot-water tank. The heating pipes are well protected by heat insulator, except for the upperside surface which is covered by glass plates.

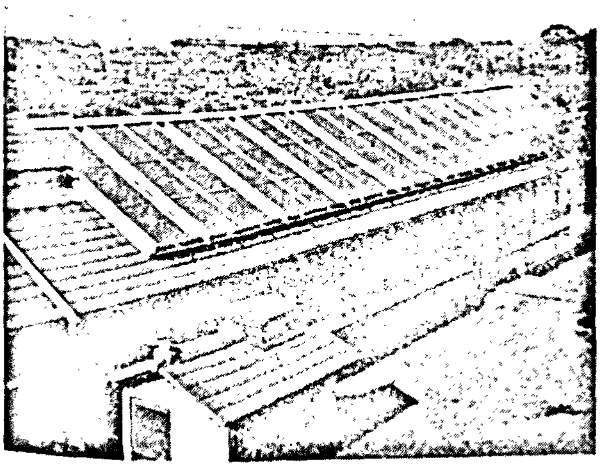

Figure 17

This heater was designed to supply 7 000 litres of hot water per day with a temperature of 50°C, except in winter. After tests of several seasons, it was found that the desired results were nearly obtained. The life-span of this solar water heater is supposed to be about 15 years. The price is about $20/m².

It is possible that the once-through type solar water heater of large size will be used widely in Japan, and a large amount of fuel will be saved.

Conclusion

This paper has briefly reported the recent developments in solar water heaters in Japan. Close to 400 000 solar water heaters are now used in Japan, and this number will probably be increased to one million within three or four years. Then, more than one million tons of fuel will be saved by the application of solar water heaters in Japan. This remarkable circumstance is chiefly due to the fact that price of fuel is comparatively high in Japan and that the country is blessed with abundant sunshine compared with other industrialized countries. Moreover, Japanese people like very much to take baths owing to the wet climate.

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Summary

Solar water heaters are now widely and economically used throughout Japan, especially in farmers' houses. It is believed that about 200 000 solar water heaters were in use at the end of 1959 and that about 150 000 were installed in 1960. Thus the total number of solar water heaters in use at the end of 1960 was about 350 000. It is believed that the number will further increase, amounting to about one million by the end of 1965.

In this paper, the reasons why Japan is suitable for the economical use of solar water heaters are discussed; the types and construction of heaters are explained in detail, their performance is described and their economical aspects are considered. The paper refers particularly to the large area solar water heater installed in the dormitory of Keio University in 1959. It seems likely that this type of large area solar water heater will be installed in many public baths in the future.

PROGRÈS RÉCENTS DES CHAUFFE-EAU SOLAIRES AU JAPON

Résumé

Les chauffe-eau solaires sont actuellement très utilisés au Japon, de par l'ensemble du pays, dans des conditions économiques satisfaisantes, particulièrement à la campagne. On estime que 200 000 chauffe-eau solaires environ étaient en service à la fin de 1959 et 150 000 autres ont été installés en 1960. En conséquence, le nombre total de chauffe-eau solaires en service à la fin de 1960 atteignait environ 350 000. On prévoit que ce nombre atteindra environ 1 000 000 avant la fin de 1965.

Dans le présent mémoire, l'auteur souligne pourquoi le Japon se prête bien à l'emploi économique des chauffe-eau solaires, et donne des explications détaillées des types et des réalisations de ces dispositifs, ainsi que des rendements et des considérations économiques applicables à ces appareils. Il décrit également le chauffe-eau solaire à grande surface installé il y a trois ans dans la maison des étudiants de l'Université de Keio. Il est probable que des chauffe-eau solaires à grande surface de ce genre seront installés dans nombre de bains publics à l'avenir.

A STANDARD TEST FOR SOLAR WATER HEATERS

A. Whillier and S. J. Richards *

The use of the sun for water heating is rapidly increasing throughout the world, and solar water heaters are now manufactured in many countries. There are probably as many designs of solar heaters as there are manufacturers, and the need has arisen for assessing the thermal performance of such equipment rapidly and accurately. It is therefore important that the test apparatus be cheap and that the cost of carrying out the test be small. With this in mind, a standard test procedure has been adopted in South Africa, by which it is possible to rate any solar heater with only 3 hours of sunshine at any time of the year.

The purpose of this paper is to outline the test system in the hope that it will be adopted, perhaps with some modifications, internationally.

General considerations

The term solar water heater as used here could include a vast variety of appliances, including the conventional flat-plate water heater, with either thermosiphon or forced circulation, and also any type of concentrating solar heater that is used for heating a flowing liquid. With slight modification, the method of test could also be extended to gas-heating appliances such as the Löf air heater.

Without exception, such devices have the following in common:

(*a*) A flowing fluid to remove heat gathered from the sun;

(*b*) An arrangement of tubes for flow of the heat-removing fluid;

(*c*) An area for absorbing or collecting the sun's radiation, with or without concentration;

(*d*) Surface "blackening" of absorber element to ensure high absorption of the incoming radiation;

(*e*) A transparent cover;

(*f*) Insulation.

When all possible variations of the above factors are coupled with the random variation in weather, the impossibility becomes apparent of accurately rating solar water heaters on an average day or other average basis. The conclusion is, then, inescapable that solar heaters must be rated on an instantaneous basis. Fundamentally, this means that the efficiency of a solar absorber must be measured at a given intensity of solar radiation, at a given fluid flow rate and at a given temperature of inflowing fluid. Repeat measurements are necessary at different inflowing fluid temperatures and different solar intensities.

* South African Council for Scientific and Industrial Research, Pretoria.

Theoretical basis for a standard test

The fundamental heat transfer phenomena in flat-plate solar heaters have been extensively studied at the Massachusetts Institute of Technology by Hottel and his co-workers, and more recently by others in Israel and, in the United States, in Arizona, Colorado, Wisconsin and Minnesota. In a paper (1) presented at the 1955 Tucson Conference on Solar Energy, it was demonstrated that the instantaneous rate of useful heat collection in a solar heater could be written as

$$q_u/A = F_R\,(HT\alpha - U\,(t_1 - t_0)) = G\,C_p\,(t_2 - t_1) \qquad (1)$$

where

q_u/A	=	rate of useful energy collection, per unit superficial area of absorber surface or collector opening
F_R	=	heat-removal efficiency factor
H	=	total insolation rate, per unit area
$T\alpha$	=	effective transmittance — absorptivity product of the transparent cover and absorber plate combination
U	=	over-all collector heat loss coefficient
t_0	=	ambient air temperature
t_1	=	temperature of inflowing water
t_2	=	temperature of outflowing water
G	=	mass flow rate of water per unit absorber area
C_p	=	specific heat of water.

For concentrating-type solar collectors, the same equation is valid except that the heat loss coefficient U must be divided by the concentration factor of the system.

The over-all efficiency of the solar absorber is then $(q_u/A)/H$. It will be presumed that the full significance of the various terms in the above relationship is fully understood, and in this regard the excellent elaboration by Bliss (2) can be recommended.

Presuming that at any one instant it is possible to measure the three temperatures t_0, t_1 and t_2, the solar intensity H, and the fluid flow rate G, then, by carrying out tests at several values of inflow temperature, t_1, and several solar intensities, H, it is possible to calculate the values of the two groups of terms in equation (1), namely $F_R\,T\alpha$ and $F_R\,U$.

Although it would be desirable to be able to determine the individual values of at least F_R, and hence of both U and $T\alpha$, this is not essential for the rating of solar water heaters, and, in fact, an experimental determination of these two factors at several temperatures suffices to determine the efficiency of the absorber as influenced by solar intensity and temperatures.

There are two other factors related to solar heater performance which can be measured with relative ease : (a) the glass transmittance at normal incidence, and (b) the pressure drop-fluid flow relationship for the collector; and it is recommended that these be done as part of the standard test procedure. The glass transmittance, T, can be measured easily using a pyrheliometer, but the pressure drop-fluid flow determination poses a practical problem in that at usual operating flow rates, the pressure drop is so small as to be difficult to measure. However, it is suggested that for qualitative comparisons, flow rates could be measured at different low-pressure drops which can be satisfactorily measured.

Method of test

The test equipment is shown schematically in figure 1. It consists essentially of a constant-head water supply tank feeding water continuously through the solar heater that is being tested. The temperature of the water entering the absorber can be regulated by a 1-kW electric immersion heater. A suitable blower provides essentially constant air speed over the absorber, in order to eliminate the effects of variable air speed on the heat loss term U.

For the test, which must be done during periods of uninterrupted sunshine of at least one hour's duration, the water flows continuously through the solar heater at a fixed rate and at a selected constant inflow temperature, and continuous measurements are made of:

(*a*) The water flow rate;

(*b*) The intensity of total radiation falling on the plane of the absorber or the collector opening;

(*c*) The temperature t_1;

(*d*) The temperature differences $(t_1 - t_0)$ and $(t_2 - t_1)$.

Tests are repeated at, say, five different values of $(t_1 - t_0)$, by adjusting the inflowing water temperature t_1 by means of the electric heater. An on-off thermostat is included for safety purposes but for tests it is preferred to adjust the electric heat input by variac to the appropriate level, and not to have the thermostat switching on and off

From the results of these five tests the numerical values of the terms $F_R\,T\alpha$ and $F_R U$ can be determined at the different temperature levels, and the efficiency of the absorber can then be computed for any practical condition of operation.

Conditions to be maintained for the tests

Some latitude is possible in choosing the conditions of the test, and the following considerations are suggested for uniformity:

(*a*) The absorber should be positioned so that the angle of incidence of the direct solar radiation is

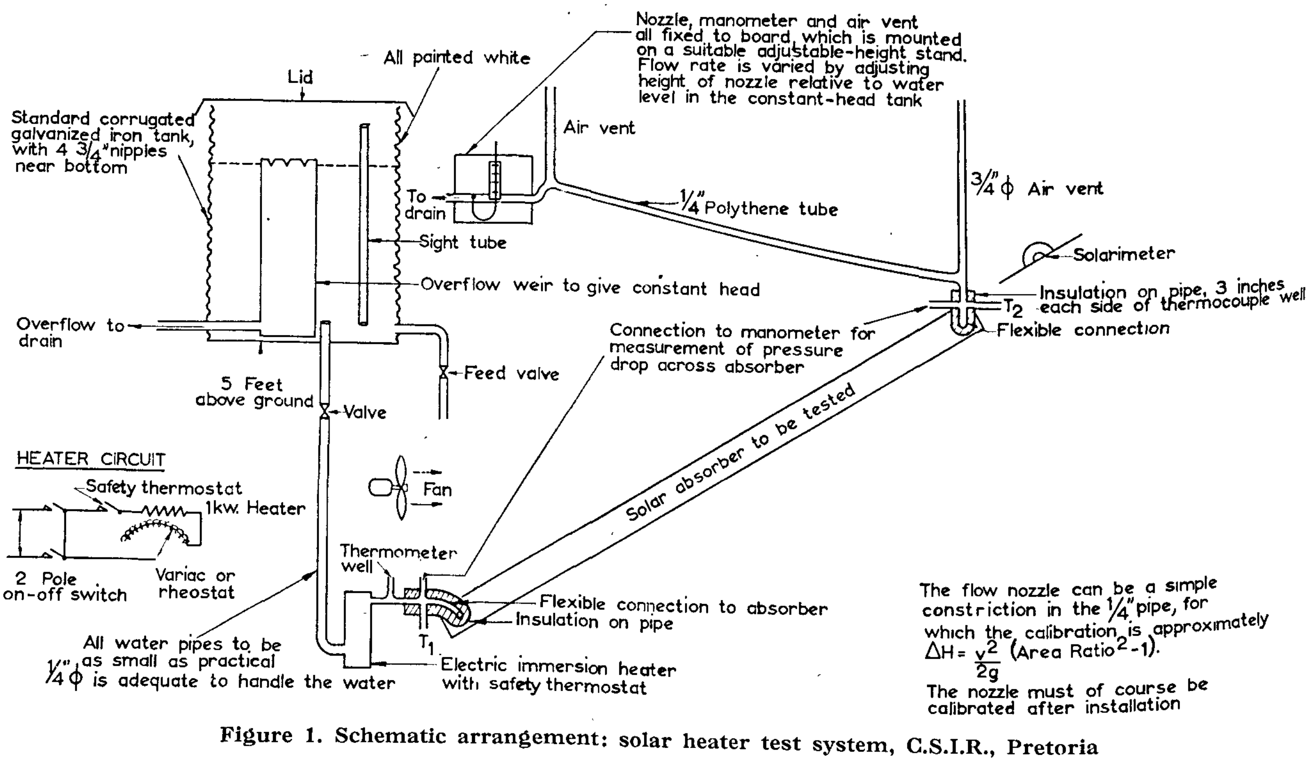

Figure 1. Schematic arrangement: solar heater test system, C.S.I.R., Pretoria

less than 30 degrees, since the glass transmittance (T) and solar absorptivity (α) are not markedly influenced by angles of incidence in this range. The actual angle of tilt of the absorber is not very important since this angle influences only the over-all heat loss factor U and only to a second order of magnitude.

(*b*) The water flow rate should be standardized at, say, 15 lb water/hr, per sq ft of absorber area (or 20 gm/sec per sq meter). The effect of changing the water flow rate to other values can be accurately assessed by use of equation 5 of reference (1), which is shown graphically in figure 5 of reference (2).

(*c*) Air speed over the transparent cover should be kept constant at a value to be agreed upon, such as 5 mph (or 8 km/h).

(*d*) The transparent cover should be cleaned off before testing.

(*e*) The absorber, if new, should be left outdoors to age in the sun for, say, four weeks before being tested.

(*f*) The instrument for measuring total radiation should be carefully calibrated, since inaccuracy in this measurement is likely to be a major source of error in the test. The instrument must be mounted with its sensitive surface parallel to the plane of the solar absorber or collector.

(*g*) The pressure drop data should be presented on a log-log plot of pressure drop in inches (or mm) or water against water flow rate in lb/hr, per sq ft of absorber (or gm/sec per sq meter).

Cost of equipment

The cost of the equipment, excluding the solar radiation measuring system and temperature recorder, is approximately as follows:

	£
Constant head tank	7
Immersion heater and thermostat	5
Variac or rheostat	10
Fan	10
Miscellaneous pipes, etc.	8
TOTAL	40 (U.S.$110)

Conclusion

The universal adoption of this test procedure will not only simplify the process of testing solar absorbers in all countries but will also provide test data for any absorber that will be immediately comparable with similar data from other absorbers, irrespective of where or by whom they have been tested.

The fact that a full test on any absorber would require only about three hours of sunshine is of particular merit since it reduces considerably the cost involved in testing absorbers.

References

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2. Bliss, R., The derivation of "... Plate-Efficiency Factors" useful in the design of ... solar heat collectors, *Solar Energy*, 1959, vol. 3, pp. 59-64.

Summary

A strong plea is made for international adoption of a standard test procedure for rating the performance of solar water heaters, so that results from all countries would be comparable. The theoretical basis for the proposed standard test procedure is given and suggestions are made for the manner in which such tests might be conducted. A description is given of the standard test apparatus that has been set up as part of the basic facilities of the South African Council for Scientific and Industrial Research in Pretoria.

ESSAIS STANDARDS POUR LES CHAUFFE-EAU SOLAIRES

Résumé

L'auteur présente un plaidoyer vigoureux en vue de l'adoption internationale d'une norme d'essais servant à déterminer le rendement des chauffe-eau solaires de telle manière que les résultats obtenus dans tous les pays soient comparables. Il indique la base théorique de la technique d'essais standard proposée et formule des recommandations sur la manière de mener ces essais. Il décrit enfin le matériel d'essais qui a été mis au point pour faire partie des installations du Conseil sud-africain des recherches scientifiques et industrielles, à Prétoria.

GENERAL REPORT — RAPPORT GÉNÉRAL

Agenda item III.C.2

USE OF SOLAR ENERGY FOR HEATING PURPOSES: SPACE HEATING

George O. G. Löf *

One of the world's largest uses of energy is for space heating. Estimates of the proportion of the world energy consumption for this purpose lie in the range of 20 per cent to 30 per cent of the total of all uses. It is logical, therefore, that considerable effort is being devoted to the development of solar energy for this particular application.

Slightly over 20 years ago, the first significant solar space heating project was initiated. Since that time, about a dozen groups throughout the world have undertaken experimental work in this field, most of which has led to the design and construction of buildings heated by solar energy. The published literature on all but the most recent works is abundant and readily available, and will not be reviewed here. These earlier efforts may be summarized, however, by observing that practically all of them showed that by use of several variations of the flat-plate solar collector, in combination with various types of thermal storage materials, a portion of the heat requirements of small buildings in the temperate zone could be conveniently supplied by solar energy. Also indicated in nearly all of the studies were the needs for short term thermal storage, auxiliary heat supply, and a reduction in the initial cost of the solar heating system.

Nine papers on solar space heating have been submitted to the U.N. Conference. Eight of these are concerned with specific solar heated structures in various parts of the world, whereas one involves a new technique for designing the heating system in solar heated structures. Two of the contributions contain mention of brief description of three other solar heated buildings with which the respective writers have been concerned. In all, therefore, eleven solar heated structures now in existence form the basis for the authors' papers. To this writer's knowledge, only seven other solar heated dwellings and one solar heated commercial building have been constructed, most of which are no longer in use. This section of the United Nations Conference therefore comprises a remarkably good coverage of world developments in solar space heating.

This rapporteur wishes to comment on another general aspect of the contributions. In the main, the papers contain a gratifying amount of quantitative data on the design and performance of the systems discussed. Only by such careful appraisal can there be substantial progress toward solar heating applications. On the other hand, there is an unfortunate lack of economic data in nearly all of the papers. This illustrates the very great difficulty, at the present development stage, of presenting significant cost information. The actual energy savings realized in a particular solar installation may have little meaning because of obviously unfavorable circumstances for *practical* demonstrations of economy. In other words, choice of design and location has usually been made on the basis of technical convenience rather than an ideal economic situation. Secondly, and much more important, estimates of costs of solar heating systems have little meaning at this stage of development. Obviously, the cost of constructing the particular system discussed by each author is far greater than that of a fully developed design, which might be suitable for factory construction, at least in part, and which would have economical features not possible in an experimental installation. The cost of building the experimental unit is therefore irrelevant in an economic appraisal. Moreover, estimation of construction costs which might be realized in fully developed systems are extremely difficult to make at this time. Most of the authors have therefore refrained from speculating on the costs which *might* be incurred in the purchase or construction of practical solar heating facilities.

The reader of most of the papers on the subject of solar space heating should be impressed with the exceptional amount of effort which has gone into the design, construction, operation, and detailed analysis of the data in the reports. He should also be impressed with the importance of thorough planning of the project and the diligent pursuit of details in performance appraisal.

A final introductory comment concerns the gratifying diversity of the solar heating systems reported at this conference. No system is like another, and only two are even similar to each other. This makes it possible to make general comparisons of the features of several modifications and designs. For several reasons, however, close appraisal or choice of the "best" system is not possible at this stage. Wide differences in solar and weather conditions, in size of solar installation compared with heat requirements of the building, in differences in quantity and quality of the data reported, and in numerous other factors preclude a selection of this sort. Absence of reliable data on system costs is in itself enough to foil selection.

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Glazing of the several collectors varies from none at all to three or four glass layers. The unglazed units are all operated at comparatively low temperatures as sources for heat pumps which deliver heat at adequate temperatures for house supply. They are also used as radiators for heat extracted from the house by means of the heat pump. Double glazing is the most commonly used design in the higher temperature collectors, and there appears to be very little use of plastic films in these units.

Storage systems

Heat storage capability varies from about 200 000 btu, in the Nagoya laboratory to 2½ million btu in the Tokyo residence and the New Jersey laboratory. Comparison of the storage capacities with normal January heating demand shows a range from about ¼ of a normal January day's requirement (Colorado house) to about one week in the Washington house. The Arizona laboratory has approximately 2½ days normal January storage; about one day's requirements can be stored in the Massachusetts house, eight days in the New Jersey laboratory, five days in the Tokyo residence, and somewhat less than one 10-hour day in the Nagoya laboratory. These figures indicate a divergence of opinion among the authors as to the value of "long-term" storage, that is, for several days. Some investigators, including this rapporteur, have concluded that provision of storage for more than one or two days average January heating demand is uneconomical because the decrease in fuel use resulting from longer term storage is so small. The occurrence of need for eight days storage (of average January heat demand), when four days storage would have been adequate is so infrequent, that an average annual incremental fuel requirement of a few gallons of oil would usually be cheaper than the additional fixed charges due to doubling the storage system. Data in the papers are not adequate for further appraisal of optimum storage capacity.

Paper S/3 on the Washington house describes a combination storage system including both water and stones. It appears that heat transfer to the stones must be by conduction from the water tank around which the stones are packed. The effectiveness of such a design may be questioned in so far as the utility of the rocks are concerned, because the rate of heat transfer in a bed of loose stones is extremely slow. The tank surface and the stones in close proximity to the tank are probably the principal heat exchange surfaces for heating air passing to the rooms. It is doubtful that the bulk of the rock in the storage chamber could be heated to the indicated temperatures.

In paper S/93 on the New Jersey laboratory, heat-of-fusion storage is reported. If all of the fusible material is effective, the large storage capacity of 2.5 million btu would be realized. It has been shown, however, that the fusible materials used heretofore tend to stratify in their containers and lose their thermal storage effectiveness. Although the author states that this factor was considered in the design, neither the nature of the storage material nor data on its performance are reported. There is consequently no way of appraising the effectiveness of the heat storage agent or of learning whether the attempt to prevent stratification was successful. Unless separation of phases was prevented, the material would have approximately the same storage capacity as water, about 0.8 million btu.

The maximum temperatures of storage appear to lie in two principal ranges. The low storage temperatures in the two Japanese buildings are characteristic of the systems employing heat pumps and unglazed collectors. The higher temperatures of 120° to 140° F are, on the other hand, suitable for direct heating. An intermediate level in the Arizona house permits direct use of heat from storage when the temperature is sufficient, and indirect use in supplying the heat pump when the temperature is too low.

Apparently all of the storage systems were satisfactory in providing for sunless hours, to greater or less extent depending upon their heat capacity and operational limitations. As in the case of the collectors, however, economic data are lacking.

Auxiliary energy

With the exception of the New Jersey laboratory, all structures employed auxiliary heat. In all cases where the subject is mentioned, the auxiliary supply is adequate for the full design heat load, although the heat pump auxiliaries would probably have to be larger if they were to employ an atmospheric air source. Use of auxiliary energy ranges from a minimum in the Washington residence, estimated at about 5 per cent by the author, to a measured maximum in the Colorado residence of about 74 per cent. None of the authors mentioned any serious difficulty with incorporating the auxiliary energy unit into the total heating system and operating it in conjunction with the solar source. Apparently all of the systems employ automatic control of the auxiliary, so that heat will be supplied to the structure whenever the solar source is inadequate.

Lack of data in paper S/93 on the New Jersey installation precludes appraisal of the effectiveness of this system having no auxiliary supply. Even with long-term (several-day) storage and a combination of 600 square feet of vertical collector, 160 langleys per day on a horizontal surface, an average January heat load of 12 500 btu per hour, and a 46 per cent collector efficiency, the solar unit could barely supply the average load. However, in any January when the average temperature might be several degrees below the normal (occurring every few years), particularly if accompanied by less than normal radiation, the building could not be fully heated without auxiliary. These factors show the difficulty of achieving an adequate heating design without use of auxiliary in any situation where low winter temperatures make space heating mandatory.

This rapporteur would also like to comment on the statement (paper S/93) that a solar collector should be large enough to supply all the *normal* heating requirements of a building in the coldest month, if *normal* radiation for the month is received. Any consideration of optimum collector size must include costs, so a categorical statement such as that in the paper cannot be logically made. Other design maxims, such as the use of one square foot of vertical collector for two square feet of floor space, and the use of 4 per cent of the floor area for heat storage purposes, must be considered arbitrary choices and not design optima.

Heat collection and distribution

Table 1 shows that in most of the systems, water is heated in the collector and is then used as the medium of energy transport to storage and from storage to the rooms. In the Washington and Massachusetts houses, however, heat is transferred from the stored hot water to air circulated through the rooms, hot air thus being the final heating and transport medium. The system in the Washington house involves air circulation around the hot water tank and between the adjacent rocks; the Massachusetts system uses a finned tube heat exchanger through which hot water is circulated from the solar tank or from the auxiliary hot water tank.

Circulation systems

In the two systems using solar air heaters, heat is transferred from air to fusible storage material (New Jersey laboratory) or to rocks (Colorado residence). Heat is transferred from storage to the heated space by circulating house air through the storage chambers. At least two motors are required for operation of pumps or blowers in all systems except that in the Colorado residence, which needs only one motor for blower operation.

It is interesting to observe that there is a fairly consistent rate of fluid circulation through the solar collectors reported. The water flow rate, in gallons per minute per square foot of solar collector, is 0.85 in the Washington residence, 0.65 in the Capri laboratory, 1.67 in the Massachusetts residence, 5.3 in the Nagoya laboratory, and 1.3 cubic foot of air per minute per square foot of solar collector in the Colorado residence. An average rate of about 1 gallon per minute for each square foot of water-heating collector appears to be suitable for the higher temperature systems, and about 1 cubic foot of air is circulated per minute per square foot of solar air heater.

Hot water supply

In four of the buildings, at least part of the house hot water supply is solar heated. A separate solar collector is used for this purpose in the Tokyo residence; it is operated at low temperature as the source for a 1 hp heat pump. In the Washington and Colorado dwellings, a small portion of the heat from the solar collector is used to preheat the house hot water supply for subsequent fuel heating to the desired temperature. The Massachusetts house employs a water preheater in the main solar storage tank. In none of the systems does water heating appear to be a major design consideration.

Automatic controls and instrumentation

Five authors indicate that major consideration was given to the automatic control system and the data recording facilities. Details of the control system in the Massachusetts and Colorado residences are presented, and there is general information on the Arizona laboratory instrumentation. Discussion of these topics is beyond the scope of this report, and the reader is referred to the papers. Several useful conclusions can be recorded here, however. Careful design of the control system appears essential to obtaining the full capability of the solar heating equipment. One of the important control requirements is that the cost of collecting low rate solar heat does not exceed its value. Of particular significance are the comments of the authors concerning control problems which they encountered and the methods for their solution. Several of the investigators reported that after difficulties had been eliminated and experience with the system had been obtained, automatic control was completely effective. The necessity for well planned and maintained instrumentation for evaluation of system performance is also indicated.

Cooling facilities

Four of the buildings were also provided with cooling equipment. Operation of each was based on the discard of heat at night when lower atmospheric temperatures usually prevailed. In the Arizona laboratory, the Tokyo residence, and the Nagoya laboratory, heat was absorbed from the rooms during the day (and at night if necessary) in cool water from the evaporator side of the heat pump. The heat so removed was temporarily stored in heated water on the condenser side of the heat pump. Circulation of the warm water through the unglazed solar collector panel at night resulted in a transfer of the heat to the atmosphere by convection and to the sky by radiation.

In the Nagoya laboratory, air from the rooms was cooled by water in a finned tube heat exchanger, whereas cool water was circulated directly through expanded tubed sheet metal in the ceilings of the Arizona laboratory. The Tokyo residence employed a combination of these two systems. It is noteworthy that 1½ hp motor was adequate for cooling the building in the extremely hot Arizona climate, where 5 hp is commonly used in a house of that size. On only two or three occasions was it necessary to allow the room temperature to rise above the desired level in order to avoid condensation on the ceiling panels.

No heat pump was employed in the Washington installation. Air from the rooms was circulated through the rocks and along the surface of the water storage tank. Transfer of heat to the water occurred during the daytime. At night, the slightly warmed water was pumped to the sloping north metal roof for cooling by evaporation, convection, and radiation.

It is clear, of course, that these installations do not use solar energy for cooling. Three of the systems, however, do use the solar collector as a heat disposal surface and the solar storage unit for temporary accumulation of heat prior to night discard. The heat pump provides energy for both heating and cooling. This joint use of much of the equipment results in more attractive load factors in economic considerations.

In another section of this Conference, solar cooling is receiving primary attention, so further reference to these systems is not made here.

Performance data

A gratifying record of performance is reported for five of the solar heated structures discussed at this Conference. The use of adequate instrumentation, careful examination of the records, and full reporting of the results make the papers valuable contributions to the literature. It is hoped that complete data on the other three installations will be forthcoming.

Of the "high" temperature units, the solar collector in Massachusetts appears to have the highest substantiated total winter efficiency of 40.8 per cent while operating. The New Jersey collector was estimated to have a 46.5 per cent efficiency in December and January, but data for the estimate are not reported. The solar air heater in Colorado had a total winter efficiency of 34.6 per cent while operating. Collector efficiencies for the Massachusetts and Colorado installations based on total incident solar radiation through the winter are 32.6 per cent and 24.5 per cent respectively. January data for the Arizona laboratory show respective efficiencies of 28.7 per cent and 17.2 per cent. Even though operating at lower temperature, the Arizona collector appears to suffer enough thermal loss to suggest the possible advantage of glazing it, perhaps with a covering easily removable in the cooling season.

The solar collector in Nagoya, operating below 55°F, is reported to have an average January solar collection efficiency of approximately 54 per cent. At this low temperature, it would be expected that some heat is also being transferred to the collector from the atmosphere. The Tokyo residence has an estimated winter collection efficiency, based on total solar radiation, of about 22 per cent.

As a general conclusion based on several of the reported results, collector efficiencies for winter operation in the cooler sections of the temperate zone may be expected to range from 35 per cent to 45 per cent while operating and from 25 per cent to 35 per cent based on total winter radiation. Comments in the papers indicate the possibility of improving these figures by devoting close attention to design and operating details. It appears that a maximum average operating efficiency of about 50 per cent may be achieved for these general designs and conditions.

Total solar heat supplied to buildings during the entire winter is seen to range from 14 million btu in the Nagoya laboratory to 52 million in the Colorado house. To supplement these solar energy deliveries, auxiliary heat supplies of 16 million btu in the Nagoya laboratory and up to 142 million btu in the Colorado house were required. In the Washington dwelling, only 5 million btu auxiliary heat were used, estimated by the author to represent about 5 per cent of the winter heating requirements. There appears to be some discrepancy in the last estimate however, because it would place the total winter demand at approximately 100 million btu (based on the 95 per cent estimate), whereas a total based on degree-days and the heat requirement per degree-day, (computed by this rapporteur from the stated days of winter storage capacity) is about 30 million btu. In either case, however, this moderate fuel use indicates a high design adequacy in the solar facilities, as previously indicated in table 2.

The portion of the total winter heating load supplied by the solar system, in the seven installations employing auxiliary heat, ranged from a measured 26 per cent in the Colorado dwelling to an estimated 95 per cent in the Washington residence. Among the other buildings, the Arizona laboratory showed the lowest portion of auxiliary energy use. Considering electric energy the direct equivalent of heat, 86 per cent of the load was supplied by solar. Recognizing the "power plant fuel equivalent" of electric energy, computed at a 30 per cent thermal efficiency, 64 per cent of the total heat requirement in the Arizona building (i.e., solar heat supplied plus fuel burned in generating the electric energy used in the heat pump) came from the solar system. Corresponding figures for the Tokyo house are 70 per cent and 42 per cent respectively, and for the Nagoya laboratory, 75 per cent and 48 per cent. The Massachusetts house had 57 per cent of its requirements supplied by solar radiation. These figures are seen to conform in a general way with the "design adequacy" indexes computed by this rapporteur in table 2.

Economic considerations

Data on energy costs and savings due to the solar heating system in the various buildings are so limited and of such variable character that their tabulation is not practical. Only four papers contained any cost data, none of which are meaningful without considerable interpretation.

The cost of auxiliary fuel oil used in the Washington house was only $6.30 for the heating season. On the basis of the author's estimate that 95 per cent of the winter requirements were supplied by solar, the value of the fuel saved would be approximately $120. Additional electric energy costs have not been reported, so an estimate of net savings cannot be made.

The cost of auxiliary electric energy for heat pump and motor operation in the Arizona laboratory was $37 for the winter heating season. No figures are presented on energy savings attributable to the solar system for heating only, but it was estimated that a conventional heating and cooling system would have involved energy costs $185 greater than actually experienced during the full year. This rapporteur estimates an approximate value of $50 to $60 for the solar heat supplied to the system during the winter.

The third set of cost estimates is for the Colorado house. It was found that about $80 worth of natural gas was saved by the solar heat supply and that $60 additional power cost was incurred, for a net energy saving of only $20. It was estimated that with minor modifications in the system, primarily to reduce power requirements, net energy savings of about $100 per year would be possible. In the Tokyo house, net energy savings of $78 were achieved through use of the solar heating system. It must be recognized that these few cost figures are specific for the local conditions under which each system operates.

It appears that the actual and potential savings in fuel and electric costs for heating these structures can be bracketed reasonably well by a $50 minimum and a $150 maximum. Both of these figures are subject to adjustment, however, by use of other proportions of collector area to house-heating requirements, other fuel prices, use in areas of different solar availability and climates, as well as other factors.

It must be clearly realized that the foregoing figures do not include consideration of amortization or maintenance costs of the solar equipment. These appraisals must await reliable figures on manufacturing and construction costs based on at least moderate production levels. At an annual cost of 10 per cent against investment, conceivably made up of 5 per cent amortization (20 year basis), 6 per cent interest on unamortized investment (equivalent to approximately 3 per cent average interest), and 2 per cent for maintenance, taxes, insurance and miscellaneous, a $150 annual saving would permit a maximum additional investment in solar facilities of about $1 500. An annual saving of $100 would allow an additional investment of $1 000. It is conceded by most of the investigators that current investment requirements in such facilities are greater than these limits, but it is felt that costs in this range are not impossible to achieve.

Part of the economics of these systems is associated with auxiliary heating facilities and the energy needed by them. For fuel-operated systems, both of these costs are or can be modest. The auxiliary equipment is relatively cheap, and because controls, distribution system, and other components are required by the solar system, the incremental cost of only the furnace is generally involved. With the major part of the heating load assumed by solar, fuel costs are also low. This rapporteur therefore believes that the use of a very large collector and storage system in an effort to eliminate auxiliary requirements is difficult to justify.

Another factor associated with auxiliary energy is the relative merit of heat pump systems and fuel systems. Even with the large collector areas in the Arizona and Tokyo installations, electricity costs for heat pump operation were substantial, and the total savings did not appear greater than with the auxiliary fuel systems. However, the investments required for the heat pump systems were far above the costs of furnaces. Justification for heat pump auxiliary must therefore be in its cooling capability. In a rough economic comparison, it appears that the heat pump investment costs associated solely with the heating function must not be appreciably greater than the cost of a furnace. It is possible, however, that the cost of a solar collector for use with heat pump auxiliary will be lower than that of a higher temperature collector used with fuel auxiliary systems, because of the need for glazing in the latter. Here again, comparisons are exceptionally difficult because of inadequate cost information. The only clear indication is that the high costs of both the heat pump and the solar collector must limit the use of heat pump auxiliary to situations where summer cooling is considered necessary and where the solar equipment can permit sufficient electricity savings in winter to justify the cost of the solar installation and any heat pump costs necessitated by its use for heating.

A final economic factor of importance in this Conference is the potential of solar heating in underdeveloped countries. Among the systems described in these papers, considerable complexity and cost are evident. There is little likelihood of early application in dwellings now either unheated or warmed by some type of direct fire. Use in larger dwellings, where central heating is now employed, or in public and commercial buildings appears much more feasible. Conditions in regions of high fuel cost appear to offer the best opportunities for application. However, practical use must await development of fully engineered and tested solar heating equipment of substantially lower cost. This rapporteur suggests the consideration of applications of this type in subsequent development work.

An electronic mechanical analogue for the design of solar heating plant

In another type of paper in this section of the Conference, R.F. Benseman describes a mechanical sun simulator which in a few minutes can effectively duplicate the sun's annual variation in intensity and position with respect to a solar collector surface in any orientation desired. The recording of effective radiation received on such a surface (by use of photoelectric detectors) can then be used as input to an electronic computer along with factors representing various thermal losses, structural heating demands, and other variables of importance in solar heating system design. The computed results may then be used in establishing the optimum design characteristics for the location and heating requirements chosen. Presumably, cost factors could also be incorporated when the data are available, so that the best and most economical design could be selected. Full results of this development, still in progress, will be awaited with interest.

Study of a Saharan solar house

Paper S/76 by E. Crausse and H. Gachon has been classified under the heading of solar cooling, but it also contains a brief description of a proposed heating system. In the northern part of the Sahara Desert at 35° north latitude (Biskra), an experimental house having 900 square feet of floor area is planned to have a heating system employing solar heated water in steel piping embedded in a radiant floor. A solar collector near the house, in conjunction with a 5 000 litre insulated water tank, is planned as the heat source.

Conclusions, topics for discussion

The development of solar space heating appears to this rapporteur to have reached a point where a "pause" for comprehensive appraisal is in order. Several technically successful systems have been developed and demonstrated. Substantial quantities of solar heat have been delivered to buildings in cold winter climates, and in some installations large fractions of the heating requirements have been met by the solar source. Even with fairly complex systems, relatively trouble-free, automatic operation has been secured for long periods. Although each of the several systems appears to have defects, there is no reason to assume that these cannot be corrected. Finally, performance improvements of modest proportions should be obtainable with further development effort.

There is, however, practically complete agreement that present costs of solar heating facilities exceed the value of energy saved by them in the areas where tested. Whether *major* design simplifications can be achieved without impairing performance is a matter of doubt. *Moderate* cost reductions appear more possible and likely. There is some difference of opinion, however, as to the potential of cost reductions through factory production of a standardized, ready-to-install set of solar heating system components. Further exploration of this possibility appears essential. There is also some difference of opinion as to the need for integration of house design and solar heating system design, in contrast with use of solar equipment on practically any style of house. The economic outlook, therefore, is highly uncertain at this time. The need for clarification is certainly evident.

Granted the validity of the situation outlined above, what direction should solar heating system development now take? This is the most important question before the Conference in regard to this agenda item. The answer to it may become evident by finding the answers to some of the following questions which are suggested for discussion:

What are the prospects for significant increases in solar collector efficiency and for substantial reduction in solar collector costs?

Should such possibilities be appraised by conducting small-scale experiments or by use of complete solar heated structures?

Along these lines, are the technical advantages of selective absorption surfaces, selective transmission surfaces, low reflection glazing, and other radiation-influencing treatments great enough to justify intensive efforts in their utilization for solar space heating improvement?

Several of the investigators have mentioned design and operating defects in the systems with which they have been working. Should there be further effort, with the present systems, to develop their maximum efficiency and heating potentialities? Can this step-by-step engineering improvement of the systems be expected to materially improve utilization prospects?

How important is the development of a rational basis for sizing solar collector and solar storage facilities? Are presently available methods adequate for these determinations?

In view of published results of analyses favoring thermal storage capacity of about 1 day's average January heating requirements, how do the proponents of larger storage capacities justify their position?

Along the same line, what justification is there for a collector and storage design capable of carrying the entire heating load under the most severe conditions that can be encountered in a cold winter climate?

Can heat-of-fusion be effectively utilized in storage systems for solar space heating? Have any methods for using hydrated salts been proven satisfactory? Are there other promising materials?

Except for its obvious utility in providing cooling, do the advantages of the heat pump auxiliary justify the use of this system in combination with the solar heat supply? What is the probable maximum solar collector cost that can be tolerated in such a combination to be competitive with conventional compressor air conditioning and fuel heating?

What minimum solar collector costs can be foreseen? Do these minima appear more readily achieved by factory production of units which could be supplied as a commercial item (like a furnace), or are they more likely achieved by development of effective combinations of house design and integrated solar collector systems built on site? How necessary and how productive might development efforts along both these lines be?

How significant is the supply of house hot water in combination with solar space heating?

To what extent should the thinking on solar space heating be associated with the possibilities of solar-operated cooling systems being investigated? If the prospects of one or more combination systems appear favorable, to what extent might the choice of solar heating systems be dictated?

Is there a need for an economic study of solar space heating, apart from technical development, and are there adequate data for procurement of meaningful results from such studies?

How necessary are the improvement and simplification of control elements and systems for solar heating installations? What minimum costs can be foreseen for such equipment?

In the under-developed areas, what additional considerations are significant in the potential of solar space heating, and what limitations existing in the developed areas are not involved?

For what types of uses does solar space heating appear to have the best potential in the under-developed countries?

For use in under-developed countries, is there a need for solar space heating systems which do not require electric power for their operation?

To what extent might new materials, such as transparent plastic films, permit collector cost reduction and improve solar space heating prospects, particularly in the under-developed countries?

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : CHAUFFAGE DES LOCAUX

(Traduction du rapport précédent)

George O. G. Löf *

Une des plus grandes quantités d'énergie qui se dépense dans le monde est utilisée pour le chauffage des locaux. Les estimations de la proportion de l'énergie mondiale consommée à cette fin varient entre 20 et 30 p. 100 de la consommation totale pour toutes les utilisations. Il est donc logique que l'on déploie des efforts considérables pour mettre au point des méthodes de chauffage des locaux par l'énergie solaire.

Le premier projet important de chauffage solaire des locaux remonte à un peu plus de vingt ans. Depuis lors, une douzaine d'équipes de chercheurs ont expérimenté en ce domaine dans le monde entier. Leurs recherches ont abouti, dans la plupart des cas, à la conception et à la construction de bâtiments chauffés à l'énergie solaire. Les études publiées sur tous ces travaux, à l'exception des plus récents, constituent une documentation abondante et facile à consulter ; nous ne les examinerons pas ici. On peut cependant résumer ces premiers efforts en faisant observer ce qui suit : la plupart d'entre eux ont démontré qu'une certaine proportion des besoins thermiques pour les petites constructions de la zone tempérée pourrait être satisfaite par l'énergie solaire captée au moyen d'un collecteur du type à plaque plane (dont il existe plusieurs variantes) associé à diverses matières capables d'emmagasiner de la chaleur (accumulateurs thermiques). Presque toutes les études font également état d'exigences auxquelles il faut satisfaire, à savoir : accumulation thermique de brève durée, source de chaleur auxiliaire et diminution du coût initial de l'installation de chauffage solaire.

Neuf mémoires sur le chauffage des locaux par l'énergie solaire ont été présentés à la Conférence des Nations Unies. Huit décrivent des bâtiments construits dans diverses parties du monde qui sont chauffés à l'énergie solaire; tandis que le neuvième traite d'une nouvelle méthode applicable à l'établissement des plans d'installations de chauffage solaire dans les bâtiments. Deux mémoires mentionnent ou décrivent brièvement trois autres bâtiments chauffés à l'énergie solaire dont les auteurs ont eu à s'occuper. Ce sont donc au total onze bâtiments actuellement existants et équipés d'une installation de chauffage solaire qui sont décrits dans les mémoires présentés. Il n'a jamais été construit, à notre connaissance, que sept autres bâtiments d'habitations et un seul immeuble commercial équipés de ce mode de chauffage, et encore la plupart ne sont-ils plus utilisés actuellement. On peut donc considérer que la documentation présentée sous cette section des travaux de la Conférence est remarquablement représentative des progrès réalisés dans le monde dans le domaine du chauffage des locaux à l'énergie solaire.

Le rapporteur désire signaler un autre trait général qu'il a relevé dans les mémoires présentés. Dans l'ensemble, ceux-ci contiennent un bon nombre de données quantitatives sur la réalisation et les performances des installations décrites, ce qui est du reste le seul moyen d'en apprécier les mérites et de progresser dans cette branche de la technique. En revanche, on peut regretter la rareté des données d'ordre économique figurant dans la plupart des mémoires. Cette rareté s'explique par la grande difficulté de fournir, au stade actuel, des renseignements significatifs sur le prix de revient des installations. Les quantités d'énergie effectivement économisées dans certaines installations n'ont souvent guère de signification, parce que les conditions qui permettraient de faire la démonstration *pratique* d'un fonctionnement économique sont notoirement défavorables. En d'autres termes, le choix du plan et de l'emplacement a en général été déterminé par des considérations d'opportunité technique plutôt que pour se placer dans une situation économique idéale. D'autre part et surtout, les estimations du prix de revient d'une installation de chauffage solaire n'ont guère de sens au stade actuel : il est évident que le prix de toutes les installations décrites dépasse très largement ce que coûterait un système parfaitement au point, dont certaines parties au moins pourraient être produites en usine et qui présenterait des caractéristiques économiques irréalisables dans le cas d'un dispositif expérimental. Le coût d'une installation destinée à l'expérimentation ne peut donc servir de base pour une évaluation économique. En outre, il est très difficile actuellement d'évaluer ce que pourrait coûter une installation tout à fait au point. La plupart des auteurs ont donc évité de se lancer dans des considérations sur le prix que *pourrait* coûter l'achat ou la construction d'une installation de chauffage solaire une fois que ce système serait entré dans la pratique.

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Le lecteur de la plupart des mémoires consacrés à l'étude du chauffage des locaux par l'énergie solaire ne manquera pas d'être impressionné par la somme exceptionnelle d'efforts qui ont été dépensés pour la conception, la construction, le fonctionnement et l'analyse quantitative détaillée des installations décrites dans cette documentation. Il appréciera aussi le soin et la minutie qui ont été apportés à la préparation des projets et à l'évaluation des performances des installations.

Pour conclure ces remarques liminaires, on peut se féliciter de la diversité des systèmes de chauffage solaire qui ont été décrits pour cette conférence. Il n'y a pas deux systèmes identiques et deux seulement se ressemblent quelque peu. D'où la possibilité d'établir des comparaisons générales entre les caractéristiques des diverses variantes et solutions proposées. Cependant, pour plusieurs raisons, une appréciation serrée ou un choix du « meilleur » système n'est pas possible au stade actuel. Les différences importantes qui interviennent dans les conditions d'ensoleillement et les conditions atmosphériques, dans les rapports entre les dimensions des installations et les besoins thermiques des bâtiments respectifs, dans la quantité et la qualité des chiffres rapportés, et dans beaucoup d'autres facteurs, rendent un tel choix impossible. L'absence de données certaines sur le coût des installations suffit à elle seule à empêcher une sélection sérieuse.

Quelques auteurs ont très franchement exposé les défauts du système sur lequel ils ont expérimenté; ils ont fait des suggestions sur la façon dont ces installations pourraient être améliorées et dont d'autres chercheurs pourraient éviter certains des écueils qu'ils ont eux-mêmes rencontrés. Cette mise en évidence des « fautes » constatées dans le plan et dans le fonctionnement des installations est certainement du plus haut intérêt pour les recherches futures.

Discussion des caractéristiques de huit bâtiments équipés d'un chauffage solaire

La principale contribution personnelle du rapporteur en vue de la Conférence des Nations Unies est une comparaison des caractéristiques des huit bâtiments chauffés à l'énergie solaire qui sont décrits dans les mémoires. Le tableau 1 est un essai de représentation graphique des principales caractéristiques de chacun des systèmes et des résultats obtenus lors de son fonctionnement; il a été établi d'après les indications des auteurs.

Quelques observations générales concernant ce tableau s'imposent d'emblée. La plupart des auteurs expriment les quantités en unités anglaises et ces dernières ont donc été adoptées pour le tableau. Les notes ajoutées au tableau contiennent des taux de conversion qui permettront de passer facilement des unités anglaises aux unités métriques. Les données quantitatives figurant dans les mémoires ont été autant que possible intégrées au tableau, mais il a souvent fallu les convertir en unités différentes pour obtenir une certaine uniformité. En général, si l'auteur n'a pas cité de chiffres, le tableau n'en contient pas non plus. Dans certains cas cependant, les chiffres d'un mémoire permettaient de calculer ou d'évaluer approximativement certaines données; le rapporteur a procédé aux déterminations correspondantes et présenté les résultats. Il demande aux auteurs de faire preuve d'indulgence pour toute erreur ou omission. Il les invite également à lui soumettre toute rectification ou adjonction qu'ils jugeront utiles et dont il sera tenu compte, le cas échéant, dans une édition définitive dudit tableau.

Quelques mémoires contiennent des affirmations et des chiffres qui, pour les besoins de la certitude scientifique, devraient s'appuyer sur de nombreuses données qui ne sont ni indiquées ni mentionnées dans le texte. Le rapporteur n'est donc pas en mesure de juger si une affirmation ou un chiffre représente simplement une opinion de l'auteur ou repose sur des données suffisamment nombreuses. Il a reproduit les chiffres indiqués par l'auteur, que ceux-ci soient ou non étayés par des données quantitatives. Sur les huit bâtiments chauffés à l'énergie solaire qui figurent dans le tableau, quatre sont des habitations régulièrement occupées et quatre des laboratoires utilisés principalement pendant le jour. Tous sont équipés de collecteurs solaires fixes, du type à plaque plane. Il semble que tous les chercheurs qui ont travaillé dans ce domaine partagent l'opinion que les systèmes à concentration du rayonnement ou même à plaque mobile ne soient pas applicables au chauffage des habitations. Sur les huit types de collecteurs solaires, six servent à chauffer de l'eau et deux à chauffer de l'air.

Parmi les systèmes de chauffage équipés de collecteurs solaires, sept emploient un dispositif auxiliaire de chauffage; seul, un laboratoire ne fait appel à aucune source de chaleur supplémentaire. L'auteur ne donne pas de chiffres concernant les performances de cette dernière installation, mais les calculs théoriques montrent qu'une source additionnelle de chaleur serait probablement nécessaire si les locaux étaient habités en permanence. Dans quatre bâtiments, l'énergie auxiliaire est fournie par une chaudière à combustible branchée sur l'installation et, dans trois autres, par des pompes à chaleur (thermopompes) actionnées par de l'eau chauffée par le soleil.

Tous les bâtiments sont équipés d'un dispositif d'accumulation de la chaleur. Dans un cas, il s'agit d'une matière qui libère de la chaleur de fusion, dans deux cas d'eau froide emmagasinée pour alimenter une pompe à chaleur, dans un cas d'eau chaude emmagasinée, soit pour le chauffage direct, soit pour alimenter une pompe à chaleur, dans deux cas d'eau chaude emmagasinée pour des usages directs, dans un cas de chaleur emmagasinée dans deux compartiments contenant des pierres, et dans un cas enfin d'une accumulation combinée dans un réservoir d'eau chaude et dans des pierres chauffées.

Les données concernant trois constructions résidentielles et deux laboratoires montrent que les

Tableau 1. *Caractéristiques des bâtiments chauffés à l'énergie solaire (A)*

Cote du mémoire ONU	*S/3*	*S/30*	*S/49*	*S/67*	*S/93*	*S/94*	*S/112*	*S/114*
Auteurs	Thomason	Bliss	Pleijel, Lindstrom	Engelbretson	Olgyay	Yanagimachi	Fukuo *et al.*	Löf, El Wakil, Chiou
Site du bâtiment	Washington, D.C., EUA	Arizona, EUA	Capri, Italie	Massachusetts, EUA	New Jersey, EUA	Tokyo, Japon	Nagoya, Japon	Colorado, EUA
Destination du bâtiment	Résidence n° 1	Laboratoire	Laboratoire	Résidence IV	Laboratoire	Résidence II	Laboratoire	Résidence
Caractéristiques du site :								
Latitude, degrés N	39°	32°	41°	42°	40°	36°	35°	40°
Altitude, pieds	Env. 50	2 600	750	Env. 200	Env. 50	Env. 200	Env. 20	5 400
Degrés-jours normaux (°F, j/an)	4 300	1 800	Env. 2 640*	Env. 6 000	5 100	3 800		6 100
Intensité solaire moyenne — janv. (/j)	160	Env. 300	Env. 125-150	160	160	228	Env. 275*	220
Température minimale théorique	13°	30°	Env. 30° *	8°, — 10° (5)	Env. 10°	32		0°
Caractéristiques du bâtiment :								
Surface de plancher (à chauffer) pieds carrés	1 500	1 440	1 940	1 450	1 200	2 460	880	3 200
Nombre d'étages chauffés	1*	1	2*	2	1	2	1	1-1/2
Puissance thermique théorique (max.) (Btu/h)		Env. 35 000		37 000 (5)	25 000	25 000		108 500
Puissance thermique moyenne en janvier (Btu/h)	Env. 8 400 (?)*	Env. 20 000*	Env. 7 400*	18 000*	12 500	Env. 20 000*	36 000 (15)	50 000 (17)
Btu nécessaires par degré - jour	Env. 7 000 (?)*	Env. 18 000*	Env. 12 000*	12 000	Env. 9 000*	17 000*	37 000 (15)	32 000 (17)
Besoins totaux pour l'hiver (Btu)		35,3 MM ('59-'60)		67 MM (4)		64 MM		194 MM
Caractéristiques du collecteur :								
Type, fluide de transfert de chaleur	Eau	Eau	Eau	Eau	Air	Eau	Eau	Air
Position, orientation	Sur mur à 60°, toit à 45°	Sur toit au sud, incliné à 7°	Vertical, mur S.O.	Sur toit au sud, incliné à 60°	Vertical, mur sud	Sur toit au sud, incliné à 15°	Sur toit au sud, incliné à 35°	Sur toit plat, incliné à 45°
Surface, pieds carrés	840	1 623	320	640	600	1 410 (11)	300	600
Surface de transfert de chaleur, type	Tôle ondulée	Feuille de cuivre garnie de tubes	Plaques radiantes métalliques	Tubes de cuivre sur tôle d'aluminium	Tôle métall.	Tôle d'aluminium garnie de tubes	Tôle d'aluminium garnie de tubes	Plaques de verre à recouvrement
Revêtement	Plastique et verre à vitre	Néant	1 plastique, 1 verre	Verre double	Verre double	Néant	Néant	3 ou 4 (16)
Accumulation de la chaleur :								
Type	Eau et pierres	Eau	Eau	Eau	Chaleur de fusion	Eau	Eau	Pierres, 1-1/2 pouce
Volume	1 600 gal. eau	4 500 gal.	800 gal.	1 500 gal.	275 pieds cubes	9 200 gal. (12)	1 480 gal. (14)	250 pieds cubes
Poids	Aussi 50 tonnes pierres	19 tonnes	3,3 tonnes	6,2 tonnes		40 tonnes	6,2 tonnes	12 tonnes
Récipient	Réservoir et bac	Réservoir à deux compartiments	Réservoir	Réservoir	Récipients placés dans des bacs	Réservoir en béton	Réservoir enfoui	2 cylindres en fibre
Capacité calorifique totale, Btu	Env. 1,6 MM	Env. 1,3 MM (?)*		Env. 0,4 MM	2,5 MM (10)	2,4 MM	0,22 MM	0,3 MM
Température normale maximale	125 à 135°F	110° (?)*		Env. 120°		Env. 70°-80 °F	55 °F	140 °F
Source auxiliaire d'énergie :								
Type	Chaudière à mazout	Pompe à chaleur électrique	Poêle et résistance électrique	Chaudière à mazout	Néant	Pompe à chaleur électrique	Pompe à chaleur électrique	Chaudière à gaz naturel
Capacité		Moteur à compression 1,5 ch		Pleine puissance		Moteur à compression 3 ch	3 ch	100 Btu/h.
Mode de distribution	Chauffe l'air des locaux, dérivation vers l'accumulateur	Pompe l'eau chaude vers l'accumulateur	Chauffe directement les locaux	Chauffe l'eau de l'accumulateur auxiliaire		Pompe du réservoir solaire au réservoir chaud	Pompe du réservoir solaire au réservoir chaud	Chauffe l'air du collecteur ou de l'accumulateur
Collection et distribution de la chaleur :								
Transport vers l'accumulateur	Emmagasine l'eau chaude, la conduit vers les pierres	Emmagasine l'eau chaude	Emmagasine l'eau chaude	Emmagasine l'eau chaude	Air chaud vers accumulateur à chaleur de fusion	Emmagasine l'eau réchauffée	Emmagasine l'eau réchauffée	Air chaud vers les pierres
Transport vers les pièces	Circulation d'air à travers les pierres	Circulation d'eau chaude dans le plafond radiant	Circulation d'eau chaude par radiateur	Échange de chaleur vers l'air	Air des locaux à travers l'accumulateur	Eau chaude dans le plafond radiant	Eau chaude vers le chauffe-air	Air des locaux à travers les pierres
Consommation des moteurs	1 pompe, 1 ventilateur	Pompes 2-1/4 ch	2 pompes 2 gal./min.	2 pompes, ventilateur		Pompes 3-1/2 ch, pompe 1,1 ch	2 pompes	Moteur 1,1 ch pour soufflante
Circulation dans le collecteur	7,15 gal./min.		2,1 gal./min.	10,7 gal./min.			16 gal./min.	770 cfm
Circulation dans les locaux				Eau 3,6 gal./min.; air 850 cfm				

Table 1 (suite)

Cote du mémoire ONU	*S/3*	*S/30*	*S/49*	*S/67*	*S/93*	*S/94*	*S/112*	*S/114*
Fourniture d'eau chaude :	Ou pré-chauffage	Néant	Collecteur distinct proposé	Oui, pré-chauffable		Oui, fournit. intégrale	Non	Oui, pré-chauffage
Chaleur auxiliaire				De l'accumulateur chauffé par combustible	De la pompe à chaleur 1 ch (13)			Chaudière à gaz automatique
Source solaire	Eau chaude du collecteur			Eau chaude du collecteur		Collecteur distinct de 350 pieds²		Air chaud du collecteur
Dispositifs de transfert	1 réservoir dans l'autre			Serpentin dans le réservoir d'emmagasinage		Via pompe à chaleur		Échangeur thermique air-eau
Dispositifs de contrôle automatique :	Partiels	Complets	Partiels	Complets	Oui	Complets	Oui	Complets
Thermostats du collecteur et de l'accumulateur	Collecteur	Collecteur et accumulateur	Collecteur et accumulateur	Collecteur et accumulateur	Collecteur	Collecteur et accumulateur	Collecteur et accumulateur	Collecteur et accumulateur
Contrôle automatique du chauffage auxiliaire		Oui	Néant	Oui		Oui	Oui	Oui
Vannes autom. ou humidificateurs		Oui	1 vanne mélangeuse	1 vanne mélangeuse		Non		2 pour humidificateurs
Chauffage direct à partir du collecteur	Non (1)	Non (1) (2)	Non (1)	Non (1)		Non (1)	Non (1)	Oui
Enregistrement automatique	Non	Oui		Oui		Oui	Oui	Oui
Pyrhéliomètre	Non	Oui	Oui	Oui		Non	Oui	Oui
Réfrigération :	Oui	Oui	Pas actuellement	Non	Non	Oui	Oui	Non
Méthode d'évacuation de la chaleur	Convection nocturne, évaporation, radiation	Radiation nocturne et convection				Radiation nocturne et convection	Radiation nocturne et convection	
Système auxiliaire	Néant	Pompe à chaleur				Pompe à chaleur	Pompe à chaleur	
Consommation d'énergie	1/4 ch	1-1/2 ch				3 ch	3 ch	
Évacuation de la chaleur des locaux	Air des locaux à travers les pierres refroidies	Eau froide dans les panneaux du plafond				Eau dans le plafond et échangeur d'air	Eau à travers échangeur d'air	
Performances : Période	Hiver '60-'61	Hiver '59-'60	Pas encore indiqué	Hiver '60-'61 (4)		Hivers '59-'60-'61	Nov.-mars, moyenne	Hiver '59-'60
Rendement moyen du collecteur (pendant le fonctionnement effectif)		28,7 p. 100 (janv. seulement)		40,8 p. 100	46,5 p. 100 (estim. déc. janv.) (9)		Janv., moy. approx. 54 p. 100	34,6 p. 100
Rendement moyen du collecteur (rayonnement total)		17,2 p. 100 (janv. seulement)		32,6 p. 100		22 p. 100 (estim.)*		24,5
Quantité totale de chaleur fournie par l'énergie solaire en hiver		30,3 MM Btu*		38,1 MM Btu (4) (8)		Env. 45 MM Btu	14,5 MM Btu	51,7 MM Btu (8)
Quantité d'énergie fournie à l'installation auxiliaire	42 gal. mazout	1 470 kWh = 5,0 MM Btu				5 580 kWh = 19 MM Btu	1 370 kWh = 4,7 MM Btu	230 200 pieds cubes de gaz (8)
Équivalent de chaleur de l'installation auxiliaire	4-5 MM Btu.	Env. 17 MM Btu* (3)		28,9 MM Btu (4) (8)		Env. 63 MM Btu	Env. 15,5 MM Btu*(3)	141,8 MM Btu (8)
Pourcentage fourni par l'énergie solaire	95 p. 100 (est.)	86 p. 100 (6); 64 p. 100* (7)	50-70 p. 100 (prévision)	56,8 p. 100 (8)		70 p. 100 (6); 48 p. 100* (7)	75 p. 100 (6); 48 p. 100* (7)	26,5 p. 100 (8)

* = Valeur calculée ou estimée par le rapporteur.
Env. = Environ.
?* = Valeur estimative incertaine calculée par le rapporteur.
MM = 1 000 000.
(A) = Toutes les valeurs exprimées en unités anglaises sauf le rayonnement solaire.
(1) = Toute la chaleur solaire fournie au bâtiment par l'intermédiaire du dispositif d'emmagasinage, c'est-à-dire en suivant la voie collecteur-accumulateur.
(2) = Locaux installation conçue pour réaliser le chauffage des locaux directement à partir de l'accumulateur de chaleur solaire (système habituel) ou à partir de la section d'emmagasinage.
(3) = Calculé en supposant un rendement du condenseur de la thermopompe de 30 p. 100 (rendement moyen d'une centrale thermique à vapeur).
(4) = Six mois seulement (octobre à mars 1960-61, chauffage d'avril non compté)
(5) = L'auteur calcule les besoins maximaux sur la base d'une température minimale de − 10 °F
(6) = Fondé sur un rendement thermique égal du travail et de la chaleur, c'est-à-dire 1 kWh = 3 412 Btu.
(7) = Calculé d'après l'hypothèse mentionnée en (3) ci-dessus, le rendement devient effectivement égal à la quantité de chaleur solaire fournie au bâtiment divisée par la somme de cette quantité et de la chaleur fournie par le combustible qui serait brûlé dans une centrale thermique moyenne pour produire la quantité d'électricité nécessaire.
(8) = Non compris le chauffage de l'eau. Les valeurs correspondantes *comprenant* le chauffage de l'eau seraient : pour le mémoire S/67, 47,4 MM Btu, 36,4 MM Btu et 56,6 p. 100; pour le mémoire S/114, 55,7 MM Btu, 264 000 pieds cubes, 145,8 MM Btu et 25,7 p. 100.
(9) = Chiffres sans données à l'appui.
(10) = Capacité théorique; pas de données à l'appui.
(11) = Pour le chauffage de locaux et le chauffage de l'eau.
(12) = Également un réservoir de 2 700 gal. pour emmagasiner l'eau réchauffée par le condenseur des pompes à chaleur.
(13) = Également une pompe à chaleur de 1/2 ch branchée sur la source solaire et servant de chauffe-bain.
(14) = Également un réservoir de 1 430 gal. pour emmagasiner l'eau réchauffée par le condenseur de la pompe de chaleur.
(15) = Valeur théorique pour les déperditions de chaleur par heure diurne (fonctionnement d'une durée de dix heures seulement par jour); et par période de 24 heures pour chaque °F de différence entre 65 °F et la température atmosphérique moyenne en janvier de 36,5 °F.
(16) = Vingt sections sur quarante ont deux plaques de verre qui se chevauchent plus une servant de couverture. Les 20 autres (panneaux [illegible]) ont [illegible] et deux plaques de couverture.
(17) = Valeurs expérimentales. Les valeurs théoriques étaient d'environ 25 p. 100 plus élevées.

Facteurs de conversion

1 pied = 0,3048 m
1 Langley = 1 cal/cm² ou 3,69 Btu/pied carré
1 pied carré = 0,0929 m²
1 Btu = 0,252 kcal, ou 0,0002928 kWh
1 gallon = 3,785 l ou 0,003785 m³
1 livre = 0,4536 kg
1 tonne = 907,2 kg
1 pied cube = 0,0283 cm³.

systèmes de chauffage installés dans ces bâtiments sont équipés d'une régulation automatique satisfaisante et de dispositifs perfectionnés d'enregistrement des performances. Les résultats obtenus avec ces systèmes sont donc particulièrement précieux. La plupart des conclusions données dans la suite de ce rapport sont tirées des mémoires décrivant ces cinq installations, à savoir celles de l'Arizona (mémoire S/30), du Massachusetts (mémoire S/67), de Tokyo (mémoire S/94), de Nagoya (mémoire S/112) et du Colorado (mémoire S/114).

Caractéristiques du site

Tous les bâtiments sont situés sous une latitude comprise entre 35 et 40° nord, donc dans une bande assez étroite. Cependant, les températures atmosphériques normales régnant en hiver sont très différentes selon les sites, et le nombre de « degrés-jours » de chauffage varie entre 1 800 et 6 100 (ce nombre se calcule en faisant la somme des différences journalières de température entre 65 °F et toutes les températures atmosphériques moyennes inférieures). De même la quantité normale de rayonnement solaire en janvier est très inégale, variant d'environ 125 langleys par jour à près de 300. Les conditions les plus « sévères » pour le chauffage solaire, exprimées comme le rapport entre le rayonnement moyen en janvier et le nombre normal de degrés-jours de chauffage, se rencontrent dans le Massachusetts, et les conditions les plus favorables dans l'Arizona.

On constate de très grandes variations dans la réalisation et les besoins calorifiques des cinq bâtiments. Le bâtiment résidentiel de Washington semble avoir les plus faibles déperditions de chaleur, qui sont d'environ 7 000 btu par degré-jour (calculées à partir de la capacité d'accumulation thermique et de la durée indiquée pour le chauffage réalisé avec l'accumulateur) et la maison du Colorado les plus fortes déperditions, soit 32 000 btu. La déperdition calorifique au laboratoire de Nagoya atteint environ 37 000 btu par degré-jour, mais ce local n'est destiné à être chauffé que 10 heures par jour. Les déperditions calorifiques de la plupart des bâtiments se situent entre 9 000 et 18 000 btu environ par degré-jour. Les besoins thermiques totaux en hiver (valeur calculée) pour quatre bâtiments vont de 35 millions à 194 millions de btu (Arizona et Colorado, respectivement).

Il est intéressant de noter que dans presque toutes les installations pour lesquelles des chiffres sont indiqués, la demande *maximale* de chaleur est environ le double de la demande moyenne pour janvier seulement. Cette différence est naturellement moindre dans les régions où la température atmosphérique est largement stabilisée par la présence de grandes étendues d'eau. Les chiffres exprimant les besoins calorifiques moyens pour le mois de janvier dans les divers bâtiments varient au moins du simple au quadruple, mais la plupart sont de l'ordre de 25 000 à 35 000 btu par heure. Les besoins semblent plus faibles dans deux bâtiments, mais les chiffres ne sont pas donnés.

Collecteurs solaires

Deux collecteurs ont des plaques verticales; tous font face au sud, sauf un qui regarde le sud-ouest; cinq sont intégrés à la pente du toit et l'un s'élève sur des appuis séparés au-dessus d'un toit plat. L'inclinaison varie de 7 à 60° par rapport à l'horizontale. La surface des collecteurs solaires varie dans une proportion de 1 à 5 environ, soit de 300 à 1 623 pieds carrés. Il semble que les ingénieurs aient choisi la surface des collecteurs plutôt en fonction des caractéristiques structurelles et des facteurs limitatifs inhérents aux bâtiments que pour réaliser les conditions théoriques les plus favorables. On comprend fort bien qu'il en soit ainsi au stade actuel des recherches, car le choix du collecteur idéal ne peut être fixé tant que l'on ne possède pas de données précises sur le prix de revient des installations de chauffage solaire. S'il avait fallu tenir compte du coût effectif de la construction dans les estimations initiales, aucune des installations de chauffage solaire n'aurait été construite et la surface optimale du collecteur serait égale à zéro. Étant donné le but expérimental de toutes ces installations, n'importe quelle surface de collecteur arbitrairement choisie peut être satisfaisante, dès lors qu'elle est assez grande pour assurer des performances statistiquement significatives. Les dimensions de la plupart des collecteurs ont donc été déterminées surtout en fonction des surfaces disponibles sur les murs ou sur la toiture.

Il est cependant intéressant d'examiner dans quelle mesure la conception des divers collecteurs paraît satisfaisante ou, en d'autres termes, leur « aptitude théorique ». Il est évident qu'un grand collecteur solaire installé dans un climat ensoleillé sur un bâtiment dont les besoins de chaleur sont assez réduits permettra de satisfaire une plus grande proportion de ces besoins qu'un collecteur relativement petit, placé sur une maison recevant une moins grande quantité de rayonnement en hiver et ayant des besoins thermiques plus élevés. Pour pouvoir comparer l'aptitude des divers systèmes de chauffage solaire à satisfaire les besoins thermiques totaux, le rapporteur a calculé à partir des chiffres figurant dans les mémoires trois rapports différents. Le premier, que l'on pourrait appeler un « facteur atmosphérique » est le rapport du rayonnement solaire aux besoins thermiques normalisés, c'est-à-dire exprimés en degrés-jours par an. La quantité de rayonnement reçu en janvier, en langleys par jour sur une surface horizontale, a été arbitrairement multipliée par 3,69 pour conversion en unités anglaises, par 1,5 pour la rapprocher de la quantité de rayonnement solaire reçue pendant toute la saison de chauffage, et par 200 pour tenir compte du nombre de jours compris dans la saison de chauffage. Les quotients obtenus sont indiqués au tableau 2. On doit admettre que leur valeur numérique n'a pas de signification physique et que seule importe leur valeur relative pour chacune des installations. Comme on l'a dit plus haut, les conditions régnant dans le Massachusetts apparaissent comme les plus sévères et celles de l'Arizona comme les plus favorables.

Le second facteur peut être dénommé « indice théorique de chauffage ». C'est le rapport entre la surface du collecteur solaire et les besoins thermiques du bâtiment exprimés en btu par degré-jour. Plus ce quotient est élevé, plus le dispositif de chauffage solaire est largement conçu pour le site considéré. Les valeurs de ce quotient apparaissent aussi sur le tableau 2. Les conditions atmosphériques mises à part, on voit que le collecteur solaire qui équipe la résidence de Washington est le plus grand par rapport à la grandeur du bâtiment et à ses caractéristiques de transfert thermique. Le quotient le plus faible est celui du laboratoire de Nagoya, mais étant donné que ce bâtiment n'est destiné à être occupé que pendant la journée, on ne peut attacher la même importance à ce rapport. Parmi les bâtiments habités en permanence, c'est la maison du Colorado qui possède le quotient le plus faible.

Le produit des deux quotients précédents représente ce que l'on peut considérer comme l'« aptitude théorique » de l'installation solaire. Là encore, ce n'est pas la valeur d'un coefficient considéré isolément qui est importante. (Pourtant, si l'on utilisait la quantité totale de rayonnement solaire effectivement reçue en hiver en l'ajustant aux valeurs applicables aux divers collecteurs inclinés et verticaux, on obtiendrait des rapports définitifs qui représenteraient la quantité totale de rayonnement solaire frappant le collecteur en hiver divisée par la quantité totale de chaleur nécessaire au bâtiment pendant cette saison. Ce mode de calcul plus raffiné n'a pas été appliqué pour l'établissement de ces rapports, si bien que seules leurs valeurs relatives les unes par rapport aux autres doivent être prises en considération; ils reflètent cependant de façon approximative le rapport dont il vient d'être question.) On voit immédiatement que le laboratoire de l'Arizona est équipé du collecteur le plus « généreusement » conçu, tandis que la maison du Colorado semble satisfaire la plus petite proportion des besoins thermiques totaux. Des quatre bâtiments d'habitation étudiés, ceux de Washington et de Tokyo devraient fournir la plus grande fraction de la chaleur requise.

Certains collecteurs ne comportent aucun revêtement, tandis que d'autres sont munis de trois ou quatre couches de verre. Les collecteurs non revêtus ont tous une température de fonctionnement relativement basse et alimentent des pompes à chaleur qui fournissent les températures voulues pour le chauffage domestique. Ils servent également de radiateurs pour la chaleur extraite de la maison au moyen de la pompe à chaleur. Le revêtement double est le plus commun dans les collecteurs atteignant une température plus élevée, et pour ceux-ci on ne se sert guère de revêtements à composition plastique.

Systèmes d'accumulation

La capacité d'emmagasinage de la chaleur varie d'environ 200 000 btu dans le laboratoire de Nagoya, à 2,5 millions de btu dans la résidence de Tokyo et au laboratoire de New Jersey. Si l'on compare les capacités d'emmagasinage aux besoins thermiques normaux pour le mois de janvier, on constate qu'elles varient de environ un quart des besoins d'une journée normale en janvier (maison du Colorado) à environ une semaine (maison de Washington). Le laboratoire de l'Arizona peut emmagasiner la chaleur nécessaire pendant environ 2 jours et demi normaux de janvier, tandis que la maison du Massachusetts peut accumuler environ un jour de chaleur, le laboratoire du New Jersey 8 jours, la résidence de Tokyo 5 jours et le laboratoire de Nagoya un peu moins de 10 heures diurnes. Ces chiffres indiquent que les auteurs n'ont pas tous la même opinion sur l'utilité d'une accumulation « à long terme », c'est-à-dire de la chaleur nécessaire pour plusieurs jours. Quelques chercheurs, dont le rapporteur, sont arrivés à la conclusion qu'il n'est pas économique d'emmagasiner la chaleur pour une durée supérieure à un ou deux jours (besoins thermiques moyens de janvier) parce que la diminution de la consommation de combustible qui résulte d'un emmagasinage d'une durée supérieure est proportionnellement trop faible. Pour prendre un exemple, le cas où une réserve de chaleur de huit jours (besoins calorifiques moyens en janvier) aurait été nécessaire alors que quatre jours d'emmagasinage sont normalement

Tableau 2. Indices d' « aptitude théorique » des installations

(1) Site du bâtiment	(2) Rayonnement en janvier langleys/jour	(3) Degrés/jours par an	(4) « Facteur atmosphérique » C* × (2)/(3)	(5) Surface du collecteur pieds²	(6) Pertes Btu par degré/jour	(7) « Indice théorique de chauffage » (5)/(6)	(8) « Indice d'aptitude théorique » (4) × (7)
Washington . . .	160	4 300	41	840	7 000	0,12	4,9
Arizona	300	1 800	190	1 623	18 000	0,09	17
Capri	140	2 640	59	320	12 000	0,027	1,6
Massachusetts . .	160	6 000	30	640	12 000	0,053	1,6
New Jersey . . .	160	5 100	34	600	9 000	0,067	2,3
Tokyo.	228	3 800	67	1 140	17 000	0,083	5,6
Nagoya	275			300	37 000	0,008	
Colorado.	220	6 100	40	600	32 000	0,019	0,76

* $C = 3{,}69 \times 200 \times 1{,}5 = 1\,110$, où 3,69 est un coefficient de conversion des langleys en Btu/pied carré, 200 est le nombre approximatif de jours compris dans la saison de chauffage et 1,5 la valeur approximative du rapport entre le rayonnement solaire moyen pendant la saison de chauffage et le rayonnement moyen en janvier.

suffisants, seront si rares que les quelques gallons de mazout qu'il faudra brûler chaque année pour faire face à ces circonstances exceptionnelles coûteront presque toujours moins cher que le supplément de frais fixes à prévoir pour doubler la capacité d'emmagasinage. Les chiffres contenus dans les mémoires ne sont pas assez détaillés pour permettre une évaluation plus complète de la capacité optimale d'emmagasinage.

Dans le mémoire S/3 concernant la maison de Washington, l'auteur décrit un système d'emmagasinage qui associe de l'eau et des galets. Il semble que le transfert de la chaleur aux galets se fasse par conduction depuis le réservoir d'eau autour duquel les pierres sont entassées. L'efficacité du système paraît sujette à caution en ce qui concerne le rôle des galets, car le transfert de chaleur dans un lit de pierres non jointives est extrêmement lent. L'enveloppe du réservoir et les galets les plus proches constituent sans doute les principales surfaces d'échange de chaleur pour l'air qui est envoyé vers les locaux. Il paraît douteux que toute la masse des galets disposés dans le compartiment d'emmagasinage puisse être portée aux températures indiquées.

Dans le mémoire S/93 concernant le laboratoire du New Jersey, l'auteur décrit un accumulateur à chaleur de fusion. Si toute la matière fusible est efficace, la forte capacité d'emmagasinage (2,5 millions de btu) sera réalisée. Toutefois, il a été démontré que les matières fusibles employées jusqu'à présent tendent à se stratifier dans les récipients où elles sont enfermées et qu'elles perdent leur capacité d'accumulation thermique. L'auteur affirme avoir tenu compte de ce facteur dans le plan de son installation, mais il n'indique ni la nature de la matière accumulatrice, ni ses performances. On ne peut donc apprécier l'efficacité de cet agent, ni savoir si la stratification a véritablement été évitée. Si la séparation des phases n'a pu être empêchée, la matière utilisée aura sans doute une capacité d'emmagasinage à peu près égale à celle de l'eau, soit environ 0,8 million de btu.

Les températures maximales d'emmagasinage semblent se situer dans deux intervalles principaux. Les faibles températures d'emmagasinage obtenues dans les deux bâtiments japonais sont caractéristiques des systèmes utilisant des pompes à chaleur et des collecteurs sans revêtement. Par contre, les températures plus élevées, de l'ordre de 120 à 140°, conviennent au chauffage direct. Un niveau intermédiaire, obtenu dans la maison de l'Arizona, permet d'utiliser directement la chaleur de l'accumulateur lorsque la température est suffisante, et de l'utiliser indirectement pour alimenter une pompe à chaleur lorsque la température est trop basse.

Il semble que tous les systèmes d'emmagasinage aient permis de compenser les heures sans soleil, dans une plus ou moins grande mesure, selon leur capacité calorifique et les facteurs limitatifs inhérents au fonctionnement. Toutefois, comme dans le cas des collecteurs, les données d'ordre économique font défaut.

Source auxiliaire d'énergie

A l'exception du laboratoire du New Jersey, tous les bâtiments décrits disposent d'une source auxiliaire de chaleur. Chaque fois que ce point est précisé, les auteurs indiquent que la source auxiliaire est capable de fournir la totalité de la chaleur requise ; toutefois, les dispositifs auxiliaires à thermopompe devraient sans doute être plus largement dimensionnés s'ils utilisaient simplement de l'air atmosphérique. La consommation d'énergie auxiliaire est minimale dans la résidence de Washington où l'auteur l'évalue à environ 5 p. 100, et maximale dans la résidence du Colorado où elle a été chiffrée à 74 p. 100 (valeur mesurée). Aucun auteur n'a fait état de difficultés sérieuses pour incorporer le dispositif auxiliaire à l'installation de chauffage générale et pour le faire fonctionner en conjonction avec la source solaire. Tous les systèmes auxiliaires paraissent contrôlés automatiquement, ce qui leur permet d'entrer en action dès que la source solaire devient insuffisante.

Le mémoire S/93 sur l'installation du New Jersey, la seule qui ne comporte pas de source auxiliaire, ne donne pas de renseignements permettant d'évaluer l'efficacité du système. Même si l'on tient compte de la longue durée d'emmagasinage (plusieurs jours) et des autres caractéristiques (collecteur vertical de 600 pieds carrés de surface, 160 langleys par jour sur une surface horizontale, puissance thermique moyenne en janvier de 12 500 btu par heure et rendement du collecteur égal à 46 p. 100), le dispositif solaire est à peine capable de fournir la quantité moyenne de chaleur requise. Cependant, au cours d'un mois de janvier où la température moyenne descendrait de plusieurs degrés au-dessous de la normale (ce qui arrive toutes les quelques années) surtout si la quantité de rayonnement solaire était aussi inférieure à la normale, le bâtiment ne pourrait être chauffé complètement sans un apport auxiliaire. Ces divers facteurs montrent combien il est difficile de réaliser une installation satisfaisante de chauffage solaire ne comportant aucun dispositif auxiliaire dans toutes les circonstances où les basses températures hivernales rendent indispensable le chauffage des locaux.

Le rapporteur tient également à s'arrêter sur l'affirmation (mémoire S/93) selon laquelle un collecteur solaire doit être suffisamment grand pour satisfaire tous les besoins thermiques *normaux* d'un bâtiment pendant le mois le plus froid, à supposer que le bâtiment reçoive une quantité *normale* de rayonnement pour le mois considéré. Étant donné qu'il est impossible de déterminer les dimensions optimales d'un collecteur sans tenir compte du prix de revient, une affirmation aussi catégorique ne peut être fondée en bonne logique. D'autres postulats théoriques, par exemple celui qui veut qu'à deux pieds carrés de surface de plancher corresponde un pied carré de collecteur vertical, ou que le dispositif d'accumulation occupe 4 p. 100 de la surface de plancher, doivent être considérés comme des hypothèses arbitrairement choisies et non comme des conditions optimales.

Collection et distribution de la chaleur

Le tableau 1 montre que dans la plupart des systèmes l'eau est chauffée dans le collecteur, après quoi elle sert de fluide intermédiaire pour le transport de la chaleur vers l'accumulateur et, de là, vers les locaux. Toutefois, dans les maisons de Washington et du Massachusetts, la chaleur est transférée de l'eau chaude emmagasinée à l'air que l'on fait circuler dans les chambres, l'air étant ainsi le véhicule final de la chaleur. L'installation de la maison de Washington comporte une circulation d'air autour du réservoir d'eau chaude et entre les pierres adjacentes; celle du Massachusetts emploie un échangeur de chaleur à tubes à ailettes à travers lequel circule l'eau chaude en provenance du réservoir solaire ou du réservoir d'eau chaude auxiliaire.

Systèmes de circulation

Dans les deux installations équipées de chauffe-air solaires, la chaleur est transférée de l'air à une matière d'emmagasinage fusible (laboratoire du New Jersey) ou à des pierres (résidence du Colorado). Pour transférer la chaleur de l'accumulateur aux locaux, on fait circuler l'air de la maison à travers les compartiments d'emmagasinage. Deux moteurs au moins sont nécessaires dans toutes les installations pour actionner les pompes ou les soufflantes, sauf dans la résidence du Colorado, où un seul moteur est nécessaire pour le ventilateur.

Il est intéressant de constater que les chiffres qui concernent la vitesse de circulation du fluide à travers les collecteurs solaires sont assez homogènes d'un mémoire à l'autre. Pour l'eau, le débit en gallons par minute par pied carré de collecteur solaire est égal à 0,85 dans la résidence de Washington, 0,65 au laboratoire de Capri, 1,67 dans la résidence du Massachusetts, 5,3 au laboratoire de Nagoya, tandis que pour l'air il est de 1,3 pied cube par minute par pied carré de collecteur solaire dans la résidence du Colorado. Un débit moyen d'environ 1 gallon par minute pour chaque pied carré de collecteur chauffant de l'eau paraît adéquat pour les installations qui atteignent les températures les plus élevées, tandis que dans les chauffe-air solaires le débit se situe à environ 1 pied cube d'air par minute et par pied carré.

Production d'eau chaude

Dans quatre bâtiments, l'eau chaude à usage domestique est produite au moins en partie par l'énergie solaire. Dans la résidence de Tokyo, elle est produite par un collecteur solaire séparé qui fonctionne à basse température et alimente une thermopompe de 1 CV. Dans les résidences de Washington et du Colorado, une petite fraction de la chaleur fournie par le collecteur solaire sert à préchauffer l'eau destinée aux usages domestiques, qui est ensuite portée à la température voulue dans un chauffe-eau à combustible. La maison du Massachusetts comporte une section de préchauffage de l'eau dans le grand réservoir d'accumulation solaire. Dans aucune des installations le chauffage de l'eau ne semble avoir été un élément primordial du projet.

Dispositifs de contrôle automatique et instrumentation

Cinq auteurs indiquent qu'ils ont accordé une grande importance aux dispositifs de contrôle automatique et d'enregistrement des données. Des renseignements détaillés sont donnés sur les dispositifs de contrôle installés dans les résidences du Massachusetts et du Colorado, et l'instrumentation du laboratoire de l'Arizona est décrite en termes plus généraux. Une discussion de ces caractéristiques sortirait du cadre du présent rapport, et le lecteur est prié de se reporter au texte des mémoires respectifs. On peut cependant faire plusieurs constatations utiles. Un grand soin doit être apporté à la conception des dispositifs de contrôle pour assurer le plein rendement de l'installation de chauffage solaire. Le contrôle doit en particulier empêcher que le prix de revient du captage de la chaleur solaire, lorsque celle-ci est peu intense, dépasse la valeur effective de cette énergie. Les mémoires contiennent des considérations particulièrement intéressantes sur les problèmes de contrôle qui se sont présentés et les méthodes adoptées pour les résoudre. Plusieurs chercheurs ont signalé qu'une fois écartées certaines difficultés, et après un certain temps d'expérience, l'automaticité du contrôle a été intégralement réalisée. Ils relèvent aussi la nécessité d'une instrumentation bien conçue et entretenue pour l'évaluation des performances.

Dispositifs de réfrigération

Quatre bâtiments ont aussi été équipés d'installations de réfrigération. Leur fonctionnement est basé sur l'évacuation de la chaleur pendant la nuit, alors que la température atmosphérique a, en général, diminué. Dans le laboratoire de l'Arizona, la résidence de Tokyo et le laboratoire de Nagoya, la chaleur est extraite des locaux pendant la journée (et la nuit si nécessaire) par absorption dans l'eau fraîche issue de l'évaporateur de la thermopompe. La chaleur ainsi évacuée est emmagasinée temporairement dans l'eau chaude du côté du condensateur de la thermopompe. La circulation de l'eau tiède à travers la plaque nue du collecteur solaire pendant la nuit permet un transfert de la chaleur vers l'atmosphère par convection et vers le ciel par radiation.

Dans le laboratoire de Nagoya, l'air venant des locaux est refroidi à l'eau dans un échangeur muni de tubes à ailettes, alors que dans le laboratoire de l'Arizona la réfrigération se fait par circulation d'eau fraîche entre des tôles ondulées disposées dans le plafond. Dans la résidence de Tokyo, ces deux systèmes sont associés. Il est remarquable que, dans le laboratoire de l'Arizona — région au climat extrêmement chaud — la réfrigération ait pu être assurée avec un moteur de 1,5 CV, alors que dans les maisons de même grandeur un moteur de 5 CV est couramment utilisé. Deux ou trois fois seulement, il a été nécessaire de laisser la température de la chambre monter au-dessus du niveau désirable pour éviter une condensation sur les panneaux du plafond.

Aucune pompe à chaleur n'a été employée dans l'installation de Washington. L'air en provenance des chambres était circulé à travers les galets et le long de la surface du réservoir d'eau. Le transfert de chaleur vers l'eau avait lieu pendant le jour. La nuit, l'eau légèrement réchauffée était pompée vers la pente nord du toit métallique où elle se refroidissait par évaporation, convection et radiation.

Ces installations, on le voit, n'utilisent pas l'énergie solaire pour la réfrigération. Toutefois, trois d'entre elles se servent du collecteur solaire pour évacuer la chaleur et du dispositif d'accumulation de la chaleur solaire pour emmagasiner temporairement la chaleur avant de l'évacuer pendant la nuit. La thermopompe fournit de l'énergie pour les besoins du chauffage et de la réfrigération. Cette utilisation combinée d'une grande partie de l'installation permet d'obtenir des facteurs de charge plus intéressants du point de vue économique.

La réfrigération par l'énergie solaire sera étudiée tout spécialement au titre du point III.D de l'ordre du jour, de sorte qu'il n'est pas nécessaire d'insister davantage ici sur ces divers systèmes.

Performances

De bonnes performances sont décrites à propos de cinq installations de chauffage solaire examinées à cette Conférence. Le choix d'une instrumentation appropriée, le soin apporté à l'examen des enregistrements et le détail dans lequel les chiffres ont été communiqués font des mémoires en question des publications de valeur.

Parmi les installations à « haute » température, c'est le collecteur solaire du Massachusetts qui, d'après les données fournies, semble posséder le rendement le plus élevé en période de fonctionnement, soit 40,8 p. 100 pendant tout l'hiver. Pour le collecteur du New Jersey, l'auteur évalue le rendement à 46,5 p. 100 pour décembre et janvier, mais ne donne pas les chiffres sur lesquels il fonde cette estimation. Le chauffe-air solaire du Colorado a présenté un rendement total de 34,6 p. 100 pendant l'hiver en période de fonctionnement. Pour les collecteurs des bâtiments du Massachusetts et du Colorado, le rendement a été calculé sur la base de la quantité totale du rayonnement solaire reçue pendant l'hiver, et les valeurs obtenues sont de 32,6 et 24,5 p. 100 respectivement. Pour le laboratoire de l'Arizona, les rendements obtenus en janvier sont de 28,7 p. 100 (en période de fonctionnement) et de 17,2 p. 100 (rayonnement total). Bien que fonctionnant à une température plus basse, le collecteur de l'Arizona semble être le siège d'une déperdition de chaleur suffisamment importante pour qu'il vaille la peine d'envisager de le revêtir peut-être d'un couvercle amovible que l'on pourrait enlever pendant la saison de réfrigération.

Le collecteur de Nagoya, qui fonctionne au-dessous de 55 °F, capterait la chaleur solaire à raison de 54 p. 100 environ (moyenne de janvier). On peut penser qu'à une température aussi basse une certaine quantité de chaleur est également transférée de l'atmosphère au collecteur. A la résidence de Tokyo, le rendement moyen de collection solaire en hiver — estimé d'après la quantité totale de rayonnement — est d'environ 22 p. 100.

D'après plusieurs séries de résultats figurant dans les mémoires, le rendement de collection solaire semble donc en définitive se situer entre 35 et 45 p. 100 en période de fonctionnement et entre 25 et 35 p. 100 si on le calcule d'après la quantité totale de rayonnement solaire reçue en hiver (chiffres obtenus pour la période d'hiver dans les parties les plus froides de la zone tempérée). Selon les indications des auteurs, ces chiffres pourraient être améliorés en consacrant plus d'attention à certains détails de réalisation et de fonctionnement. Il semble que le rendement moyen en période de fonctionnement pourrait atteindre environ 50 p. 100 au maximum pour les installations et les conditions générales décrites.

La quantité totale de chaleur solaire fournie aux bâtiments pendant la période d'hiver a varié de 40 millions de btu (laboratoire de Nagoya) à 52 millions (maison du Colorado). En plus, les dispositifs auxiliaires ont dû produire 16 millions de btu pour le laboratoire de Nagoya et 142 millions pour la maison du Colorado. Dans la résidence de Washington, il n'a été utilisé que 5 millions de btu de chaleur auxiliaire qui, selon l'auteur, ont représenté à peu près 5 p. 100 des besoins calorifiques pour la saison d'hiver. Cette dernière estimation semble toutefois contenir une contradiction, car elle signifierait que la quantité totale de chaleur nécessaire en hiver est d'environ 100 millions de btu (5 millions $\times$ 20); or, les besoins calorifiques totaux calculés d'après le nombre de degrés-jours et la quantité de chaleur requise par degré-jour (calcul effectué par le rapporteur d'après le nombre de jours de capacité d'accumulation de chaleur en hiver cité par l'auteur) s'établissent à environ 30 millions de btu. Quoique qu'il en soit, l'usage restreint qui a été fait de l'installation auxiliaire à combustible indique que les dispositifs solaires ont été particulièrement bien conçus, ce qui ressortait déjà du tableau 2.

La proportion de la chaleur totale nécessaire en hiver qui est fournie par le dispositif solaire varie, pour les sept installations équipées d'un chauffage auxiliaire, de 26 p. 100 (valeur mesurée) dans la résidence du Colorado à 95 p. 100 (valeur estimative) dans la résidence de Washington. Parmi les autres bâtiments, c'est le laboratoire de l'Arizona qui a utilisé le plus petit pourcentage de chaleur auxiliaire. En prenant l'énergie électrique comme l'équivalent direct de la chaleur, 86 p. 100 de la chaleur a été fourni par l'énergie solaire. En revanche, si l'on prend pour base l'« équivalent combustible d'une centrale thermique » de l'énergie électrique (calculé d'après un rendement de 30 p. 100), la proportion des besoins thermiques totaux qui ont été satisfaits au moyen du dispositif solaire (c'est-à-dire, la chaleur solaire fournie au bâtiment plus le combustible brûlé pour produire l'électricité utilisée dans la pompe à chaleur) n'a été que de 64 p. 100 dans le bâtiment de l'Arizona. Les chiffres correspondants sont, pour la maison de Tokyo, 70 et 42 p. 100 respectivement et, pour le laboratoire de Nagoya, 75 et 48 p. 100. La maison du Massachusetts a reçu 57 p. 100 de la chaleur requise du dispositif solaire. Ces chiffres concordent donc, dans l'ensemble, avec les indices d'« aptitude théorique » que le rapporteur a calculés au tableau 2.

Considérations économiques

Les données sur le prix de revient de l'énergie et les économies réalisées dans les divers bâtiments grâce aux installations de chauffage solaire sont si fragmentaires et si variables qu'il n'est pas possible de les présenter sous forme de tableau. Quatre mémoires seulement donnent quelques indications sur les prix de revient, mais un gros effort d'interprétation est nécessaire pour en définir la portée.

Le prix du mazout brûlé dans l'installation auxiliaire de la maison de Washington n'a été que de 6,30 dollars pour la saison de chauffage. En reprenant l'évaluation de l'auteur selon laquelle 95 p. 100 de la chaleur nécessaire en hiver a été fournie par le chauffage solaire, le combustible économisé peut être évalué à 120 dollars environ. L'auteur n'indique pas le montant supplémentaire dépensé en électricité, si bien qu'on ne peut estimer les économies nettes.

Dans le laboratoire de l'Arizona, l'énergie électrique dépensée pour le fonctionnement de la pompe à chaleur et du moteur de l'installation de chauffage auxiliaire a atteint 37 dollars pour la saison de chauffage hivernale. L'auteur n'indique pas à combien peuvent être évaluées les économies imputables à l'installation solaire pour les seuls besoins du chauffage, mais il estime qu'un système de chauffage et de climatisation classique aurait entraîné une dépense d'énergie dépassant de 185 dollars ce qui a été effectivement dépensé pendant l'année entière. Le rapporteur estime que la valeur de la chaleur solaire qui a été fournie à l'installation pendant l'hiver représente entre 50 et 60 dollars.

La troisième série d'évaluations du prix de revient concerne la maison du Colorado. L'auteur a calculé qu'environ 80 dollars d'équivalent de gaz naturel ont été économisés par la chaleur solaire, mais que l'énergie supplémentaire a coûté environ 60 dollars, ce qui représente une économie de 20 dollars seulement sur la consommation d'énergie. Il a émis l'opinion que des modifications mineures de l'installation, destinées avant tout à réduire la consommation d'énergie, permettraient d'économiser environ 100 dollars d'énergie par an. Dans la maison de Tokyo, le chauffage solaire a permis de réaliser une économie nette de 78 dollars sur la consommation d'énergie. Il faut cependant noter que ces quelques données sur le prix de revient ne sont valables que dans les conditions de fonctionnement particulières à chaque installation.

Il semble que les économies effectives et possibles de combustible et d'électricité réalisables pour le chauffage de ces bâtiments puissent être raisonnablement situées entre un minimum de 50 dollars et un maximum de 150 dollars. Ces deux limites peuvent cependant être modifiées, par exemple, si l'on change les proportions entre la surface du collecteur et les besoins thermiques du bâtiment, ou si le prix du combustible varie, ou si l'installation est réalisée dans des régions où la distribution du rayonnement solaire et le climat sont différents, etc.

Les chiffres précédents ne tiennent évidemment pas compte de l'amortissement ni des frais d'entretien de l'installation solaire. Des estimations sur ces points ne pourront être faites que lorsqu'on connaîtra avec une certaine précision le prix de fabrication et de construction d'installations produites à une échelle même modeste. Si l'on admet que les dépenses de capital représentent 10 p. 100 par an, soit par exemple 5 p. 100 pour l'amortissement (en 20 ans), 6 p. 100 d'intérêts sur le capital non amorti (équivalant à un intérêt moyen de 3 p. 100 environ) et 2 p. 100 pour les dépenses d'entretien, impôts, assurances et charges diverses, une économie de 150 dollars par an ne permettrait pas un investissement supplémentaire de plus de 1 500 dollars environ pour une installation de chauffage solaire (par rapport à une installation classique). De même une économie annuelle de 100 dollars permettrait un investissement supplémentaire de 1 000 dollars. La plupart des auteurs admettent que les sommes à investir actuellement dans de telles installations dépassent ces limites, mais on pense qu'il n'est pas impossible d'arriver à un prix de revient de cet ordre de grandeur.

L'économie de ces installations dépend en partie de l'appareillage de chauffage auxiliaire et de l'énergie qu'il consomme. Pour les systèmes à combustible, ces deux dépenses sont ou peuvent être modestes. L'appareillage auxiliaire est relativement peu coûteux, et si l'on considère que l'installation solaire nécessite déjà des dispositifs de contrôle, un système de distribution et encore d'autres éléments, la seule dépense supplémentaire est en général le prix de la chaudière. Lorsque la plus grande partie de la chaleur utilisée est d'origine solaire, les dépenses de combustible sont également peu importantes. Le rapporteur estime par conséquent qu'il n'y a guère d'intérêt à vouloir construire un très grand collecteur et un vaste système d'accumulation thermique tendant à éliminer la nécessité d'un chauffage auxiliaire.

Une autre considération intervient dans le choix de l'installation de chauffage auxiliaire, à savoir les avantages respectifs des systèmes à thermopompe et des systèmes à combustible. Même dans les installations dotées d'un grand collecteur — Arizona et Tokyo, l'électricité qui a été consommée pour actionner la pompe à chaleur a coûté assez cher, et les économies totales n'ont pas semblé dépasser celles qui ont été réalisées avec les dispositifs auxiliaires marchant au combustible. En revanche, les sommes investies dans une installation équipée d'une pompe à chaleur ont dépassé de beaucoup le prix d'une chaudière. On ne choisira donc un dispositif auxiliaire à thermopompe que s'il y a nécessité d'assurer une réfrigération. Si l'on s'en tient à une comparaison économique très superficielle, les frais d'investissement encourus pour l'installation d'une pompe à chaleur utilisée uniquement pour le chauffage ne semblent pas devoir dépasser de beaucoup le prix d'une chaudière. Il est toutefois possible que le prix d'un collecteur solaire conçu pour être utilisé en association avec une pompe à chaleur soit inférieur à celui d'un collecteur à température plus élevée utilisé en association avec un chauffage auxiliaire à combustible, parce que le second collecteur devra être muni d'un revêtement. Ici encore, il est extrêmement difficile de procéder à des comparaisons, étant donné l'insuffisance des données sur le prix de revient. La seule indication vraiment nette est que la pompe à chaleur et le collecteur solaire sont tous deux d'un coût élevé qui doit nécessairement réserver l'emploi de la pompe à chaleur comme dispositif auxiliaire pour les cas où la réfrigération doit être assurée pendant l'été et où le dispositif solaire permet de réaliser, pendant l'hiver, des économies d'électricité capables de justifier la dépense de l'installation solaire plus toutes les dépenses résultant du fonctionnement de la pompe à chaleur pour le chauffage.

Enfin, un facteur économique est important pour cette Conférence : les possibilités inhérentes au chauffage solaire dans les pays insuffisamment développés. Les systèmes décrits dans les mémoires sont tous très complexes et coûteux. Il ne paraît guère probable qu'ils puissent être appliqués dans un proche avenir au chauffage des maisons qui actuellement ne disposent d'aucun moyen de chauffage ou sont simplement tiédies par quelque source ou chaleur directe. On conçoit mieux l'adoption de ces systèmes pour des immeubles d'habitation plus vastes, actuellement équipés d'un chauffage central, ou pour des bâtiments publics et commerciaux. Les conditions les plus favorables paraissent réunies dans les régions où le combustible coûte cher. Toutefois, il ne pourra être question de véritable application pratique tant que l'équipement de chauffage solaire ne sera pas techniquement tout à fait au point et éprouvé; son coût devra aussi diminuer considérablement. Le rapporteur suggère que les recherches ultérieures soient orientées vers des applications de ce genre.

Machine à analogie électronico-mécanique pour la réalisation d'une centrale de chauffage par l'énergie solaire

Dans un autre mémoire (S/19) présenté sous ce même point de l'ordre du jour, R. F. Benseman décrit un simulateur mécanique du soleil qui, en quelques minutes, reproduit effectivement les variations annuelles du soleil en intensité et en position par rapport à la surface d'un collecteur orienté sous un angle quelconque. L'enregistrement du rayonnement effectivement reçu par cette surface (au moyen de détecteurs photo-électriques) fournit les données qui sont transmises à une calculatrice électronique, laquelle tient également compte d'autres éléments : déperditions thermiques, besoins calorifiques du bâtiment, et autres variables qui influent sur la conception d'une installation de chauffage solaire. Les résultats du calcul sont ensuite utilisés pour déterminer les caractéristiques optimales de l'installation, compte tenu de l'emplacement choisi et de la demande thermique. Il est probable que les éléments du prix de revient pourront également être intégrés aux calculs lorsqu'on disposera des données nécessaires; on pourra ainsi déterminer l'installation la plus intéressante du point de vue de ses performances et de son coût. L'expérience se poursuit actuellement et l'on en attend les résultats avec intérêt.

Étude d'une maison solaire au Sahara

Le mémoire S/76 par E. Crausse et H. Gachon, bien qu'il ait été placé sous la rubrique « réfrigération par l'énergie solaire » contient également une brève description d'un projet d'installation de chauffage solaire. On envisage d'installer dans une maison expérimentale (surface de plancher : 900 pieds carrés) située dans la partie septentrionale du Sahara, à 35° de latitude nord (Biskra), un système de chauffage où de l'eau chauffée à l'énergie solaire circulerait dans des tuyaux d'acier enrobés dans un plancher radiant. La source de chaleur serait un collecteur solaire installé près de la maison et relié à un réservoir d'eau calorifugé d'une contenance de 5 000 litres.

Conclusions et sujets à discuter

Les études sur le chauffage des locaux par l'énergie solaire ont actuellement atteint le stade où, de l'avis du rapporteur, un « temps d'arrêt » permettant une évaluation générale paraît opportun. Sur le plan technique, plusieurs systèmes ont été construits et essayés avec succès. Des quantités importantes de chaleur solaire ont été distribuées à des bâtiments situés dans des régions à hiver froid et, dans quelques cas, la source solaire a permis de satisfaire une partie substantielle des besoins thermiques. Même dans des installations assez complexes, l'automaticité de fonctionnement a été réalisée pendant de longues périodes sans donner lieu à des difficultés sérieuses. Sans doute, aucun des systèmes décrits n'est exempt de défauts, mais il n'y a pas de raison pour que ceux-ci ne puissent être corrigés. Enfin, quelques efforts de mise au point devraient permettre d'obtenir une amélioration assez sensible des performances.

La quasi-totalité des chercheurs reconnaissent cependant que les prix de revient actuels des installations de chauffage solaire ne compensent pas la valeur des économies que ces installations permettent de réaliser dans les régions où on les a essayées. Il n'est pas certain que l'on puisse apporter des simplifications *majeures* au plan des installations sans en altérer les performances. En revanche, des réductions *modestes* du prix de revient paraissent plus réalisables. Les opinions divergent néanmoins quant aux économies qui pourraient être obtenues par une production en série d'éléments standardisés, prêts à installer, d'installations de chauffage solaire. Une étude plus poussée de cet aspect paraît indispensable. Les auteurs ne sont pas toujours d'accord non plus sur la nécessité d'intégrer le plan de l'installation de chauffage solaire à celui de la maison, certains prétendant qu'un chauffage solaire peut être adapté sur à peu près n'importe quel type de maison. Les perspectives économiques sont donc éminemment incertaines à l'heure actuelle et des précisions doivent être obtenues.

Compte tenu des considérations précédentes, dans quelle direction les recherches sur la mise au point des installations de chauffage solaire doivent-elles s'orienter? Telle est la question la plus importante dont la Conférence est appelée à s'occuper sous ce point de l'ordre du jour. La réponse se dégagera peut-être des solutions qui seront données à un certain nombre de problèmes qui sont proposés ci-après pour examen :

Quelles sont les perspectives de réaliser des augmentations importantes dans le rendement des collecteurs solaires et des diminutions sensibles dans le prix de revient des collecteurs solaires?

Faut-il, pour étudier ces perspectives, se baser sur des recherches expérimentales à échelle réduite, ou travailler sur des bâtiments normaux équipés d'un chauffage solaire?

Dans ce sens, les avantages techniques des surfaces absorbantes sélectives, des surfaces de transmission sélectives, des revêtements à faible pouvoir réfléchissant et d'autres procédés permettant d'agir sur le rayonnement sont-ils suffisamment importants pour qu'il vaille la peine d'en étudier intensément l'application à des installations plus perfectionnées de chauffage des locaux par l'énergie solaire?

Plusieurs chercheurs ont signalé des défauts dans la conception et le fonctionnement des installations sur lesquelles ils ont travaillé. Doit-on continuer les recherches sur les installations actuelles pour obtenir un rendement maximal et les pousser jusqu'à la limite de leurs possibilités? Cette méthode d'amélioration technique progressive est-elle susceptible d'augmenter sensiblement les possibilités d'utilisation?

Quelle importance faut-il accorder à la formulation d'une base rationnelle qui permettrait de dimensionner les collecteurs solaires et les dispositifs d'emmagasinage de la chaleur solaire? Les méthodes actuelles sont-elles satisfaisantes pour les déterminations de ce genre?

Compte tenu des analyses publiées par certains auteurs qui préconisent d'adopter une capacité d'accumulation correspondant aux besoins thermiques moyens d'une journée de janvier, quels arguments les partisans d'une capacité d'emmagasinage supérieure ont-ils à faire valoir?

Dans le même sens, quels sont les arguments qui militent en faveur d'une installation où le collecteur et l'accumulateur sont capables de fournir la totalité de la chaleur nécessaire à un bâtiment dans les conditions les plus sévères que l'on puisse rencontrer dans un climat à hivers froids?

La chaleur de fusion peut-elle être utilisée efficacement dans des accumulateurs de chaleur associés à une installation de chauffage des locaux par l'énergie solaire? A-t-on obtenu des résultats satisfaisants avec des sels hydratés? Existe-t-il d'autres matériaux intéressants?

A part son utilité évidente lorsqu'il faut assurer une réfrigération, le dispositif auxiliaire à thermopompe présente-t-il des avantages qui justifient son emploi en association avec une source de chaleur solaire? Quel paraît être le prix de revient maximal d'un collecteur solaire pour que l'on puisse encore l'utiliser en association avec une thermopompe tout en restant dans des limites compétitives par rapport au prix d'une installation classique de conditionnement d'air par compresseur et de chauffage par combustible?

Quels sont les prix minimaux prévisibles pour un collecteur solaire? Ces prix minimaux semblent-ils devoir être atteints plus facilement par une fabrication industrielle d'articles vendus sur le marché (comme des chaudières) ou par une intégration effective de l'architecture et du collecteur, ce dernier étant construit sur place? Quel est le degré de nécessité et quels sont les résultats à attendre des recherches qui pourraient être entreprises dans ces deux directions?

Quel est l'intérêt d'une production d'eau chaude à usage domestique associée au chauffage par la chaleur solaire?

Dans quelle mesure convient-il d'associer les recherches sur le chauffage solaire des locaux à celles qui sont entreprises sur les systèmes de réfrigération par l'énergie solaire? Si les perspectives offertes par un ou plusieurs systèmes assurant les deux opérations semblent favorables, dans quelle mesure le choix d'une installation de chauffage solaire en sera-t-il influencé?

Doit-on procéder à une étude économique du chauffage des locaux par l'énergie solaire distincte des études techniques, et dispose-t-on de données significatives pouvant constituer une base féconde pour ces études?

Dans quelle mesure est-il nécessaire d'apporter des améliorations et des simplifications à l'appareillage de contrôle utilisé dans les installations de chauffage solaire? Quels sont les prix de revient minimaux prévisibles pour ces dispositifs?

Quels sont, dans les régions insuffisamment développées, les facteurs additionnels capables d'influer sur les possibilités d'utilisation de l'énergie solaire pour le chauffage des locaux, et existe-t-il des facteurs limitatifs valables pour les régions plus évoluées qui ne s'appliquent pas dans ces régions?

Dans quelles circonstances le chauffage des locaux par l'énergie solaire semble-t-il avoir les plus grandes possibilités d'utilisation dans les pays insuffisamment développés?

Faut-il étudier, pour les appliquer dans les pays insuffisamment développés, des systèmes de chauffage solaire ne faisant pas du tout appel à l'électricité?

Dans quelle mesure des matières nouvelles comme les pellicules transparentes de composition plastique permettent-elles d'abaisser le prix des collecteurs et d'améliorer les perspectives de chauffage des locaux par l'énergie solaire, notamment dans les pays insuffisamment développés?

USE OF SOLAR ENERGY FOR HEATING PURPOSES: SPACE HEATING

Rapporteur's summation

Since the scientific and technical aspects of the use of solar energy for heating were so well covered at the Conference, this summation on space heating (agenda item III.C.2) and two which follow — on solar drying (III.C.3) and on solar cooking (III.C.4) — emphasize economic and practical prospects in the use of solar energy.

So far as the general status of space heating is concerned, about two dozen solar heated buildings have been constructed to date; about eight of them were reported at the Conference. They include air heating systems and water heating systems, heat storage in the form of hot water, hot rocks, and in chemicals undergoing phase changes, and auxiliary heat supplies from natural gas furnaces, oil furnaces and heat pumps.

All the systems have been reportedly successful in supplying substantial portions of the heating requirements of the buildings, and there do not seem to be large differences in the performance and capabilities of the systems per unit of solar heat exchange area. Several of the buildings are also provided with cooling systems utilizing day-night heat exchange, night sky radiators, heat pump refrigeration, or some combination of these components.

Although subject to further improvement, these systems appear to perform adequately from the technical point of view. The few systems on which cost estimates have been made, however, show that the actual investments cannot be amortized from fuel savings in these experimental installations. There are prospects for savings, however, in future non-experimental, practical installations, where investment requirements will be reduced.

In regard to development needs, it is clear that the system cost must be reduced, particularly in connection with the collector. A total system investment of $2 per sq ft, or $20 per sq metre, of collector has often been mentioned as a reasonable objective. At this level, solar heating could compete with fuel heating in many areas.

How can such an objective be achieved? One method would be simpler solar collector design. Several papers indicated promising steps in this direction. Another measure would be the mass production of standard collector sections or modules, thereby reducing collector costs. A third economy, mentioned by several speakers, would be through savings in materials and labor by close integration of the collector and the building design. A fourth possible gain would be in the use of new and cheaper materials for collector construction. Several types of insulating glass system have been suggested, and the use of durable plastic films of low cost is being studied.

Another possibility for cost reduction is in combining air conditioning with heating, thereby increasing the collector's load factor and effectively paying for it over the entire year rather than during the heating season only. The possibility of more nearly optimum system design and resulting cost reductions was indicated in a paper dealing with a computer and sun simulating device.

The incentives for development of solar space heating appear to justify further and perhaps more intensive efforts. One fourth of the world's energy is used for this purpose. In improving living conditions in many areas, the provision of heat in dwellings and other buildings would contribute greatly to human comfort. In the long-range view, solar space heating will be significant in the conservation of fuel resources. And, finally, the potential economy of solar heating is an incentive for its maximum development. It is to be hoped that efforts in this field will be continued and fruitful.

In comparing the needs and opportunities for solar space heating in developed and under-developed countries, certain points should be emphasized. Several speakers discussed some of these differences. In dwellings in the industrialized countries, particularly the United States, solar space heating would simply involve a substitution of solar energy for the fuel energy now being used in a sophisticated and automatic system. In under-developed areas, domestic heating systems of this cost and complexity would be very few, at least in the near future, primarily for economic reasons. Attention should be given, according to several speakers, to improving the design of the dwelling itself, so that maximum advantage of sun, shade, wind, and so on, can be taken. Wall and roof structure and material, window location and size, and other factors can be chosen so as to minimize discomfort, without excessive cost. Solar heating appears to be better suited in the under-developed areas to use in public buildings such as schools, offices, shops, theatres, and the like, where purchasing power is adequate for the initial investment.

As a brief conclusion to this topic, a mention of some of the major problems ahead and the directions in which solar development might proceed should be in order. Should we continue to build all kinds of solar heated structures and test the modest improvements and simplifications which can result from such efforts, or should there be more fundamental studies on solar collector design and performance? Should we make surveys of fuel costs in various areas so that we may know what we are competing with? In what other directions might we advantageously proceed?

I believe some of these questions have been at least partially answered in the technical sessions here. Certainly, the importance of costs has been emphasized, and all efforts in the direction of their reduction and their accurate appraisal are to be desired. It is possible that some of these improvements can be made on a comparatively small experimental scale, thereby obviating the immediate need for expensive, complete solar heated buildings. Ultimately, however, this construction is required, because the system of solar collector, storage, auxiliary heat source, and controls is too complex for theoretical verification. It has to be tested in order that we can eliminate the defects in the system and determine its operating requirements and costs. In the over-all view, there is thus a need for a full range of effort, good basic design concepts, the substitution of new materials, the analysis of existing technical and economic data on solar heating, and finally the construction and testing of promising systems.

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : CHAUFFAGE DES LOCAUX

Résumé du rapporteur

Les aspects scientifiques et techniques de l'emploi de l'énergie solaire pour le chauffage ayant été particulièrement bien étudiés à la Conférence, les présentes conclusions relatives au chauffage des locaux (point III.C.2) et celles qui suivent sur le séchage par la chaleur solaire (point III.C.3) et sur les cuisinières solaires (point III.C.4) portent essentiellement sur les aspects économiques et pratiques de l'emploi de l'énergie solaire.

En ce qui concerne le chauffage des locaux d'une manière générale, plus d'une vingtaine de bâtiments chauffés par l'énergie solaire ont été construits à ce jour; des mémoires concernant huit d'entre eux ont été présentés à la Conférence. Ils traitent notamment des systèmes de chauffage de l'air et de l'eau, de l'accumulation de chaleur sous forme d'eau chaude, de galets surchauffés et de réactions chimiques, ainsi que de sources de chaleur d'appoint : foyers à gaz naturel et à mazout et pompes à chaleur.

Tous ces systèmes auraient permis de fournir une part importante des besoins de chauffage des bâtiments et il ne semble pas qu'il y ait une grande différence en ce qui concerne le rendement et la capacité de production des différents systèmes par unité de superficie des échangeurs de chaleur solaire. Plusieurs des bâtiments en question sont également équipés de systèmes de climatisation faisant appel au principe de l'échange de chaleur entre le jour et la nuit, ou du rayonnement céleste nocturne, ou de la réfrigération par pompes à chaleur ou à plusieurs de ces principes à la fois.

Encore qu'on puisse encore les perfectionner, ces systèmes semblent fonctionner de manière satisfaisante du point de vue technique. Mais il ressort des estimations de coût qui ont été faites pour quelques-uns d'entre eux que l'économie de combustible réalisée dans ces installations expérimentales ne permet pas d'amortir les sommes effectivement investies. Toutefois, certaines installations non expérimentales de l'avenir qui ne nécessiteront que des investissements limités semblent devoir être économiques.

Quant aux perspectives d'avenir, il est manifeste qu'il faut abaisser le coût du système, en particulier celui du collecteur. Plusieurs orateurs ont indiqué qu'il serait raisonnable de chercher à mettre au point un système dans lequel l'investissement total serait de l'ordre de deux dollars par pied carré, soit environ 20 dollars par mètre carré, de collecteur. A ce prix, le chauffage solaire pourrait concurrencer le chauffage par combustible dans bien des régions.

Comment atteindre cet objectif? En premier lieu, en simplifiant le collecteur. Plusieurs mémoires ont signalé des progrès intéressants dans cette voie. En second lieu, en fabriquant en série des sections ou des éléments types de collecteur, ce qui en réduirait le prix. Plusieurs orateurs ont indiqué qu'on pourrait aussi réaliser des économies sur les matières et la main-d'œuvre en intégrant plus étroitement le collecteur dans le plan du bâtiment. Enfin, on pourrait peut-être construire le collecteur avec des matières nouvelles et moins onéreuses. On a proposé plusieurs types de collecteur en verre isolant et on envisage actuellement l'utilisation de pellicules en matière plastique résistante à bon marché.

Un autre moyen possible d'abaisser le prix consiste à combiner la climatisation et le chauffage, ce qui accroît le facteur de charge du collecteur et permet de l'utiliser effectivement toute l'année et non pas seulement pendant la période de chauffage. Un mémoire relatif à un appareil électronique et à un système simulant l'ensoleillement a laissé entrevoir la possibilité de concevoir un système de chauffage perfectionné et, de ce fait, une réduction des coûts.

Les perspectives qu'offre la mise au point du chauffage solaire des locaux semblent justifier des efforts nouveaux et peut-être plus grands encore. Un quart en effet de l'énergie utilisée dans le monde est employé pour le chauffage. En améliorant les conditions de vie dans de nombreuses régions, le chauffage solaire des logements et autres bâtiments contribuerait singulièrement au bien-être des hommes. A longue échéance, il entraînera une économie sensible des ressources en combustible. Enfin, les perspectives d'économie qu'ouvre le système feront beaucoup pour stimuler son développement maximal. Il faut souhaiter la poursuite et le succès des efforts entrepris dans ce domaine.

Quand on compare les besoins de chauffage solaire des locaux dans les pays développés et les pays sous-développés, et les possibilités offertes à cet égard, il convient de souligner un certain nombre de points. Plusieurs orateurs ont parlé de ces différences. Dans les pays industriels, notamment aux États-Unis, le chauffage solaire des locaux nécessiterait simplement la substitution de l'énergie solaire à l'énergie produite actuellement par des combustibles brûlés dans un système automatique complexe. Dans les régions sous-développées, en revanche, les installations de chauffage domestique de ce coût et de cette complexité seraient peu nombreuses, tout au moins dans un avenir proche, surtout pour des raisons économiques. Il y a donc lieu de s'attacher, selon plusieurs orateurs, à améliorer la disposition et la construction des logements, de manière à tirer le maximum d'avantages de l'ensoleillement, de l'ombre, du vent, etc. La structure et les matériaux des murs et du toit, l'emplacement et la dimension des fenêtres, etc., peuvent être déterminés de manière à réduire l'inconfort au minimum sans dépense excessive. Mais c'est aux bâtiments publics (écoles, bureaux, magasins, théâtres, etc.), pour lesquels on a les moyens d'investissement initial nécessaires, que le chauffage solaire paraît convenir le mieux dans les régions sous-développées.

Pour conclure brièvement l'examen de cette question, il serait utile de mentionner certains problèmes majeurs qui se posent et de voir de quel côté pourrait s'orienter la mise en valeur de l'énergie solaire. Doit-on continuer à construire toutes sortes de bâtiments chauffés par l'énergie solaire, à expérimenter les modestes améliorations et changements auxquels ces efforts peuvent aboutir, ou bien doit-on étudier de manière plus approfondie les modèles de collecteurs solaires et leur rendement? Faut-il procéder à des enquêtes sur le prix des combustibles dans diverses régions afin de savoir avec quoi l'énergie solaire doit entrer en compétition? Quelle autre direction pourrait-on suivre avec profit?

Les réponses au moins partielles à quelques-unes de ces questions ont été données, à mon avis, dans les séances techniques de la Conférence. Certes, on a insisté sur l'importance des coûts et il est à souhaiter que tous les efforts soient faits pour les réduire et les évaluer avec précision. Peut-être les améliorations proposées pourraient-elles être réalisées expérimentalement, à une échelle relativement limitée, ce qui éviterait d'avoir à construire immédiatement des bâtiments entièrement chauffés par l'énergie solaire, qui coûtent cher. Mais, en fin de compte, il faut construire ces bâtiments parce que le système du collecteur solaire, d'emmagasinage de l'énergie, de source calorique d'appoint et de réglage est trop complexe pour pouvoir être vérifié en théorie. Le système doit être mis à l'épreuve de manière à éliminer les défauts et à préciser les besoins et les coûts de fonctionnement. Dans l'ensemble, il nous faut donc fournir toute une série d'efforts, concevoir de bons modèles, trouver des matières nouvelles, analyser les données techniques et économiques actuelles du chauffage solaire, et enfin construire et mettre à l'épreuve les installations qui paraissent les plus intéressantes.

AN ELECTRONIC-MECHANICAL ANALOGUE FOR THE DESIGN OF SOLAR HEATING PLANTS

R. F. Benseman *

Solar heating is not widely used throughout the world. Yet in most latitudes there is more than enough heat from the sun to satisfy the immediate or foreseen heating requirements of the people. On the technical side there is no paucity of practical and encouraging information. Even the simple flat plate collector can gather solar energy at efficiencies ranging between 50 and 70 per cent. Heat storage procedure, although is poses problems, is well tabulated with a wide range of possibilities for any potential builder of a solar heating plant. So neither availability nor technical shortcomings account for its infrequent use.

The crux of the problem is, of course, the vexing question of economics. What will it cost to build and maintain a solar heating plant to meet a given set of conditions? Is this the "best" design possible in the light of present knowledge and with the existing cost structure? Conditional on the "best" design evolving after consultation between the "solar engineer" and the economist, the prospective user will be able to evaluate the merits of a solar plant as compared with the more conventional methods available to him.

The solar engineer, however, is faced with a confusing assortment of methods and data from which he must first arrive at this "best" design. One authority will state that heat storage beyond a period of two or three days is uneconomic; another stresses the virtues of long-term storage because of increased collector efficiency and the resulting savings in initial construction costs. Which method does the engineer choose? Of course the alternatives are both right in a sense. The results are conditioned by the circumstances that obtain in the experiments or calculations that give rise to the results. The "best" design in a particular case may demand a combination of both types of store, or perhaps no store at all. Furthermore, economics change from place to place. Fuel oil costs about $3.00 per gallon in the Antarctic, but only a few cents per gallon in other parts of the world. What is economic in one situation may be completely unreasonable somewhere else.

The point should have been made by now — what is "best" for one site will almost certainly not be the "best" for another.

To arrive at the optimum design, two methods are possible. One is to go to the site concerned and build every possible combination of collector storage and booster service, monitor these over a period of years to eliminate the vagaries of the weather, and then see which combination gives the "best" results. This is a patent impossibility.

The alternative is to calculate the expected performance from past meteorological records. For a significant study the relationships must be computed on a dynamic basis because of the interaction of the many components. For example, collector efficiency depends on the collector temperature, which is conditioned in turn by storage capacity, standing losses, and particularly by previous supply and demand of heat. The interactions are complex and the calculations tedious to manipulate unless an analogue or digital computor can be used.

Given either of these, it becomes possible to settle finally whether an economic solar plant *can* be designed for any particular situation under specified conditions of use. If solar heating doesn't stand up to this test, at least it will not have failed because of shortcomings in the design. This is the most that can be expected for the moment. Major breakthroughs in technique, or a change in the cost structure of an economy, may mean a revision of the optimum design from time to time, but a rapid method of evaluation that treats with the purely technical aspects of solar plant design can accommodate these changes. The remainder of this paper describes briefly the construction of an analogue specifically designed for solar heating problems. Results of a few preliminary tests are given.

Description of the analogue

General

The analogue described here treats a solar design problem in two stages. The first stage, which is achieved by a mechanical simulator, determines the relationship between the collector and the sun. i.e., it takes account of the changing angles of incidence and variations in insolation. The second stage is entirely electronic and deals with the interactions of all the other features that affect the completed plant's performance — heat storage, domestic usage, ambient air temperature, and the various avenues of heat loss from the system.

Figure 1 shows the "sun simulator". The electronic components of the analogue are not illustrated;

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Figure 1. The mechanical sun simulator

they conform to normal practice. The only interaction between the two parts lies in the choice of a time scale acceptable to both.

THE ARTIFICIAL SUN

The "sun" consists of a lamp and mirror that rotate about a vertical axis at a speed of one revolution per second; each revolution represents one day in solar time. The mirror is parabolic in section with the lamp at its focus, so that parallel light falls at all times on a small adjustable platform set at the center of the system. As it rotates, the arm holding lamp and mirror makes a slow oscillation from 23½ degrees above the horizontal plane to 23½ degrees below this plane, and back again. The angular movement is sinusoidal, and a cycle is completed during 365.2 revolutions of the mirror lamp assembly. Thus a rather idealised "sun" is produced. The adjustable platform at the center of the system represents the earth and can be tilted to simulate any latitude.

Remote from the sun simulator, but rigidly linked to it mechanically, is a devise for feeding 16 mm film through a film reading head. On this film are three tracks. One indicates the solar radiation recorded by a chosen meteorological station, another the air temperature recorded at the same station. There is also a third that for the moment is being reserved for contingencies. Only the track displaying the radiation record is of immediate concern.

The radiation level indicated by the film at any instant is duplicated by the sun-lamp. The light intensity is monitored by a photoelectric cell set horizontally on the surface of the center platform. In a sense it duplicates the original recording station. Its purpose is to ensure that the light from the lamp conforms to the signal on the film strip. It is part of a feedback loop, in this case an optical link. The result is a source of parallel light that falls on an inclined platform (the "earth's surface") at angles and with intensities that approximate closely to the angles and solar radiation intensities experienced in the past by the selected recording station.

Incorporated into the same platform as the monitoring photocell is a second cell that can be orientated in any direction. This represents the unit area of the collector that forms part of any solar heating plant that is being analysed. The current generated by the light falling on this photocell will be proportional to the solar radiation received by the analogous solar collector on the particular "day" that is being fed into the reader. Thus in one operation, angular corrections and the hour by hour changes in solar radiation are duplicated.

One further correction is possible, and that is for losses occasioned by total reflection. Flat plate collectors become inoperative at large angles of incidence because of total reflection from the glass cover-plate. A direct duplication in the simulator is effected by placing a sheet of polished opal over the "collector" photocell. This causes total reflection at corresponding angles in the simulator. For collectors that may not need this correction, the photoelectric cell is covered instead with a sheet of depolished opal.

Further aspects of the practical manipulation of the simulator are obvious. Collector orientation and shading factors are easily duplicated for any given situation, and a signal emerges representing the solar radiation that actually falls on the collector plate (corrected if necessary for reflective losses). With small additions, the unit will accommodate not only flat plate collectors, but also units using focusing units or incorporating equatorial mountings.

There are obvious deficiencies in the design of the simulator and the data available that make the result something less than perfect. The major sources of error are listed below.

1. All radiation is assumed to be directed. This has been necessary because, in general, solar radiation records make no distinction between diffuse and directed radiation. In the event of complete data or reliable correcting factors becoming available, it is planned to utilise the third signal strip on the film. This is the contingency for which this section of film is being reserved.

2. The system uses mean solar time rather than true solar time. In extreme cases this could result in an error of up to five degrees in the angular setting of the artifical "sun". If it proves necessary, corrections can be made to this feature.

3. Records of solar radiation (and air temperature) are tabulated normally in the form of hourly means. These are a very convenient form of record for the film preparation and have been retained for this reason. It has meant, however, that part-hours of radiation near sunrise and sunset have had to be eliminated from the film recording because of the difficulty of keeping the artifical sun under control. It will be appreciated that if the "sun" is shining below the "horizon", the monitoring photocell is set an impossible task. As with the departure from true solar time, this last feature can be remedied if it proves essential.

Briefly then, although the simulator is not perfect, it is expected that the three sources of error just described will all be second order and will not introduce an over-all deviation of more than five per cent. An accuracy of this order should be more than adequate for most solar design problems. Should this accuracy be unattainable or unacceptable, two of the three sources of error can be corrected exactly. The third (diffuse radiation) can be compensated for in part, but it is hard to say how effective any compensation would be in the face of a complete lack of data in existing radiation records. Complete vindication of the simulator can only come from analyses of existing solar heating systems, and this work will be attempted at an early date.

Checks on the angular collection are to be made with an IBM 650 computer, but results are not available yet. It is interesting to note that the simulator will process one year's radiation data in six minutes while the corresponding check on the computer will take some two to three hours.

The electrical analogue

From the collector on the sun simulator comes a small current representing the heat falling on unit area of the collector. This is amplified by any required factor so that the output signal now represents the heat received by a collector of any specified size. A network of resistors, capacitors, and biassed diodes duplicates the effect of the thermal mass of the collector and the front and back heat losses, leaving finally as the output of this system a current representing the net heat collected.

At the same time, and exactly synchronised with the radiation output, a signal is received directly from the film head representing the relevant air temperature. Wherever applicable, this signal is used to generate a voltage that becomes the "ambient temperature" that determines such things as the standing losses from storage tanks, the demand for house heating or hot water, or the extent of the front and back losses from the collector.

The remainder of the system has been made as flexible as possible to allow a wide range of variables to be attempted. Capacitors are incorporated that simulate heat stores that may range in capacity from 1 to 100 000 btu/°F. High-speed relays will switch heat demand to various parts of the circuit to duplicate the thermal demands made on the solar heating plant, while high-speed recorders, integrators, and counters will keep a record of heat flows and temperatures in any part of the circuit.

Scaling factors

The conversion factors used throughout the analogue are as follows:

Solar plant	*Analogue*
1°F	0.25 volts
1 btu/hr	0.25 microamps (typical)
1 day	1.00 sec.

The temperature/voltage relationship was decided on the basis of the temperature ranges likely to be encountered in practice as related to a convenient voltage swing that would allow full utilisation of the conventional electronic valves that compose the analogue.

Over-all scaling may be achieved by changing the relationship between heatflow and current. The figure shown above is one that would be used for most domestic applications, i.e., collectors of an area of up to 400 square feet. For dealing with smaller or larger installations the ratio may be adjusted as required.

An acceptable time base was the most difficult feature to settle. From the point of view of the electronics, a time base much shorter than one second for one solar day would have been convenient since it would allow the use of smaller components. On the other hand, at speeds greater than one revolution per second, the sun simulator would have given trouble due to excessive strain on some of the components and synchronising difficulties due to variable blacklash within the gear trains caused by the dynamic unbalance of the system at certain parts of the cycle. In addition, the lamp of the artificial sun could not respond adequately to applied voltage changes at frequencies much in excess of 24 changes/second, i.e., the number of changes of radiation level indicated by the 16 mm film.

By selecting as a mutual compromise a conversion of one second equal to one solar day, it has been found possible to retain accuracy within the mechanical simulator without allowing the electronics to become impossibly large or imposing too great a strain on recording and switching facilities. At the same time, six minutes for one year's analysis does not seem unreasonable.

Results

The results that follow come from *testing* runs being made on the analogue at the time of writing; they are therefore subject to confirmation. They demonstrate principally the performance of the sun simulator. The film used throughout is that for Wellington, New Zealand (Latitude 41° 17′ south, Longitude 176° 46′ east), and is for the first 300 days of the year 1957. Records came from observations made by the New Zealand Meteorological Service using a conventional Eppley Pyrheliometer.

Figure 2 illustrates the relationship between the initial radiation records and the output as measured with the "collector" photocell mounted horizontally. Ideally the points should fall exactly on the horizontal sections of the histogram. The three consistent deviations in January, April, and late September may be due to faulty film preparation and will be checked as soon as possible.

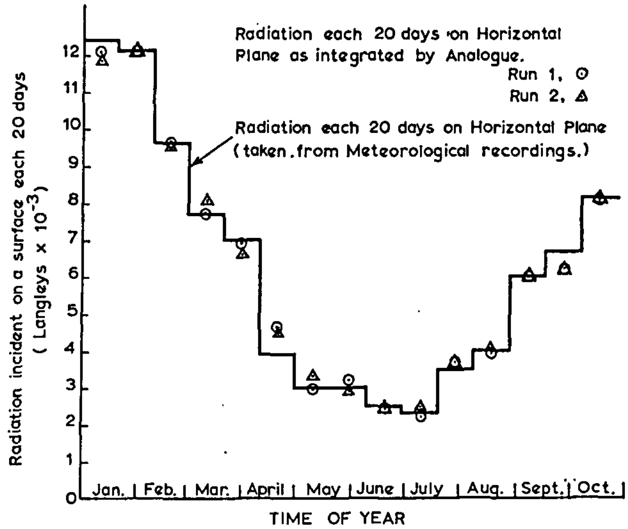

Figure 2. Analogue correlation

As an example of the use of the analogue, consider a simple solar water heater. Latitude plus 5° (a total of 46° for Wellington) is a common working rule for deciding the optimum tilt of collectors for solar water heaters. Figure 3 shows that this gives a reasonably constant amount of incident heat over the year. However, if lower winter air temperatures are included in the problem and consideration given to the effect that this will have on collector efficiency, standing losses, and primary water supply, it is probable that the net hot water available for winter use will be considerably lower than the summer supply.

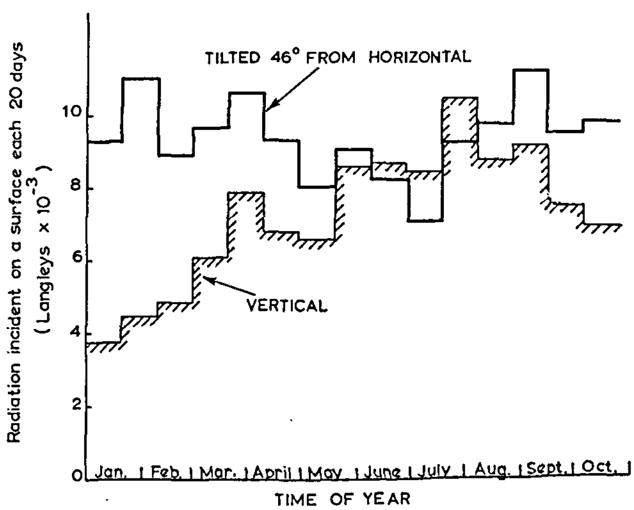

Figure 3. Analogue determination: radiation incident on north facing collectors

Shown in the same figure are the results for a vertical wall. Here there is a pronounced peak in mid winter, the peak being in excess even of that for the collector tilted at 46°. When account is taken of the over-all efficiency of the system, it is not impossible that for the Wellington anyway it may be preferable to use vertical collectors. This would certainly ease construction difficulties, especially with thermosyphon systems where it is often difficult to arrange the necessary minimum head between collector and storage tank. However, this is all speculation, since only a small fraction of the parameters have been considered. It does suggest, though, the type of investigation that will arise from the use of the analogue.

One test was made on the effect of reflective losses from collectors. It was found that for a horizontally mounted collector with a glass cover-plate, reflection at high angles of incidence reduced the gross incident heat over 300 days by some 7 per cent. Losses in winter were nearly twice those of the summer months.

Conclusions

The analogue described shows promise of being accurate enough for design and re-design problems in solar heating, and has already indicated some promising lines of investigation. It is versatile enough to accommodate most types of solar heating installation and should allow the optimum in economic design to be reached in a relatively short time.

The greatest cause of error is that diffuse radiation has not been duplicated in the analogue, but whether this will cause substantial deviations from practical results can only be decided by test analysis on established solar heating plant.

Summary

If solar heating is to become widely used, or to compete economically with other sources of heat, then it must be possible to predict with some accuracy the performance that can be expected from a given design under specified conditions of use. One method of doing this is to use an analogue.

The analogue described here treats a solar design problem in two stages. The first stage, which is achieved by a mechanical simulator, determines the relationship between the collector and the sun. It takes account of the changing angles of incidence and variations in insolation. The second stage is entirely electronic and deals with the interactions of all the other features that affect the completed plant's performance: heat storage, domestic usage, ambient air temperature, and the various avenues of heat loss from the system.

The "sun" consists of a lamp and mirror that rotate about a vertical axis at a speed of one revolution per second; each revolution represents one day in solar time. The mirror is parabolic in section with the lamp at its focus, so that parallel light falls at all times on a small adjustable platform set at the center of the system. As it rotates, the arm holding lamp and mirror makes a slow oscillation from $23\frac{1}{2}$ degrees above the horizontal plane to $23\frac{1}{2}$ degrees below this plane, and then back again. The angular movement is sinusoidal, and a cycle is completed during 365.2 revolutions of the mirror-lamp assembly. Thus a rather idealised "sun" is produced. The adjustable platform at the center of the system represents the earth and can be tilted to simulate any latitude.

Remote from the sun simulator, but rigidly linked to it mechanically, is a devise for feeding 16 mm film through a film reading head. There are three tracks on the film, one of which is of the solar radiation recorded by a selected meteorological station. This track controls the intensity of illumination of the artificial "sun". The result is a source of parallel light that falls on an inclined platform (the "earth's surface") at angles and with intensities that approximate closely to the angles and solar radiation intensities experienced in the past by the selected recording station.

A photoelectric cell mounted on the inclined platform can be orientated in any direction and represents the "collector" of the solar heating plant, and the signal from it, the gross heat collected by the system. Some errors are inherent in the mechanical part of the analogue. The most serious of these is the assumption that all solar radiation is directed. If records become available which discriminate between direct and diffuse radiation, then this feature can be built into the existing analogue. It is not expected that this discrepancy in presentation will invalidate the use of the analogue, but complete vindication can only come from analyses carried out on existing solar heating systems.

The electrical part of the analogue is conventional in its construction. The conversion factors used throughout are: 1°F = 0.25 volt, 1 btu/hr = 0.25 microamps, and 1 day = 1 second. Scaling is achieved by manipulating the heat flow/current relationship and allows a wide range of variables to be attempted.

Preliminary testing is being confined to the mechanical part of the unit for the moment. The results so far show that the artificial "sun" gives an acceptable reproduction of the solar radiation records, and the unit has already indicated several useful lines of investigation.

MACHINE A ANALOGIE ÉLECTRONICO-MÉCANIQUE POUR LA RÉALISATION D'INSTALLATIONS DE CHAUFFAGE PAR L'ÉNERGIE SOLAIRE

Résumé

Si on doit faire un usage généralisé du chauffage solaire ou le perfectionner à un degré tel qu'il puisse faire concurrence aux autres sources de chaleur, il faut être en mesure de prévoir avec quelque exactitude les résultats que l'on peut attendre d'une installation donnée dans des conditions d'utilisation spécifiées. L'emploi d'une machine à analogie constitue l'un des moyens d'atteindre ce résultat.

Le dispositif décrit dans le présent mémoire traite le problème d'établissement du projet en deux stades. Dans le premier, qui est réalisé au moyen d'un simulateur mécanique, on détermine les rapports qui existent entre le soleil et le collecteur, en tenant compte des variations de l'angle d'incidence et de l'ensoleillement. Le deuxième stade est entièrement électronique, et a trait aux effets réciproques de tous les autres éléments qui influent sur le fonctionnement de l'installation : accumulation ou emmagasinage de la chaleur, applications ménagères, température de l'air ambiant et causes possibles de pertes de chaleur par le système.

Le « soleil » est constitué par une lampe et un miroir qui tournent autour d'un axe vertical à raison d'un tour par seconde, chaque tour représentant un jour solaire. Le miroir est parabolique et la lampe se trouve au foyer, si bien qu'un faisceau de rayons parallèles vient porter de façon continue sur une petite plate-forme réglable située au centre du dispositif. Le bras qui porte la lampe et le miroir décrit une oscillation lente, pendant sa rotation, ce qui l'amène de 23,5 degrés au-dessus du plan horizontal à 23,5 au-dessous, et ainsi de suite. Le mouvement angulaire est sinusoïdal et le cycle complet prend 365,2 tours du groupe miroir-lampe. On réalise donc ainsi un « soleil » quelque peu simplifié. La plate-forme réglable, qui se trouve au centre du système, représente la terre; on peut l'incliner à volonté pour simuler toute latitude choisie.

A quelque distance du dispositif qui simule le soleil, mais lié mécaniquement avec lui de façon rigide, on trouve un appareil permettant de faire passer un film de 16 mm devant un lecteur optique. Le film porte trois pistes, dont l'une est constituée par l'enregistrement du rayonnement solaire à un poste météorologique choisi comme il convient. Cette piste sert à régler l'intensité de l'éclairement que fournit le « soleil » artificiel. On réalise donc, avec les deux groupes ainsi décrits, une source de rayons lumineux parallèles qui portent sur une plate-forme inclinée (la « surface de la terre »), de telle manière que leur incidence et leur intensité reproduisent avec une grande fidélité celles que l'on avait déterminées auparavant au poste d'enregistrement choisi.

Une cellule photo-électrique montée sur la plate-forme inclinée peut s'orienter dans toute direction choisie et représente le « collecteur » de l'installation de chauffage solaire. Elle émet un signal qui correspond à la chaleur brute que recueille l'ensemble du système. Le fonctionnement de la partie mécanique de la machine à analogie souffre d'un certain nombre d'erreurs intrinsèques. La plus grave de celles-ci est évidemment l'hypothèse sur laquelle repose sa construction, suivant laquelle tout le rayonnement solaire est orienté. Si on peut un jour se procurer des enregistrements qui font la distinction entre le rayonnement direct et le rayonnement diffus, on pourra incorporer ce perfectionnement au dispositif. On ne s'attend pas à ce que cette différence entre la réalité et la reproduction des phénomènes en cause rende l'emploi de la machine injustifié, mais cet appareil ne peut faire complètement ses preuves qu'à la suite d'analyses du fonctionnement de systèmes de chauffage solaire en service.

Le groupe électrique de la machine est d'une réalisation classique. Les facteurs de conversion dont il est fait usage sont les suivants : 1 °F = 0,25 volt, 1 btu/h = 0,25 microampère, 1 jour = 1 seconde. On détermine l'échelle à volonté en agissant sur le rapport entre le débit de chaleur et le courant, ce qui permet la mise en œuvre d'un grand nombre de variables.

Les essais préliminaires se limitent, pour le moment, à la partie mécanique du système. Les résultats obtenus jusqu'à présent indiquent que le « soleil » artificiel permet de réaliser une reproduction acceptable des données sur le rayonnement solaire antérieurement enregistrées, et le dispositif a déjà indiqué aux chercheurs plusieurs orientations fructueuses de leurs travaux.

THE PERFORMANCE OF AN EXPERIMENTAL SYSTEM USING SOLAR ENERGY FOR HEATING, AND NIGHT RADIATION FOR COOLING A BUILDING

*Raymond W. Bliss, Jr.**

A system using sunshine as the major energy source for heating a building in an economically under-developed region usually should meet the following design criteria:

1. No auxiliary electrical energy should be used.
2. Moderate and simple use of auxiliary fuel is permissible.
3. Moderately wide variations of interior temperature are permissible.
4. Initial cost of the system *must* be low.

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None of the above criteria are met by the experimental heating-cooling system to be described in this article. It uses auxiliary electrical energy exclusively, gives very close temperature control, and is expensive. Designed primarily for study and as a teaching aid, it is probably not a prototype of any economically practicable solar-heating system which may appear in the future. It is certainly not an example of a practical solar-heating system for an economically under-developed region. Nevertheless, since the basic principles of using sunshine are the same regardless of the design approach taken, a description of this system may be of interest.

Table 1. Summer and winter climatic data — Tucson, Arizona
(Latitude 32° N, Elevation 2 400 ft)

		June	*July*	*Aug.*	*Dec.*	*Jan.*	*Feb.*
Long-term averages: [a]							
Average daily maximum temp.	F.	98.4	99.4	95.8	65.6	63.1	66.1
Average daily minimum temp.	F.	65.8	73.0	71.8	38.4	36.3	39.5
Average dew point (summer months)	F.	38	56	61			
Percent of possible sunshine		92	76	80	83	80	84
Rainfall	in.	0.30	1.80	2.15	0.94	0.63	0.95
Wind velocity	mph.	7.7	7.5	6.9	7.2	7.2	7.2
Data for year 1960: [b]							
Average daily maximum temp.	F.	101	100	98	65	62	64
Average daily minimum temp.	F.	66	74	72	33	34	33
Maximum temp.	F.	111	106	105	83	75	78
Minimum temp.	F.	58	63	65	18	24	24
Maximum dew point (summer months)	F.	62	70	71			
Percent of possible sunshine		86	77	81	84	73	82
Rainfall	in.	trace	1.41	2.38	0.85	2.20	0.58
Average total solar energy striking a horizontal surface g-cal/cm²-day		687	657	620	339	328	447
Average total solar energy striking a south-facing surface tilted 7° from horizontal (winter months) g-cal/cm²-day					376	357	490

[a] U.S. Weather Bureau station at airport.
[b] Measured at site.

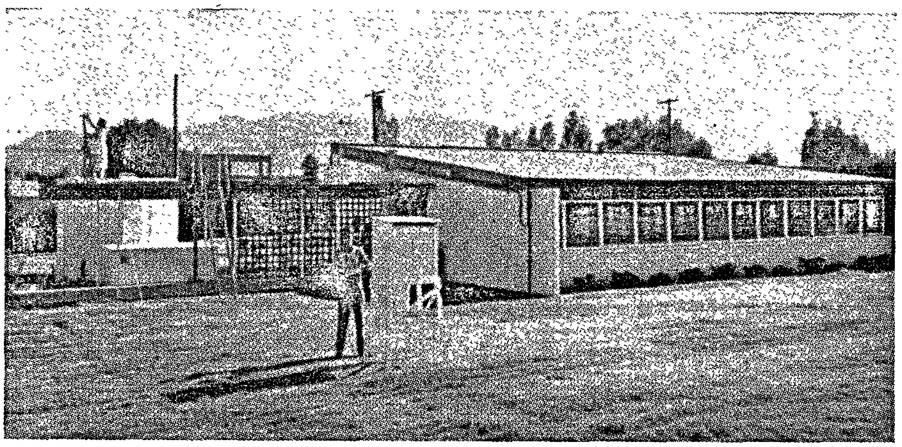


Figure 1. General view of solar energy laboratory. Camera looking north-east

At this writing (March 1961) it has been in operation for about two years, and its performance has been thoroughly monitored for about eighteen months.

Location, climate, pertinent structural features of building

Tucson, Arizona, the site of this building, has a climate typical of the valley areas of the arid southwestern part of the United States: low rainfall, high percentage of sunshine, hot summers, mild winters, and rather low wind velocities. Some pertinent climatological data are given in table 1.

The building to which the experimental heating-cooling system has been applied is a small, single-story office building. Outside dimensions are 50 × 32 ft; inside floor area is 1 440 sq ft. Figures 1, 2, and 3 are photographs of the building. Figure 4 indicates the floor plan and placing of various measuring instruments. Heavy, well-insulated cavity-type masonry walls are used. The roof is well insulated with 5-layer, commercial, reflective insulation ("Infra Type 6"). The building has a concrete floor, a fact of thermal importance because of the relatively large storage capacity of such floors.

The building has 435 sq ft of glass, all of the double layer ("Thermopane") type. The windows do not open, and ventilation air is controlled, normally at about 200 cu ft/min. South-facing windows are shaded by the roof overhang, and north-facing windows by vertical fins, in such a way that no direct sunshine strikes these windows during the warm season from March 21st to September 21st.

Calculations by standard air-conditioning handbook procedures indicate that a steady-state heating rate of 35 000 btu/hr would be required to hold the building interior temperature to 75°F at night with an outdoor temperature of 30°F (1). The figure includes the heating required for the ventilation air (200 cu ft/min). Calculations for summer conditions indicate a peak cooling requirement of 39 000 btu/hr. The summer calculations

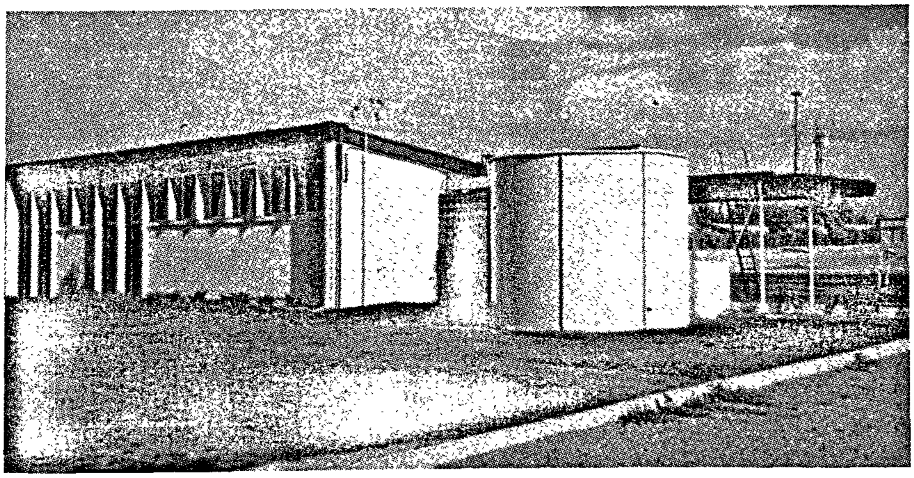


Figure 2. General view of solar energy laboratory. Camera looking south-east. Note vertical fins for shading of north-facing windows. Global and normal-incidence pyrheliometers are mounted at west end of roof deck

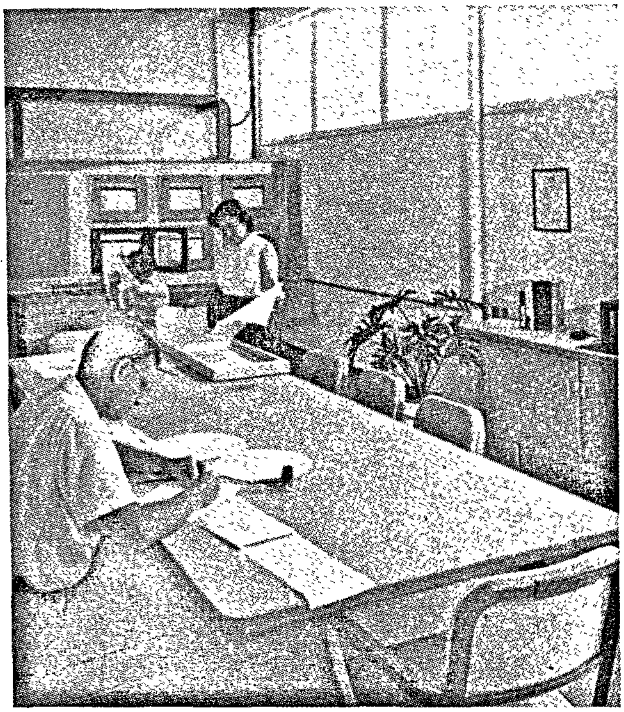


Figure 3. Control panel and recorders are installed at west end of lecture room

assume an indoor temperature of 75°F, peak outdoor temperature 107°F, ventilation 200 cfm, and internal heat generation of 4 500 btu/hr. They are unsteady-state heat flow calculations in so far as the heat transfer through the walls is concerned, and include the necessary allowance for the thermal lag of the heavy walls.

The experimental heating-cooling system

The system, which has the flow scheme shown in figure 5, uses water for the transportation and storage of energy.

The entire roof of the building is a large flat-plate heat-exchanger, made of copper sheet with built-in water-circulating tubes ("Tube-in-strip"). Water is heated as desired by circulating it through this roof panel during sunny periods. The water is cooled during summer operation by circulating it through the roof panel at night. The roof panel is painted a dark green, a color which is aesthetically more attractive than black but reflects very little more solar energy than does ordinary black paint. The roof faces south at a 7° tilt from the horizontal.

A second, large, flat-plate heat-exchanger forms the ceiling of the building interior. This ceiling panel is made of the same "Tube-in-strip" material as used for the roof panel. Warm water is circulated through the ceiling panel in order to heat the building; cold water is circulated through the ceiling in order to cool the building. Some construction details of both the ceiling panel and the roof panel are shown in figure 6.

The insulated storage tank is divided into two compartments by a horizontal baffle across the mid-portion of the tank. The division between compartments is purposely *not* watertight. Thermospihon flow and equalization of temperature between compartments occurs whenever the water temperature in the lower tank is higher than that in the upper tank. On the other hand, hot water, can be stored in the upper tank and cold water in the lower tank with no thermosiphon mixing. The heat pump utilizes a conventional motor-driven

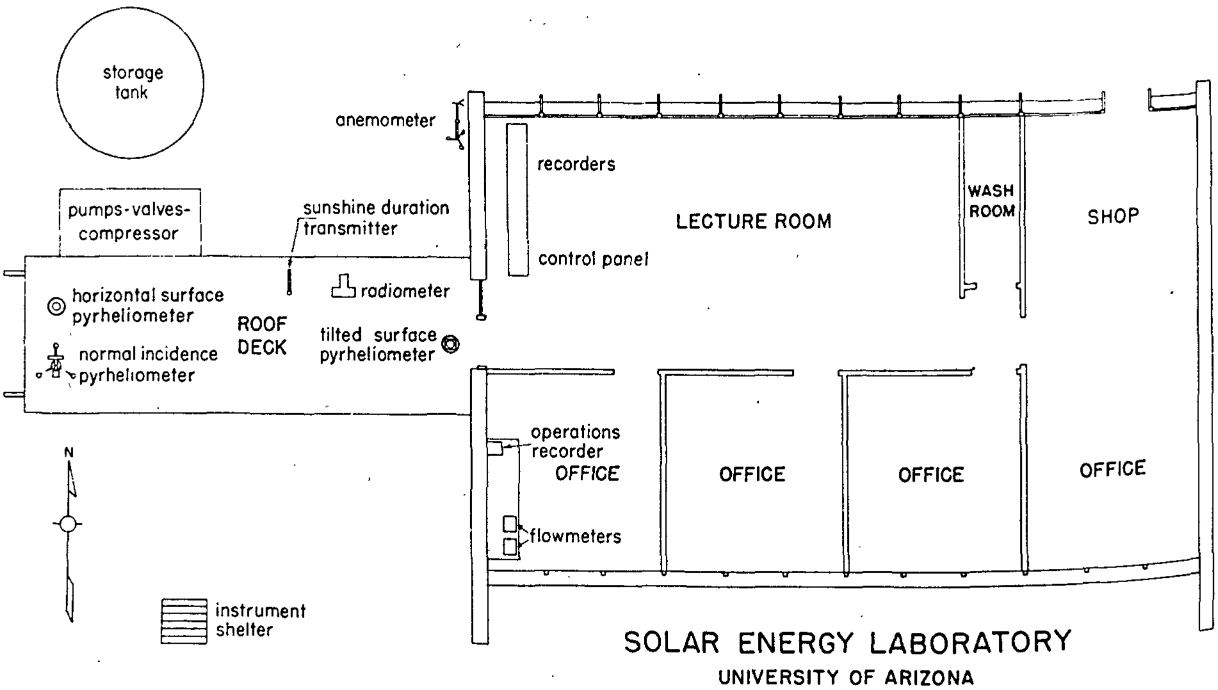


Figure 4. Floor plan and arrangement of instrumentation

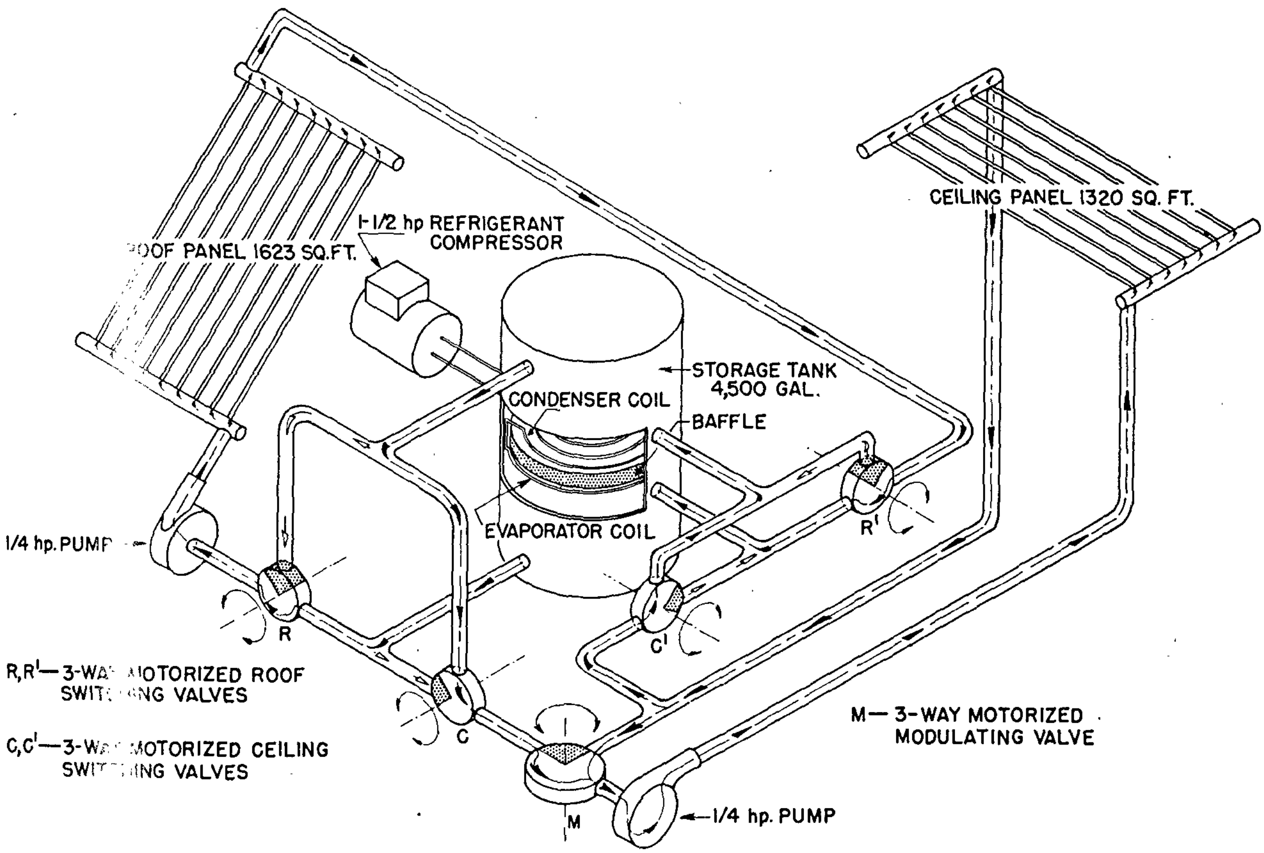
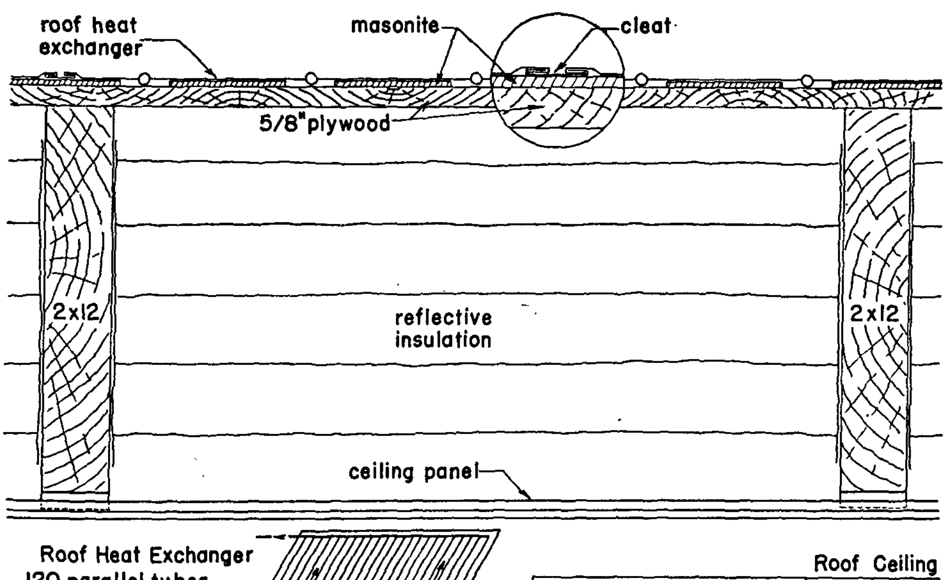


Figure 5. Flow scheme of experimental heating-cooling system



	Roof	Ceiling
Length, ft.	50.0	46.3
Width, ft.	32.5	28.5
Copper sheet thickness, in.	.025	.025
Tube inside diameter, in.	5/16	1/2
Tube spacing, in.	5	5
Approx. water flow rate, gpm	30	30

Figure 6. Some construction and dimensional details of roof panel and ceiling panel

compressor, and has its evaporator coils in the lower tank and its condenser coils in the upper tank. Operation of the compressor results in a movement of energy from the lower to the upper tank, thus raising the temperature of the upper tank while lowering that of the lower tank.

The two centrifugal pumps, together with associated piping and motorized valves, are so arranged that water from either half of the tank can be circulated through either the roof panel or the ceiling panel.

The control system incorporates a manual selector switch which may be set at any one of three positions: "Heating Only", "Cooling Only", and "Heating-Cooling". Except for the operation of this switch and the setting of the building thermostat, all control is fully automatic. Operation at the various selector switch settings is as follows:

1. When set at "Heating Only" (used in the winter), the lower tank is heated whenever possible by circulating water between that tank and the roof panel. Hot water for the ceiling panels is obtained from the upper tank, with appropriate temperature modulation by valve M (see figure 5). The compressor operates whenever it is necessary to raise the water temperature in the upper tank in order to fulfil the building heating requirements.

2. When set at "Cooling Only" (used in summer) the upper tank is cooled whenever possible, and cooled water for the ceiling panels is obtained from the lower tank. The compressor operates whenever it is necessary to lower the water temperature in the lower tank in order to fulfil the building cooling requirements.

3. When set at "Heating-Cooling" (used in spring and fall) the system operates to store solar-heated water in the upper tank and night-cooled water in the lower tank. The building is heated or cooled, as required, by circulation from the appropriate tank through the ceiling panel. The compressor operates whenever it is necessary to raise or lower the water temperature in the upper or lower tank in order to fulfil building heating or cooling requirements.

Performance data

The performance of the heating-cooling system has been monitored continuously from 1 July 1959 to the present writing (March 1961). Throughout this period, it has been operated to maintain the indoor air temperature at 75°F at all times (24 hours daily, 7 days a week). With the exception of three summer days, discussed in a later section, actual indoor air temperatures (as continuously measured in the lecture room) have practically always been within 3 fahrenheit degrees of the 75° F thermostat setting. A summary of some of the data obtained thus far is given by figures 7 and 8, and table 2.

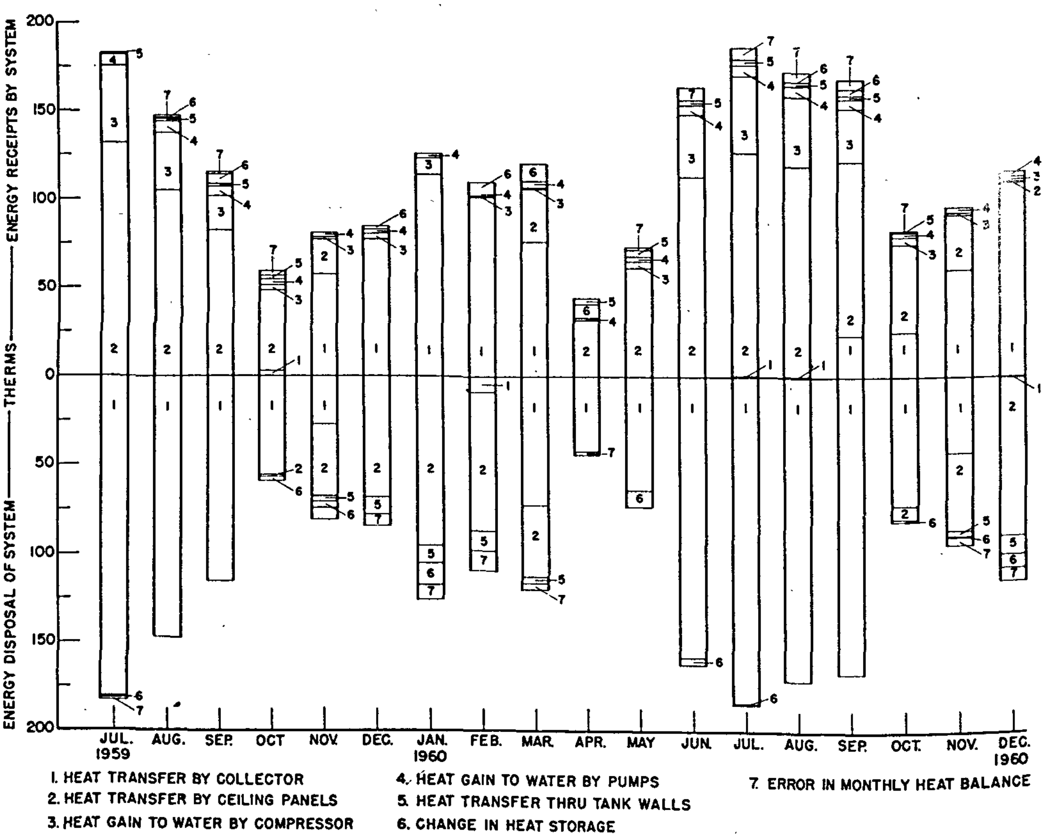


Figure 7. Monthly summary of energy received and rejected by the water of the heating-cooling system

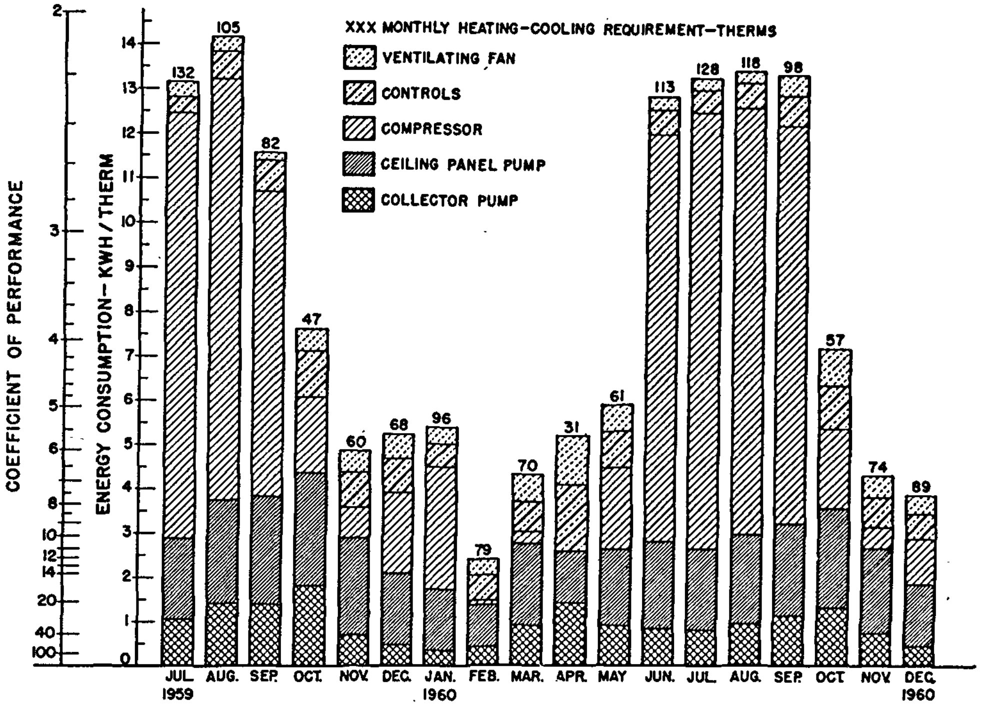


Figure 8. Monthly energy requirements of the heating-cooling system, expressed as kWh per therm of useful building heating or cooling

A few figures for the year 1960 are:

1. The system delivered 35.3 million btu to the building for heating purposes. The total electrical energy consumed during the heating season for operation of pumps, compressor, controls system, and ventilating fan was 5 million btu. The ratio between these two figures, about 7.1, may be defined as the "over-all heating coefficient of performance" of the system.

2. A total of 6.58 million btu were removed from the building by the cooling system, which required a total electrical energy consumption of 24.6 million btu. The corresponding over-all cooling coefficient of performance was thus about 2.7.

3. About 85 per cent of the solar energy collected during January, February, and December was at a high enough temperature level for direct use in heating the building. The remaining 15 per cent required "up-grading" in temperature level by the compressor.

4. On the other hand, during the hot months of June, July, and August, practically all of the energy removed from the building required "upgrading" by the compressor prior to rejection from the roof.

5. During January, the efficiency of the roof collector, expressed as the ratio between energy added to the water in passing through the collector and the total solar energy striking the roof, was

Table 2. Miscellaneous performance data — 1960

	Average temperature of upper tank, F.	*Average temperature of lower tank, F.*	*Electrical energy used by compressor, kWh*	*Total electrical energy used by heating-cooling system, kWh*	*Electrical energy used in building (instruments, shop, lights, etc.) kWh*	*Approx. energy removed from lower tank by compressor, therms*	*Approx. energy added to upper tank by compressor, therms*
January . . .	92	89	264	517	332	28.7	37.4
February . .	102	102	8	192	279	0.9	1.2
March . . .	94	59	19	304	293	2.0	2.6
April	48	49	0	164	270	0	0
May	58	58	113	363	280	12.9	16.8
June	82	65	1 035	1 451	317	113.0	148.3
July	88	65	1 261	1 707	318	133.0	176.0
August . . .	86	66	1 141	1 597	287	121.0	160.0
September. .	80	65	882	1 306	271	93.3	123.4
October. . .	73	57	103	408	313	11.2	14.7
November. .	90	54	35	320	341	4.0	5.2
December . .	94	93	93	346	294	10.5	13.7

17.2 per cent. Expressed as the ratio between the energy added to the water and the solar energy striking the collector during collector operating periods, the efficiency was 28.7 per cent.

Comparisons between actual and calculated performance

A great many such comparisons are possible with a continuously operating, well-instrumented system such as this one. Three will be mentioned briefly.

Figure 9 compares the actual hourly useful heat gain rates of the collector with the calculated values for the same period, for 30 typical hours during January 1960. The actual hourly collection rates are those obtained from continuous record measurements of water flow rates and temperature rises in passing through the collector. The calculated values are obtained from the equation:

$$q_u = F_o [\alpha\, q_i - U_L\, (t_{w-o} - t_a) - \varepsilon R]$$

in which

q_u = Useful energy collection rate per unit area of collector, btu/sq ft-hr.
F_o = Over-all efficiency of collector as a heat-exchanger, dimensionless.
α = Solar absorptivity of collector plate, dimensionless.
q_i = Intensity of sunshine striking collector plate, btu/sq ft-hr.
U_L = Combined convention-radiation loss-rate coefficient, btu/sq ft-hr-°F.
t_{w-o} = Temperature of water entering collector, °F.
t_a = Temperature of outdoor air, °F.
ε = Emissivity of collector plate, dimensionless.
R = Net long-wave radiation exchange from an exposed thermally black horizontal surface at air temperature to the sky, btu/sq ft-hr.

The derivations of equations such as the above are given by Hottel & Woertz (2), Hottel & Whillier (3), Jordan & Threlkeld (4), Tabor (5) and Bliss (6). It is evident from figure 9 that actual and calculated hourly values of useful heat collection are in very satisfactory agreement.

The quantity R appearing in the preceeding equation is, to a good approximation, a function of the outdoor air temperature and dewpoint. Figure 10 presents some apparent actual values of R as determined during hours when the roof panels were operating with entering water temperature equal to the outdoor air temperature. Also shown on the same graph are the values of R used in designing the system, and a later set of values calculated by this writer (7). The "design values", the dashed curves on the figure, are based on the work of Dines (8). The apparent actual values were obtained from roof panel performance data of April-July 1960. They are, in general, lower than the design curves and somewhat higher than our calculated curves.

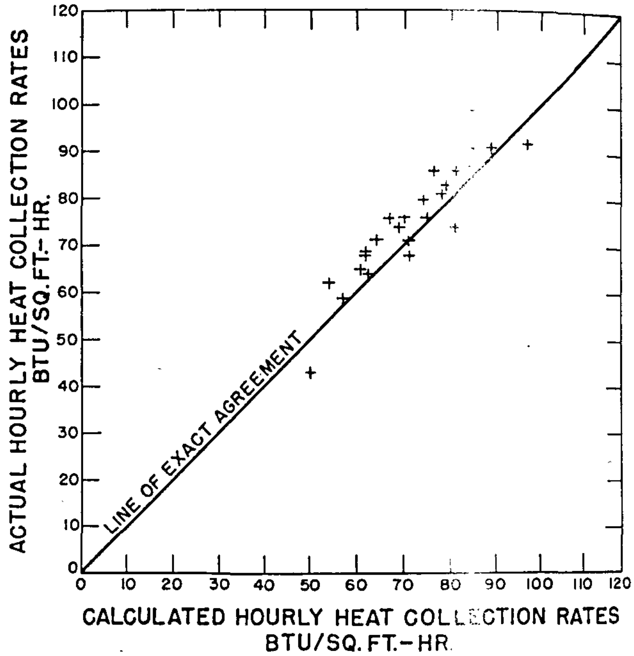


Figure 9. Comparison of actual and calculated useful solar heat collection rates for 30 typical hours of January, 1960

The ceiling panel heat transfer rate into the rooms is given by an equation very similar in form to that used for the roof collector. Figure 10 compares the calculated heat transfer from the ceiling panel with twenty apparent actual values recorded in January and June 1960. The calculated curves are based on the assumption that the mean radiant temperature of all interior surfaces other than the ceiling panel are at air temperature. Since in actuality these surfaces are somewhat warmer than indoor air temperature during the summer, and somewhat cooler than indoor air temperature in winter, one

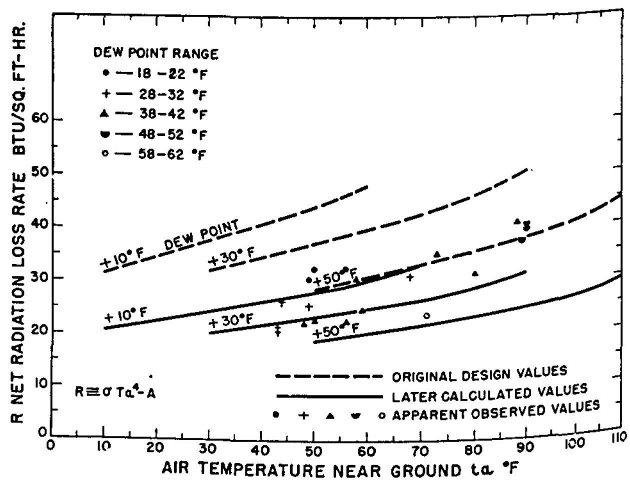


Figure 10. Net radiation exchange between an exposed horizontal thermally black surface at air temperature and a clear night sky. Comparison of values used in original design, average values resulting from later calculations, and values obtained from roof panel heat rejection rates

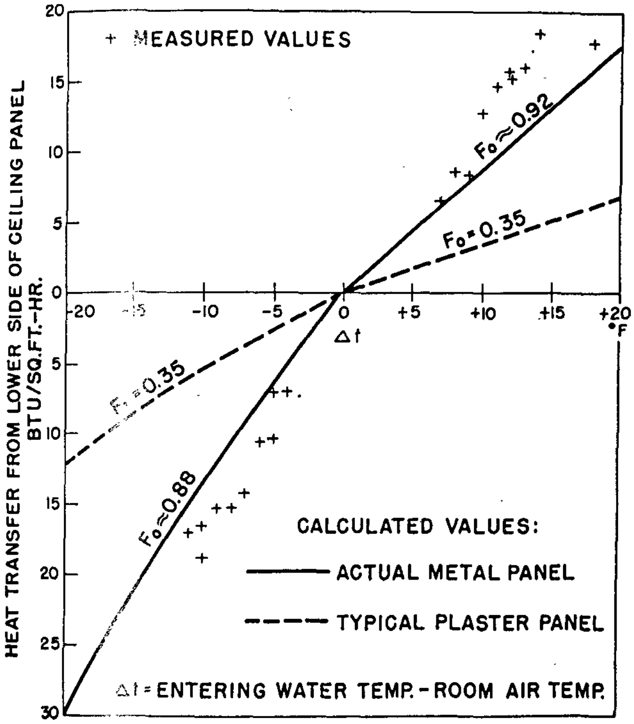


Figure 11. Comparison of calculated and apparent actual heat transfer rates from the lower side of ceiling panels

would expect the actual heat transfer rates from the ceiling panels to the room to be a little higher than the curves so calculated. It is evident from figure 11 that this is the case, and agreement between calculated and apparent actual values may be considered very good. Also shown on figure 11 is the calculated heat transfer rate from a typical ceiling panel formed of copper tubing embedded in plaster. Such a panel has a much lower heat exchanger efficiency than the metal panels actually used, and would not have been satisfactory in this installation.

These comparisons suggest, correctly, that a good deal of careful attention must be given to all details of heat transfer in designing a solar heating system of this type. We have found this to be true of practically all equipment designed to use solar energy.

Design oversights and operating difficulties

This experimental heating-cooling system has operated about as predicted from design calculations, and has given very little trouble.

One difficulty encountered, in this case not an unexpected one, has been condensation on the ceiling panels during humid summer months. Dehumidification apparatus for the incoming ventilation air was purposely omitted in the original installation, in order to see how the system would fare without it. Two summers of operation have shown that it is possible to maintain an excellent comfort level at practically all times without dehumidification, but that the ceiling panels often operate much too close to the dewpoint of the outdoor air for safety. A thin film of moisture forms regularly on parts of the ceiling panel during the humid days of July and August. During two particularly humid days in 1959 and one such day in 1960 it proved necessary to shut the system down for several hours in order to avoid condensation and dripping from the ceiling panel. In each case the building air temperature rose to between 80 and 85°F and, because of the high relative humidity, was quite uncomfortable. On the other hand, the effect of relative humidity on comfort seems to be very small as long as the indoor air temperature is held near 75°F. We presently consider that dehumidification equipment would not particularly improve the already excellent summer comfort level in the building, but that it would be desirable as a safety factor to preclude the severe nuisance which could result from unchecked formation of heavy condensation on the ceiling panel.

Several troubles and near-troubles with this particular installation now seem, in retrospect, to have been "design errors":

1. On mild winter days the offices on the south side of the building become overheated, even though heating may be required for the lecture room. Rather surprisingly, too little attention was paid to the easily calculable effects of winter sunshine entering the south-facing windows.

2. During summer, the compressor operates more than was expected, particularly in June. This is connected with the fact that our design estimate of outgoing nocturnal radiation (see figure 10) was apparently too high.

3. The design of the piping layout can permit the pumps to become airbound under certain circumstances, and this has happened on about six occasions.

4. The placing of condenser and evaporator coils inside the tank makes them very inaccessible. A major disassembly will be required should they develop a leak.

5. Flow equalization in the roof panel is accomplished by adjustment of a small balancing valve for each tube. These valves become somewhat plugged over a period of time, and it has proved necessary to "rebalance" the roof panel every four or five months.

So far, the only mechanical breakdowns of importance have been:

1. The valve stems on the three-way valves were defective, and all failed within a few months after installation. Since replacement with new stems they have given no further trouble.

2. Five leaks have occurred in the roof panel. Three came in November 1958, soon after the system was placed in operation; one occurred in 1960, and the latest one in 1961. The first three are believed to have been caused by tube freezing due to improper drainage; the other two may have been poorly soldered joints.

Economics

The entire experimental heating-cooling system was fabricated and installed by a University mechanic and two paid student assistants. Total installed cost, if all materials had been purchased, is estimated at about $8 000. Actual installed cost was less because some materials were donated. Since the heating-cooling system furnishes the roofing and ceiling of the building, it seems appropriate to deduct about $1 000 from the system cost for these items, and estimate the installed cost chargeable to the heating-cooling system as about $7 000, not including design labor. Design labor was extremely high, probably about $10 000. The operating cost of the system (electrical energy at 2.5 cents kWh) is about $215 per year. The conventional air-conditioning system for this building in this locality would have been a combination of gas furnace and 5-horsepower "air-to-air" refrigerating unit, whose total installed cost would have been about $2 500 and whose yearly operating cost would have been about $400.

General conclusions

We believe that the following remarks are generally applicable to the matter of developing economically practicable systems intended to use sunshine to supply a major portion of the winter heating requirements of a building:

1. Such systems are not presently available. The technological problems of developing them, though real, do not appear insuperable. Neither does it appear that the solution of these problems would be very costly.

2. The use of sunshine for building heating, in the United States at least, represents far and away the largest potentially practical fuel-saving use for sunshine.

3. The design of such systems cannot be divorced from the design of the building itself, and practicable solar-heating systems may always be expected to be best adapted to new construction.

4. Conversion of solar energy to thermal energy external to the building to be heated is an obviously roundabout and awkward solution. It seems most likely that an economically practicable solution will come via systems using conversion inside the building, for example, by some use of large windows through which the sunshine could be directly admitted to the building.

5. There are dozensof worthwhile specific problems awaiting solution in this field. The most promising individual one is probably in the further improvement of the sunshine transmittance and heat insulating properties of low-emissivity transparent coatings for glass, such as the tin oxide coatings now used on various commercial glasses ("NESA", "Electrapane", "Heat Shield").

Although admitting the necessity for an occasional vital spark of invention or ingenuity, it is our own view that progress in making practical use of sunshine for building-heating results chiefly from a painstaking application of one's best knowledge of heat transfer principles to the design of equipment which *must* use simple and inexpensive materials. Our experience over the past ten years has been that it is possible to make slow, steady progress in this way, that it is possible to interest talented students in such work, and that it is extremely difficult to obtain funds to prosecute the work. We assume that a somewhat similar situation will prevail during the next ten years.

Acknowledgement

The author is pleased to acknowledge in addition to the financial support of the National Science Foundation the generous cooperation of many local and national firms which contributed equipment, materials, and services for the construction of the laboratory and its experimental heating and cooling system. The material contributions of Minneapolis-Honeywell Regulator Company, Revere Copper and Brass Incorporated, and Libbey Owens Ford Glass Company are especially appreciated.

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Summary

An experimental heating-cooling system for a small laboratory building in southern Arizona is described, and its performance evaluated. The system uses a bare water-circulating solar heat collector to collect heat in the winter, and to reject heat (by night operation) in the summer. The heated (or cooled) water is stored in an insulated tank and circulated through ceiling panels in the building to provide necessary heating or cooling. An auxiliary conventional heat pump is part of the system, and is used to further raise (or lower) the water temperature when necessary.

Operation of the system has been monitored in detail for the past eighteen months. Data are presented concerning solar heat collection efficiency, heat storage effectiveness, auxiliary heat pump energy requirements, control system operation, and operating difficulties. Calculated and observed values of solar heat collection and night heat rejection are compared. Similar comparisons are made for the heat transfer rates of the ceiling panel. A complete listing (on a monthly basis) is given of collector heat collection or rejection, building heating and cooling requirements, tank energy losses, and electrical energy consumption of each component.

Although useful as a study and teaching aid, the system is economically unsound because of its high initial cost. Conversion of solar energy to thermal energy outside of the building shell (as is done in this installation) is considered a cumbersome approach for an economically practical system. The most promising avenue for the development of commercially sound solar building-heating is considered to be in the direction of further improvement of presently available transparent low-emissivity coatings for glass. Such coatings would permit the use of large windows in structures designed to make the building itself an efficient means of collecting and storing solar energy.

In general, ingenuity and invention are felt to play a relatively small (although vital) part in the development of practical solar heating. The problem involves chiefly a thorough and painstaking application of the best knowledge of heat transfer to the design of equipment which must use inexpensive materials. In the author's laboratory it has been found relatively easy to attract talented students to this type of work, but extremely difficult to obtain the necessary funds to prosecute it. If this difficulty is not confined to this laboratory, it probably represents a fundamental bottleneck in the development of better means of using sunshine.

FONCTIONNEMENT D'UN SYSTÈME EXPÉRIMENTAL UTILISANT L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE ET LE RAYONNEMENT NOCTURNE POUR LA CLIMATISATION D'UN BATIMENT

Résumé

L'auteur décrit une installation expérimentale de chauffage et de climatisation pour un petit bâtiment dans l'Arizona du sud qui sert de laboratoire, et évalue le rendement de cette installation. Elle comporte un collecteur de chaleur solaire, où l'eau circule dans des tuyaux découverts, pour capter la chaleur en hiver, et pour la diffuser (de nuit) en été. On garde dans un réservoir calorifugé l'eau chauffée (ou rafraîchie), et on la fait circuler derrière les panneaux du plafond pour fournir le chauffage ou la climatisation nécessaires. Une pompe à chaleur ordinaire fait partie du système et on s'en sert comme auxiliaire, s'il le faut, pour augmenter (ou baisser) davantage la température de l'eau.

Le fonctionnement de l'installation a été soigneusement observé depuis dix-huit mois. Ce mémoire présente des données sur l'efficacité de la collection de chaleur solaire, sur celle de la conservation de la chaleur, sur l'énergie requise pour faire marcher la pompe à chaleur auxiliaire, sur l'opération des appareils régulateurs, et sur divers problèmes se rapportant à la marche du système. L'auteur compare les valeurs calculées et observées de la collection de la chaleur solaire et de la diffusion nocturne de la chaleur. Il compare également les chiffres qui indiquent l'efficacité du transfert de chaleur opéré par les panneaux du plafond. Il donne en outre toutes les valeurs mensuelles de la collection et de la diffusion de la chaleur par le collecteur, du chauffage et de la climatisation dont a besoin le bâtiment, des pertes d'énergie du réservoir, et de la consommation d'énergie électrique de chaque élément du système.

Malgré son utilité pour des recherches et dans l'enseignement, le système n'est pas pratique pour des raisons économiques, car le prix initial est élevé. La conversion de l'énergie solaire en énergie thermale en dehors du bâtiment même (comme cela se fait dans cette installation) ne fournit guère le moyen d'arriver à un système pratique du point de vue économique. On considère qu'on a le plus de chances de résoudre le problème de la mise au point d'un système économique de chauffage solaire des locaux en cherchant à perfectionner davantage les revêtements transparents dont on dispose actuellement pour réduire la capacité d'émission du verre. De

tels revêtements perfectionnés permettraient l'emploi de fenêtres très larges dans des bâtiments conçus de façon à faire de l'édifice même un appareil efficace pour la collection et la conservation de l'énergie solaire.

En général, on considère que l'ingéniosité et l'invention jouent un rôle assez restreint (et pourtant essentiel) dans le développement d'un système pratique de chauffage solaire. Le problème nécessite surtout un examen approfondi et minutieux des meilleures données sur le transfert de la chaleur, et leur application au développement d'appareils qui doivent se construire avec des matériaux peu coûteux. Dans le laboratoire de l'auteur, on a eu en somme peu de peine à attirer vers ce genre de recherches des étudiants doués, mais il a été beaucoup moins facile d'obtenir les fonds nécessaires pour poursuivre ces travaux. Si ce problème financier se pose ailleurs que dans notre laboratoire, il représente sans doute l'obstacle fondamental à la mise au point de moyens plus efficaces d'employer l'énergie solaire.

THE USE OF SOLAR ENERGY FOR SPACE HEATING — M.I.T. SOLAR HOUSE IV

C. D. Engebretson *

The design of a solar heated house, whether it is to be an engineering test, a prototype dwelling, or both, is a complex and demanding task requiring the collaboration of engineer and architect, both well informed in the field. The problems facing the architect who must incorporate a large solar collector and provide space for energy storage are no less difficult than those of the engineer who must attempt prediction of the thermal performance of the structure and components in the face of unknowable weather sequences. Construction and later operation are severe tests of ability to anticipate the behavior of familiar materials in unfamiliar circumstances.

The effective layout and operation of a workable system presents numerous additional complications if the house is to function as an engineering test and yield continuous, worthwhile data. The results of long-term full-scale testing will deviate from those implied by controlled laboratory experiments with both materials and components. This lack of coincidence of expectations and results, predicted weather and actual weather, constitutes the principal justification for construction of solar houses in North America at the present time. The components and concepts under test in presently uneconomical solar heated houses have application to most domestic solar energy experiments, and therefore these efforts may advance the state of the art as a whole.

Considering the magnitude of the planning and design effort involved and the labor which must be expended to analyze and interpret continuous test results, it is not difficult to understand why so few solar house tests exist. It is hoped that this account of experience gained with a solar heated house operated as both a dwelling and a continuous engineering test for a period of three years will benefit other investigators involved in similar pursuits.

The present M.I.T. Solar House was described in a recent paper (1), and detailed description is omitted here. In review, it is a two-story house containing 1 450 square feet of usable living area designed for contemporary living by the standards of its locality. Prominent in the view of the house shown in figure 1 is the flat plate collector incorporated in the structure. The collector has an area of 640 square feet and is tilted 60° to the horizontal. This is near the slope considered optimum for winter heating at its latitude. The design was intended to derive 75 per cent of the house-heating requirements from the sun. This house has demonstrated that the space and comfort requirements considered desirable by American home owners need not be compromised in space heating by solar energy.

Solar energy collector

A solar collector as a part of a house envelope must be evaluated with a number of considerations in mind. Important among these are its thermal performance, its original cost and maintenance, and any effect it may have on the living space behind it. This particular collector has exhibited good thermal performance and both good and undesirable effects on the living space, but its orginal cost and maintenance requirements are not encouraging.

Collector performance

If, in considering the thermal performance of a particular collector, the equation for the instantaneous rate of energy collection developed by Hottel and Whillier (2) is written in the following form:

$$\frac{q_u}{A} = F_R \left[I \left(\overline{\tau_e \alpha}\right) - U_L \left(t_1 - t_0\right) \right] \qquad [1]$$

in which

$\frac{q_u}{A}$ = rate of useful energy collection per unit area of collector surface,
F_R = heat removal efficiency for the collector plate,
I = total insolation rate per unit area on the plane of the collector,
$(\overline{\tau_e \alpha})$ = mean value of the effective cover glass transmittance-collector plate absorptivity product for the total insolation, including allowance for dirt on the cover glasses and shading of the collector plate by glass supporting structure,
U_L = over-all heat loss coefficient for the collector,
t_0 = temperature of the outdoor ambient air,
t_1 = temperature of the energy transport stream at the collector inlet,

it becomes apparent that, as a thermal device, the collector will lose heat to its environment in direct proportion to the difference in its temperature and that of the ambient air by some value of proportionality factor U_L. Heat removal efficiency, F_R, is relatively constant for a given design, but $(\overline{\tau_e \alpha})$ is

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subject to seasonal variations and diurnal variations in the case of a fixed plate collector. The numerical value of $(\overline{\tau_e \alpha})$ is the maximum fraction of I that can be absorbed by the collector plate. If equation [1] is rewritten to relate q_u/A to I, so as to develop the expression for instantaneous collector efficiency, η, which follows

$$\eta = F_R \left[(\overline{\tau_e \alpha}) - U_L \frac{(t_1 - t_0)}{I} \right] \qquad [2]$$

it becomes evident that collection efficiency is sensitive to the ratio $(t_1 - t_0)/I$ and is limited by $F_R\,(\overline{\tau_e \alpha})$. Figure 2 is a plot of equation [2] for the Solar House IV collector using an experimentally determined value for F_R, and a reasonable mean value for U_L. Values of $(\overline{\tau_e \alpha})$ used are the mid-hourly values before and after noon on days of mean monthly declination. The heavy dashed line indicates a representative mean curve. The use of this curve permits approximation of average efficiencies typical of heating season operation. The dotted lines illustrate the interrelation of the various scales of the plot.

The determination of what constitutes the optimum number of hours of operation of the collector must clearly be based on the premise that operation is economically justified at all times when the value of the energy collected exceeds the cost of water circulation. The limiting hours are then at the extremes of the day, and their inclusion of necessity reduces the average value of energy collection per unit of energy on pumping below the value one could achieve by operating only at hours near noon. Plainly, that energy ratio is no measure of whether the system is operated at its economic optimum.

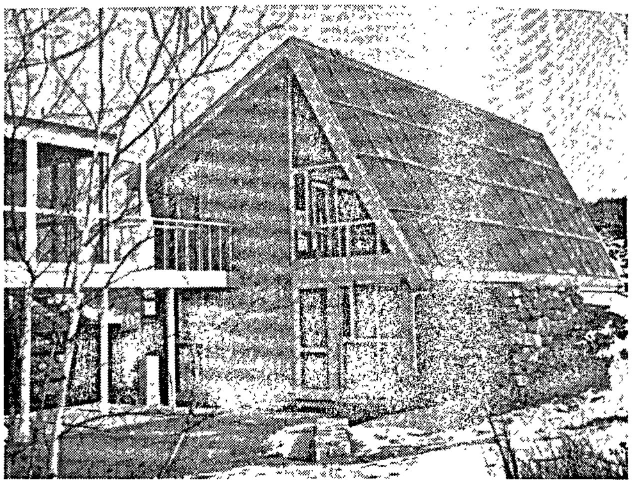

Figure 1. M.I.T. Solar House IV, Lexington, Massachusetts (42° N. lat, 71° W. long)

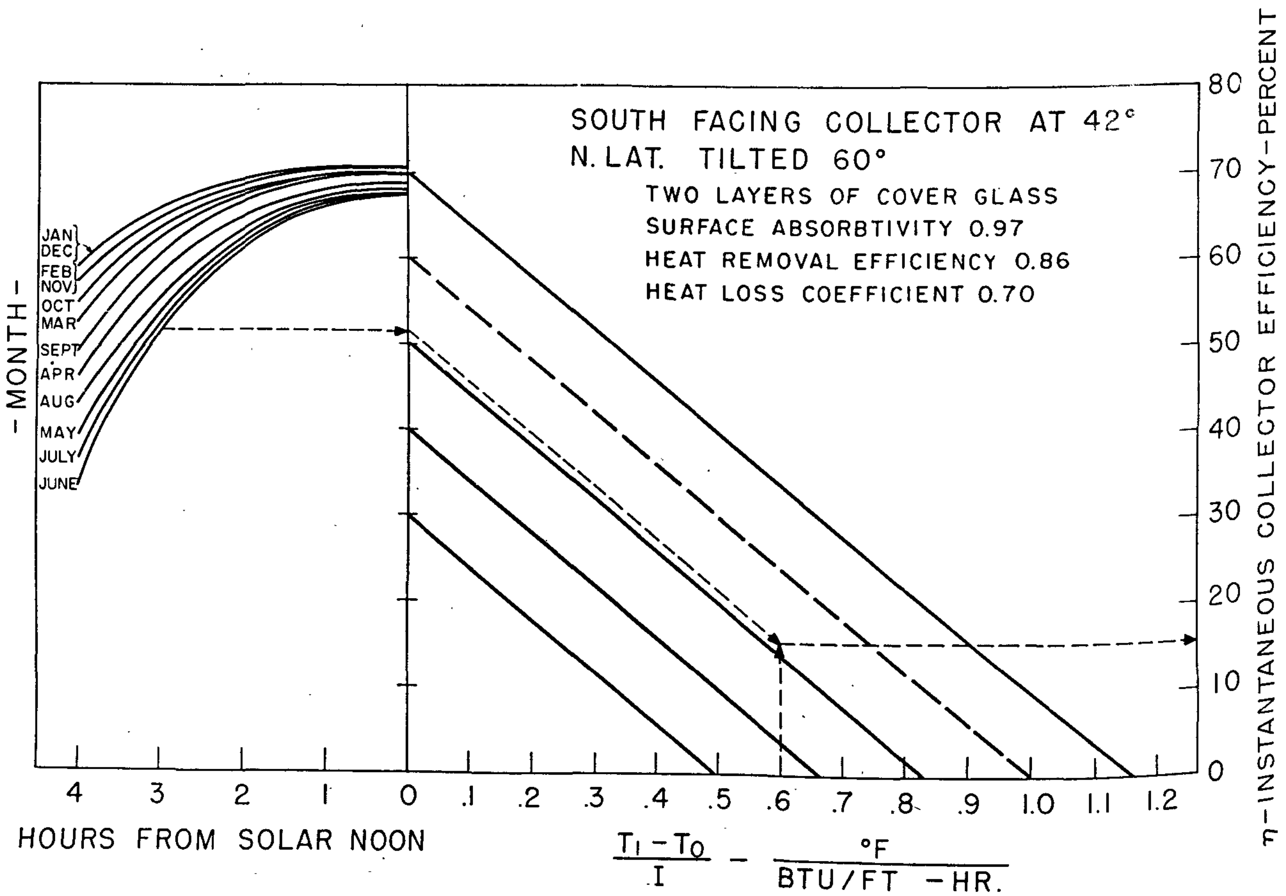

Figure 2. Instantaneous collector efficiency for solar time and months

Table 1. Solar collector performance

		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	Total	Ave.
Solar incidence on 60° plane	1959-1960	33 720	19 330	26 160	34 140	33 890	44 000	32 530	223 780	31 961
(btu/ft^2)	1960-1961	39 360	33 090	40 730	43 125	36 750	44 208		237 263	39 544
Solar incidence on 60° plane while collector operating	1959-1960	22 890	12 920	18 360	25 730	27 020	34 690	24 790	166 400	23 771
(btu/ft^2)	1960-1961	26 380	27 860	33 480	36 984	29 734	35 322		189 760	31 627
Collection	1959-1960	9 890	5 390	8 520	11 590	12 630	15 770	11 040	74 830	10 690
(btu/ft^2)	1960-1961	9 910	11 640	13 810	15 375	12 656	13 944		77 335	12 889
Average hourly collection,	1959-1960	96.1	88.3	103.3	103.1	102.3	106.6	80.9		99.3
q_u/A (btu/hr ft^2)	1960-1961	80.8	86.0	92.9	92.8	102.2	89.3			90.9
Average collector efficiency	1959-1960	43.2	41.8	46.4	45.1	46.7	45.4	44.5		45.0
(per cent)	1960-1961	37.6	41.8	41.3	41.5	42.6	39.5			40.8
Utilization factor	1959-1960	67.9	66.8	71.6	75.4	79.7	78.8	76.2		74.4
(per cent)	1960-1961	67.0	84.3	82.2	85.4	80.9	79.9			80.0
Over-all efficiency	1959-1960	29.3	27.9	33.2	34.0	37.3	35.8	33.9		33.4
(per cent)	1960-1961	25.2	35.2	33.9	34.0	34.4	31.5			32.6

One wants the value of the energy collected, minus the cost of the pumping energy, to be a maximum.

The collector operating efficiency is related to what may be defined as over-all efficiency, the percentage of the total incidence on the collector that is actually collected, by a utilization factor which may be defined as the ratio of the solar incidence during the fraction of time the collector is operating to the total incidence for a given period.

The numerical values for incidence on the surface, both operating and over-all efficiencies, with utilization factors for months of the 1959 and 1960 heating season, are given in table 1. The increase in utilization factor during the last two months of 1960 and during 1961 was deliberate and resulted in increased collection (for the particular operating conditions). The collection per unit of power for this period averaged 178 500 btu per kWh, while in an equivalent period of 1959, a yield of 192 000 btu per kWh was realized. If the cost of the additional solar energy collected is compared with the cost of heat from another source, the additional operation on low grade incidence can be justified. In this collector design and system, an excess of 7.1 btu/ft^2 hr or 14 000 btu per kWh of pumping power must be collected to operate competitively with the auxiliary system.

The utilizability, or ϕ curve method of solar weather description of Hottel and Whillier (2), provides a convenient method for evaluating collector performance. An experimental value of ϕ can be developed for a given collector operation and compared with a theoretical value of ϕ for the same period. ϕ theoretical is defined as:

$$\phi_{TH} = \frac{1}{n} \sum_{1}^{n} \left(\frac{I}{I_{\text{ave}}} - \frac{I_c}{I_{\text{ave}}} \right)^{+} \qquad [3]$$

in which n is number of hours and subscript "ave" denotes average and "c" denotes "critical", or that insolation necessary to raise the collector temperature to the threshold of operation. The + denotes that the summation is made at all periods when the bracketed term is positive. ϕ experimental is approximated as:

$$\phi_{EX} = \frac{q_u}{A} \frac{1}{(\tau_e \alpha) F_R I} \qquad [4]$$

The results of this performance evaluation indicate that the Solar House IV collector could utilize from four to ten per cent more of the available radiation than it does. This is considered a reasonable correlation considering the differences in the real and theoretical operation. The ϕ curve method as used here does not take into account the following:

(*a*) Collector operating economics and the fraction of utilizable but uneconomical incidence which is ignored in the real case;

(*b*) Delay in collector control response to changes in incidence;

(*c*) Loss due to collector heat capacity as defined by Hottel and Woertz (3) and Tabor (4).

Average values of ϕ experimental and ϕ theoretical for a portion of the heating season months are given in table 2. It does not seem reasonable to expect that a closer correlation between theoretical and actual utilizability can be economically achieved. More operating experience and better control would probably cause the difference to be more uniform and slightly but not appreciably less.

Collector design

A cross-section of the collector design used in M.I.T. Solar House IV with design details is shown in figure 3. This design has exhibited good thermal

Table 2. Monthly average utilizability values for 1960-1961 heating season

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
ϕ_{TH}	0.47	0.67	0.63	0.65	0.61	0.58
ϕ_{EX}	0.41	0.57	0.55	0.55	0.57	0.53

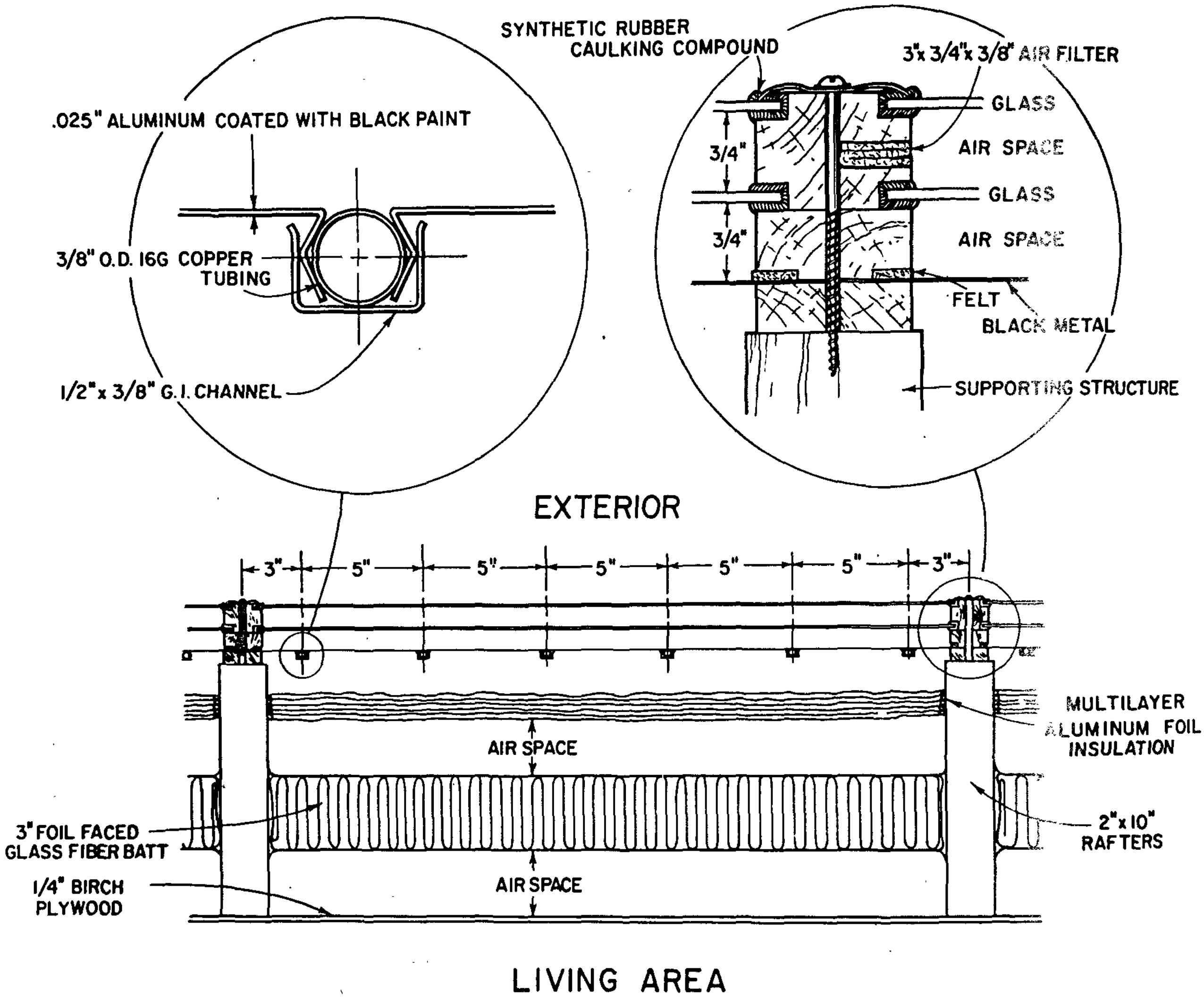

Figure 3. Cross-section and details of solar collector assembly

characteristics and does utilize a portion of the conventional house envelope in its structure to reduce cost. The probable reduction in expenditure for the collector proper by this type of construction is presented by Dietz (5).

Anderson (6) observes, in a discussion of the architectural problems created by solar collectors, that unless the interior of the house is to be maintained warmer than the outside there is no advantage in making the collector surface a part of the house envelope. This is certainly true if no structural economy is to be realized or if an uneconomical house configuration results.

It is doubtful that a sufficient heat requirement will exist in the living space during all sunlit hours of the year to permit collector back loss to be always utilized to advantage.

Experience with this solar house has shown that while the collector utilizes common structural elements and effects a reduction in heat loss and at times a beneficial indirect contribution to house heating, at other times it creates a cooling problem. The structural members passing through the insulation cause an increase in thermal conductance for the entire collector wall in excess of three times the conductance of the insulation proper. The heat flow path should be lengthened by creating a thicker or less continuous structure.

Solar collector area must be determined by its probable useful collection and the demand of the particular application. The fraction of time the collector will be required to yield its maximum useful output will determine the relative value of a unit of area. If a base collector size is considered and the effect of incremental increase of collector size is explored, it will be found that as the area is increased, the use factor of each additional increment decreases.

If the net monetary value of collection from each unit area of base collector is established from local energy costs, then the actual value of a unit area of an additional increment can be determined by taking the product of the ratio of the use factor of the additional increment to the use factor of the base collector and the value of the collection per unit area. For example, an increment of collector having a use factor of 0.5 is worth just half as much and will require twice as long to justify itself economically in terms of useful collection as one with a use factor of unity.

Incremental use factors developed from the performance of the 640 square foot collector of Solar House IV during two heating seasons are given in table 3. The heating load applied to this particular collector equals 18.8 btu/ft^2 per heating degree day (65°F base) and results in a use factor near unity for the heating season. A severe winter with unfavorable solar weather such as 1959-1960 tends to increase the use factor of additional increments. For this reason, data over as long a period of time as possible are desirable for sizing a collector.

The collector plate construction by which the water tubes are clamped into the plate has been found satisfactory in maintenance. The performance of the portion of the collector between the plate and the outside has been disappointing. The synthetic rubber caulking compounds used do not bond well to the cover glasses for long periods of time through numerous temperature cycles. Intrusion of water in the wooden structure causes rapid deterioration. Unwanted moisture is also introduced into the air space between the cover glasses by the induction of air as the collector cools. It is impractical to seal this space because thermal stresses exceed the strength of edge-bonded double glazed units and the expansion of air between the glasses would create prohibitive pressures. The filters provided to exclude dust are effective but the moisture in the air does condense on the inside surface of the outer glass layer. This moisture accumulates in the collector, contributes to the maintenance problem, and also reduces the transmittance of the glass. The extent of the effect on transmittance has not been evaluated. However, the visual effect of moisture in the collector in full sunlight is dazzling. In general, with regard to gaskets, seals, and structural battens, it is observed that any portion of a collector not specifically and firmly anchored in place will sooner or later go adrift.

The costs of construction of this collector are not treated here on an individual or mass production basis because it is not considered satisfactory. The group responsible for this test is not in possession of a superior design, nor do they have knowledge of any design which would be suitable for mass production.

Operating experience indicates that a house heating collector at these latitudes will yield approximately the energy equivalent of one gallon of fuel oil per square foot per year. On this expected return, a collector of this thermal performance and all attendant apparatus for storage and utilization of energy would have to be produced for less than one-fifth the cost of this installation if it were to pay for itself in ten years of operation.

Heating system

The present arrangement of the collecting and heating system is shown in schematic diagram (figure 4). Water from storage is circulated through the collector at the rate of 8.36 lb/ft^2 hr, and returned to storage by way of the expansion tank. The expansion tank functions to reduce pressure fluctuation with temperature change and to allow gravity draining of the collector during the off cycle to prevent freezing and reduce collector heat capacity. In this system, where all water returned from the collector must pass through an air volume, a small quantity of air will be entrained in the liquid stream. The expansion tank must be of an internal design to minimize such entrainment and be located so as to provide a hydrostatic head for operation of an air venting or scavenging system to function for the water-containing portions of the system. Lack of a properly designed venting system results in numerous interruptions in service due to air binding in the circulating pump, piping, and the heat exchanger.

Water from solar energy storage is pumped through the heating system heat exchanger and returned to the tank from which it was withdrawn. The same is true when the auxiliary unit is utilized for space heating. The return water from the heat exchanger when operating on the auxiliary will be warmer than the solar storage when this storage has been fully depleted for space heating purposes.

The two sources of hot water for the heat exchanger must be connected in parallel rather than series to prevent heat exchanger returns from raising the temperature of storage by the addition of relatively high cost auxiliary heat, thus increasing storage losses and impairing collector efficiency by raising the inlet temperature. Figure 5 shows the relationship of heat exchanger inlet and outlet temperatures for various conditions and the relationship of required heat exchanger inlet temperature to outside temperature and heating demand.

Table 3. Incremental use factor for fractional collector area increase

	Multiple of present collector area (640 sq ft)									
	1.0	*1.2*	*1.4*	*1.6*	*1.8*	*2.0*	*2.2*	*2.4*	*2.6*	*2.8*
1959-1960	0.96	0.75	0.71	0.60	0.44	0.42	0.31	0.29	0.11	0
1960-1961	0.99	0.92	0.67	0.35	0.33	0.32	0.01	0	0	0
Two seasons . . .	0.97	0.83	0.68	0.48	0.39	0.38	0.20	0.15	0.06	0

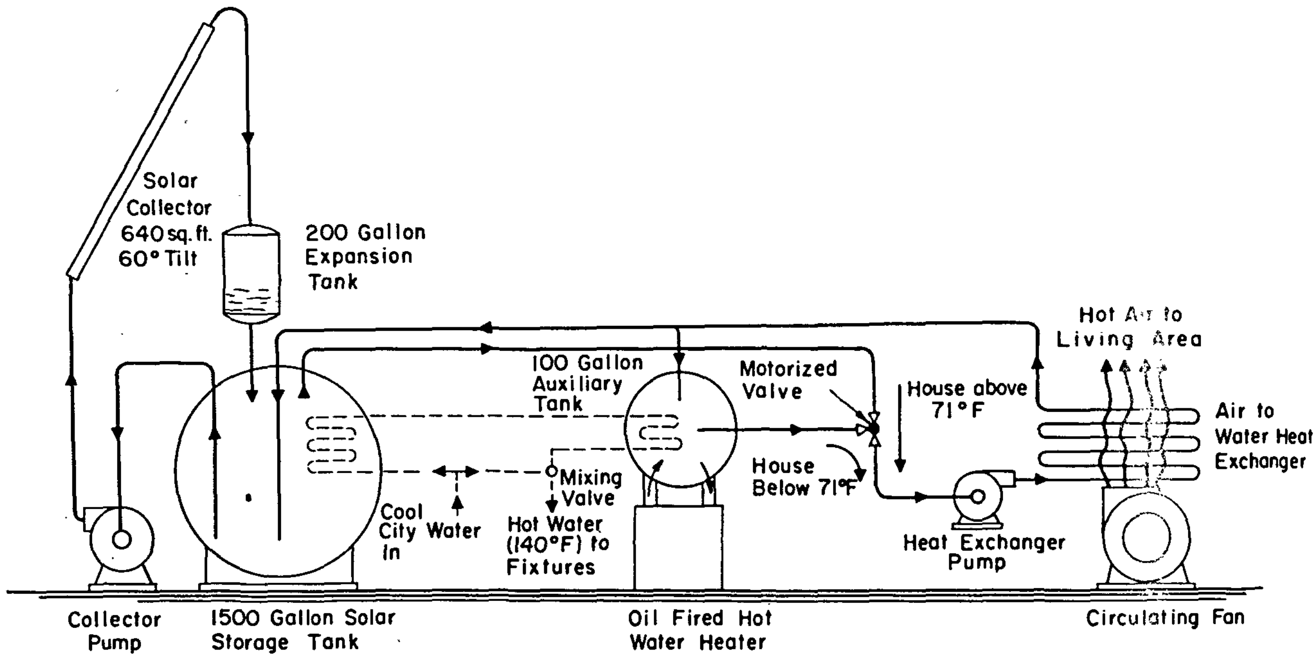

Figure 4. Schematic diagram of solar house heating system

A space heating demand of approximately 12 000 btu per heating degree day (65°F base) must be supplied. The domestic water system requires an additional amount averaging about 75 000 btu per day, of which approximately 45 per cent is "topping up" energy supplied by the auxiliary unit.

Heating and domestic hot water loads and the fractional contributions of the solar heating system are given in table 4.

Auxiliary requirement

The auxiliary heating system must be capable of supplying the maximum probable heating demand

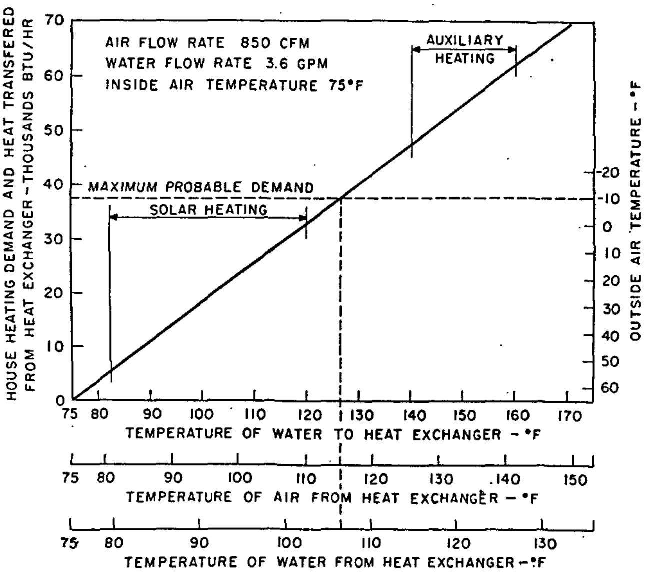

Figure 5. Plot of house heating demand and heating system characteristics

plus the domestic hot water requirement of the house. Extremely cold weather is generally accompanied by clear skies and high solar incidence, but the possibility of conditions combining extreme cold and lack of insolation following a prolonged period of overcast weather during which the energy storage has been depleted makes this criterion necessary. In a system where domestic hot water is heated to the temperature of solar storage and then "topped up" in the auxiliary unit, the temperature level of the auxiliary is determined by the necessary domestic hot water temperature. Modern laundry and dishwashing appliances require a minimum temperature of 140°F. This requirement also determines the time the auxiliary unit is placed in operation in the fall and shut down in the spring. The temperature of the auxiliary exceeds that required to satisfy the maximum heating demand of the house when supplied to the heat exchanger as illustrated in figure 5. However, this over-capacity causes a rapid air temperature response which helps overcome any droop in the system or control. It is preferable that the auxiliary be controlled to supplement the solar energy only when demand or depletion of storage requires it, so that a maximum amount of heating is done with lower cost solar energy.

The actual portion of the heating and domestic hot water loads supplied by the auxiliary system can be determined from table 4.

Auxiliary heating system

The form of the auxiliary heating system depends on the location of the solar house and local fuel availability. A hot water heater fired by the most economical locally available fuel has been found satisfactory where both auxiliary space heating

Table 4. Performance of Solar House IV

		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	Total	Ave.
Space heating demand (10^5 btu)	1959-1960	30.6	77.0	125.4	139.9	188.7	133.3	62.3	687.2	98.2
	1960-1961	36.9	68.0	156.9	184.1	111.8	112.6		670.3	111.7
Space heating demand supplied by solar heating system (10^5 btu)	1959-1960	30.4	14.9	34.7	49.7	60.7	84.3	43.4	318.1	45.4
	1960-1961	36.9	54.5	69.7	80.6	68.7	70.5		380.9	63.5
Fraction of space heating demand by solar heating system (per cent)	1959-1960	98.7	19.4	27.6	35.6	51.2	63.3	69.7		46.3
	1960-1961	100.0	80.7	44.4	43.8	61.4	62.6			56.8
Domestic hot water heating demand (10^5 btu)	1959-1960	15.8	15.0	20.2	21.6	23.7	23.3	19.7	139.3	19.9
	1960-1961	22.9	25.3	29.5	31.0	24.4	34.1		167.1	27.9
Domestic hot water heating demand supplied by solar heating system (10^5 btu)	1959-1960	14.6	8.4	9.8	11.4	12.0	12.1	11.7	80.0	11.4
	1960-1961	21.8	13.7	14.6	13.6	11.3	17.4		92.4	15.4
Fraction of domestic hot water heating demand by solar heating system (per cent)	1959-1960	92.3	56.0	48.5	52.8	50.7	51.8	59.4		57.4
	1960-1961	95.3	54.3	49.5	43.8	46.3	55.4			55.3
Total heating demand (10^5 btu)	1959-1960	46.5	92.0	145.6	161.5	142.4	156.5	82.0	826.5	118.1
	1960-1961	59.8	93.2	186.4	215.1	136.2	146.7		837.4	139.6
Total heating demand supplied by solar heating system	1959-1960	45.0	22.3	44.5	61.1	72.7	96.4	55.1	397.1	59.9
	1960-1961	58.7	68.6	84.3	94.2	80.0	87.9		473.7	79.0
Fraction of gross heating demand supplied by solar heating system (per cent)	1959-1960	96.7	25.4	30.5	37.8	51.1	61.5	67.2		48.2
	1960-1961	98.0	73.6	45.2	43.8	58.7	59.9			56.6

and domestic hot water are required. In other systems, a conventional hot air furnace for space heating and a water heater for domestic hot water heating would be utilized to advantage.

Energy storage

The desirability of energy storage by reversible chemical reactions is quite obvious. In the absence of suitable processes for its accomplishment, sensible energy storage in high heat capacity materials has merit. Both solids and liquids have been used and each has advantages.

M.I.T. Solar House IV uses water both as an energy transport and as a storage medium. Water is desirable and convenient for testing since determinations of the rate of energy flow and the energy remaining in storage are quite easily made.

Liquid storage systems tend to stratify, offering the possibility of selecting the hottest water from the top of the tank and the coolest from the bottom. However, mixing does occur, destroying this desirable stratification. The greatest mixing force is the removal and replacement of water circulated through the collector (10.7 gpm) and heat exchanger (3.6 gpm). Special precautions to insure minimum turbulence will therefore increase the effectiveness of storage. It has been observed that the period of collector operation required to cause the temperature of the 1 500 gallon storage tank to become uniform is approximately 30 minutes.

The impracticality of long-term storage has previously been established. The 1 500 gallons of water for storage — about 2.35 gallons per square foot of collector, has a heat capacity of 19.55 btu/°F ft^2 of collector and consequently a one degree rise for each 19.55 btu/ft^2 collected. Considering the house heating demand, this storage is capable of supplying heat for 1.04 heating degree days per degree Fahrenheit. The effective length of storage is dependent on weather and heating demand. The optimum storage temperature range of 105° to 115°F reported in reference (1) for this system was determined considering collector behavior and all operating costs, including that of recovering energy from storage. During operation of Solar House IV, the daily average storage temperature is usually below optimum but generally very near it. Six hours of collection in one day at the long-term average rate of 90.9 btu/ft^2 hr would cause a temperature rise of approximately 28°F if no heat was removed from storage. If the storage at start of collection were at the minimum economical recovery temperature, 82.5° F, the temperature at the end of collection would be very near optimum. Considering the usual concurrence of collection and utilization, the 28°F rise is unlikely to occur. The behavior of this storage during three years of operation has presented no evidence that any other apportionment of storage to collector area would be better.

Storage depletion is gradual rather than immediate after a fixed period of time. As the storage temperature decreases, a fixed demand requires a greater ratio of auxiliary operating time to solar heating time until an uneconomically low temperature is finally reached.

The effectiveness of storage can be described by ratio of the total energy removed to that put into storage. For short-term storage, the losses are small and the effectiveness, depending on temperature and activity, ranges from 92 to 98 per cent.

Control system

The satisfactory operation of a solar house requires two basically independent control systems. One system must concern itself with the circumstances surrounding the collector and energy storage unit to control energy collection while the other must monitor conditions in the living space and regulate energy utilization in response to space heating demand. While these two processes are not entirely unrelated, they are not sufficiently concurrent to permit a single control system to suffice.

Collector control

The fundamental requirement of the collector control is that it respond to solar radiation in the plane of the collector surface while being aware of the temperature of the storage unit. It must function to initiate and sustain collector operation through all periods during which the radiation incident on the surface is great enough to permit withdrawal of a quantity of heat of equal or greater value than the energy required to operate the collector.

One satisfactory means is the installation of resistance type sensors in the collector and in the storage unit, the sensors in turn being connected electrically in the legs of an alternating current bridge circuit. An electronic relay responding to circuit unbalance will perform the control operations once the circuit has been calibrated and adjusted. Any mechanism capable of comparing these two temperatures with reasonable accuracy can be applied. The actual case becomes more complex as transient conditions and the change in response of the collector to a given amount of radiation due to varying weather are encountered. There is evidence that probably the bridge circuit or equivalent, with sensors in the collector plate and storage, is sufficient for initiating collector operation, but that the decision whether to sustain or terminate collection should be based on measurement of the temperature rise in the energy transport stream through the collector. The comparison of collector inlet and outlet temperatures is a more direct indication of the output of the collector and storage temperatures after the collector is in operation. The considerations in the design of a collector control are as follows.

(*a*) The sensor element applied to the collector plate must have thermal characteristics nearly identical to those of the collector plate assembly to obtain an appropriate response.

(*b*) The control bridge must incorporate a differential adjustment to compensate for the difference in response of the collector to radiation in its "dry plate" condition at start-up from that when operating. A small amount of overheating of the collector plate is necessary on starting to prevent cycling. A compromise setting of this differential will prevent uneconomical collector operation during periods of cold weather.

(*c*) Delay in collector sensor response must be incorporated in the sensor in its mounting or in the electrical circuit. The first portion of the transport medium to reach the collector on start-up does not represent storage temperature but that of environment with which the transport system has reached equilibrium during the collector off-cycle. This first cold "slug" of transport fluid generally chills the collector sufficiently to cause the control to terminate collection unless delay is incorporated by a partial thermal bond between sensor and collector plate or by electrical means. It seems contradictory to design a sensitive control and then render it insensitive to collector performance, but this means is infinitely less complex than attempting to program the transient response of the collector at start-up into the control system.

(*d*) The storage unit sensor element must be located to transmit a temperature representative of the transport stream leaving storage to the control rather than that of some other portion of storage.

Space heating control

The space heating control is required to function to maintain living space temperature within predetermined limits using as much energy from solar energy storage as possible and then supplementing this with heat from the auxiliary system. A conventional thermostat bimetal can be used to initiate operation of the heating system pump and fan in the case of the Solar House IV system to supply heat to the living space from storage. As long as the temperature of storage is sufficiently high to satisfy heating demand, this operation is all that is required. However, if the temperature of the living space should continue to fall even with solar heating, another similar device can be utilized to permit heat to be supplied to the house by the auxiliary system. When the demand no longer requires auxiliary operation, the second bimetal of the thermostat returns the system to solar operation. In the case of Solar House IV, the first-stage bimetal controls operation of the fan and circulating pump (figure 4) and the second stage bimetal the position of the motorized valve. Figure 5 shows the operating characteristics, the system, and the regions of solar and auxiliary operation. Some heating benefit can be obtained by use of rather low temperature storage. However, there is a limit below which the cost of reclaiming energy from storage is greater than the value of the energy itself due to the great amount of pump and fan operating time. A low limit thermostat is applied to the storage to prevent operation on energy of a grade below that which can economically be reclaimed. This thermostat permits operation to be transferred directly to the auxiliary system on evidence that the storage has been exhausted.

Examination of figure 5 will indicate the solar energy storage temperature required for a particular demand or, if the temperature is too low, the proportion of solar and auxiliary operation required.

Solar collector-heat pump combinations

A word about the combination of heat pumps (reverse cycle mechanical refrigeration systems) and solar collector combinations is appropriate, not because they have been used in this test, but because their use has been avoided. The economic considerations involved in solar house heating are rather complex, and the addition of another system between the solar heating system and the auxiliary heating system does nothing to simplify the situation.

There may be cases where the heat pump can be used effectively to reduce the operating time of auxiliaries, but it does not reduce the auxiliary demand, which is a determining factor in the capital expenditure necessary to build a workable solar heated house.

If the heat pump, of appropriate capacity for space heating, can be justified by a summer cooling requirement so that first cost complication applied to the heating system is minimal, then it is logical to apply it to winter heating use either with or without a solar collector. Justification of mechanical refrigeration for summer cooling involves proving power availability costs sufficiently low to make comfort cooling attractive. If power is available and reasonably priced, then the air source heat pump with electric resistance supplementary heat comprises a reasonably good heating system and the justification for a solar collector as an auxiliary becomes difficult.

If one considers operating circumstances alone, a heat pump coefficient of performance of from four to five is necessary to compete costwise with oil or gas fuel. If the heat pump is used for heating domestic hot water and with a condensing temperature of about 150°F, a coefficient of performance of this magnitude cannot be achieved. Operation at this coefficient of performance for space heating would require a sufficiently high storage temperature whereby heat was economically recoverable without pumping.

It was found for the M.I.T. Solar House IV (1), considering all costs of delivering solar heat to the living space and effect of storage temperature of collector performance, that the optimum collector inlet and storage temperature was between 105° and 115°F and that is was uneconomical to reclaim

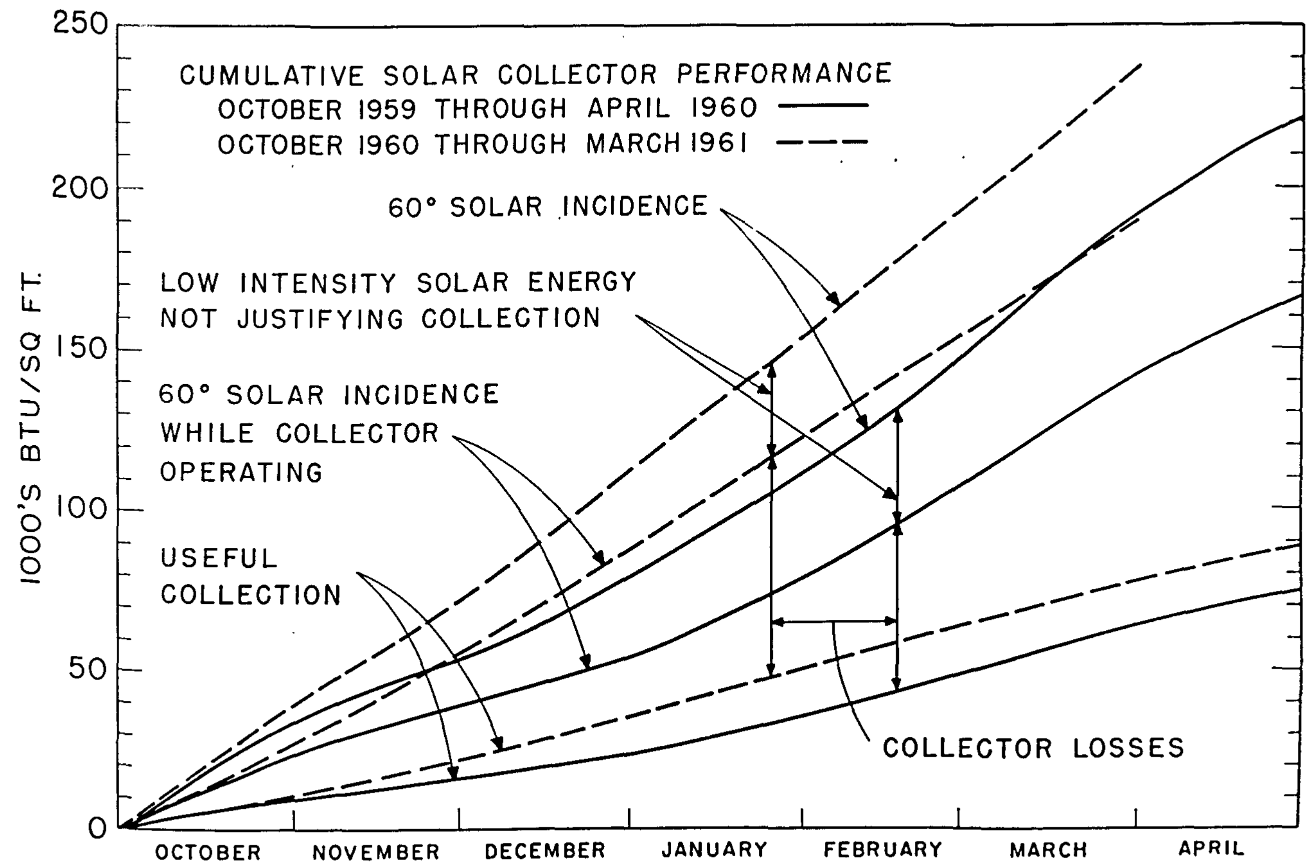

Figure 6. Solar collector performance

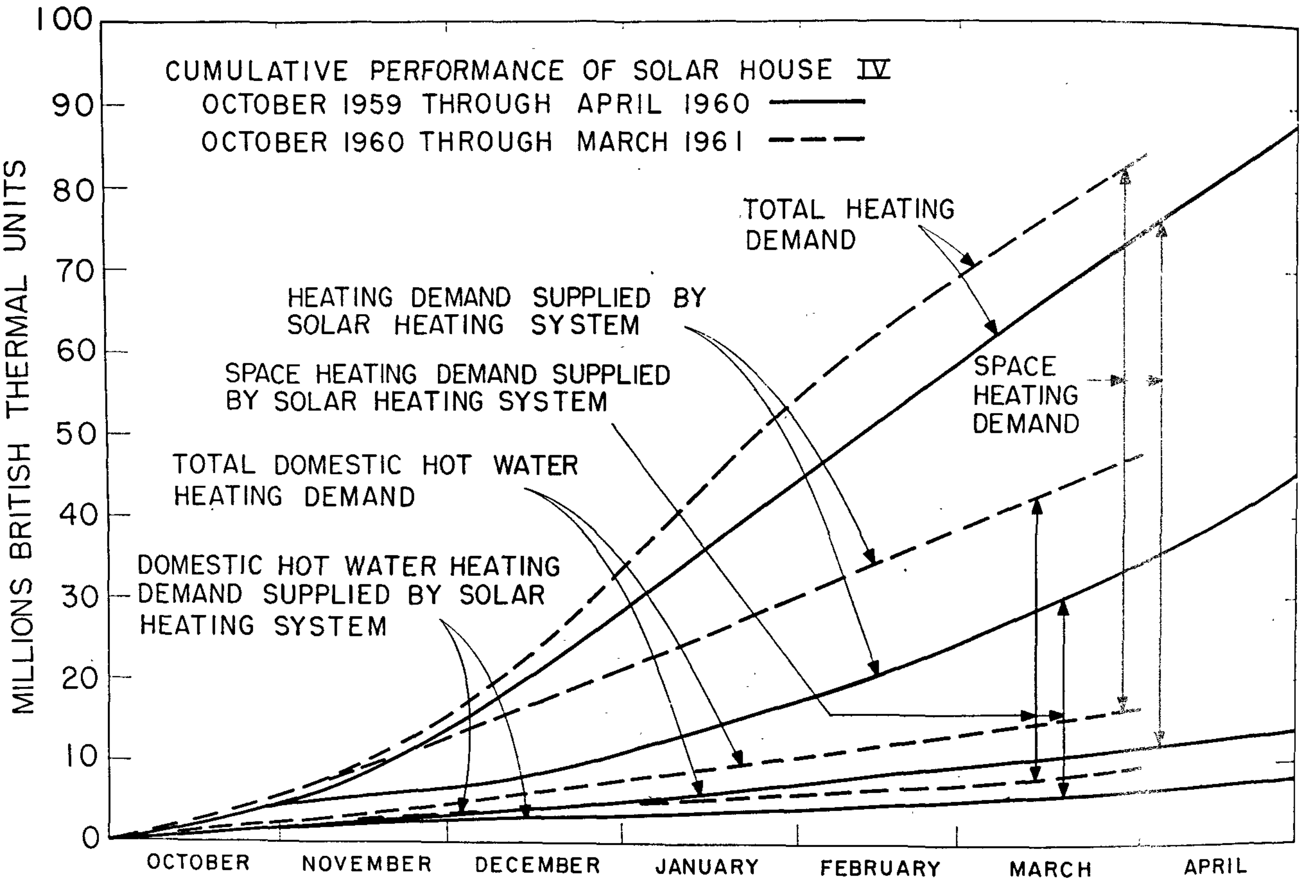

Figure 7. Performance of Solar House IV

heat from storage if the storage temperature was 82.5°F or below. These temperatures will vary with individual systems but they show quite clearly that there is a point below which the cost of reclaiming energy exceeds the value of the energy itself. The utilization factor in table 1 indicates the fraction of solar radiation which was of higher grade than storage for this system. None of the data obtained by this test can be interpreted to indicate that operation of the collector at lower temperatures in conjunction with heat pumping would have been more advantageous.

Results and conclusions

The solar radiation data from table 1 are shown pictorially in figure 6 and the house heating data from table 4 in the same manner in figure 7. During the winter of 1959-1960, the total solar incidence on the collecting area during the season was 143.2 million btu, of which 36.9 million btu were of too low intensity to justify attempted collection. The solar collector operated with an average efficiency of 45 per cent on the residue of 106.3 million btu, extracting 48.0 million btu on the surface of 640 square feet at 60 degree tilt. A 48 per cent sharing of the total heat load by the solar system was realized. The solar heating system supplied 39.8 million btu of the total heating load of 82.8 million btu. The winter at the site of the experiment was more severe that that predicted when the house was originally designed and the total solar incidence during the season was lower than normal.

During six months of the winter of 1960-1961, the total solar incidence on the collecting area was 152 million btu, of which 31 million btu was of too low intensity to justify attempted collection. The solar collector operated with an average efficiency of 41 per cent on the residue of 121.4 million btu, extracting 49.1 million btu. A 56.6 per cent sharing of the total heat load by the solar system was realized. The solar heating system supplied 47.4 million btu of the total heating load of 83.7 million btu. The winter at the site of the experiment was again more severe than that predicted when the house was originally designed, but the total solar incidence during the season was nearer normal than during the previous season.

The design objective of obtaining 75 per cent of the heat for the house from the sun could have been achieved by a collector and storage 1.4 times their present size for the 1959-1960 season and 1.22 times present size for the 1960-1961 season. Collector use factor would be less for these collector sizes — 0.92 and 0.96 respectively — and the larger collector harder to justify economically.

Considerable development is necessary to produce a design for a highly weatherable, efficient, low-cost collector. If solar cooling is to be used to obtain high use factors, then cost reduction and simplification by omission of parts is a highly unlikely solution.

Collector and heating system operating costs must be treated realistically as part of the cost of using solar energy. The cost of competitive fuel determines the value of a unit of solar energy and the amount of pumping and transport cost that is economically justified. Sound and thorough engineering must be used in the planning and design of solar houses. The actual value of solar heating can only be determined by long-term testing from which quantitative data can be obtained.

Acknowledgements

The author would like to acknowledge and express appreciation for the guidance and suggestions of the M.I.T. Committee on Space Heating with Solar Energy: Professors L. B. Anderson, A. G. H. Dietz, H. C. Hottel, A. L. Hesselschwerdt, and the late J. Kaye. Sincere thanks are due Mr. Godfrey L. Cabot, whose generous financial contribution made this research possible, and to Mr. Ken-Ichi Kimura for his assistance in the preparation of data.

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Summary

The design of a solar heated house is a complex and demanding task requiring the collaboration of engineer and architect, both well informed in the field. The effective layout and operation of a workable system presents numerous additional complications if the house is to function as an engineering test and yield continuous, worthwhile data. Lack of coincidence of expectations and results, predicted weather and actual weather, constitute the principal justification for construction of solar houses in North America at the present time.

It is hoped that this account of experience gained with a solar heated house operated as both a dwelling and a continuous engineering test for a period of three years will benefit other investigators involved in similar pursuits.

The present M.I.T. Solar House was described in a recent paper (1), and detailed description is omitted here. The collector has an area of 640 square feet and is tilted 60° to the horizontal. The design was intended to derive 75 per cent of the house heating requirements from the sun. This house has demonstrated that the space and comfort requirements considered desirable by American home owners need not be compromised in space heating by solar energy.

Solar energy collector

A solar collector as a part of a house envelope must be evaluated with a number of considerations in mind. This particular collector has exhibited good thermal performance and both good and undesirable effects on the living space, but its original cost and maintenance requirements are not encouraging.

Collector performance

If, in considering the thermal performance of a particular collector, the equation for the instantaneous rate of energy collection developed by Hottel and Whillier (2) is written in the following form

$$\frac{q_u}{A} = F_R \left[I \left(\overline{\tau_e \alpha} \right) - U_L \left(t_1 - t_0 \right) \right] \qquad [1]$$

in which

$\frac{q_u}{A}$ = rate of useful energy collection per unit area of collector surface
F_R = heat removal efficiency for the collector plate
I = total insolation rate per unit area on the plane of the collector

$\overline{(\tau_e \alpha)}$ = mean value of the effective cover glass transmittance-collector plate absorptivity product for the total insolation, including allowance for dirt on the cover glasses and shading of the collector plate by glass supporting structure

U_L = over-all heat loss coefficient for the collector

t_0 = temperature of the outdoor ambient air

t_1 = temperature of the energy transport stream at the collector inlet,

it becomes apparent that, as a thermal device, the collector will lose heat to its environment in direct proportion to the difference in its temperature and that of the ambient air by some value of proportionality factor U_L. Heat removal efficiency, F_R, is relatively constant for a given design, but $\overline{(\tau_e \alpha)}$ is subject to seasonal variations and diurnal variations in the case of a fixed plate collector. If equation [1] is rewritten to relate q_u/A to I, so as to develop the expression for instantaneous collector efficiency, η, which follows

$$\eta = F_R \left[\overline{(\tau_e \alpha)} - U_L \frac{(t_1 - t_0)}{I} \right] \qquad [2]$$

it becomes evident that collection efficiency is sensitive to the ratio $(t_1 - t_0)/I$ and is limited by $F_R \overline{(\tau_e \alpha)}$. Figure 2 is a plot of equation [2] for the Solar House IV collector. The heavy dashed line indicates a representative mean curve. The use of this curve permits approximation of average efficiencies typical of heating season operation. The dotted lines illustrate the interrelation of the various scales of the plot.

The determination of what constitutes the optimum number of hours of operation of the collector must clearly be based on the premise that operation is economically justified at all times when the value of the energy collected exceeds the cost of water circulation. The limiting hours are then at the extremes of the day, and their inclusion of necessity reduces the average value of energy collection per unit of energy on pumping below the value one could achieve by operating only at hours near noon. Plainly, that energy ratio is no measure of whether the system is operated at its economic optimum. One wants the value of the energy collected minus the cost of the pumping energy to be a maximum.

The collector operating efficiency is related to what may be defined as over-all efficiency, the percentage of the total incidence on the collector that is actually collected, by a utilization factor which may be defined as the ratio of the solar incidence during the fraction of time the collector is operating to the total incidence for a given period.

The numerical values for incidence on the surface, both operating and over-all efficiencies, with utilization factors for months of the 1959 and 1960 heating season, are given in table 1. In this collector design and system, an excess of 7.1 btu/ft² hr or 14 000 btu per kWh of pumping power must be collected to operate competitively with the auxiliary system.

The utilizability, or ϕ curve method of solar weather description of Hottel and Whillier (2), provides a convenient method for evaluating collector performance. ϕ theoretical is defined as:

$$\phi_{TH} = \frac{1}{n} \sum_1^n \left(\frac{I}{I_{\text{ave}}} - \frac{I_c}{I_{\text{ave}}} \right)^+ \qquad [3]$$

in which n is number of hours and subscript "ave" denotes average and "c" denotes "critical", or that insolation necessary to raise the collector temperature to the threshold of operation. The + denotes that the summation is made at all periods when the bracketed term is positive. ϕ experimental is approximated as

$$\phi_{EX} = \frac{q_u}{A} \frac{1}{\overline{(\tau_e \alpha)} F_R I} \qquad [4]$$

The results of this performance evaluation indicate that the Solar House IV collector could utilize four to ten per cent more of the available radiation than it does. This is considered a reasonable correlation considering the differences in the real and theoretical operation. The ϕ curve method as used here does not take into account the following:

(*a*) Collector operating economics and the fraction of utilizable but uneconomical incidence which is ignored;

(*b*) Delay in collector control response to changes in incidence;

(*c*) Loss due to collector heat capacity as defined by Hottel and Woertz (3) and Tabor (4).

Average values of ϕ experimental and ϕ theoretical for a portion of the heating season months are given in table 2.

Collector design

A cross-section of the collector design with design details is shown in figure 3. This design does utilize a portion of the conventional house envelope in its structure to reduce cost. The probable reduction in expenditure for the collector proper by this type of construction is presented by Dietz (5). Experience with this solar house has shown that, while the collector utilizes common structural elements and effects a reduction in heat loss and at times a beneficial indirect contribution to house heating, at other times it creates a cooling problem.

Solar collector area must be determined by its probable useful collection and the demand of the particular application. If a base collector size is considered and the effect of incremental increase of collector size is explored, it will be found that as the area is increased, the use factor of each additional increment decreases.

If the net monetary value of collection from each unit area of base collector is established from local energy costs, then the actual value of a unit area of an additional increment can be determined by taking the product of the ratio of the use factor of the additional increment to the use factor of the base collector and the value of the collection per unit area.

Incremental use factors developed from the performance of the 640 square foot collector of Solar House IV during two heating seasons are given in table 3. The heating load applied to this particular collector equals 18.8 btu/ft^2 per heating degree day (65° base) and results in a use factor near unity for the heating season.

The collector plate construction has been found satisfactory in maintenance. The performance of the portion of the collector between the plate and the outside has been disappointing. The synthetic rubber caulking compounds used do not bond well to the cover glasses for long periods of time through numerous temperature cycles. Unwanted moisture is also introduced into the air space between the cover glasses by the induction of air as the collector cools. The filters provided to exclude dust are effective, but the moisture in the air does condense on the inside surface of the outer glass layer.

The costs of construction of this collector are not treated here on an individual or mass production basis because it is not considered satisfactory. The group responsible for this test is not in possession of a superior design, nor do they have knowledge of any design which would be suitable for mass production.

Heating system

The present arrangement of the collecting and heating system is shown in schematic diagram (figure 4). Water from storage is circulated through the collector at the rate of 8.36 lb/ft^2 hr, and returned to storage by way of the expansion tank. The expansion tank functions to reduce pressure fluctuation with temperature change and to allow gravity draining of the collector during the off-cycle to prevent freezing and reduce collector heat capacity. In this system, where all water must pass through an air volume, a small quantity of air will be entrained in the liquid stream. The expansion tank must be of an internal design to minimize such entrainment and so located as to provide a hydrostatic head for operation of an air venting or scavenging system to function for the water-containing portions of the system. Lack of a properly designed venting system results in numerous interruptions in service due to air binding in the circulating pump, piping, and the heat exchanger. The two sources of hot water for the heat exchanger must be connected in parallel rather than series.

Figure 5 shows the relationship of heat exchanger inlet and outlet temperatures for various conditions and the relationship of required heat exchanger inlet temperature to outside temperature and heating demand. Heating and domestic hot water loads and the fractional contributions of the solar heating system are given in table 4.

Auxiliary requirement

The auxiliary heating system must be capable of supplying the maximum probable heating demand plus the domestic hot water requirement of the house. In a system where domestic hot water is heated to the temperature of solar storage and then "topped up" in the auxiliary unit, the temperature level of the auxiliary is determined by the necessary domestic hot water temperature. The actual portion of the heating and domestic hot water loads supplied by the auxiliary system can be determined from table 4.

Auxiliary heating system

The form of the auxiliary heating system depends on the location of the solar house and local fuel availability. A hot water heater fired by the most economical locally available fuel has been found satisfactory where both auxiliary space heating and domestic hot water are required.

Energy storage

M.I.T. Solar House IV uses water both as an energy transport and as a storage medium. Water is desirable and convenient for testing since determinations of the rate of energy flow and the energy remaining in storage are quite easily made.

The 1 500 gallons of water for storage — about 2.35 gallons per square foot of collector, has a heat capacity of 19.55 btu/°F ft^2 of collector. Considering the house heating demand, this storage is capable of supplying heat for 1.04 heating degree days per degree Fahrenheit. The optimum storage temperature range of 105° to 115°F reported in reference (1) for this system was determined considering collector behavior and all operating costs, including that of recovering energy from storage. The behavior of this storage during three years of operation has presented no evidence that any other apportionment of storage to collector area would be better.

As the storage temperature decreases, a fixed demand requires a greater ratio of auxiliary operating time to solar heating time until an uneconomically low temperature is finally reached.

For short-term storage, the losses are small and the effectiveness, depending on temperature and activity, ranges from 92 to 98 per cent.

Control system

Collector control

The fundamental requirement of the collector control is that it respond to solar radiation in the plane of the collector surface while being aware of the temperature of the storage unit.

One satisfactory means is the installation of resistance type sensors in the collector and in the storage unit, the sensors in turn being connected electrically in the legs of an alternating current bridge circuit. An electronic relay responding to circuit unbalance will perform the control operations once the circuit has been calibrated and adjusted.

The following are considerations in the design of a collector control.

(*a*) The sensor element applied to the collector plate must have thermal characteristics nearly identical to those of the collector plate assembly to obtain an appropriate response.

(*b*) The control bridge must incorporate a differential adjustment to compensate for the difference in response of the collector to radiation in its "dry plate" condition at start-up from that when operating.

(*c*) Delay in collector sensor response must be incorporated in the sensor in its mounting or in the electrical circuit. The first portion of the transport medium to reach the collector on start-up does not represent storage temperature but that of the environment with which the transport system has reached equilibrium during the collector off cycle.

(*d*) The storage unit sensor element must be located to transmit a temperature representative of the transport stream leaving storage to the control.

SPACE HEATING CONTROL

A conventional thermostat bimetal can be used to initiate operation of the heating system pump and fan in the case of the Solar House IV system to supply heat to the living space from storage. As long as the temperature of storage is sufficiently high to satisfy heating demand, this operation is all that is required. However, if the temperature of the living space should continue to fall even with solar heating, another similar device can be utilized to permit heat to be supplied to the house by the auxiliary system. When the demand no longer requires auxiliary operation, the second bimetal of the thermostat returns the system to solar operation. A low limit thermostat is applied to the storage to prevent operation on energy of a grade below that which can be reclaimed economically.

Examination of figure 5 will indicate the solar energy storage temperature required for a particular demand or, if the temperature is too low, the proportion of solar and auxiliary operation required.

Solar collector-heat pump combinations

There may be cases where the heat pump can be used effectively to reduce the operating time of auxiliaries, but it does not reduce the auxiliary demand which is a determining factor in the capital expenditure necessary to build a workable solar heated house.

If power is available and reasonably priced, then the air source heat pump with electric resistance supplementary heat comprises a reasonably good heating system, and the justification for a solar collector as an auxiliary becomes difficult.

If one considers operating circumstances alone, a heat pump coefficient of performance of from four to five is necessary to compete costwise with oil or gas fuel. Operation at this coefficient of performance for space heating would require a sufficiently high storage temperature whereby heat was economically recoverable without heat pumping. None of the data obtained by this test can be interpreted to indicate that operation of the collector at lower temperatures in conjunction with heat pumping would have been more advantageous.

Results and conclusions

The solar radiation data from table 1 are shown pictorially in figure 6 and the house heating data from table 4 in the same manner in figure 7. During the winter of 1959-1960, the total solar incidence on the collecting area during the season was 143.2 million btu, of which 36.9 million btu were of too low intensity to justify attempted collection. The solar collector operated with an average efficiency of 45 per cent on the residue of 106.3 million btu, extracting 48.0 million btu on the surface of 640 square feet at 60 degree tilt. A 48 per cent sharing of the total heat load by the solar system was realized. The solar heating system supplied 39.8 million btu of the total heating load of 82.8 million btu.

During six months of the winter of 1960-1961, the total solar incidence on the collecting area was 152 million btu, of which 31 million btu was of too low intensity to justify attempted collection. The solar collector operated with an average efficiency of 41 per cent on the residue of 121.4 million btu, extracting 49.1 million btu. A 56.6 per cent sharing of the total heat load by the solar system was realized. The solar heating system supplied 47.4 million btu of the total heating load of 83.7 million btu.

The design objective of obtaining 75 per cent of the heat for the house from the sun could have been achieved by a collector and storage 1.4 times their present size for the 1959-1960 season and 1.22 times present size for the 1960-1961 season.

Considerable development is necessary to produce a design for a highly weatherable, efficient, low-cost collector.

Collector and heating system operating costs must be treated realistically as part of the cost of using solar energy. The cost of competitive fuel determines the value of a unit of solar energy and the amount of pumping and transport cost that is economically justified. The actual value of solar heating can only be determined by long-term testing from which quantitative data can be obtained.

UTILISATION DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE DES LOCAUX : MAISON SOLAIRE Nº IV DU M.I.T.

Résumé

La mise au point d'une maison à chauffage solaire est une tâche complexe et difficile, exigeant la collaboration de l'ingénieur et de l'architecte, qui doivent l'un et l'autre bien connaître la question. L'établissement des plans d'un système utilisable et son exploitation soulèvent un grand nombre de complications additionnelles si la maison doit être utilisée aux fins d'essais techniques et donner des résultats exploitables de façon continue. La différence entre les prévisions et les résultats, le temps prévu et le temps qui se manifeste réellement, représente la principale justification que l'on puisse donner à la réalisation de « maisons solaires » en Amérique du Nord en ce moment.

On espère que la présente description de l'expérience acquise avec une maison à chauffage solaire dont on se sert à la fois comme de maison d'habitation et de « sujet » d'essais continus sur une période de trois ans, rendra service aux autres chercheurs qui s'intéressent à des sujets analogues.

La maison solaire actuelle du M.I.T. a été décrite dans un mémoire récent (1), par conséquent nous n'en donnerons pas ici une description détaillée. Le collecteur a une surface de 640 pieds carrés (59,5 m²) et présente une inclinaison de 60° sur l'horizontale. Sa conception était telle que l'on se proposait d'y faire appel pour couvrir 75 p. cent des besoins de chaleur de la maison par l'énergie solaire qu'il recueillerait. Cette maison a démontré que les exigences quant à la place et quant au confort qui sont considérées comme souhaitables par les propriétaires américains, n'ont aucunement lieu de souffrir du chauffage des locaux par l'énergie solaire.

Collecteur

Le collecteur solaire, envisagé comme élément faisant intégralement partie d'une maison, doit être évalué en tenant compte d'un certain nombre de considérations. Le modèle examiné ici a donné un bon rendement thermique et ses répercussions sur les locaux ont été à la fois bonnes et mauvaises, mais ses premières exigences quant au prix et à l'entretien ne sont pas encourageantes.

Rendement du collecteur

Si, en examinant le rendement thermique d'un collecteur donné, on écrit l'équation qui donne le régime instantané de récupération d'énergie établie par Hottel et Whillier (2), de la façon suivante :

$$\frac{q_u}{A} = F_R \left[I \, (\overline{\tau_e \alpha}) - U_L \, (t_1 - t_0) \right] \qquad [1]$$

équation dans laquelle

$\frac{q_u}{A}$ = régime de récupération d'énergie utile par unité de surface de collecteur

F_R = rendement de l'extraction de chaleur de la plaque du collecteur

I = taux d'insolation totale par unité de surface dans le plan du collecteur

$(\overline{\tau_e \alpha})$ = valeur moyenne du produit de la transmittance utile du couvercle en verre par l'absorptivité de la plaque du collecteur pour l'insolation totale, en tenant compte de la poussière accumulée sur les vitres de couverture et l'ombre projetée sur la plaque du collecteur par la structure qui supporte le verre

U_L = coefficient global de perte de chaleur pour le collecteur

t_0 = température de l'air extérieur ambiant

t_1 = température du courant de transport d'énergie à l'admission du collecteur,

on voit que, en tant que système thermique, le collecteur perd de la chaleur au bénéfice de son milieu en raison directe de la différence qui existe entre sa température et celle de l'air ambiant, suivant un facteur de proportionalité U_L.

Le rendement d'extraction de la chaleur F_R est relativement constant pour une conception donnée, mais $(\overline{\tau_e \alpha})$ fait l'objet de variations saisonnières et diurnes dans le cas d'un collecteur fixe à plaque. Si on remanie l'équation [1] pour établir un rapport entre q_u/A et I de manière à développer l'expression du rendement instantané du collecteur, η, qui suit :

$$\eta = F_R \left[(\overline{\tau_e \alpha}) - U_L \frac{(t_1 - t_0)}{I} \right] \qquad [2]$$

il devient manifeste que le rendement de la récupération de chaleur est sensible au rapport $(t_1 - t_0)/I$ et limité par $F_R \, (\overline{\tau_e \alpha})$. La figure 2 est un graphique de l'équation [2] pour le collecteur de la maison solaire nº IV. La ligne en traits gras interrompus est une courbe moyenne-type. L'utilisation de cette courbe permet d'obtenir une valeur approchée des rendements moyens qui sont typiques de l'exploitation pendant la saison où le chauffage est nécessaire. Les lignes pointillées indiquent le rapport entre les diverses échelles utilisées pour le graphique.

La détermination de ce qui constitue le nombre idéal d'heures de fonctionnement du collecteur doit clairement reposer sur l'hypothèse que ce fonctionnement est économiquement justifiable chaque fois que la valeur de l'énergie recueillie dépasse les frais

nécessaires pour assurer la circulation de l'eau. Les heures qui fixent des limites à cette condition se situent donc au début et à la fin de la journée, et leur inclusion ramène naturellement la moyenne de récupération d'énergie par unité de force motrice consacrée au pompage à une valeur inférieure à celle qui pourrait être réalisée en ne faisant fonctionner l'installation qu'aux alentours de midi. De toute évidence, ce rapport des énergies n'indique pas si le système est exploité à son optimum économique. On désire que la différence entre la valeur de l'énergie récupérée et celle de l'énergie de pompage soit au maximum.

Le rendement d'exploitation du collecteur est en rapport avec ce que l'on peut définir comme étant un rendement global, à savoir le produit du pourcentage de l'énergie solaire totale incidente au collecteur effectivement recueillie, par un facteur d'utilisation que l'on peut définir comme étant le rapport entre l'énergie solaire incidente pendant la fraction du temps où le collecteur fonctionne et l'énergie incidente totale pendant une période donnée.

Le tableau 1 donne, les valeurs numériques de l'énergie incidente sur la surface, le rendement de fonctionnement et le rendement global avec les facteurs d'utilisation pour les mois de la saison de chauffage 1959 et 1960. Avec cette conception du collecteur et du système, il faut recueillir un excédent de 7,1 btu/pied carré/heure, ou 14 000 btu par kWh d'énergie de pompage, pour assurer la marche du système dans des conditions économiques lui permettant de faire concurrence au système auxiliaire.

La méthode de description du temps solaire au moyen de la courbe d'utilisabilité, ou courbe ϕ, par Hottel et Whillier (2), est un moyen commode d'évaluation du rendement du collecteur. La valeur théorique de ϕ est définie comme étant :

$$\phi_{TH} = \frac{1}{n} \sum_{1}^{n} \left(\frac{I}{I_{\text{moy}}} - \frac{I_c}{I_{\text{moy}}} \right)^{+} \qquad [3]$$

expression dans laquelle n est le nombre d'heures, les indices « moy » dénotent une valeur moyenne et c une valeur critique, ou l'insolation nécessaire pour porter la température du collecteur au seuil de son fonctionnement. Le signe + indique que l'on totalise pour toutes les périodes pendant lesquelles le terme entre parenthèses est positif. La valeur expérimentale approchée de ϕ est

$$\phi_{EX} = \frac{q_u}{A} \frac{1}{(\tau_e \alpha) F_R I} \qquad [4]$$

Il ressort des résultats de cette évaluation du rendement que le collecteur de la maison solaire nº IV pourrait utiliser une fraction comprise entre 4 et 10 p. 100 de plus de l'énergie rayonnante disponible qu'il ne le fait. On estime que c'est là une corrélation raisonnable, compte tenu des différences entre le fonctionnement réel et le fonctionnement théorique. La méthode de la courbe ϕ, telle qu'elle est appliquée ici, ne permet pas de tenir compte des points suivants :

a) Économie du fonctionnement du collecteur et fraction de l'énergie incidente utilisable, mais anti-économique;

b) Inertie de la réponse des commandes du collecteur aux variations d'incidence;

c) Pertes dues à la contenance thermique ou calorifique du collecteur, définies par Hottel et Woertz (3), ainsi que par Tabor (4).

Les valeurs moyennes expérimentales et théoriques de ϕ sur une fraction des mois de la saison de chauffage figurent au tableau 2.

Réalisation du collecteur

La figure 3 montre une coupe du collecteur, avec certains détails de sa réalisation. Cette conception fait effectivement usage d'une partie de la maison dans sa structure, pour réduire les frais. La réduction probable des dépenses afférentes au collecteur proprement dit grâce à ce mode de construction est présentée par Dietz (5). L'expérience acquise avec cette maison solaire a démontré que, tandis que le collecteur utilise des éléments ordinaires de la structure de la maison, tout en assurant une réduction des pertes de chaleur, et fait parfois indirectement un apport utile au chauffage de la maison, il soulève aussi, à d'autres époques, un problème de réfrigération.

La surface du collecteur solaire doit être calculée en fonction de la quantité utile probable d'énergie à recueillir et en tenant compte des exigences relatives à l'application en cause. Si on considère une taille de base du collecteur et si on étudie les effets d'une augmentation de ses dimensions par échelon, on découvre que le facteur d'utilisation de chaque élément ajouté diminue avec l'augmentation de la surface.

Si la valeur monétaire nette de la quantité d'énergie recueillie par chaque élément de surface du collecteur de base est établie à partir du prix local de l'énergie, la valeur réelle de l'unité de surface de toute addition à l'aire primitive peut être déterminée en prenant le produit du rapport qui existe entre le facteur d'utilisation de l'élément ajouté au facteur d'utilisation du collecteur primitif par la valeur de l'énergie récupérée par unité de surface.

Le tableau 3 donne les facteurs ajoutés d'utilisation obtenus à partir du rendement du collecteur de 640 pieds carrés (59,5 m²) de la maison solaire nº IV sur deux saisons de chauffage. Le charge de chauffage appliquée à ce collecteur est égale à 18,8 btu/pied carré par degré F/jour de chauffage, par rapport à une base de 65 °F, ce qui donne un facteur d'utilisation voisin de l'unité pour la saison de chauffage.

Le mode de construction de la plaque du collecteur s'est montré satisfaisant pour l'entretien. Le rendement de la partie de ce collecteur comprise entre la plaque et l'extérieur a été décevant. Les produits de calfatage en caoutchouc synthétique ne se lient pas bien aux vitres de couverture pendant de longues périodes, sur nombre de cycles thermiques. Une humidité indésirable est également introduite dans l'espace qui se trouve entre ces vitres de couverture en raison des admissions d'air dont s'accompagne le refroidissement du collecteur. Les filtres prévus pour arrêter la poussière sont efficaces, mais l'humidité de l'air se condense sur la surface interne de la couche de verre extérieure.

Les frais de construction de ce collecteur ne sont pas étudiés ici ni sur la base d'une production limitée, ni en grande série. L'équipe chargée de ces essais ne détient pas de conception supérieure, et n'a connaissance d'aucune formule qui soit appropriée pour la production en série.

Système de chauffage

La disposition actuelle du système de récupération et de chauffage est donnée au diagramme schématique de la figure 4. L'eau tenue en réserve circule dans la masse du collecteur à raison de 8,36 livres/pied carré/heure, et fait retour à la réserve par l'entremise d'un réservoir de compensation. Celui-ci réduit les fluctuations de pression que provoquent les variations de température et permet la vidange du collecteur par la simple pesanteur pendant les périodes de repos, pour éviter le gel et réduire la capacité thermique du collecteur. Dans un tel système, où il faut que toute l'eau traverse un volume d'air donné, une petite quantité de cet air est entraînée dans le jet de liquide. Le réservoir de compensation doit être agencé intérieurement de telle sorte que cet entraînement soit réduit au minimum; il doit être situé de façon à fournir une pression hydrostatique pour actionner un système d'évents ou de balayage à l'usage des parties du circuit qui contiennent de l'eau. En l'absence d'un tel système d'évents convenablement conçu, il se produit de nombreuses interruptions de service causées par des engorgements d'air dans la pompe de circulation et dans l'échangeur. Les deux sources d'eau chaude destinée à cet échangeur doivent être branchées en parallèle, plutôt qu'en série.

La figure 5 donne les rapports entre les températures à l'admission et à la sortie de l'échangeur pour diverses conditions, ainsi que le rapport entre la température d'admission souhaitable pour l'échangeur, la température extérieure et les exigences de chauffage. Les charges attribuables au chauffage et à la fourniture ménagère d'eau chaude, ainsi que les fractions de l'apport total attribuables au système de chauffage solaire, figurent au tableau 4.

Exigences auxiliaires

Le système auxiliaire de chauffage doit être en mesure de couvrir les besoins maximaux probables plus les exigences d'eau chaude de la maison. Dans un système où l'eau chaude destinée à des emplois ménagers est portée à la température d'emmagasinage solaire puis finalement chauffée dans le groupe auxiliaire, le niveau de température de cette installation auxiliaire est déterminé par la température exigible pour l'eau chaude recevant des emplois ménagers. La fraction des charges d'eau chaude et du chauffage pour les emplois ménagers fournie par le système auxiliaire peut être déterminée à partir du tableau 4.

Système auxiliaire de chauffage

La disposition du système auxiliaire dépend de l'emplacement de la maison solaire et des disponibilités locales de combustible. Un chauffe-eau dont l'énergie est fournie par le combustible le plus économique qui soit disponible localement a été jugé satisfaisant quand on a besoin tant de chauffage auxiliaire des locaux que d'eau chaude pour emplois ménagers.

Emmagasinage d'énergie

La maison solaire n° IV du M.I.T. utilise l'eau, tant comme moyen de transport de la force motrice que comme moyen d'accumulation d'énergie. L'eau est un liquide indiqué et commode pour les essais, pour autant que les déterminations du régime d'écoulement d'énergie et de l'énergie qui reste en réserve sont très faciles à faire.

Les 1 500 gallons d'eau destinés à la mise en réserve (environ 2,35 gallons par pied carré de collecteur) ont une capacité thermique de 19,55 btu/°F/pied carré de collecteur. Si on considère les exigences de chauffage de la maison, cet emmagasinage peut fournir de la chaleur pendant 1,04 degré/jour/degré Fahrenheit. La température idéale de mise en réserve, de 105 à 115 °F pour ce système (1), a été déterminée en tenant compte du comportement du collecteur et de tous les frais d'exploitation, y compris ceux afférents à la récupération de l'énergie de ces accumulateurs. Le comportement de cette réserve pendant trois ans de fonctionnement ne donne aucune raison de croire qu'une autre répartition entre la réserve et la surface du collecteur serait préférable.

La température de mise en réserve diminuant, l'existence d'une demande constante exige un plus grand rapport entre la durée de fonctionnement du système auxiliaire et le temps de chauffage solaire, jusqu'à ce que l'on atteigne une température trop basse pour être économiquement acceptable.

Pour les mises en réserve à court terme, les pertes sont faibles et le rendement du système, suivant la température et l'activité, s'échelonne entre 92 et 98 p. 100.

Système de commande

Commande du collecteur

L'exigence fondamentale est que cette commande réagisse au rayonnement solaire présent dans le plan du collecteur, tout en tenant compte de la température du système d'emmagasinage.

Un moyen satisfaisant est constitué par l'installation d'appareils lecteurs du type à résistance dans le collecteur et l'accumulateur. Ces appareils, à leur tour, sont électriquement liés aux branches d'un pont de Wheatstone à courant alternatif. Un relais électronique, réagissant aux déséquilibres du circuit, assurera la commande, après étalonnage et réglage. Les considérations suivantes régissent la conception de ce genre de commande :

a) L'élément de perception ou de lecture que l'on monte sur la plaque du collecteur doit avoir des caractéristiques thermiques presque identiques à celles de cette plaque, pour que les réactions ou réponses soient celles que l'on souhaite.

b) Le pont de commande doit comporter un réglage différentiel pour compenser les différences dans les réactions du collecteur au rayonnement quand il est à l'état de « plaque sèche » au départ et quand il fonctionne.

c) Des retards à la réponse du dispositif de lecture du collecteur doivent être prévus, soit dans sa monture, soit dans son circuit électrique. La première partie du véhicule qui atteint le collecteur au départ ne représente pas la température d'emmagasinage ou d'accumulation, mais plutôt celle du milieu, avec lequel le circuit qu'emprunte ce liquide ou véhicule a établi son équilibre pendant la période où le collecteur était au repos.

d) Le dispositif de lecture de l'accumulateur doit être situé de telle sorte qu'il transmette une température-type du courant de transport de la chaleur qui sort de la réserve pour aller à la commande.

Réglage du chauffage des locaux

Un dispositif classique à thermostat bimétallique peut être utilisé pour mettre en route la pompe du système de chauffage, ainsi que le ventilateur, dans le cas du système de la maison nº IV, de manière à fournir de la chaleur aux locaux d'habitation à partir de la réserve. Tant que la température d'accumulation est suffisamment élevée pour faire face aux besoins du chauffage, ce mode de fonctionnement est satisfaisant. Cependant, si la température des locaux continue à tomber, même avec le chauffage solaire, on peut utiliser un autre dispositif analogue pour permettre qu'il soit fourni de la chaleur à la maison par un système auxiliaire. Quand les besoins ne sont plus tels qu'il y ait besoin de faire fonctionner les auxiliaires, le second couple bimétallique du thermostat rétablit la marche solaire du système. Un thermostat à limite inférieure est prévu dans le système d'accumulation pour s'opposer au fonctionnement avec une énergie d'une qualité inférieure à celle que l'on peut récupérer économiquement.

L'examen de la figure 5 indiquera la température de mise en réserve de l'énergie solaire nécessaire pour des exigences particulières ou, si la température est trop basse, la proportion entre le fonctionnement en énergie solaire et avec les auxiliaires.

Combinaison collecteur solaire-pompe à chaleur

Il peut se présenter des situations dans lesquelles une pompe à chaleur peut être utilisée efficacement pour réduire la durée de fonctionnement des auxiliaires sans diminuer les exigences de ces auxiliaires, facteur décisif quant aux mises de fonds nécessaires pour construire une maison à chauffage solaire utilisable.

Si on dispose de force motrice à des prix raisonnables, la pompe à chaleur à source d'air, avec complément fourni par un dispositif à résistance, constitue un système de chauffage acceptable, et la justification du collecteur solaire en tant qu'auxiliaire devient chose difficile.

Si on considère les circonstances de fonctionnement seules, un coefficient de 4 à 5, en faveur de la pompe à chaleur, est nécessaire pour faire concurrence, quant aux prix, au pétrole ou aux combustibles gazeux. Le fonctionnement à ce coefficient, pour le chauffage des locaux, exigerait une température de mise en réserve suffisamment élevée pour récupérer économiquement de la chaleur, sans pompage. Aucune des données fournies par le présent essai ne saurait être interprétée comme indiquant que le fonctionnement à des températures plus basses serait plus avantageux en liaison avec le pompage de chaleur.

Résultats et conclusions

Les données du tableau 1 sur le rayonnement solaire sont résumées graphiquement à la figure 6, et les données du tableau 4 sur le chauffage de la maison de la même manière à la figure 7. Pendant l'hiver 1959-1960, l'incidence totale d'énergie solaire sur la surface de récupération a été de 143,2 millions de btu, dont 36,9 millions d'une intensité trop faible pour justifier les tentatives de récupération. Le collecteur solaire a fonctionné avec un rendement moyen de 45 p. 100 sur le résidu de 106,3 millions de btu, extrayant 48,0 millions de btu avec sa surface de 640 pieds carrés inclinée à 60°. Le système solaire a couvert 48 p. 100 de la demande totale. Il a fourni 39,8 millions de btu sur une charge totale de 82,8 millions de btu.

Pendant six mois de l'hiver 1960-1961, l'énergie solaire incidente totale sur la surface de récupération a été de 152 millions de btu, dont 31 millions de btu d'une intensité trop faible pour justifier les tentatives de récupération. Le collecteur solaire a fonctionné avec un rendement moyen de 41 p. 100 sur le résidu de 121,4 millions de btu, extrayant 49,1 millions de btu. Ce système solaire a couvert 56,6 p. 100 des besoins. Le système de chauffage solaire a fourni 47,4 millions de btu sur une charge totale de 83,7 millions de btu.

L'objectif visant à récupérer du soleil 75 p. 100 de la chaleur nécessaire aurait pu être réalisé au moyen d'un collecteur et d'un système d'accumulation 1,4 fois plus grands que leur taille actuelle pour la saison 1959-1960 et 1,22 fois leur taille actuelle pour la saison 1960-1961.

Il faudra réaliser d'importants progrès pour établir un système donnant un collecteur peu sensible aux intempéries, à grand rendement et d'un prix modique.

Les frais de fonctionnement du collecteur et du système de chauffage doivent être traités avec réalisme en tant qu'élément des coûts d'utilisation de l'énergie solaire. Le coût des combustibles capables d'y faire concurrence détermine la valeur de l'unité d'énergie solaire et l'importance des frais de pompage et de transport de l'énergie qui sont économiquement justifiés. La valeur réelle du chauffage solaire ne peut être déterminée que par des essais à long terme qui fourniront des données quantitatives.

INSTALLATIONS FOR SOLAR SPACE HEATING IN GIRIN

Nobuhei Fukuo, Takeshi Kozuka, Shozo Iida, Ikuya Fujishiro, Toshiaki Irisawa, Masaie Yoshida and Hisao Mii *

The design, construction and performance of a heating and cooling device using solar energy, which has been studied at the Government Industrial Research Institute, in Nagoya, Japan (35° 10′ N, 136° 58′ E) since September 1958, are described in this paper.

Determination of heating and cooling system

The following system was adopted as the method of collecting heat, of storing solar energy for heating on cloudy or rainy days and of using a heating system also for cooling in order to save the cost of construction:

(the sun) —Radiation→ (heat collector) —H.T. storage medium / H.T. storage tank→ (evaporator)

—refrigerant / heat pump→ (condenser) —L.T. storage medium / L.T. storage tank→ (air heater) —blower / air→ (air-conditioned laboratory)

The arrow indicates the direction of heat transmission, the word above the arrow the heat transmission medium, and the word below the arrow the heat transmission apparatus. "H.T. storage medium" or "tank" signifies high temperature storage medium or tank and "L.T. storage medium" or tank" signifies low temperature storage medium or tank. Water was used as both the H.T. and L.T. storage media and Fleon 12 was used as the refrigerant. For cooling, the system is switched over as follows:

(air conditioned laboratory) —air / blower→ (air cooler) —L.T. storage medium / L.T. storage tank→ (evaporator)

—refrigerant / heat pump→ (condenser) —H.T. storage medium / H.T. storage tank→ (radiator) —radiation at night (air)→

where the air cooler and the radiator are the same apparatus as the air heater and the heat collector, respectively, in the first system described.

This system has the following feature. A unit of installations may be used for heating as well as for cooling. It is advantageous in that water is cheap as the storage medium; it is good in heat exchangeability; it circulates well in the system; it hardly corrodes the material of the system; and it improves the coefficient of performance (c.o.p.) of the heat pump.

Although the adoption of the two storage tanks somewhat increases the cost of the installation, it saves the capacity of the heat pump and evens the power consumption.

This system has four stages of heat exchange. However, the number of the stages is compensated by the better stability of the heat exchange, the improved safety from the leakage of the refrigerant, and the economy of the consumption of the refrigerant.

The heat collector does not require thermal insulation. The high efficiency of collecting or radiating heat saves the area of the heat collector.

Design

Air-conditioned laboratory

The air-conditioned laboratory consists of three rooms. The total floor area is 82 m² and the height of the rooms is 3.7 m. The laboratory is a part of the first floor of the solar energy research building shown in figure 1.

Heating load

The heating loss was calculated from the following assumptions: the heat loss by conduction through the windows, wall, etc., is 450 kcal/h °C; the heat loss by ventilation of the air in the room is 130 kcal/h °C on the assumption of the natural rate of ventilation of the air, 1.5 times per hour.

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Figure 1. Solar energy research building

Such means of reducing the heating load as solar beam penetration through the windows and the existence of heat sources in the rooms are neglected.

The air conditioning of the laboratory is 20°C and 50 per cent r.h.

In January, the coldest month of the year in Nagoya, the average temperature throughout the month is 2.5°C, the average maximum temperature is 7.9°C, and the average minimum temperature is —1.7°C. For heating for 10 hours per day, in daytime only, the outdoor temperature during the heating time may be $(2.5 + 7.9)/2 = 5.2$°C.

Therefore, with the coefficient 5 per cent correcting the overload during the starting time, the heating load is $(450 + 130) \times (20 - 5.2) \times 1.05 \times 10 =$ 90 000 kcal/day.

Cooling load

The heat loss by conduction is 450 kcal/h °C. The heat loss by ventilation is based on the natural rate, once an hour. The heat of cooling and drying accompanied by the enthalpy change from the outdoor air of 30°C and 70 per cent r.h. to 20° C and 70 per cent r.h. is 2 300 kcal/h.

The average temperature throughout August, the hottest month of the year in Nagoya, is 26.6°C and the average maximum temperature is 32.3°C. Therefore, the planned average outdoor temperature for 10 hours in daytime may be $(26.6 + 32.3 /2 =$ 29.5°C. The cooling load is, therefore, $\{450\ (29.5 - 20) + 2\,300 + 1\,000 + 1\,200\}\ 1.05 \times 10 = 93\,000$ kcal/h.

Storage tanks

The minimum temperature of the L.T. storage tank is 3°C. (The water should not be frozen by the evaporator of the heat pump.) The maximum temperature of the L.T. storage tank is 13°C (for both heating and cooling).

The minimum temperature of the H.T. storage tank is 30°C. (Heating in daytime or the discharge by radiation at night should be possible.) The maximum temperature of the H.T. storage tank is 40°C. (The c.o.p. of the heat pump should not be lowered.)

The capacities of the L.T. and H.T. storage tanks should be large enough to keep the specified temperature of the laboratory for cloudy or rainy hours of 1.3 days.

The tanks are insulated under the ground where the temperature change is small.

The heat loss from the H. T. storage tank in winter, the heat penetration into the L.T. storage tank in summer, and the heat loss from the H.T. storage tank in summer are 20, 10, and 10 per cent of the heat storage per day, respectively.

On the assumption that the c.o.p. of the heat pump is 4, the heat storage of the L.T. tank is 4/3 of that of the H.T. tank under the same temperature difference. The capacities of both the tanks are equalized.

On these assumptions, it was calculated that the necessary heat storage of a tank is 56 000 kcal for 1.3 days of heating and 54 000 kcal for cooling. For the capacity of a tank, 5.6 m^3 is enough if the heat is stored at 10°C temperature difference.

Incidentally, the tanks were insulated by a carbonated cork panel, 5 cm thick, under the assumption of 9°C at 1.2 m under the ground.

Heat pump

Since the temperature of the evaporator of the heat pump is 2°C and that of the condenser is 41°C at 8°C of the average water temperature of the L.T. tank and 35°C of that of the H.T. tank, the c.o.p. of the heat pump with Fleon 12 is 4 in the heating period and 3 in the cooling period.

The heat to be supplied from the condenser to the H.T. storage tank during the heating period is 90 000 kcal/day of the heating load, plus 11 200 kcal/day of the leakage from the H.T. tank, the total being 101 200 kcal/day. The heat to be removed by the evaporator during the cooling period is 93 000 kcal/day of the cooling load, plus 5 600 kcal/day of the penetrating heat, the total being 98 600 kcal/day.

With 24-hour operation of the heat pump, the heat generation of the condenser should be

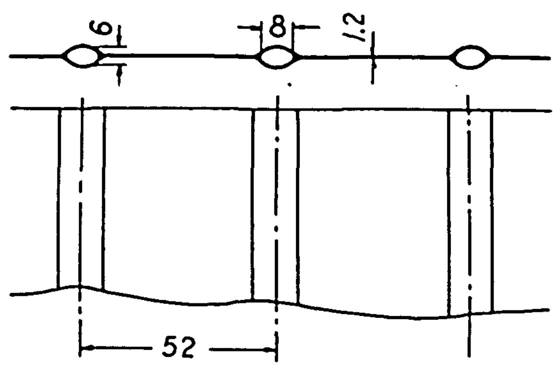

Figure 2. Pipe sheet used for the collector (in mm)

5 500 kcal/h, and the necessary output of the motor is 2.15 h.p. The use of a 3 h.p. motor is sufficient.

COLLECTOR OR RADIATOR

The heat collector or heat radiator is made of aluminum pipe sheet, as shown in figure 2. The surface of the sheet is coated with black paint.

Collector

It was assumed that the solar radiation absorbing coefficient of the collector is 90 per cent, owing to the covering of sand or dust on its surface.

The surface of the collector was inclined 35° southward in accordance with the latitude of Nagoya. The average solar radiation incident upon the surface with this inclination is 5 000 kcal/m² day.

A preliminary test indicated that the temperature of the collector is nearly the same as the water temperature at the outlet of the collector. The water temperature at the inlet of the collector is equal to the water temperature in the L.T. storage tank.

The water flow through a pipe of the pipe sheet of the collector is 9 cm³/sec. The total flow through the 110 pipes is 60 lit/sec.

The time available for collecting the solar radiation is 8 hours, from 8 a.m. to 4 p.m., in January. The average radiation is 625 kcal/m²h.

It was assumed that the coefficient of heat transfer on the surface of the collector is 20 kcal/m²h°C. The heat of the collector is radiated to the air from both its surfaces.

Under these assumptions, from the equation.

(the efficiency of the collector × (heat collecting area) × (average solar radiation)
= (water flow) × {(water temperature at the outlet) — (water temperature at the inlet)}
— 2 × (coefficient of heat transfer on surface)
× (heat collecting area) × {(temperature of the collector) — outdoor temperature)},

a heat collecting area of 28 m² and an efficiency of the collector of 54 per cent is obtained.

Radiator

The average temperature at night in August is 24.1°C in Nagoya, the average temperature throughout the month is 26.6°C and the average minimum temperature throughout the month is 22.5°C.

The time available for the heat radiation to the air amounts to 12 hours.

The water temperature at the outlet of the radiator is 32.2°C. It is equal to the temperature of the radiator.

Thus the heat radiation by convection and conduction is

2 × (coefficient of heat transfer) × {(temperature of the collector) — (outdoor temperature)} × (hours for radiation to the air)
= (heat discharge) = 3 900 kcal/m².day.

The emissive power of the radiator to the hemisphere is 0.9. The space temperature of the atmosphere is 273°K.

The weather conditions of Nagoya limit heat radiation to the atmosphere to only 50 per cent of the total hours at night. Thus the heat radiating to the atmosphere is 830 kcal/m²day.

Therefore, the necessary area for discharging the heat of 122 500 kcal/day (the heat to be discharged for cooling, 93 000 kcal/day; plus the input to the L.T. storage tank from the heat pump under 3 of c.o.p., 29 500 kcal/day; plus the heat penetrating to the L.T. storage tank, 5 600 kcal/day minus the leakage from the H.T. storage tank, 5 600 kcal/ day) is 122 500/(3,900 + 830) = 25.9 m².

For the area of the collector or the radiator, 28 m² is sufficient.

Installations

Figure 1 is the outside view of the solar energy research building. There is a black heat collector on the roof, as shown in the right side of figure 1. The room on the right side of the first floor is the air-conditioned laboratory. In order to minimize the heat penetration through the wide opening of the windows, Tetoron polyester fiber curtains plated with aluminum by vacuum evaporation were installed on the windows.

Figure 3 shows the heat collector (4.7 × 6 = 28 m²). It consists of 10 pieces of pipe sheet, as shown in figure 2, and there are 110 pipes longitudinally in the collector. The inlet of the water is at the right

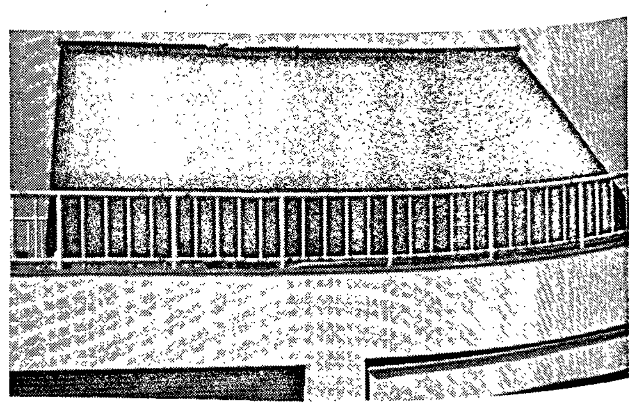

Figure 3. Solar heat collector (also used for radiator)

end of the bottom and the outlet is at the left end of the top of the collector. The white pipe running around the collector from the left end of the top to the right end of the bottom is to return water. It is made of rigid vinyl chloride resin insulated with foamed polystyren, 5 cm thick. Neither the surface of the collector nor of the radiator is insulated.

The inside wall of the storage tanks is made of steel plate coated with anti-corrosion paint and vinyl paint. The outside of the storage tank is directly insulated with carbonated cork, 5 cm thick, and reinforced with concrete.

The pipings in the control room shown in figure 4 are also made of rigid vinyl chloride resin insulated with foamed polystyren resin.

The controller in the control room shown in figure 5 consists of two temperature recorders with six readings each, an operating desk, and an automatic temperature controller.

Running test

Record of temperatures

Some examples of the charts of the recorders with six readings at running tests are shown in figures 6, 7 and 8. Figure 6 shows the temperatures of several important points in the system during 24 hours on a sunny day. The temperature of the H.T. storage tank fell temporarily through the discharge of heat when the air heater started, but it rose as a whole during the heating period.

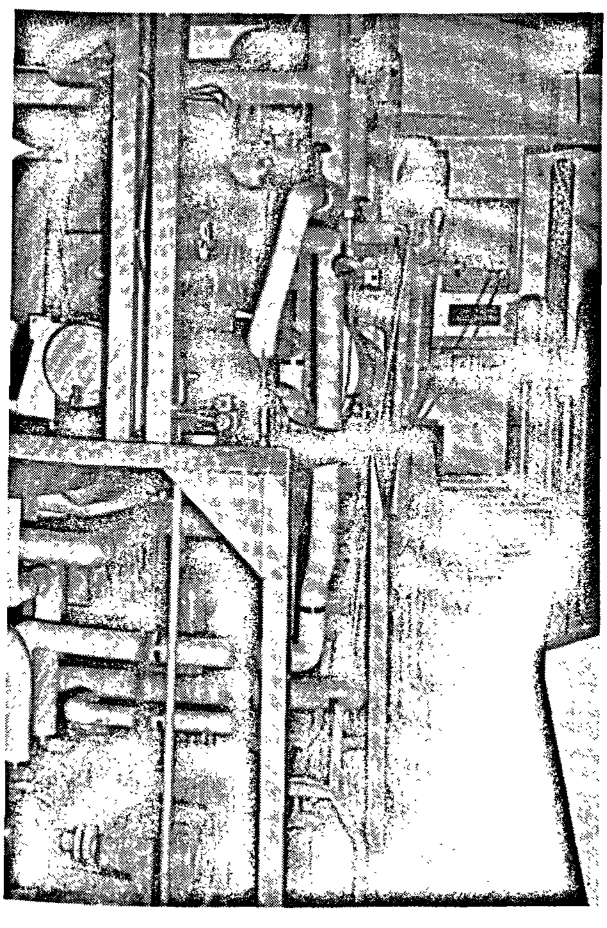

Figure 4. Pipings in control room

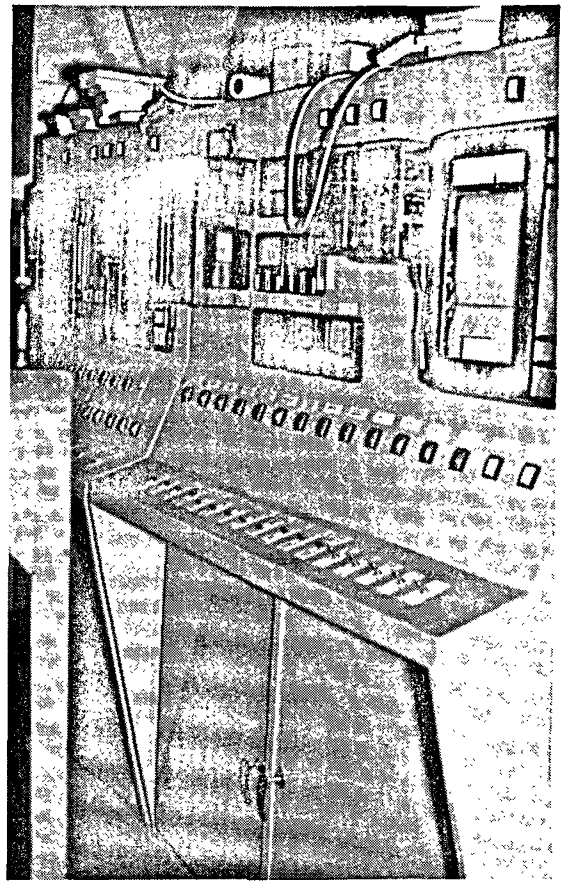

Figure 5. Controller

The temperature of the L.T. storage tank increased in spite of the cooling by the heat pump. It indicates the heat storage by the surplus of the collection of the solar radiation. The heat collection was made from 8:30 to 16:30 and the temperature of the water at the outlet of the collector was maximum in early afternoon. As assumed in the design, the water temperature at the outlet of the collector is nearly the same as the temperature of the collector itself.

Figure 7 shows a running test on a cloudy day. While the temperature of the H.T. storage tank is not so different from that on a sunny day, the temperature of the L.T. storage tank is cooled by the heat pump continuously and the heat storage is decreased.

The dry and wet temperatures of the laboratory are shown in figure 8. The range of the controlled temperature is $\pm$ 2°C and the relative humidity is kept within 7 per cent of the deviation.

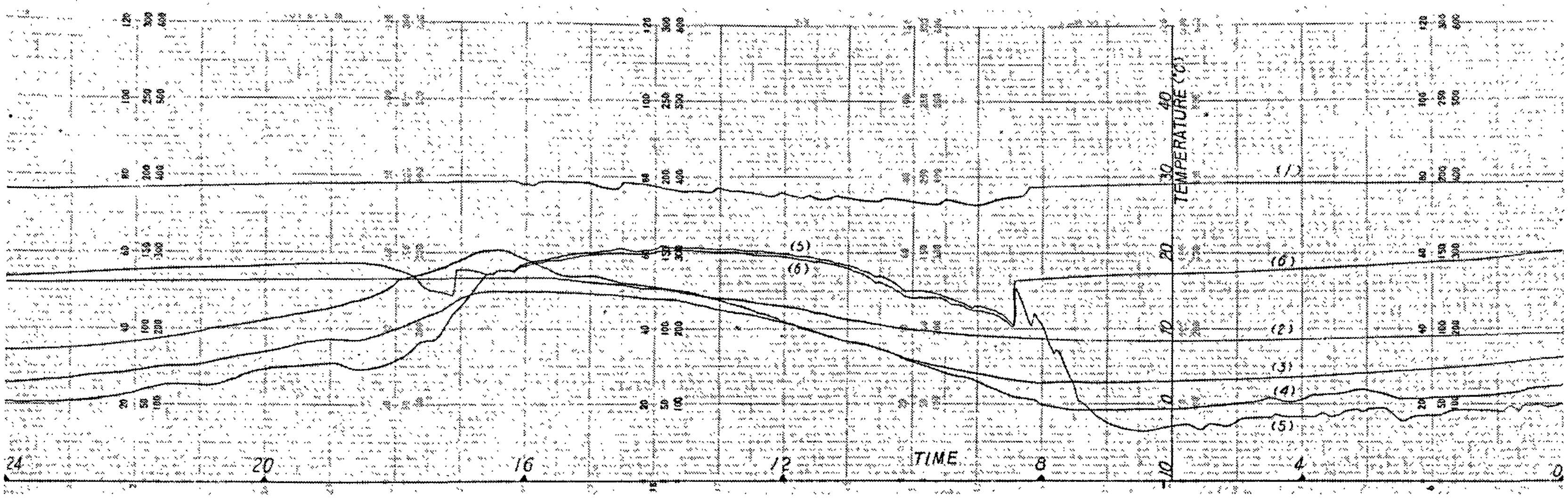

Figure 6. Temperature records of running test on a sunny day. Legend : (1) H.T. storage tank; (2) L.T. storage tank; (3) outside the laboratory; (4) on the roof; (5) collector; (6) water at the outlet of the collector

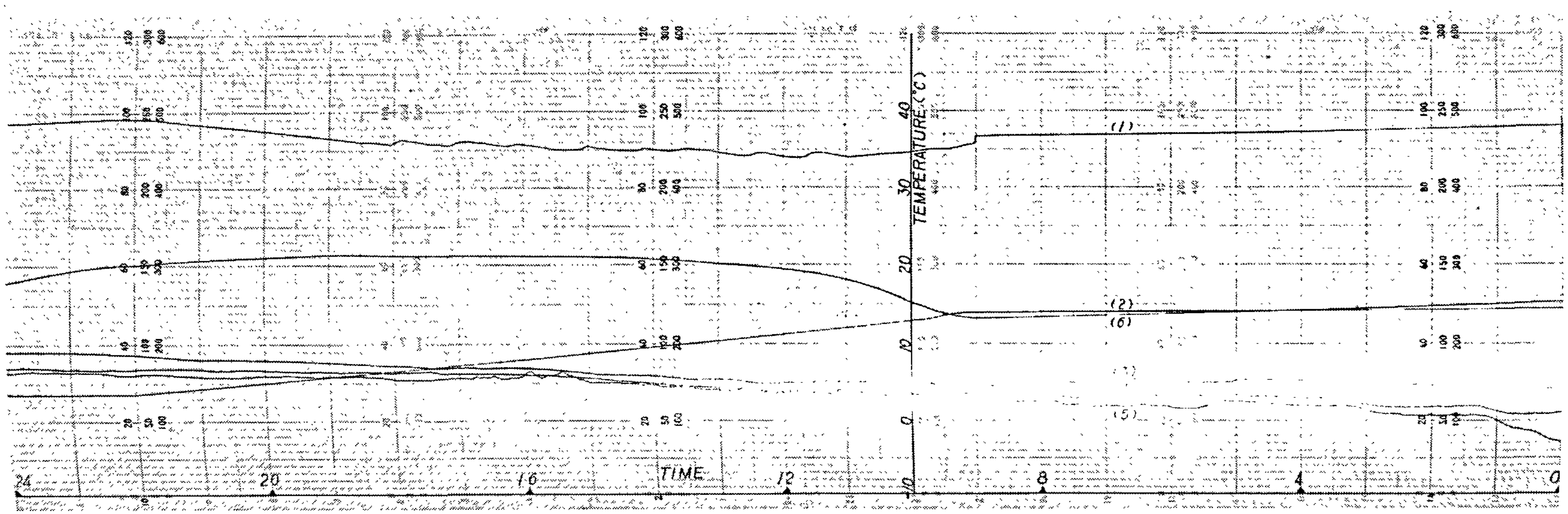

Figure 7. Temperature records of running test on a cloudy day (same legend as figure 6)

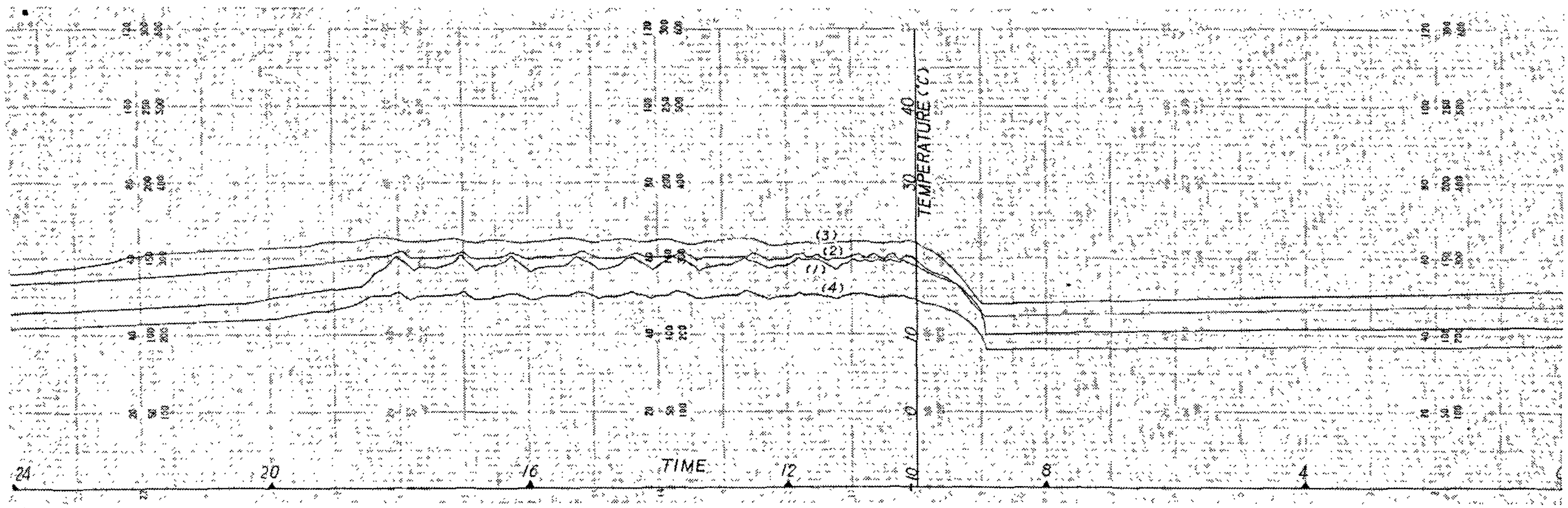

Figure 8. Dry and wet temperatures in the Laboratory. Legend : (1) dry temperature of main room; (2) dry temperature of auxiliary room; (3) dry temperature of control room; (4) wet temperature of main room

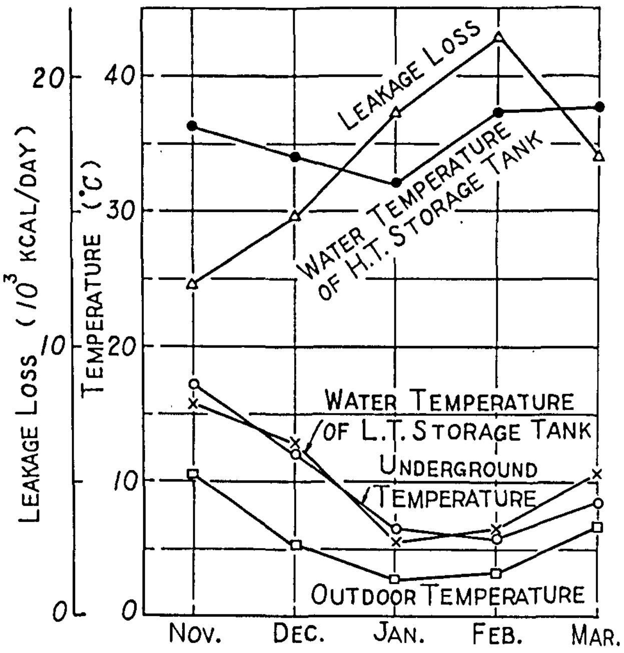

Figure 9. Monthly averages of water temperatures of H.T. and L.T. storage tanks, outdoor and underground (—1.2 m) temperatures, and leakage loss from H.T. storage tank

Performance of heat collection

. Referring to the results of the running test from November through March, the collected heat was proportional to the sine of the angle between the incident solar beam and the plane of the collector, and it was minimum in December. The average heat collected on a unit area perpendicular to the solar beam during the winter was 0.96 cal/cm².min. This is about 70 per cent of the incident direct solar radiation, 1.3 cal/cm².min.

The water temperature at the inlet of the collector, which is equal to that in the L.T. storage tank, decreases with the outdoor temperature, and the temperature difference is kept within 2.6°C. When the temperature of the L.T. temperature is higher than the outdoor temperature, the heat discharge from the collector to the air is increased and the heat collected is decreased. When the temperature of the L.T. temperature is lower than the outdoor temperature, the heat received from the air is increased and the temperature of the water in the tank is increased. These actions for automatic compensation keep the temperature difference small.

Even on rainy or cloudy days, heating is possible because the L.T. storage tank water gains the heat from the air through the collector. In the example of three consecutive days in February on which it was not sunny, heat may be collected because the outdoor temperature was comparatively higher, 10 to 15°C, and the temperature of the L.T. tank was 5 to 8.5°C, lower than the outdoor temperature. The average heat received on a unit area was

Table 1. Heat balance in the heating period from November to March

	Heat gained		*Heat discharged*		*Heat stored*
	From the sun	*From the heat pump*	*For the room heating*	*Leaked from the storage tanks*	
Heat (10^6 kcal) .	3.65	1.18	2.98	1.56	0.29
Percentage . . .	75.5	24.5	62.0	32.0	6.0

0.081cal/cm².°C.min and the coefficient of heat transfer was 24.5 kcal/h.°C.cm², while it was assumed in the design that the coefficient was 20 kcal/h.°C.cm².

Heating performance

The measured average heat loss during the winter, 480 kcal/h.°C, was smaller than the value assumed in the design by 100 kcal/h.°C. From this difference, 1 000 kcal/h of solar heat penetration through the windows and the heat source in the laboratory may be estimated.

Storage performance

The average water temperatures of the H.T. and L.T. storage tanks during the winter are shown in figure 9. The decrease of the water temperature in the H.T. tank from November to January indicates the shortage of heat storage which accompanies the increase of the heating load. The higher temperatures in February and March partly depended on the switch-over of the operation of the heat pump from 10 hours to 24-hour automatic operation.

While the leakage from the L.T. storage tank may be neglected because of the small difference between the water temperature and the underground temperature, the leakage from the H.T. storage tank was 18 600 kcal and 50 per cent more than the design value.

Heat balance

The heat balance sheet is shown in table 1. The percentages shown in the table refer to the total heat gained. Of the total gain of heat, 75.5 per cent was collected from the sun and 24.5 per cent was from the output of the heat pump. The c.o.p. of the heat pump was 3.9 and nearly the reciprocal of 24.5 per cent, the output of the heat pump. Of the gained heat, 62 per cent was used for heating the rooms, and the leakage of heat from the storage tank was 32 per cent, which was considerably large. This means that stricter thermal insulation should be applied to prevent the thermal leakage.

This report is based on a running test with small capacity tanks for temporary use. Since this test was made, a pair of tanks, 20 m³ each, has been constructed and a further continuous running test is under operation using both the smaller and the larger pairs of tanks.

DESIGN AND PERFORMANCE OF DOMESTIC HEATING SYSTEM EMPLOYING SOLAR HEATED AIR — THE COLORADO SOLAR HOUSE

George O. G. Löf, M. M. El Wakil ** and J. P. Chiou ****

One of the most inviting applications of solar energy is in the large fuel-using function of space heating, often estimated at one-fourth of total energy consumption (1). House heating with solar energy has attractive possibilities because temperature requirements are modest, heating needs of a house in the temperate zones are reasonably comparable with solar energy incidence on the building, and the equipment is not too complex for non-technical users.

Considerable development of solar heating by use of flat-plate solar heat exchangers (collectors) and short-term thermal storage units has taken place in the past decade or two. Roof-mounted solar heating units employing water as a transport and storage medium have been tested in the United States in Massachusetts (2), Arizona (3), New Mexico (4), Kansas (5), and Washington, D.C. (6); and in Japan in Nagoya (7) and Tokyo (8). Several of these installations have included a heat pump for supply of a portion of the heat requirements; the others have employed fuel or electric auxiliary heating facilities.

Space heating by use of solar heated air from roof-mounted or wall-mounted collectors has been tested in Massachusetts (9), Arizona (10), and Colorado (11). Heat was stored in a fusible salt in the Massachusetts house, and in bins of loose rock in the others. The solar source was supplemented by fuel or electric resistance heating in all but the Arizona house.

In general, solar space heating requires two principal components in addition to the conventional hot air heating system: a solar energy collector and a heat storage unit. The former is used to receive solar radiation when it is available and transfer it to the heat transport medium. The storage unit receives heat from the medium and releases it whenever required and possible. In most cases, a conventional heating unit is used with the solar system to avoid oversized collector and storage facilities and to meet heating requirements during extended periods of cloudiness.

In comparison with the conventional system, a solar heating unit is less costly to operate and maintain. High initial cost is its principal disadvantage. Most of the development efforts are, therefore, directed toward reducing the investment required for a given heat delivery capacity. These include improving the system efficiency, simplifying the combination of solar and conventional facilities, designing collector units suitable for low-cost factory production, and providing for summer use of equipment in water heating and air cooling.

One of the projects in which these factors are being studied involves a solar heating unit on a moderately large residence near Denver, Colorado. The system comprises a solar air heater in combination with heat storage in crushed rock and a conventional natural-gas furnace. The investigation is part of a solar energy development program of the American St. Gobain Corporation. This paper is largely a report of the performance of the system during the winter of 1959-60, analyzed in co-operation with the University of Wisconsin.

Description of house and heating system

The Colorado solar house (figure 1) contains about 3 200 square feet of living area, i.e., 2 100 square feet on the main level and 1 100 square feet in the basement. Large window areas are employed, those on the south being under a projection of the roof to maximize heat gain in the winter and minimize it in the summer. The house is an effective and pleasing combination of an experimental unit and a comfortable home.

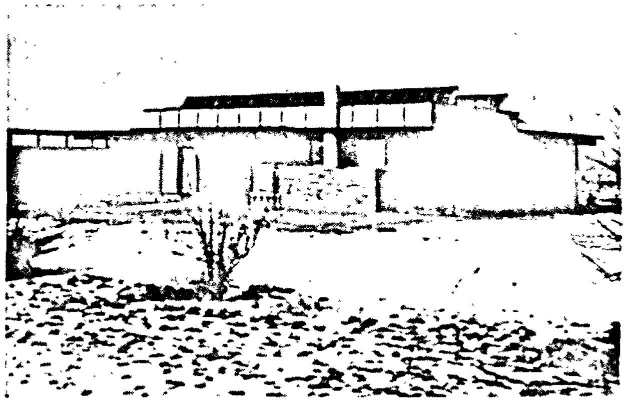

Figure 1. North-west view of the Denver Solar House

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Air is used as the heat transport medium and crushed rock as the solar energy storage material. The system consists of two solar collector banks, two vertical heat storage cylinders, hot water preheater, blower, conventional natural gas furnace, control equipment, and the necessary air ducts. The design heat load was computed at 108 500 btu per hour at outdoor conditions of zero F. and 8.8 mph wind velocity. This heat loss rate is equivalent to about 40 000 btu per degree-day. In subsequent measurements, the heat demand was found to average about 32 000 btu per degree-day. A schematic diagram of the complete heating system is shown in figure 2.

Solar collector

Two collector banks are on the roof, surrounded by a 4-foot parapet wall as shown in figures 1 and 3. They are 50 feet long, 6 feet high, and face south at an angle of 45 degrees with the horizontal. Each consists of 10 "cold panels" and 10 "hot panels" located alternately. Glass wool insulation is provided on the back of the panels. Cold air from the house or storage unit enters the cold air manifold and is then distributed to the 10 "cold collector panels" in each bank. After partial heating in the "cold panels", the air passes to the corresponding "hot panels" via cross connecting ducts. The air is heated further in the hot panels and delivered to the house or storage unit via the hot air manifold and duct system.

The collecting panels, figure 4, are of the overlapped glass plate type (12). Each panel has six black plates 12 × 27 inches, and seven clear glass plates, five of which are 24 × 27 and two are 12 × 27 inches. They are common "single strength" window glass (about 1/10 inch thick), spaced 1/4 inch apart. The black plates were made by thermal fusion of black glass particles to the surface of clear glass. The "cold panels" have a single cover glass, approximately 2½ by 6 feet, whereas double cover plates are used on the hot panels. The total area of the two collector banks containing 40 panels is 600 square feet, of which about 550 square feet is effective heat collection area.

Heat storage unit

The heat storage system comprises two vertical fibre-board cylinders 3 feet in diameter and 18 feet long, extending from the cover of the bottom plenum chamber on the basement floor to the plenum chamber on the roof. Wire mesh forms the lowest two feet

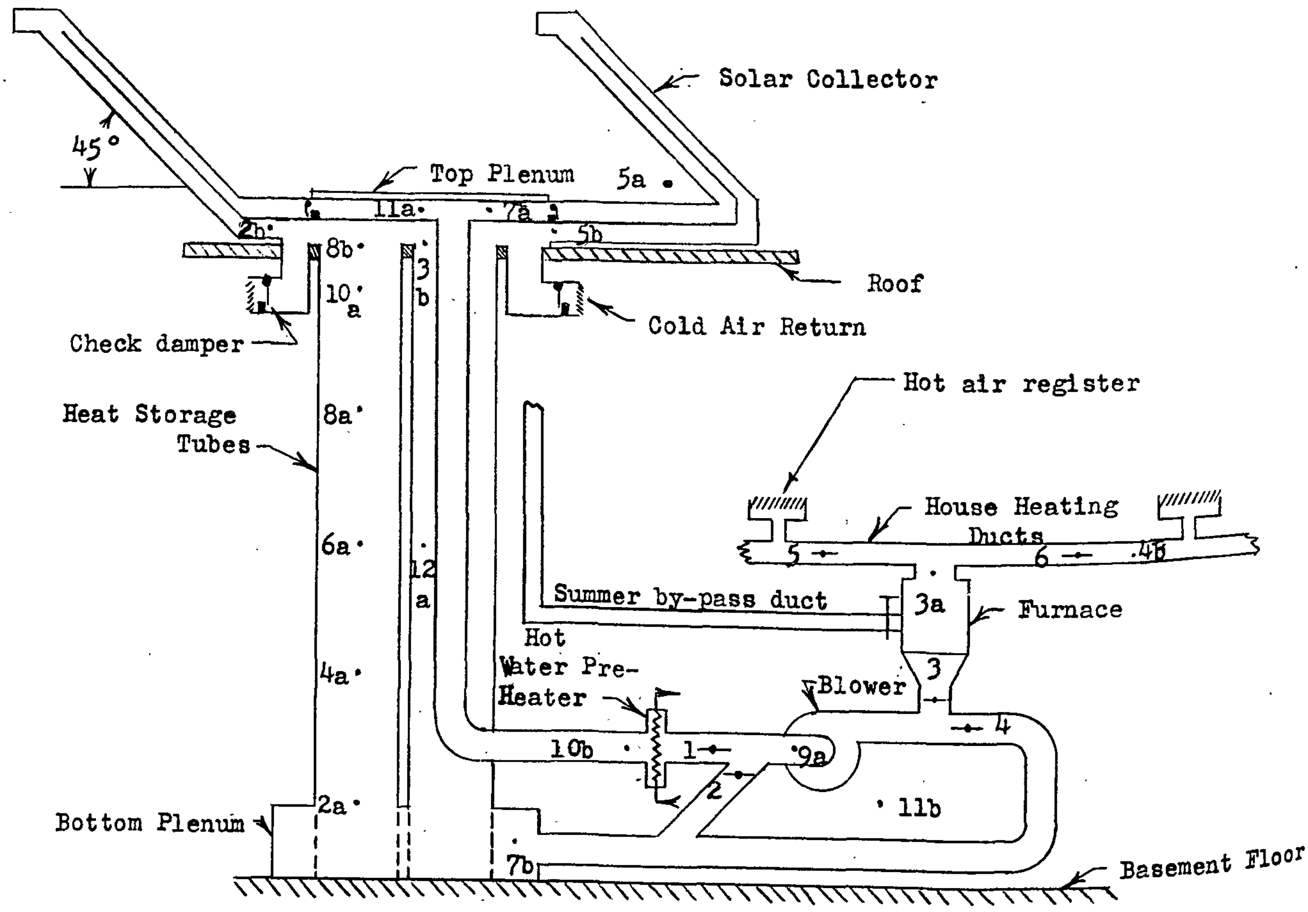

Figure 2. Sketch of Denver solar space heating system
(Not to scale)

of the tubes and allows air to flow freely to and from them. In the center of one cylinder, an 11 inch duct extends from the top to a side opening about 2 feet from the bottom.

The two cylinders contain a mixture of crushed and uncrushed rock, primarily granitic, closely sized to 1 to $\frac{1}{2}$-inch equivalent spherical diameter. Its specific heat is approximately 0.18 btu /lb°F and its bulk density is about 96.4 lb/cu ft. The total quantity is 23 460 pounds.

Hot water preheater

A finned-tube, single-row heat exchanger in the hot air duct entering the blower (figure 2) is used as a preheater for the house hot water supply. A small portion of the heat in the solar-heated air is transferred to water circulating by gravity-temperature difference from an 80 gallon tank. After being preheated, the water passes to an automatic gas-fired heater. In summer operation, this is the only use of the collected solar energy.

Air blower and motor

A centrifugal blower with a 9-inch impeller is driven by a two-speed, single phase electric motor, rated at one and at one-half horsepower at 1 800 and 1 200 rpm respectively. At the high speed, the blower delivers 770 scfm at a pressure difference of 1.81 inch of water; low speed capacity is 620 scfm at 0.8 inch pressure difference.

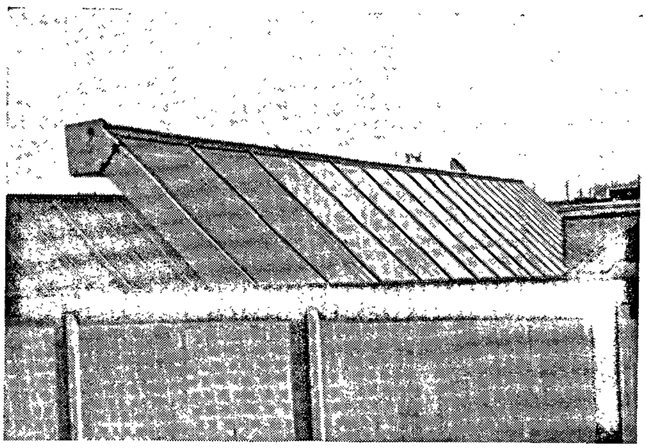

Figure 3. South collector bank

Gas furnace

A conventional natural gas furnace, but without built-in blower, nominally rated at 160 000 btu (sea-level) output, was provided with controls permitting two levels of gas supply and heat delivery. Slightly over 100 000 btu per hour is supplied to the house air stream at a gas rate of 184 cu ft/hr and a

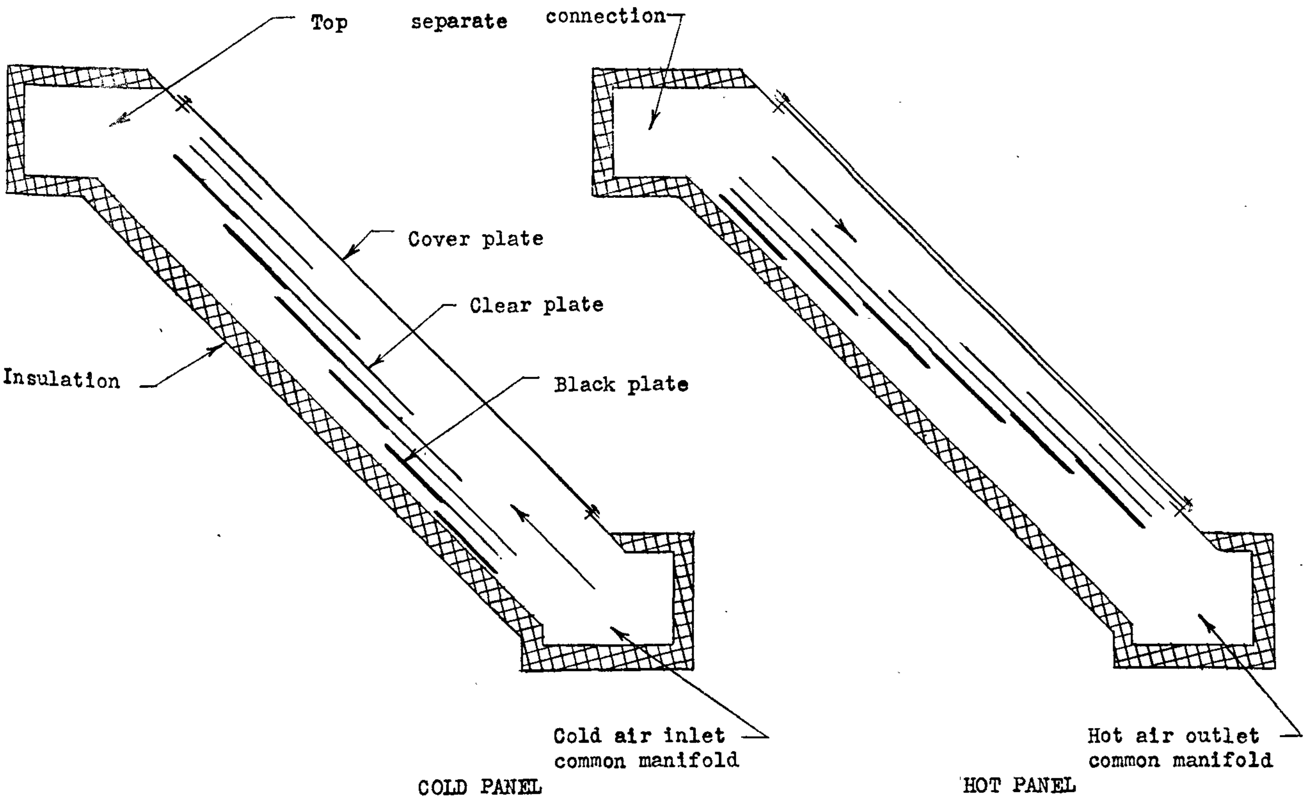

Figure 4. Cross sections of collectors
(Not to scale)

combustion efficiency of 74 per cent. The lower gas supply rate is 93.5 cu ft/hr.

Control system

Solar radiation detector (collector thermostat)

A resistance thermometer element is mounted on a blackened metal plate in a glass-covered closed metal box above one of the collector banks. The thermal inertia of the control element simulates that of the collector itself and senses the solar intensity. Through an amplifier and Wheatstone bridge circuit, this unit supplies signals to start and stop the blower motor and other system components involved in solar heat supply.

Storage compensation thermostat

Another resistance thermometer in the top of the heat storage unit supplements the action of the solar radiation detector. Control of the storage operation is based on the setting of a suitable temperature difference between the collector thermostat and the storage compensation thermostat.

Room thermostats and modulating dampers

Two ducts fitted with variable flow dampers supply hot air to rooms in two zones of the house. A double contact thermostat in each zone controls the blower, the main dampers, and one of the modulating dampers. If the temperature in one of the zones decreases below the thermostat set-point, the first contact closes and the appropriate modulating damper slowly starts to open. The two pairs of main control dampers immediately move to permit air flow either from the collector or the storage unit, and the blower motor is actuated at the low speed if air is being supplied from the collector or at high-speed if from storage. If the zone temperature does not rise past the control point by the time the modulating damper reaches the full-open position (about 10 minutes), gas is supplied to the furnace at the lower rate. If the zone temperature falls further, at this condition, the second thermostat contact closes, starting the fuel gas supply rate to the furnace.

Control dampers

Four dampers operated in pairs by two damper motors are controlled by the several thermostats. One pair of dampers directs hot air leaving the blower either to a house zone needing heat or to storage. The other pair selects the blower air supply either from collector or from storage.

Other dampers

Four swing-type check dampers are provided at various points to prevent reverse flow of air when not desired and to decrease air leakage. When the system is first put in service, a manual damper at the bottom of each hot collector panel can be adjusted to provide uniform air flow through each panel. Conversion from winter to summer operation is accomplished by inserting a sheet metal blank in the hot air duct leaving the furnace and removing a blank in the air bypass from the furnace exit to the top plenum chamber.

Instrumentation

Solar radiation was continuously measured by an Eppley pyrheliometer mounted on the top of the south collector bank at the same angle as the collectors. Air flow rates at the blower outlet and at the two cold air return grills were measured periodically by a hot-wire anemometer.

A manometer, and static pressure taps in the bottom plenum chamber, water preheater inlet, blower inlet and outlet were used occasionally for pressure measurements in the system.

Nineteen copper constantan thermocouples are located at all positions where significant temperature data may be secured. Several of these are indicated by numerals and letters in figure 2. They were continuously recorded, along with solar radiation data, on a standard multipoint instrument. Damper positions were also recorded on the chart by use of low voltage indicator circuits containing mercury switches on the damper lever arms. Air temperature at the bottom of each hot panel and at the top of cold panels was occasionally measured by thermometer.

Gas and electricity consumption were obtained by daily readings of a main gas supply meter (house and water heating), a gas meter for the furnace only, and an electric meter for the entire power supply to the heating system.

Operation of the solar heating system

House heating season

There are three cycles of system operation:

House heating from the collectors.
Storing heat.
House heating from storage.

In addition, natural gas may or may not be supplied to the furnace during both house heating cycles. Figure 2 shows the features related to these air circulation arrangements under these several conditions.

House heating from collectors

Hot air is supplied directly from the collector to the rooms of the house when heat is demanded and when adequate solar energy is being received. This cycle is used the least of the three. Occasionally, gas heat may also be supplied to the air passing through the furnace under these operating conditions.

Positions of control dampers: Nos. 1 and 3 open, 2 and 4 closed.

Blower speed: low.

Air flow route: collectors — down through vertical duct — water preheater — blower — furnace — hot air registers — rooms — cold air return — grills — top plenum chamber — collectors.

Storing heat

This cycle operates when the house does not need heat and the intensity of solar radiation is great enough to justify collection. This operation is fairly continuous on sunny days.

Positions of control dampers: Nos. 1 and 4 open, 2 and 3 closed.

Blower speed: high.

Air flow route: Collectors — down through vertical duct — water preheater — blower — bottom plenum chamber — storage unit — top plenum chamber — collectors.

House heating from storage

This cycle operates intermittently whenever the house requires heat and the sun is not shining. If the air reaching the rooms is not warm enough to meet the thermostat demands, gas heat at the low rate is added to the air. If this is not sufficient, the full gas fuel supply rate is utilized. Air is circulated through the storage unit even if it contains little or no heat, thereby insuring its full utilization, but at the same time requiring blower power use.

Positions of control dampers: Nos. 2 and 3 open, 1 and 4 closed.

Blower speed : high.

Air flow route: Rooms — cold air return grills — top plenum chamber — storage unit — bottom plenum chamber — blower — furnace — hot air registers—rooms.

Note that the heat storage medium is heated from the bottom upward and cooled from the top downward. Maximum heat recovery is thereby obtained.

Summer water heating

At the start of the summer, a stationary shutoff damper or "blank" is manually removed from its winter position in a bypass air duct from the top of the furnace to the roof plenum chamber. A small vent in the roof plenum is opened and a second "blank" is inserted in the main air duct leading from the furnace to the rooms. Then, with a higher setting on the collector thermostat, water preheating takes place in sunny weather.

Position of control dampers: Nos. 1 and 3 open, 2 and 4 closed.

Route of air flow: ambient air — top plenum chamber — collectors — down through vertical duct — water preheater — blower — furnace — summer bypass duct — top plenum chamber.

Blower speed: low.

Performance analysis

The performance of the solar heating system was determined by three types of analysis. In the first consideration, general functioning of all components and their adjustment to satisfactory operation were given primary attention. The elimination of design and fabrication defects, insofar as possible, was based on observations made during this period. Next, tests of heating effectiveness, response to thermostatic setting, extent of air leakage, and other short-duration experiments were performed, and additional adjustments made where possible. Finally, complete data on day-to-day system performance through the entire winter were secured and analyzed.

Changes and improvements in the system were being made even during the heating season analyzed. In particular, inadequate air circulation rates were increased by making a few design changes. Table 1 shows the principal changes and their results.

Table 1. Air flow rate at blower outlet (scfm)

Period	*Storage cycle*	*Heating from storage*	*Heating from collector*
Up to November 17, 1959	495	522	405
November 18, 1959 to December 15, 1959. Inserted dividers in the top (cross-connecting) manifold.	735	772	616
December 16, 1959 to present. Adjusting dampers at the bottom of each hot panel to equalize air distribution	770	782	620

Investigation of air leakage rates was another performance analysis of importance. The sizable static pressure differences and the many possibilities for small openings in such an extensive array of ducts, collector panels, and storage components, even with careful fabrication and caulking of joints, make air leakage a problem. Any flow of hot air from the equipment is counterbalanced by cold air flow into the system, with a resultant efficiency loss. Temperature, static pressure, and air velocity at various points were therefore measured, and used in energy and mass flow balances by which leakage rates in several sections of the system were evaluated.

Heating performance during the winter of 1959-60 was determined by day-by-day analysis of gas and electric meter readings and the temperature and solar radiation data from the recorder chart. Air flow rates in each operating cycle and for each of the

Table 2 Amount of air leakage at various points (scfm)
(After December 16, 1960)

Cycle	*Blower outlet*	*Into collectors*	*Into lower plenum and basement ducts*	*Into storage from house*	*Into vertical duct to basement*
Heating from storage .	782		35	47	0
Storing heat	770	154.8	28.2	31.4	—
Heating from collector .	620	171	0	0	104

Table 3. Energy balance of Denver solar house

Winter 1959-60 : all values in million btu

	September (18-30)	*October*	*November*	*December*	*January*	*February*	*March*	*April*	*May*	*June (1-10)*	*Total*
1. Total solar incidence on 45°-600 sq ft collector area.	9.93	26.84	25.81	21.98	25.48	22.10	30.43	26.56	29.61	8.13	226.86
2. Total solar incidence available on 45°-600 sq ft collector area when collection cycles operated.	6.94	20.16	17.55	15.67	17.05	13.38	22.03	19.94	22.60	6.00	161.33
3. Gross collected solar heat	—*	—*	—*	—*	5.99	4.33	9.08	9.16	8.86	2.40	—*
4. Gross collector efficiency, per cent .	—*	—*	—*	—*	34.7	32.4	41.1	45.9	39.8	40.0	—*
5. Useful collected heat	1.93	5.91	5.34	5.61	5.59	3.79	8.45	8.66	8.25	2.18	55.72
6. Net collector efficiency, per cent .	27.9	29.4	30.3	35.8	32.7	28.3	38.3	43.5	36.5	36.4	34.6
7. Solar heat absorbed by storage tubes	1.12	3.04	2.77	2.79	2.64	1.92	3.99	3.68	3.01	0.50	25.46
8. Storage tube inventory	— 0.03	0.07	— 0.002	— 0.008	0.017	— 0.023	— 0.008	0.07	0.17	— 0.05	—*
9. Solar heat absorbed by water preheater.	0.11	0.35	0.30	0.32	0.27	0.21	0.51	0.72	0.87	0.29	3.95
10. Heat delivered by natural gas for house heating.	3.19	12.26	19.65	22.16	26.90	28.10	17.45	7.09	4.78	0.25	141.83
11. Heat delivered by natural gas for water heating	0.67	1.49	1.79	2.01	1.84	2.68	2.60	3.23	3.24	0.88	20.43
12. Total heat load.	5.79	19.66	26.78	29.78	34.33	34.57	28.50	18.98	16.27	3.31	217.98
13. Per cent of useful collected heat absorbed by water preheater . . .	5.7	5.91	5.63	5.7	4.84	5.55	6.04	8.2	10.56	13.4	7.09
14. Per cent of total water heating load supplied by solar energy	14.1	19.0	14.4	13.75	12.80	7.26	16.4	18.25	21.20	28.40	16.25
15. Per cent of house heat load supplied by solar energy (including water preheating but excluding water heating)	37.5	32.3	21.4	20.2	17.2	11.87	32.6	55.3	63.4	89.6	28.20
16. Per cent of house heat load supplied by solar energy (including both water preheating and heating) . .	37.0	30.2	19.9	18.9	16.25	10.95	29.6	45.8	50.7	65.8	25.7

* Not determined.

three periods of the winter test were used in computing useful collected solar heat.

Appraisal of solar heating performance involved determination of several types of heat collection and efficiency. These quantities and their explanation are as follows:

Useful collected solar heat

Heat delivered from collector to rooms or to storage based on temperature change in air supplied from collector and air returning to collector.

Gross collected solar heat

Useful collected solar heat plus the solar heat which was used in heating air leaking into the collectors, from atmospheric temperature to the average return air temperature at collector inlet.

Net collector efficiency

For a certain cycle, the useful collected solar heat divided by the incident solar energy during the cycle.

For a day, the daily useful collected solar heat divided by the daily incident solar energy.

Gross collector efficiency

Analogous to net collector efficiency, with gross collected solar heat in place of useful collected solar heat.

Storage tube inventory

Energy content of rock at a particular time, as determined by rock temperature profiles.

Solar heat absorbed by storage tubes

Difference in energy content of rock at start and end of storing cycle, as determined by rock temperature profiles.

Solar heat absorbed by water preheater

Heat transferred to water from air as measured by drop in temperature of air passing through heat exchanger.

Results

Results of daily performance of the heating system during the 1959-1960 winter season are summarized on a monthly basis in table 3. Included are data on total solar incidence, total solar incidence available when various collection cycles are in operation, gross collected solar heat (this item does not show for the months before January, 1960, because no dependable leakage data were available for those days), useful collected heat, gross and net collector efficiencies, solar heat stored energy, solar heat absorbed by the water preheater, heat delivered by natural gas for house heating, heat delivered by natural gas for water heating, total heat load, percentage of useful collected heat absorbed by water preheater, percentage of total heating load supplied by solar energy, and percentage of house heat load supplied by solar energy with and without the water heating load.

Figures 6, 7, and 5 show the cumulative results of a heating system operation during the full season. The average net collector efficiency (including both the storing and the direct heating cycles) during the entire season, based on incident solar energy received during operating periods, is 55.72/161.3, or 34.6 per cent. A 28.2 per cent sharing by solar energy of the total heat load (including water preheating but excluding subsequent final water heating) or 25.7 per cent sharing of the total heat load (including both water preheating and heating loads) was realized during this heating season.

Several studies of daily performance of the solar collector and the heat storage unit, as affected by

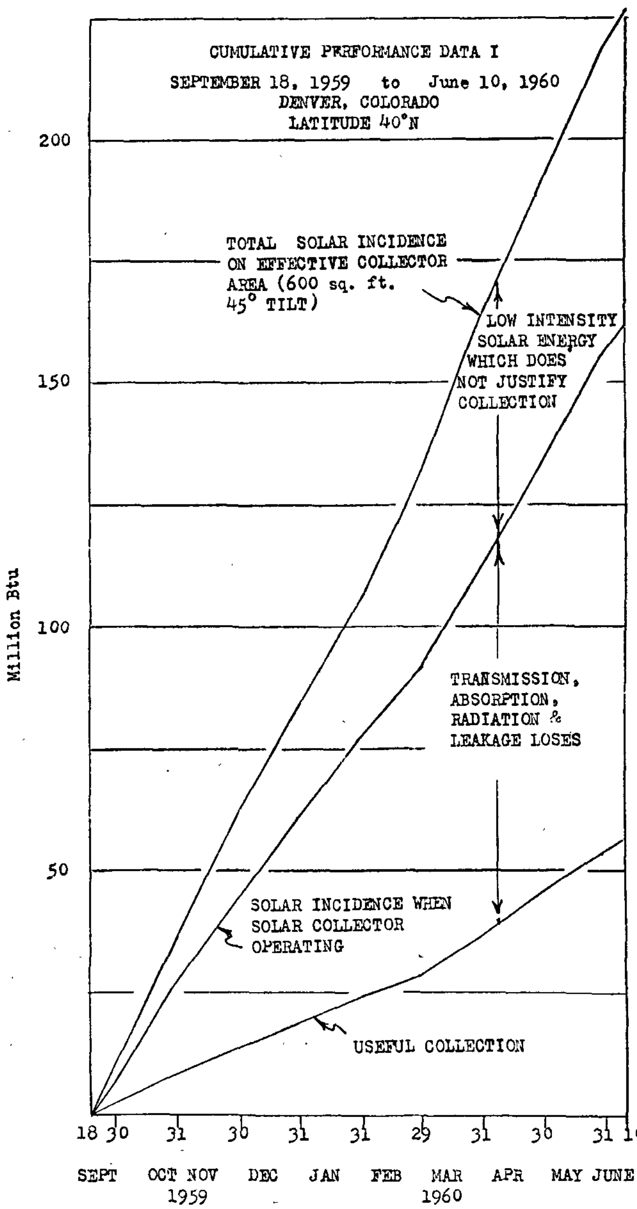

Figure 5

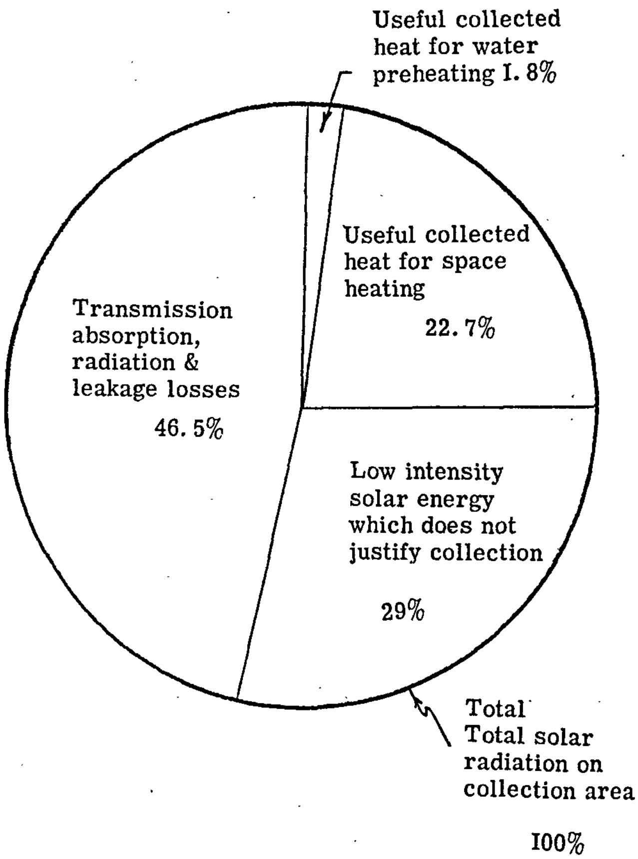

Figure 6

system variables, were also made. The results and their discussion are beyond the scope of this paper, but they may be summarized as follows:

Effects of air circulation rate and ambient temperature on net collector efficiency. In general, efficiency ranged from 25 per cent to 45 per cent.

Effects of air circulation rate and solar intensity on net collector efficiency. Values ranged from 25 per cent to 45 per cent.

Effects of ambient temperature and solar intensity on net and gross efficiencies. Gross efficiency ranged 1 per cent to 5 per cent higher than net.

Daily useful heat recovery as affected by ambient temperature and air circulation rate. Maximum value about 450 000 btu per day.

Daily useful heat recovery as affected by solar radiation intensity and air circulation rate.

Heat storage effectiveness as influenced by ambient temperature, solar radiation, air flow rate and rock temperature at start of storing cycle. Maximum value about 90 per cent, and average value about 80 per cent.

It is expected that the results of the above studies will be published elsewhere.

Economics of the solar heating system

Table 4 shows a comparison of the operational costs of the solar house heating system with those of conventional heating systems. Gas and electricity use were read directly from meters, and costs were based on prevailing utility prices. Gas consumption in a conventional air heating system was computed from measured heating requirements by use of the formula:

Gas consumption for conventional air heating system in 100 cu ft

$$= \frac{\text{total heat load in btu}}{0.74 \times 830 \times 100}$$

$$= \frac{\text{useful collected heat} - \text{storage inventory}}{0.74 \times 830 \times 100}$$

$$+ \text{gas consumption of solar system}$$

where 0.74 = average furnace efficiency
830 = heating value of natural gas (btu/cu ft)

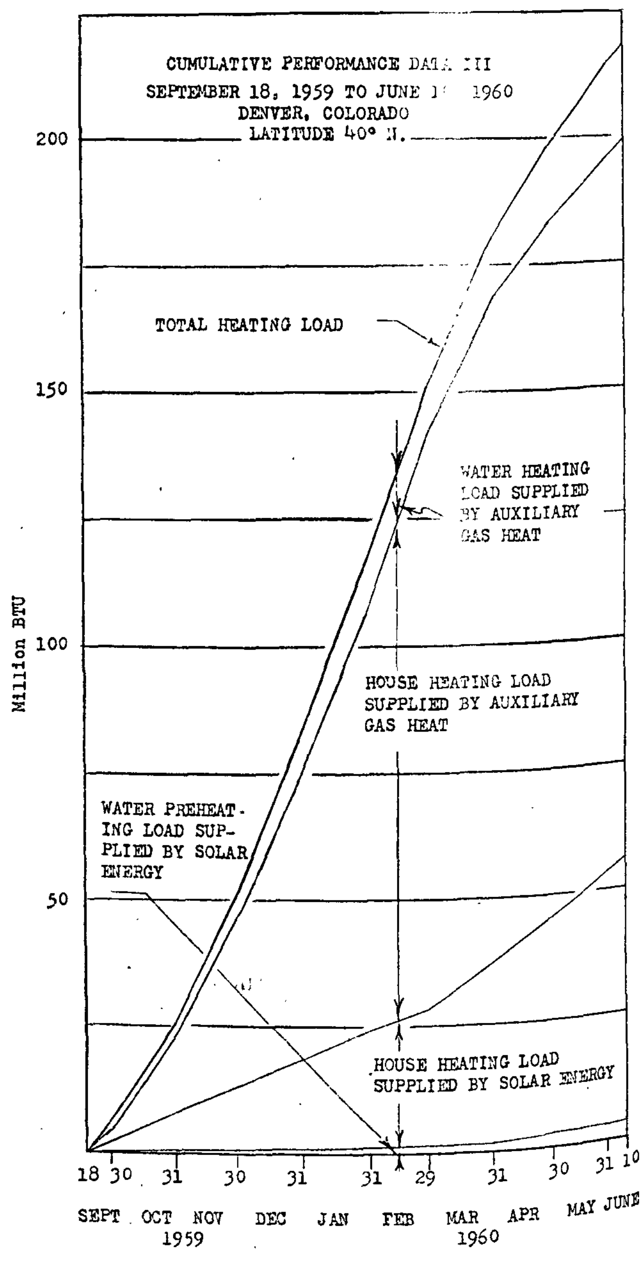

Figure 7

Table 4. Economics of the Denver solar house
1959-60 heating season

		Denver solar heating system	Corresponding conventional hot air system	
			Gas furnace	Oil furnace
Gas or oil consumption (assume 9 cents per 100 cu ft of gas and $1.50 per million btu oil)	Quantity	2 642 (100 cu ft)	3 548 (100 cu ft)	294 million btu
	Cost $	238.78	319.33	441.00
Total electricity consumption (assume 2 cents per kWh)	kWh	3 876.0	873.5	873.5
	Cost $	77.52	17.47	17.47
TOTAL OPERATION COST $		316.30	336.80	458.47
Saving obtained by using present Denver solar heating system rather than conventional hot air heating system with natural gas as fuel $		20.50		
Saving obtained by using present Denver solar heating system rather than conventional hot air heating system with oil as fuel $		142.17		
Estimated electricity consumption with modified air circulating system	kWh	1 400		
	$	28.00		
Estimated fuel consumption with system improvements $		2 400 (100 cu ft) 216.00		
TOTAL OPERATION COST $		244.00		
Estimated saving with system improvements	Solar + gas auxiliary over gas. $	92.80		
	Solar + oil auxiliary over oil . $	130.00		

Electricity consumption in a conventional air heating system is based on an experienced estimate of 100 kWh per month.

It is seen that slightly over 90 000 cu ft of natural gas were saved by the use of the solar heating system during the season. At a current price of 9 cents per hundred cubic feet, a seasonal saving of $80.55 was realized. This was partially offset by an additional electrical requirement of about 3 000 kWh, at an extra cost of $60.05. Under these conditons, the net seasonal energy saving was valued at $20.50.

Natural gas is unusually cheap in this area, so figures are also presented for costs of equivalent heating with fuel oil at an efficiency of 74 per cent and a price of $1.50 per million btu heating value (roughly 20 cents per gallon total cost, including on-site storage and pumping). These are more representative of typical costs of domestic heat in the U.S.A. than are the Colorado prices of natural gas. It is seen that the net seasonal fuel and electrical energy cost of the present solar-natural gas system is $142.17 less than if fuel oil had been used.

As explained in the following section, some modifications in the air circulation and storage system would permit reduction in power requirements. In addition, if the present system had been operated without air leakage for the whole season at the higher air rate employed after December 15, solar heat recovery would have been about 70 million btu (rather than 55.7 million) and natural gas use would have been about 240 000 cubic feet. Costs and savings are shown in table 4, under these conditions. Net winter energy savings of $92 for a solar-natural gas system and $130 for a solar-fuel oil system would result.

Although not evaluated in this analysis, additional small savings through the summer months are obtainable by use of the solar water heater.

The capital cost of the solar space heating system is considerably higher than that of a conventional hot air system. The small energy saving which was actually realized with this unit may therefore appear unattractive. But it must be realized that numerous economic and technical factors in the experiment require interpretation in light of the particular conditions employed. It must also be understood that the unit under investigation is a "first of a kind," for purposes of evaluation and improvement of the design. Use of an optimized rather than a primarily aesthetic storage design, improvement in collector performance through reduction of leakage and optimizing collector and storage sizes will substantially increase savings. If factory production of standardized collector modules can be developed, and if an effective solar cooling system can be combined with the heating function, increased saving and lower investment requirement should add considerably to the economic attractiveness of the system.

It is not yet possible to appraise the energy cost savings against the added investment required for solar equipment. A careful examination of production costs for this type solar collector has not been made, primarily for lack of sufficient data on which such an analysis must be based. The additional expenses of the storage unit, control system, installation, contractor overhead and profit are dependent on several indeterminate factors which require more experience for evaluation. Based on experience with the Colorado installation, it appears that if the total additional expense of the solar facilities were not to exceed $2 per square foot of collector, i.e., $1 200 total investment, an annual energy saving of $100 believed attainable in an improved unit of this size would make the solar system competitive with conventional heating facilities in this situation. The $2 per square foot collector cost is speculative at this time, and the need for establishing some sort of firm cost figure based on sizable factory production is evident.

More favorable comparisons could be made in regions of higher fuel cost, whereas the economy would be less attractive in areas of lower solar energy supply. Further efficiency increases attainable through additional design changes and optimization studies would reduce the effective collector area requirements and increase savings. It is clear that continued development effort is desirable.

Discussion of results and potential improvements

Figure 8 shows a comparison between the total heat load, total solar incidence on collectors, total solar incidence on collectors during operating periods, and the useful collected heat. During the winter months, the heat requirements of this comparatively large house were greater than the total incident solar energy on the 600 square-foot collector, and much greater than the recovered energy. Only in early fall and in the spring was solar radiation greater than the heating load. Because optimization of collector size was not attempted in this experimental system, this difference simply indicates that a small solar unit, relative to the total heat requirements of the house, was used.

Architectural limitations resulted in a limited amount of collector shading during early morning and late afternoon hours in a few weeks near the winter solstice. The collector efficiency and the percentage of the heat load supplied by solar energy suffered small decreases because of this loss.

On occasional mornings, snow covered most of the collector surface, but none was on the cover of the collector thermostat. Under these conditions, air would be circulated through the collector if the sun shone, and for a time, at least, air leaving the collector was colder than the entering air. Thus, the circulated air supplied heat from the house or storage to melt the snow on the collector. The average daily collector efficiency decreased greatly under these conditions, but the frequency of this occurrence was not high, and the seasonal effect was small. The bottom manifold design may be altered so that snow can slide from the collectors more rapidly.

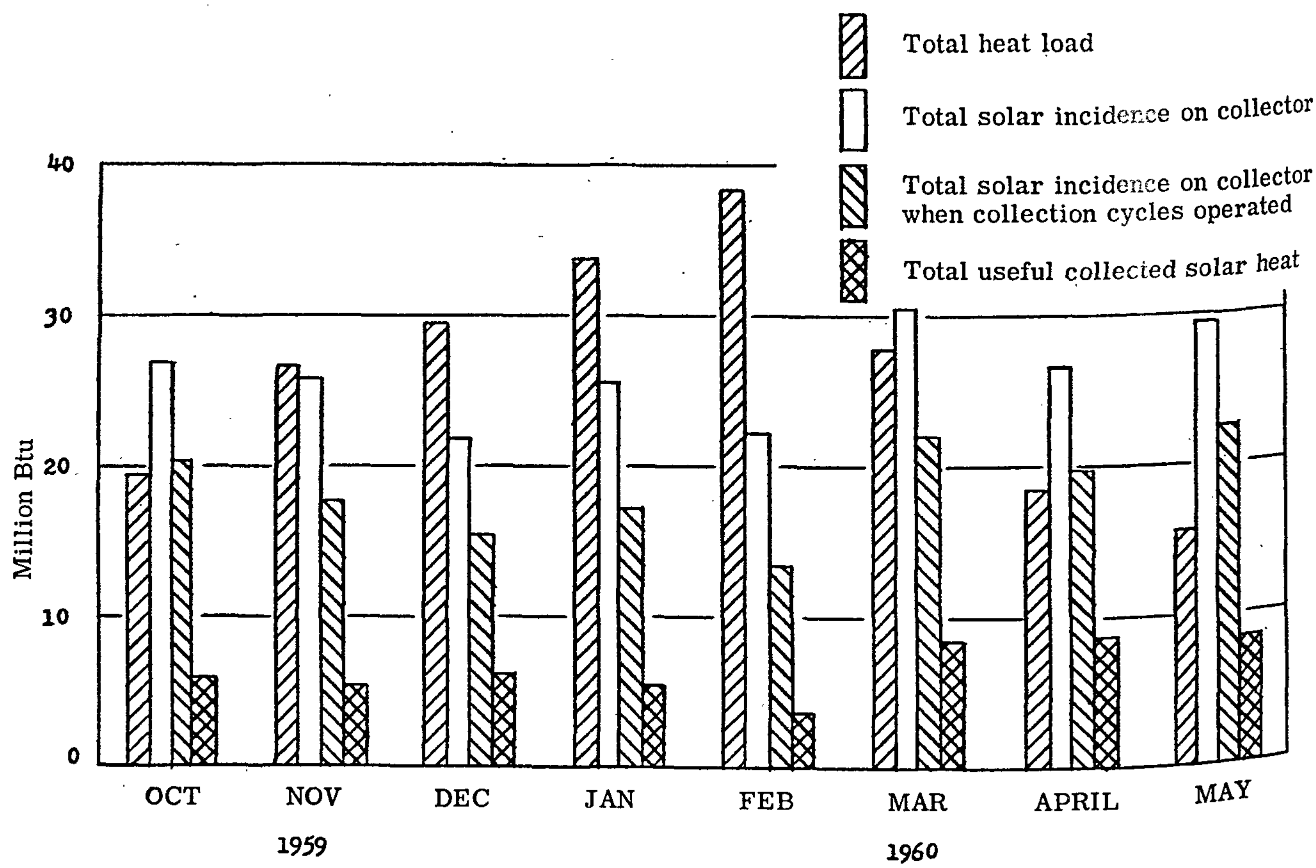

Figure 8

The ideal point for stopping and starting the heat storing cycle is that at which the cost of operating the blower equals the value of the heat being so recovered. Based on data from the third operating period, total electricity consumption (including the blower, control system and instrument) was about 762 watts or 0.0127 kWh/min. At a gas cost of 9 cents per 100 cu ft and an electricity price of 2 cents per kWh, the minimum operating air temperature difference between the collector outlet and inlet should be about 12.5°F. The present setting for controlling solar collection is several degrees too high, so a small gain could be realized by resetting the control point.

In the present system, the cold air returns from the rooms are connected directly to the top plenum chamber. When heating the house other than by hot air directly from the collector, air must therefore be passed through the crushed rock. Even when there is no heat available from storage, as is the case during part of nearly every winter night, the air must be circulated through the relatively high flow-resistance storage system. Considerable power savings would result if a separate duct were installed which directly connected the blower inlet to the cold air return grills and bypassed the storage. The control for such a bypass damper and the furnace gas valve can be a thermostatic element in the lower end of the storage medium.

In order to attain maximum solar transmission, the solar collector, as first built, contained low reflectivity glass throughout. However, extensive glass breakage due to defects in the original supporting frames resulted in the need for nearly complete replacement with ordinary glass. This substitution caused a sizable decrease in collector efficiency below that of the original design. Another collector efficiency reduction is probably due to lack of uniformity in air flow through the large number of collector sections, even after damper adjustment. Improved control arrangements and a design providing air travel paths of more nearly equal length would result in better performance.

Air leakage, particularly in the collector, has been the most troublesome problem with the system. Although much reduced from its initial severity, it has not been eliminated. The fabrication technique involving extensive on-site construction and assembly of the collector is to be avoided because of the practical impossibility of tight joints and closures of metals and glass. It is concluded that factory-production of complete, ready to install collector panels or modules, of small size, for example, 2-1/2 feet by 6 feet, is the most dependable technique for insuring airtight design. In addition, collector costs can be greatly reduced by such standard production methods. Application to a house would then require that the heating contractor procure a sufficient number of collector panels to meet requirements, erect them on the roof, provide air-tight duct connections to and from them, and incorporate these components in a full system with storage and conventional furnace. With such arrangements, leakage should be no problem.

In appraising the overall performance of this solar heating system, it is helpful to consider a design objective quite unique in this development. In contrast with the other solar-heated dwellings currently or previously tested, the plan and architectural design of the Colorado house were independent of the solar heating feature. In other words, if conventional heating had been installed, the same house would have been built. This type heating system has therefore proved useful without imposition of architectural limitations on house design. It must be recognized, however, that this design philosophy resulted in somewhat less than an ideal solar design, concessions having been made in storage configuration, air flow pattern, solar collector position and other factors tending to reduce efficiency and fuel savings. As a conclusion, it may be claimed with assurance, that this solar air heating system needs further design improvements to maximize efficiency, but that it can readily supply a substantial part of the heat demand of a house without impairing the appearance and utility of the dwelling. Although the economic aspects of this application appear encouraging, substantial work remains before cost/benefit ratios can be determined and technical problems can be fully resolved.

Acknowledgement

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Summary

The experimental Denver Solar House is a large residence with a living area of 2 100 sq ft on the main level and 1 100 sq ft in the basement. Air is used as the heat transport medium and crushed rock as the solar energy storage material. Two solar collector banks of the overlapped glass plate type, mounted on the flat roof at a 45 degree angle, provide a total effective area of 530 square feet. There are two vertical heat storage cylinders, each 3 feet in diameter and 18 feet high, filled with about 12 tons of large-size gravel. A natural gas furnace is incorporated into this system for secondary heat supply.

Records of heating performance have been obtained over the past three winters, and detailed analysis of the daily performance of this system, from September 18, 1959 to June 10, 1960 has been made. It was found that during this period the total solar incidence on the effective collector area was 226.9 million btu, of which 161.3 million btu was of high enough intensity to justify collection. The useful collected solar heat was 55.7 million btu, of which 3.95 million btu were extracted by the water preheater. Solar heat absorbed by the storage material was about 25.5 million btu. Average solar collecting efficiency during operation (including both the storing cycle and heating cycle) through the entire season was therefore about 34.6 per cent.

The amount of gas used for heating during the same period was 264 200 cu ft, of which 230 200 cu ft were for space heating, and 33 300 cu ft were for water heating. Net heat supplied by this fuel was 141.8 million btu. The total electricity required for the operation of the system (including air blower, damper motors, and instruments) was 3 876 kWh.

The paper includes data on solar incidence, solar heat collected, average collecting efficiency, solar heat to storage, the lower and higher storing efficiency, solar heat extracted by the water preheater, percentage of useful collected solar heat extracted by the water preheater, percentage of water heating load supplied by solar energy, and the percentage of the total heating load supplied by solar energy through the season. It was found that solar energy provided 25.7 per cent of the heat requirements of the house during the 1959-60 winter.

Several improvements in design and operation were made during the season, so separate performance analyses were made in each period of consistent data. From Sept. 18 to Nov. 17, 1959, air flow rate during the storing cycle was 495 scfm; from Nov. 18 to Dec. 15, the rate was increased to 735 scfm; and from Dec. 16 to June 10, 1960, the highest rate of 770 scfm was used. After June 10 summer operation of the solar system was conducted.

Defects in system design and operation, some of which have been corrected, include excessive air leakage in and out of the ducts, lack of an air by-pass around the storage unit for use when no heat is available there, loss of control system accuracy during periods when snow was on the collector, slight shadowing of the two collector banks, more frictional resistance through the storage unit than necessary, and occasional faulty operation of check dampers. On the favorable side, once the system had been fully adjusted to routine operation, it supplied adequate heat to the house whenever needed, with complete freedom from personal attention and maintenance.

Even though operating at less than ideal conditions, about $80 fuel savings were achieved during the heating season. This saving was offset by a $60 increase in electricity use. With minor system changes, electrical requirements can be reduced to about $10 to $15 more than conventional systems and fuel savings increased to about $100, thereby yielding net savings of about $90 in a typical season. Analogous figures for oil heating, with and without solar supplement, show anticipated net seasonal savings of $130. Initial investment and depreciation are not taken into consideration in these estimates. Principal changes required for the increased savings are reduction in air leakage, doubling the cross-section and cutting the storage system height by half, and providing an air duct to by-pass the storage when it contains no heat. If low reflectivity glass is used in the collector, considerably larger fuel savings would be realized. Summer use of fuel for water heating could be materially reduced by another minor design change.

The extent of fuel savings or the portion of the total load carried by solar energy in this experimental house-heating system is not, by itself, a measure of the worth of the design or of its solar components.

Factors such as collector area, house heating load, solar radiation, ambient temperature, and fuel cost affect this proportion. Optimum design depends also on the costs of collector, storage, and auxiliaries. In the system tested in the Colorado house, its evaluation could be made without attempting to optimize the design or to collect and store sufficient solar energy for more than a modest portion of the heating load.

It has been concluded that this house-heating system employing solar-heated air can be conveniently used to provide a minor to a major portion of the winter heat requirements of as house. Trouble-free automatic operation can be achieved. The small experimental system in the large Colorado House was successfully operated, providing about one-fourth of the demand, and operating at an average solar collection efficiency of 35 per cent. Improvements are needed and can be anticipated. Due to inadequate data on cost of equipment in large-scale manufacture, the overall economics of the system are yet to be determined.

CONCEPTION ET PERFORMANCES D'UN SYSTÈME DE CHAUFFAGE MÉNAGER QUI FAIT USAGE D'AIR CHAUFFÉ PAR LE SOLEIL : LA MAISON SOLAIRE DU COLORADO

Résumé

La maison solaire expérimentale de Denver est une demeure de vastes proportions dont la surface utilisable est de 2 100 pieds carrés (195 m²) à l'étage principal ou rez-de-chaussée et 1 100 pieds carrés (102 m²) au sous-sol. Le fluide employé pour le transport de la chaleur est l'air, et la roche écrasée sert de matériau de mise en réserve de l'énergie solaire. Deux rangées de collecteurs solaires du type à plaque en verre à recouvrement et montés sur le toit plat à une inclinaison de 45° donnent une surface utile totale de 530 pieds carrés (49 m²). On trouve en outre deux cylindres accumulateurs de chaleur verticaux, dont chacun a trois pieds de diamètre (0,91 m) et 18 pieds de haut (5,5 m) remplis d'une douzaine de tonnes américaines (11 tonnes métriques) d'un gravier de fort calibre. Un four à gaz naturel est prévu dans le système et fournit un appoint de chaleur.

On a pu faire des relevés relatifs au fonctionnement du système au cours des trois derniers hivers, et on a procédé à une analyse détaillée de sa marche quotidienne du 18 septembre 1959 au 10 juin 1960. On a pu établir que, pendant cette période, l'apport total de chaleur à la surface utile du collecteur a été de 226,9 millions de btu (57 000 000 cal), dont 161,3 millions (40 500 000 cal) d'une intensité suffisante pour justifier leur récupération. La quantité de chaleur solaire utile récupérée a été de 55,7 millions de btu (14 000 000 cal), dont 3,95 millions (991 000 cal) par le réchauffeur d'eau. La quantité de chaleur solaire absorbée par le matériau de mise en réserve a été de l'ordre de 25,5 millions de btu (6 400 000 cal). Le rendement moyen de la récupération d'énergie solaire pendant la période de fonctionnement (qui comporte le cycle d'accumulation et le cycle de chauffage) pour la totalité de la saison a donc été d'environ 34,6 p. 100.

La quantité de gaz consommée par le chauffage pendant la même période a été de 264 200 pieds cubes (7 481 m³) dont 230 200 pieds cubes (6 519 m³) pour le chauffage des locaux et 33 000 pieds cubes (943 m³) pour le chauffage de l'eau. L'apport net de chaleur attribuable à ce combustible a été de 141,8 millions de btu (35 592 000 cal). La consommation d'électricité par le système, y compris la soufflante, les moteurs des volets de réglage du tirage et les instruments a été de 3 876 kWh.

Le mémoire donne des renseignements sur l'apport d'énergie solaire, la chaleur récupérée, le rendement moyen de cette récupération, la quantité de chaleur solaire mise en réserve, les rendements inférieur et supérieur de ce processus de mise en réserve, la quantité de chaleur solaire extraite par le réchauffeur d'eau, le pourcentage de la chaleur solaire utile récupérée qui est absorbé par le réchauffeur d'eau, le pourcentage de la charge imposée par le chauffage de l'eau couvert par l'énergie solaire et le pourcentage de la charge totale de chauffage qu'apporte l'énergie solaire pendant la saison. On a observé que l'énergie solaire a couvert 25,7 p. 100 des besoins de chaleur de la maison pendant l'hiver 1959-1960.

On a réalisé plusieurs améliorations de construction et d'exploitation du système pendant la saison si bien qu'il a été procédé à des analyses individuelles du fonctionnement de ce système pour chaque période où les données recueillies étaient compatibles. Du 18 septembre au 17 novembre 1959, le débit d'air, pendant le cycle d'accumulation, a été de 495 scfm (14 m³). Du 18 novembre au 15 décembre il a été porté à 735 scfm (21 m³), puis, du 16 décembre au 10 juin 1960, on est passé au maximum de 770 scfm (22 m³). Après le 10 juin on a procédé à l'exploitation du système solaire dans des conditions correspondant à celles de l'été.

Les défauts de construction et les erreurs d'exploitation du système, qui ont donné lieu à certaines mesures de correction, comportaient de trop grosses fuites d'air vers l'intérieur et l'extérieur des conduits, l'absence d'une dérivation d'air autour du système d'accumulation de chaleur entrant en jeu quand il est vide, une perte de précision du système de

commande pendant les périodes où il y a de la neige sur le collecteur, l'apparition de certaines ombres légères sur les deux rangées de collecteurs, une résistance au frottement indue dans le système d'accumulation et parfois un fonctionnement défectueux des dispositifs de réglage du tirage. Du côté favorable, une fois le système parfaitement disposé pour la marche normale, il a fourni un chauffage suffisant à la maison chaque fois qu'il le fallait, sans jamais avoir besoin de surveillance ou d'entretien.

Même dans des conditions non idéales, le système a permis de réaliser des économies de combustible d'environ 80 dollars pendant la saison où il faut chauffer. Cette économie a été compensée en partie par une augmentation de 60 dollars de la consommation d'électricité. Avec de légères modifications du système, les besoins en électricité peuvent être ramenés à 10 ou 15 dollars de plus qu'avec les systèmes classiques, et les économies de combustible portées à environ 100 dollars, donnant une économie nette de l'ordre de 90 dollars pour une saison type. Des chiffres comparables pour le chauffage au mazout, avec et sans apport de soleil, donnent des économies saisonnières nettes prévues de 130 dollars. Les frais de premier établissement et ceux qui sont imputables aux dispositifs de réglage du tirage ne sont pas pris en considération dans ces évaluations. Les modifications principales qu'il faut pour augmenter l'économie sont constituées par la réduction des fuites d'air, le doublage de la section des conduits et la réduction de moitié de la hauteur du système d'accumulation, le tout complété par l'installation d'un conduit de dérivation qui met l'accumulateur hors-circuit quand il ne contient pas de chaleur. Si on utilise, pour le collecteur, un verre à faible réflectivité, on peut réaliser des économies de combustible beaucoup plus fortes. La consommation de combustible pour le chauffage de l'eau en été pourra être réduite d'une façon sensible par d'autres modifications légères dans la construction du système.

L'importance des économies de combustible ou la fraction de la charge totale couverte par l'énergie solaire dans ce système expérimental de chauffage des locaux n'est pas, en elle-même, une mesure de la valeur de la conception du dispositif ou de ses éléments solaires. Certains facteurs tels que la surface du collecteur, la charge de chauffage de la maison, le rayonnement solaire, la température ambiante et les prix du combustible viennent modifier cette proportion. La conception idéale est également conditionnée par les frais de réalisation du collecteur, ceux qui sont imputables au système d'emmagasinage ou d'accumulation et ceux des auxiliaires. Dans les systèmes mis à l'essai pour la maison du Colorado, l'évaluation a pu se faire sans tenter d'améliorer la construction du système au maximum ou de récupérer et d'accumuler des quantités d'énergie solaire suffisant à couvrir davantage qu'une proportion modique de la charge qu'impose le chauffage.

On a conclu que ce système de chauffage de la maison faisant usage d'air chauffé par le soleil peut être utilisé commodément pour fournir une faible ou une forte proportion des besoins du chauffage d'une maison pour l'hiver. On peut réaliser le fonctionnement automatique sans difficultés. Le petit système expérimental de la grande maison du Colorado a été utilisé avec succès, couvrant environ un quart de la demande et fonctionnant avec un rendement de récupération solaire moyen de 35 p. 100. Des améliorations s'imposent, et se produiront certainement. Étant donné l'insuffisance des données relatives au prix du matériel dans le cas d'une production à grande échelle, l'économie d'ensemble du système reste encore à déterminer.

DESIGN CRITERIA OF SOLAR HEATED HOUSES

Aladar Olgyay *

Architectural considerations of solar radiation are important in both positive and negative aspect. We need houses or shelters mainly to counterbalance extreme climatic conditions which exceed comfort limits tolerable to man. Technical methods in the building field, which use natural forces directly to fulfill this task, can be divided into two categories:

1. A "climate balanced" building is designed according to the climatic environment. The combined effects of temperature, radiation, humidity and winds on human reaction can be evaluated with bioclimatic charts, and desirable comfort conditions can be defined. (1) In a specific climate region, the year can be divided into underheated and overheated periods, when heating or cooling are required to secure comfort conditions. This categorization will show the desirability for using solar radiation or the need of shading.

With proper planning, the factors of orientation, layout, form of buildings, distribution of openings, shading, insulation and time-lag characteristics of materials, and interior comfort conditions can be extended throughout the year with purely architectural means. (2) The "climate balanced" building design is very important in utilizing or counteracting solar radiation in housing. It is especially important in countries where mechanical means of heating or cooling are economically prohibitive.

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Solar energy can be used directly through heat-transfer devices to heat or cool houses. This theme is the topic of the present paper.

Please note that the data refer to latitude 40°N on the east coast of the United States.

Solar radiation incidence on buildings

Statistical results of solar radiation on horizontal surfaces are available in Weather Bureau Publications. In buildings, however, differently oriented surfaces — walls and roof — receive various amounts of radiation. Extensive calculations have been made and equations have been developed to estimate the amount of solar radiation received on differently oriented and tilted surfaces. The applications of these calculations to buildings are illustrated for latitude 40° on clear days during summer-winter conditions, as shown in the following table:

Solar radiation on clear days on:	*Winter (Jan. 21)*	*Summer (Jul. 21)*
	Daily amount, btu/sq ft	
Roof (horizontal) . .	747	2 612
South wall.	1 440	777
West wall	386	1 330
North wall	122	450
East wall	386	1 330

As it can be seen, the south side has a favorable relationship with the seasons, receiving the largest amount of heat in the winter time, and relatively

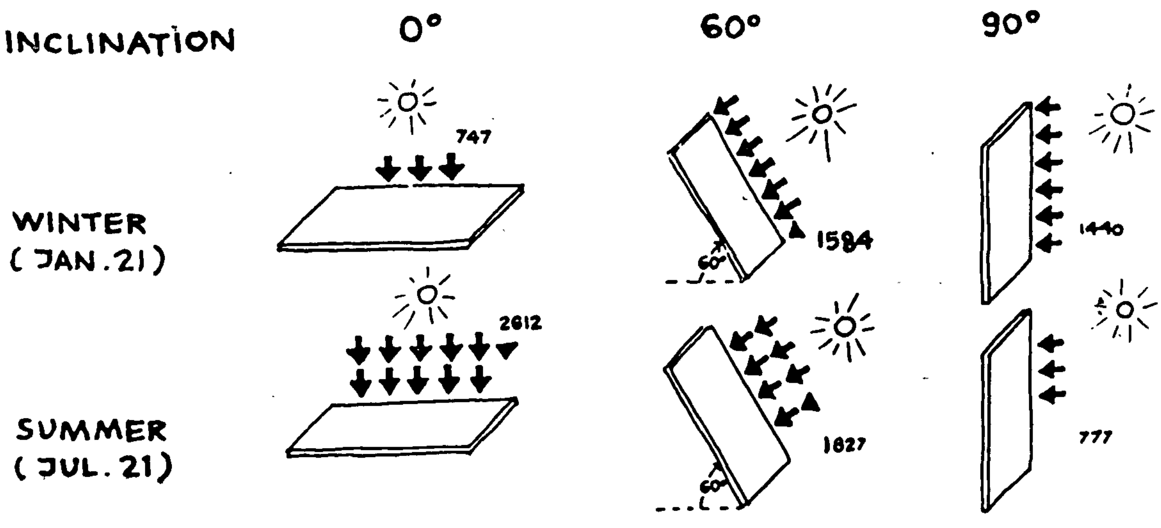

Figure 1

little in summer. East and west are less advantageous, and of the two, west is less desirable, due to high afternoon temperatures, which are coupled with radiation effects in summer. The north side receives relatively small amounts of radiation, while a horizontal surface receives its maximum impact in summertime. It is evident, then, that a heat collector surface should have southern orientation.

Tilting a south-facing surface will change the amount of heat received by radiation, see figure 1 which slows the amount of total radiation for clear-sky conditions on a south-facing surface, with various inclinations, in the New York-New Jersey area. Each arrow represents 250 btu/sq ft/day. A 60-degree tilt will increase the radiation impact in both seasons. But while, in winter, the difference compared with a vertical wall is only 10 per cent, in summer, when collection of heat is undesirable, it increases by 235 per cent. This makes the use of tilted collector surfaces rather questionable, since they are advantageous only if the summer shading of the surfaces is adequately solved. Moreover, such a tilted surface, as far as buildings are concerned, limits freedom in planning.

Heat gain and heat loss budget

It is essential to observe the records of solar radiation and temperature variations in the regions where the solar heated house is built and to derive statistics from these records. The most important problem is the sequence of clear, partly cloudy and cloudy days, during the winter.

To illustrate the use of solar statistics, an analysis of "heat-budgeting" is given.

The required heat storage capacity for solar heating can be predicted by analyzing the net amount of solar energy and comparing it with the heating loss of the house. It is sufficient to prepare an analysis for the coldest months i.e., December and January. During these months, the monthly *average* solar energy should be equal to the *average* heat loss of the house.

Heat collected from the sun, therefore, must equal heat loss from the house. The heat loss of the house is proportional to the degree days (the difference between 65°F and the average daily outdoor temperature). The degree days and the amount of solar energy were obtained from the Weather Bureau's Climatological Data for New York City.

Using established correlations, the amount of solar energy that can be collected on one square foot of a south facing vertical wall was calculated. In accordance with previous experimental results, it was assumed that, of the radiation falling on the collector, 55.5 per cent can be collected on clear days, 35 per cent on partly cloudy days and none on cloudy days. Results for December-January were tabulated and shown in figure 2. The top part of this figure shows the sequences of clear, partly cloudy and cloudy days. The center part shows the net amount of collected solar energy and the heat loss during each day. The bottom line shows the heat balance, the difference between heat loss and heat gain from the sun. At times there was an accumulation of heat equal to 6 or 8 days of heating. The accumulated heat was sufficient to balance heat losses on cloudy days.

The chart (figure 2) illustrates clearly that a heat storage bin capable of storing 5 to 6 days' heating requirements would be quite satisfactory for accumulating surplus heat and equalizing the heating load for that particular season. (3) During this particular time, the longest sequence was three cloudy days. In other months, sequences of 4 or even 5 cloudy days occur sometimes. An analysis of many years shows that a sequence of 7 days is very infrequent in the vicinity of New York.

Solar house heating is essentially a problem of collection and storage of solar heat, and these two elements are discussed in the following paragraphs.

Solar heat collectors

Several research projects have been concerned with solar heat collectors. Air-spaced, glass panes were used to prevent heat loss from a black metal absorber plate. Air or water circulation was used to carry heat from the black plate to a heat storage bin. It has been realized that the use of multiple air-spaced panes can diminish heat losses from the black plate, but increasing number of panes diminish the transmission of solar energy. A collector with two or three glass panes represents the "standard collector" used at the present time.

Heat storage

Heat storage is one of the major problems of solar house heating. Economically acceptable heat storage methods must occupy a small volume of the house, because this volume is rather expensive.

In conventional homes, the heater-room generally does not occupy more than four percent of the total volume of the house. The heating load of a well-insulated average modern house, in the 5 000 degree-day region, may average around 300 000 btu per day during the winter season. Exceptionally cold days may require nearly twice as much heat, but these are rather infrequent in the 5 000 degree-day zone. The presently used materials can be classified into two categories:

Specific-heat type of heat storage

Water and rocks have been suggested as the most available heat storage materials, heat being stored as their specific heat. One cubic foot of water has a heat storage capacity of 62.5 btu/°F, while one cubic foot of solid rock has about 36 btu/°F. Assuming a temperature rise of 30°F, the heat-storage capacity of one cubic foot of water will be 1 880 btu and that of rock 1 080 btu. The above-mentioned average,

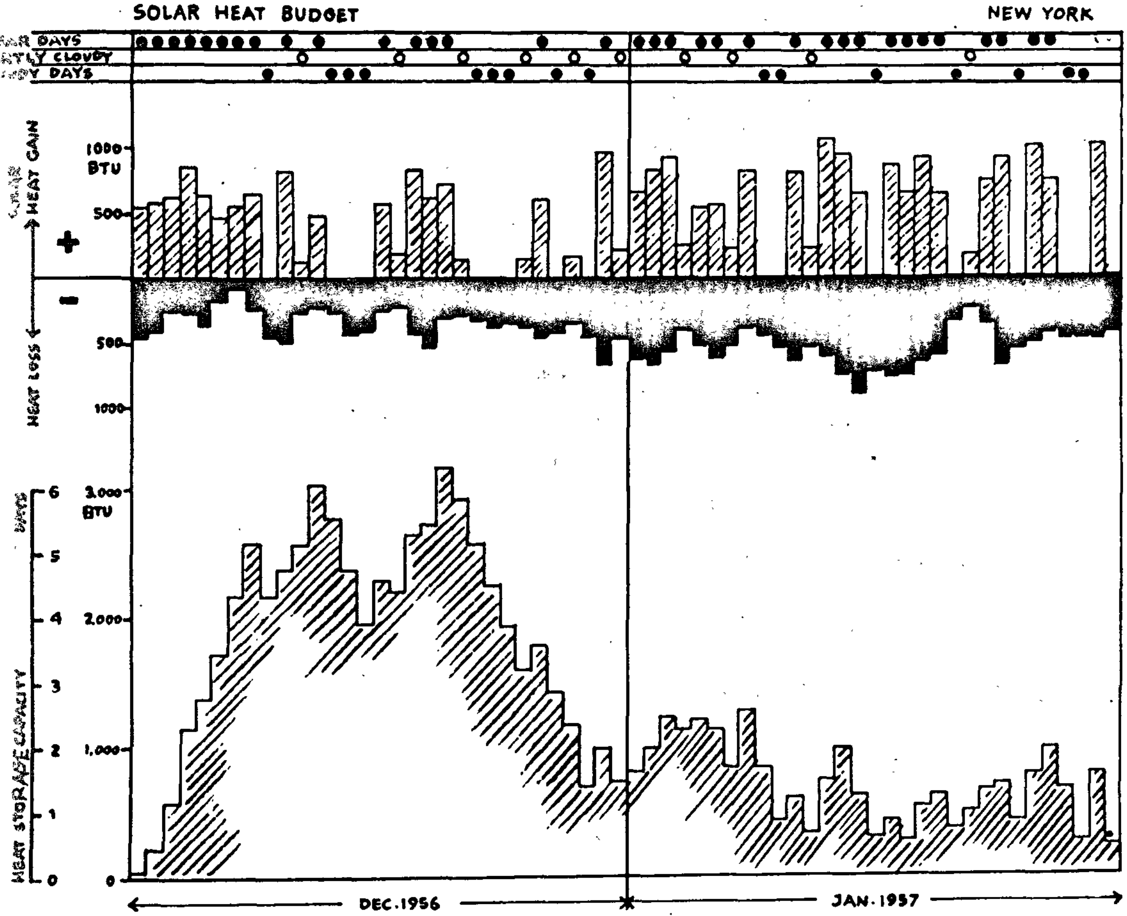

Figure 2. Solar-heat budget for New York, N.Y., during December 1956 and January 1957

300 000 btu day, will require about 160 cubic feet of water (5 tons) and about 280 cubic feet of solid rock (25 tons). It is necessary to provide additional space for the circulation of air or water to deliver solar heat to the storage and to recover the heat when needed. Thus the economically available space in the heater-room may be sufficient for the storage of the heating requirement for about two average days when using water and only for about 1.3 days when using rocks.

Heat-of-fusion type of heat storage

Telkes suggested a more effective method: the use of heat-storage materials which melt at a moderate temperature level and store heat as their heat of fusion, or heat of transition. (4,5) Low cost salt hydrates, which are easily available, can be used for this purpose. Their heat of fusion is around 100 btu/lb; density is 90-100 lb/cubic ft, and therefore one cubic foot of such materials can store 9 000 to 10 000 btu as their heat of fusion at the transition temperature. The specific heat of these materials is comparable to that of water on an equal volume basis and is also available for heat storage. The stored heat can be recovered as the materials crystallize again. The salts are permanently sealed nto durable containers with large surfaces for heat exchange, preferably by the circulation of air. The salts are mixed with additives, to eliminate stratification or settling of solid layers. With a temperature rise of 30°F, the total heat-storage capacity of such materials can be as high as 12 000 btu per cubic foot, i.e., six times greater than that of water and thirteen times greater than that of rocks, on an equal volume basis. With the heat-of-fusion type of materials it is possible, therefore, to store more heat per cubic foot or conversely to use a smaller heat storage volume. The usual heater-room, therefore, should be sufficient to store heat for 10 cloudy days when such salts are used.

Seasonal balance

As the ultimate purpose of a house is to maintain comfort conditions inside throughout the seasons, its thermal balance is of interest not only in winter but also in summer.

A collector, therefore, should be so arranged that it should collect less heat as summertime approaches, and ceases to collect heat during the over-heated period. This can be achieved with properly dimensioned shading devices, which work favorably when applied on southern exposures. (6) Shading can be solved with overhangs, or the same efficiency can be achieved with a small-scaled trellis-like device, which is put up in summertime, as are screens on the windows. The principle of this "dressed-wall" solution on a vertical surface is demonstrated in figure 3. With the use of shading devices, it is possible to exclude most of the solar radiation reaching the south-facing solar collector.

Additional cooling effect during the summer can be obtained by circulating the relatively cool night air through the bin and in this way accumulating "coolness-storage" during the night for use during the daytime. Part of the roof can be used for ducts which reflect solar radiation during the day and provide for additional cooling, by radiation effect, into the night sky. Cooler air circulated through such ducts during the night is cooled further by night sky radiation. Thus a temperature conditioning is achieved with the same equipment, which is similar to the well-known cooling effect of a thick walled building, but far superior to it.

Design considerations

A solar heated house will differ from a conventional one. From the above data, generalizations can be derived for its design. It is obvious that the dimensions stated below will differ in various regions, according to the local ratio of degree days to sunshine hours. Generally speaking, the smaller the ratio, the easier the heating requirement. Recommendations below refer to the New York-New Jersey region with a ratio number between 6 and 7 (while in Arizona this number would be 3-4). At actual planning, detailed calculations should be made. Nevertheless, for preliminary planning, the following recommendations could be followed:

1. For each two square feet floor area of the house, one square foot of collector surface is required. This means, that if a collector is 10 feet high, it will heat a house 20 feet wide. If the house is wider than this, the collector surface should be extended beyond the southern wall of the house.

2. The heat-storage area of the house, in case of chemical bin or bins, will occupy about 4 per cent of the floor area.

3. The heat storage bin can be placed directly behind the collector, provided that it is well-insulated from the collector to prevent the loss of heat from the bin during the night. It is more practical to separate the bin from the collector, connecting them with ducts or pipes for the circulation of air. The bin should be located within the space that is to be heated (and cooled) to avoid unnecessary heat exchange with outside walls or unheated (uncooled) spaces.

4. The insulation of the walls should have a U value of 0.13, or lower. The windows should be double glazed. The ratio of window surfaces to wall surfaces is 1 : 3, or 20 per cent fenestration.

Schematic plans (figure 4) show various types of solar heated houses, where the collector surface is indicated with dots, while the heat storage bins are in black. The plans include 2 and 3 bedroom houses, one or two storied types with vertical collectors.

An experimental solar laboratory has been built at Princeton, N. J., by the Curtiss Wright Corporation

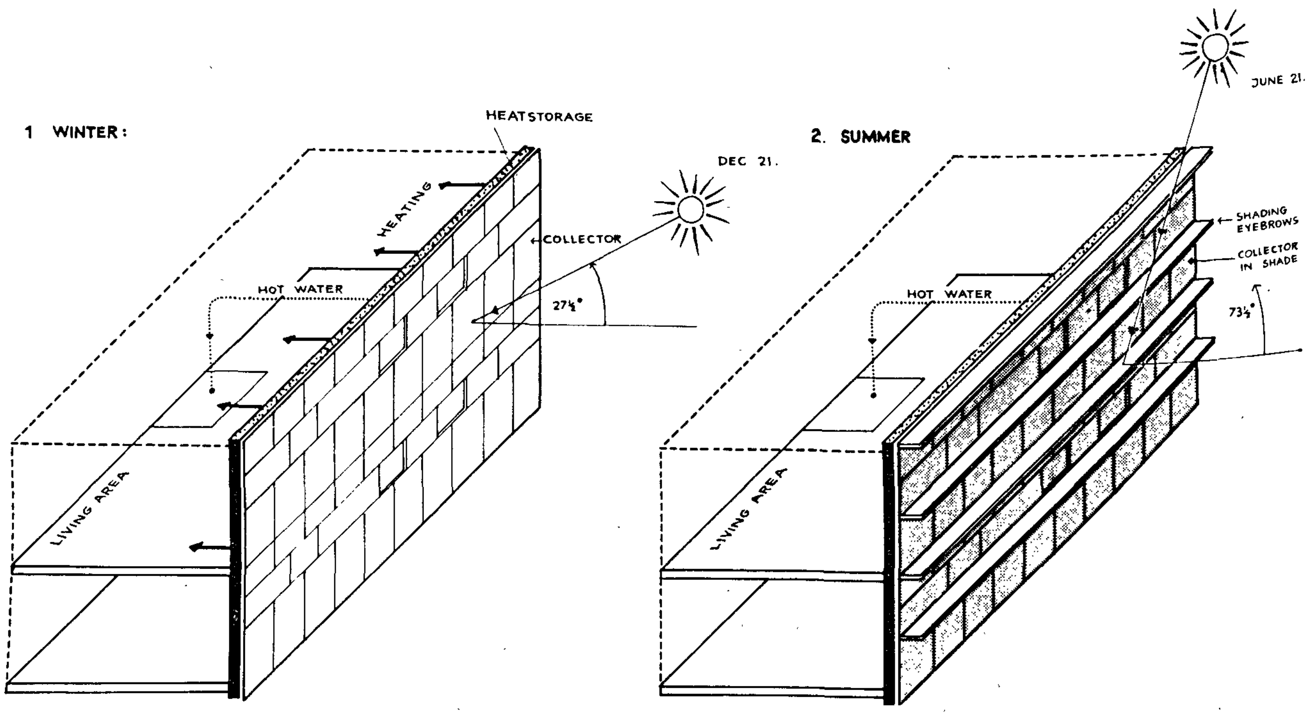

Figure 3. Principle of solar wall

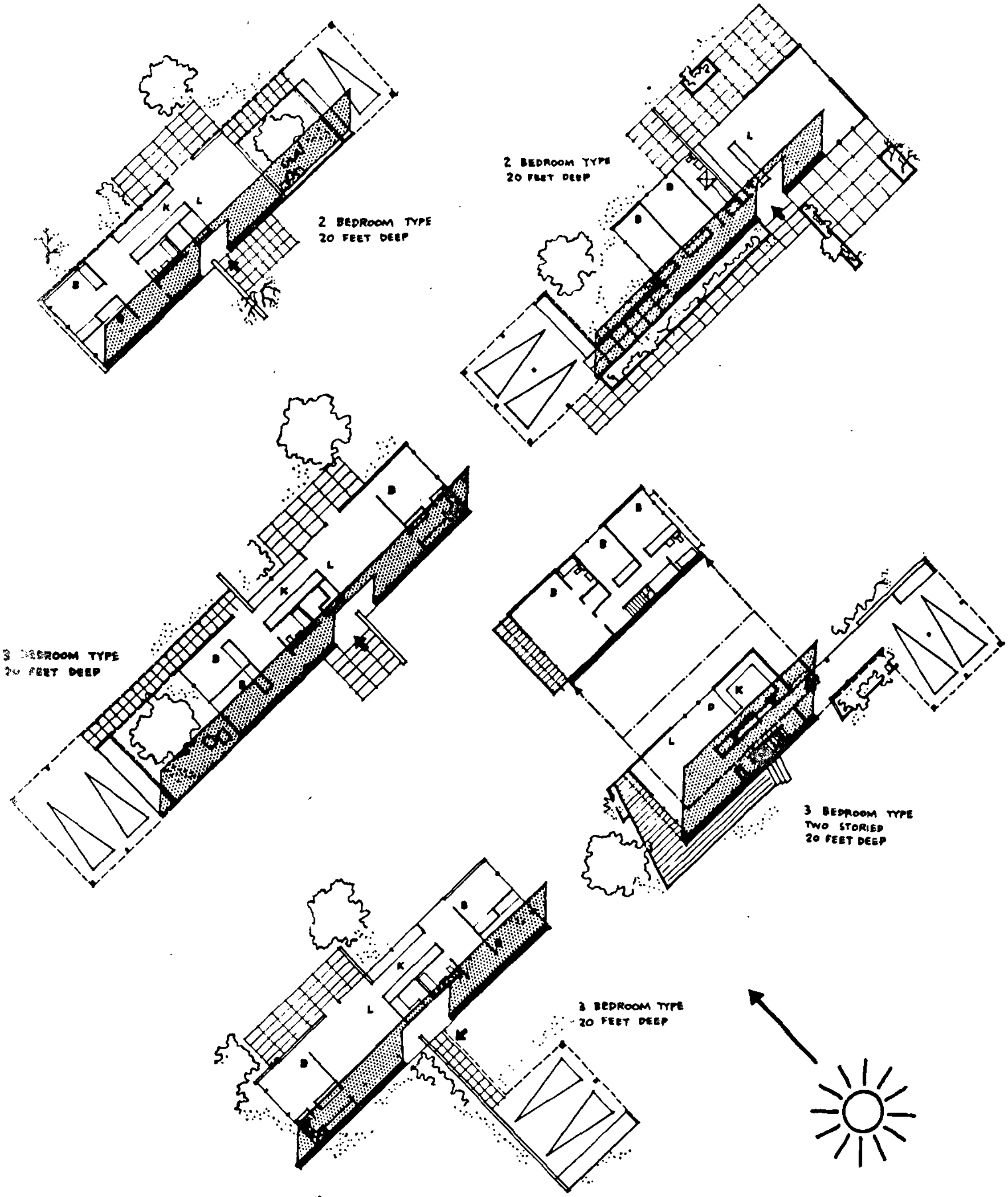

Figure 4

in a group of other solar testing devices. Figure 5 shows the terrace between the laboratory building and the solar pool heater with the pool, solar cookers, dryers and other solar devices. The writer designed the architectural parts of this group, including the laboratory building, which was designed on the basis of the principles described in the previous pages, with the shape and heat-loss characteristics of the house plans shown in figure 4. Due to the experimental character of this building, the solar collectors were designed to be changeable, and therefore no windows were installed on the south side (figure 6). The north side faces the terrace (figure 7), from where a solar water-heater is visible on the roof. This laboratory building was designed to be heated with solar energy alone, and has no other heat source. The building was operated experimentally through two heating seasons and has performed with sufficient success. Auxiliary heating has not been used.

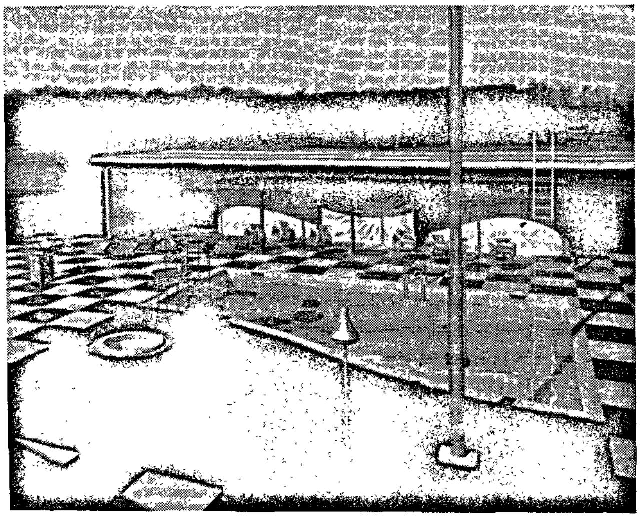

Figure 5. Experimental terrace at the Princeton Solar House

This building has the following features:

Floor area	1 200 sq ft
Roof area (U = 0.082)	1 200 sq ft
Solar collector	600 sq ft
Total wall area (U = 0.13)	650 sq ft
Window and door (U = 0.55)	360 sq ft
Fenestration	29 per cent of the wall area
Design heat loss	600 000 btu/day
Daily heat loss during average December-January	300 000 btu/day

The collector consists of a black surface with insulation behind it forming the south wall of the house. Two air-spaced glass panes are mounted in front of the black surface. Air could be circulated either between the inner glass and the black surface or in a duct behind the black surface. The collector loses heat only from its front surface. Any heat leakage from the back surface is a net gain in the heating of the house. This is a definite advantage as compared to free standing solar collectors or collectors located on the roof over an unheated attic. The estimated heat collection efficiency of the solar

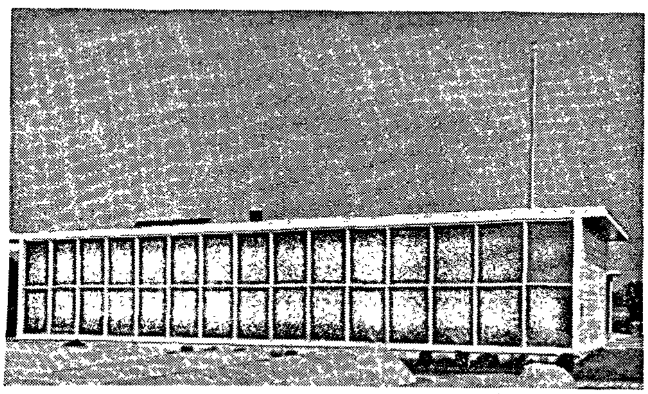

Figure 6. South facing collector-wall of the Princeton Solar House

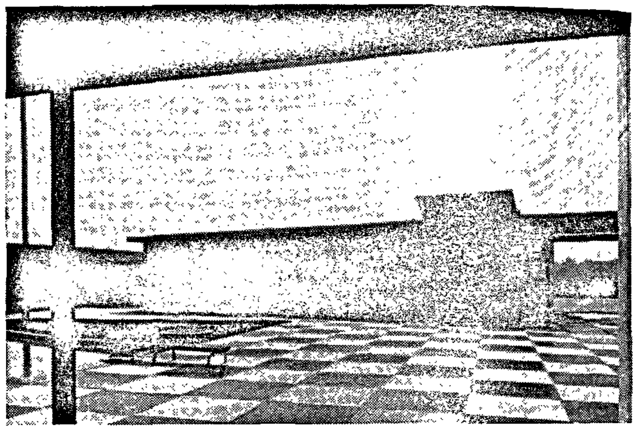

Figure 7. North side of the Princeton Solar House

collector during December-January including all days, was 46.5 per cent, on the basis of the principles described in the previous pages, with the shape and heatloss characteristics of the house plans shown in figure 4.

Heat-of-fusion type heat storage material was sealed into containers and placed into heat bins. The total volume of the heat storage material is 275 cubic feet, representing design heat storage capacity of 2 500 000 btu. The heat transfer area of the containers was variable because different container configurations were tested.

The heat from the collector is transferred to the bin by air circulation, controlled thermostatically. The building is heated by circulating air from the rooms through the bin. Conventional air distributing ducts were used.

Economy of solar heating

The economic aspect of solar-heating feasibility can be expressed by a comparison with the usual heating systems. This comparison must be based not only upon initial installation costs, but also upon operational expenses since the "fuel", so to speak, is "built in" a solar-heated house. Thus, to get the whole picture, the expense of a 20-year operational period is a realistic basis for comparison (7).

Let us consider an average oil-heated house in a 5 000- to 6 000-degree-day zone, with a heating equipment cost of $1 800 and a yearly consumption of 1 300 gal of oil. The yearly operational expenses (at 13.7 cents/gal) will run around $180 per year, or about 10 per cent of the installation cost. Electrical and maintenance costs are supposed to be the same in both types of heating, and are therefore disregarded in this comparison. The present value of future fuel savings ($180/year) based on an interest rate of four and a half per cent in a 20 year period is 20 × 180 × 0.65, or $2 340. Adding to this amount the installation cost of the conventional fuel operated heating system the total amount is $4 140, a sum representing the present-day equivalent of keeping the house heated for 20 years. This amount is 2.3 times larger than the installation cost of the heating equipment.

Thus, a "design criterion" can be established: a solar-heated house will break even, economically, if the installation of the system costs 2.3 times as much as a conventional heating equipment. If it costs less, it will save money.

In this economic comparison, the summer cooling of the system is not even included. In a cost breakdown, the price of the walls, replaced by collectors, should be deducted.

Many estimates of the commercial feasibility of solar house heating conclude that the major task is to design collector units and heat-storage bins as marketable items, tacitly implying that such components could be tacked on to any conventional house design. It is probable that separate solar heating systems cannot be marketed as independent units the same way as conventional furnaces, but the solution is in the building of complete solar heated homes. On the basis of our experience we believe that the solar heating system and the design of the house must be integrated.

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Summary

Solar radiation is of importance in housing in both positive and negative aspect. This energy should be utilized in cool climatic periods and counteracted in hot ones. Houses should be "climate balanced" to ameliorate climate impact comfort conditions. This can be achieved by design methods, using purely architectural means.

A south-facing wall has favorable relationship with the seasons. A vertical solar collector can replace the south-facing wall of a house.

Heating a house with solar energy requires a careful heat budgeting. On Lat. 40°, east coast, U. S., 5-6 days heat storage is needed. In this region for each two square feet floor area of the house, one square foot of collector surface is required.

The heat storage area of the house, using chemical heat storage, will occupy about 4 per cent of the floor area. During hot periods the collector surface, as well as the house itself, should be shaded. Cooling can be obtained by circulating night-air through the bin, which stores coolness for the daytime.

An experimental solar laboratory has been built at Princeton, with the characteristics of a house. This building was heated through two years with solar energy only without any auxiliary heating, and has performed with sufficient success.

A solar heated house will break even economically if the installation of the system costs 2.3 times as much as a conventional heating equipment. It is probable that separate solar heating systems cannot be marketed economically as independent units, but the solution is in the building of complete solar heated homes. On the basis of our experience we believe that the solar heating system and the design of the house must be integrated.

CRITÈRE POUR L'ÉTABLISSEMENT DES PLANS DE MAISONS A CHAUFFAGE SOLAIRE

Résumé

Le rayonnement solaire présente son importance au point de vue des maisons d'habitations, tant par ses aspects positifs, que par ses aspects négatifs. Cette énergie doit être utilisée pendant les périodes où il fait frais, et il faut la neutraliser pendant les chaleurs. Les maisons d'habitation doivent être dotées d'un « climat interne » équilibré pour compenser les répercussions du climat dans le sens du confort. Cela peut se faire par des méthodes qui font appel à des moyens purement architecturaux.

Tout mur orienté vers le sud présente des rapports favorables avec les saisons. Un collecteur vertical

solaire peut remplacer un mur de maison à exposition méridionale.

Le chauffage d'une maison par l'énergie solaire exige une sage « administration » ou « gestion » de la chaleur. Par la latitude de 40° N, sur la côte est des États-Unis, il faut pouvoir mettre la chaleur en réserve pendant 5 ou 6 jours. Dans cette région, il faut un mètre carré de surface de collecteur pour deux mètres carrés de surface de plancher de la maison.

La zone de mise en réserve de la chaleur, dans la maison en cause, avec un dispositif chimique d'accumulation de chaleur, occupera environ 4 p. 100 de la surface des planchers.

Pendant les périodes chaudes, la surface du collecteur, ainsi que la maison elle-même, doit être mise à l'ombre. Le rafraîchissement peut être réalisé en faisant circuler l'air nocturne par le bac d'accumulation, ce qui permet de mettre la fraîcheur en réserve pour la journée.

On a construit un laboratoire solaire expérimental à Princeton, qui a les caractéristiques d'une maison. Ce bâtiment a été chauffé pendant deux ans par l'énergie solaire exclusivement, sans aucun chauffage auxiliaire. Et il a fonctionné dans des conditions de succès satisfaisantes.

Une maison à chauffage solaire pourra couvrir ses frais économiquement si l'installation du système coûte 2,3 fois le prix d'une installation classique. Il est probable que des systèmes de chauffage solaire indépendants ne sauraient être vendus économiquement, mais la solution réside dans la construction de maisons complètes à chauffage solaire. Sur la base de notre expérience, nous estimons que le système de chauffage solaire et la construction même de la maison doivent être intégrés.

A SWEDISH SOLAR-HEATED HOUSE AT CAPRI

*Gunnar Pleijel * and Bert Lindström ***

In 1960, the Swedish Royal Academy of Science erected a building for the Swedish Astrophysical Station on the Isle of Capri, Italy. When working out the plans for the building, the director of the Station, Professor Yngve Öhman, invited one of us, Pleijel, to design the building as a solar heated house and calculate the availability of solar radiation. Co-operation was established with a contractor firm, Bygg-Oleba, and a heating and ventilation firm, Installatör, Ltd., both in Stockholm. The technical staff of the latter worked out the details of the solar heating system. On Capri, the contractor was Mr. Guiseppe Asarita and the heating installation was made by Mr. Mauro-Visone. The work was performed by Professor Öhman.

Later on, there is also to be a solar hot water installation and equipment for cooling the house in summer. These installations are intended for experiments in the utilization of solar energy for space heating and cooling and for hot water supply. Other problems concerning the use of solar energy are also to be investigated at the Station.

The building

The piece of ground on which the new Station was erected is situated in the south-western part of Anacapri (see figure 1). The elevation is 240 meters. The ground has a rather steep slope towards the south-west. To the south-east, there is a very high mountain, Monte Solaro, which has an elevation of 590 meters. The mountain obstructs the sun for one and a half hours in the morning. (See figure 3.)

The main façade of the house, with the solar collectors, faces south-west. (See figure 2). Because of the slope of the terrain, it was impossible to turn it to the south. As the mountain obstructs the sunshine in the morning, the heat radiation lost by this orientation is only 20 per cent. The heat collector has an area of 30 square meters. This seems to be very small compared with the floor area of the house, which is 180 square meters.

The climate

There were no actual meteorological data to be had at Capri and thus no exact calculations of the radiation could be made. In an old book entitled *Il Clima dell'Isola di Capri* there was some information on the temperature, the water vapor content in the air, the precipitation and the number of clear, cloudy and overcast days during the year. Relative time of sunshine was calculated from the patrol hours at the station for the years 1957 and 1958. (See table 1.)

Solar chart

A solar chart in stereographic projection (1,2) was constructed for the latitude 40° N. (the latitude of Anacapri is 40°33'N.) (see figure 3). This chart shows graphically the paths of the sun over the sky. Zenith is the center of the chart and the horizon is the circle at the edge of it. There are seven solar paths for twelve months: one for the winter solstice, one for the summer solstice, and between them five paths each for one day in the spring and one day in the autumn paired together, which are symetrically situated with respect to the solstices, i.e., have the same declination of the sun. The paths lie at similar distances from each other. They are marked in Roman numerals at the curves. The solar paths are intersected by hour-lines, the hour being marked in Arabic numerals at the path for the summer solstice. A scale of solar altitude (h) and zenith angle is laid out from the zenith to the horizon in the north. Around the horizon is set off a scale of azimuth from the north clockwise over east, south, west and back to the north. For every time of the day and every day of the year, it is possible to read off the position of the sun. The chart is drawn up for true solar time. The times of the day must be corrected for the equation of time and the longitude in order to obtain local time.

The solar chart is intended for determining the obstructing effect of the terrain, trees, shrubs and surrounding buildings or other objects. In figure 3, the *screen figure* for the façade facing south-west has been designed and the obstructed parts of the solar tracks can be read off the figure.

Calculation of the radiation

The altitude and azimuth of the sun were calculated according to the astronomical equations:

$$\sin h = \sin d \cdot \sin \varphi - \cos d \cdot \cos \varphi \cdot \cos t \quad (1)$$

$$\sin a \cdot \cos h = \cos d \cdot \sin t \quad (2)$$

where h is the altitude, a is the azimuth, φ is the latitude, d is the declination and t is the hour-angle. (See table 2.)

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** Installatör, Ltd., Stockholm.

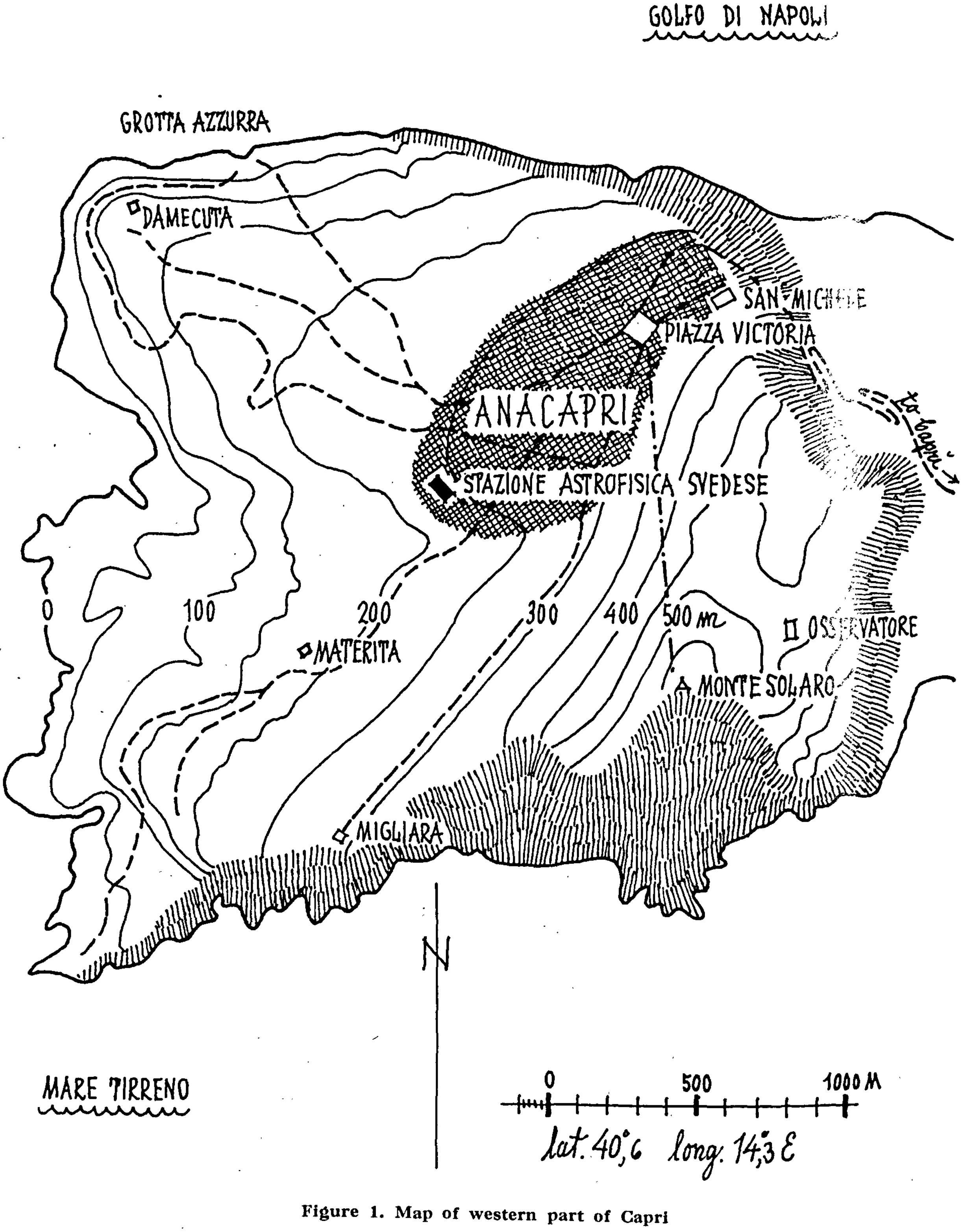

Figure 1. Map of western part of Capri

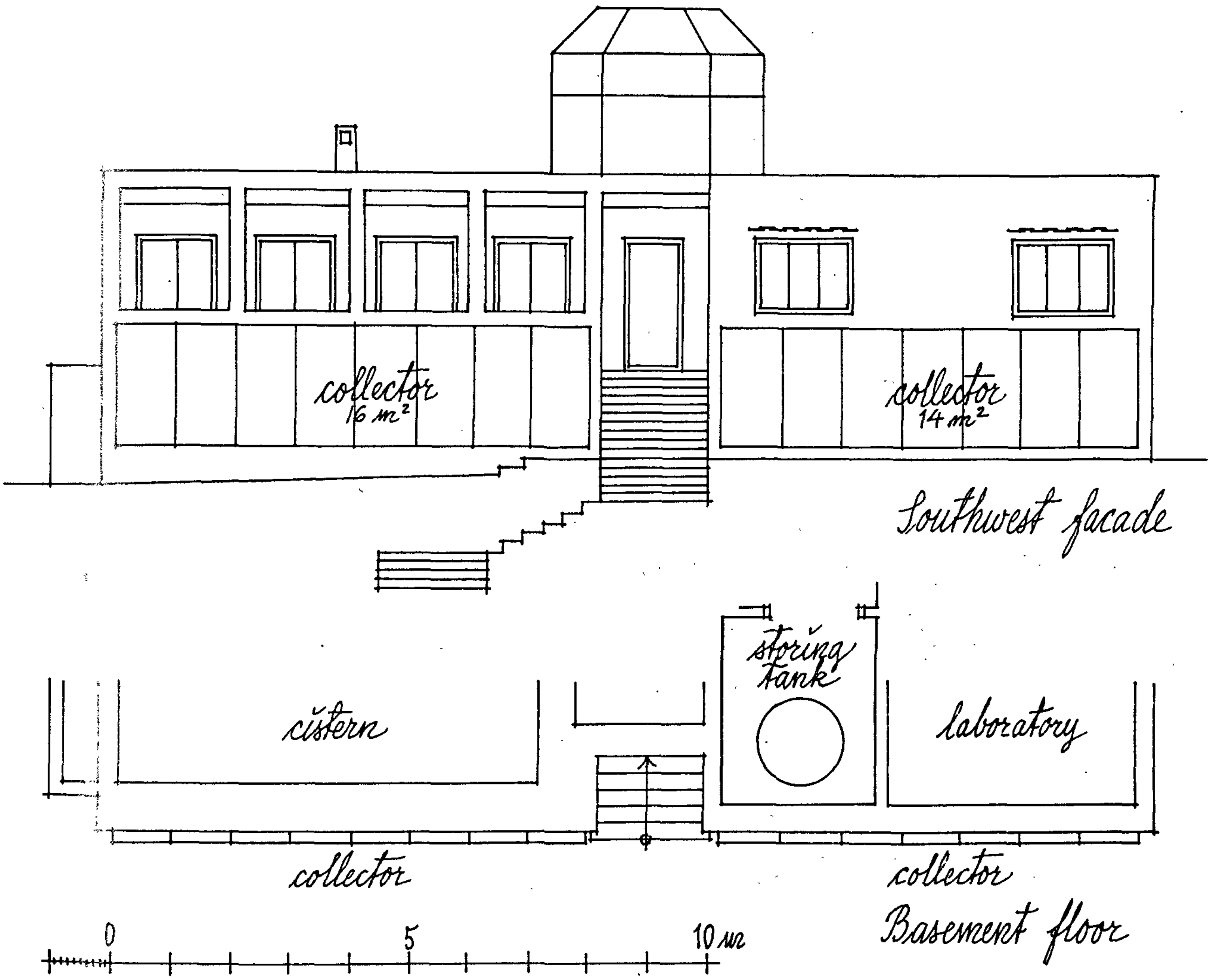

Figure 2. Elevation and part of the basement floor of the station

The calculation of the heat radiation has been carried out according to the "Component method" devised by Pleijel (2). The radiation vector is divided into three components in a convenient perpendicular co-ordinate system with axes x, y and z. For these, the following equations apply:

$$E_x = E_o \cdot \cos h \cdot \cos a \quad [3]$$

$$E_y = E_o \cdot \cos h \cdot \sin a \quad [4]$$

$$E_z = E_o \cdot \sin h \quad [5]$$

where E_o is the radiation perpendicular to the direction of the radiation, E_x is the north-south component, E_y is the east-west component, E_z is the vertical component, and h and a are the altitudes and azimuth of the sun.

A component table was calculated for the latitude 40°N. (see table 3). For the radiation perpendicular to the direction of the radiation (E_o), a curve was interpolated between Lunelund's curve for Helsinki (6) and Moon's curve for 20 mm water vapor content

Table 1. Temperatures at Capri for the years 1890-1911 (3) and the relative time of sunshine according to the patrol hours in 1957 and 1958 (4) (S = maximum duration of sunshine; s = sunshine duration according to patrol hours)

Month	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Temperature, °C												
Mean-maximum	14.1	14.3	16.2	19.0	21.9	26.4	28.8	29.2	26.5	23.3	29.5	15.4
Mean	9.0	8.8	10.5	12.8	16.3	20.0	22.9	23.3	20.9	17.4	13.6	10.2
Mean-minimum	2.2	2.2	4.6	6.9	10.1	13.4	17.0	17.5	10.6	12.0	6.8	5.0
S	217	210	279	330	310	300	310	310	300	279	240	233
s	101	93	143	160	214	241	289	274	240	174	92	100
s/S	0.47	0.44	0.52	0.51	0.69	0.81	0.93	0.88	0.80	0.62	0.36	0.43

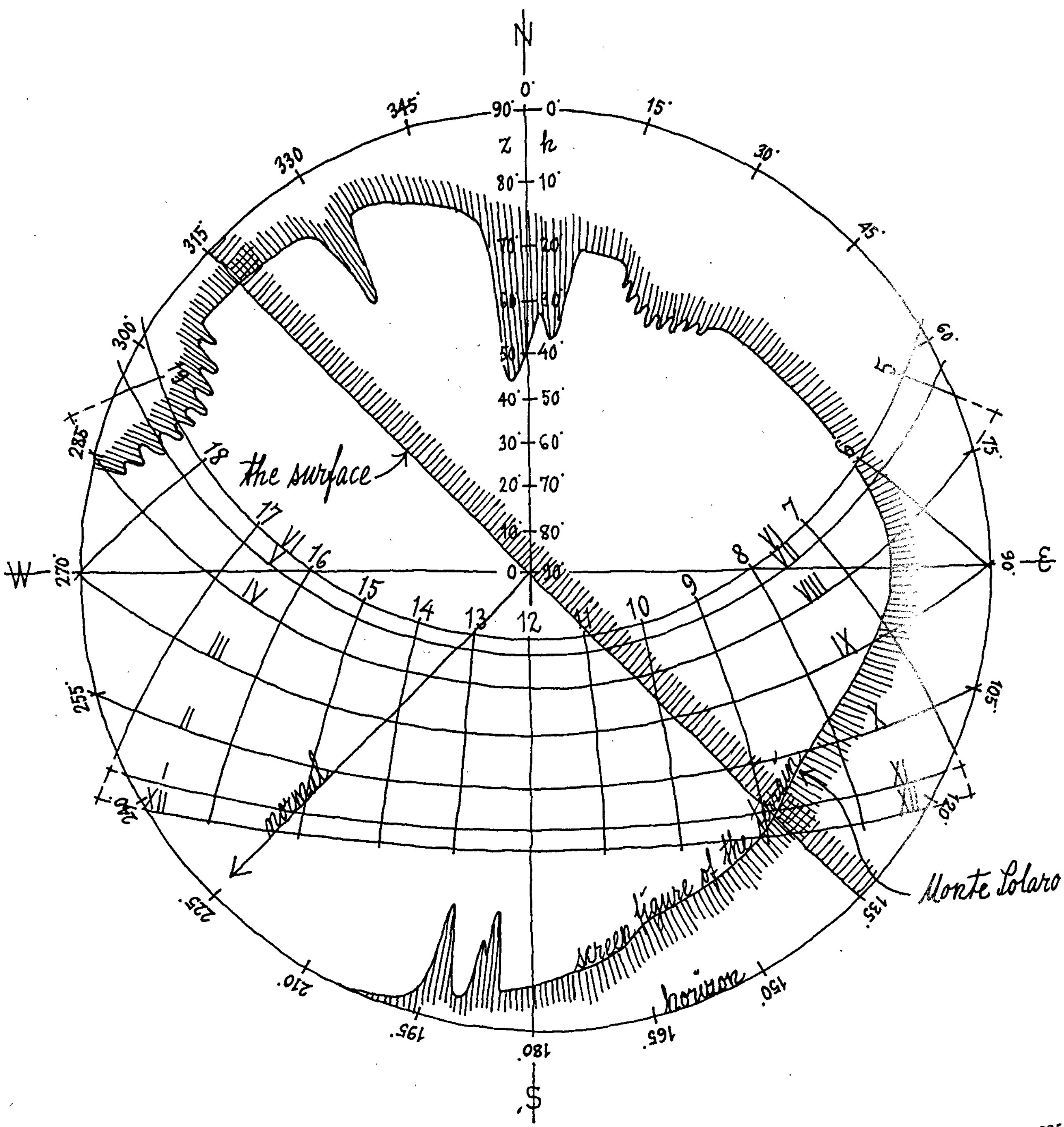

Figure 3. Solar chart for latitude 40°N. with screen figure of the environment and a vertical surface with the azimuth 225° (south-west)

in the air (5). This curve might hold good for Capri where the mean water vapor content for the year is 10 mm. (See figure 4.)

From the component table, the radiation on any surface can be calculated. The following equation applies to this calculation:

$$E_A = E_x \cdot \cos h_A \cdot \cos a_A + E_y \cdot \cos h_A \cdot \sin a_A + E_z \cdot \sin h_A \qquad [6]$$

where E_A is the radiation on the surface A; E_x, E_y and E_z are the components; and h_A and a_A are the altitude and azimuth of the normal to the surface A.

The radiation was calculated for vertical surfaces with azimuths round the horizon at intervals of 15°. Table 4 shows the results of this calculation for a surface with the azimuth 225°, the south-west façade of the house with the solar collectors. In this table, the obstructing effect of the surface it self and the terrain and vegetation has been considered. (See figure 3.)

The reduction of the radiation for the heat loss in double window panes was made for a 3 mm

Table 2. Solar altitudes and azimuths for the latitude 40°N. (h = altitude; a = azimuth (positive during a.m., negative during p.m.); d = declination of the sun)

Date	d		True solar time								
			12	11.13	10.14	9.15	8.14	7.16	6.18	5.19	4.20
21/6	+ 23°.45	h	73°.4	69°.2	59°.8	48°.8	37°.4	26°.0	14°.8	4°.2	
		a	180°.0	138°.1	114°.2	99°.8	88°.6	80°.2	71°.6	62°.7	
21/5	+ 20°.16	h	70°.1	66°.3	57°.6	46°.6	35°.5	24°.1	12°.8	2°.0	
22/7		a	180°.0	119°.1	103°.8	92°.8	83°.2	74°.3	65°.1		
20/4	+ 11°.48	h	61°.5	58°.5	51°.1	41°.2	30°.2	18°.8	7°.4		
23/8		a	180°.0	150°.9	128°.8	112°.9	100°.8	90°.7	81°.2		
20/3	+ 0°.	h	50°.0	47°.7	41°.6	32°.8	22°.5	11°.4	0°.0		
23/9		a	180°.0	157°.4	138°.1	122°.7	110°.4	99°.8	90°.0		
19/2	— 11°.48	h	38°.2	36°.7	31°.5	23°.8	14°.3	3°.8			
23/10.		a	180°.0	161°.6	144°.9	130°.8	118°.9	108°.4			
20/1	— 20°.16	h	29°.8	28°.2	23°.7	16°.7	7°.9				
22/11.		a	180°.0	164°.0	149°.2	136°.1	124°.8				
21/12.	— 23°.45	h	26°.5	25°.0	20°.7	14°.0	5°.5				
		a	180°.0	164°.8	150°.7	138°.1	127°.0				

Belgian glass of low iron content. The transmission curve for that glass is shown in figure 5. The transmitted heat was calculated according to the equations:

$$E_{At} = E_A \cdot \tau_t \qquad [7]$$

$$i = \arccos (E_A/E_o) \qquad [8]$$

where E_A is the radiation on the surface A; τ_t is the transmission factor for the angle of incidence i; E_{At} is the transmitted radiation; and E_o is the radiation perpendicular to the direction of the radiation.

The transmitted heat in the solar collectors was calculated, but the result is not shown here in detail. From table 7, however, the 24-hour totals and the monthly totals can be read.

In order to get the radiation modified for the cloud cover, the solar radiation values for a clear sky were multiplied by the relative time of sunshine s/S. (See tables 1 and 7.)

The radiation from the sky is significant and must therefore also be calculated and added to the solar radiation.

Table 3. Solar radiation components E_x, E_y and E_z for 40°N. latitude (E_y is positive during a.m. and negative during p.m.)

Unit: 1 kcal/m²h.

Date	Component	True solar time								
		12	11.13	10.14	9.15	8.16	7.17	6.18	5.19	4.20
21/6 . . .	E_x	— 223	— 207	— 159	— 86	+ 14	+ 96	+ 149	+ 102	
	E_y	± 0	± 186	± 354	± 488	± 562	± 557	± 450	± 197	
	E_z	+ 751	+ 730	+ 667	+ 566	+ 429	+ 275	+ 125	+ 16	
21/5 . . .	E_x	— 266	— 248	— 201	— 121	— 28	+ 66	+ 120	+ 53	
	E_y	± 0	± 189	± 361	± 495	± 566	± 553	± 426	± 114	
22/7 . . .	E_z	+ 735	+ 713	+ 648	+ 545	+ 405	+ 249	+ 100	+ 4	
20/4 . . .	E_x	— 369	— 351	— 298	— 213	— 102	— 6	+ 50		
	E_y	± 0	± 195	± 371	± 503	± 561	± 520	± 319		
23/8 . . .	E_z	+ 679	+ 657	+ 589	+ 478	+ 333	+ 177	+ 42		
20/3 . . .	E_x	— 485	— 466	— 405	— 309	— 191	— 71	± 0		
	E_y	± 0	± 194	± 364	± 481	± 515	± 412	± 0		
23/9 . . .	E_z	+ 578	+ 554	+ 482	+ 368	+ 228	+ 84	± 0		
19/2 . . .	E_x	— 558	— 536	— 467	— 364	— 225	— 65			
	E_y	± 0	± 179	± 328	± 422	± 409	± 195			
23/10 . .	E_z	+ 444	+ 420	+ 350	+ 245	+ 119	+ 14			
20/1 . . .	E_x	— 572	— 548	— 477	— 358	— 194				
	E_y	± 0	± 157	± 284	± 344	± 279				
22/11 . .	E_z	+ 328	+ 306	+ 243	+ 149	+ 47				
21/12 . .	E_x	— 566	— 542	— 466	— 347	— 161				
	E_y	± 0	± 147	± 262	± 307	± 214				
	E_z	+ 283	+ 262	+ 202	+ 114	+ 26				

Table 4. Radiation from the sun alone on a vertical surface with the orientation 225° (south-west) (Obstructions according to figure 3 have been considered)

Latitude, 40°N. Unit : 1 kcal/m²h. Clear sky.

Date	Time	True solar time								
		12	11.13	10.14	9.15	8.16	7.17	6.18	5.19	4.20
21/6 . . .	a.m.	158	14							
	p.m.		278	362	406	387	326	213		
21/5 . . .	a.m.	188	41							
22/7 . . .	p.m.		309	397	436	420	344	216		
20/4 . . .	a.m.	261	110							
23/8 . . .	p.m.		386	743	507	469	372	191		
20/3 . . .	a.m.	343	193	29						
23/9 . . .	p.m.		467	543	558	499	341	0		
19/2 . . .	a.m.	395	252	98						
23/10. . .	p.m.		506	562	552	448	184			
20/1 . . .	a.m.	404	276	136	10					
22/11 . .	p.m.		498	538	496	334				
21/12 . .	a.m.	400	279	145						
	p.m.		487	515	462	267				

Table 5. Radiation from the sky alone on a horizontal surface without any obstructions

Latitude, 40°N. Unit : 1 kcal/m²h. (k = clear sky, m = cloudy sky.)

Date	Sky	True solar time								
		12	11.13	10.14	9.15	8.16	7.17	6.18	5.19	4.20
21/6 . . .	k	87	85	80	72	62	51	39	19	
	m	201	196	182	158	127	90	53	15	
21/5 . . .	k	85	83	78	70	60	49	36	11	
22/7 . . .	m	197	192	177	153	121	85	46	7	
20/4 . . .	k	81	79	73	65	55	44	26		
23/8 . . .	m	185	179	163	138	105	67	26		
20/3 . . .	k	73	71	66	58	48	34	0		
23/9 . . .	m	161	156	139	113	80	41	0		
19/2 . . .	k	63	61	56	49	38	17			
23/10 . .	m	131	125	109	84	51	13			
20/1 . . .	k	55	54	49	41	28				
22/11 . .	m	103	98	84	61	29				
21/12 . .	k	52	50	46	38	22				
	m	94	88	73	50	20				

Table 6. Radiation from sun and sky on a vertical surface with orientation 225° (south-west) (Obstructions according to figure 3 have been considered).

Latitude, 40°N. Unit : 1 kcal/m²h. Clear sky.

Date	Time	True solar time								
		12	11.13	10.14	9.15	8.16	7.17	6.18	5.19	4.20
21/6 . . .	a.m.	198	53	37	33	28	23	18	9	
	p.m.		317	399	439	415	349	231	9	
21/5 . . .	a.m.	227	79	36	32	28	22	17	5	
22/7 . . .	p.m.		347	433	468	448	366	233	5	
20/4 . . .	a.m.	298	146	34	30	25	20	12		
23/8 . . .	p.m.		422	507	537	494	392	203		
20/3 . . .	a.m.	377	226	59	27	22	16	0		
23/9 . . .	p.m.		500	573	585	521	357	0		
19/2 . . .	a.m.	424	282	125	22	17	8			
23/10 . .	p.m.		534	588	574	465	192			
20/1 . . .	a.m.	429	301	158	29	13				
22/11 . .	p.m.		523	560	515	347				
21/12 . .	a.m.	424	302	166	17	10				
	p.m.		510	536	479	277				

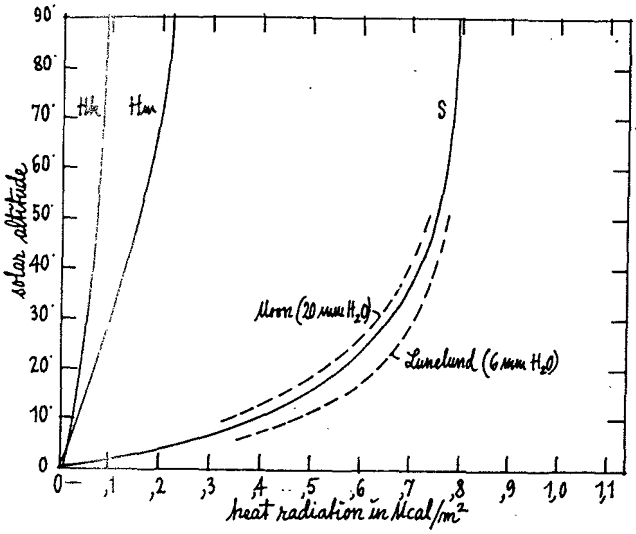

Figure 4. Radiation from the sun perpendicular to the direction of the radiation (S), the radiation from clear sky (Hk) and from cloudy sky (Hm) on a horizontal plane)

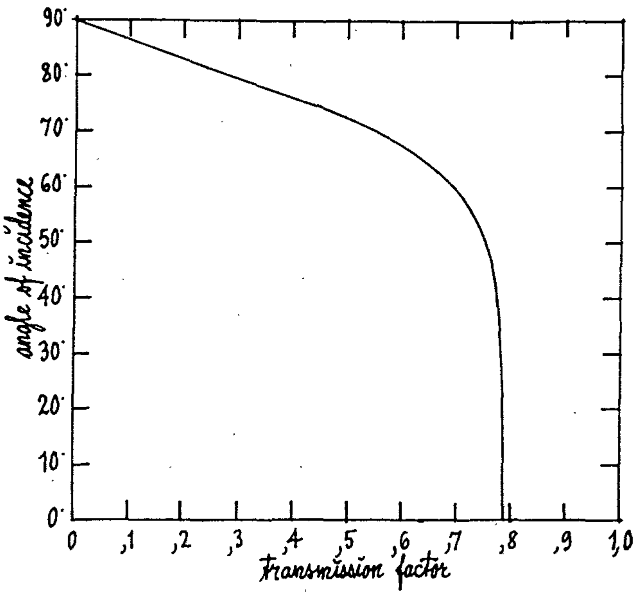

Figure 5. Transmission curve for 3 mm Belgian glass of low iron content

Table 7. Radiation from sun and sky on a vertical surface and through double glass panes with orientation 225° (south-west)

Clear sky and local nebulosity. Latitude, 40°N. Unit : 1 Mcal/m². (S = 24-hour totals from the sun; H = 24-hour totals from the sky; s/S = relative time of sunshine; M = monthly totals from sun and sky.)

Month	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
s/S	0.47	0.44	0.52	0.51	0.69	0.81	0.93	0.88	0.80	0.62	0.36	0.43
Days	31	28	31	30	31	30	31	31	30	31	30	31
On the surface of the collector												
(*a*) With clear sky												
S	2.66	2.96	2.98	2.82	2.42	2.17	2.30	2.70	2.94	3.00	2.76	2.56
H	0.18	0.22	0.28	0.34	0.38	0.41	0.40	0.36	0.30	0.24	0.20	0.18
S + H	2.84	3.18	3.26	3.16	2.80	2.58	2.70	3.06	3.24	3.24	2.96	2.74
M	88	89	101	95	87	77	81	95	97	100	89	85
(*b*) With local nebulosity												
S	1.25	1.30	1.55	1.44	1.67	1.76	2.14	2.38	2.35	1.86	0.99	1.10
H	0.30	0.38	0.52	0.68	0.78	0.84	0.82	0.72	0.58	0.42	0.32	0.26
S + H	1.55	1.68	2.07	2.12	2.45	2.60	2.96	3.10	2.93	2.28	1.31	1.36
M	48	47	64	64	76	78	92	96	88	71	39	42
Through double glass pane												
(*a*) With clear sky												
S	1.98	2.20	2.18	2.00	1.64	1.42	1.54	1.90	2.16	2.20	2.04	1.94
H	0.14	0.16	0.20	0.24	0.26	0.28	0.28	0.24	0.20	0.16	0.14	0.12
S + H	2.12	2.36	2.38	2.24	1.90	1.70	1.82	2.14	2.36	2.36	2.28	2.06
M	66	66	74	67	59	51	56	66	71	73	68	64
(*b*) With local nebulosity												
S	0.93	0.97	1.13	1.02	1.13	1.15	1.43	1.67	1.73	1.36	0.73	0.83
H	0.20	0.27	0.37	0.48	0.55	0.59	0.57	0.50	0.41	0.30	0.22	0.18
S + H	1.13	1.24	1.50	1.50	1.68	1.74	2.00	2.17	2.14	1.66	0.95	1.01
M	35	35	47	45	52	52	62	67	64	52	29	31

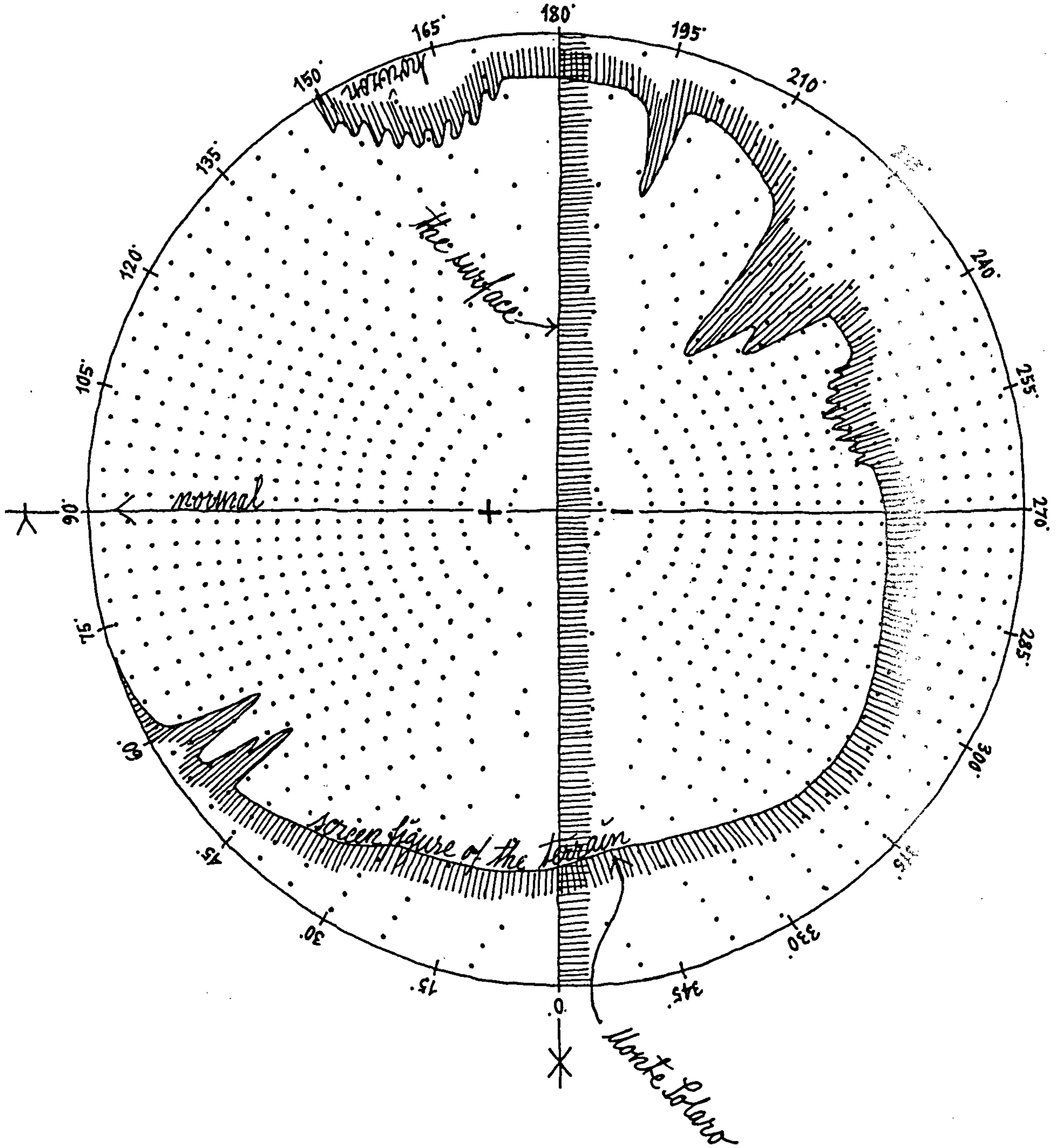

Figure 6. Sky card for the horizontal component D_y of the radiation factor, with the screen figure as in figure 3

First the sky radiation on horizontal plane without obstructions was calculated. This was made both for clear and cloudy sky. Two curves, which are shown in figure 3, were used in combination with the solar altitudes in table 2. (See table 5.)

The sky radiation on any surface can then be calculated with aid of a *radiation factor* which is the relation between the radiation on the surface in question and the horizontal surface without obstructions. The following equation applies:

$$E_A = E_z \cdot D_A \qquad [9]$$

where E_A is the radiation on the surface A; E_z is the radiation on the horizontal surface without obstructions; and D_A is the radiation factor of the surface A.

The radiation factor is divided into two components, one horizontal component, D_y, and one vertical component, D_z. These components are added according to the equation:

$$D_A = D_y \cdot \cos h_A + D_z \cdot \sin a_A \qquad [10]$$

where D_A is the radiation factor for the surface A; D_y and D_z are the components of the radiation

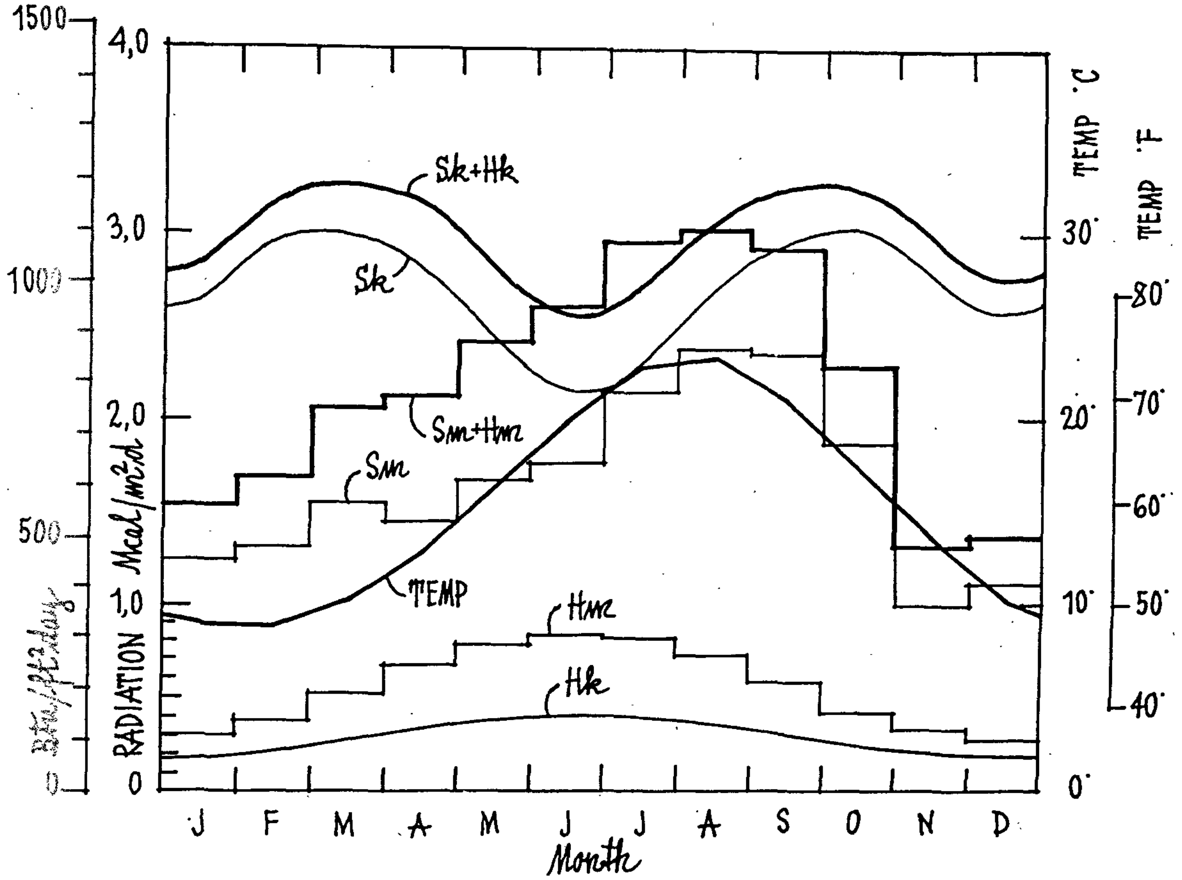

Figure 7. Radiation from sun and sky on a vertical surface with orientation 225° (south-west) during the year

(S = sun, H = sky, k = clear sky, m = cloudy sky, TEMP = Mean temperature for the month)

factor; h_A and a_A are the altitude and azimuth of the normal to the surface A.

For the calculation of D_y and D_z, two radiation cards have been constructed. They give the entire sky in stereographic projection, the same as was used for the solar chart. Zenith is the centre of the cards and the horizon is the circle forming the edge of it. It has been assumed that the radiation is uniform over the entire sky. (See figures 6, 9 and 10.)

The card for D_z contains 1 000 points which are equivalent with respect to the radiation on the horizontal plane. The card for D_y also contains 1 000 points, of which 500 are positive and 500 are negative. These points are equivalent with respect to the radiation on the two sides of a vertical surface,

Table 8. Approximate calculation of the radiation from sun and sky (global) through horizontal, sloping and vertical double glass panes. Orientation 180° (south) and different altitude of the normal to the glass surface (h)

Local nebulosity and obstruction. Latitude 40°N. Unit: 1 kcal/m² day
(The maximum value in every month is in italics.)

	Month	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
s/S		0.47	0.44	0.52	0.51	0.69	0.81	0.93	0.88	0.80	0.62	0.37	0.43
h	90°	941	1 383	2 290	2 984	4 266	*5 025*	5 351	4 421	3 095	1 710	830	711
	75°	1 303	1 693	2 603	*3 124*	*4 270*	4 953	*5 374*	*4 694*	3 596	2 157	1 111	1 001
	60°	1 575	1 911	*2 754*	3 100	4 075	4 616	5 125	4 677	*3 842*	2 473	1 322	1 227
	45°	1 723	*1 982*	2 702	2 856	3 552	3 908	4 455	4 320	3 801	*2 594*	1 431	1 355
	30°	*1 754*	1 925	2 477	2 432	2 823	3 035	3 520	3 674	3 505	2 542	*1 445*	*1 392*
	15°	1 667	1 745	2 044	1 839	1 910	1 919	2 343	2 749	2 916	2 320	1 364	1 340
	0°	1 481	1 454	1 549	1 173	956	884	1 112	1 702	1 194	1 943	1 205	1 198

which is half the horizontal radiation. The cards are used in the following way.

The same *screen figure* that was used for calculation of the solar radiation is also used in this case. It is laid on the D_z card and the number of points falling on free sky are counted. This number divided by 1 000 gives the D_z component. Then the screen figure is moved to the D_y card and turned until the horizontal projection of the normal to the surface coincides with the y axis. The positive and the negative points which fall on free sky are counted, the latter are subtracted from the former and the result divided by 1 000, which gives the D_y-component. The D_z and Dy components are added according to equation [10] and then the radiation factor D_A is obtained.

The radiation factor can be reduced for the loss in the two window panes by multiplying it by the transmission on factor for diffuse radiation, which in this case is 0.70.

For the calculation of the sky radiation on the heat collector, the radiation card for the D_y component has been used. It was not neccessary to use

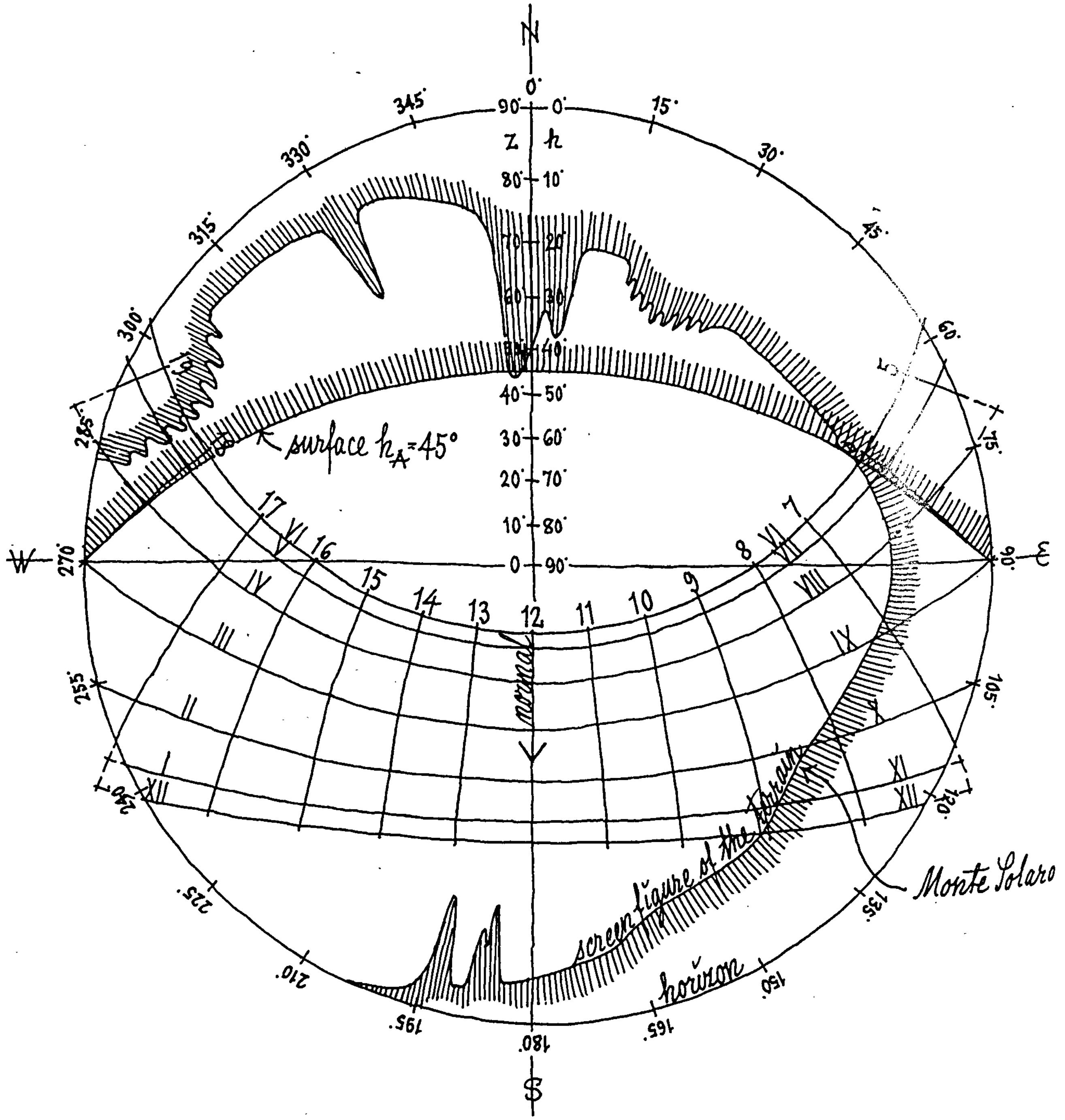

Figure 8. Solar chart for latitude 40°N. with the screen figure of the environment and a sloping surface with the azimuth 180° and the altitude 45° of the normal

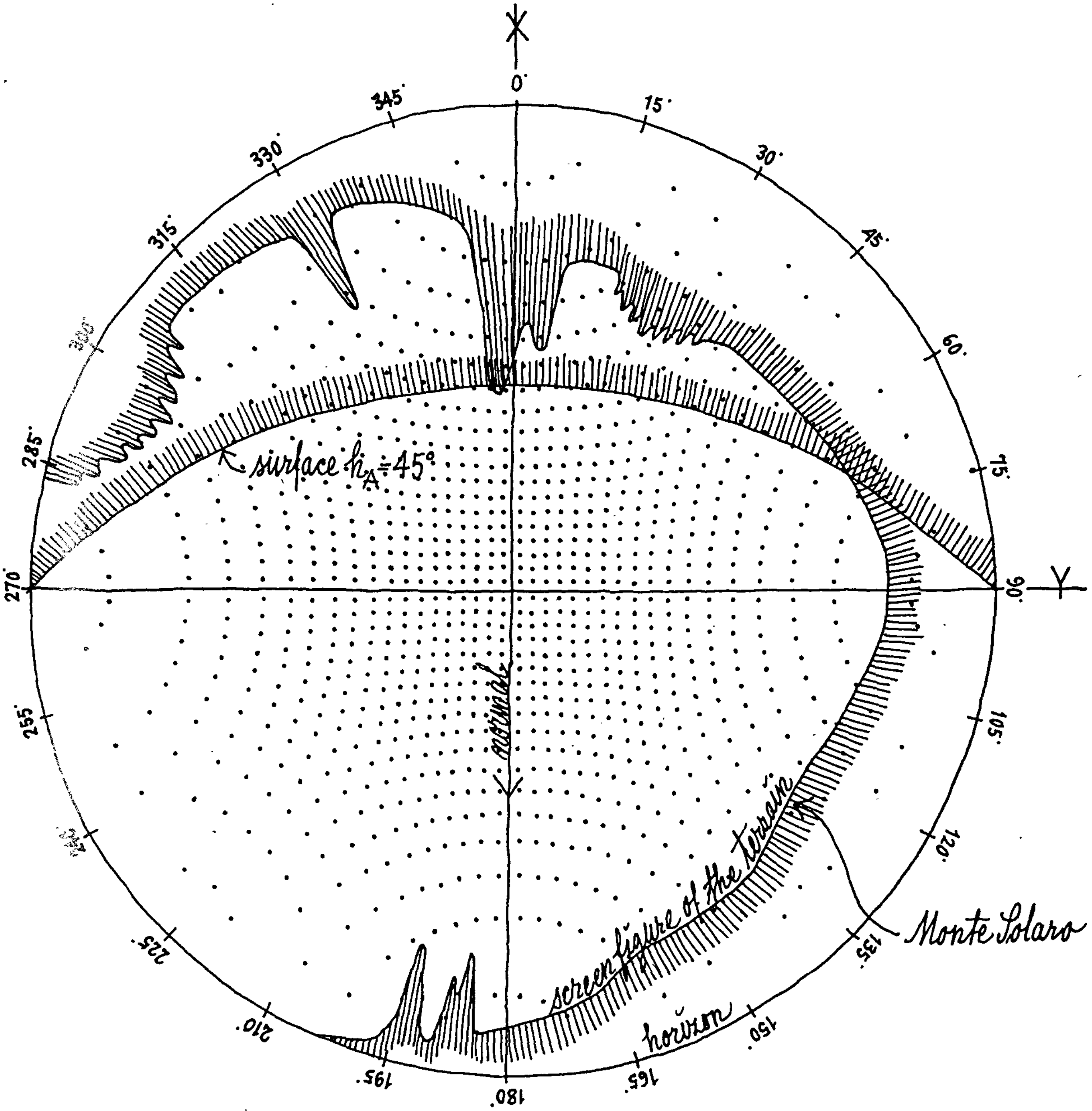

Figure 9. Sky card for the vertical component D_z of the radiation factor with the same screen figure as in figure 8

the D_z card because sin $h_A = 0$. From figure 6, the D_y-component 0.495 can be determined for the surface of the collector. Reduced for the heat loss in the glass panes, it is 0.321. These components are also the radiation factors. Then the radiation from clear and cloudy sky have been calculated according to equation [9]. In table 6, the radiation from clear sky has been added to the radiation from the sun.

Calculations have been carried out for clear sky and local nebulosity and for the collector surface, and also for the transmission through double glass panes. The result is not shown here in detail but table 7 gives 24-hour totals and monthly totals.

The result is also shown graphically in figure 7, in which the temperature curve for the year is also given.

The installation for hot water supply is to be placed on the roof of the house. Then it is possible to let the collector face due south and to give it the slope that provides maximum solar heat during the coldest part of the year (February). Calculation of the heat input was therefore carried out for this collector using the same method as above.

First, an approximate calculation was made to determine the sloping angle that gives maximum radiation during February. The result for vertical and horizontal surfaces and for five sloping surfaces between these is shown in table 8. The maximum values for each month are underlined, and for February the maximum radiation occurs for a slope of 45°.

A more precise calculation was then made for the 45° slope. A new screen figure was designed and it was combined with the solar chart and the sky component cards (see figures 8, 9 and 10). The result of this calculation is shown in tables 9 and 10 and also in figure 11. It can be seen that the solar collector on the roof will get 50 per cent more heat in February than the vertical collector at the façade.

The solar heat collector

The solar heat collector is made of ordinary Swedish radiators for central heating with hot water. They are protected against heat loss by a glass pane and a plastic folium (see figure 12). Behind the radiators there is an insulation of 10 cm mineral wool covered with aluminium foil as a protection against water vapor which can give condensation at the inside of the glass pane. It serves also as reflector of heat from the radiators.

The radiators are painted black on the front side in order to absorb as much as possible of the solar radiation.

The heat balance

As the size of the solar heat collector area was given because of its position on the front of the house,

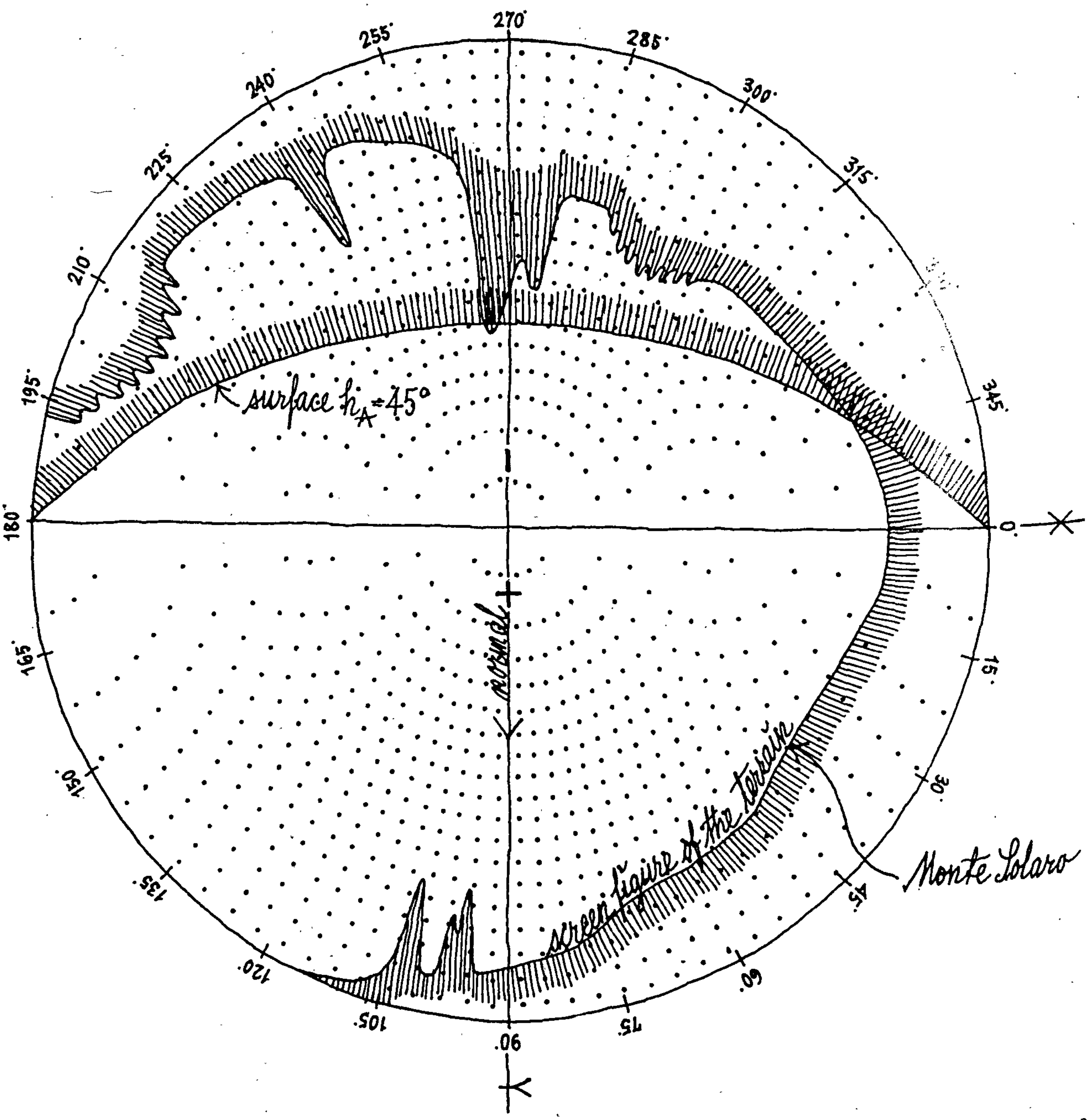

Figure 10. Sky card for the horizontal component D_y of the radiation factor with the same screen figure as in figure 8

Table 9. Radiation from sun and sky on a surface with orientation 180° (south) and the altitude of the normal = 45° (Obstructions according to figure 8 have been considered)

Latitude, 40°N. Unit : 1 kcal/m²h. Clear sky

Date	Time	True solar time 12	11.13	10.14	9.15	8.16	7.17	6.18	5.19	4.20
21/6 . . .	a.m.	757	728	646	517	341	166	30	15	
	p.m.		728	646	517	341	166	30	15	
21/5 . . .	a.m.	774	743	661	525	353	167	28	9	
22/7 . . .	p.m.		743	661	525	353	167	28	9	
20/4 . . .	a.m.	804	774	684	540	350	163	20		
23/8 . . .	p.m.		774	684	540	350	163	20		
20/3 . . .	a.m.	809	777	678	523	333	26	0		
23/9 . . .	p.m.		777	678	523	333	135	0		
19/2 . . .	a.m.	758	723	621	468	30	13			
23/10 . .	p.m.		723	621	468	273	69			
20/1 . . .	a.m.	679	645	547	390	22				
22/11 . .	p.m.		645	547	390	192				
21/12 . .	a.m.		607	509	356	149				
	p.m.		607	509	356	149				

the calculations were only made as a control to see how much of the heat loss from the house could probably be compensated by the solar heating.

The heat loss from the house was calculated on the following basis : room temperature, +17°C; outdoor temperature, the mean value of each month. The total input of solar heat was calculated from values given above. In figure 13, the calculated heat loss is compared with total input at two different efficiencies (η). As can be seen from the diagram, about 50 per cent of the heat loss can be supplied if $\eta = 0.50$ and about 70 per cent if $\eta = 0.75$.

Table 10. Radiation from sun and sky on a sloping surface and through sloping double glass panes with orientation 180° (south) and 45° altitude of the normal to the surface

Clear sky and local nebulosity. Latitude, 40°N. Unit : 1 Mcal/m². (S = 24-hour totals from the sun, H = 24-hour totals from the sky, s/S = relative time of sunshine, M = monthly totals from sun and sky.)

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
s/S	0.47	0.44	0.52	0.51	0.69	0.81	0.93	0.88	0.80	0.62	0.36	0.43
Days	31	28	31	30	31	30	31	31	30	31	30	31
On the surface of the collector												
(a) With clear sky												
S	3.62	4.28	5.00	5.26	5.12	4.96	5.06	5.24	5.16	4.50	3.86	3.26
H	0.30	0.38	0.46	0.58	0.66	0.70	0.68	0.60	0.50	0.40	0.32	0.28
S + H.	3.92	4.66	5.46	5.84	5.78	5.66	5.74	5.84	5.66	4.90	4.18	3.54
M	122	130	169	175	179	170	178	181	170	152	125	110
(b) With local nebulosity												
S	1.70	1.88	2.60	2.68	3.53	4.01	4.71	4.61	4.13	2.79	1.43	1.40
H	0.49	0.67	0.91	1.15	1.34	1.42	1.38	1.23	0.98	0.73	0.53	0.44
S + H.	2.19	2.55	3.51	3.83	4.87	5.43	6.09	5.84	5.11	3.52	1.96	1.84
M	68	71	109	115	151	163	189	181	153	109	59	57
Through double glass panes												
(a) With clear sky												
S	2.84	3.34	3.84	3.98	3.80	3,62	3.72	3.94	3,94	3.48	3.00	2.52
H	0.22	0.26	0.34	0.40	0.46	0.48	0.48	0.42	0.36	0.28	0.23	0.20
S + H.	3.06	3.60	4.18	4.38	4.26	4.10	4.20	4.36	4.30	3.76	3.23	2.72
M	95	101	130	131	132	123	130	135	129	117	97	84
(b) With local nebulosity												
S	1.33	1.47	2.00	2.03	2.62	2.93	3.46	3.47	3.15	2.16	1.11	1.08
H	0.34	0.46	0.63	0.81	0.94	0.99	0.96	0.86	0.70	0.52	0.37	0.31
S + H.	1.67	1.93	2.63	2.84	3.56	3.92	4.42	4.33	3.85	2.68	1.48	1.39
M	52	54	82	85	110	118	137	134	116	83	44	43

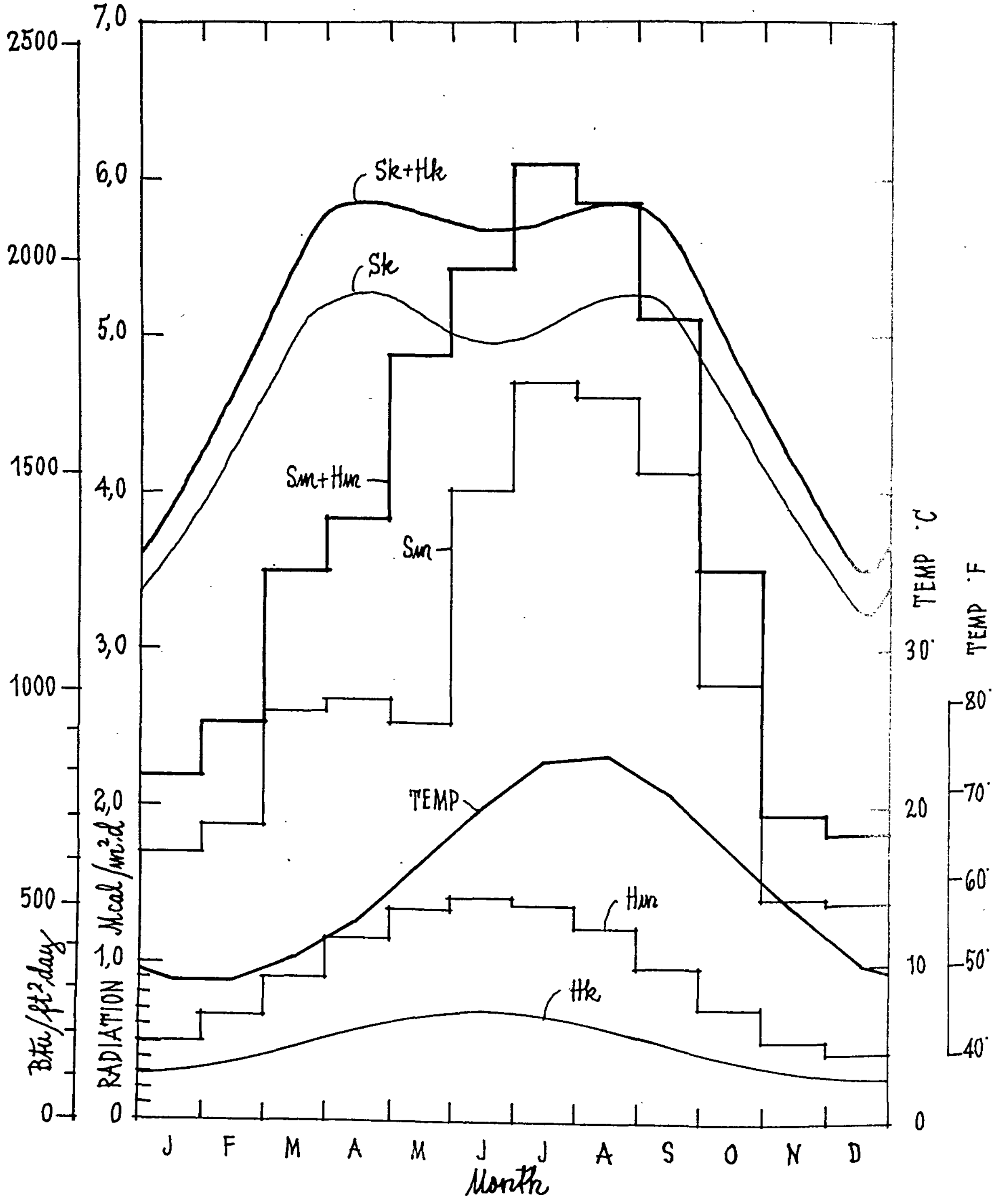

Figure 11. Radiation from sun and sky during the year on a sloping surface with the azimuth 180° and the altitude 45° of the normal

(S = sun, H = sky, k = clear sky, m = cloudy sky, TEMP = mean temperature for the month)

During the period December-March, auxiliary heating is necessary. A stove is installed in the living part of the house and the laboratories have portable electrical radiators as a complement.

The radiators are calculated to operate with water temperatures of 40-35°C, inflow and return, respectively. Temperatures are chosen with regard to operating possibilities even at slight sun radiation and to feeling of pleasantness. A radiator should in fact have such a temperature that one gets a feeling of heat when one touches it.

The final shape of the system

A schematic diagram of the solar heating system is shown in figure 14. The solar energy collector

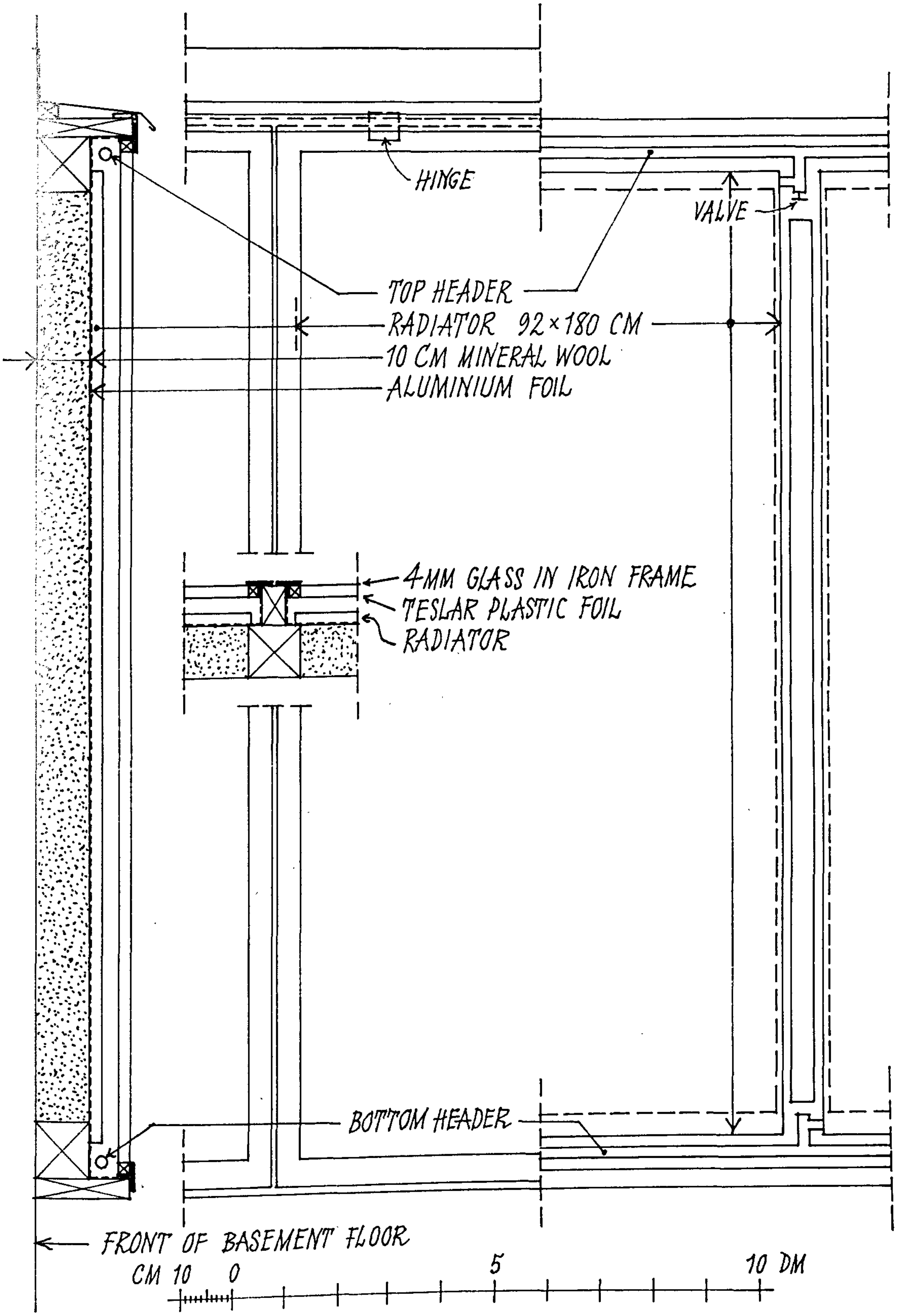

Figure 12. Construction of the collector in the solar heating system

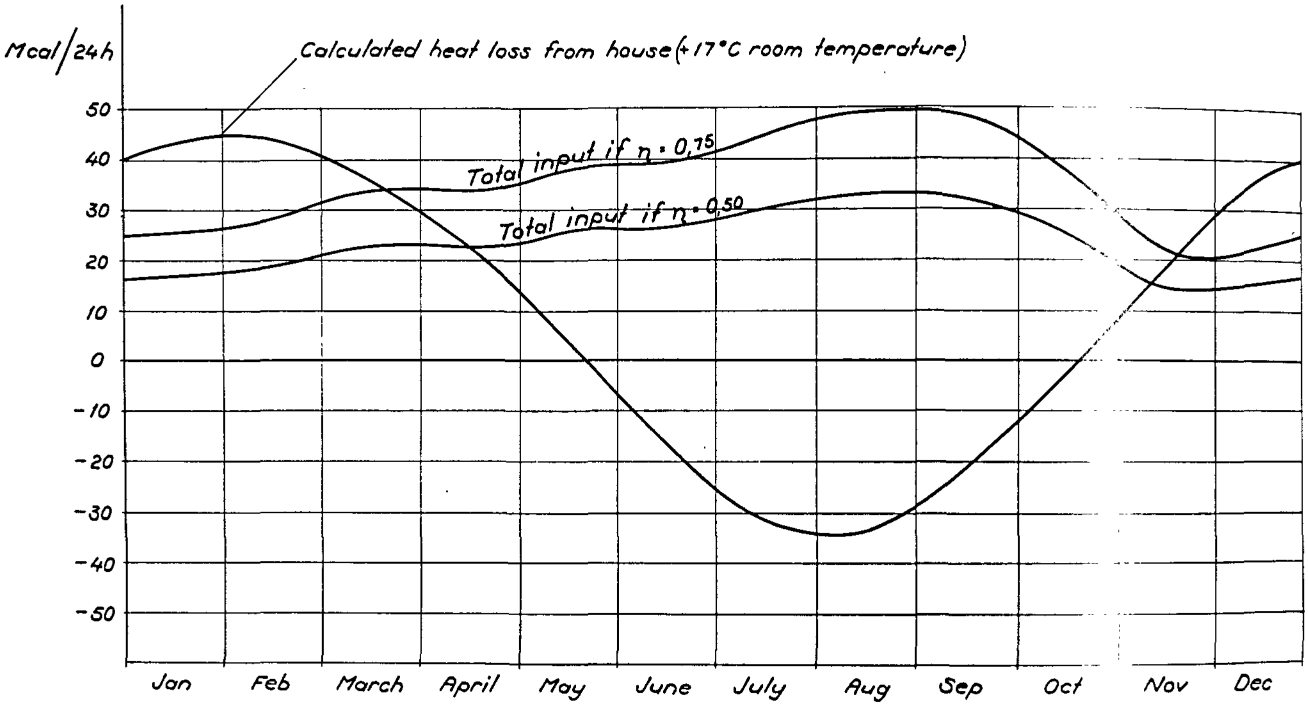

Figure 13. Diagram showing calculated heat loss compared with total input at different efficiencies

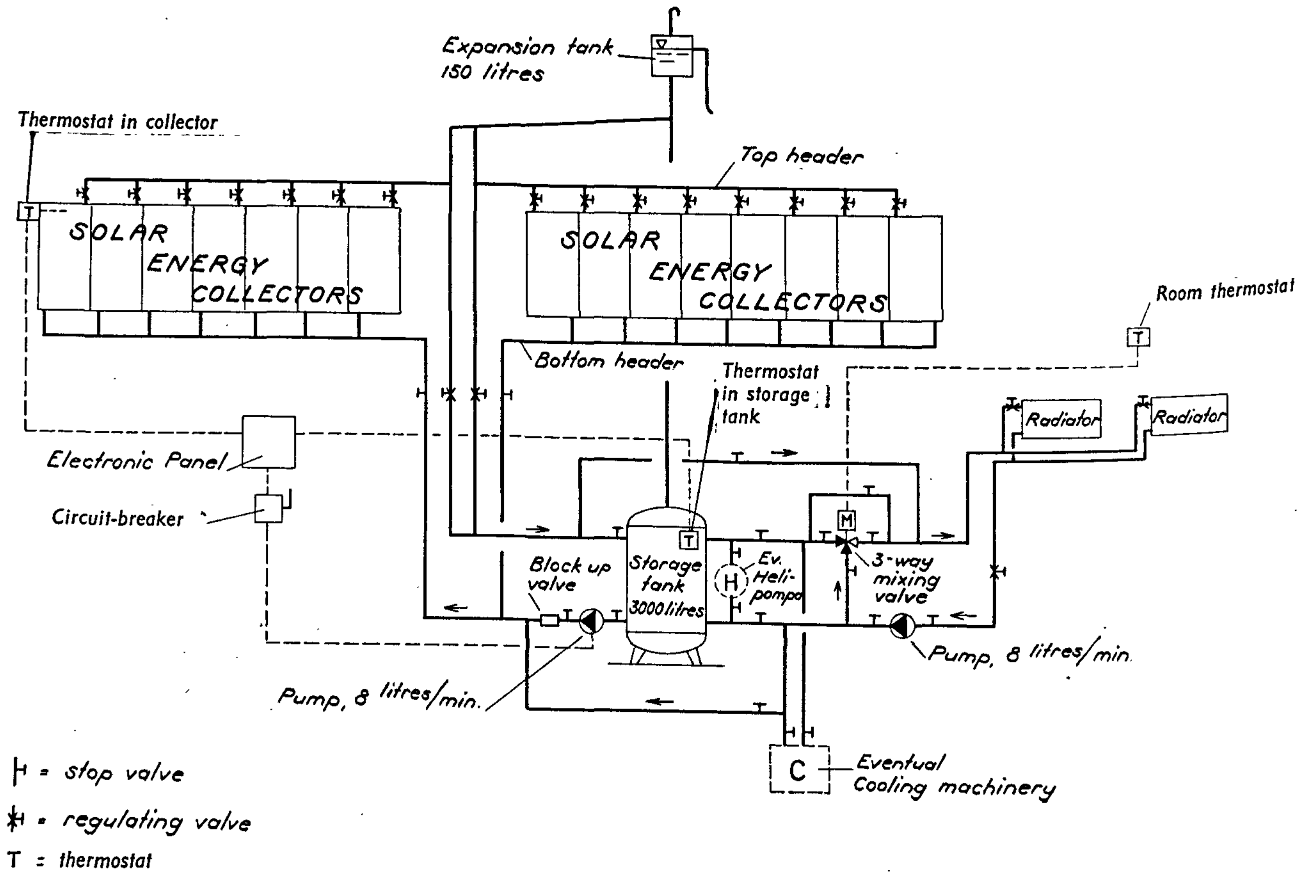

Figure 14. Schematic diagram of the solar heating installation

system and the radiator system are calculated for the same pump capacity. This is of great advantage if one pump should fail. The two systems can be driven by one pump if the storage tank is disconnected. The diagram also shows the connections available for future installations of, for example, cooling machinery In order to get uniform circulation, every part of the collector has a regulating valve.

Some components were bought in Sweden, including, on the one hand, things that could in all probability not be obtained in Italy, and on the other hand, things that, in the designer's opinion, ought to be controlled during manufacturing. Thus the radiators were manufactured in Sweden and pumps, regulating valves, and insulating materials were delivered from Sweden. The automatic regulator equipment was ordered from Sweden by the mechanical designer for delivery through an Italian representative. There was no difficulty at all in fixing the Swedish and the Italian outfits together.

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Summary

In 1960, the Swedish Royal Academy of Science erected a building for the Swedish Astrophysical Station on the Isle of Capri, Italy. This building is provided with a solar space heating system. Later there is also to be a solar hot water system and cooling equipment. These installations are intended for experimental purposes.

The paper describes the climate of the island. Calculations for the heat collector input have been carried out with the aid of a solar chart for latitude 40°N. and two cards for the radiation from the sky. The screening effect of the surroundings has been considered. Tables and diagrams have been made for two collectors, one vertical and facing southwest (for space heating), and one sloping 45° and facing south (for the hot water supply). The heat loss from the building has been calculated and compared with the heat input from the collector. It is probable that 70 per cent of the heat requirement will be provided by the solar space heating system.

LA MAISON A CHAUFFAGE SOLAIRE DE CAPRI

Résumé

Au cours de l'année 1960, l'Académie royale des sciences de Suède a construit un bâtiment pour la station d'astrophysique suédoise à Capri, lequel est doté d'une installation de chauffage solaire pour les locaux de la station. On y ajoutera par la suite un système de chauffe-eau solaire et une installation de climatisation. Tout ceci présente un caractère expérimental.

Le mémoire décrit le climat de l'île. On calcule l'apport de chaleur au collecteur, à l'aide d'une carte solaire pour la latitude 40°N et de deux tables de rayonnement en provenance du ciel. On a pris en considération l'effet réducteur du rayonnement dû au milieu. On a mis au point les tables et les diagrammes applicables à deux collecteurs possibles, l'un vertical et faisant face au sud-ouest (pour le chauffage des locaux), l'autre incliné à 45° et faisant face au sud (pour le chauffe-eau). On a calculé les pertes de chaleur du bâtiment que l'on a comparées à l'apport de chaleur par le collecteur. On estime que 70 p. 100 des besoins de chaleur seront couverts par le système solaire de chauffage des locaux.

SOLAR SPACE HEATING, WATER HEATING, COOLING IN THE THOMASON HOME

Harry E. Thomason *

Two solar heated houses have been constructed near Washington, D.C., by their inventor, Harry E. Thomason. For one complete winter the sun supplied all of the heat required for the first of these houses, except for 31 gallons of oil which cost $4.65. For the second winter this house was heated by solar energy and $6.30 worth of oil despite temperatures as low as 1° below zero F, and snow totalling approximately 40 to 50 inches for the winter. Most of the domestic water is heated by the sun. The house is cooled reasonably well during the summer by water which is chilled by circulating it over the north-sloping roof at night.

It is estimated that approximately 95 per cent of the heat requirements of the house are met by trapping and storing solar energy. The first house cost $13 000 with heating-cooling system costing $2 500. It is estimated that a conventional heating-cooling system would have cost about $1 500. Therefore, the solar system added about $1 000 to the cost of the house. This house has approximately 1 500 square feet of floor space.

The second solar house heating system is more simplified and less expensive. This paper reports results of the author's inventions as applied in his solar heated houses.[1]

General observation

It is ironic that here in the 20th century we should be seeking new *sources* of energy from among the oldest forms of energy known. What could be older than geothermal energy from mother earth herself, or energy from movement of the winds? Only the most powerful, oldest and primary source of all energy, i.e., solar energy, from our brightest star called the sun. The magnitude of this source of energy is so great that it defies comprehension by the human mind. It has been estimated that all known fuels on earth, including nuclear fuels, equal only three days of energy received on earth from the sun.

This tremendous solar power being available, why do we fail to use more of it? In the field of heating houses, cooling houses, heating domestic water and such, proposed systems for using solar energy have been expensive, or complicated, or inefficient, or short lived, or have been usable for one purpose only, or had other drawbacks, such that the value received would not justify the costs of installation, operation and maintenance.

Solar heat collectors

In the Thomason solar system, attempts have been made to solve the problems by attacking them from all sides simultaneously. To this end a simple solar heat collector was invented to trap solar energy. The more common water heating solar heat collector has expensive copper tubing soldered to expensive sheet copper, with expensive brass flow restricting fittings, and uses expensive solder and expensive labor. In cold climates there is the possibility of freezing and bursting of the tubing with resultant expensive repair bills.

In the 840 square foot heat collector on the Thomason solar heated home, the expensive materials referred to above were replaced by simple inexpensive blackened corrugated sheet metal. The corrugations run down the incline. A distributor manifold introduces hundreds of small streams of water into the valleys at the top of the collector and this water flows down the valleys, heated by the solar heated metal as it descends to the bottom of the collector. The small streams at the bottom are gathered into one large stream of hot water and flows to a heat storage bin where domestic water is heated and heat is stored.

The simple collector described is low in cost, approximately $1.00 to $1.25 per square foot, as contrasted with a minimum of $2.50 to $3.00 per square foot for conventional collectors. In mass production the heat collector could probably be produced at approximately $0.75 to $1.00 per square foot and sold at a retail price of $1.25 to $1.50 per square foot. Experts in the field agree that solar heat collectors for space heating cannot be considered economical anywhere in the United States unless they can be produced at less than $1.50 per square foot.[2]

The efficiency of this collector is very high in its normal working range (approximately 40 per cent to 75 per cent in boosting water temperatures in the range of 32°-135°). There are so many factors that affect efficiency that the author can give specific figures only when particular conditions are specified.

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[1] See also "Solar Energy", 4th quarter 1960, and "The Sun At Work", 1st quarter 1960, 4th quarter 1960 and 1st quarter 1961, these four publications from the Association For Applied Solar Energy, Arizona State University, Tempe, Arizona.

[2] See article by Mr. Edward Speyer, "Solar Energy", journal for December 1959, published by AFASE, Tempe, Arizona.

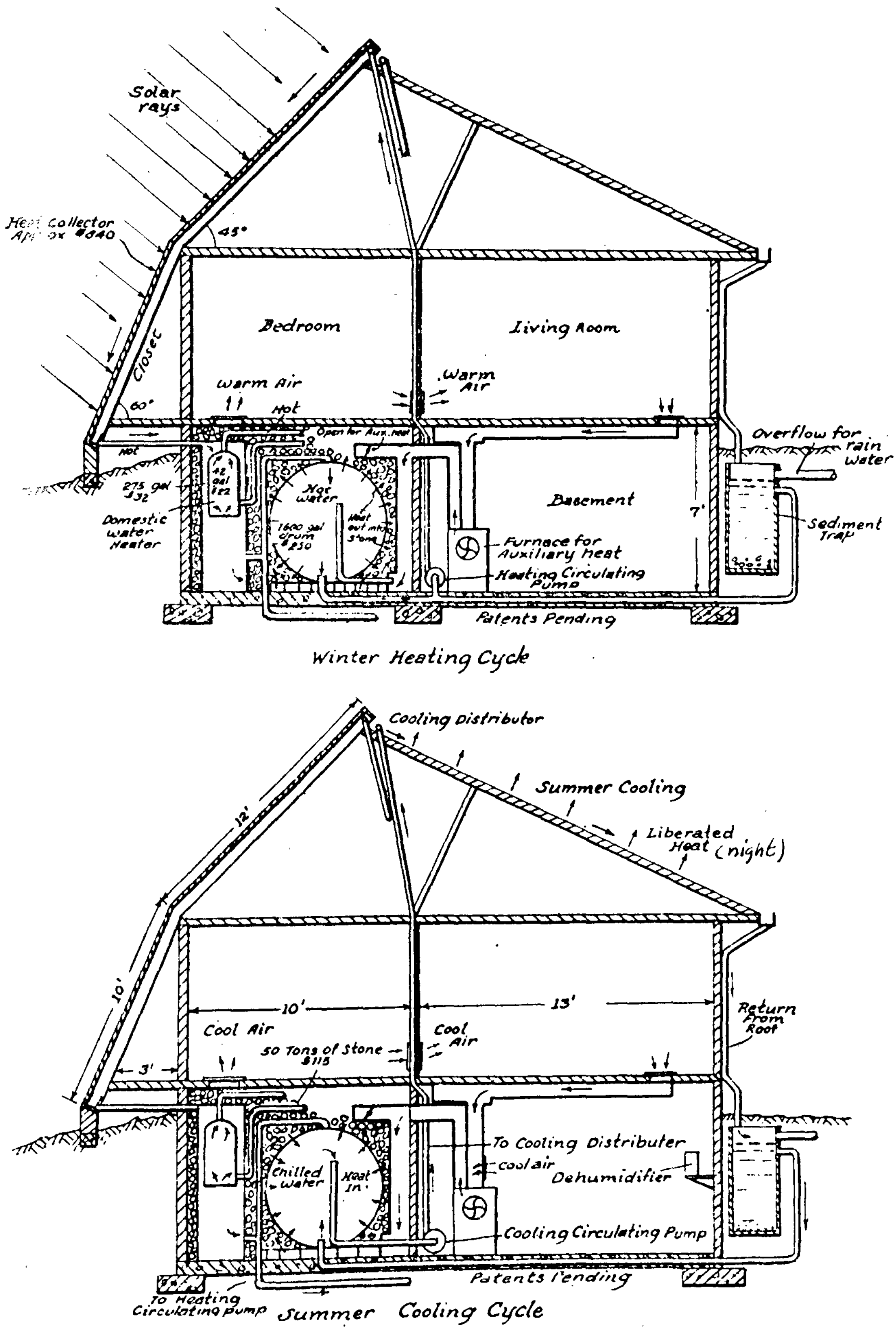
Solar rays
Heat Collector
45°
60°
Closet
Bedroom
Living Room
Warm Air
Hot
Open for Aux. heat
Warm Air
Hot
275 gal
Domestic water Heater
Hot Water
1600 gal drum $250
Heat out into Stone
Basement
7'
Furnace for Auxiliary heat
Heating Circulating Pump
Overflow for rain water
Sediment Trap
Patents Pending
Winter Heating Cycle
Cooling Distributor
Summer Cooling
Liberated Heat (night)
12'
10'
10'
13'
3'
Cool Air
50 Tons of Stone $115
Cool Air
Return From Roof
Chilled Water
Heat In
To Cooling Distributer
cool air
Dehumidifier
Cooling Circulating Pump
Patents Pending
To Heating Circulating Pump
Summer Cooling Cycle

Figure 1

For example, in producing melt water for ice or preheating domestic water in a range of 32°F to 60°F with outside temperatures of say 10°F to 40°F, efficiency is in the range of 70 per cent to 80 per cent. For home space heating, temperatures as low as 60°-70° are useful and the collector operates to raise the temperature of water in the range of 60° to 90° with an efficiency of 55 per cent to 70 per cent. For heating water in this range, the heat collector is actually useful at times when there is absolutely no visible sunshine, as explained below. As the reserve of stored heat rises and water is heated in the range of 90° to 135°, efficiency is of the order of 30 per cent to 55 per cent. During the colder months, temperatures in excess of 135° are rarely used. From the foregoing it is seen that the system "works harder" and produces more heat per day after a long cloudy spell when the reserve of heat is lowest and heat is needed most, i.e., when the temperature of the water in the storage drum is reduced to 60°-70° and is boosted to, say 100°, by the heat collector.

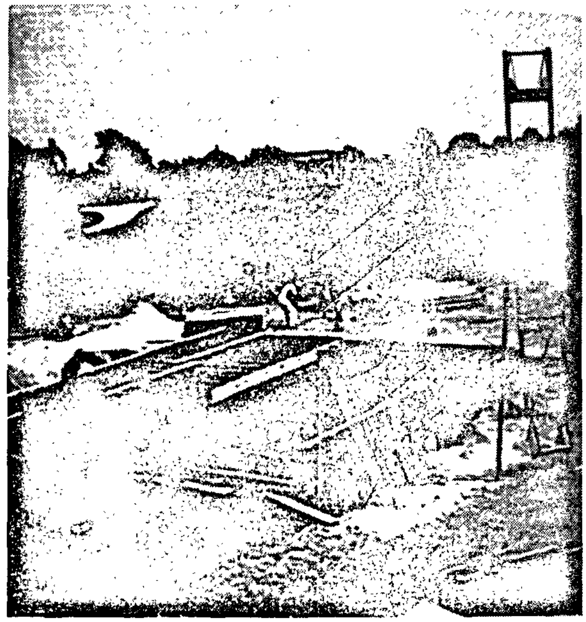

Figure 3. Substructure nears completion: children's Ferris wheel at right

Specific performance data

A specific example of the performance of the heat collector is as follows: on 9 Dec. 1959, near the shortest day of the year, solar input to the collector was checked with a pyrheliometer by Terrence H. MacDonald of the U.S. Weather Bureau and was reported at 4.65 btu per square foot per minute. Mr. MacDonald checked reflection from the collector at 15 per cent. Water was circulated through the collector at a rate of approximately 7.15 gallons per minute and was heated from 92°F to 119°F. The entire heat collector is approximately 38 ft by 22 ft, a total of nearly 840 square feet. The net heat collector surface is nearly 700 square feet after deducting for glass supporting members. Thus, the rate of heat collection was approximately 2.2 btu per sq ft per min and efficiency was approximately 47 per cent.

For heating cold city water on this same day from 51° to a swimming pool temperature of 83° at a rate of approximately 10 gpm the rate of heat collection was more than 150 000 btu per hour or approximately 3.6 btu per sq ft per min with an efficiency of approximately 78 per cent.

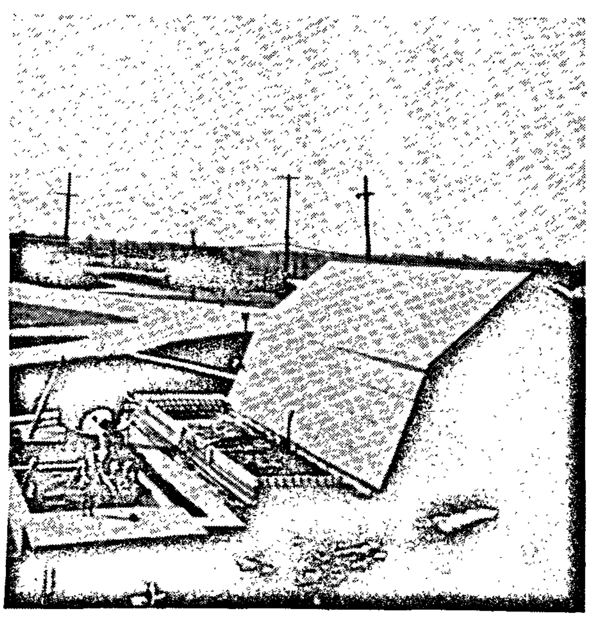

Figure 2. Solar-heated outdoor pool at Thomason home

Surge of solar heat energy stored, domestic water heated

The heat collector described yields a tremendous surge of heat energy for only about 6 to 8 hours per day, and on sunny days only. Something must be done to heat the domestic water supply for the house and to store the 6- to 8-hour surge of heat for use on cold nights and cloudy days. Simplicity and low cost apparatus are essential. In this system the problem was solved as follows. A 42 gallon fresh water preheater tank (costing $22) is placed inside a 275 gallon drum (costing $36). Hot water from the solar heat collector passes into the 275 gallon drum and bathes the 42 gallon fresh water tank in hot water to heat the fresh water inside. The hot water from the heat collector, after flowing through the 275 gallon domestic water preheater, then flows into a 1 600 gallon drum for temporary storage of the tremendous surge of heat collected during the sunny day. The 1 600 gallon drum is surrounded by 50 tons of stone. Then, 24 hours per day the heat from the 1 600 gallon drum passes into the stone to heat the stone and store the heat while the water cools back down ready to take on another "load of heat" whenever the next sunny day occurs. Cold water from the bottom of the drum is recirculated by a small circulating pump. It flows to the top and is heated as it descends through the heat collector.

Getting the heat out of storage

What low-cost and simple apparatus can be used to get the heat back out of the storage apparatus? Large quantities will be demanded on bittely cold nights and the apparatus should be automatic. There is little comfort in knowing that you have tremendous quantities of heat trapped in your basement if you cannot get it back out of storage in large quantities as needed. In the house described herein, a thermostat automatically turns a blower on when heat is needed. The chilled air is circulated to the bottom of the heat storage bin. As it rises gently around the warm drum and millions of warm stones the air is warmed. Thus, the drum and stone provide thousands of square feet of heat exchange surface, in addition to providing for storage of tremendous quantities of heat. Registers distribute the warmed air to the living quarters. When the house is warm enough (72°-75°) the thermostat cuts the blower off.

With this system, the heat in the water and stone can be used down to a level as low as 60°-70°. Due to this, the heat storage apparatus has a greater useful capacity (7 to 10 day maximum capacity) *and* the solar heat collector itself operates more efficiently because it is working at a lower temperature and less heat is lost.

Auxiliary heating apparatus

What can we do when the solar input is insufficient to meet the heat demand? In the house described herein a thermostat cuts in an auxiliary oil furnace for a few minutes. A total of 31 gallons of oil at a cost of $4.65 was used for auxiliary heat for the entire winter of 1959-1960 despite temperatures as low as 10°F and several snows of 6 in to 12 in. It is estimated that 95 per cent of all heat requirements for this 3 bedroom house was supplied by solar energy despite the fact that more than half of the days were cloudy and the winter was slightly colder than normal. During the winter of 1960-1961, temperatures at this house dipped as low as 1° below zero. December was the coldest in 43 years, and snow in December, January and February totalled 40-50 inches, near to an all-time record for the area. Total auxiliary fuel for the season amounted to 42 gallons of oil at a cost of $6.30.

Cooling the house

Thus far only heating apparatus has been discussed. This house is also cooled during the summer as follows. For summertime operation, water from the solar heat collector flows through the 275 gallon domestic water heater only and bypasses the 1 600 gallon drum. Thus, domestic water is still heated during the summer, but the heat bin is turned into a "cold storage" bin for this season. On clear, cool

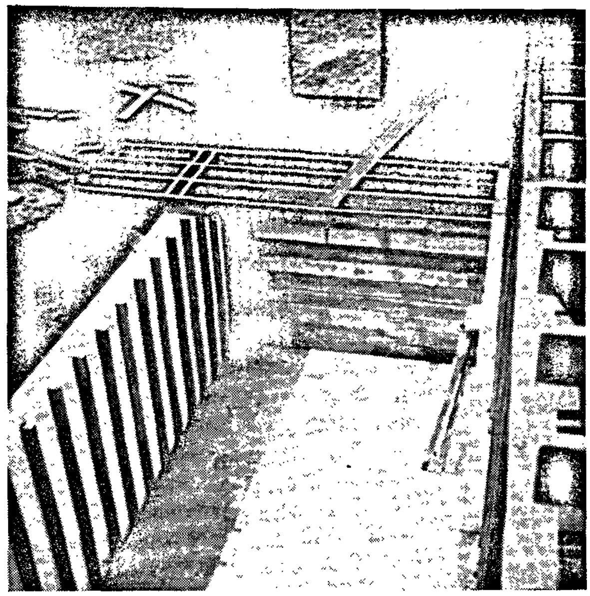

Figure 4. Heat bin under construction

nights, warm water from the 1 600 gallon drum is circulated to the north sloping roof of the house where it is chilled by radiation, evaporation, and contact with the cool night air. This chilled drum of water, in turn, chills the surrounding stone. During the hot day, air from the house is circulated around the cooled drum and through the cooled stone to cool the home. This simple apparatus adds only about $150 to the cost of the system as compared with $600-$1 000 for conventional central air conditioning. Further, only about ¼ hp is used to circulate the water as contrasted with 2 to 3 hp for compressors for conventional central air conditioners.

In the Washington area the humidity is generally high during the summer (60 per cent to -100 per cent at night), and there is little wind many nights. This reduces evaporative cooling. Many nights are cloudy, which reduces cooling by radiation. The lowest air temperature is sometimes 70°-75°F and this reduces cooling by contact with the air. Nevertheless, cooling has exceeded 25 000 btu per hour under reasonably favorable conditions of a cool summer night.

Specific cooling performance of roof cooler

On the night of 18 June 1960 the following readings were taken to illustrate cooling capability of the cooling apparatus.

Time	*°F to roof*	*°F from roof*	*Air temp. °F*	*Humidity % (approx.)*	*Weather*
10 : 30 p.m. .	72	67	63	65-75	Clear, calm
11 : 00 . . .	71½	66½	62	65-75	Clear, calm
11 : 30 . . .	71	65	61	65-75	Clear, calm
05 : 00 a.m. .	64	59	56	65-75	Clear, calm

The rate of flow was 5 gal in 37 sec, and the cooling was approximately 5°F to 6°F. This yields approximately 19 000 to 23 000 btu of cooling per hour.

It is to be noted that the relative humidity was quite high (68 per cent at 11:30 pm according to the Washington Weather Bureau). Had it been lower, or had there been a brisk breeze, cooling would have been at a better rate.

On the night of 14 July, the rate of cooling was at 25 700 btu per hr at the peak when the sky was overcast, but there was a breeze of about 15 mph. Outside air was at 68°F, water to the roof was at 73°F with a return temp. of 65½°F and a flow rate of 5 gal in 41 sec. Relative humidity was about 65 per cent.

During some nights the air temperature may remain high (about 75°F), the humidity high (about 95 per cent), the sky overcast, and the air still. Under such conditions the roof chiller is not used at all and air from the house is cooled by the "coolness" stored in the 50 tons of stone and 1 600 gal of water. A dehumidifier helps keep humidity low. The temperature in this house has not exceeded 85°F, and it is generally kept to 82°F or 83°F, even when outside temperatures rise to 95°F or 98°F. Fortunately, even if outside temperatures go to 98°F at 5:00 pm they are back down to about 82°F by bedtime. Thus, cooling is generally required only about six to ten hours per day, some cool days requiring no cooling.

Typical home temperatures are represented as follows. In late August of 1960 Washington had a hot spell. On August 26 when the official high was 93°F and the temperature in the shade on the north side of the house reached 96°F, the temperature inside reached a maximum of only 82°F, the humidity being lowered from 63 per cent to 60 per cent between 11:00 am and 6:00 pm.

In many parts of the world cooling would be much better than in the Washington area.

Water lost from the system due to evaporation is automatically replenished by rainwater from the roof by a simple sediment trap and automatic excess rainwater diverter (costing about $10 and having no working parts to cause trouble).

Children's pool heated

During warmer periods of the colder months, when the heat supply from the collector exceeds demands for home heating and domestic water heating, the excess heat is used to heat water for the children's 2 000 gallon outdoor pool. About 1 000 to 1 200 gallons of solar heated water is used for each filling.

Heat storage "battery"

The heat storage apparatus may be likened to a huge battery which stores heat instead of electricity. When this "battery" is charged to about 125°F we have a heat reserve good for about a week, more or less. This heat is used day by day during cloudy weather to keep the house warm. When the stone and water temperature have dropped to about 75°F our battery is "dead" and must be recharged with sun heat, or we must use auxiliary heat to keep the home temperature above 70°F. Actually the heat is used down to a level of about 65° in the bottom of the heat bin (stone and water) and to a level of about 75°F in the top during a long cloudy spell.

Contrary to operation of an ordinary battery, the "heat" battery is reversely chargeable with "coolness" during the summer nights to cool the house on hot summer days. This increases usefulness of the storage bin.

In addition, this heat storage bin is extremely useful during variable spring and fall weather. The heat "battery" is allowed to go "dead" at about 75°F. When a cold snap occurs, the stone and water at 75°F keep the house warmed to 70°-72°F. When a hot spell occurs, the 75°F stone and water keep the house cooled to 78°-80°F.

From the foregoing it is seen that the heat storage "battery" is very useful the year around to store heat during the winter, to store "coolness" during the summer, and to stabilize home temperatures during variable spring and autumn weather.

Second house

The second solar-heated house is slightly smaller than the first. Each room is larger but it has fewer rooms. It has 2 bedrooms, dinette, living room, bath, basement and bomb shelter. This house cost less than $10 000 including solar heating. It is estimated that the cost of solar heating and air conditioning will be about $1 900 as contrasted with

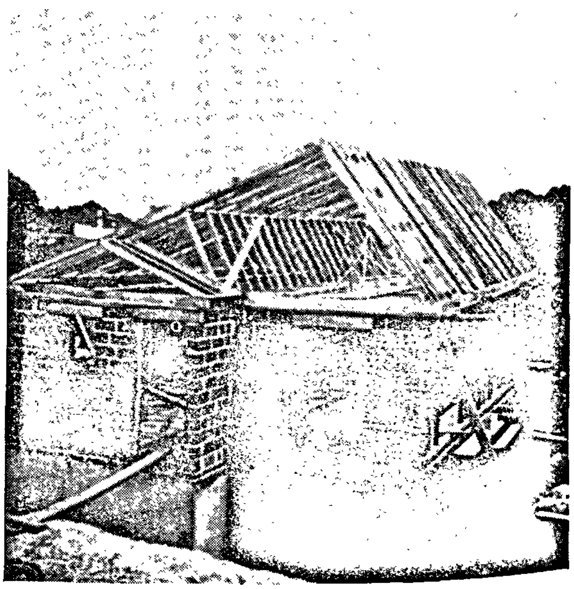

Figure 5. Second solar-heated house takes shape

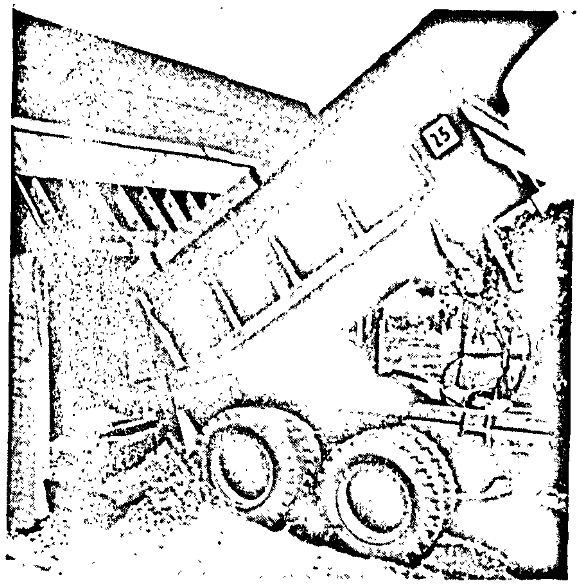

Figure 6. 60 tons of stone dumped into heat storage bin for low-cost heat or "cold" storage

$2 500 for the system in the original house. The heat bin includes 60 tons of stone and the heat collector covers 530 square feet.

A simple electric resistance heating element is used for auxiliary heat, thus eliminating the cost of a chimney, the cost of a furnace and the cost of an oil drum. Heat losses through a chimney are avoided. A considerable amount of space in the house and basement are saved by eliminating the chimney, furnace and oil drum. Depreciation and repairs should be from $25 to $40 lower per year due to the change from oil to electric auxiliary heat. Also the original investment is considerably lower. However, the cost of electricity is considerably higher than the cost of oil so that some of the savings are offset by increased electric bills during the coldest cloudy weather when solar input is insufficient to meet the heat load.

Starting the system on borrowed heat

These two houses are located near one another, about 125 feet apart. The first was constructed in 1959 and the second in 1960. Tenants of the second house were scheduled to move into the house in late November when the heating systems was not yet completed. No auxiliary heating apparatus had been provided and for several days before the moving date there was no sunshine and the weather was rather cold. The family wondered how to heat the new home for a day or two until the clouds rolled by?

Necessity is the mother of invention. The 11 year old daughter, Teresa, suggested the solution. She said, "Daddy, I remember you said that our heat collector could have been built away from the house as a fence or on a garage and we could transfer the hot water to our house to heat it. I notice we have a surplus of heat at our house, so why not transfer our 1 600 gallons of hot water down to the new house? Then their house can stay warm from the hot water and our house will stay warm from the heat in the 50 tons of stone." A plastic hose pipe and pump did the job within a few hours and very little heat was lost during the transfer process.

Questions on solar-heated houses

Popular misconceptions are represented by some of the questions I am asked over and over. For example, the question is asked: "Don't you think your system would be more valuable in Florida where there is more sunshine and less cold weather?" My answer is no. In the colder areas the fuel bills are much greater and therefore we can save much more money where the heating season is longer and the total fuel bill is higher. However, less of this Washington cloudiness and haze and more bright sunshine would be very helpful.

Another typical question: "Hail storms will smash the glass, won't they?" My answer, possibly so. However, my insurance company considers the risk so slight that they have insured both solar heated houses at no increase for the premium. An employee at the U.S. National Bureau of Standards has verified my thinking that the larger panes of glass, being more resilient and being set at a steep angle, are less likely to be smashed by hail.

Another very lively question in view of our repeated snows is: "What do you do when it snows and blankets the heat collector under a foot of snow?" My answer, we do nothing but sit tight and keep warm by solar energy. There is no snow shoveling to clear off the collector because it is self-cleaning. The apparatus operates automatically as follows. The solar heat collector is made up of two sections, one section being at a steep slope of 60°, the other being less steep at 45°. Generally speaking, the snow slides off the lower steeper section as it falls and thus it is relatively clear when the snow stops falling. The circulating pump cuts on at about 8:45 am as usual. Water stored in the 1 600 gallon drum, now likely to be at 65°-100°F, enters the collector at the top and begins warming the heat collector glass under the snow on the top section. As this water passes through the lower section, which is clear of snow, it is warmed considerably and returns to the heat storage bin warmer than when it left. For an hour or two this condition exists. Then, about 10:00 to 11:00 am, the glass under the snow is warmed enough to cause the snow to turn loose and slide off leaving the heat collector clean and more effective than it was prior to the snow.

The increase in heat collector output is a result of bright snow reflecting much of the sunlight from surrounding areas to intensify the light and heat striking the collector. The snow piles up at the bottom of the collector some 2 to 4 feet deep. Nevertheless, with some 10 per cent to 20 per cent of the collector under a snow bank, the heat output of the collector is actually greater than when there was no snow. In other words, the water coming out of the collector is several degrees hotter than it is on a similarly cold day without snow.

Occasionally I am asked the question: "Since you are using water in your heat collector and inasmuch as outside temperatures at your home approach 0°F, will not this water freeze up and damage the collector?" My answer is no, it cannot freeze up in the first place and no damage would occur even if freezing did occur. The circulating pump cuts off automatically whenever the weather becomes cloudy or at 3:30 pm if it is still sunny at that time. In either event the collector is completely drained within about 10 seconds. There is no valve which could fail and hinder draining. There are no tubes to freeze up and burst.

Skeptics sometimes ask the question: "Yes, you cut your fuel bill, but what about your electric bill?" The answer is that our bill for electricity is also cut considerably. At other houses which we own the domestic water is heated by electricity and, for our family with 5 children, we formerly used an estimated 250 to 400 kilowatt hours of electricity per month to heat domestic water. In our solar heated house most of the water heating is done by solar energy and hence our electric bill is reduced an estimated average of $50 to $75 per year due to solar domestic water heating. For about 9 to 10 months of the year the saving in electricity is 200 to 350 kilowatt hours per month. However, during the coldest periods of the winter, the electrically operated blower operates more or less continuously and thus the saving in electricity is not as great during periods when outside temperatures are in the range of say 0° to 30°F.

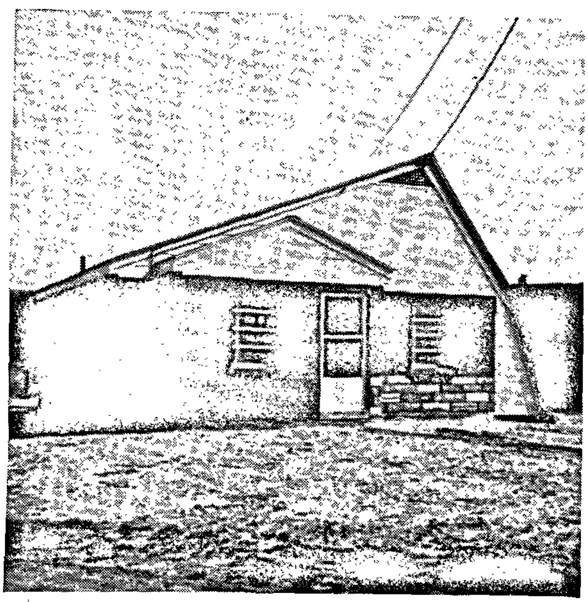

Figure 7. Newer solar-heated house has no chimney but uses *small electric heater for auxiliary heat when temperatures* approach 0°F

A further substantial saving in electricity comes during the summertime when the house is cooled without a conventional 2 to 3 hp compressor. In our house a small circulating pump is operated from about midnight to 7:00 am to circulate water over the north sloping roof for chilling. From about noon to 8:00 pm the small blower cuts on to distribute coolness from the cool water and stone throughout the house. This cooling apparatus kept home temperatures some 8° to 15°F below outside temperatures for the entire summer. The maximum home temperature for the summer of 1960 was 85°F while outside temperatures reached about 97°F maximum. Cooling in many areas of the world would have been much better because Washington, D.C. often has hot muggy cloudy nights which are adverse to chilling water by air contact, by evaporation cooling, or by radiation cooling. Under Washington weather conditions, about the best rate of cooling was 25 000 btu per hour, similar to the cooling of a 2 to 3 hp compressor unit. Nevertheless, the home cooling was achieved with a considerable saving in electricity as compared with a conventional compressor unit.

Another question often asked is: "What about your water bill?" The answer, the water in the system is recirculated and very little water need be added. Rain water automatically replenishes the supply by way of an automatic rainwater makeup and sediment trap located underground just outside the basement. When we fill the children's pool we use some water from the city water main at 40°-50°F, and boost it to 85°-100°F by solar energy.

The question is asked: "What about cloudy weather, you cannot get solar heating then?" Answer: On 13 Feb. 1961 the sun never "showed its face" at our house. Not even a faint outline of the sun could be seen; it was completely obscured by clouds covering the entire sky. The outside temperature on that morning went to a low of about 27°F and the high for the day was about 40°F at our house. Approximately eight of the previous twelve days of February had been cloudy, snowy and cold with a temperature of 1° below zero on 2 Feb. Our reserve of stored solar heat was nearly exhausted. The solar heat collector went into operation (automatically) and water was circulated to the collector at temperatures of approximately 66°F and heated to 76° to 78°F, a rise of 10° to 12°F at a rate of approximately 7 gallons per minute. Thus, with absolutely no visible sunshine and outside air temperatures at approximately the freezing point, the heat collector was trapping approximately 35 000 to 40 000 btu of heat per hour, the equivalent of a reasonable sized oil or gas heater. Heat at the 76° to 78°F range is definitely usable to help heat the house. Heat collection under a cloudy sky is much greater where water is being heated in the range of 32° to 60°F, such as for melt water for ice, or preheating domestic water for a house, a hotel or such.

Conclusions

With the system described in this paper it is believed that we are now in the realm of economic feasibility in solar space heating. This is true even in an area such as Washington, D.C., where nearly half the winter days are cloudy, where temperatures range as low as 0°F, and where snow is quite common. The system is believed to be economically competitive with fuel oil here at a cost of 15 cents per gallon. The system can save a considerable amount of money for the homeowner in addition to conserving precious fossil fuels.

With mass production techniques, and further inventions now being tested, it is believed that the original installation cost can be lowered still further so that a free-heating solar house can be constructed at as low a price as one with conventional heating and cooling.

Summary

Simplicity, high efficiency, low cost and long life were the objects of the present system. The system (patents pending) contains a solar heat collector on the back side of the house facing slightly west of south. The heat collector is made up of an insulating base, covered by sheets of blackened corrugated metal and a transparent plastic and window glass over the blackened sheet metal. Solar energy heats the sheet metal. Cold water is circulated to the top of the heat collector by a small pump and is dispersed into hundreds of small streams to flow down the valleys of the corrugations. The small streams of water are thus heated as they descend and are collected together by a collector manifold at the bottom of the heat collector. Heated water from the collector flows into a heat storage bin which includes a heat exchanger unit to heat domestic water for the house. From this heat exchanger it flows into a 1 600 gallon heat storage drum where it gives up part of its heat to surrounding stone. Cold water from the bottom of the drum is recirculated to the heat collector for re-heating. Cool air from the house is circulated through the warmed stone and around the warmed drum by a thermostatically controlled blower and the air is thus warmed. The warmed air warms the house.

During the summer, the heat collector continues to heat the domestic water supply. However, the warm water from the 1 600 gallon drum is circulated to the north sloping roof at night to cool the water. The cool drum of water cools the stone. Air circulated through the cooled stone and around the cool drum is cooled, and cools the house.

Part of the excess heat in spring and fall is used to heat the children's 2 000 gallon pool.

The second solar heated house was constructed without a chimney, furnace, oil drum, etc. A simple electrical resistance heater is used to supply auxiliary heat. Thus, initial installation costs are cut considerably and space is saved in the house. Also heat loss through the chimney is avoided. Repairs and maintenance of the electrical heating apparatus should be nil. Tending to offset these advantages is the higher cost of electricity for auxiliary heat.

At the time of writing, very little information can be given as to the new home air conditioning except to say that it will not cost as much to install or to operate as a conventional air conditioning system. The total cost of the solar heating system *with* air conditioning will be reduced to approximately $1 900, which is not appreciably greater than the cost of conventional apparatus for heating the home, cooling the home and heating the domestic water supply.

CHAUFFAGE DES LOCAUX, CHAUFFAGE DE L'EAU ET CLIMATISATION DE LA MAISON THOMASON

Résumé

La simplicité, le rendement, l'économie de construction et la durée de service sont les premières qualités que l'on s'attache à donner à cette installation. Le système (brevets en instance) comporte un collecteur de chaleur solaire installé sur l'arrière de la maison et orienté au sud (un rien vers l'ouest). Le collecteur en question est doté d'une base isolante, sur laquelle reposent des tôles ondulées en métal noirci, avec sur ce métal un couvercle transparent en composition plastique et en verre à vitres. L'énergie solaire chauffe la tôle métallique. On fait circuler de l'eau froide à la partie supérieure du collecteur au moyen

d'une petite pompe, et ce liquide se disperse en centaines de petits filets qui s'écoulent par les parties déprimées des ondulations de la tôle.

Chauffés au cours de cette descente, les filets d'eau sont reçus par une tubulure située à la base du collecteur de chaleur. L'eau chauffée que contient ce collecteur passe à un bac d'accumulation de chaleur qui comporte un échangeur servant au chauffage des eaux ménagères. Elle passe ensuite dans un cylindre de 1 600 gallons (près de 6 400 litres), où elle abandonne une partie de sa chaleur à la masse de pierre qui entoure le cylindre.

L'eau froide provenant du fond de ce tambour accumulateur de chaleur est renvoyée au collecteur, où elle est de nouveau réchauffée. L'air frais en provenance de la maison circule autour de la pierre chaude et du tambour, sous l'impulsion d'une soufflante à commande thermostatique, si bien qu'il s'échauffe, lui aussi. Il va ensuite chauffer la maison.

Pendant l'été, le collecteur continue à chauffer l'eau à fournir à la maison. Cependant, l'eau chaude en provenance du tambour de 1 600 gallons est envoyée au toit incliné vers le nord pendant la nuit, pour y être refroidie. Le tambour d'eau fraîche rafraîchit la pierre qui l'entoure. L'air qui circule autour de la pierre rafraîchie et du tambour rafraîchit à son tour la maison.

Une partie de l'excédent de chaleur disponible pendant le printemps et l'été sert à chauffer l'eau de la piscine des enfants, qui contient 2 000 gallons (environ 7 500 l).

La deuxième maison à chauffage solaire a été construite sans cheminée, calorifère, tambour à mazout, etc... On se sert d'un simple élément chauffant à résistance pour fournir l'appoint de chaleur nécessaire. Ceci réduit sensiblement les frais de première installation, et on économise de la place dans la maison. On évite de même les pertes de chaleur par la cheminée. Les frais de réparation et d'entretien du matériel de chauffage électrique doivent être nuls. Le coût plus élevé de l'électricité qui sert à fournir l'appoint de chaleur tend à contrebalancer ces avantages.

Au moment où ce mémoire est écrit, on ne peut pas dire grand'chose quant à la climatisation de la nouvelle maison, sauf que son installation coûtera moins que celle d'un système classique et que son exploitation sera également d'un prix plus modique. Les frais d'installation globaux du système de chauffage solaire (climatisation comprise) seront ramenés à 1 900 dollars environ, ce qui n'est pas sensiblement supérieur au prix d'une installation classique pour le chauffage de la maison, sa climatisation et la fourniture d'eau.

REPORT ON TWO AND A HALF YEARS' EXPERIMENTAL LIVING IN YANAGIMACHI SOLAR HOUSE II

Masanosuke Yanagimachi *

The author has been thinking about and studying an effective system for the utilization of solar energy for space heating, year-round air conditioning and domestic hot water supply, and has developed a system for the utilization of solar energy as described in a paper (1) presented to the World Symposium on Solar Energy held at Phoenix, Arizona, in 1955. Subsequently he has built four solar houses in Japan. (2) Two of them are in his own residence in Tokyo. The third was built at Karuizawa, in the International Student House, and the fourth has recently been completed in a residence having a floor area of 140 square meters, located at Funabashi in the vicinity of Tokyo.

The first was built as an experimental installation of year-round air conditioning in the fall of 1956 for a section of the author's residence (3 rooms, about 55 square meters total floor area), unfortunately it was destroyed by fire in January 1957. Then Yanagimachi Solar House II was newly designed and built, and was completed in the fall of 1958. (3) His family, consisting of four or sometimes five persons, have spent two and a half years there, through two and a half heating seasons and two cooling seasons. Throughout this period, this house showed quite satisfactory results and provided comfort for its residents. This paper is a report mainly on Yanagimachi Solar House II and its actual operating data.

Summary of the house and the solar system

The house is wooden-framed, two storied, with a concrete basement and a total floor area of 223 square meters as shown in figure 2.

(*a*) Floor area:
  1. First floor (excluding garage) . . . . . 112.0 m²
  2. Second floor . . . . 105.0 m²
  3. Basement (machine room only) . . . . 6.6 m²

(*b*) Roof area employed as heat collector for space heating and for heat sink for space cooling . . . . 98.0 m²

(*c*) Roof area employed as heat collector for domestic hot water supply . . . . 33.0 m²

(*d*) Radiant heating and cooling ceiling panels. 104.0 m²

(*e*) Reflective wall surfaces . . . . 110.0 m²

(*f*) Reflective curtains . . . . 140.0 m²

(*g*) Reflective foil insulation for the stud space of the outside frame walls and the joist space of the first floor and upper surfaces of radiant ceiling panels on the second floor . 510.0 m²

(*h*) Capacity of the air conditioner . . . . . . 6.0 m³/min

(*i*) Heat pumps
  1. One 3-hp heat pump (F-22) for space heating and space cooling
  2. One 1-hp heat pump (F-12) for hot water supply
  3. One 1/2-hp heat pump (F-21) for heating the bottom of a Japanese-style bath tub

(*j*) Circulation pumps
  1. One 1-hp circulation pump between the roof collector plate and heat storage tanks used for heat collecting in winter and heat sinking in summer;
  2. One 1/2-hp circulation pump between the radiant ceiling panels and heat storage tanks;
  3. One 1/2-hp circulation pump between the air conditioner and heat storage tanks;
  4. One 1/2-hp circulation pump between a smaller part of the roof collector plate and the city water storage tank for preheating the water in the tank.

(*k*) Capacity of heat storage water tanks
  1. One lower temperature tank with a capacity of 40 tons of water;
  2. One higher temperature tank with a capacity of 10 tons of water;
  3. One city water storage tank with a capacity of 5 tons of water.

(*l*) The capacity of the hot water storage tank or boiler is 400 litres.

Details of house structure and the solar system

(*a*) The outer wall is wood-framed, has wood sheathing, a metal lath, a 1 inch stucco outside and wood lath, $\frac{3}{4}$ inch of plaster and reflective wallpaper on the inner surface, plus 4 inches of aluminum foil insulation between the framing members.

(*b*) The first floor is also wooden framed, with a $\frac{5}{8}$ inch plywood subfloor, finished in vini-as-tile, and having a $\frac{3}{8}$ inch wood sheathing on the underside, plus 4 inches of aluminum foil insulation between the framing members.

(*c*) The entire exposed surface of the roof is covered with black painted aluminum tube-in-strip sheets, which not only act as roofing material but as a device for collecting solar heat in winter and sinking

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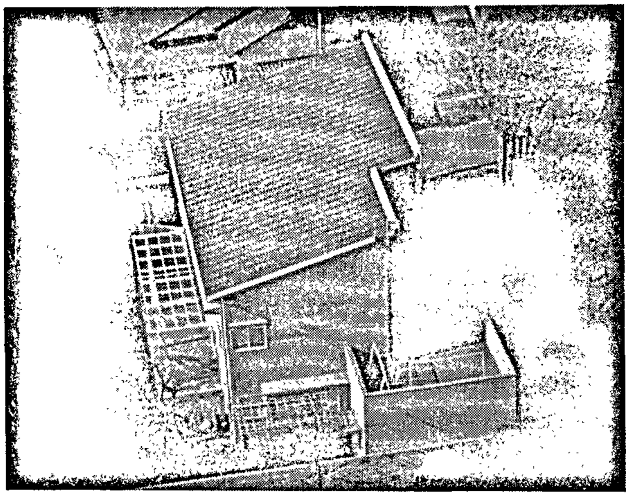

Figure 1. Bird's eye view of Yanagimachi Solar House II

heat, produced by the cooling cycle of the heat pump, in summer. The roof surface faces south at an angle of about 15 degrees to the horizontal and is constructed with a $\frac{3}{4}$ inch wooden sheathing, covered with building paper. One inch of aluminum foil insulation and a layer of thin aluminum sheet is laid underneath the above-mentioned aluminum tube-in-strip sheet. The fabrication of these tube-in-strip sheets to be attached in position is simple but to hold them closely and make them completely weather-proof it was necessary to use the means indicated in figure 8.

(*d*) The radiant ceiling panels are of the same material as the roof collector, namely aluminum tube-in-strip sheet as indicated in figure 9.

The arrangement of these ceiling panels for each room is shown in figure 4.

(*e*) The air-conditioner is a conventional fan-coil unit with air filter of a 6 m^3/min capacity, located in the second floor attic. Conditioned air is distributed to each room by air ducts.

(*f*) The heat pump system for space heating and space cooling consists of a 2-hp Tecumseh, Freon 22 hermetic compresser, 4 condensing coils, and 6 evaporating coils. Each coil is installed in the heat storage tanks and submerged below the water level. The evaporating coils are in the large tank and the condensing coils in the small tank.

(*g*) The central hot water supply system, for domestic use in the bath-shower, kitchen, laundry, lavatory, etc., consists of a 1-hp Freon 12 heat pump, a hot

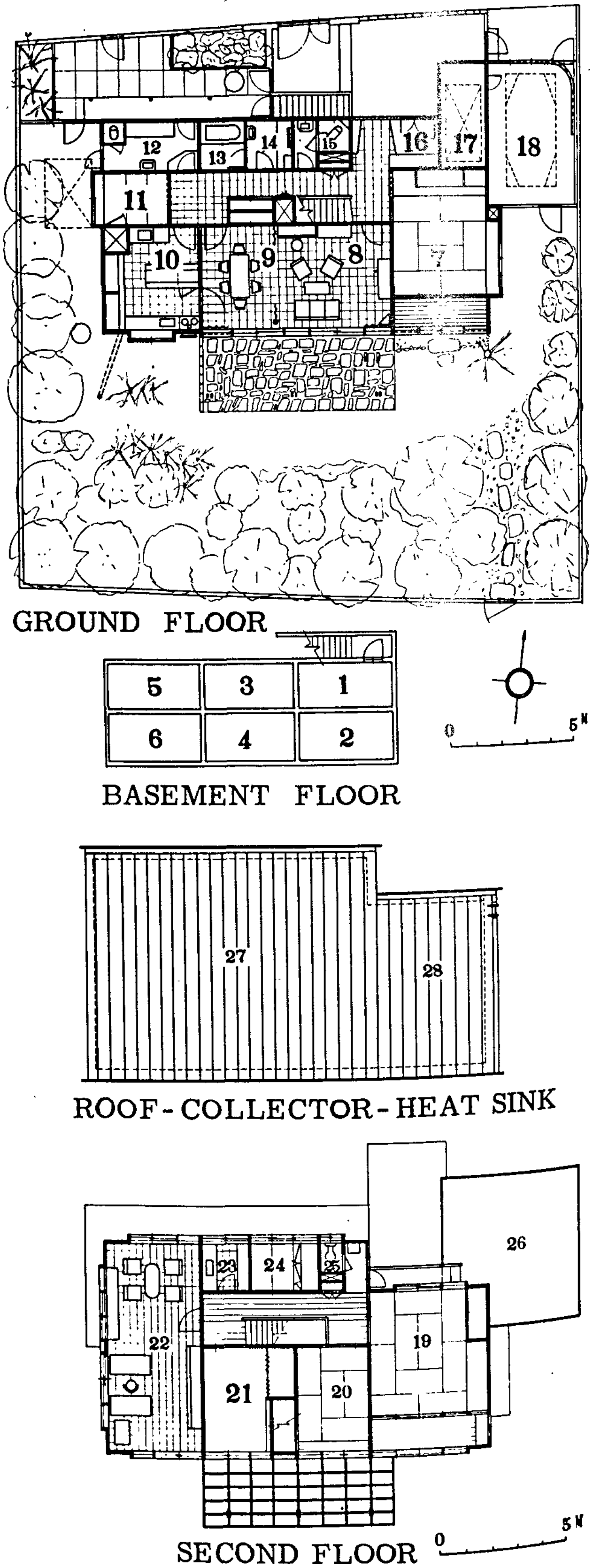

Figure 2. Plans of the Solar House ⟶

1, basement machine room; 2, higher temperature heat storage water tank; 3, 4, 5, 6, lower temperature heat storage water tank; 7, Japanese style living room; 8, 9, living & dining room; 10, kitchen; 11, maid's room; 12, utility; 13, bath; 14, dress; 15, toilet; 16, entrance; 17, city water storage tank; 18, garage; 19, Japanese style bedroom; 20, Japanese style room; 21, bedroom; 22, study; 23, dark room; 24, back room; 25, toilet; 26, drying place; 27, roof collector for space; heating and cooling; 28, roof collector for hot water supply.

water storage tank with a 400 litre capacity, a condensing coil inside, and a heat exchanger with an evaporating coil inside which recovers the heat from sewage discharge. There is a 5-ton capacity city water storage tank annexed to the garage and ½-hp circulation pump which circulates water between the roof collector for the hot water supply and the tank.

(*h*) The heat pump system for heating the bottom of the bath tub consists of a ½-hp Freon 21 heat pump, a condensing copper coil embedded in mortar under the bottom tiles of the tub, and an evaporating coil submerged in the city water tank.

Principles of operation

The general principles of operation are shown in figure 5. The roof top collector area is divided into two sections. The larger area (98 m²) is used as a heat collector in winter and a heat sink in summer, and the smaller area (33 m²) is used as a heat collector for the heat pumps providing the hot water supply and bath tub heating. During the heating season, on every fine day, the water in the larger tank is circulated continuously by the pump P1 between the roof collector and the said tank and thus collects and stores solar heat. The working temperature of the water in the tank is usually kept about 15°C ± 5°C according to weather conditions and in some rare cases goes down to 5°C or lower. An air vent is located at the highest point of the roof, and the return to the tank is opened at a point above the water level, so that the entire system drains completely, whenever the pump P1 is stopped, thus eliminating the ever-present danger of freezing during the winter.

Since there is no glazing over the roof collectorls the collection efficiency would fall off quite rapidy, if attempts were made to collect the absorbed heat at a high temperature. This difficulty is minimized by allowing the heat to be collected at relatively low temperature levels, and up-grading the collected heat by means of a 3-hp heat pump. The water temperature in the smaller water tank is warmed and kept about 30-40°C, depending on the outdoor temperature by means of the said heat pump operation. This hot water is circulated and distributed to the radiant ceiling panels throughout most of the rooms and to a unique combination of heating and lighting fixtures in the study which occupies about one-third of the second floor to heat these rooms.

During the summer season, the operation of the heat pump is exactly the same as in winter, and the water temperature in the larger tank is cooled down to about 6-10°C, while the water temperature in the smaller tank is heated up to 30-45°C. The roof heat collector is used as a heat sink during the night to reject the heat of the water in the smaller tank. As soon as the sun goes down, pump P1 is started and the warm water is circulated up through the roof-top collectors, where it is cooled by radiation to the night sky and by convection to the outer air.

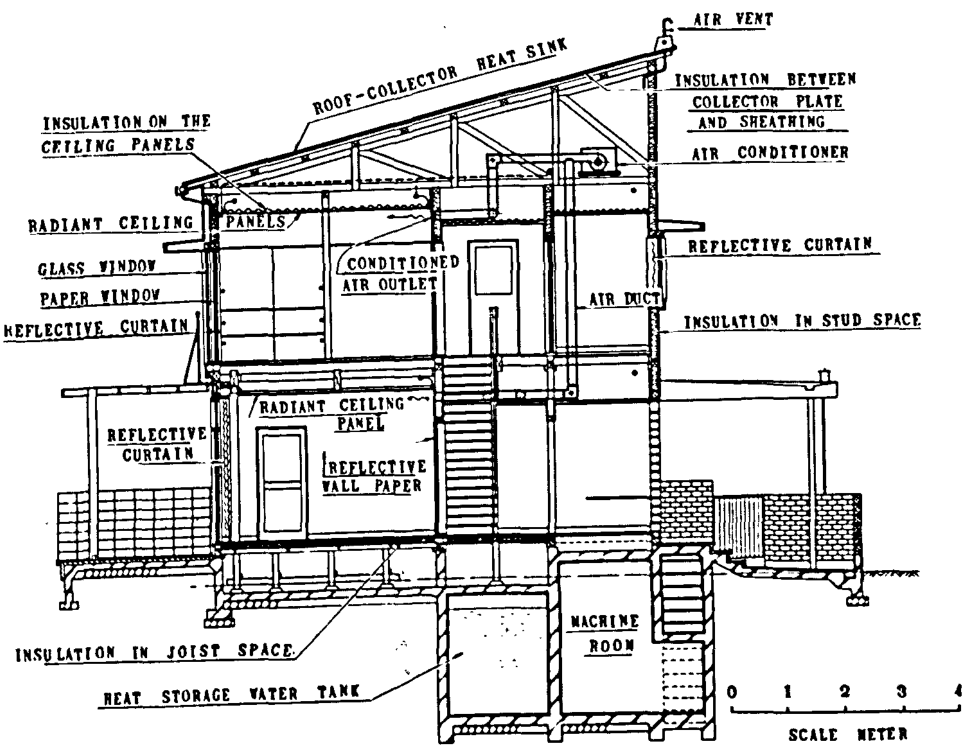

Figure 3. Cross section showing the construction of the house and the system

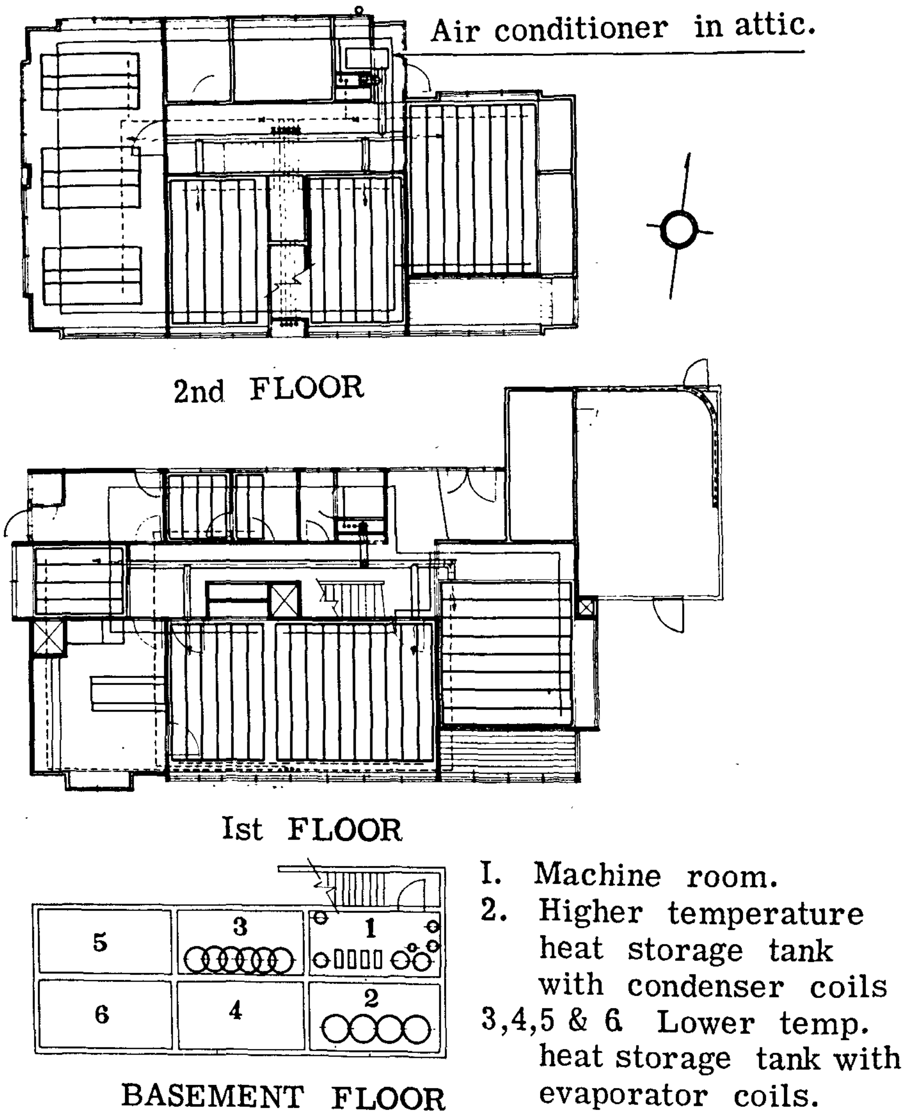

Figure 4. Arrangement of the solar system, including radiant ceiling panels, air conditioner, air duct, machinery and heat storage tanks

One part of the chilled water in the larger tank is circulated by the pump P2 directly to the air conditioner to cool and dehumidify the air to be distributed to the rooms, and one part of it is mixed with return water and then circulated to the radiant ceiling panels, while maintaining its temperature a little higher than the dew-point temperature of the room air in order to prevent condensation on panel surfaces. Thus most of the space cooling is accomplished by the radiant ceiling panels by means of sensible cooling, while the remainder is achieved by means of air conditioned by latent cooling.

An important feature in maintaining comfort within the residence during both summer and winter is the use of reflective curtains and reflective wall papers which not only prevent excessive absorption of solar heat and minimize heat loss and heat gain, but give a more comfortable condition in conjunction with the radiant ceiling panels. With conventional curtains and wall surfaces, almost all the radiant energy from the ceiling panels would be absorbed, but by using reflective curtains and reflective wall papers, all the radiant energy is reflected to the interior of the room, thus providing its occupants with a comfortable degree of warmth and relatively lower room air temperature in winter, and a refreshing coolness with higher room air temperature in summer.

Calculated heating and cooling load and seasonal load

(*a*) Intensity of solar and sky radiation on a horizontal surface in the vicinity of Tokyo, kcal/m^2 day

	Spring	*Summer*	*Autumn*	*Winter*
1. Average for clear days only	4 342	4 510	3 141	2 891
2. Average for clear, cloudy and rainy days	3 270	3 280	2 240	1·910
Ratio (1)/(2)	1.33	1.37	1.40	1.54

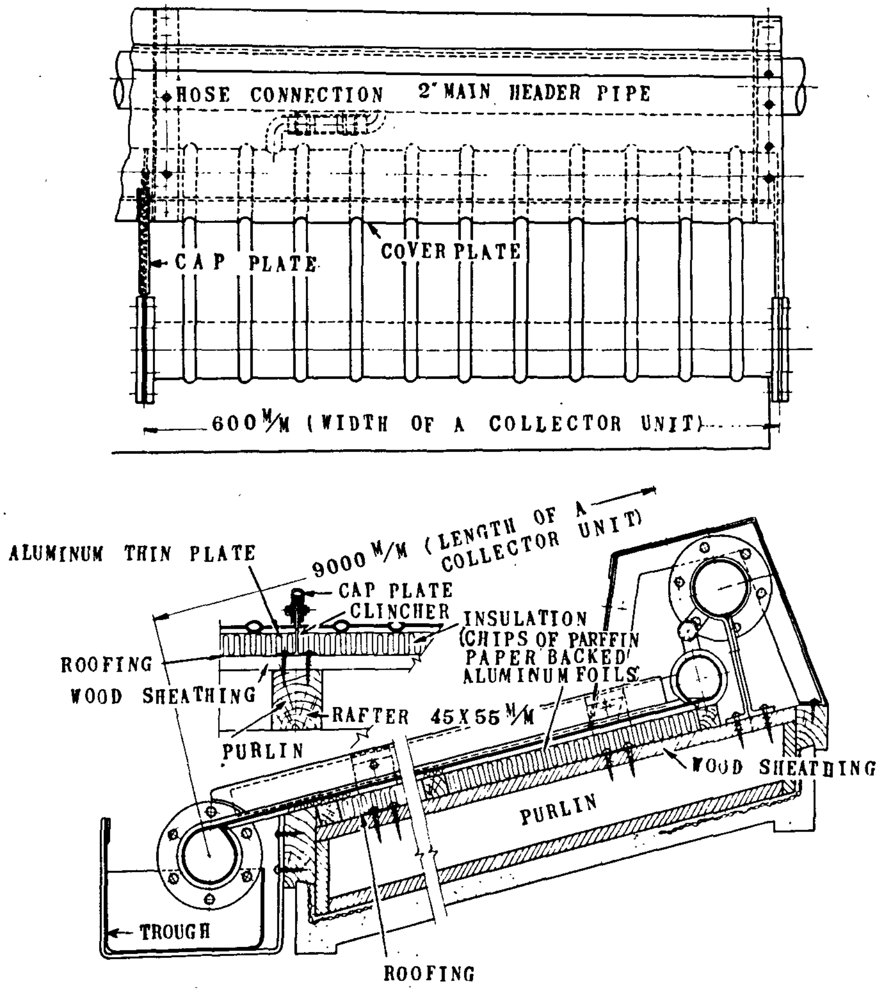

Figure 8. Details of roof and collector construction

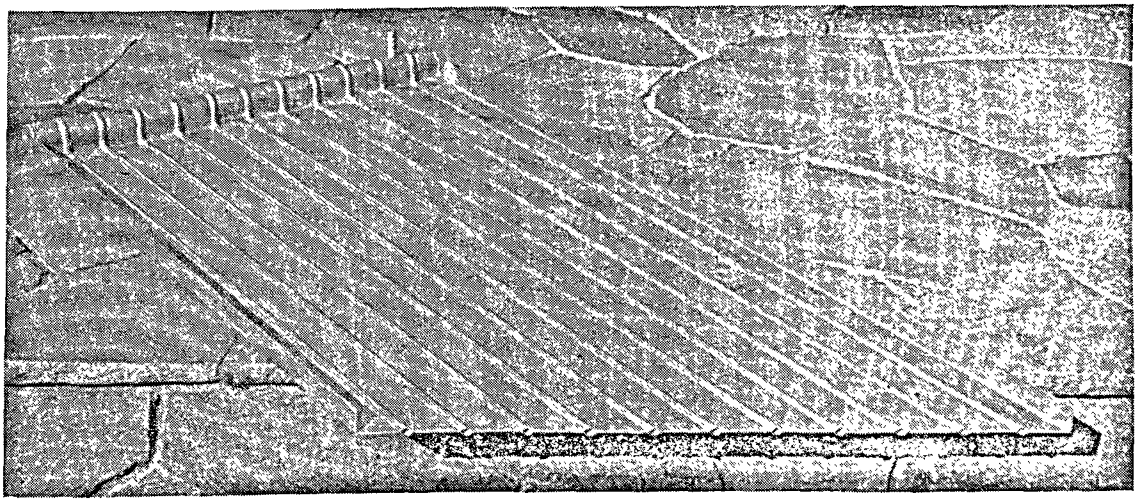

Figure 9. Sample of radiant ceiling panel

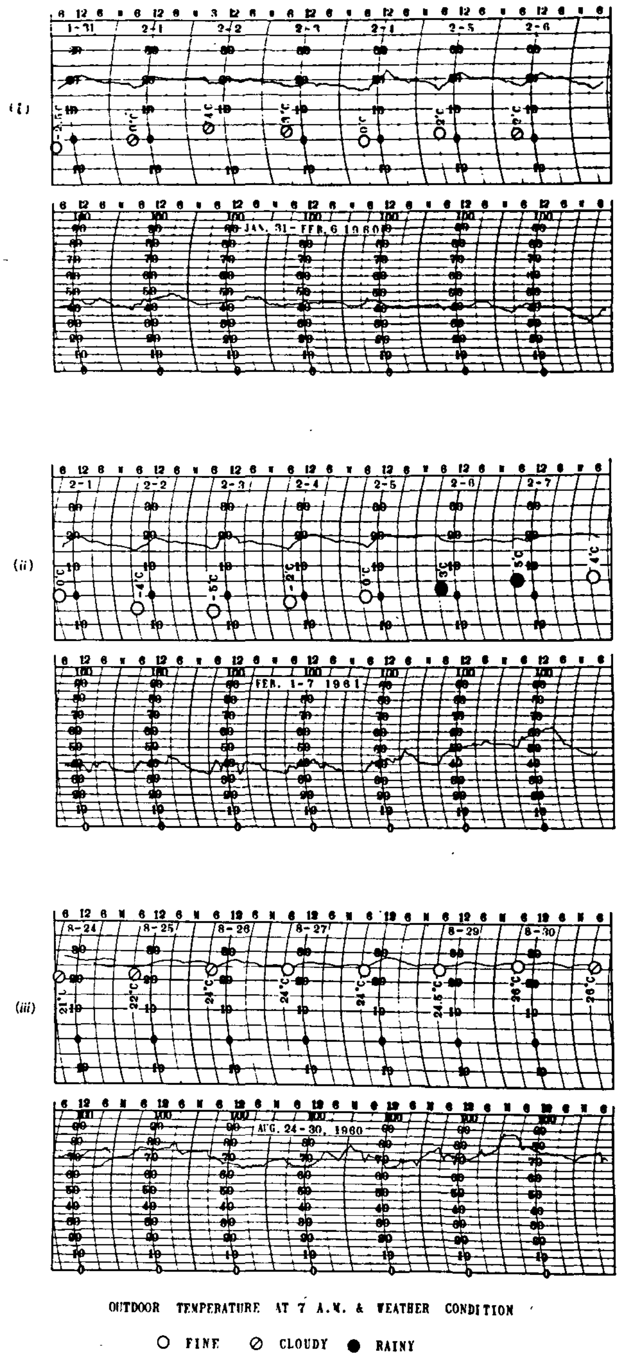

Figure 10. Recording charts for room air temperature and humidity, outdoor air temperature at 7 am and weather conditions

(i) Jan. 31 to Feb. 6, 1960; (ii) Feb. 1 to Feb. 7, 1961; (iii) Aug. 24 to Aug. 30, 1960

perature in the larger heat storage tank was about 20°C average, and although there were six consecutive days of rainy or cloudy weather during which the heat could not be collected, the rooms remained favorably heated.

(*g*) Thus we can calculate the efficiency of the solar system as a means of space heating and the coefficient of the performance of the heat pump system for space heating from the above-mentioned results as follows:

Efficiency of the solar system

$$= \frac{16\,200\,000}{50\,800\,000} = 32.5\ \%,$$

COP of the heat pump system

$$= \frac{16\,200\,000 \times 100}{860 \times 5580} = 3\text{[illegible]}\ \%$$

(*h*) As regards the operating cost of the systems, the cost of the electricity account for the greater part of it. Table 1 shows respective monthly payments to the electric company using 200 volt current for power and 100 volt current for general service.

From table 1 it may be calculated that the average cost of 200 volt electricity is 4.85 yen/kWh.

We can calculate several charges as follows:

Charge for space heating	5 580 × 4.85 = 27 063 yen
Charge for space cooling	5 050 × 4.85 = 24 492 yen
Charge for hot water supply . . .	6 630 × 4.85 = 32 155 yen

(*i*) Comparison with other systems for space heating.

If we use light fuel oil at 60 per cent boiler efficiency, supposing the cost to be 16 000 yen × 1 000 kg, the cost of oil to produce a total heating load of 16 200 000 kcal/season would be as follows:

$$\frac{16\,200\,000 \times 16\,000}{10\,000 \times 0.6 \times 1\,000} = 43\,200 \text{ yen}$$

The cost of electricity for an oil burner and circulation pump is estimated to be at least

1 500 kWh × 8 = 12 000 yen per heating season.

As a result, we can save

(43 200 + 12 000) — 27 063 = 28 137 yen per heating season.

Suggested improvements

(*a*) The quiet operation of machinery.

(*b*) The need for a unique automatic on-off control for the circulation pump P1. By means of such a control the whole system will be operated more effectively from the point both of maintenance and economy.

(*c*) Adequate measures to deal with the problem of corrosion of aluminum tube-in-strip sheet.

Economic feasibility

As regards the initial cost installation of the solar system, when simply compared with conventional space heating systems, it cannot be competitive, but even now costs can be kept down to the point where they are at least as low as those of a conventional central air conditioning system as far as planning, construction and materials for the house itself are concerned. Maintenance and operating

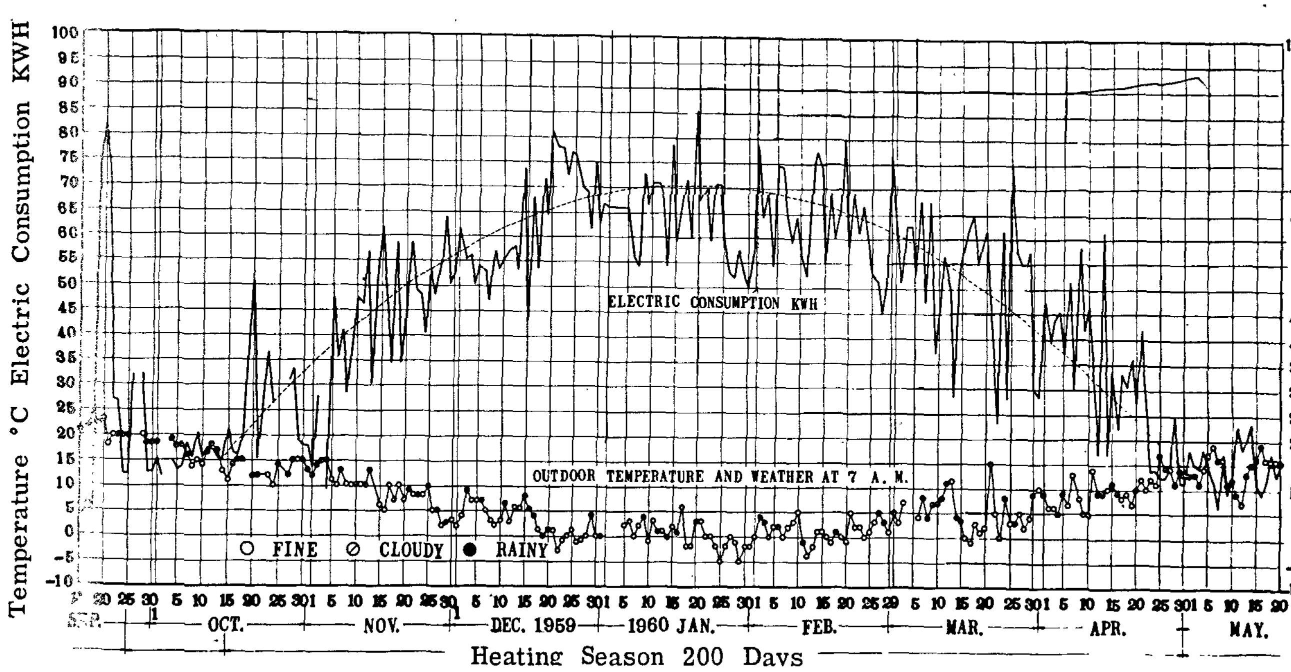

Figure 11. Daily electric consumption, outdoor air temperature at 7 am, and weather conditions throughout the heating season of 1959-1960

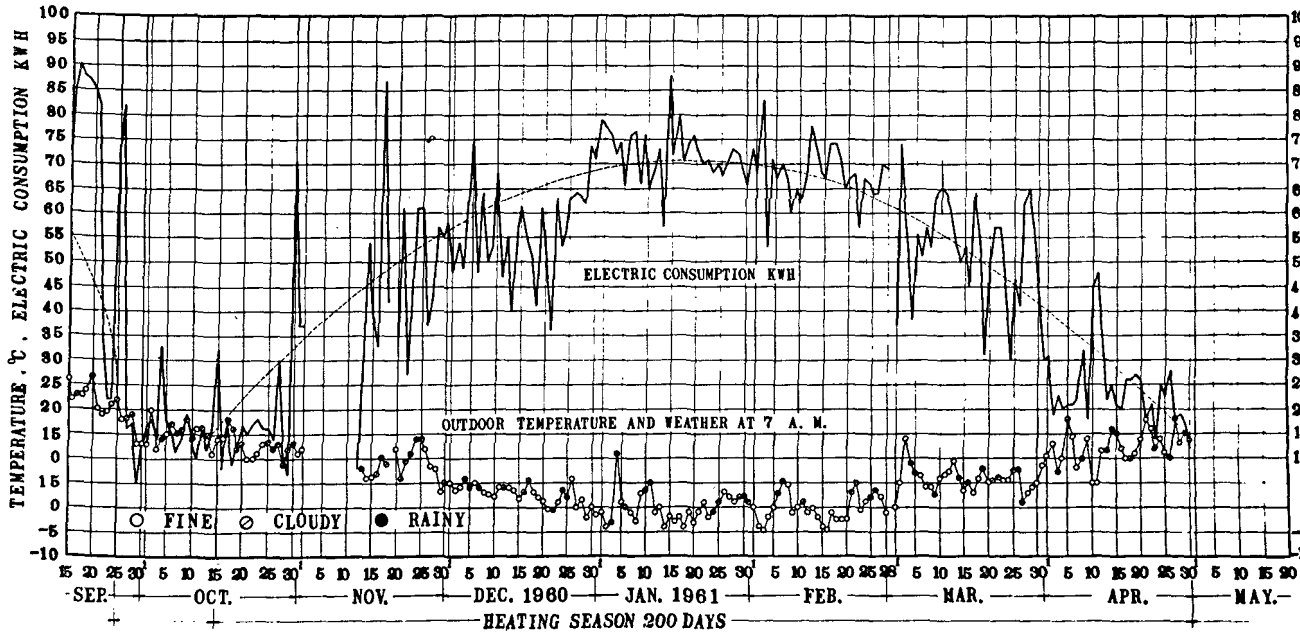

Figure 12. Daily electric consumption, outdoor air temperature at 7 am, and weather conditions throughout the heating season of 1960-1961

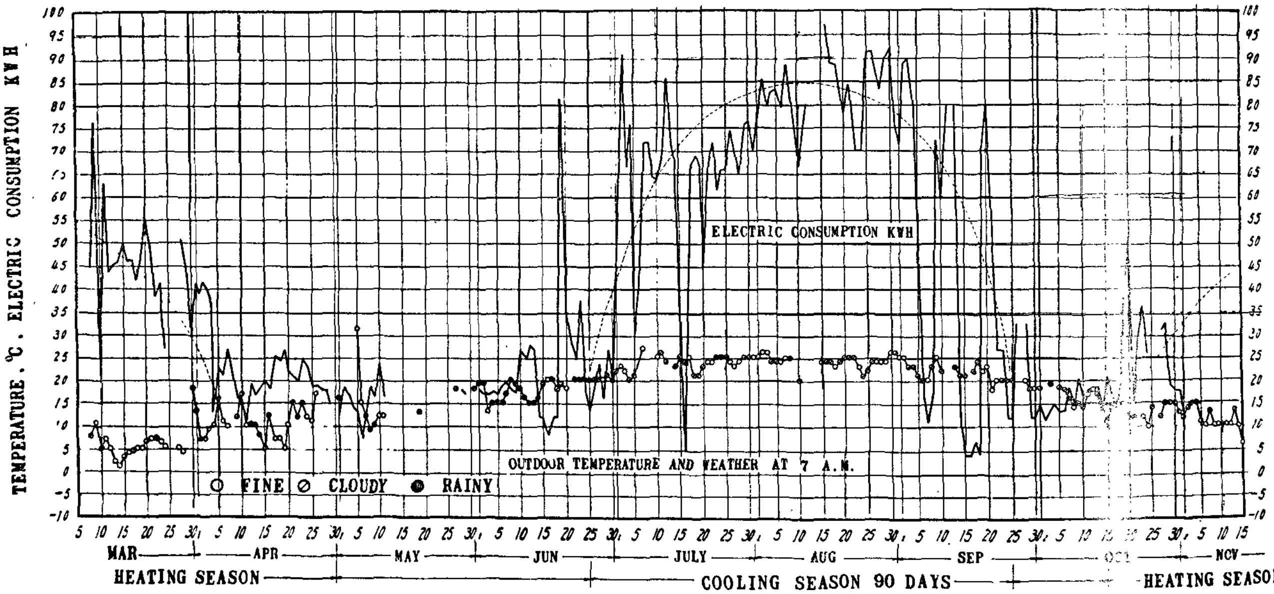

Figure 13. Daily electric consumption, outdoor air temperature at 7 am, and weather conditions throughout the cooling season of 1959

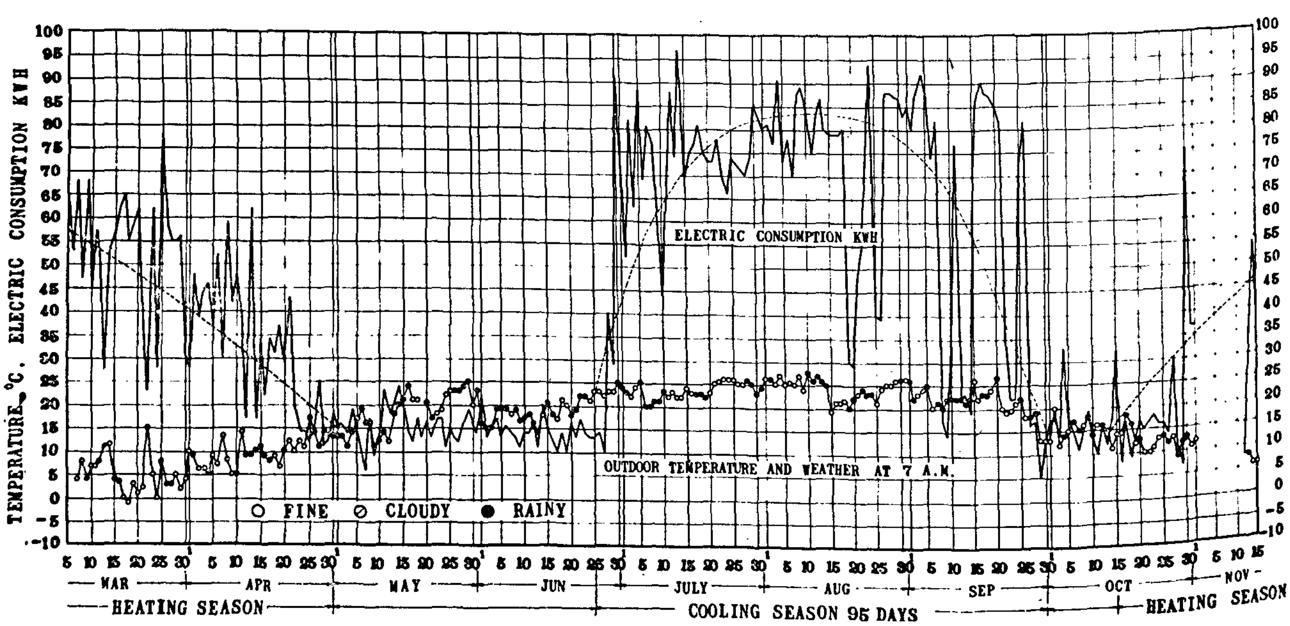

Figure 14. Daily electric consumption, outdoor air temperature at 7 am, and weather conditions throughout the cooling season of 1960

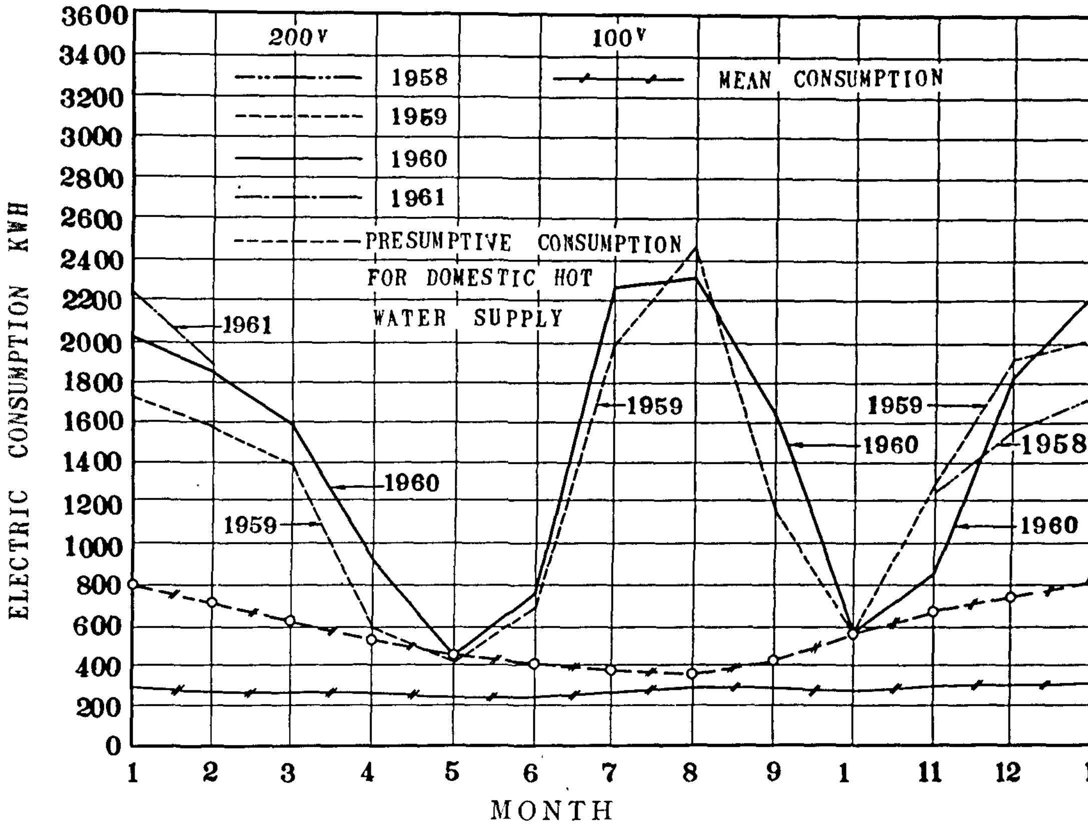

Figure 15. Electric consumption for each month throughout the two and a half year experiment period

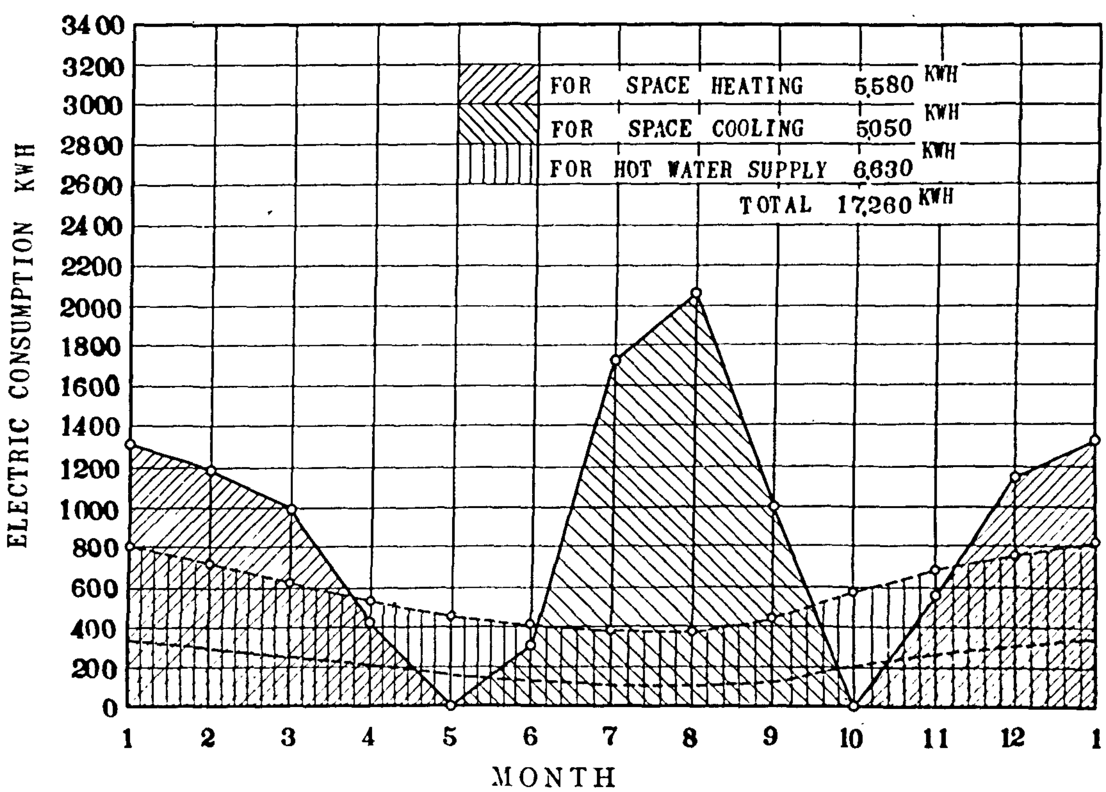

Figure 16. Probable monthly and yearly electric consumption, subsequently classified according to uses

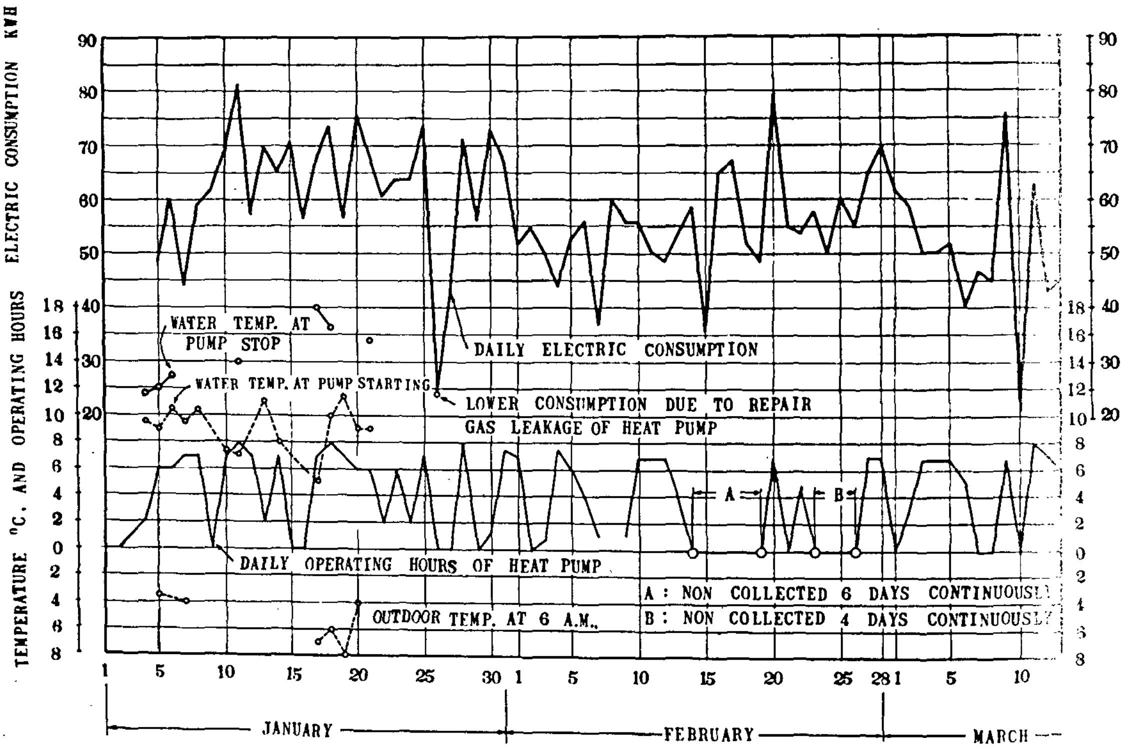

Figure 17. Daily electric consumption, operating hours of the collecting pump, circulating water temperatures, and the outdoor temperature at 6 am during the period from January 1 to March 13 1959

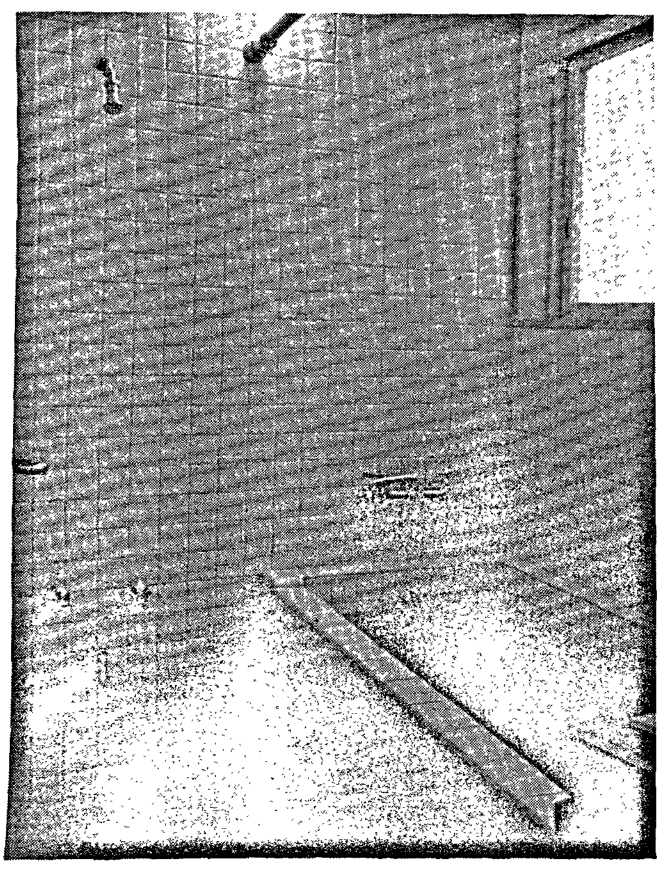

Figure 18. Japanese style bath tub provided with bottom warming coils by heat pump

costs of the system are already as low as indicated in table 1.

At any rate, it is considered a useful thing that this solar system of air conditioning and domestic hot water supply has not only an auxiliary heating system, which will normally be used to ensure comfortable conditions during protracted sunless periods, but, with a 3-hp heat pump for air conditioning and 1-hp and ½-hp heat pumps for hot water supply, will also be used to achieve a satisfactorily comfortable environment for the entire 220 square meter residence throughout the year, which would normally require at least 9-hp instead 3-hp.

The sucess of this solar house is mainly due to the following factors:

(*a*) The use of the principle of the heat pump.

(*b*) Combining the roof and the solar collector, and making triple use of this surface as a radiation absorber in winter, a radiation emitter in summer and as a roof itself.

(*c*) The use of reflective curtains or draperies and reflective wall surfaces combined with radiant heating and cooling panels, which bring a refreshing coolness to the rooms by virtue of their attractive appearance and special thermal characteristics.

At the present stage, it is premature to appeal to the public with this solar system. However, it will become essential for most residences to have air conditioning installations in the very near future. Then it may become economically feasible to have such a solar system in every residence.

ne sauraient faire concurrence à ces systèmes. Dès maintenant, toutefois, il est possible de tenir ces frais à un niveau où ils sont tout au moins aussi bas que ceux d'un système central de climatisation, lorsque l'on tient compte de la préparation des plans, de la construction et des matériaux pour la maison elle-même. Le système, au surplus, est facile à entretenir et d'une exploitation économique. Dans l'état actuel des choses, il serait encore prématuré de compter intéresser le public avec un tel système, mais il deviendra essentiel pour presque toutes les résidences d'avoir des installations de conditionnement d'air dans un avenir très proche. C'est alors, estime l'auteur, qu'il sera économiquement valable de doter chaque habitation d'une telle installation solaire.

GENERAL REPORT — RAPPORT GÉNÉRAL

Agenda item III.C.3

USE OF SOLAR ENERGY FOR HEATING PURPOSES: SOLAR DRYING

George O. G. Löf *

Although drying is one of the oldest uses of solar energy, the proportion of modern solar development activity devoted to this application is comparatively small. There may be several explanations for the limited studies in this field. Where solar drying is practiced, particularly with agricultural crops, simple and crude methods are reasonably effective. The spreading of the crop on the ground or on a platform and drying it directly in the sun is cheaply and successfully employed for many products throughout the world. Practically no capital outlay for equipment is required, and although considerable labor may be involved, this is seldom costly. A high quality product is not often demanded, so that over-drying, contamination by dirt and insects, degradation of the material, and so on, is frequently tolerated.

Another deterrent is the intermittent and sometimes extended cloudiness which precludes satisfactory solar drying. Hence, if a material *must* be dried, reasonably promptly, auxiliary energy is required. It then often becomes more practical simply to operate these "auxiliary" means continuously, making them as small as possible in order to minimize investment and using artificial heat for the drying operation. Finally, large drying operations require sizable heating installations and correspondingly large solar collection areas and facilities.

Recent work in solar drying has been oriented in both of the directions implied above. That is, there has been work in *direct* drying, wherein the material is exposed to solar radiation, and by energy absorption and air circulation, the moisture is vaporized into the atmosphere. In the other system, drying is *indirectly* accomplished by use of a solar air heater of some type which furnishes hot air to a separate drying unit. In this latter system, another source of heat could usually be substituted for solar energy, in the same general drying facility. It should be pointed out, however, that the design of the drying unit itself, apart from the solar heat supply system, may have features which are specifically adapted to the solar heat source.

Studies have also been devoted to combinations of these two primary types of solar drying systems. A solar collector can be employed for providing a supply of hot air to a drying unit in which a material is also directly irradiated by solar energy. Another type of "solar dryer" that has been considered is a conventional steam-heated dryer of one of several standard types, to which steam is supplied from a solar boiler. Solar drying is not really involved in this system, however, because the solar energy aspects of the process are simply associated with the generation of low pressure steam by means of solar collectors. A similar argument might be applied to the use of solar air heaters, but unique problems due to the relatively low air temperatures, fluctuating heat supply, and other factors make the use of solar heated air much more directly connected with the drying operation itself.

In the general guide lines for this Conference, it was recommended that papers be devoted to solar drying processes other than the widely used method of exposing materials directly to the sun on uncovered surfaces. However, it was stated that presentation of new data on this conventional process, the results of research with new materials dried by this method, or any other useful new information pertaining to this type of direct drying should be of interest to the Conference. The topics deemed of most significance to the Conference are those concerning the application of better methods and improved equipment for solar drying, as means for improving product quality, reducing spoilage of crops and foods, and effecting economies in drying operations ordinarily employing fuels for supplying heat.

Four papers on the use of solar energy for drying have been contributed to the Conference. Two of the papers are devoted to indirect solar drying, a process of using solar energy to heat air for delivery to a separate drying unit. Two others deal with absorption of solar energy directly in or on the materials being dried, without protective transparent surfaces. One of the latter, however, also contains a brief study of separate solar air heaters and drying chambers and a comparison of the two systems.

The four papers may also be classified as to the type of products being dried. Three of the contributions are concerned with the drying of agricultural crops, whereas the other is on the drying of a water-containing mineral. Two of the papers are primarily concerned with the drying of grain, such as corn, whereas the third deals with fruit, in this case grapes. The mineral in the fourth is oil shale with a high water content. The only important materials being commercially dried which are not represented in the agenda are wood (primarily in the form of lumber) and various manufactured products such as chemicals, ceramic ware, and paper.

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Although there are a few solar drying investigations and some research workers in this field not represented in the agenda of the Conference, the four papers constitute a very satisfactory coverage of this topic. It is not necessary, therefore, to review prior work in order to place the current papers in adequate perspective. Most of the investigations in solar drying during the past decade have been by the authors of these particular papers, references to which are contained in the papers themselves. Prior to the last decade, the literature in this field was largely in the form of numerous patents issued for various types of solar drying devices, very few of which have been utilized.

This rapporteur would like to call attention, however, to a significant work not represented in the Conference contributions. This is the paper by Ismailova of the USSR, entitled "Possibility of Applying Solar Energy to Drying Fruit and Vegetables" and published in *Teploenergetica*, vol. I, 1957. This investigation, based primarily on the drying of sliced apples in (a) a direct heated, glass-covered solar dryer, (b) an indirect dryer heated by air from a flat plate solar collector, and (c) a dryer employing a combination of the other two, was an analysis of the characteristics of the three systems and their relative effectiveness in drying this crop. Measurements of drying rates over a range of operating conditions were made, the duration of the necessary drying period was determined, the quality of the product was evaluated by chemical and other tests, and comparisons of the three types with each other and with natural drying and fuel drying systems were made. In addition to the drying studies themselves, an analysis of the heat transfer relationships in an air heater of the flat plate type was made, and correlations of performance of such heaters with air velocity, temperature, and the other variables were developed.

The studies may be summarized as follows.

(*a*) In comparison with drying systems utilizing fuel, fruits and vegetables can be satisfactorily dried in solar heated units with a saving in fuel; in comparison with "natural drying", that is, materials being exposed directly to the sun and air, a substantial saving in time is realized.

(*b*) Fruits dried in enclosed solar-heated units have higher quality, cleanliness, and vitamin C content, than those processed by natural drying.

(*c*) The three types of solar dryers tested can all be effectively used with fruits and vegetables. Direct radiation drying permits the shortest and fastest operation, whereas the process employing a closed drying chamber supplied with solar heated air yields a product of somewhat higher quality, probably because of the lower maximum temperatures achieved by the fruit.

(*d*) Flat plate solar heaters with one or two glass covers can be successfully used for supplying hot air up to 100°C, and such units were used in the tests reported.

(*e*) Recommended relationships for calculating the heat transfer from a solar-heated plate toward the upper glass surface are as follows:

$$Nu_m = 0.42\, Re_m^{0.65} \text{ when } 250 < Re < 620$$

$$Nu_m = 11.1\, Re_m^{0.156} \text{ when } 620 < Re < 1\,400$$

If there is an air space below the irradiated black plate, the heat transfer toward the bottom of the unit from this plate can be represented by the following equations:

$$Nu_m = 0.026\, Re_m^{1.06} \text{ when } 170 < Re < 520$$

$$Nu_m = 1.5\, Re_m^{0.423} \text{ when } 520 < Re < 1\,200$$

In the above equations, Nu_m is the Nusselt number and Re_m is the Reynolds number, in dimensionless units.

Solar drying principles

A discussion of drying theory is beyond the scope of this paper, but a few principles may be advantageously outlined here. These are particularly those applicable to direct radiation drying, inasmuch as the principles involved in the drying of materials in various types of opaque enclosures by means of hot air, whether from a solar heater or some other type of heating unit, are well outlined in the drying literature. The first requirement is a transfer of heat to the surface of the moist material by conduction from heated surfaces in contact with the material, or by conduction and convection from adjacent air at temperatures substantially above that of the material being dried, or by radiation from surrounding hot surfaces or from the sun. Absorption of heat by the material supplies the energy necessary for vaporization of water from it, about 1 050 btu per pound of water evaporated or 590 calories per gram. Water starts to vaporize from the surface of the moist material when the absorbed energy has increased the temperature enough for the water vapor pressure to exceed the partial pressure in the surrounding air. Steady state is achieved when the heat required for vaporization becomes equal to the rate of heat absorption from the surroundings.

To replenish the moisture removed from the surface, diffusion of water from the center to the surface of the drying material must take place. This may be a rapid or a slow process, depending upon the nature of the material being dried and upon its moisture content at any time. It may thus be the limiting rate in the drying operation, or if moisture diffusion is rapid, the rate of heat absorption on the surface or the rate of vaporization may be the controlling factor. In some very porous materials, vaporization may take place even below the apparent surface of the material, vapor then diffusing through pores in the solid.

In the case of direct radiation drying, part of the radiation may penetrate the material and be absorbed within the solid itself. Under such conditions, heat is generated inside the material as well as at the surface, and thermal transfer in the solid is facilitated.

For economic reasons, maximum drying rates are usually desired. Product quality must be considered, however, and excessive temperatures must be avoided in many materials. In addition, because drying occurs at the surface, those materials which have a tendency to form hard, dry surfaces relatively impervious to liquid and vapor transfer must be dried at a rate sufficiently low to avoid this crust formation. Close control of heat transfer and vaporization rates, either by limiting the heat supply or by control of the humidity of the surrounding air, must be provided.

The drying of a product simply by permitting relatively dry air to circulate around it, without the use of any direct or indirect heat source, is known as adiabatic drying. The heat required for vaporizing the moisture is supplied by the air to the solid material, thereby reducing the air temperature while increasing its absolute and relative humidity. Because of the low heat capacity of air, in comparison with the high latent heat of vaporization of water, large volumes of air at reasonably low relative humidity must be used in this type of drying process. Air leaving the dryer is nearly saturated with water at the wet-bulb temperature. The air supply, at its initial dry-bulb temperature and humidity, is thus cooled and humidified toward its wet-bulb temperature, while the moist solids in contact with this air approach the wet-bulb temperature also.

The foregoing generalization must be somewhat modified if the materials being dried are at all soluble in the water present. Fruits and other agricultural products contain salts and sugars which cause a lowering of the vapor pressure. The surface temperatures of these materials must therefore be higher than the wet-bulb temperature of the air in order for vaporization to take place. This means that the adiabatic drying of these solids requires air at lower relative humidities than do the materials having no solutes in the aqueous phase.

An important property of materials processed by direct radiation drying is their absorptivity for radiation. Fortunately, most solids have relatively high absorptivities, but they may change as drying proceeds, the surfaces of the materials becoming less or sometimes more "black" during the process. Also, there may be changes in opacity of the surface of the materials which are partially transparent to some of the wavelengths in the spectrum of the radiant source.

The thermal conductivity of the material is also an important property, particularly if the solids are dried in a layer of sufficient depth to require conduction of heat from particle to particle. If the thermal conductivity is poor, circulation of heated air through and between the particles of moist solid would permit better heat transfer than direct radiation on the surface of a relatively deep bed of particles.

Indirect solar drying of grains and other field crops

The two papers on the drying of crops with solar-heated air, by F. H. Buelow (S/17) and by C. P. Davis and R. I. Lipper (S/55), are directed toward the same objectives and are based on similar experimental studies. Both papers are concerned with the drying of grains in simple equipment which could be "home made" and which could be advantageously used in small installations. Both studies deal mainly with the use of simple, flat-plate air heaters on the roofs of small drying sheds or barns in which the grain or other crop is stored and dried simultaneously. Each system is intended as a supplement to natural air drying, which is often ineffective, because of excessive atmospheric humidity, in reducing the crop moisture sufficiently to prevent spoilage. Another common characteristic of the two studies is the use of large air flow rates and correspondingly low temperature increases in the solar collector, thereby dictating the use of either an uncovered solar absorber plate, or a collector with no more than one transparent cover.

In these studies, the authors show that the essential requirement in the drying of corn and other grains by means of circulating atmospheric air through the grain bins is a humidity low enough to permit vaporization of the moisture from the grain. This "in storage" drying, particularly of fall-produced grains, must be completed in a matter of a few weeks in order that damage to the moist grain be avoided. Typical requirements and procedures involve storage of grain in bins with perforated floors through which air is circulated for two or three fall months, reducing the moisture content from 18-20 per cent down to 10-12 per cent. It has been found that the relative humidity of the air being circulated through the grain must be below about 62 per cent in most cases in order to lower the moisture content of the crop sufficiently so that it can be stored without spoilage. When the atmospheric humidity is above this level, practically no drying takes place, and if the duration of high humidity conditions is prolonged, losses may be severe when no other heat source is available.

These investigators found that a 10° to 15°F increase in the temperature of the air used for drying is enough to reduce the relative humidity of even very humid air to make it effective for crop drying. Both groups have shown that the use of a simple solar collector in the form of a double roof on a drying bin permits increasing the temperature of large volumes of air 10° to 20°F, thereby materially increasing the drying rate and reducing the chances of grain spoilage. In one system, a blackened corrugated sheet metal roof on the drying-storage building acts as a solar energy absorber. An air space of one to four inches beneath the metal plate forms a passage through which air is drawn by means of a circulating fan prior to its delivery under the perforated floor of the drying bins. Sheathing under the roof supporting members confines the flow of air an ', if desired, insulation can be provided beneath the sheathing. In some tests (by both groups), glass or plastic covers were used above the sheet metal absorber to reduce thermal loss.

Air circulation rates and blower capacities in most of the tests were those commonly used in natural air drying. Thus, air flows of 2 to 4 cubic feet per minute per bushel of grain (Davis and Lipper) were employed. The solar collector areas used in both studies were such that air rates of 10 to 15 cubic feet per minute per square foot of collector were obtained. Under these conditions, the pressure drop due to the solar collector and necessary duct work was not sufficient to require alteration of the fan designed for unheated air drying.

In tests by Buelow, the total time for drying a crop was reduced as much as 50 to 75 per cent by supplementing natural forced air drying with solar preheating. It was concluded that a building suitable for crop drying by this process can be constructed at a cost only slightly above that of an unheated air crop drying building. Because a temperature rise of only a few degrees was found adequate for satisfactory drying performance, the uncovered solar collector was found most suitable, even though higher temperatures could be obtained from a well-built collector having a transparent cover. Buelow concludes that this simple solar crop drying system best filled the need of the farmer who cannot economically justify the cost of a fuel-heated air crop-drying system for reasonably small capacity.

Studies by Davis and Lipper show that solar supplemented, forced air drying of grain with an initial moisture content of about 18 per cent (wet basis) can be satisfactorily accomplished when only moderate solar radiation levels (above 160 calories per square centimeter per day) are available, and when the average ambient day-time temperatures are above freezing. It was found also that electricity requirements for fan operation were considerably reduced in the solar heated system because of shorter periods of operation at the favorably low relative humidities achieved in the air stream. At the conditions in Kansas, air from the solar heater was at a relative humidity below 50 per cent during four-fifths of the operating time, whereas this humidity level was achieved in the unheated dryer only about half the operating time. This difference is the principal reason that the natural air dryer required 80 per cent more electric energy for each per cent moisture reduction. In these tests, a solar collector consisting of a plastic-covered ground surface served as the heater for the air supply to one grain drying bin; another identical bin was supplied with unheated air. During the fall months, maximum temperature increases in the air stream through the heater were about 18°F, whereas the average throughout the day was about 13°. Under these conditions, a collector efficiency of about 45 per cent was achieved.

Both groups of investigators have satisfactorily correlated the performance of the simple solar air heaters used in their experiments by means of the following equations, first reported by Buelow. For an uncovered solar collector comprising a metal absorber plate coated with black asphalt roofing paint, the air temperature rise, $t - t_0$, where t_0 is the atmospheric temperature and t is the temperature of the air leaving the heater, can be related to the solar radiation, R, (btu/sq ft, hour) and the air flow rate, v, expressed in cubic feet per minute per square foot of solar collector surface, by the following equation :

$$t - t_0 = 0.108\,R\,(1 - e^{-8.08/v}),\ \text{temperatures in °F}$$

For a heater with a single glass covering, the equation becomes

$$t - t_0 = 0.362\,R\,(1 - e^{-2.16/v})$$

The equations used by Davis and Lipper are essentially the same, with very slight differences in the coefficients. For a plastic-covered collector, they use

$$t - t_0 = (1/3)\,R\,(1 - e^{-2.0/v})$$

Davis and Lipper have also investigated the use of a plastic, air-inflated solar heater which is lightweight, portable, and capable of supplying hot air to a bin for "in storage" drying.

As a general summary to these two papers, it may be stated that by means of very simple additions to certain types of grain drying bins or storage buildings, forced circulation, natural air drying can be economically augmented through the use of an uncovered solar heat absorber incorporated into the roof of the structure. The rise in temperature and reduction in relative humidity of the ambient air, particularly in the fall season in the central United States, provide much greater assurance of satisfactory drying of the grain below the moisture level necessary for long-term storage. Solar supplemented air drying also permits a reduction in the electrical power requirement for fan operation. Although still in the testing stage, these authors indicate that solar drying facilities of this type may become practical under suitable conditions, particularly in comparatively small installations for which the cost of artificial drying facilities is not justified. The economics of the process appear favorable where the low additional cost of the solar drying unit can be offset by savings in fan power cost, economies due to reduced unit size and faster drying, or savings in fuel if solar heat is substituted. Although bare collectors appear to be favored, particularly where comparatively large volumes of air are heated only 10 to 15 degrees above ambient temperature, the use of cheap glazings comprising one layer of glass or plastic above the solar absorbing surface, either as a bin roof or as a separate solar heat collector, may prove useful, particularly if higher temperatures are required.

Solar energy in fruit drying

In his paper, "The Role of Solar Energy in the Drying of Vine Fruit" (S/4), B. W. Wilson compares the drying of sultana grapes by several methods employing solar energy. The method most generally used in Australia for the production of raisins from grapes, is "natural drying" by atmospheric air, solar radiation, or both. As in the drying of crops such as hay, nuts, coffee, and other agricultural products, fruits may be dried by spreading them on the ground. But as contamination by dirt and insects is more objectionable with fruits than with the other materials, other methods have been developed. Sensitivity of the crop to temperature, ultraviolet light, bacterial action, and other factors must be carefully considered in any process used. In addition to solar drying systems, fuel-heated dryers of the tray or cabinet type through which heated air is circulated may be employed.

The author has made a quantitative study of a natural drying system commonly used in Australia for grapes. In this method, bunches of grapes are laid on long, narrow-tiered, wire screen racks under the shelter of a sheet iron roof only slightly wider than the stack of wire racks. The author states that it is generally supposed that the principal source of heat is the surrounding air, but that there is evidence that solar radiation during early morning and late afternoon hours may be of considerable significance as a heat source. Several investigations were conducted, including measurement of temperature inside shaded and irradiated grapes during drying, measurements of transparency of grape skins to solar radiation, studies of drying rates in a full-scale drying rack, and comparisons of drying rates and product quality between the conventional system, a closed drying chamber heated by an internal solar energy absorber, and a full-scale drying rack covered with a plastic sheet to form a drying chamber supplied with solar heated air.

In the first of these studies, it was found that the interior temperature of grapes exposed to solar radiation was 4 to 8 degrees C above ambient air temperature, whereas in the shade, the internal temperature was a few degrees below ambient. Grapes being dried in tiered racks clearly showed this effect as the roof shadow moved across the fruit during the day. Thermal storage in the grapes themselves was noted, solar energy absorbed by the fruit being subsequently utilized for water vaporization during the shaded midday period as well as after sundown. The importance of direct solar absorption in the fruit, as a supplement to the natural drying from warm ambient air, was thus established.

In other measurements, it was found that the skins of grapes are transparent particularly in the red portion of the visible spectrum and the near infra-red below about 0.90 micron wavelength. Natural grapes showed 20 to 40 per cent transmission in this wavelength range. Grape skins coated with an emulsion in which the fruit is dipped prior to drying showed a considerably higher solar transmission, ranging from one third to one half more penetration in these wavelengths. The measurements show that a considerable amount of solar radiation penetrates to the interior of the fruit, thereby facilitating the heat transfer and drying processes.

The internal temperatures of emulsion-dipped grapes exposed to solar radiation were 3 to 5 degrees above ambient temperature, whereas natural grapes under the same conditions showed a 5 to 8 degree rise. These measurements were interpreted to indicate that the rate of moisture transmission through the dipped grapes was sufficiently greater to account for the lower internal temperature even though somewhat more solar radiation was being received inside the fruit.

In tests of drying rate and total loss of moisture from fruit in full-scale weighed drying racks, it was found that over a period of six to ten days there was a rough correlation between the total weight loss (total evaporation) and the total solar energy reaching the fruit. The author states that although heat is supplied to the fruit both by solar radiation and by air, the amount of evaporation taking place requires a quantity of heat roughly equivalent to the incident solar radiation. In other words, energy loss from the fruit by solar reflection and by thermal loss when the surface is warmer than the surrounding air, combined with any temperature changes in the fruit, approximately equals the heat transfer to the grapes from the surrounding air. Several tables in the paper show daily evaporation loss from the fruit, as observed, along with values of the incident solar energy and a "calculated" evaporation loss, based on the incident solar energy. Although there appears to be some correlation of the observed and calculated figures, particularly during the first few days of the drying test, large differences are observed on some days. The method of calculation is not outlined, and it is therefore not possible to appraise the significance of the differences.

The drying of grapes in other types of solar heated dryers was studied, for purposes of comparing rate of drying and quality of product with those of the conventional racks. In one unit, a cabinet dryer was heated by an internal solar energy absorber of 1.5 square meters area. The temperature of ambient air, ranging from 24 to 39 degrees, was increased to a range of 39 to 57 degrees, at a solar absorption efficiency generally above 50 per cent. The drying rate in the unit was found to be comparatively low, however, and the quality of the fruit was poor. In another system, air was heated in a simple type of solar energy absorber from 24 to 37°C to a range of 42 to 57°C at solar absorption efficiencies usually between 25 and 35 per cent. The drying rate in a separate dryer in which grapes were exposed to the stream of heated air was found to be practically the same as in the open racks, and the quality of the fruit was good.

A third set of drying experiments involved the use of a large (102 square meter) solar air heater consisting essentially of a loosely woven black fabric (burlap). Air was drawn through the cloth by means of a fan and then delivered to standard drying racks. Plastic curtains were used to enclose the drying racks so that they would receive only the hot air from the solar heater. Atmospheric air was drawn through the solar energy absorber at the rate of 338 cubic meters per minute by a fan driven by a two-kilowatt electric motor, and delivered to the drying chamber. A temperature rise of 3° to 6°C was secured under these conditions in sunny weather. Maximum temperatures of the air supplied from the solar collector to the dryer usually ranged from 41° to 45°C, and the collector efficiency appeared to average about 50 per cent. The rate of drying was about equal to that observed on the open tiered racks, but the quality of the product was not as good.

In a brief cost analysis, the author shows that the total cost of drying vine fruits by the conventional natural system, involving the long, tiered racks and a combination of air and solar drying, is about one-half the cost of tunnel drying with artificial heat.

The results of experiments reported in the paper, as well as the economic consideration, lead the author to the general conclusion that the vertical tiered racks used for drying fruits in Australia operate partly by absorption of direct radiation and partly by natural air circulation, and that this system is less expensive and more effective for grape drying than others using solar energy absorbers and supplementary sources of power. While the method is dependent on good weather, the same limitation applies to other solar devices, which, in the author's opinion, are less efficient and more expensive to operate. Finally, the need for electric power to operate a forced circulation dryer, whether solar or fuel heated, is an additional economic drawback. The author believes that the drying system based on designs of this general type may be well adapted to drying other crops and materials, particularly in arid areas where fuel and power are expensive. In latitudes where there are long periods of solar radiation at low angles, the use of a stack of horizontal drying surfaces for absorption of solar radiation should receive greater attention.

It is of interest to compare the results obtained by Wilson in the drying of grapes by this simple process and those obtained by Ismailova in the drying of apples in direct solar heated dryers. Ismailova found that rapid drying and good quality products could be obtained even under the rather intensive conditions experienced in a glass-covered irradiated dryer supplied with preheated air from separate solar collector. Although a strictly comparable system was not used by Wilson (nor was the Australian system tested directly by Ismailova), the results of these investigators appear to be reasonably consistent. It is probable that higher drying rates could be achieved in the drying of grapes if the more intensive energy supply used by Ismailova for apple drying were used. However, loss of quality, perhaps by overheating or by excessive surface drying without moisture transfer from the interior of the fruit, might result. The tiered-rack system might also be useful in the drying of apple slices, but the absence of a natural skin on the cut surfaces would make contamination of the product more serious.

Solar drying of oil shale

The fourth paper in this section of the Conference deals with the drying of a naturally occurring mineral. Oil shale mined in the Paraiba Valley of Brazil has a high moisture content, averaging about 33 per cent on the wet basis. The subsequent processing of this material for liquid fuel production requires high temperature thermal decomposition of the hydrocarbons in the shale, called retorting. Heat for this process is usually provided by combustion of a portion of the organic material in the shale. It is clear that the moisture requires heat for its vaporization and that if a dry shale were supplied to the retorting process, a greater net yield of liquid and gaseous hydrocarbons could be obtained. Solar drying of the shale prior to retorting was therefore considered as a means for increasing the efficiency of shale oil recovery.

The very low value of a ton of oil shale precludes any substantial expenditure for drying it. The method therefore considered potentially useful requires the spreading of crushed wet shale on a large area of gound, allowing it to dry in the sun until the moisture content has been sufficiently reduced, and then collecting the dried shale for further processing. Machinery would be employed in a commercial plant to handle the thousands of tons considered a minimum practical daily throughput.

In their study (S/83), Talwalkar, Duffie, and Löf have developed an over-all energy balance for a layer of a moist solid on the ground, exposed to solar radiation and the atmosphere. The net incident energy is equated to the sum of latent and sensible heat transfer from the material to the surroundings, convection to the surroundings, conduction through the bottom, radiation from the material to the sky, and the gain or loss in energy content of the material. Some of the terms are negligibly small in the overall energy balance, whereas the useful heat of evaporation and the convective heat loss terms are most significant. Each of these terms is evaluated and correlated with measurable variables such as air temperature, material temperature, air velocity, and the optical properties of the material.

Preliminary studies of the process by Petroleo Brasileiro indicated that the percentage moisture lost (or gained during a rain storm) is an inverse function of the bed thickness and that with layers more than a very few inches deep, occasional agitation of the material is decidedly useful. The University of Wisconsin study was devoted primarily to evaluating the terms in the energy balance, correlating the various energy quantities and drying rates with atmospheric variables, determining efficiency of solar utilization as drying proceeds, investigating the mechanism of drying individual particles, and evaluating the economics of the process.

Of fundamental importance was the finding that at a constant solar radiation level, the drying rate decreased non-linearly with the moisture content regardless of shale moisture content. In other words, there was no constant drying rate period such as that obtained with wet sand and other granular materials. Because the drying is entirely in the "falling rate period", internal diffusion of moisture in the shale particle and the shale bed is the controlling rate, increasing with shale temperature and decreasing with bed thickness. Air velocity change therefore has no appreciable effect on drying rate, and inasmuch as the absorption of radiation results in a shale temperature well above that of the atmosphere, air humidity change has negligible effect.

Although the coefficient of thermal convection from the shale was found to be insensitive to wind velocity, the rate of heat loss by convection is a direct function of the temperature difference between the shale and the surrounding air. As the shale becomes dryer, its surface temperature rises due to the decreased cooling effect of evaporation and the reduced proportion of the absorbed radiation being utilized for water vaporization. Convection loss thus increases as drying proceeds.

Studies of temperature gradients in the shale bed showed that surface temperatures on a clear day ranged from 10 to 15°F above the temperature several inches below the surface. The interior temperature averaged 5 to 10°F above ambient temperature during clear weather. Temperature gradients in a single piece of shale at the surface of the bed were found to be relatively small. The maximum difference in temperature at a point one-quarter inch inside a piece of shale and at another location one and one-half inch below the surface reached about 10 degrees.

Because the shale serves also as the solar radiation absorber, its absorptivity for solar radiation is an important property. This was measured both for wet shale and for the solar-dried product and found to decrease from about 92 per cent to approximately 83 per cent.

In a series of shale drying tests, each covering several days of solar exposure, the distribution of the radiation was determined. The results are presented in tabular form in the paper. A summary of these data shows that over a four-day period, at an average radiation level of 1 900 btu/sq ft, the moisture content of 33 pounds of shale in a three-inch bed of one to three-inch shale pieces could be reduced from 40.8 per cent (dry basis) to 12.3 per cent. The corresponding efficiency of solar energy use ranged from 44 per cent at the start to 18.5 per cent on the last day. Approximately five days were required, at an average radiation level of about 1 800, to reduce the moisture from 41.5 to 14.4 per cent (dry basis) with an average solar utilization efficiency ranging from 45.8 to 18.5 per cent.

In an approximate economic appraisal of the drying of oil shale at a rate of 12 000 tons per day from an original 33 per cent moisture content (wet basis), it was found that a drying field of approximately 470 hectares would be required. Vehicles would spread the shale in a one-foot layer on this area, and in about 10 days, the shale moisture would have been reduced to approximately 10 per cent under average weather conditions. This performance is based on an average solar utilization efficiency of 30 per cent. Machinery would then pick up the dried shale for supply to retorts. It was estimated that the labor and equipment for the solar drying of the shale would cost approximately U.S.$50 per million kilocalories of heat utilized in drying. At the cost of petroleum in Brazil, the fuel that would be required to evaporate this moisture from the shale, roughly equal to the decrease in oil yield if the shale were not dried, would require an expenditure of about $5.00 per million kilocalories. Based on these rough figures, it is clear that if this oil shale deposit is commercially developed, solar drying prior to retorting has sufficient economic attractiveness to demand its thorough evaluation.

General review

It is surprising that a process used as commonly as solar drying has received so little technical development. With the enormous tonnage of materials being processed by this method, greater effort in its development and improvement would seem in order. It is not unreasonable to believe that annual savings in millions of dollars might be realized through lowering the costs of drying, improving the quality of the products, and reducing losses by spoilage, deterioration, transport delays, and other factors. The substitution of solar drying for fuel drying or simply the reduction in fuel demand by a cheap supplementary solar heat supply would appear of considerable benefit in many areas. It is suggested by this rapporteur that the discussions of this topic should bear on the questions of needs, prospects, and merits of increased technical study of solar drying in order that these benefits may be achieved.

Pertinent topics for discussion

(*a*) The extent, to which product quality may be suffering from poor solar drying methods;

(*b*) The types and quantities of agricultural products that are now being wasted through loss and spoilage which might otherwise be saved if effective and economical drying means were provided;

(*c*) The economics of incorporating cheap solar air heaters as supplementary units in fuel-heated drying systems, simply as fuel saving devices;

(*d*) The possibility of developing indirect solar dryers for grains, fruits, and other materials, which would not require electric power for circulating heated air from a solar collector to an enclosed drying unit of some type;

(*e*) The possibility that some solar dried products might have uniquely valuable properties such as exceptional quality, appearance, or nutritive value;

(*f*) The need for more fundamental data on the mechanism of drying by direct solar energy absorption in the material;

(*g*) The extent to which new and much cheaper transparent materials, such as the plastic films, might reduce the cost and increase the applicability of solar heaters for indirect drying.

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : SÉCHAGE PAR LA CHALEUR SOLAIRE

(Traduction du rapport précédent)

George O. G. Löf *

Bien que le séchage constitue une des utilisations les plus anciennes de l'énergie solaire, la proportion des travaux qui lui ont été consacrés dans les recherches modernes sur l'emploi de l'énergie solaire est relativement faible, et ceci pour plusieurs raisons. Le séchage par la chaleur solaire, là où il est pratiqué, et notamment en agriculture, s'effectue assez bien par des méthodes simples et rudimentaires. La méthode peu coûteuse et efficace qui consiste à répandre les produits agricoles sur le sol ou sur une plate-forme pour les faire sécher directement au soleil est appliquée avec succès dans le monde entier à beaucoup de denrées. Elle ne demande pas d'investissement en biens de capital et même si elle exige parfois beaucoup de main-d'œuvre, celle-ci est rarement onéreuse. Comme, d'autre part, le consommateur ne demande en général pas un produit de haute qualité, un excès de séchage, une contamination par des impuretés et des insectes ou une certaine dégradation sont souvent tolérés.

Un autre facteur défavorable est la nébulosité intermittente et parfois prolongée qui empêche un séchage satisfaisant par la chaleur solaire. Si donc un produit *doit* être séché assez rapidement, il faut faire appel à une source auxiliaire d'énergie. Dans ce cas, il s'avère souvent plus simple d'utiliser les dispositifs « auxiliaires » de façon continue; on les maintient dans des dimensions aussi réduites que possible pour diminuer l'investissement et l'on emploie de la chaleur artificielle pour le séchage. Enfin, si le séchage se fait en grand, les installations de chauffage doivent être assez importantes, et il faut prévoir des collecteurs solaires à grande surface ainsi que divers autres dispositifs.

Les recherches récentes sur le séchage par la chaleur solaire ont été orientées dans les deux directions qui ressortent des considérations précédentes. Autrement dit, les travaux ont porté : premièrement, sur le séchage *direct*, procédé selon lequel le produit est exposé au rayonnement solaire et l'humidité vaporisée dans l'atmosphère par absorption d'énergie et circulation d'air; deuxièmement, sur le séchage *indirect*, réalisé au moyen d'un chauffe-air solaire (dont il existe plusieurs types) qui alimente en air chaud une section de séchage distincte. Dans le deuxième procédé, l'énergie solaire pourrait en général être remplacée par une autre source de chaleur pour l'alimentation de la même unité de séchage. Il faut cependant signaler que le plan de la section de séchage, indépendamment du dispositif de chauffage par l'énergie solaire, présente parfois des caractéristiques particulières qui découlent de la nature de la source thermique solaire.

Les recherches ont également porté sur des combinaisons de ces deux procédés fondamentaux de séchage solaire. Un collecteur solaire peut être employé pour alimenter en air chaud une unité de séchage dans laquelle le produit est aussi exposé directement au rayonnement solaire. On a également étudié un autre type de « séchoir solaire » qui n'est qu'un séchoir classique chauffé à la vapeur, mais où la vapeur est produite dans une chaudière solaire. En fait, il ne s'agit pas vraiment dans ce cas de séchage par la chaleur solaire, puisque le seul problème d'utilisation de l'énergie solaire consiste à produire de la vapeur à basse pression au moyen de collecteurs solaires. La même observation pourrait s'appliquer à l'utilisation des chauffe-air solaires, mais les problèmes très particuliers qui résultent des températures relativement basses de l'air, des fluctuations de la source thermique et d'autres facteurs font que l'emploi de l'air chauffé par l'énergie solaire intéresse beaucoup plus directement le processus même du séchage.

Dans les directives générales concernant la Conférence, il était recommandé que les mémoires soient consacrés à des procédés de séchage solaire autres que la méthode très répandue qui consiste à exposer les produits directement au soleil en les disposant sur des surfaces non protégées. Il était cependant précisé qu'il serait intéressant de présenter à la Conférence des données nouvelles sur ce procédé classique, ainsi que les résultats des recherches effectuées sur de nouveaux produits séchés par cette méthode, ou tous autres renseignements utiles concernant ce type de séchage direct. Les sujets qui ont paru les plus intéressants pour la Conférence sont ceux qui touchent au progrès des procédés et de l'appareillage de séchage par la chaleur solaire et qui permettraient d'améliorer la qualité des produits, de diminuer les pertes de produits agricoles et de denrées alimentaires par détérioration et de

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réaliser des économies dans les opérations de séchage pour lesquelles un combustible est en général employé comme source de chaleur.

Quatre mémoires traitant de l'emploi de l'énergie solaire pour le séchage ont été présentés à la Conférence. Deux de ces mémoires sont consacrés au séchage indirect, procédé selon lequel l'énergie solaire sert à chauffer de l'air qui alimente une section de séchage séparée. Deux autres traitent de l'absorption directe de l'énergie solaire sur ou dans les produits à sécher, sans l'emploi de surfaces protectrices transparentes. Toutefois, un de ces deux derniers mémoires contient aussi une brève étude sur des chauffe-air solaires séparés alimentant des compartiments de séchage et établit une comparaison entre les deux systèmes.

Ces quatre mémoires peuvent aussi être classés selon le type des produits à sécher. Trois s'occupent du séchage de produits agricoles, tandis que le quatrième traite du séchage d'un produit minéral contenant de l'eau. Deux traitent surtout du séchage des céréales, maïs par exemple, alors que le troisième concerne les fruits, et spécialement les raisins. Le produit minéral qui fait l'objet du quatrième mémoire est un schiste argileux pétrolifère à haute teneur en humidité. Les seuls produits d'importance qui font l'objet d'un séchage commercial et ne sont pas représentés dans l'ordre du jour sont le bois (surtout le bois de construction) et divers produits manufacturés comme les substances chimiques, les articles en céramique et le papier.

Bien que quelques investigations sur le séchage par la chaleur solaire et quelques chercheurs spécialisés en ce domaine ne soient pas représentés dans l'ordre du jour de la Conférence, les quatre mémoires en question couvrent assez complètement le sujet. Il n'est donc pas nécessaire de passer en revue les travaux antérieurs pour replacer ces mémoires dans une perspective adéquate. La plupart des travaux qui ont été consacrés au séchage par la chaleur solaire au cours des dix dernières années sont dus aux auteurs des mémoires cités, et des références à ces travaux figurent dans le texte même des mémoires. Les études publiées auparavant sur cette question avaient surtout pris la forme de nombreux brevets d'invention relatifs à divers types d'appareils de séchage par la chaleur solaire, dont très peu ont été utilisés.

Le rapporteur voudrait cependant appeler l'attention des participants sur un travail important qui n'apparaît pas dans la documentation de la Conférence. Il s'agit du rapport préparé par Ismaïlova en URSS, et qui a été publié dans *Teploenergetica*, vol. 1, 1957, sous le titre « Possibilité d'application de l'énergie solaire au séchage des fruits et légumes ». Ce rapport décrit surtout les opérations de séchage des pommes coupées dans trois types d'installations : *a*) un séchoir solaire chauffé directement et recouvert de verre; *b*) un séchoir indirect chauffé par l'air sorti d'un collecteur solaire à plaque plate; *c*) un séchoir réalisant une combinaison des deux systèmes précédents. L'auteur analyse les caractéristiques de ces trois systèmes et compare leur efficacité. Il a effectué des mesures du régime de séchage dans des conditions de fonctionnement très variées, a déterminé la longueur du temps de séchage nécessaire, a évalué la qualité du produit par des tests chimiques et autres, et a comparé les trois systèmes en question l'un avec l'autre et avec des systèmes de séchage au moyen d'un combustible. En outre, il a analysé les caractéristiques du transfert de chaleur dans un réchauffeur d'air du type à plaque plate et établi des corrélations entre le rendement d'un tel réchauffeur et diverses variables telles que la vitesse de l'air, la température, etc.

Ces études peuvent se résumer comme suit :

a) Par comparaison avec les systèmes de séchage utilisant un combustible, les fruits et les légumes peuvent être séchés de façon satisfaisante dans des installations solaires et il en résulte une économie de combustible. Par rapport au « séchage naturel », c'est-à-dire la simple exposition directe des produits au soleil et à l'air, on réalise une économie substantielle de temps.

b) Les fruits mis à sécher dans des compartiments fermés chauffés à la chaleur solaire sont de meilleure qualité, plus propres et plus riches en vitamine C que ceux qui sont traités par un procédé de séchage naturel.

c) Les trois types de séchoirs solaires expérimentés sont efficaces pour traiter les fruits et légumes. Le séchage par rayonnement direct est le plus rapide, tandis que le procédé avec compartiment de séchage fermé, alimenté par de l'air chauffé à l'énergie solaire, donne un produit de qualité un peu supérieure, sans doute parce que les températures maximales atteintes par le fruit sont moins élevées.

d) Les réchauffeurs solaires à plaque plate munis d'une ou de deux enveloppes de verre peuvent fournir de l'air jusqu'à 100 °C et ont été employés dans les expériences décrites.

e) Pour calculer le transfert de chaleur d'une plaque solaire vers l'enveloppe supérieure de verre, l'auteur recommande d'appliquer les relations suivantes :

$$Nu_m = 0{,}42\ Re_m^{0.65} \text{ si } 250 < Re < 620$$

$$Nu_m = 11{,}1\ Re_m^{0.156} \text{ si } 620 < Re < 1\,400$$

S'il y a un espace d'air au-dessous de la plaque noire irradiée, le transfert de chaleur vers le fond du compartiment à partir de cette plaque peut être calculé par les équations suivantes :

$$Nu_m = 0{,}026\ Re_m^{1.06} \text{ si } 170 < Re < 520$$

$$Nu_m = 1{,}5\ Re_m^{0.423} \text{ si } 520 < Re < 1\,200$$

Dans ces équations, Nu_m est le nombre de Nusselt et Re_m le nombre de Reynolds, en unités non dimensionnelles.

Principes du chauffage par la chaleur solaire

Un examen de la théorie du séchage sortirait du cadre de ce rapport, mais il peut être utile d'indiquer quelques principes. Il s'agit notamment des principes applicables au séchage par rayonnement direct, car ceux qui interviennent dans le séchage des produits dans divers types de compartiments opaques alimentés à l'air chaud, que celui-ci soit produit par un réchauffeur solaire ou par tout autre système de chauffage, sont assez bien décrits dans la littérature consacrée au séchage. La première condition est qu'un transfert de chaleur se produise vers la surface du produit humide par conduction des surfaces chauffées en contact avec le produit, ou par conduction et convection à partir de l'air adjacent à des températures dépassant sensiblement celle du produit à sécher, soit enfin par radiation à partir du soleil. L'absorption de la chaleur par le produit fournit l'énergie nécessaire à la vaporisation de l'eau qu'il contient, cette énergie équivalant à environ 1 050 btu par livre (0,45 kg) d'eau évaporée, ou 590 calories par gramme. L'eau commence à se vaporiser à partir de la surface du produit humide lorsque l'énergie absorbée a augmenté suffisamment la température pour que la pression de vapeur excède la pression partielle dans l'air environnant. L'état stable est réalisé lorsque la chaleur nécessaire à la vaporisation devient égale au taux d'absorption de la chaleur provenant du milieu ambiant.

Pour compenser l'humidité qui s'est échappée de la surface, il faut que se produise dans le produit mis à sécher une diffusion de l'eau du centre vers la périphérie. Ce processus peut être rapide ou lent selon la nature du produit et sa teneur en humidité à un moment quelconque. C'est lui qui, par conséquent, peut être le facteur limitatif dans l'opération de séchage ou, si la diffusion d'humidité est rapide, le facteur limitatif peut être le taux d'absorption de chaleur à la surface du produit, ou bien la vitesse de vaporisation. Dans quelques produits très poreux, la vaporisation peut même se produire en-dessous de la surface visible, la vapeur se diffusant dans ce cas à travers les pores du solide.

Dans le cas du séchage par rayonnement direct, une partie du rayonnement peut pénétrer dans le produit et être absorbée à l'intérieur du produit lui-même. Dans ces conditions, la chaleur est engendrée à l'intérieur du produit, de même qu'à sa surface, et le transfert de chaleur dans le produit s'en trouve facilité.

Pour des raisons économiques, on désire en général que le séchage s'effectue aussi rapidement que possible. Il faut cependant tenir compte de la qualité du produit, car des températures excessives sont à éviter dans beaucoup de cas. En outre, étant donné que le séchage a lieu en surface, les denrées qui ont tendance à former une couche superficielle dure et sèche relativement imperméable au transfert de liquide et de vapeur doivent être séchées à un régime suffisamment bas pour éviter la formation de cette croûte. Il faut exercer un contrôle rigoureux des taux de transfert de chaleur et de vaporisation, en réglant soit l'apport de chaleur, soit la teneur en humidité de l'air ambiant.

Le séchage d'un produit par simple circulation d'un air relativement sec, sans recours à une source de chaleur directe ou indirecte, est connu sous le nom de séchage adiabatique. La chaleur nécessaire pour vaporiser l'humidité est apportée par l'air au produit solide, ce qui réduit la température de l'air tout en augmentant son humidité absolue et relative. Étant donné la faible capacité calorifique de l'air, par comparaison avec la haute chaleur latente de vaporisation de l'eau, de grands volumes d'air ayant une humidité relative assez faible doivent être utilisés dans ce type de séchage. L'air quittant le séchoir est presque saturé d'humidité à la température du thermomètre à boule mouillée. L'air d'admission, à sa température (lue au thermomètre à boule sèche) et son humidité relative initiales, est ainsi refroidi et humidifié pour atteindre la température du thermomètre à boule mouillée, tandis que les produits humides en contact avec cet air s'approchent également de la température du thermomètre à boule mouillée.

La généralisation précédente doit être quelque peu modifiée si le produit mis à sécher présente une solubilité quelconque dans l'eau. Les fruits et certains autres produits agricoles contiennent des sels et des sucres qui provoquent un abaissement de la pression de vapeur. Les températures superficielles de ces produits doivent donc être plus élevées que la température de l'air au thermomètre à boule mouillée pour que la vaporisation puisse avoir lieu. Il s'ensuit que le séchage adiabatique de ces produits exige de l'air à une humidité relative plus faible que les produits ne contenant pas de matières solubles en phase aqueuse.

Une propriété importante des denrées séchées par exposition directe au rayonnement est leur absorptivité vis-à-vis du rayonnement. La plupart des produits solides ont heureusement des absorptivités assez élevées, mais des changements peuvent survenir au cours du séchage, la surface d'un produit devenant moins « noire » ou parfois plus, au cours de l'opération. De même, il peut se produire des modifications de l'opacité de la surface des denrées qui sont partiellement traversées par quelques-unes des longueurs d'ondes du spectre de la source radiante.

La conductivité thermique du produit joue également un rôle important, en particulier s'il est mis à sécher en une couche d'épaisseur suffisante pour qu'une conduction de chaleur soit nécessaire d'une particule à l'autre. Si la conductivité thermique est médiocre, une circulation d'air chauffé à travers et entre les particules du produit humide permettra un meilleur transfert de chaleur que le rayonnement direct à la surface d'une couche de particules relativement épaisse.

Séchage solaire indirect de céréales ou autres produits agricoles

Les deux mémoires qui traitent du séchage de produits agricoles par de l'air chauffé à l'énergie solaire, S/17 par F. H. Buelow et S/53 par C. P. Davis et R. I. Lipper, tendent au même but et se fondent sur des expériences similaires. L'un et l'autre envisagent le séchage de céréales avec un équipement simple qui pourrait être réalisé par les utilisateurs eux-mêmes et se prêterait fort bien à de petites installations. Ils étudient principalement l'emploi de réchauffeurs d'air de type simple, à plaque plate, fixés sur le toit de petits abris ou granges de séchage qui servent en même temps à l'emmagasinage et au séchage des céréales ou autres produits. Le but de ces systèmes est de compléter le séchage naturel par l'air — lequel est souvent inefficace à cause de l'excès d'humidité atmosphérique — de façon à diminuer la teneur en humidité des produits jusqu'au point où ils ne risqueront plus de se détériorer. Les deux systèmes ont aussi pour caractéristique commune d'employer des débits d'air importants et des températures qui, de ce fait, ne sont que faiblement augmentées dans le collecteur solaire, ce qui exige l'emploi d'une plaque solaire absorbante sans aucun revêtement, ou d'un collecteur muni au maximum d'une seule enveloppe transparente.

Dans ces études, les auteurs montrent que pour faire sécher du maïs ou d'autres céréales au moyen d'une circulation forcée d'air atmosphérique à travers les casiers à grains, la condition indispensable est que l'air soit suffisamment sec pour permettre à l'humidité des grains de se vaporiser. Ce mode de séchage « en stockage », surtout s'il est appliqué à des céréales récoltées en automne, doit être réalisé en l'espace de quelques semaines pour mettre les grains humides à l'abri de la détérioration. Parmi les conditions et méthodes à respecter, l'une concerne le stockage des grains dans des casiers à fond perforé à travers lesquels on fait circuler l'air pendant deux ou trois mois d'automne, réduisant ainsi la teneur des grains en humidité dé 18-20 p. 100 à 10-12 p. 100. On a constaté que l'humidité relative de l'air que l'on fait circuler entre les grains doit être inférieure à 62 p. 100 environ dans la plupart des cas si l'on veut que la teneur en humidité du produit diminue suffisamment pour assurer une bonne conservation pendant l'emmagasinage. Lorsque l'humidité atmosphérique dépasse ce chiffre, le produit ne sèche pratiquement pas et, à supposer que cet état hygrométrique élevé se prolonge, de graves pertes peuvent survenir, à moins que l'on ne dispose d'une autre source de chaleur.

Ces chercheurs ont observé qu'une augmentation de 10 à 15 °F de la température de l'air utilisé pour le séchage réduit suffisamment l'humidité relative, même d'un air très humide, pour le rendre propre au séchage des produits agricoles. Les uns et les autres ont montré que l'emploi d'un simple collecteur solaire constitué par un double toit posé au-dessus d'un compartiment de séchage permet d'augmenter de 10 à 20 °F la température de gros volumes d'air et d'accélérer ainsi sensiblement le régime de séchage, tout en diminuant les risques de pourrissement des grains. Dans un des systèmes décrits, le local de séchage-stockage est couvert d'un toit en tôle ondulée passé à la peinture noire qui sert d'absorbeur d'énergie solaire. Un espace d'air de 1 à 4 pouces (2,5 à 10 cm) est prévu au-dessous de cette couverture métallique pour former un passage à travers lequel l'air est aspiré au moyen d'un ventilateur avant d'être envoyé sous le fond perforé des compartiments de séchage. Un revêtement appliqué sous le poutrage qui supporte le toit sert à enfermer le circuit d'air; un isolant peut éventuellement être appliquée sous ce revêtement. Dans quelques essais (effectués par les deux groupes de chercheurs) une enveloppe de verre ou de matière plastique a été placée au-dessus de la surface métallique absorbante pour réduire la perte de chaleur.

Dans la plupart des essais, la vitesse de circulation de l'air et la capacité des soufflantes étaient les mêmes que dans le procédé de séchage naturel par l'air. Ainsi, on a utilisé des débits de 2 à 4 pieds cubes (0,05 à 0,11 m^3) par minute par boisseau de grain (environ 36 litres). Les surfaces des collecteurs solaires employés dans les deux études étaient telles que les débits d'air se situaient entre 10 et 15 pieds cubes (0,28 à 0,42 m^3) par minute et par pied carré de collecteur. Dans ces conditions, la chute de pression due au passage dans le collecteur solaire et les conduits indispensables n'était pas assez importante pour qu'il soit nécessaire de remplacer le ventilateur prévu pour le séchage par air non chauffé.

Dans ses essais, Buelow est parvenu à réduire de 50 et même 75 p. 100 la durée totale de séchage d'un produit agricole en complétant le séchage par circulation forcée d'air naturel par un préchauffage à l'énergie solaire. Il a conclu que le coût de construction d'un bâtiment approprié à ce type de séchage ne dépassait guère celui d'un local de séchage à l'air non chauffée. Étant donné qu'une hausse de quelques degrés seulement de la température suffit à assurer un rendement satisfaisant du processus de séchage, le collecteur solaire sans revêtement a paru tout à fait approprié, même si un collecteur plus perfectionné muni d'une enveloppe transparente permettait d'obtenir des températures plus élevées. Buelow conclut que ce système simple de séchage des produits agricoles par l'énergie solaire répond le mieux aux besoins des agriculteurs pour qui le prix d'une installation de séchage de capacité modeste à l'air chauffé par un combustible ne présente pas des avantages suffisants.

Les études de Davis et Lipper montrent que le séchage des céréales par circulation forcée d'air et appoint de chaleur solaire, lorsque le produit a une teneur initiale en humidité d'environ 18 p. 100 (par rapport au poids humide), peut être réalisé de façon satisfaisante dès lors que le rayonnement solaire atteint une valeur même très moyenne (plus de 160 calories par centimètre carré et par jour) et que les températures moyennes ambiantes pendant la journée dépassent 0 °C. Ces auteurs ont aussi constaté que la consommation d'électricité pour le fonctionnement des ventilateurs était beaucoup moins grande dans le système chauffé par l'énergie solaire, parce que l'humidité relative assez basse obtenue dans le flux d'air permettait de diminuer la durée de fonctionnement des soufflantes. Au Kansas, l'air sorti du réchauffeur solaire était à une humidité relative inférieure à 50 p. 100 pendant les quatre cinquièmes de la durée de fonctionnement, alors que ce degré d'humidité n'était obtenu dans le séchoir non chauffé que pendant la moitié environ de la durée de fonctionnement. Cette différence est la principale explication du fait que le séchoir à l'air naturel consomme 80 p. 100 d'énergie électrique de plus pour réduire la teneur en humidité de 1 p. 100. Dans ces essais, un collecteur solaire constitué par une surface recouverte d'une enveloppe en matière plastique servait à réchauffer l'air qui alimentait un compartiment de séchage contenant du grain ; un autre compartiment identique au premier était alimenté par de l'air non chauffé. Pendant les mois d'automne, les températures maximums enregistrées dans le courant d'air traversant le réchauffeur étaient d'environ 18 °F et la moyenne journalière d'environ 13 °F. Dans ces conditions, le rendement du collecteur était d'environ 45 p. 100.

Les deux groupes de chercheurs sont parvenus à établir une relation mathématique satisfaisante pour calculer le rendement des chauffe-air solaires du type simple employés dans leurs expériences; ils se sont basés sur les équations ci-après, rapportées initialement par Buelow. Pour un collecteur solaire non revêtu, composé d'une plaque absorbante métallique recouverte d'un enduit d'étanchéité noir à l'asphalte, l'augmentation de la température de l'air, $t - t_0$, où t_0 est la température atmosphérique et t la température de l'air à la sortie du réchauffeur, peut s'exprimer en fonction du rayonnement solaire, R (en btu par pied carré et par heure) et de la vitesse d'écoulement de l'air, v (en pieds cubes par minute, par pied carré de surface du collecteur solaire) au moyen de l'équation suivante :

$$t - t_0 = 0{,}108\, R\, (1 - e^{-8{,}08/v}), \text{ température en °F}$$

Pour un réchauffeur muni d'une seule enveloppe en verre, l'équation devient :

$$t - t_0 = 0{,}362\, R\, (1 - e^{-2{,}16/v})$$

Les équations employées par Davis et Lipper sont essentiellement les mêmes, avec des différences minimes dans les coefficients. Pour un collecteur recouvert d'une enveloppe de composition plastique, ils posent :

$$t - t_0 = (1/3)\, R\, (1 - e^{-2{,}0/v})$$

Davis et Lipper ont également étudié l'emploi d'un réchauffeur solaire en matière plastique gonflé d'air, qui est léger, transportable et capable de fournir de l'air chaud à un local pour un séchage en cours de stockage.

Pour résumer l'idée générale de ces deux mémoires, on peut dire qu'ils montrent comment, en ajoutant des dispositifs très simples à certains types de granges ou de compartiments servant au séchage des céréales, on peut, sans grands frais, intensifier le séchage réalisé par circulation forcée d'air naturel en lui adjoignant un absorbeur de chaleur solaire non revêtu que l'on incorpore au toit du bâtiment. L'augmentation de la température et la réduction de l'humidité relative de l'air ambiant, notamment en automne dans le centre des États-Unis, augmentent beaucoup les chances d'arriver à faire tomber la teneur des grains en humidité au-dessous du niveau qui assure un stockage prolongé. Le séchage à l'air avec appoint de chaleur solaire diminue aussi la consommation de courant électrique du ventilateur. Bien que les recherches en soient encore au stade des essais, les auteurs indiquent que de telles installations de séchage par la chaleur solaire peuvent trouver leur application pratique dans des conditions appropriées, notamment dans les petites entreprises agricoles où le prix de revient d'une installation de séchage artificiel n'est pas justifié. Le bilan économique du système semble favorable dès que le coût (peu élevé) du dispositif de séchage à la chaleur solaire peut être compensé par des économies sur l'électricité nécessaire au fonctionnement du ventilateur, sur les dimensions (plus modestes) de l'installation de séchage, sur la durée des opérations, ou sur la consommation de combustible lorsque celui-ci est remplacé par la chaleur solaire. La préférence semble aller aux collecteurs non revêtus, en particulier s'il s'agit de chauffer des volumes d'air relativement importants à 10 ou 15 degrés seulement au-dessus de la température ambiante, mais l'emploi de revêtements peu coûteux comprenant une couche de verre ou de composition plastique appliquée au-dessus de la surface absorbante, soit comme toiture du local de séchage, soit sous forme de collecteur solaire séparé, peut présenter des avantages, notamment si l'on veut obtenir des températures plus élevées.

Utilisation de l'énergie solaire pour le séchage des fruits

Le mémoire intitulé « Le rôle de l'énergie solaire dans le séchage des fruits » (S/4), par B. W. Wilson, compare les mérites respectifs de plusieurs procédés de séchage des raisins sultans par l'énergie solaire. La méthode le plus généralement employée en Australie pour la production des raisins secs est le « séchage naturel » par l'air atmosphérique, le rayonnement solaire, ou ces deux agents à la fois. Comme d'autres produits agricoles (foin, noix, café, etc.), les fruits peuvent être séchés par simple étalement sur le sol. Toutefois, la contamination par les impuretés et les insectes est plus grave avec les fruits qu'avec d'autres denrées, en sorte que l'on a mis au point d'autres méthodes. Dans n'importe quel procédé, on doit tenir compte de la sensibilité du produit à la température, aux rayons ultraviolets, à l'action des bactéries et à d'autres facteurs. En plus des procédés de séchage par la chaleur solaire, on peut utiliser des séchoirs du type à claies ou à casiers, chauffés au moyen d'un combustible et à travers lesquels on fait circuler de l'air chaud.

L'auteur a fait une évaluation quantitative d'un système de séchage naturel couramment employé en Australie pour les raisins. Il consiste à disposer des grappes de raisin sur des claies longues et étroites en treillis de fil de fer, disposées en étages et abritées par un toit de tôle à peine plus large que le clayonnage. Selon l'auteur, bien qu'il soit généralement admis que la principale source de chaleur est l'air ambiant, les faits semblent indiquer que le rayonnement solaire du début de la matinée et de la fin de l'après-midi constitue une source de chaleur très importante. Les investigations ont porté sur les points suivants : mesures de la température à l'intérieur des raisins placés à l'ombre ou au soleil, mesures de la perméabilité de la peau des raisins au rayonnement solaire, étude des régimes de séchage dans une claie de grandeur réelle, et comparaison entre les régimes de séchage et la qualité des produits obtenus, d'une part, avec le procédé classique (compartiment de séchage fermé, chauffé au moyen d'un absorbeur d'énergie solaire placé à l'intérieur du local), et, d'autre part, avec une claie de grandeur réelle recouverte d'une enveloppe de matière plastique et formant une chambre de séchage alimentée avec de l'air chauffé par l'énergie solaire.

Dans la première de ces investigations, l'auteur a constaté que la température intérieure des raisins exposés au rayonnement solaire dépassait de 4 à 8 °C la température de l'air ambiant, alors que la température interne des raisins placés à l'ombre était inférieure de quelques degrés à la température ambiante. Cette différence s'observait parfaitement sur des raisins mis à sécher dans des claies superposées pendant que l'ombre du toit se déplaçait sur les fruits au cours de la journée. On a noté qu'une accumulation de chaleur avait lieu dans les raisins eux-mêmes, les fruits utilisant ensuite l'énergie solaire ainsi absorbée pour vaporiser de l'eau au milieu de la journée, pendant qu'ils se trouvaient à l'ombre, et après le coucher du soleil. L'importance de l'absorption directe de la chaleur solaire dans le fruit, qui complète le séchage naturel réalisé par l'air ambiant tiède, a ainsi été démontrée.

Dans d'autres mesures, l'auteur a constaté que la peau des raisins est particulièrement perméable à la lumière rouge du spectre visible, ainsi qu'aux rayons infrarouges adjacents d'une longueur d'onde inférieure à 0,90 micron environ. Des raisins à l'état naturel ont été pénétrés par 20 à 40 p. 100 des rayons compris dans cet intervalle de longueur d'ondes. Les mesures effectuées sur des raisins trempés dans une émulsion avant d'être mis à sécher ont montré que la pénétration des rayons solaires était fortement augmentée par ce traitement, l'augmentation étant de 33 à 50 p. 100 pour ces longueurs d'ondes. Les mesures montrent qu'une quantité considérable de rayonnement solaire pénètre à l'intérieur du fruit, facilitant le transfert de chaleur et les processus de séchage.

Les températures internes des raisins trempés dans une émulsion et exposés au rayonnement solaire dépassaient de 3 à 5 degrés la température ambiante, tandis que ce dépassement atteignait 5 à 8 degrés pour des raisins non traités placés dans les mêmes conditions. Selon l'auteur, ces mesures indiquent que l'accélération du passage de l'humidité à travers les raisins traités est suffisamment forte pour expliquer un tel abaissement de la températurei nterne, même en tenant compte de la plus grande quantité de rayonnement solaire reçue par les fruits traités.

L'auteur a pratiqué des expériences sur le régime de séchage et la perte totale d'humidité des fruits placés dans des claies grandeur nature soumises à des pesées, et il a constaté que sur une période de 6 à 10 jours il existait une certaine corrélation entre la perte de poids totale (évaporation totale) et la quantité totale d'énergie solaire qui avait effectivement atteint le fruit. L'auteur indique que, bien que la chaleur soit fournie au fruit à la fois par le rayonnement solaire et par l'air, la quantité d'évaporation qui se produit exige une quantité de chaleur à peu près équivalente à celle du rayonnement solaire incident. En d'autres termes, l'énergie perdue par le fruit par réflexion solaire et par perte thermique lorsque la surface du fruit est plus chaude que l'air ambiant, associée aux modifications de la température à l'intérieur du fruit, équivaut approximativement au transfert de chaleur qui se produit de l'air ambiant vers les raisins. Le mémoire contient plusieurs tableaux montrant l'évaporation journalière subie par le fruit, telle qu'elle ressort de l'observation, ainsi que les valeurs de l'énergie solaire incidente et la perte par évaporation « calculée » sur la base de l'énergie solaire incidente. Bien qu'il paraisse exister une certaine corrélation entre les chiffres obtenus par l'observation et les chiffres obtenus par le calcul, en particulier au cours des premiers jours de l'essai, on constate des différences importantes certains jours. La méthode de calcul n'étant pas indiquée, il n'est pas possible d'apprécier la signification de ces différences.

L'auteur a étudié le séchage des raisins dans d'autres types de séchoirs chauffés par l'énergie solaire afin d'établir des comparaisons avec les claies classiques en ce qui concerne le régime de séchage et la qualité du produit. Une des installations étudiées se composait d'un dessiccateur à casiers chauffé par un absorbeur interne d'énergie solaire d'une surface de 1,5 m². La température de l'air ambiant, qui variait de 24 à 39 °C, a été portée à 39-57 °C, le rendement d'absorption solaire dépassant en général 50 p. 100. On a cependant constaté que le régime de séchage de cette installation était relativement faible et la qualité du fruit médiocre. Dans une autre installation, l'air était chauffé dans un absorbeur solaire de construction simple et porté de 24-37 °C à 42-57 °C, le rendement d'absorption solaire variant en général de 25 à 35 p. 100. Le régime de séchage obtenu dans un séchoir séparé où les raisins étaient exposés au courant d'air chauffé a été pratiquement le même que dans les claies ouvertes et le fruit obtenu a été de bonne qualité.

Dans une troisième série d'expériences, l'auteur a utilisé un grand réchauffeur d'air à l'énergie solaire (102 m²), composé essentiellement d'un tissu noir, tissé lâche (toile d'emballage). L'air était aspiré à travers le tissu au moyen d'un ventilateur avant d'être envoyé vers des claies de modèle standard. Les claies étaient enfermées dans des rideaux de matière plastique de façon à ne recevoir que l'air chaud en provenance du réchauffeur solaire. L'air atmosphérique était aspiré à travers le réchauffeur à raison de 338 m^3 par minute au moyen d'un ventilateur actionné par un moteur électrique de 2 kW avant d'être envoyé dans la chambre de séchage. L'augmentation de température réalisée dans ces conditions était de 3 à 6 °C par temps ensoleillé. Les températures maximums de l'air envoyé du collecteur solaire vers le séchoir se situaient en général entre 41 et 45 °C et le rendement du collecteur était en moyenne de 50 p. 100. Le régime de séchage était à peu près le même que celui observé sur les clayonnages ouverts, mais la qualité des fruits n'était pas aussi bonne.

Dans une brève analyse du coût, l'auteur montre que le prix de revient total du séchage des raisins par le système naturel classique, où l'on utilise les longues claies étagées et un séchage combiné par l'air et par le soleil, s'établit à environ la moitié du prix du séchage en tunnel à la chaleur artificielle.

Les résultats des expériences décrites dans ce mémoire, de même que les considérations économiques, conduisent l'auteur à la conclusion générale que le système des clayonnages verticaux employé pour le séchage des fruits en Australie fonctionne en partie par absorption du rayonnement direct et en partie par circulation naturelle de l'air, et qu'il est moins coûteux et plus efficace pour le séchage des raisins que d'autres procédés qui font appel à des absorbeurs d'énergie solaire et à des sources additionnelles de chaleur. Il est vrai que cette méthode dépend des conditions atmosphériques, mais la même limitation s'applique à d'autres dispositifs solaires qui, de l'avis de l'auteur, sont d'un fonctionnement moins efficace et plus onéreux. Enfin, le fonctionnement d'un séchoir à circulation forcée, qu'il soit chauffé par le soleil ou par un combustible, consomme de l'électricité, ce qui constitue un inconvénient supplémentaire du point de vue économique. L'auteur pense que des dispositifs de séchage conçus selon le modèle décrit plus haut peuvent fort bien être réalisés pour d'autres produits agricoles et diverses matières, en particulier dans les régions arides où le combustible et l'électricité coûtent cher. Sous les latitudes où l'on bénéficie de longues périodes d'ensoleillement à faible angle d'incidence, l'emploi de clayonnages à plans de séchage horizontaux pour l'absorption du rayonnement solaire devrait retenir une plus grande attention.

Il est intéressant de comparer les résultats obtenus par Wilson pour le séchage des raisins par ce procédé simple et ceux obtenus par Ismaïlova pour le séchage des pommes dans des dessiccateurs chauffés directement par l'énergie solaire. Ismaïlova a constaté que l'on pouvait réaliser un séchage rapide et obtenir des produits de bonne qualité même dans les conditions assez intenses créées dans un séchoir revêtu de verre et exposé au soleil, alimenté avec de l'air préchauffé provenant d'un collecteur solaire séparé. Bien que Wilson n'ait pas utilisé un système rigoureusement comparable (et qu'Ismaïlova n'ait pas non plus expérimenté directement sur le système australien), les résultats des deux chercheurs semblent assez concordants. Le régime de séchage pourrait sans doute être accéléré pour les raisins si on leur appliquait une plus grande source d'énergie, comme Ismaïlova l'a fait pour les pommes; mais la qualité du produit serait peut-être altérée, soit par surchauffe, soit par un excès de séchage en surface sans transfert d'humidité depuis l'intérieur du fruit. De son côté, le système des clayonnages pourrait, lui aussi, être utile dans le séchage des pommes coupées, mais l'absence d'une peau naturelle sur le produit augmenterait les risques de contamination.

Séchage du schiste argileux pétrolifère par la chaleur solaire

Le quatrième mémoire présenté sous cette section de l'ordre du jour de la Conférence traite du séchage d'un produit minéral naturel. Le schiste argileux pétrolifère extrait dans la Vallée de Paraiba, au Brésil, a une forte teneur en humidité, représentant en moyenne 33 p. 100 du poids à l'état humide. Le traitement ultérieur de ce minéral pour la production de combustibles liquides exige une décomposition thermique à haute température (distillation) des hydrocarbures contenus dans le schiste. La chaleur nécessaire à cette opération est en général fournie par la combustion d'une fraction des matières organiques présentes dans le schiste. Il est évident que la vaporisation de l'humidité contenue dans le produit exige de la chaleur et que si le schiste soumis à la distillation était sec, on obtiendrait un rendement supérieur dans la production des hydrocarbures liquides et gazeux. D'où l'idée qu'un séchage du schiste par la chaleur solaire avant la distillation pourrait augmenter l'efficacité des opérations de traitement.

Étant donné qu'une tonne de schiste argileux pétrolifère a une valeur très faible, le séchage du produit ne doit pas entraîner de dépenses importantes. On a donc envisagé la possibilité de répandre le schiste, après broyage, sur une aire assez vaste, puis de le laisser sécher au soleil jusqu'à ce que sa teneur en humidité ait suffisamment diminué et de l'acheminer ensuite vers les autres opérations de traitement. Un équipement mécanique serait nécessaire pour manutentionner les milliers de tonnes considérées comme le minimum à traiter quotidiennement dans une entreprise à but commercial.

Dans leur mémoire (S/83), Talwalkar, Duffie et Löf ont établi un bilan énergétique global pour une couche de produit humide déposée sur le sol et exposée à l'air et au rayonnement solaire. L'énergie incidente nette est mise en équation avec la somme du transfert de chaleur latent et sensible du produit vers le milieu ambiant, de la convection vers le milieu environnant, de la conduction par le fond, du rayonnement du produit vers l'atmosphère et du gain ou de la perte de teneur énergétique du produit. Quelques-uns de ces termes ont une valeur négligeable dans le bilan énergétique global, tandis que les plus importants sont la chaleur utile d'évaporation et la perte de chaleur par convection. Les auteurs analysent chacun de ces termes et les mettent en corrélation avec des variables mesurables telles que la température de l'air, la température du minéral, la vitesse de l'air, et les propriétés optiques du produit.

Des études préliminaires effectuées par la Petroleo Brasileiro avaient indiqué que le pourcentage d'humidité perdue (ou gagnée, au cours d'un orage) est en raison inverse de l'épaisseur de la couche et que pour les couches d'une épaisseur dépassant quelques pouces il est certainement utile de remuer le produit de temps à autre. Les chercheurs de l'Université du Wisconsin ont surtout voulu évaluer les termes du bilan énergétique en mettant en corrélation les diverses quantités d'énergie et les régimes de séchage avec les variables atmosphériques, et en déterminant le rendement d'utilisation de l'énergie solaire à mesure que le séchage se poursuit, en étudiant le mécanisme de séchage des particules individuelles, et en évaluant l'intérêt économique du procédé.

Une constatation d'importance fondamentale a été que pour un rayonnement solaire constant le régime de séchage ne décroît pas en relation linéaire avec la teneur du produit en humidité. En d'autres termes, il n'y a pas de période où le régime de séchage reste constant, comme cela se produit avec le sable humide ou d'autres matières granulaires. Étant donné que le séchage est toujours en « régime décroissant », la diffusion interne de l'humidité dans la particule schisteuse et dans la couche de schiste constitue le facteur limitatif; son taux augmente avec la température et diminue avec l'épaisseur de la couche. Un changement de la vitesse de l'air n'a donc pas d'effet appréciable sur le régime de séchage et, pour autant que l'absorption du rayonnement solaire permette à la température du minéral de dépasser largement celle de l'atmosphère, les variations de l'état hygrométrique de l'air n'exercent pour ainsi dire aucune influence.

Bien que le coefficient de convection thermique à partir du schiste ait été reconnu insensible à la vitesse du vent, le taux des pertes de chaleur par convection est directement fonction de la différence de température entre le schiste et l'air ambiant. A mesure que le schiste sèche, sa température superficielle augmente, parce que l'effet refroidissant dû à l'évaporation diminue et qu'une moins grande proportion du rayonnement absorbé est utilisée pour la vaporisation de l'eau. La perte par convection augmente ainsi au cours du séchage.

Des études des gradients de température dans les couches de schiste ont montré que par temps clair les températures superficielles dépassaient de 10 à 15 °F la température du produit à quelques pouces au-dessous de la surface. La température à l'intérieur du schiste se situait elle-même à 5-10 °F en moyenne au-dessus de la température ambiante par temps clair. Les gradients de température dans un morceau de schiste situé à la surface de la couche étaient relativement faibles. La plus grande différence de température entre un point situé à un quart de pouce (0,6 mm) à l'intérieur d'un morceau de schiste et un autre point situé à un pouce et demi de profondeur (37 mm) a été d'environ 10 °F.

Étant donné que le schiste joue également le rôle d'absorbeur des rayons solaires, son absorptivité est une caractéristique importante. On l'a mesurée sur le schiste humide et sur le produit séché au soleil et constaté qu'elle diminuait de 92 p. 100 à environ 83 p. 100.

Dans une série d'essais de séchage, portant chacun sur plusieurs jours d'expositions au soleil, on a déterminé la distribution du rayonnement. Les résultats sont présentés sous forme de tableaux dans le texte du mémoire. Un résumé des données montre que sur une période de quatre jours, pour un rayonnement moyen de 1 900 btu par pied carré, l'humidité contenue dans 33 livres (15 kg) de schiste (morceaux de 1 à 3 pouces — 2,5 à 7,5 cm — disposés en couche de 3 pouces — 7,5 cm — d'épaisseur) pouvait être réduite de 40,8 p. 100 (par rapport au poids sec) à 12,3 p. 100. Le rendement correspondant d'utilisation de l'énergie solaire variait de 44 p. 100 au début de l'opération à 18,5 p. 100 le dernier jour. Cinq jours environ étaient nécessaires pour un flux moyen de rayonnement d'environ 1 800 btu par pied carré pour réduire la teneur en humidité de 41,5 à 14,5 p. 100 (par rapport au poids sec), le rendement moyen d'utilisation de l'énergie solaire se situant entre 45,8 et 18,5 p. 100.

Les auteurs ont effectué une évaluation économique approchée de ce procédé de séchage en prenant pour base 12 000 tonnes par jour de schiste argileux pétrolifère contenant initialement 33 p. 100 d'humidité (par rapport au poids humide) et constaté que l'aire de séchage devrait mesurer environ 470 hectares. Des engins répandraient le minéral sur cette aire en une couche de 1 pied d'épaisseur (environ 30 cm) et, après une dizaine de jours, l'humidité du schiste aurait été ramenée à 10 p. 100 environ dans des conditions atmosphériques moyennes. Ce résultat correspond à un rendement moyen d'utilisation de l'énergie solaire de 30 p. 100. Le schiste serait alors ramassé par des engins mécaniques et acheminé vers les cornues. Il a été calculé que la main-d'œuvre et l'équipement nécessaires pour le séchage solaire coûteraient à peu près 1,50 dollar par million de kilocalories de chaleur utilisée. Compte tenu du prix du pétrole au Brésil, la quantité de combustible qui serait nécessaire pour évaporer cette humidité (et qui équivaut à peu près à la quantité de pétrole qui ne serait pas produite si le schiste n'était pas séché) coûterait environ 5,00 dollars par million de kilocalories. Ces chiffres approximatifs montrent bien que, si le filon de schiste argileux pétrolifère est mis en exploitation, le séchage par la chaleur solaire avant la distillation présente suffisamment d'intérêt du point de vue économique pour qu'il vaille la peine de l'évaluer très sérieusement.

Analyse générale

Il est étonnant qu'un procédé aussi communément utilisé que le séchage par la chaleur solaire ait donné lieu à si peu de perfectionnements techniques. Si l'on considère les quantités énormes de produits divers qui sont traités de cette manière, il semble que des progrès et des améliorations doivent être recherchés. Des économies qui seraient peut-être de l'ordre de plusieurs millions de dollars par an pourraient sans doute être réalisées si l'on parvenait à diminuer le coût des opérations de séchage, à améliorer la qualité des produits et à diminuer les pertes dues à la pourriture, à la détérioration, à la lenteur des transports et à d'autres facteurs. Dans beaucoup de régions, le remplacement du séchage au moyen d'un combustible par le séchage à la chaleur solaire, ou la simple diminution de la consommation de combustible par l'installation d'une source d'appoint, peu coûteuse, de chaleur solaire, présenterait des avantages considérables. Le rapporteur suggère que les discussions sur ce sujet soient consacrées aux besoins, aux perspectives et aux résultats concrets à attendre d'une étude technique plus poussée du séchage par la chaleur solaire, de manière à faire profiter les hommes des possibilités inhérentes à ce procédé.

Sujets de discussion à retenir

a) Dans quelle mesure la qualité des produits est-elle compromise par des conditions médiocres de séchage solaire?

b) Quels produits agricoles, et en quelles quantités, sont actuellement perdus ou détériorés, alors que des méthodes de séchage efficaces et économiques permettraient de les préserver?

c) Économie du système consistant à installer dans des séchoirs chauffés au combustible des réchauffeurs d'air peu coûteux alimentés à l'énergie solaire, comme simple source d'appoint destinée à réduire la consommation de combustible.

d) Possibilité de construire des séchoirs indirects à l'énergie solaire pour les céréales, les fruits et d'autres produits, sans qu'il soit nécessaire d'avoir recours à l'électricité pour faire circuler l'air chaud d'un collecteur solaire à une chambre de séchage de type quelconque.

e) Y a-t-il des produits auxquels le séchage solaire confère des qualités exceptionnelles (apparence, valeur nutritive, etc.)?

f) Nécessité de réunir des données fondamentales plus complètes sur le processus de séchage par absorption directe d'énergie solaire dans le produit.

g) Dans quelle mesure des matières transparentes nouvelles et beaucoup moins coûteuses, par exemple des pellicules de composition plastique, peuvent-elles diminuer le prix de revient et augmenter les possibilités d'application des réchauffeurs d'air à l'énergie solaire pour le séchage indirect?

USE OF SOLAR ENERGY FOR HEATING PURPOSES: SOLAR DRYING

Rapporteur's summation

The session on solar drying may have been somewhat disappointing simply because of the small number of contributions in comparison with the widespread use of this process all over the world. Only four papers were presented. Two of these dealt with similar developments in the field of grain drying in small, home-made solar drying sheds or bins. A third paper concerned a traditional method of drying grapes in Australia. The fourth paper was a study of the drying of oil shale so that the subsequent retorting process might yield a larger oil recovery. World use of solar drying, with an annual thermal equivalent of millions of gallons of oil, would appear to justify a considerably larger development effort.

This summation does not review or discuss these papers, but mentions some of the important points developed in the discussion and suggests topics for further consideration. The first significant commentary concerns the substitution of well designed solar drying systems for crude solar drying methods now in use. In the drying of fish, for example, which is a very widespread solar application, the quality of the product is subject to great variations depending on weather conditions and methods of drying. Enormous tonnages of fish are handled in these crude processes, and spoilage and loss of much of the product occurs because of inadequate drying techniques and facilities. The development of improved, dependable, and cheap solar drying methods is long overdue.

There also appears to be much loss and spoilage of agricultural crops which might be saved by the use of effective and economical solar drying facilities. Estimates of these losses would be of interest and value in an appraisal of the magnitude of the problem. There is no doubt, however, that the cycles of abundance and starvation could be ameliorated by application of adequate solar drying methods in the under-developed countries.

A third topic of particular interest concerns the possible extent to which new and cheap plastic films may reduce the cost and increase the applicability of solar air heaters for indirect drying of many products. Several types of plastic are now available, and other durable films will probably be developed for applications of this type. Nearly all of the drying studies reported at this Conference involved use of these materials in cheap solar air heaters. The potential of these advances in materials is indeed interesting and perhaps far-reaching.

As a summary to the solar drying topic, it therefore appears that there is much reason to increase the very limited effort in this field of development. In the under-developed countries, there are needs for the substitution of effective and dependable solar drying systems for the crude methods now used, and there are needs for the introduction of such methods for the preservation of animal and human foods, now spoiling because of periodic abundance and shortage.

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : SÉCHAGE PAR LA CHALEUR SOLAIRE

Résumé du rapporteur

La séance consacrée au séchage par la chaleur solaire (point III.C.3 de l'ordre du jour) a pu paraître quelque peu décevante, ne fût-ce qu'en raison du nombre de mémoires présentés qui a été relativement faible, compte tenu du très large emploi de ce procédé dans le monde entier. Quatre documents seulement, en effet, ont été communiqués. Deux d'entre eux traitaient de façon similaire des progrès réalisés dans le domaine du séchage des récoltes au moyen de petits séchoirs solaires de fabrication artisanale. Un troisième mémoire concernait une méthode traditionnelle de séchage des raisins en Australie. Le quatrième étudiait le séchage des schistes argileux pétrolifères en vue de récupérer une plus grande quantité de pétrole grâce à une distillation ultérieure. L'usage du séchage par la chaleur solaire dans le monde, correspondant à l'équivalent thermique annuel de plusieurs millions de gallons de pétrole, semblerait justifier un effort de mise au point bien plus considérable.

Le présent résumé n'a pas pour objet d'analyser ou d'examiner les mémoires présentés, mais de signaler un certain nombre de points importants qui ont été exposés au cours de la discussion et de proposer des sujets appelés à faire l'objet d'un examen plus poussé. La première observation concerne le remplacement des méthodes rudimentaires actuellement employées par des procédés de séchage bien conçus. C'est ainsi que dans le séchage du poisson, qui est une application très répandue du séchage solaire, la qualité du produit varie beaucoup selon les conditions climatiques et les méthodes de séchage. De très grandes quantités de poisson sont traitées de façon rudimentaire et, du fait de l'insuffisance des techniques et des installations de séchage, une grande partie de la production est abîmée ou perdue. La mise au point de procédés meilleurs, sûrs et peu coûteux n'a que trop tardé.

Il apparaît également qu'une grande partie des récoltes qui pourrait être conservée si l'on utilisait des installations de séchage solaire efficaces et économiques est perdue et gaspillée. Il serait intéressant de faire une estimation des pertes en évaluant l'ampleur du problème. Mais il n'est pas douteux qu'on pourrait corriger un peu mieux les cycles d'abondance et de disette en appliquant des méthodes de séchage satisfaisantes dans les pays sous-développés.

Un troisième point est particulièrement intéressant : dans quelle mesure des pellicules en matière plastique nouvelle et bon marché permettent-elles de diminuer les frais et d'étendre l'emploi de séchoirs solaires à air en vue de sécher indirectement de nombreux produits? Plusieurs types de matières plastiques existent actuellement et l'on mettra probablement au point d'autres pellicules résistantes destinées au même usage. Presque toutes les études sur le séchage dont on a fait état à la Conférence impliquaient l'emploi de ces matières pour la fabrication de séchoirs solaires à air d'un prix peu élevé. Les perspectives qu'ouvrent les progrès réalisés en ce qui concerne les matériaux sont réellement intéressantes et peut-être de grande portée.

Pour résumer la question du séchage solaire, il apparaît par conséquent qu'il y a tout lieu d'intensifier les efforts très limités fournis jusqu'à ce jour dans ce domaine. Dans les pays sous-développés, il faut substituer des procédés de séchage solaire efficaces et sûrs aux méthodes rudimentaires utilisées actuellement et mettre en œuvre ces procédés en vue de conserver les aliments destinés au bétail et aux hommes, qui sont maintenant gaspillés en raison des cycles d'abondance et de pénurie.

DRYING CROPS WITH SOLAR HEATED AIR

Frederick H. Buelow *

Many farmers of the world are confronted with the problem of reducing the moisture content of their harvested crops to prevent spoilage during storage. The drying process is not difficult to accomplish with proper equipment and sufficient power, some of which may be required for the production of heat. The problem is that the cost of drying is not economical. A farmer who dries large quantities of a crop every year can usually justify economically the equipment and operating costs. It is the farmer with small crop volume, the one who cannot afford an expensive system, that requires new design information and assistance for the construction and operation of crop drying systems that are economical in his situation.

The drying systems currently in use for drying small crop volumes are either the process of spreading the crop on the ground, or the process of forcing natural outside air through the crop to remove the excess moisture. Both of these systems are slow processes. The first system also requires a considerable amount of handling and sometimes damages the crop because of exposure to adverse weather conditions. The effectiveness of the second method, though economical and satisfactory for many situations, is also subject to weather conditions.

It is the purpose of this paper, therefore, to give a solar crop drying design procedure for farmers with small volumes. The system is more profitable than those previously mentioned for many farmers since a low-cost solar energy air heater is used to warm the air which is forced through the wet crop. During the design and development of the system, emphasis was placed on making the system suitable for drying crop volumes too small to be processed economically with conventional heated air drying systems. The primary features, therefore, are low initial cost and almost negligible operating cost.

Crop drying requirements

The rate at which an agricultural crop can be dried is a function of (*a*) the relative humidity of the air which is forced through the crop; (*b*) the air flow rate; and (*c*) the moisture content of the crop.

At a given relative humidity, each crop has a certain moisture content at which there will be moisture transfer neither to nor from the crop. For example, shelled corn of about 25 per cent moisture content (dry basis) will be in equilibrium with air having a relative humidity of 92 per cent; 15 per cent corn moisture content will be in equilibrium with air at about 62 per cent; and 11 per cent corn moisture content will be in equilibrium with air at 41 per cent (1). It must be noted that these relationships depend slightly on air temperature and are therefore not exact.

In general, it may be stated that grain and hay crops will not spoil in storage if their moisture content is a value which is in equilibrium with air having a relative humidity of 62 per cent or less. It is obvious, then, that air being used for crop drying must have a relative humidity less than 62 per cent.

The relative humidity of air is easily lowered by raising its temperature. It would appear that the higher the air temperature, the better it is for drying. Actually, high air temperatures and the resulting low relative humidities can over-dry the crop, and may affect germination of seed, or the crop feed value. The greatest danger of over-drying with hot air occurs when deep layers of a crop are dried. The over-drying then occurs in the layers nearest the air entrances. For this reason, it is not desirable to heat air to temperatures that will lower its relative humidity to less than about 30 per cent for drying in storage.

It can be shown that a given rate of heat energy input can be used most effectively for crop drying when the energy is used to raise the temperature of larger quantities of air a few degrees, rather than smaller quantities of air to higher temperatures. It is assumed that the air is used with equal effectiveness in all cases. Normally, the drying efficiency of hot air is less than cooler air in properly designed systems, and, therefore, the lower temperatures appear even better than first indicated.

Air characteristics

When air is heated for crop drying purposes, the temperature should be increased to bring the relative humidity below 62 per cent.

A psychrometric chart shows that air at 100 per cent relative humidity, when heated 14°F, will have a relative humidity at or less than 65 per cent. However, 100 per cent relative humidity is usually temporary, and 85 per cent relative humidity would be considered a more typical design condition. Then about ten degrees F temperature increase is all that is necessary to be assured of a relative humidity

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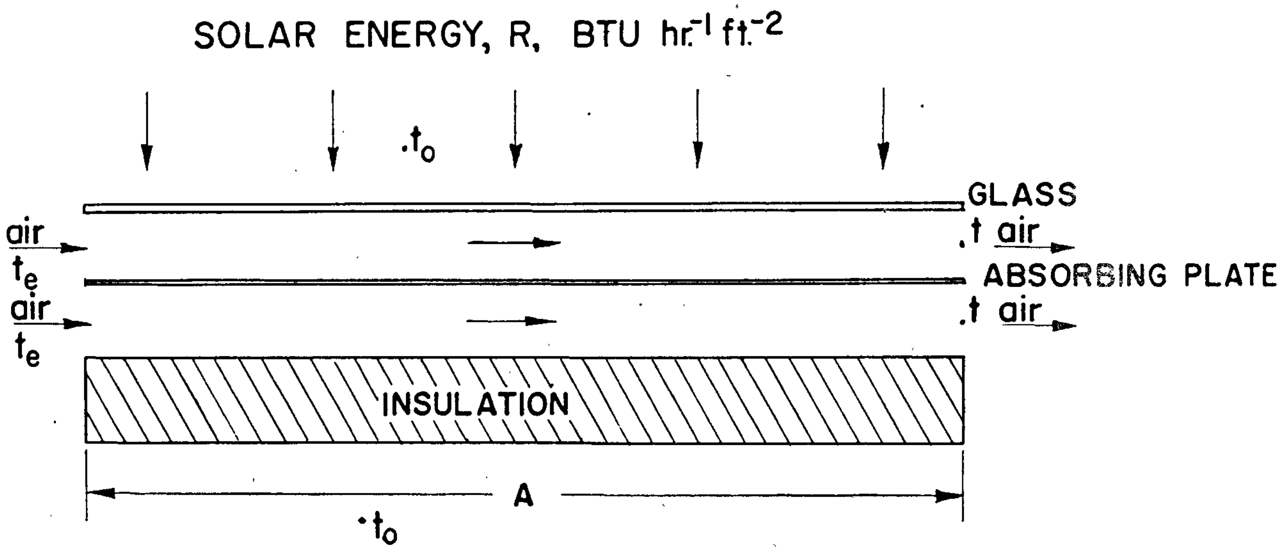

Figure 1. Solar energy air heater model, showing air passageways

low enough to dry most crops. It is also obvious from a psychrometric chart that relative humidity is appreciably reduced with only a few degrees of air temperature rise.

Characteristics of solar air heaters

The solar energy air heater proposed for crop drying consists essentially of a flat plate with air passing below it to remove the heat. The unit may be modified by adding glass or a plastic film above it to form another air passageway along the top side of the absorber plate. (See figure 1.) The mathematical and experimental study (2) of this type of solar air heater shows that the temperature rise of air passing through the heater follows the equation

$$t - t_o = (ER/U)\,(1 - e^{-N}) + (t_e - t_o)^{e^{-N}} \quad [1]$$

in which

- R = rate at which solar energy falls on surface of air heater, btu/ (ft^{2}hr)
- U = over-all coefficient of heat transfer between air in the heater and outside air, btu/(ft^{2}hr°F)
- E = fraction of incoming radiation absorbed by heater
- t = temperature of the air leaving heater, °F
- t_o = outside air temperature, °F
- t_e = temperature of air entering heater, °F
- N = UA/mC
- A = area of heater, ft^2
- m = mass flow rate of air through heater, lb/hr
- C = specific heat at constant pressure of air passing through the heater, btu/(lb°F)

When the air entering the heater is at the same temperature as outside air, the equation simplifies to the form

$$t - t_o = (ER/U)\,(1 - e^{-N}) \quad [2]$$

Experimental evidence for metal absorber plates coated with black asphalt roofing paint shows that the equations may be simplified to

$$t - t_o = 0.362\,R\,(1 - e^{-2.16/v}) \quad [3]$$

for a heater with a single glass covering, and

$$t - t_o = 0.108\,R\,(1 - e^{-8.08/v}) \quad [4]$$

for a heater without glass covering (3); (v = air flow rate, ft^3/min per ft^2 of heater surface).

Equation [2], together with experimental values for U and E, was used to evaluate solar air heaters having two layers of glass, one layer of glass, and no glass above the black absorbing surface (4). Figure 2 shows when each of these types of units

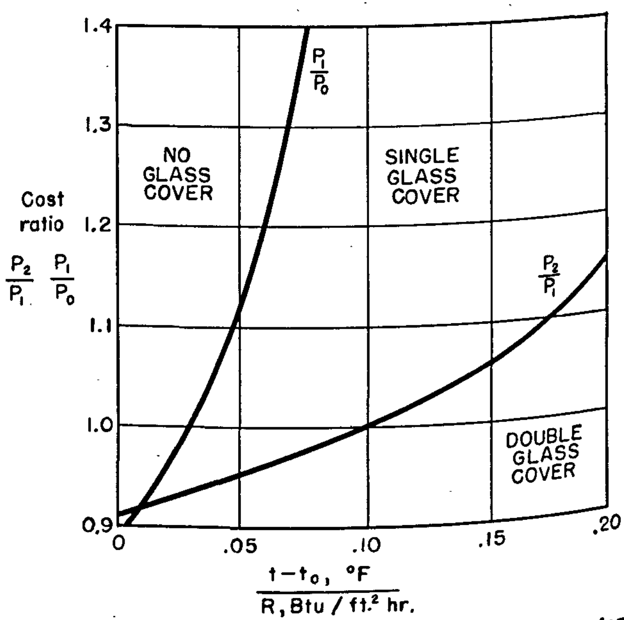

Figure 2. Graph showing area where each type of solar air heater is most economical

is most economical and is based on the ratio of the costs of the two units in question, as well as the temperature rise required and the intensity of solar radiation at the given conditions. For example, if the desired temperature rise is 15°F with an incoming energy rate of 300 btu/(ft²hr) and the cost ratio, P_1/P_0, between a single glass solar air heater and a no glass heater (on a ft² basis) is 1.2, the intersection on figure 2 is in the "no glass cover" area, therefore, showing it to be the most economical.

The flow of air through the solar heater should be relatively unimpeded so that larger fan capacities than those used for unheated air crop drying systems are not required. A limit of about 0.1 inch of water pressure drop through the solar heater would meet this requirement. However, the air velocity through the solar heater must be high enough to give relatively good convection coefficients to have reasonable solar heater efficiencies. The recommendations, based on the author's pressure drop measurements on various "no glass" heater designs are, therefore, as follows for air flow rates of 10 ft³/min per ft² of solar heater (5):

(*a*) A 1.6-inch depth is acceptable if the air passage length is not over 10 feet;

(*b*) A 3.6-inch depth has very low pressure drops for duct lengths normally encountered on farms;

(*c*) If the air is removed downward from the heater, the horizontal width of opening for the air outlet should be at least 6 inches to minimize pressure drops at that point;

(*d*) The air inlet accounts for a significant part of the pressure drop through the solar air heater and should be designed to minimize the losses.

Of the commercially available coatings tested, it was found (6) that black asphalt paint has the most desirable solar energy absorption characteristics. An additional advantage is that the asphalt paints are relatively low in cost.

The solar crop drying system

Since the sun is an intermittent source of energy and the most economical system is to use the solar energy for heating whenever it is available, the solar crop drying system should be designed basically as an unheated forced air drying system. Therefore, the first step in design, after determining the batch size, is to find the recommended air flow rate, the depth to which the crop can be placed in the dryer, the maximum moisture content of the wet crop, and the pressure drop of air passing through the crop. These values will vary with the crop and local weather conditions at the time the crop is dried.

These recommendations may then be used for selecting a fan to move the air.

Combining the information given above, one can conclude that the solar air heater should be of a size that will have an air flow rate of 10 to 15 ft³/min per ft². Using these values, one can determine the area of the solar air heater absorbing surface.

Metal roofing may be used for the absorbing surface as well as for the roof of the crop drying building. As a roof, it has its best water shedding characteristics when the corrugations or ridges are placed perpendicular to the ridge of the roof. The roofing provides the greatest strength when the supports are horizontal. Since air must flow between the supports or girts, the air flow should, therefore, be horizontal along the under side of the roofing. It is preferable to have the air enter at both ends of the heater and leave the collector in a center section to minimize power requirements for air movement. If the metal sheets can be supported properly with rafters, however, it is satisfactory to draw the outside air into the heater at the eaves and remove it at the ridge.

The sheeting on the underside of the rafters or girts for forming the bottom of the air heater passageway may be of any material that is air-tight. Although some insulation would be desirable, it can seldom be justified economically. In many systems, the wet air leaving the crop being dried is immediately below this sheeting and care must be taken that this air does not re-enter the drying cycle through the sheeting. It is also necessary to place the exhaust air openings and intake openings on the building in such a way that the exhaust air does not re-enter the system at the intake.

Current studies being carried on by the author show that a given fixed area of solar air heater is most effective when tilted toward the south (in the Northern Hemisphere) at an angle from horizontal that is equal to or somewhat more than the latitude at which the heater is located. However, many buildings have roofs with two slopes in opposite directions. When such a design, with solar heaters on both roof slopes, is planned, the slopes should face in easterly and westerly directions for greatest effectiveness. The slopes should then be as nearly horizontal as possible for most parts of the world.

A typical solar grain drying and storage building (3) is shown in figure 3. This system is designed so that the air will move up through the grain and has a drying bin on each side of the air duct. Each bin will hold about 1 000 ft³ of grain when filled to a depth of five feet. Only one-half of the roof is used

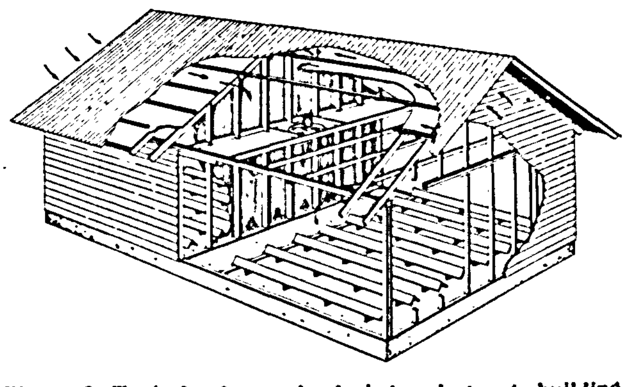

Figure 3. Typical solar grain drying and storage building

for heating air. The system is designed to dry one bin at a time; however, both bins could be given air at the same time in an emergency. The roof construction consists of 2 by 6 inch rafters on which is placed wood or metal sheeting. Horizontal roof girts 2 inches high are placed on the sheeting, and the corrugated roofing is fastened onto these girts. The air enters the roof at the ends of the building, moves toward the center section and into the upper plenum chamber. The air is then forced into the lower chamber by the fan, from where it moves through the lateral ducts and the grain. The wet air leaves the bins through openings at the gables or in the north roof.

Similar systems may be designed for hay and other crops, considering the basic drying requirements for the crop and the information provided in this paper.

Economics of solar crop drying

A solar crop drying building can be constructed for very little more cost than an unheated air crop drying building. The solar heating unit will cost only as much as the sheeting for the underside of the rafters or girts and the paint for the absorbing surface. In some cases, somewhat more ductwork is necessary.

Experiences by researchers and farmers indicate that the addition of a solar air heater to an unheated air crop drying system will reduce drying time 50 to 75 per cent. On some days, it is possible to dry a crop with solar heated air and not with unheated air because of high outside relative humidities.

The economics in each situation will depend on the quantity of crop dried and weather conditions. The extra cost of a solar dryer is offset by (*a*) the saving of at least 50 per cent in fan power cost; (*b*) a smaller system and less initial cost in some cases since drying can be done more readily; and (*c*) a saving in fuel if solar heat is used instead of fuel heat.

It can be shown for grain or hay drying systems that the added cost of a solar drying system will be recovered in one to five years' time. Estimates of economic feasibility can be made easily by estimating the added costs of construction and the probable savings.

In some situations, the solar air heater can be used for tempering the ventilating air for livestock shelters in wintertime, thus making the shelter drier and warmer. Such an application also adds to the economic value of a solar air heater.

Conclusion

The drying of crops with solar heated air is not only possible but economicallly feasible in many situations. The equipment and supplies required are readily available and low in cost. Construction of a solar crop drying building is no more difficult than the construction of the building itself. In many cases existing buildings can be modified easily to take advantage of the energy from the sun for crop drying.

The solar crop drying system fills the need of the farmer who cannot economically justify the cost of a commercial heated air crop drying system because of limited volume of crop to be dried. The system can easily be expanded, however, to handle large volumes.

Hay drying with solar heated air is especially advantageous because the drying is done at a time when solar energy is usually most abundant. Also, fuel air heating systems are a great fire hazard, which the solar heating system is not.

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Summary

Many farmers of the world need to reduce the moisture content of their harvested crops economically. The farmer who has large quantities of a crop to dry each year can usually justify the large capacity commercial drying equipment. It is primarily the farmer with limited drying requirements who needs a better system for crop drying.

The paper presents a solar crop drying system design which consists basically of an unheated forced air drying system with the addition of a solar air heater to accelerate the drying process.

When a crop is dried with forced air, the relative humidity must be below 62 per cent in most cases to lower the moisture content of the crop sufficiently so that it can be stored without spoilage. Air relative humidity can be lowered by heating. Excessively low humidities or high temperatures, however, may over-dry or damage the quality of the crop.

It can be shown that a given rate of heat energy input can be used most effectively for crop drying when the energy is used to raise the temperature of larger quantities of air a few degrees, rather than smaller quantities of air to higher temperatures.

A psychrometric chart shows that air with a relative humidity of 85 per cent can be reduced to a relative humidity favorable for crop drying by raising its temperature about 10°F.

The solar energy air heater proposed for crop drying consists essentially of a flat plate with the air to be warmed passing below it. The paper gives the mathematical equations that describe the characteristics of this type of air heater. Based on experimental evidence, the equation for such a heater may be simplified to the form

$$t - t_o = 0.108R\,(1 - e^{-8.09/v})$$

in which

- t_o — outside air temperature, °F
- t — temperature of the air leaving heater, °F
- R — rate at which solar energy falls on surface of air heater, btu/(ft² hr)
- v — air flow rate, ft³/min per ft² of heater surface.

A graph showing most economical heater design, based on temperature rise required, incoming solar energy, and costs of various heater designs, is shown in the paper. For crop drying purposes, the unit without glass covering is shown to be the most economical.

The distance between the absorbing plate and the sheeting at the bottom of the heater air passageway should be about 3-6 inches for most farm solar air heaters.

The recommended solar air crop drying system has an air flow rate of 10 to 15 ft³/min of air for each ft² of absorbing surface. The metal absorber, which is coated with black asphalt roofing paint, is also used as the roof of the building. The outdoor air passes under the absorber to be heated and is then blown through the crop by a fan.

The solar crop drying building can be constructed for very little more cost than an unheated air crop drying building. The solar heating unit will cost only as much as the sheeting for the underside of the rafters or girts, the paint for the absorbing surface, and some ductwork.

The drying time of a crop is reduced as much as 50 to 75 per cent.

SÉCHAGE DES PRODUITS AGRICOLES AU MOYEN D'AIR CHAUFFÉ PAR LE SOLEIL

Résumé

Nombreux sont les agriculteurs qui, de par le monde entier, auraient besoin de réduire économiquement la teneur en eau des produits qu'ils récoltent. L'entreprise agricole dont une forte proportion des récoltes doit être séchée chaque année peut habituellement justifier l'emploi de matériel de séchage commercial à grande capacité. C'est surtout l'agriculteur dont les besoins de cet ordre sont plus réduits qui a besoin de meilleurs systèmes de séchage de ses récoltes que ceux dont on dispose actuellement.

Ce mémoire décrit un système solaire de séchage des produits agricoles constitué essentiellement par un circuit de séchage à l'air non chauffé, complété par un chauffe-air solaire destiné à accélérer le processus.

Quand on fait sécher un produit dans un courant d'air forcé, il faut, dans la plupart des cas, que l'état hygrométrique relatif soit inférieur à 62 p. 100 pour réduire la teneur de ce produit en eau suffisamment pour permettre son emmagasinage sans pertes. L'état hygrométrique relatif de l'air peut être abaissé par le chauffage. Les états hygrométriques indûment bas ou les températures trop élevées peuvent cependant sécher trop complètement les produits ou porter préjudice à leur qualité.

On peut démontrer qu'un régime donné de fourniture d'énergie peut être utilisé avec un maximum d'efficacité pour le séchage des produits agricoles quand cette énergie sert à faire monter la température de quantités d'air importantes de quelques degrés plutôt qu'à élever davantage celle de masses d'air plus réduites.

La table psychrométrique indique qu'il est possible de ramener l'état hygrométrique de l'air de 85 p. 100 à une valeur favorable au séchage des produits agricoles en élevant sa température d'une dizaine de degrés F.

Le chauffe-air ou réchauffeur à énergie solaire dont on propose l'utilisation pour le séchage des produits agricoles se compose essentiellement d'une plaque plate au-dessous de laquelle on fait circuler l'air à chauffer. Le mémoire donne les équations mathématiques qui décrivent les caractéristiques des chauffe-air de ce genre. Sur la base des indications expérimentales, l'équation d'un tel dispositif de chauffage peut être simplifiée et s'écrire

$$t - t_o = 0.108R\,(1 - e^{-8.09/v})$$

expression dans laquelle

- t_o — température de l'air extérieur en °F
- t — température de l'air à la sortie du réchauffeur en °F
- R — régime d'apport de l'énergie solaire à la surface du réchauffeur d'air en btu/pied carré/heure
- v — débit d'air en pieds cubes par minute par pied carré de surface de réchauffeur

Un graphique indiquant le mode de réalisation le plus économique du réchauffeur pour la montée de température cherchée, la quantité d'énergie solaire fournie et les frais afférents aux diverses conceptions de réchauffeurs est reproduit dans le mémoire. Pour le séchage des produits agricoles, le dispositif sans couvercle de verre s'avère être le plus économique.

La distance entre la plaque absorbante et la tôle qui se trouve à la partie inférieure du passage d'air doit être de l'ordre de 3,6 pouces (91 mm) pour la plupart des réchauffeurs solaires agricoles.

Le système de séchage solaire des produits agricoles utilise un régime d'écoulement d'air s'échelonnant de 10 à 15 pieds cubes d'air par pied carré de surface absorbante. L'absorbeur en métal, revêtu de peinture pour toitures à l'asphalte noire, sert également de toit au bâtiment. L'air qui vient de l'extérieur passe sous l'absorbeur, est chauffé et chassé dans les produits à sécher par une soufflante.

Le bâtiment qui abrite les séchoirs de produits agricoles à énergie solaire peut se réaliser moyennant un supplément très modique sur les frais qui s'imposent pour un bâtiment de séchage à l'air naturel. Le coût du groupe de chauffage solaire se réduit à celui de la tôle destinée à la surface inférieure des chevrons ou fermes, de la peinture destinée à la surface absorbante et de quelques conduites.

La durée de séchage d'un produit se trouve ainsi réduite de 50 à 75 p. 100.

SOLAR ENERGY UTILIZATION FOR CROP DRYING

*Chester P. Davis * and Ralph I. Lipper ***

Use of solar heat to heat forced natural air for crop drying has been adopted by a few farmer innovators. Research investigations by agricultural engineers of the United States Department of Agriculture (U.S.D.A.) and several agricultural experiment stations have produced important design criteria. The practicability of using solar energy in this manner is confined at present to "in storage" use where rapid drying and large reductions in moisture content are unnecessary. From an economic and conservation stand-point, adoption is most practical where the cost of fuels is high or their availability is limited.

It is probable that production of good quality, low-cost collectors similar to those developed and studied can be accomplished best by industrial organizations if the quantity demand develops to encourage efficient mass production techniques. Without a demonstrably large market, manufacturers hesitate to produce, so that for the immediate future most collectors will be of hand-tailored design and fabricated on the work site or in small shops. The recent development of solar resistant and stable film plastic materials is a significant contribution to relatively efficient and low-cost absorbers.

During the years since the Second World War, crop drying by forced air has increased rapidly in the United States. Adoption has come as electric energy has become almost universally available and as those engaged in agriculture have learned the advantages of drying in reducing harvest losses and maintaining the quality of grain in storage. Drying also provides flexibility in management by providing a considerable degree of independence from the vagaries and damaging effects of unfavorable harvest weather. Early harvest to allow land preparation for further cropping is also possible.

Methods and capacity of air for drying

Three general methods of forced air drying are in use :

1. Drying with heated air (150°-180°F);
2. Drying with unheated (ambient) air;
3. Drying with supplementary heated air (5°-20°F temperature rise above ambient air conditions).

Conventional systems utilize a fuel to heat air for drying by methods 1 and 3. Where "in storage" drying on the farm is desirable and feasible, and where early disposition of the crop is not anticipated, the drying capacity of natural air is employed when it is suitable. In most of the production areas and in most years, natural air is suitable for summer harvest season drying. Use of ambient air is unsatisfactory or of marginal value for fall drying in some seasons.

Solar heating of the natural air to achieve a satisfactory moisture removal capacity is feasible. As a psychrometric chart with lines added to show equilibrium moisture content indicates (figure 1), satisfactory moisture removal capacity can be achieved by the addition of 13° to 14°F[1] to saturated air (1 and 2). Smaller temperature rises with the less humid air than is commonly found will also achieve satisfactory drying air.

Early research investigations

As early as the middle 1930s, research investigators of the Tennessee Valley Authority in the United States (3), in a preliminary research report, considered utilization of solar energy for hay drying.

Collector efficiencies of approximately 25 per cent were obtained using air flows approaching 5 cfm/sq ft of absorber. The absorber surface was weathered (oxidized) galvanized-sheet-metal roofing. The maximum air temperature rises of 25° lowered relative humidity 40 per cent. The sunshine period average rise of 15°F reduced the relative humidity 20 per cent, providing air with an enhanced drying potential.

Air volume reduction of almost 25 per cent was observed with the design studied. In this design, air entered at the roof eaves and was subsequently drawn down through a vertical duct from a ridge plenum. The greater drying potential appeared to be counteracted by the reduced air flow, since little significant acceleration in drying was observed when compared with a similar system using natural air.

Preliminary investigations of low-cost solar absorbers (4 and 5) had indicated that a relatively modest

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[1] Psychrometric changes of air for heating and drying show that this temperature increase will enable grain drying to safe storage contents during high humidity periods. A temperature rise of 6° to 8°F is sufficient to accomplish this objective on nearly any sunny day. Solar collectors investigated have shown capability of attaining these temperature rises.

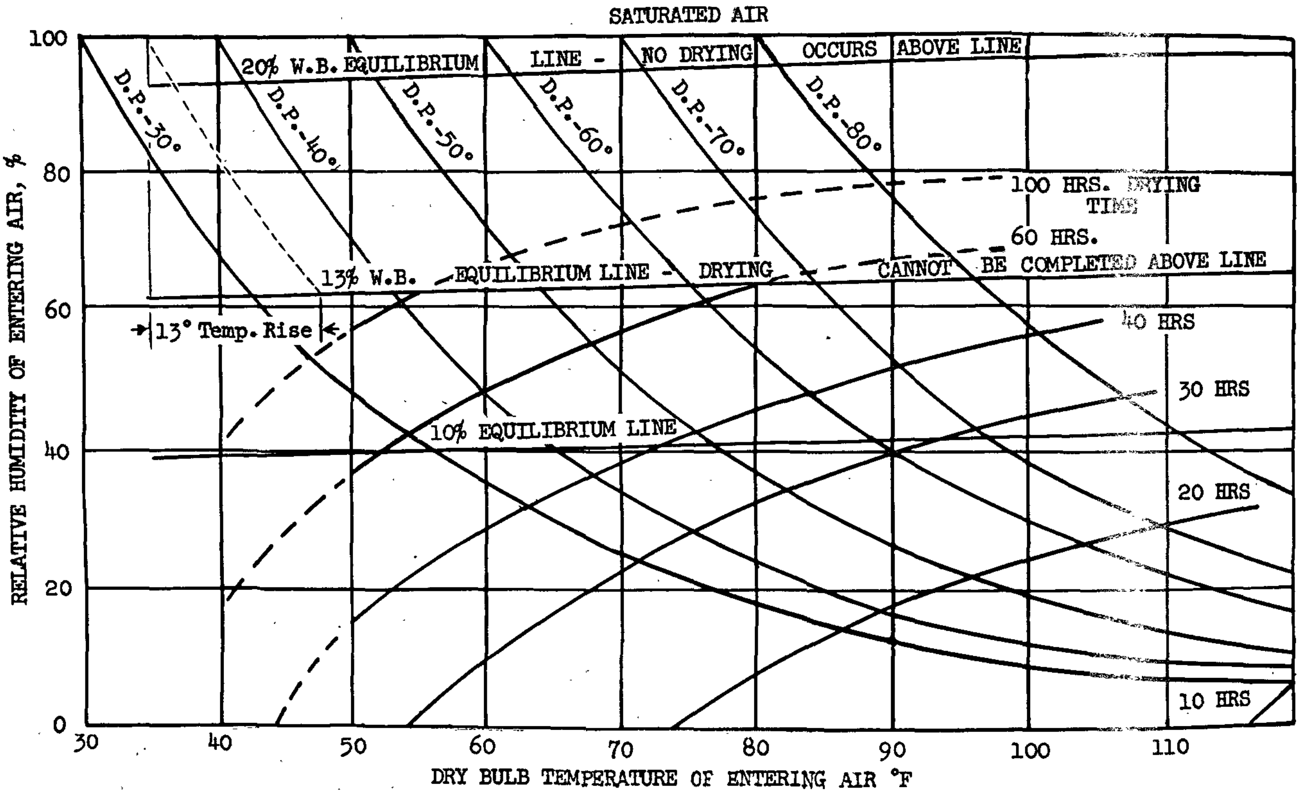

Figure 1. Psychrometric chart with equilibrium moisture content lines superimposed. Relative drying times of different temperatures and humidities are shown

temperature rise up to 40°F could be readily achieved with flat plate type collectors. Both uncovered and film-plastic covered, sun-facing, black-painted corrugated-sheet-metal absorbers were studied. It was observed that efficiencies of solar collection varied between 20 to 50 per cent. The higher efficiencies were associated with the covered type collector.

Availability of solar energy has been investigated by many workers. A useful analysis of the energy falling on collector surfaces at different latitudes and orientations and at different times of year (in the United States) has resulted in knowledge of optimum tilt angles for collectors (3). Assuming that optimization of total energy absorbed is more important than maximum temperature in the use of solar heat for crop drying, selection of roof or collector orientation can be made from the graphical presentation of this study.

Design considerations and recommendations for the drying system

Since reception of solar energy by any collector is highly variable, a grain drying system using solar energy must be designed to operate as an unheated air dryer. Table 1 presents recommendations of

Table 1

Grain or crop	*Maximum moisture content (per cent)*	*Maximum recommended depth (ft)*	*Minimum air flow (cfm/bu)*	*Pressure drop (inches of water)*[a]	*Moisture content (per cent)*[b]
Wheat	20	4	3	1.2	18
Grain sorghum	20	4	3	1.3	17
Ear corn	30	15	5	0.45	—
Shelled corn	25	5	5	1.0	19
Soybeans	20	6	4	0.80	17
Barley	20	4	3	0.85	18
Oats	20	6	2	1.1	16
Chopped hay	40	12 [c]	400 cfm/ton	1.00	—
Long hay	40	15 [c]	400 cfm/ton	1.00	—

[a] Includes .25 in. allowance for duct friction and other losses.

[b] Moisture level below which fan may be stopped (at night or during periods of high humidity).

[c] First curing.

the U.S.D.A. and the Crop Dryer Manufacturers Association for such dryers and includes other important information related to system design and operation.[2]

Production of air temperature rise for solar air heaters

Solution and use of derived empirical constants in a simplified heat balance differential equation

$$t - t_o = \frac{IE}{U}\,(1 - e^{-N})$$

obtained by correlation with collector studies has provided satisfactory heater design information. The energy balance equation in which the energy absorbed by collector is equated to the energy lost from the collector and picked up by the air being heated may be expressed as:

$$t - t_o = \tfrac{1}{10} I\,(1 - e^{-8.0/v})$$

for an uncovered collector, and

$$t - t_o = \tfrac{1}{3} I\,(1 - e^{-2.0/v})$$

for a plastic covered collector.[3]

The notation used is as follows:

A = collector area, sq. ft.
E = portion of incoming radiation not reflected by glass or collector plate.
I = rate of incoming radiation, btu hr $^{-1}$ ft $^{-2}$
N = UA/mC
C = specific heat of air at constant pressure, btu lb $^{-1}$°F $^{-1}$
m = mass flow rate of air through the collector, lb hr $^{-1}$
t = temperature of air leaving the collector, °F.
t_o = outside air temperature, °F.
U = over-all coefficient of heat transfer between the air in the collector and the outside air, btu ft $^{-2}$hr $^{-1}$°F $^{-1}$
v = air flow through the heater, cfm ft. $^{-2}$

The relation of air flow to absorber area required was determined from plotting the above equations to have practical values of 3 to 8 cfm/sq ft for the covered collector and 10 to 15 cfm/sq ft for the uncovered roof collector. Maximum temperature rise of the air on a sunny day will be approximately 15°F for the uncovered air heater. The roof area of a practical structure for housing the crop being dried will also approximate the required collector area.

A plastic-film-covered air heater has been found to have a ratio of heating efficiency of almost 2 to 1 when compared with the bare metal collector. The additional cost of constructing the plastic cover and its supporting structure should be weighed against the superior performance of the covered collector. Potential failure due to high winds, hail, and other factors should also be kept in mind.

Collector orientation

It may be observed from research studies (2 and 3) that east or west facing surfaces are quite ineffective for collection of winter sunshine. They collect relatively less sunshine during (except for equal amounts at the summer solstice) spring or fall drying periods than a south-facing collector. Therefore it is obvious that the more south-facing the collector, the better. This should be taken into consideration if integrated as a part of a permanent storage structure or in the siting of a separate collector.

The optimum angle of slope of the collector in the vertical orientation for any latitude may be chosen from information on solar energy availability (2 and 3). This may be usable as a guide in choosing the appropriate pitch design for the building roof.

Maximum energy that falls on a stationary surface at optimum slope and orientation will approach 3 000 btu per day for each sq ft of surface.

Practical considerations such as adequate slope to provide good collector drainage of rain water from the collector surface and, in areas of considerable snowfall, to provide a slope that will enable snow clearance, should be kept in mind.

Air heater and duct design

Small pressure drops with relatively unimpeded air flow through the heater are desirable so that significantly larger fan capacities and energy requirements are not required when the solar collector is added to an unheated air drying system. A pressure drop limit of approximately 0.1 inch of water will result in sufficient air velocity to give relatively good convection coefficients of heat transfer and satisfactory heater efficiency. These air velocities and pressure drops are controlled by the cross-sectional area and length of air space in the heater and ductwork.

Space between the metal roof and plastic cover or the sheathing on the underside of rafters or girts depends on the length of air passage.

For air flow rates approaching 10 cfm/sq ft of collector area (for designs that will later be reviewed), air pressure drops will be excessive unless at least a minimum space for air passage of approximately 1¾ inches is provided for air passage lengths up to 10 feet. For longer air paths, low pressure drops may be maintained by increasing this depth up to 3⅝ inches (conventional dimensioned lumber size).

Width of air outlets from the collector should be 6 to 12 inches with the lower dimension associated

[2] For more detailed drying system information and detailed drying duct lateral systems, see reference (6).

[3] These equations take the same form but the laboratory tests conducted provide slightly different and somewhat more simplified empirical coefficients than those obtained by Dr. Fred Buelow (7).

with length of air travel of up to 10 feet (at 10 to 15 cfm/sq ft) and the larger used for greater lengths of air travel.

With these conditions, the pressure drop through the solar heater will be small enough so that a fan designed for unheated air drying can be used satisfactorily.

Where a plastic film cover to gain collector efficiency is to be used, consideration should be given to the several solar resistant films that have been developed. Solar life of these films varies as does the per cent radiation they transmit (85-95 per cent). Some of those known to the authors are "weatherable" polyethylene and polyester, polyvinyl fluoride, cellulose acetate butyrate, and fluorinated ethylene propylene copolymer fluorocarbon films. These vary in cost, depending on thickness and chemical formulation, from as little as one cent per square foot per mil to several times this amount.

Other plastic films (polyethylene, acrylonitrile styrene copolymer, polyester, polyvinyl chloride) were found to discolor, become brittle, and ultimately tear away when exposed to the sun because of the ultraviolet degradation of plasticizers or other components of the film. It is understood that research directed toward increased weatherability on some of these materials is being conducted.

Application of these films requires judgment, and slipshod methods should be avoided. Tensioning of film by air pressure, bowed wooden strips, or welded steel wire, or by fastening between rigid wooden frames at relatively close intervals (20 to 35 inches) should be practiced to avoid film fluttering or billowing.

Fastening to supports by staples at two-inch intervals and covering with lath or lattice stock nailed every 6 to 8 inches has been successfully used.

Care should be taken to ensure adequate slope for drainage of rain water.

Recent development of fabric films using nylon, fiber glass or similar type fabric laminated between two films has provided material with much added tear strength.

Farm applications design

An over-all design should consider the building and the drying system to be employed. The shape and orientation of the building will have its influence on the solar collector as will the type and location of the drying fan. These factors must be considered together and compromises in design minimized.

If the collector is part of a roof surface, air may be introduced at the eaves and removed at the ridge. It could also be introduced at one end of the roof and removed at the other. A third alternative is to place air intakes at both ends of the roof and remove it at the center through a slot in the sheathing. In the latter two cases, additional roof girts will need to be provided for the air flow channel unless a departure is made from conventional roof construction designs.

Theoretical analysis (8) has indicated that, for the same pressure drop through a collector, the most efficient design will have the greatest practical width of air intake and the least practical length of air travel. Comparing two systems with the same collector area and the same resistance to air flow but with different length and width configurations, the system with the greatest practical width for air intake and discharge and the least length of air travel will have the greatest log mean temperature difference between air and absorber surface and therefore the greatest rate of heat transfer and the best efficiency. A larger proportion of the temperature rise of the air passing through the collector takes

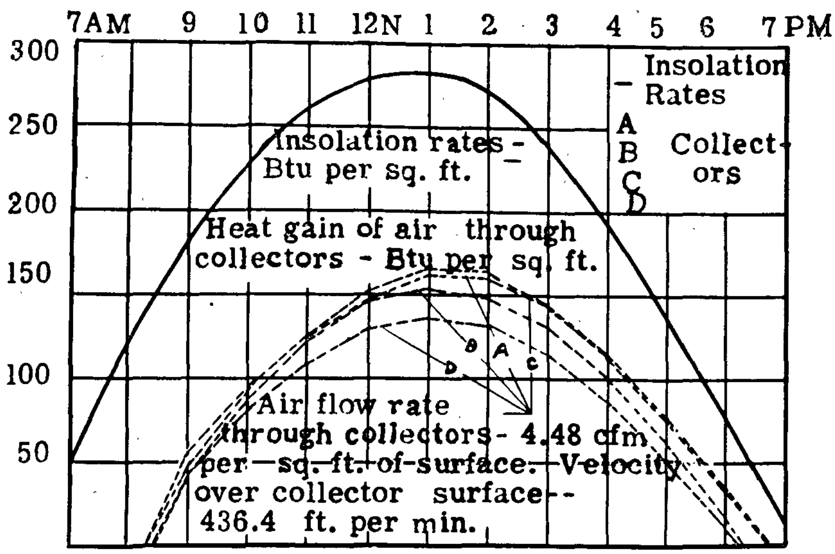

Figure 2. Insolation rate and heat gains through collectors on August 18, 1958. (Collector descriptions as given in table 2.)

Table 2. Summarized description of collectors. First test 1958 series (9)

	Collectors			
	A	B	C	D
Type	Flat (1)	Flat (1)	Flat (1)	Flat (1)
Elevation	Above ground	Above ground	Above ground	Above ground
Effective collector area (sq ft)	18.75	18.75	18.75	18.75
Cover sheet	Acetate butyrate	Acetate butyrate	Acetate butyrate	Vinyl
Collection surface	Flat steel (2) sheet	Corrugated steel sheet (2) parallel to air flow	Corrugated steel sheet (2) perpendicular to air flow	Flat steel (2) sheet
Air passage	Under collection surface	Under collection surface	Under collection surface	Under collection surface

place at the intake end since the temperature difference between the absorber and the air being heated is greatest at that point. Fom a practical standpoint, the configuration of the collector and the roof must be compatible and this will determine whether it is most practical to introduce air at the eaves or at the roof edge.

If conventional corrugated galvanized sheet metal is utilized, heat transfer from the absorber may be increased from 7 to 10 per cent by directing air flow perpendicular to the corrugations rather than parallel with them (see figure 2 and table 2). Again, as a matter of practical concern, rain drainage from the collector surface should be considered.

It is apparent that precautions should be taken to ensure that the sheathing under the sheet metal collector is air tight. In some system designs, the damp air leaving the drying crop is below the sheathing, and it is desirable that no part of this air re-enter the air stream through the heater to the grain. It is likewise obvious that exhaust and intake openings for the air must be separated to avoid moisture laden air re-entering the air heater system.

The design of one system that has been operated during several drying seasons is based on a quonset-type sheet metal structure. Air is introduced at the east end of the south-facing side of the building. It is drawn longitudinally through a channel under the entire south side, which is painted black, and is collected in a plenum built into the west end of the building. Heated air in the plenum is picked up by a fan and is forced into a slotted main duct under the center of the stored ear corn. Moisture laden air emerges from the ear corn into the void space between the corn surface and the roof. It is discharged through louvered openings in the end of the building, (figures 3 and 4).

Solar heated air in an alternate design may be drawn down through a slot in the sheathing, distri-

Figure 3. Quonset solar supplemented grain drying building (foreground) interconnected by duct to second drying quonset

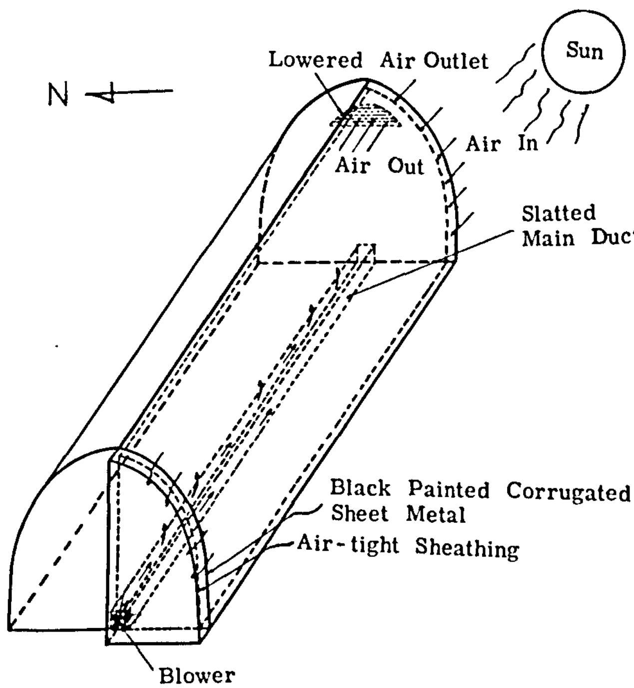

Figure 4. South-facing black sheet metal covered quonset with solar supplemented forced air drawing system

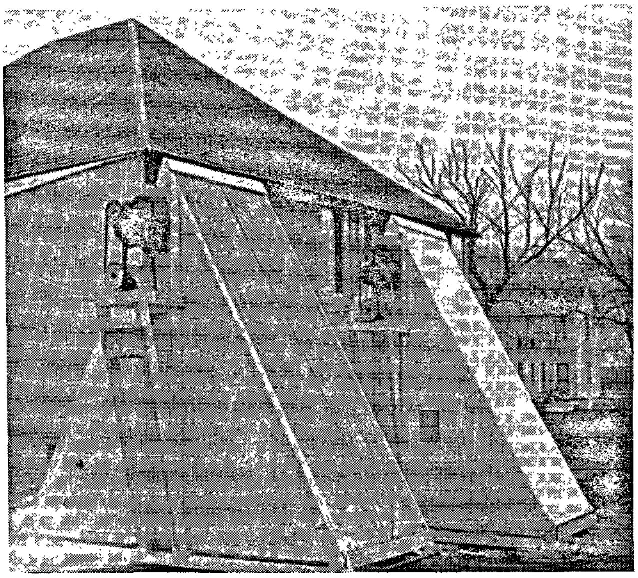

Figure 5. Grain drying bins used in the study of solar-heat-supplemented grain drying. Bin utilizing the collector is shown in the foreground and the check bin can be seen to the right

buted over and drawn down through the grain to a floor lateral and main duct system from which the fan exhausts air to the outside. A disadvantage of this type of design is the relatively greater difficulty in observing the grain. The tendency may be for the dryer operator to terminate blower operation before drying is complete. Another limitation is the necessity for tight construction. Any air leak on the suction side of the fan may cause short circuiting of the air around the grain and poor system operation.

The length of air path through the solar heater and the necessary air space to keep air pressure drops to the desirable 0.1 inch of water may be reduced by introducing air at both ends of the building or alternately at the eave of the building (for long buildings).

Drying tests — Preliminary series

Fall season grain drying has been conducted in experimental 125 bu triangular shaped drying bins. This shape provided a wall well oriented for fall drying conditions (figure 5), as well as a satisfactory collector area to bin volume ratio.

The collector design used was black-painted corrugated sheet metal suspended at mid depth of the 2 × 4 inch external framing. Air was drawn down from the peak (apex) (figure 6) over both surfaces of the absorber and introduced under the drying grain.

The transparent plastic film used over the absorber was of solar resistant 3 mil (.003 inch) " weatherable" polyester.

The solar supplemented drying was compared with an identical dryer using outside air alone. Two air flows (of 6 and 12 cfm/sq ft of net collector area) were used in both systems during successive fall seasons providing an air flow of approximately 2 and 4 cfm/bu of the drying grain.

Grain sorghum and corn were used, respectively, in the successive fall periods with initial moisture contents of 17.5 to 18 per cent. Figures 7 and 8 summarize the drying test information. Though results of these two tests are too limited and not sufficiently comprehensive to reach final conclusions, some tentative observations are possible.

Solar-supplemented, forced air drying with grain of initial moisture content in the vicinity of 18 per cent (w.b.) can be satisfactorily accomplished when average solar radiation levels (between 160 and 305 Langleys per day) are available and average ambient daytime temperatures are generally above freezing.

In general, the increased air flow (4 *vs.* 2 cfm per bushel of drying grain) accomplished more rapid drying but required additional energy for operation of the blower. For that reason, where "in storage" drying is considered, it is doubtful that air flows above those normally recommended for natural-air drying are profitable (6).

The electric energy required for fan operation using solar-supplemented heated air was approximately one-half that required for natural, forced-air drying. This was true whether comparable air flows were continuous or controlled by humidistats set for operation below 85 per cent relative humidity.

Full-scale drying tests

With this background of small-scale drying, a conventional 1 000-bushel, 14-foot round steel grain

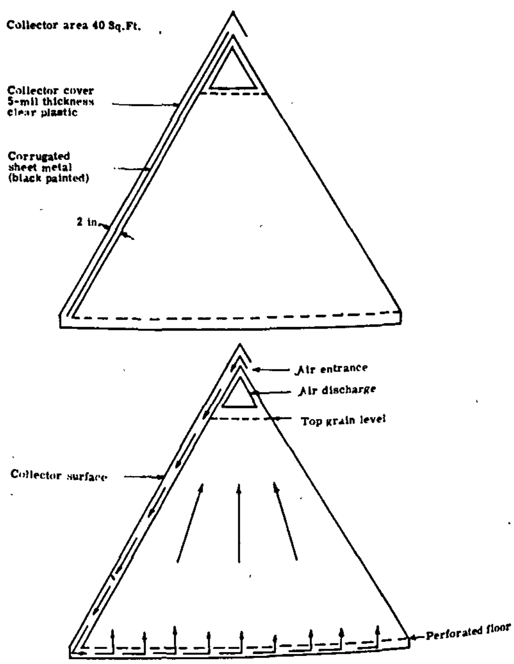

Figure 6. Collector design

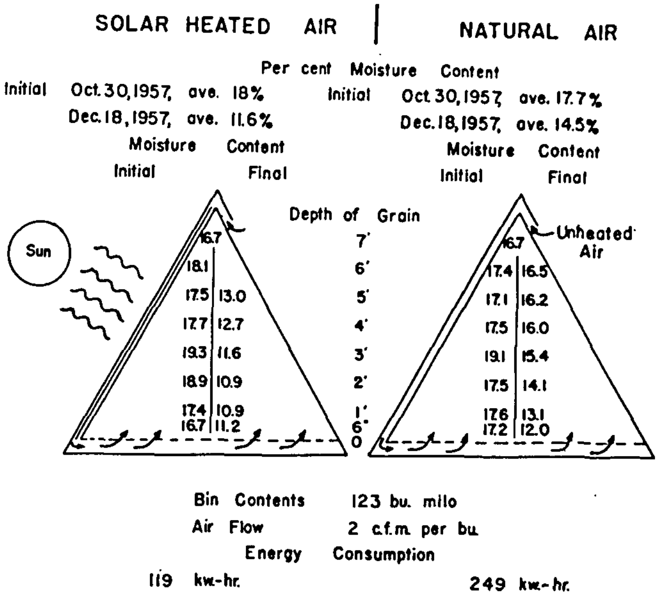

Figure 7. Solar-supplemented *vs.* natural air drying (fan controlled by humidstat — control point of 85 per cent r.h.)

bin was used in conjunction with a collector placed on the ground.

The solar supplemented forced air system was compared with a conventional natural air system that introduced air into a plenum under the 8-foot depth of grain and forced it up through a perforated false floor and the sorghum grain.

Comparable rates of air flow (3.6 to 3.7 cfm/bu) were used in both bins. The static pressure under the floor at these air flow rates was 2.75 to 3.00 inches of water.

A sod-stripped ground surface provided the absorber for the collector. Transparent polyethylene solar resistant film was supported on 1 × 4 inch wooden girts resting on the soil. The film (8) was first stapled to the girts and later restrained by lath nailed over the film.

A total collector area of 800 sq ft was provided (figures 9 and 10). The length of air flow was 12 feet from the air heater edge to the triangular main collection duct leading to the drying bin. The air velocity in the main duct was less than 1 000 feet per minute.

Blowers were controlled by humidistats set to provide operation when the relative humidity was below 65 per cent. At this humidity, air is in moisture equilibrium with safely storable grain. The system using outdoor air had its control located in a louvered weather bureau type shelter, while the solar dryer was controlled from a humidistat located in the collector plenum.

Drying results

Results obtained during the drying period were summarized (figure 11). Both systems were operated during the same period as in previous fall drying tests (October 28 to December 2). Moisture content at all levels in the two bins reached safe storage levels (below 13 per cent) during this period.

While slightly more drying was accomplished during this period with the natural air dryer, it also operated more of the period and required 80 per cent greater energy for each per cent moisture reduction.

The reason for the increased operational period of the natural air dryer is obviously related to its control and to the differences in relative humidity sensed by that humidistat.

Hygrothermograph and recording potentiometer records were studied for clear, sunny periods with control of fan operation as previously noted. It was observed that drying air from the solar air heater was less than 50 per cent relative humidity for 80 per cent of the operating time, while the unheated air dryer provided air under 50 per cent relative humidity only 55 per cent of the operating time.

An operational recorder and hygrothermographs indicated that on a clear, sunny day the solar dryer started a few minutes earlier in the morning than the natural air dryer. After shading of the collector became complete in the evening or during heavycloud overcast, the humidistat cut off the solar collector system. The humidistat of the natural air system reacted relatively more slowly in response to ambient air condition.

A sharp humidity rise under the collector cover due to the evolution of soil moisture from the ground surface absorber was observed after the collector became shaded. Use of a black plastic film in contact directly with the ground would be a desi-

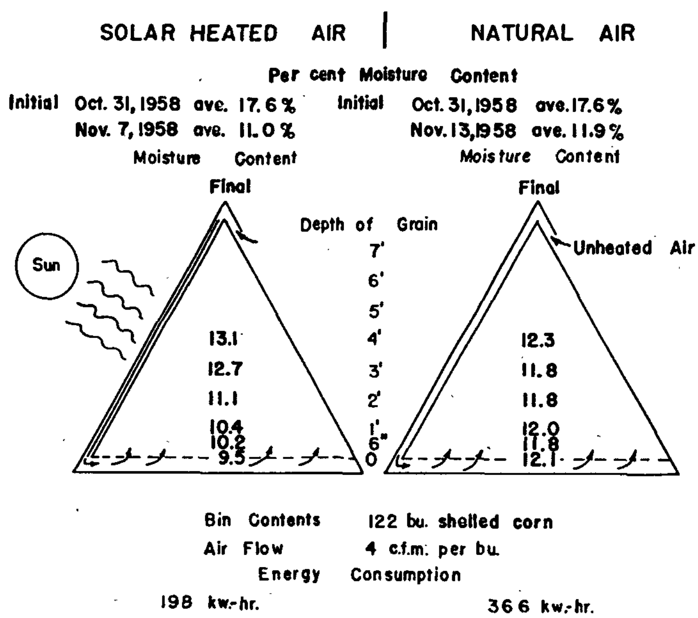

Figure 8. Solar-supplemented *vs.* natural air drying (fan operated continuously)

rable alternate construction method to reduce the moisture transfer noted. Subsequent preliminary observations of air supported collectors have shown this to be mechanically feasible. While acting as an absorber, the ground also performs a limited heat storage function. This was indicated by thermocouples which indicated the extent of heat storage and release taking place.

The design equation previously developed indicated that the clear weather solar noon temperature rise through the heater at the orientation and time of year involved would be approximately 17-3/4°F. Operational performance indicated an actual rise of 17°F under those conditions. For a sunny clear day, an average temperature rise of 13°F was recorded for the period 9 a.m. to 4 p.m., providing a collector efficiency of 45 per cent.

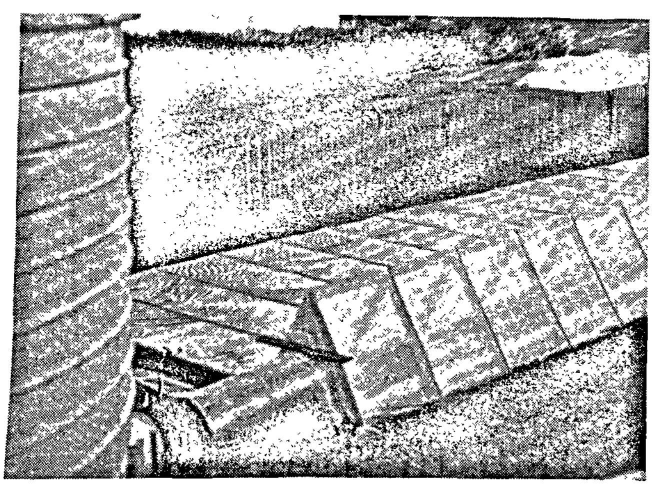

Figure 9. Solar collector and system for utilizing supplementally heated forced air in grain drying

Blower control

When wet grain is being dried, it usually is considered desirable to operate fans continuously until a moisture level of 16 to 18 per cent is reached, to prevent deterioration. It is theoretically desirable to allow continuous operation except during periods when the air relative humidity is above the current equilibrium grain moisture of the drying grain. This increased drying speed will result, however, in greater fan energy usage, and the mechanical and economic practicability of such a control system may be questioned.

The use of time switches, humidistats, thermostats, and other control elements is possible alone or in combination to achieve automatic operation or a specific mode of control. Their use should be justified on the basis of total drying cost and is related to the quantity of grain dried.

Current research

A 10 × 10 foot air inflated collector has been designed and constructed (figure 12). A layer of solar resistant transparent polyethylene film is heat-sealed at the edges to a layer of black film which acts as the absorber.

Such a heater is readily portable and compactly storable. This collector has been used in tests up to a static pressure of one inch of water but probably cannot withstand higher pressures. For pressures in excess of this, it may be necessary to employ two fans with matched air delivery. One fan would keep the collector inflated and the other would draw air from the collector and force it through the grain mass without exposing the collector to destructive pressures. It is possible that advances in techniques of sealing and strengthcharacteristics of nylon or

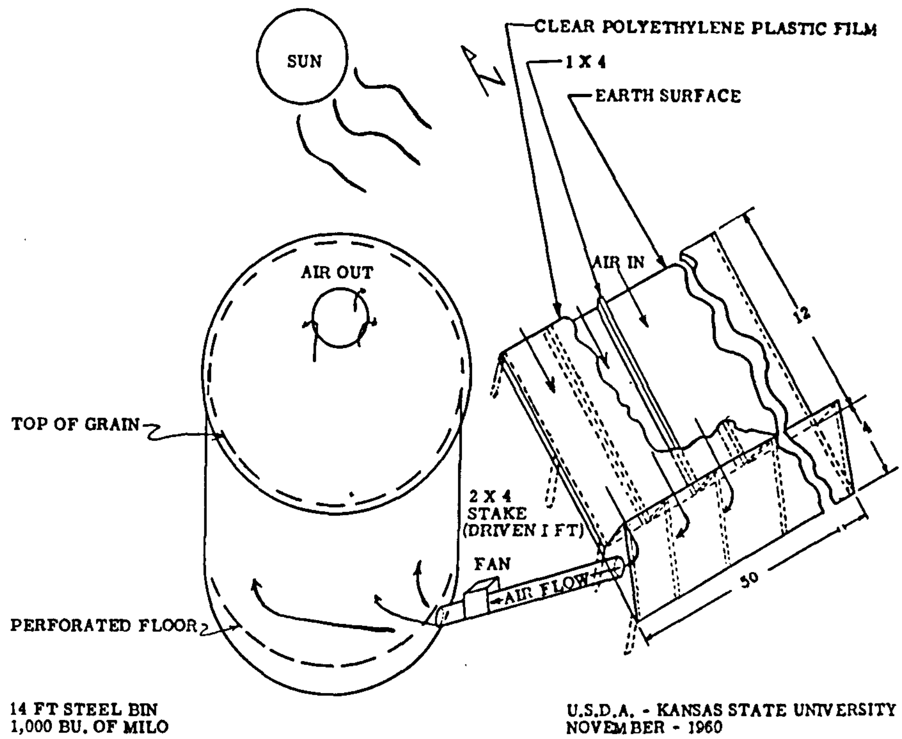

Figure 10. Experimental earth absorbing solar collection system for use in forced air drying (schematic)

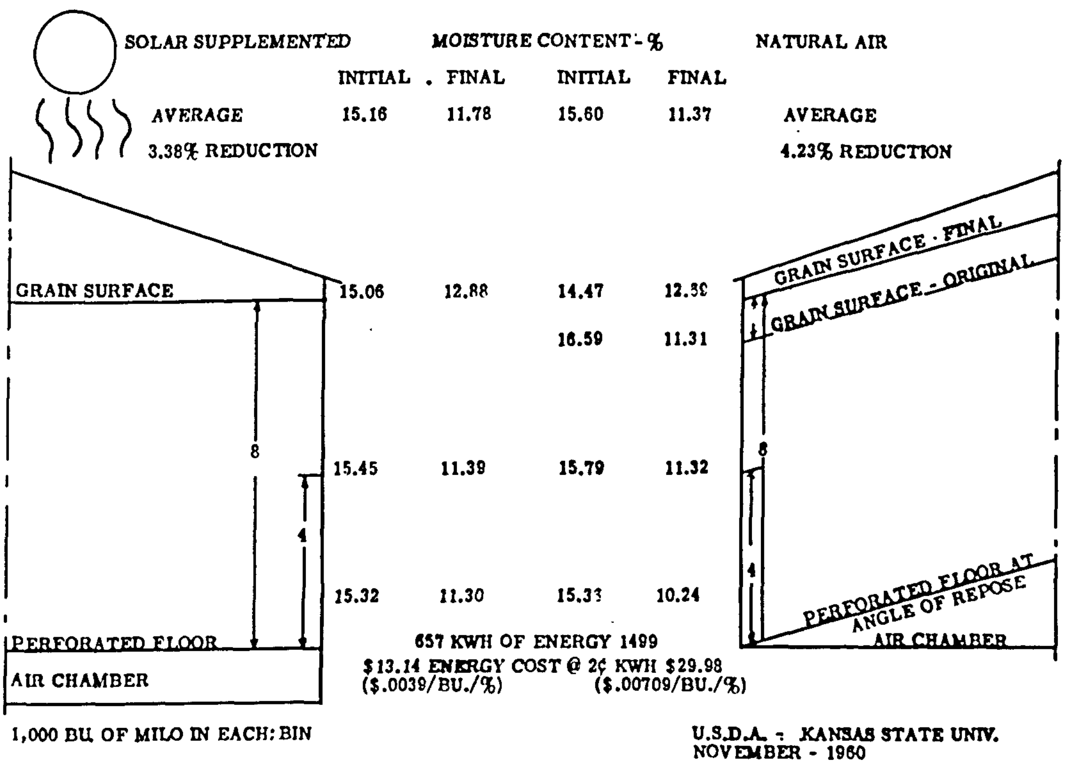

Figure 11. Summary information of comparative natural air *vs.* solar supplementally heated air grain drying test

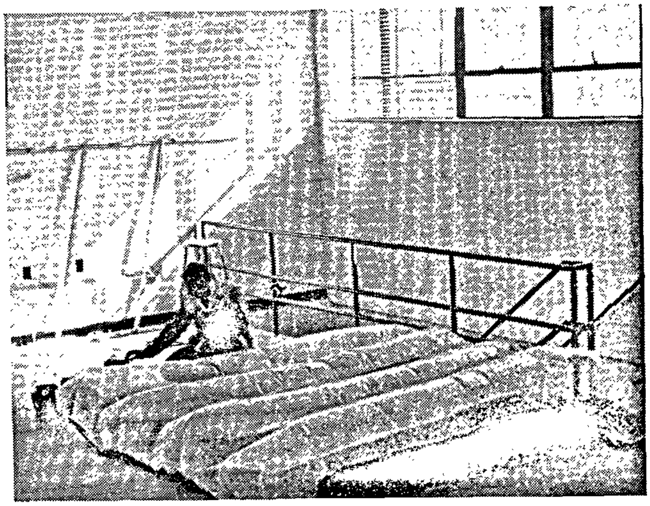

Figure 12. Experimental air inflated (supported) plastic film solar collector

other thread reinforced films may allow direct collector use at pressures commonly encountered in "in storage" drying.

Supplementary heating equipment

Since the sun is an inconstant and variable source of energy, the grain dryer using solar energy as the only heat source must be designed and operated as an unheated air dryer.

The effectiveness of a solar supplemented forced air drying system may be improved by adding supplemental electric or other type heaters that will raise the air temperature when the sun is not available. Such an addition provides an additional margin of safety when drying wet (above 1[illegible] to 18 per cent) grain. Both the supplemental and the solar heater reduce operating time of the fan and therefore effect a reduction in fan energy requirement.

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Summary

A solar air heater suitable for crop drying can be basically a metal roof coated with black paint with air moving along the underside, or made more elaborate and expensive and provide more heat by including a transparent plastic film or glass cover supported above the roof. The desirable air flow rates that are practical for either type have been suggested from mathematical analyses and limited results of laboratory study.

It is felt that while more research in collector design remains to be accomplished, work has progressed to the point that a satisfactory design can be produced for farm construction for further field type research. These conceptional designs are not yet generally recommended but innovators may wish to consider them for possible future construction.

Research has indicated that solar air heater usage can be useful where "in storage" drying of fall produced grains is practiced. Only with other supplementation can rapid drying be insured and damage to wet grain avoided.

Current research is being devoted to study of additional designs of low-cost film plastic air heaters that may be more portable, storable, and flexible in multiple-purpose agricultural use, such as for animal or poultry shelter ventilation, in addition to crop drying.

UTILISATION DE L'ÉNERGIE SOLAIRE POUR LE SÉCHAGE DES PRODUITS AGRICOLES

Résumé

Un chauffe-air solaire approprié pour le séchage des produits agricoles peut être constitué essentiellement par un toit en métal enduit de peinture noire, avec circulation d'air sur sa surface inférieure. Il peut être plus compliqué et plus coûteux et débiter plus de chaleur dans le cas où il comporte une pellicule transparente en composition plastique ou un couvercle en verre installé au-dessus du toit. On recommande des régimes de circulation d'air souhaitables, pratiques pour un type ou pour l'autre d'installation, à partir d'analyses mathématiques et des résultats limités d'études faites en laboratoire.

On estime que, bien qu'il reste à réaliser de nouveaux travaux de recherches ayant trait à la conception des collecteurs, le travail a progressé suffisamment pour qu'une formule satisfaisante puisse être mise au point en vue de leur construction dans les entreprises agricoles pour poursuivre les recherches sur place. Ces conceptions d'ensemble ne sont pas encore généralement recommandées, mais les innovateurs peuvent désirer les prendre en considération pour leurs réalisations ultérieures possibles.

D'après les recherches menées jusqu'à présent, l'emploi d'un chauffe-air solaire peut être indiqué lorsque l'on pratique le séchage des grains produits pendant l'automne au cours de leur entreposage. Ce n'est qu'avec d'autres dispositifs qu'un séchage rapide peut être assuré et que l'on peut éviter les dégâts aux grains humides.

Les recherches en cours s'attachent à l'étude d'autres versions des chauffe-air à pellicule en composition plastique de coût modique qui peuvent être faciles à déplacer, susceptibles d'être conservés, adaptables à des emplois agricoles multiples, tels que la ventilation des abris destinés aux animaux ou à la volaille, à part le séchage des produits agricoles.

SOLAR DRYING OF OIL SHALE

A. T. Talwalkar, J. A. Duffie and G. O. G. Löf *

Solar energy may be effectively used for drying, particularly where the cost of fuel for conventional drying methods is high or in regions where usual fuels are not available. It presents the possibility of drying oil shale of the Paraiba Valley of Brazil, which has an initial moisture content of about 33 per cent on a wet basis. The removal of at least a part of this moisture, prior to retorting of the shale, can result in an increase in the oil yield and also permit the use of lower grade shales than would otherwise be possible.

Solar drying processes may be classified according to the method of absorption of solar radiation. Radiation may be absorped in a solar heat collector and used to heat air for a conventional drier, or the drying substance itself may be used as the radiation absorbing material in a covered or an uncovered solar collector. In radiation drying, the collector and the drier are a common unit and usual solar collector energy balances must be modified to account for the latent loads. In this paper, the possibility of drying the Brazilian oil shale by direct absorption of solar radiation is investigated.

Although solar energy has been utilized since ancient times for evaporation of water and drying, data on radiation drying were scarce in the literature. In recent years, solar evaporation from water surfaces has been studied in some detail. Cummings (1) has developed an energy equation to determine the evaporation from a lake in such a way that wind velocity does not enter the calculations and air temperature and humidity enter only as terms in a correction which is relatively small under typical conditions. Wilson (2,3) has studied the drying of vine fruit, both by direct absorption of solar radiation and by using solar energy absorbers to heat the air for the conventional tray driers. He found that radiation drying was as fast as, if not faster than, that in the tray drier. He has also studied drying of peanuts (4) by absorption of solar radiation.

A. A. Ismailova (5) has investigated the possibility of using solar energy for drying fruits and vegetables. He dried apples by direct absorption of radiation, by hot air obtained from a solar heat collector and by combination of radiation and air-drying, and found that radiation drying is faster than the other two methods.

In recent years, infrared radiation drying has received some attention, especially for drying paint coatings and baking enamel. Stout, Caplan and Baird (6) have investigated the mechanism and the rate of infrared radiation drying of sand and soap and compared it with various other methods of drying. They concluded that radiant energy is another and more rapid method of heat transmission, one which is peculiarly free of any film resistances to the heat flow. The similarity between infrared radiation drying and solar drying is obvious, as heat for drying is supplied by radiation. However, in radiation drying, a steady radiation level is used and the spectral distribution of the radiation may also be different than solar energy. Further, solar drying is influenced by such unpredictable factors as varying weather conditions and precipitation.

General considerations

A drying problem can be studied from two viewpoints. The "internal" viewpoint involves the study of drying from the standpoint of the movement of liquid inside the solid, while the "external" viewpoint considers the effect of external drying conditions on the drying rate. The latter approach is reported in this study. The study of internal mechanism of liquid flow consists in the development and the verification of the differential equation, which will adequately describe the drying process, relating moisture content, time, temperature and position in the bed of drying material. From the external viewpoint, one can study the effect of process variables such as bed depth, particle size, agitation of the material being dried, time of exposure and the advantages of through circulation of air. Further, the effect of meteorological variations can be determined by means of an over-all energy balance and the relative magnitudes of the terms in the energy equation ascertained experimentally.

Petroleo Brasileiro (Petrobras) has carried out a number of experiments to optimize the bed thickness and particle size range of the shale and to ascertain the advantages of agitation of material and through circulation of air. Most of their experiments consisted in exposing the shale in wooden trays (3′ × 2′), having fine wire screens as bottom, to all weather conditions. The trays were weighed twice a day to determine the loss (or gain) in weight. Some experiments were also run to study the effect of varying moisture grades on the rate of drying and to determine the effect of decrepitation on the shale.

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The following conclusions were drawn from these experiments:

(*a*) Agitation of material is decidedly useful;

(*b*) The particle size range of — 4″+2″ presents maximum moisture loss during sunny days and minimum moisture gain during precipitation;

(*c*) The per cent moisture lost or gained per day is an inverse function of the bed thickness;

(*d*) The moisture lost per square foot of exposed area increases with the bed depth up to 12″ thick beds, beyond which the increase is insignificant;

(*e*) Natural through circulation of air increases the drying rate but slightly.

It was further found that lower grade shale decrepitated more during the drying. However, there is no relation between total carbon content of the shale and size of the decrepitated exposed shale.

Over-all energy balance

An over-all energy balance on a unit area basis over a tray filled with the shale, as shown in figure 1, may be written as

$$q_t = (q_\lambda + q_s) + q_c + q_{\text{cond.}} + q_{r_{\text{net}}} + q_{cp} \quad [1]$$

where,

q_t = amount of incident energy absorbed and converted to heat per sq. foot of tray area

$= \alpha \cdot I$ [2]

q_λ = latent heat transferred by evaporation of moisture per sq. foot of tray area

$= m \cdot \lambda$ [3]

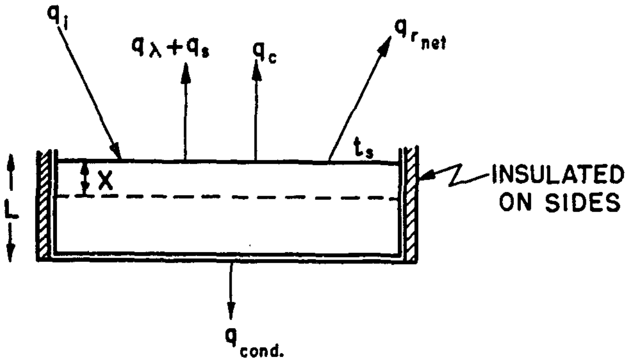

Figure 1. Over-all energy balance on the bed

q_s = sensible heat transferred by evaporation of moisture /ft² of tray area

$= m \cdot C_{pw} (t_s - t_a)$ [4]

q_c = heat lost by convection/ft² of tray area

$= h_c \cdot (t_s - t_a)$ [5]

$q_{\text{cond.}}$ = heat lost by conduction through the bottom of the bed/ft² of tray area

$= -K_e \left.\frac{dt}{dx}\right|_{x=L}$ [6]

$q_{r,\text{ net}}$ = heat lost by radiation exchange between tray and sky/ft² of tray area

$= \sigma [\varepsilon (460 + t_s)^4 - \alpha (460 + t_{\text{sky}})^4]$ [7]

q_{cp} = gain (or loss) in heat stored in the bed, per ft² of tray area

$= W_{av} C_{ps} (t_2 - t_1)$ [8]

Combining equations [2] to [8] with [1], we get

$$\alpha \cdot I = m [\lambda + c_{pw})t_s - t_a)] + h_c (t_s - t_a) + k_e \left.\frac{dt}{dx}\right|_{x=L} + \sigma [\varepsilon (460 + t_s)^4 - \alpha (460 + t_{\text{sky}})^4] + W_{av} \cdot C_{ps} (t_2 - t_1) \quad [9]$$

The physical properties of the bed, such as absorptivity, heat capacity, and conductivity, may vary with the moisture content, but these are assumed constant as a first approximation and assigned a suitable average value.

The effect of different variables on the terms of the energy equation [9] must be clearly understood and, hence, it is discussed in some detail below.

Heat input q_I

The heat input depends on the intensity of solar radiation and the absorptivity of the material. The absorptivity of the shale varies slightly with moisture content, but an average value can be satisfactorily assigned. The intensity of total (direct + diffuse) radiation is, however, subject to hourly and seasonal variations. In addition to these inherent variations, such indeterminent and unpredictable factors as cloudiness further complicate the problem. Clouds vary the fraction of diffuse radiation from about 10 per cent on clear days to about 100 per cent on cloudy days (7). Hence, energy balances are here obtained by averaging the radiation over a short period (an hour) and noting the corresponding amount of evaporation, temperature changes of bed and atmospheric conditions.

Useful heat q

Latent heat transferred by evaporation of moisture represents the amount of useful heat and is directly proportional to the rate of drying which, in turn, is dependent on the intensity of solar radiation available, magnitude of heat loss terms and the moisture content of the shale. Humidity appears to have insignificant influence in radiation drying.

Sensible heat loss q_s

The magnitude of this term is negligible. However, the term tends to nullify the variation in latent heat of evaporation due to changes in surface temperature and reduces the error in using an average value of latent heat for the day.

Convective heat loss q_c

This is one of the most important terms in the energy equation for it represents the major loss of energy. The magnitude of q_c is dependent on a number of factors. The convective heat transfer coefficient h_c, in equation [5], depends on the temperature drop as well as the air velocity. In case of porous beds of non-uniform particle size, such as that of oil shale, it also depends on the ratio of actual to projected area of heat transfer. Unfortunately, there is no convenient way to determine this factor, and h_c is calculated on the basis of unit projected area in this investigation.

The temperature dependence of h_c for horizontal plates facing upwards in air, at atmospheric pressure and temperature, is given by [8]

$$h_c = 0.38\,(t_s - t_a)^{0.25}$$

for natural convection. However, natural convection is rarely significant, as any wind will control the convective loss, and the effect of air velocity on h_c, for parallel flow of air, is given by [9] :

$$h_c = 0.0128\,G^{0.8}$$

where G = mass velocity of air, lb/hr. ft². Hottel and Wœrtz [10] have assumed a wind coefficient of $4.07\,\frac{\text{btu}}{\text{hr. ft}^2\,°\text{F}}$ corresponding to 10 mph wind.

In conventional drying, high air velocity and a large temperature drop is desirable for better convective heat transfer to the drying material and subsequent higher drying rate. But in the case of solar drying, both high wind velocity and a large temperature difference are determental to the drying rate as they increase the convective heat loss while having no effect on the heat supply rate. The most efficient utilization of solar energy is obtained at small temperature differences between the shale and the surroundings.

Conductive losses $q_{cond.}$

For sufficiently thick beds, there is little temperature gradient at the bottom and hence little heat is lost by conduction through the bottom of the bed.

Back radiation losses q_{rnet}

This is the heat lost due to net radiation exchange between the shale and the sky. There was no convenient way to determine the long wave diffuse radiation which is emitted by the sky, and in this study it was approximated as black body radiation from a source at 20°F below ambient temperature. The radiation from the shale depends on its emissivity and surface temperature. Therefore, equation [7] may be rewritten as :

$$q_{r_{\text{net}}} = 0.171 \times \alpha \left\{ \left(\frac{460 + t_s}{100}\right)^4 - \left(\frac{460 + (t_a - 20)}{100}\right)^4 \right\}$$

Change in heat stored in bed q_{cp}

This quantity may be either positive or negative, depending upon whether the heat is gained or lost during the interval. It is difficult to determine q_{cp} accurately as it involves determination of the average temperature of shale in the tray. The problem of averaging the temperature of the bed lies in the fact that the temperature of shale exposed to direct radiation fluctuates widely if a cloud covers the sun or a gust of wind blows, whereas the temperature of shale inside the bed is not as susceptible to atmospheric variations. Thus, the fraction of shale exposed to direct radiation, which will follow the variations of surface temperature, is estimated and internal temperatures at various depths are used to calculate the change in heat stored in different layers of the bed.

Experimental work

The experimental work consisted of: (*a*) measurement of absorptivity of shale; (*b*) determination of temperature variations in the bed in order to determine a method of averaging temperature of the bed; (*c*) the solar drying tests.

(*a*) The absorptivity of shale was measured by means of a hemispherical reflectometer, by a technique of comparison with standard samples of known reflectance. Shale samples were prepared by cutting pieces of different shades and moisture content into thin slices on a band saw and polishing them with sandpaper. It was found that the reflectivity of shale varies from 8 to 17 per cent, i.e., the absorptivity varies from 92 per cent when wet to about 83 per cent when dry. As the higher figure appears to be valid only for the first day of drying, an average value of 85 per cent absorptivity may be used in the energy balance.

(*b*) Temperature gradients were determined in order to estimate the average temperature of bed. The temperature variations through the day at three positions in the bed (near the surface, in an intermediate layer, and at the bottom) are plotted for two days in figure 2. It is evident that on the cloudy day, the surface temperature varied considerably more than that of the interior. Figure 3 shows temperature variations for a clear day at various depths of 1/4″, 1/2″, 1″, and 1½″ in a single piece of shale exposed to direct radiation. This figure shows gradients and variations similar to those of figure 2. Thus, it may be assumed that only a layer one particle deep has temperature variations as the surface temperature while the rest of the bed temperature varies as t_i, the interior temperature of the bed. This fact will have to be considered, at least on cloudy days, while calculating the change in the sensible heat of the bed. On clear days, variation of either t_s or t_i may be used without significant error, as is seen from figure 2.

(*c*) In the solar drying tests, the shale was dried in a tray placed on a balance, as shown in figure 4. Thermocouples were inserted at the top, bottom,

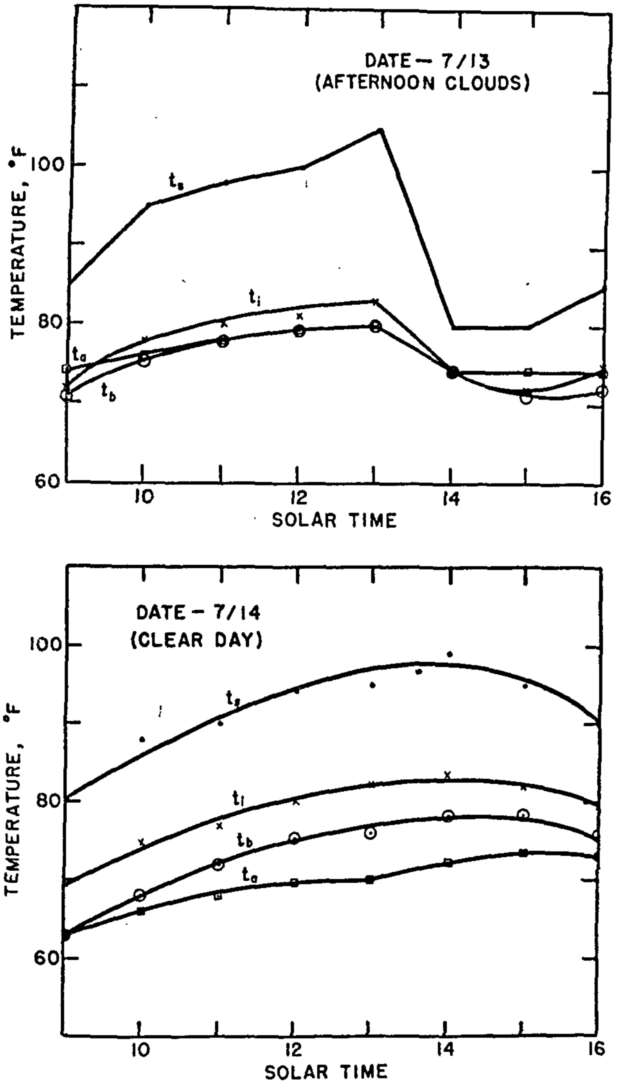

Figure 2. Temperature gradients in the bed

and intermediate positions in the bed and provided temperature records. The ambient temperature was also measured by means of another thermocouple shaded from direct radiation. The incident radiation was measured by means of an Eppley pyrheliometer. The wind velocity and humidity data were obtained from the weather bureau. The weight and area of the tray and the initial moisture content of the shale were determined before the start of each test. The tray was weighed every hour, the amount of moisture evaporated being given by the difference in two consecutive weights. The average temperatures for the hour were also noted.

The calculated data for two clear-weather solar drying tests are shown in tables 1 and 2. In the first test, it was found that the temperature at the bottom of the bed was, at times, slightly higher than that of its interior, as the metallic tray became heated. This means that some heat was conducted in at the bottom. This heat would probably be insignificant. However, the error was remedied in a second test by shielding the sides of the tray from radiation by means of aluminum foil. Table 3 summarizes the more detailed data of the other tables, and shows the daily radiation, moisture content, drying efficiency and amount of evaporation per square foot for these two experiments.

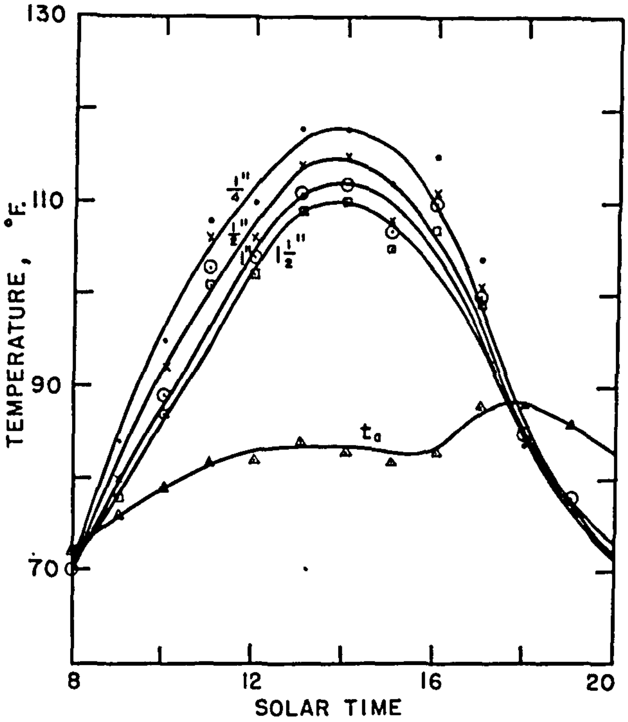

Figure 3. Temperature gradients in a piece of shale

Discussion

By inspection of the tabulated data on solar drying, it is seen that the major heat loss is due to convection. The variation in other heat loss terms is small compared to that of convective heat loss. For example, the back radiation loss varies from 20 to

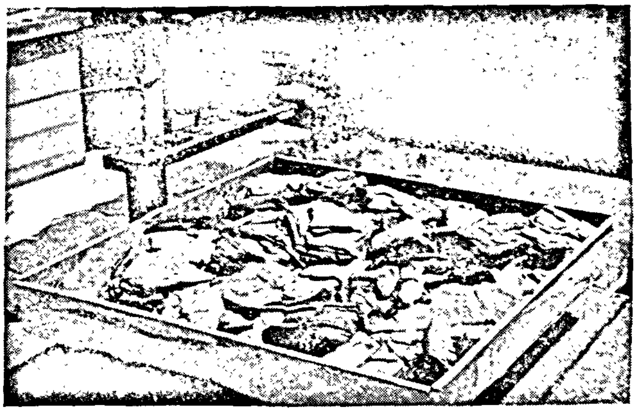

Figure 4. Tray of partially dried shale on a balance

Table 1

(particle size, 1-3″; bed depth, 3″; area of tray, 4.7 ft²; initial moisture content, 32 per cent; weight of dry shale, 33.4 lb)

Date	*Time*	*Notes*	*Corrected solar radiation*	$q_i = \alpha \cdot I$	*m lb/hr.ft.²*	λ *Btu/lb*	*Avg. surface temp.* $t_{s_{avg}}$ *(°F)*	*Avg. ambient temp.* $t_{a_{avg}}$ *(°F)*	*Change in avg. bed temp.* $t_2 - t_1$ *(°F)*	$q_\lambda = m\lambda$	$q_r = \sigma\varepsilon(T^4_s - T^4_{sky})$	$q_{cp} = W_{avg}/A \cdot Cp(t_2 - t_1)$	$q_c = q_i - q - q_r - q_{cp} = h_c \cdot A \cdot (t_{s_{avg}} - t_{a_{avg}})$	*h Btu hr.ft.²°F*	*Wind velocity (knots)*
12 May. .	11-12 M.D.	Initial	358.7	305.0	0.1461	1 049	76.0	58.5	0	153.2	30.83	0.00	121.00	6.91	11.5
	12- 1 P.M.	wt. of	357.5	304.0	0.1461	1 048	77.5	60.0	0	153.1	31.60	0.00	119.30	6.82	9.5
	1- 2 P.M.	wet	336.2	286.0	0.1330	1 049	78.5	61.5	2	139.4	30.40	4.54	111.66	6.55	9.0
	2- 3 P.M.	shale =	298.2	254.0	0.1330	1 049	77.0	62.0	— 1	139 4	26.42	— 2.20	90.38	6.01	9.5
	3- 4 P.M.	$48 \cdot \frac{12}{16}$ lb	237.6	202.0	0.1063	1 050	72.0	62.0	1	111.0	23.20	2.18	64.72	6.47	9.5
	4- 5 P.M.		166.0	141.0	0.0665	1 054	67.0	61.5	— 2	70.1	20.41	— 4.33	54.82	9.95	8.0
13 May. .	8- 9 A.M.	Initial	242.2	206.0	0.6665	1 059	64.0	52.0	10	70.4	23.55	21.20	90.85	7.56	6
	9-10 A.M.	wt. of	298.0	253.8	0.0665	1 050	74.5	56.5	7	69.9	28.65	14.75	140.50	7.80	4
	10-11 A.M.	wet	331.0	281.5	0.0798	1 046	83.5	60.5	5	83.4	34.60	10.42	153.10	6.44	5
	11-12 M.D.	shale =	346.0	294.0	0.0931	1 041	88.5	63.0	4	97.0	38.20	8.45	150.35	5.90	6
	12- 1 P.M.	$44 \cdot \frac{10}{16}$ lb	344.0	292.5	0.1063	1 041	88.5	65.0	0	110.9	36.80	0	144.80	6.15	5
	1- 2 P.M.		322.0	274.0	0.0931	1 043	86.0	67.0	2	97.3	33.80	4.05	138.85	7.30	5
	2- 3 P.M.		288.0	245.0	0.0798	1 045	84.0	66.5	— 2	83.4	30.85	— 4.01	134.75	7.70	7
	3- 4 P.M.		233.5	198.5	0.0798	1 048	78.5	64.5	— 4	83.5	28.20	— 8.14	95.00	6.79	3
	4- 5 P.M.		165.3	140.8	0.0531	1 049	73.0	64.5	1	55.6	22.35	1.97	60.90	7.16	4
	5- 6 P.M.		91.0	77.4	0.0266	1 052	63.0	65.0	— 3	28.0	16.90	— 5.89	39.00	13.00	4
14 May. .	8- 9 A.M.	Initial	232.0	197.0	0.0531	1 052	70.0	58.5	14	56.0	26.90	27.20	87.00	7.56	7
	9-10 A.M.	wt. of	286.0	245.0	0.0531	1 048	82.5	67.5	8	55.6	29.40	15.44	144.56	9.70	7
	10-11 A.M.	wet	314.0	267.0	0.0665	1 042	87.5	70.5	7	69.4	32.00	13.42	152.18	8.96	7
	11-12 M.D.	shalès =	332 0	282.0	0.0798	1 040	95.0	73.0	5	83.0	38.20	9.51	151.30	6.89	7
	12- 1 P.M.	$40 \cdot \frac{14}{16}$ lb	326.0	277.5	0.0665	1 039	97.0	75.0	0	69.0	38.20	0.00	170.30	7.74	9
	1- 2 P.M.		281.5	239.2	0.0665	1 041	92.0	75.5	— 2	69.3	34.10	— 3.74	139.54	8.45	10
	2- 3 P.M.		197.9	168.0	0.0531	1 048	85.0	75.0	— 4	55.6	27.95	— 7.42	91.87	9.19	8
	3- 4 P.M.		140.0	119.0	0.0398	1 049	79.5	74.5	— 2	41.7	21.77	— 3.63	59.16	10.75	7
15 May. .	8- 9 A.M.	Initial	234.0	199.0	0,0531	1 044	86.0	70.5	8	55.5	30.60	14.45	98.45	6.35	14.5
	9-10 A.M.	wt. of	292.5	249.0	0.0531	1 040	92.5	71.5	3	55.3	36.45	5.39	151.86	7.21	13.5
	10-11 A.M.	wet	331.0	281.5	0.0531	1 038	98.5	74.0	5	55.1	39.40	8.90	178.10	7.27	11.0
	11-12 M.D.	shale = 33.0 lb	347.5	295.5	0.0531	1 035	105.0	77.0	7	55.0	44.05	12.40	184.00	6.57	11.5

Table 2

(particle size, 2-3″; bed depth, 4″; area of tray, 4.7 ft²; initial moisture content, 34 per cent; weight of dry shale, 45.35 lb)

Date	*Time*	*Notes*	*Corrected solar radiation*	$q_i = \alpha \cdot I$	*m* *lb/hr.ft.*²	λ *Btu/lb*	*Avg. surface temp.* $t_{s_{avg}}$ *(°F)*	*Avg. ambient temp.* $t_{a_{avg}}$ *(°F)*	*Change in avg. bed temp.* $t_2 - t_1$ *(°F)*	$q_\lambda = m\lambda$	$q_r = \sigma\varepsilon(T_s^4 - T_{sky}^4)$	$q_{cp} = W_{avg}/A \cdot C_p(t_2 - t_1)$	$q_c = q_i - q - q_r - q_{cp} = h_c \cdot A \cdot (t_{s_{avg}} - t_{a_{avg}})$	*h* *Btu/hr.ft.²°F*	*Wind velocity (knots)*
13 July. .	9-10 A.M.	Initial wt. of	288.5	245.5	0.1198	1 040	90.0	75.0	8.0	124.5	30.6	25.00	65.4	4.35	9.0
	10-11 A.M.	wet shale =	312.8	266.0	0.1330	1 039	96.0	77.0	2.0	138.0	36.0	6.20	85.8	4.51	9.0
	11-12 M.D.	65 · $\frac{15}{16}$ lb	337.0	286.0	0.1461	1 038	98.5	78.5	2.0	151.7	37.2	6.13	91.0	4.55	9.0
	12- 1 P.M.		311.0	264.0	0.1197	1 036	102.5	79.5	3.5	124.0	41.1	10.49	88.4	3.84	14.0
	1- 2 P.M.		133.6	113.5	0.1063	1 040	92.5	77.0	−17.0	110.8	33.5	−51.10	40.4	2.70	15.0
	2- 3 P.M.		109.0	92.6	0.0665	1 049	80.0	74.0	−1.0	55.7	22.0	−2.96	17.86	2.98	15.0
	3- 4 P.M.		214.5	182.5	0.0531	1 048	82.5	74.0	−4.0	60 6	23.5	11.90	109.50	12.90	12.0
14 July. .	9-10 A M.	Initial wt. of	303.5	258	0.1063	1 045	84.0	64.5	7.0	111.0	32.6	20.40	94.00	4.82	8.0
	10-11 A.M.	wet shale =	332.5	282.5	0.0531	1 041	89.0	67.0	2.0	55.4	25.3	5.89	195.9	8.90	6.0
	*11-2 P.M.	61 · $\frac{5}{16}$ lb	1 032.0	879	0.0399	1 040	95.0	70.0	8.0	41.5	120.3	22.85	231.5	9.25	7.0
	2- 3 P.M.		295.0	250.5	0.0930	1 039	97.5	72.5	−3.0	96.5	39.7	−8.40	122.7	4.90	4.0
	3- 4 P.M.		260.5	222	0.0665	1 041	95.2	73.0	−2.0	69.3	36.45	−5.60	121.85	6.24	3.0
15 Jyly. .	9-10 A.M.	Initial wt. of	292.0	248.0	0.0665	1 041	92.5	69.0	5.5	69.3	40.0	15.10	123.6	5.26	7.0
	10-11 A.M.	wet shale =	328.0	279.5	0.0665	1 039	97.5	71.5	5.0	69.0	40.5	13.68	156.3	6.01	7.0
	11-12 M.D.	57 · $\frac{14}{16}$ lb	264.0	225.0	0.0665	1 036	100.0	74.0	0.0	68.9	41.9	0.0	114.2	4.40	9.0
	12- 1 P.M.		240.0	204.0	0.0531	1 038	98.5	76.0	−2.5	55.1	38.2	−6.76	117.5	5.22	9.0
	* 1- 3 P.M.		517.5	440.0	0.1331	1 036	100.0	80.0	−3.0	138.0	73.6	−8.05	118.2	5.91	10.0
	3- 4 P.M.		199.5	169.5	0.0531	1 041	92.5	83.5	1.5	55.5	28.0	3.99	82.1	9.12	9.0
16 July. .	9-10 A.M.	Initial wt. of	287.5	244.0	0.0798	1 045	84.0	76.5	7.0	83.50	22.80	18.30	119.15	15.90	9.0
	10-11 A.M.	wet shale =	301.5	256.0	0.0531	1 040	91.5	78.5	6.5	55.40	30.84	16.95	152.50	11.71	8.0
	11-12 M.D.	55 · $\frac{2}{16}$ lb	331.0	281.0	0.0665	1 039	97.5	80.5	3.5	69.00	33.05	9.05	169.40	9.97	9.0
	12- 1 P.M.		328.0	279.0	0.0798	1 036	102.0	83.5	4.0	82.55	36.75	10.30	148.75	8.04	8.0
	1- 2 P.M.		227.5	193.2	0.0531	1 034	107.0	83.0	3.5	56.00	40.70	8.97	87.00	3.62	7.0
	2- 3 P.M.		260.5	222.0	0.0266	1 036	102.5	81.5	−9.5	27.55	53.00	−24.20	165.40	7.88	8.0
17 July. .	9-10 A.M.	Initial wt. of	278.0	236.0	0.0531	1 036	100.5	78.5	7.5	55.00	40.45	18.78	121.80	5.53	7.0
	10-11 A.M.	wet shale =	298.2	254.0	0.0399	1 034	107.5	81.0	4.5	41.25	41.90	11.20	159.65	6.02	5.0
	11-12 M.D.	52 · $\frac{10}{16}$ lb	264.5	225.0	0.0399	1 034	107.5	82.0	−3.0	41.25	41.35	−7.45	149.85	5.86	8.0
	12- 1 P.M.		288.5	245.5	0.0665	1 035	105.0	83.0	−1.0	68.80	38.50	−2.47	183.70	8.35	8.0
	1- 2 P.M.		277.5	236.0	0.0399	1 034	106.5	84.5	2.5	41.30	39.00	6.15	191.00	8.69	10.0
	2- 3 P.M.		211.5	179.7	0.0399	1 035	104.0	85.0	−5.0	41.35	36.00	−12.22	114.60	5.50	11.0
	3- 4 P.M.		194.0	165.0	0.0399	1 036	102.0	84.5	1.0	41.40	36.00	2.44	85.56	4.89	8.0

* Readings for more than one hour.

Table 3. Summary of experimental drying data

Date	Radiation (Btu/ft²)	Avg. moisture content (%)	Moisture evaporated (lb/ft²)	Efficiency (%)
Test 1 :				
12 May	1 754.2	40.8	0.731	43.7
13 May	2 570.0	28.6	0.718	29.3
14 May	2 108.9	19	0.4784	23.8
15 May	1 205.0	12.3	0.2124	18.5
Test 2 :				
13 July	1 706.4	41.5	0.7445	45.8
14 July	2 223.5	35	0.3588	17.0
15 July	1 841.0	25.4	0.4388	25.0
16 July	1 736.0	19.7	0.3589	21.7
17 July	1 812.2	14.4	0.3191	18.48

50 btu/hr. ft² and the heat stored in the bed may increase or decrease by up to 20 btu/ft² in an hour, but the convective heat loss varies from about 40 btu/hr. ft² to above 200 btu/hr. ft², depending upon the time of the day, the condition of the shale and the meteorological conditions.

The experimental convective heat transfer coefficient, h_c, is obtained by dividing the convective heat loss (obtained as the difference between heat input by radiation and other heat quantities) by the temperature difference between the shale and the surrounding air and by the projected bed area. The values of h_c thus obtained are rather inconsistent. The main difficulties lie in averaging the surface temperature, which fluctuates widely, and calculating the correct change in the sensible heat of the bed. An error of a few degrees in averaging the surface temperature leads to an erroneous value of h_c, particularly in the morning and evening when the temperature difference and the convective loss are both of low magnitude. In addition, the error in calculating the sensible heat change of the bed is also more significant in the morning and evening when the material is being rapidly heated or cooled. Accounting for all the erroneous values of h_c that may be obtained, it appears that wind velocity has little effect on the magnitude of the experimental coefficient. This may be explained by the fact that only the surface temperature fluctuates as a result of wind, and h_c is obtained

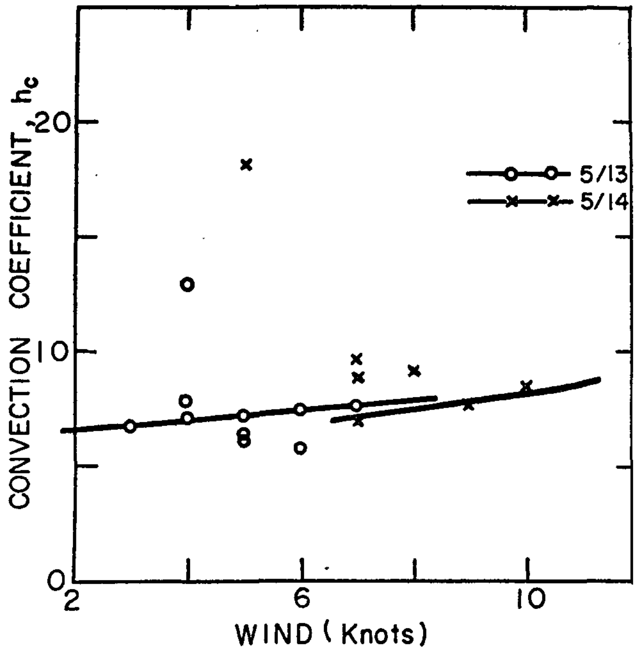

Figure 5. Convective heat transfer coefficient as a function of wind velocity

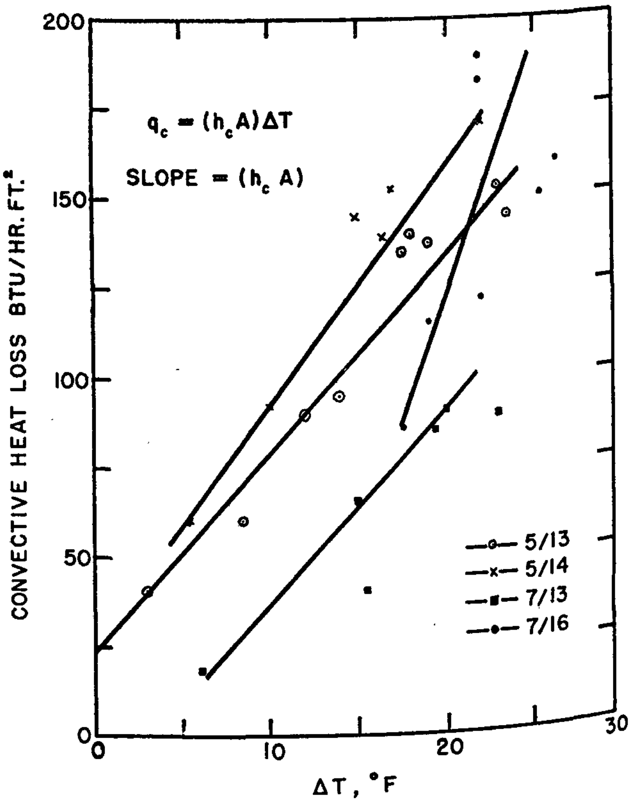

Figure 6. Heat lost by convection as a function of temperature drop

from averaged surface temperatures over the hour. The value of h_c varies between 5-10 btu/hr.ft^2 depending mainly on the temperature difference between shale and the ambient air. In figure 5, the heat transfer coefficient h_c is plotted against the wind velocity, for two days.

As regards the effect of temperature drop, ΔT, on the magnitude of the experimental coefficient, h_c, no definite relation could be obtained between the two from the available data. The average value of h_c by days, based on the projected area of heat transfer, shows an increasing trend as the drying proceeds. This may be seen from figure 6, in which q_c is plotted against ΔT. One explanation of the higher values of h_cA obtained on subsequent days of drying could be the increase in actual heat transfer area due to the cracking and decrepitation which this shale undergoes on drying. This increase in actual heat transfer area tends to mask any change in the heat transfer coefficient h_c.

It is found that the drying rate, and the efficiency of drying, generally decreases with decreasing moisture content except when the radiation for the preceding day is considerably lower than that for the day following it. No definite relation between incident radiation and the drying rate could be obtained from the available data. It appears that the dependence on the radiation would go on decreasing as the drying proceeds.

Mechanism of solar drying

Petrobras data for several drying experiments are shown in figure 7, where the drying rate is plotted as the function of average moisture content. The radiation fluxes for each day are also noted on the graph. It may be seen that a smooth curve cannot be drawn through the points on account of varying radiation flux on different days. To eliminate this effect of varying radiation, a fictitious drying rate corresponding to a common radiation flux of 2 000 btu/ft^2 per day is calculated (by assuming a linear relationship between the incident radiation and the drying rate) and plotted against the average moisture content in figure 8. It is expected that such a plot would at least give a general trend of solar drying curves. It may be seen from figure 8 that no constant rate period of drying is obtained. The general trend of the curves is concave upwards. Similar curves are obtained in the air drying of soap and wood. For air drying, the internal diffusion may be expected to control the rate of drying in the regions where curves, concave upwards are obtained. In such regions, the rate depends on temperature, varies inversely as the thickness of bed, is not affected by air velocity, and is affected by humidity only in so far as the equilibrium moisture content is concerned. The same may be expected to hold for radiation drying also, except that in this case the humidity has no effect on the hygroscopic moisture as the surface temperature rises far above the ambient air temperature.

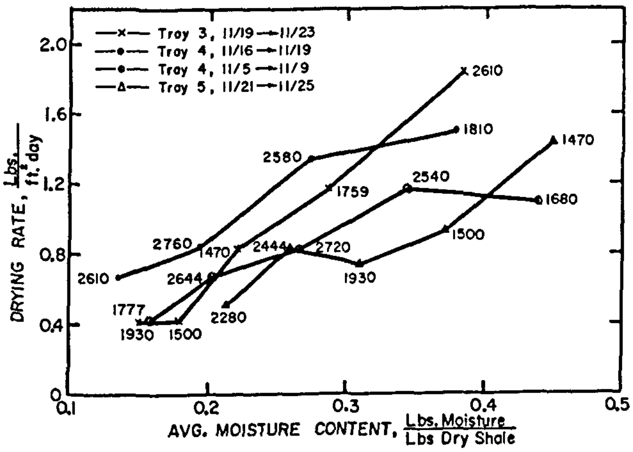

Figure 7. Drying rate as a function of average moisture content

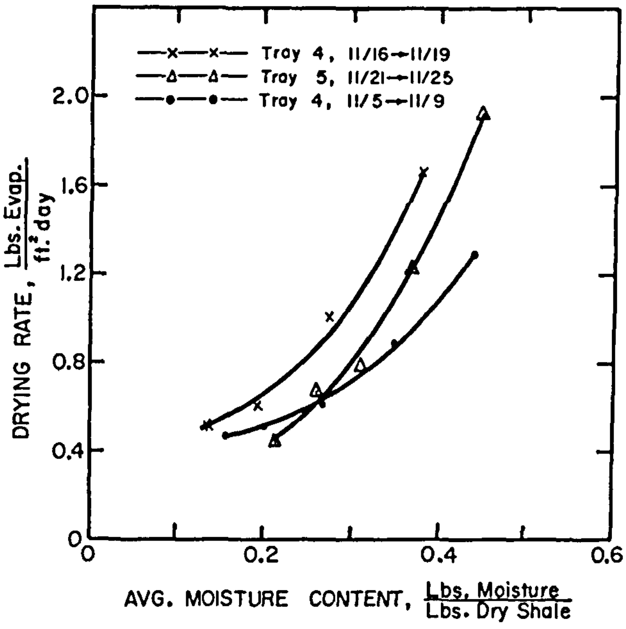

Figure 8. Fictitious drying rate at 2 000 btu/ft² day, as afunction of average moisture content

A plot of average moisture content against time in days for three of the experiments referred to in the above paragraph, on a semi-log graph paper, gives a straight line as shown in figure 9. This again indicates that the internal diffusion is the rate controlling step and the rate of drying is directly proportional to the free moisture content (8).

Agitation

In solar drying, the surface layer, which receives direct radiation, dries out faster and its temperature rises considerably higher than the temperature of the bulk of the material. Also, as the drying proceeds, the rate of drying falls off. A part of the energy is conducted into the bed, depending on the effective conductivity of the bed, but most is lost to the surroundings, mainly by convection. The maximum temperature reached by the surface during a day depends on the moisture content of the shale. The surface temperature will not rise excessively if the shale on top is not dry. This can be done by stirring the bed so that lower moist layers are brought to the surface. This results in lower convective losses and reduced back radiation losses. Thus the most efficient utilization of solar energy can be achieved by maintaining surface temperatures as low as possible during the entire process. However, the feasibility of mixing depends on the economic balance between the mixing cost and the gain realized by the increased rate of drying.

Precipitation

Precipitation is a major problem of solar drying. To avoid excessive moisture gain during rainfall, the material may be either covered or piled in conical heaps having large slopes. If heavy rainfall is expected it is best to remove the material from the field. In the case of oil shale, it was found that drying rates obtained after rainfall are higher than those of shale of the same moisture content before rain (for the same radiation intensity). This indicates that much of the moisture gained is surface moisture. It is noted that shallower beds show greater per cent loss in weight per day and, therefore, require fewer days of exposure for the desired moisture loss, though the efficiency of drying is lower, than that for the thicker beds. It seems reasonable, therefore, to use shallow beds, which require less exposure time, in unfavorable weather. However, this would increase the operating cost slightly. Thicker beds requiring longer exposure time but having better drying efficiency may be used in non-rainy seasons, when clear weather for long stretches of time is assured.

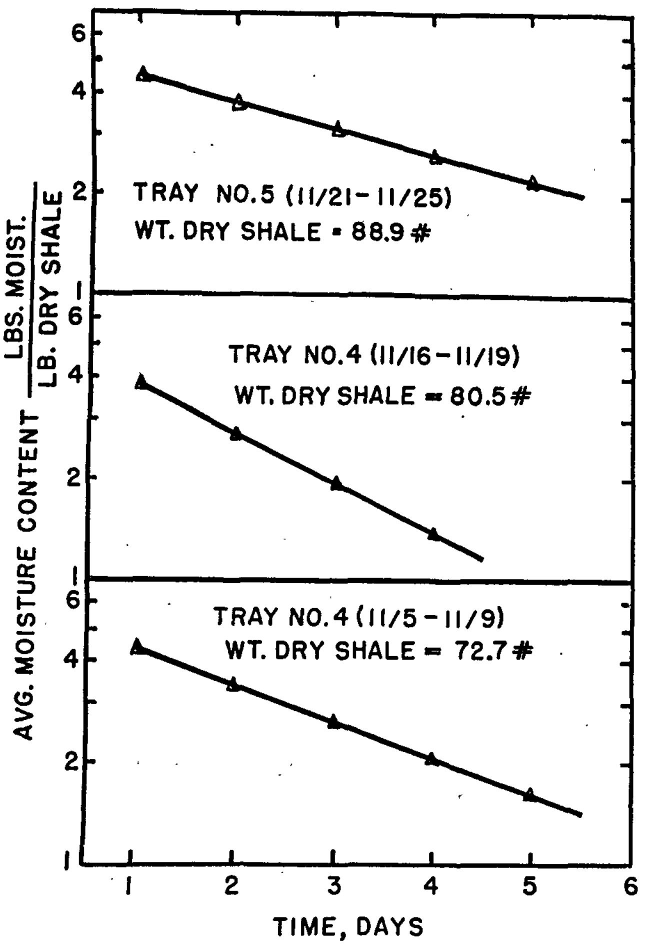

Figure 9. Log moisture content as a function of time

Economic considerations

The ultimate practicality of any solar process depends on the cost of heat delivered by the solar facilities in comparison with that from conventional fuel. In general, the cost of solar heat is largely the fixed charges on the installation, i.e., depreciation, interest on investment, taxes and insurance. Labor and maintenance costs should be small in a well-designed system. These expenses, for example on an annual basis, divided by the average annual heat delivery, yield the cost of one heat unit. If no energy storage is required, this cost may be compared with the total fuel, labor, and fixed costs in a conventional heat supply facility, and the cheapest source or method thus can be chosen. When direct solar drying is being compared with a process of drying with heat from fuel, a straightforward heat cost comparison cannot be made because the solar heat supply facility is combined with the dryer; separate heating and drying units are required for the conventional operation. It is therefore necessary to compare the costs of the entire processes—heat supply plus drying. This situation places direct solar drying in a more favorable light because of the modest requirements for equipment.

An approximate economic appraisal of a process for direct solar drying of Brazilian oil shale from the Tremembe deposit has been made by R. C. Cameron, in collaboration with one of the authors. The shale (33 per cent moisture) is assumed to be mined at a rate of 12 000 tons per day and moved by machinery to a slightly sloping drying field of approximately 5 million square feet (470 hectares). Here it would be spread in a 1 foot layer by scraper vehicles. After about 10 days, the shale moisture would have been reduced approximately 10 per cent, under average conditions. These figures correspond to an evaporation rate of 2.1 kg/square meter, equivalent to a solar utilization efficiency of 30 per cent. Scrapers and trucks would then "harvest" the dried shale for supply to retorts. For an operation of this type, it was estimated that an investment in machinery of U.S. $250 000 would be required and that labor, depreciation, and other cost items would total 8.3 cents per metric ton of shale handled. This cost is equivalent to $1.50 per million kcal. To supply heat for shale drying by use of imported petroleum would require an outlay of about $5 per million kcal for fuel alone (based on fuel oil at $34 per metric ton and 100 cruzeiros per dollar. This might also be considered the total cost of drying with crude shale oil, or the value of the oil which would be consumed in vaporizing moisture from the wet shale in the retorting process.

It may thus be concluded from this preliminary evaluation that direct solar drying of this oil shale would cost about one-third as much as the resulting increase in product value, and that unless some very cheap waste heat were available in the plant, other types of drying would be more expensive than solar. This estimate is, of course, based on assumptions and approximations which may require revision in the light of additional information on weather conditions, shale-handling techniques, equipment costs, and so on. There may also be factors in the retorting of wet and dry shales which would affect the economics of the process beyond the simple heat requirements for moisture removal. It is clear, however, that, if this oil shale deposit is to be commercially developed, solar drying prior to retorting has sufficient economic attractiveness to demand thorough evaluation.

Nomenclature

A = area, ft^2
C_{ps} = specific heat of shale, btu/lb · °F
C_{pw} = specific heat of water, btu/lb · °F
G = mass velocity, lb/hr · ft^2
h_c = convective heat transfer coefficient, btu/hr · ft^2 · °F
I = intensity of radiation incident on a horizontal surface, btu/hr · ft^2
k_e = effective thermal conductivity of the bed, btu · ft/hr · ft^2 °F
L = depth of bed, ft
m = drying rate, lb moisture evaporated/hr · ft^2
q_t = amount of incident radiation absorbed, btu/hr · ft^2
q_λ = heat utilized for evaporation of moisture, btu/hr · ft^2
q_s = sensible heat lost by the evaporating moisture, btu/hr · ft^2
q_c = heat lost by convection, btu/hr · ft^2
$q_{cond.}$ = heat lost by conduction through the bottom of bed, btu/hr · ft^2
$q_{r,\,net}$ = heat lost by radiation exchange between shale and the sky, btu/hr · ft^2
q_{cp} = change in heat stored in the bed, btu/hr · ft^2
t = temperature, °F
T = temperature, °R
α = absorptivity of the shale for solar radiation
ε = emissivity of the shale
λ = latent heat of evaporation of water at the surface temperature, btu/lb
σ = Stefan-Boltzmann constant, 0.173×10^{-8} btu/hr · ft^2 °R^4

Subscripts:
s = surface
a = ambient
i = interior
1 = initial state
2 = final state

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Summary

The possibility of solar drying of oil shale, mined in the Paraiba Valley of Brazil, is investigated. This oil shale has an initial moisture content of about 33 per cent, and the removal of at least a part of this moisture, prior to retorting of the shale to recover the organic materials, results in an increase in oil yield and permits the use of lower grade shales than would otherwise be possible. Solar drying is one possible means of removing this moisture. This paper outlines a study by Petroleo Brasileiro of the process variables and reports a University of Wisconsin study of energy balance for the drying material.

The Petrobras investigations included study of the effect of bed depth, particle size range, agitation of material and time of exposure on the rate of drying. These studies indicated that the per cent moisture gained or lost is an inverse function of the bed thickness and that the agitation of material is decidedly useful.

The energy balance studies indicated that the incident radiation, useful heat of evaporation and convective heat loss terms are of prime importance. If the bed is thick enough, heat lost by conduction through the bottom of the bed is negligible. The back radiation loss is about 10 per cent and the sensible heat change ranges are between 0-10 per cent of the absorbed radiation on an hourly basis.

The variation in absorptivity of the fresh and exposed shale is about 9 per cent, fresh shale having an absorptivity of about 92 per cent and that for partially dried shale being 83 per cent. As the higher figure appears to be valid only for the first day of drying, an average value of 85 per cent absorptivity may be used for the energy balance on the drying process. It was found that the shale can be dried below its apparent equilibrium moisture content by means of solar radiation, probably because the shale temperature is considerably higher than the ambient air temperature during the drying operation.

The major loss of incident energy is by convection, which appears to depend mainly on the temperature difference between the surface of bed and the ambient air. The magnitude of the convective heat transfer coefficient appears to be affected only slightly by wind velocity.

The drying rate and the efficiency of drying depend on the moisture content of the shale and the amount of radiation available. It was found that efficiency of solar energy use varies from about 45 per cent to about 18 per cent as the average moisture content changes from about 40 to 14 per cent, on the dry basis. If a fictitious drying rate corresponding to a common radiation flux of 2 000 btu/day.ft² (calculated by assuming a linear relationship between the incident radiation and the drying rate) is plotted against average moisture content, a constant rate period is not obtained and the general trend of the curves is concave upwards.

For similar curves, in air-drying, the internal diffusion may be expected to control the rate of drying which depends on temperature, varies inversely as the thickness of bed and is not affected by air velocity. The same may be expected for radiation drying.

An approximate economic appraisal of the process, assuming an average solar utilization efficiency of 30 per cent, indicates that the cost per million kcal of equivalent water evaporated is about U.S. $1.50, with most of the cost attributable to materials handling operations. This is about one-third as much as the resulting increase in product value. This estimate is, of course, based on assumptions and approximations which may require revision in the light of additional information on weather conditions, shale-handling techniques, equipment costs and so on. It is clear, however, that the solar drying of the oil shale prior to retorting has sufficient economic attractiveness to demand thorough evaluation.

SÉCHAGE SOLAIRE DES SCHISTES ARGILEUX PÉTROLIFÈRES

Résumé

Ce mémoire présente une étude sur la possibilité de sécher au moyen de l'énergie solaire les schistes argileux pétrolifères extraits de la vallée de Paraîba, au Brésil. Ces schistes argileux ont une teneur initiale en humidité d'environ 33 p. 100, et l'élimination d'une partie tout au moins de celle-ci avant de faire passer les schistes argileux à la distillation pour en récupérer les substances organiques permet d'augmenter le rendement en pétrole et d'utiliser des produits de moindre teneur qu'il ne serait possible autrement. Le séchage par le soleil constitue un moyen possible d'éliminer cette humidité. Le mémoire résume une étude des variables du procédé faite par la société Petróleo Brasileiro et donne les résultats d'une étude du bilan énergétique des schistes à sécher, faite par l'Université du Wisconsin.

Les recherches de la Petrobras comportaient une étude de l'effet de la profondeur du gîte, du grain des particules, de l'agitation du produit et de la durée d'exposition sur le régime de séchage. Ces études indiquaient que le pourcentage d'humidité gagnée ou perdue est une fonction inversement proportion-

nelle à l'épaisseur du gîte et que l'agitation des produits est indubitablement utile.

Les études faites sur les bilans énergétiques indiquaient que ce sont la quantité d'énergie reçue, la chaleur utile d'évaporation et les pertes de chaleur par convection qui ont une importance primordiale. Si le gîte est assez épais, la chaleur perdue par la conduction au fond de ce dernier est négligeable. La perte due au contre-rayonnement est de l'ordre de 10 p. 100 et l'échange de chaleur sensible s'échelonne entre 0 et 10 p. 100 du rayonnement absorbé, sur une base horaire.

La variation d'absorptivité des schistes argileux frais et exposés est de 9 p. 100 environ, l'absorptivité du schiste argileux frais étant de 92 p. 100 et le chiffre de 83 p. 100 devant s'appliquer au cas des schistes argileux partiellement desséchés. Pour autant que le plus élevé des deux chiffres ne semble être valable que pour le premier jour du séchage, une valeur moyenne d'absorptivité de 85 p. 100 peut être utilisée pour les calculs des bilans énergétiques du processus de séchage. On a découvert que le schiste argileux peut être desséché au point de ramener sa teneur en humidité à une valeur inférieure à celle de l'équilibre apparent, en faisant appel au rayonnement solaire, probablement parce que la température de ces schistes argileux est beaucoup plus élevée que celle de l'air ambiant pendant l'opération de séchage.

La plus grosse perte d'énergie incidente se fait par convection, laquelle semble dépendre au premier chef de la différence entre la température du gîte et celle de l'air ambiant. L'importance du coefficient de transfert de chaleur convective ne semble souffrir que dans une faible mesure de la vitesse du vent.

Le régime de séchage et le rendement de cette opération dépendent de la teneur du schiste argileux en humidité et de la quantité de rayonnement disponible. On a constaté que le rendement d'utilisation de l'énergie solaire tombe de 45 à 18 p. 100 environ quand la teneur moyenne en humidité varie de 40 à 14 p. 100, sur la base du produit sec. Si le régime relatif de séchage correspondant à un flux de rayonnement usuel de 2 000 Btu par jour par pied carré (calculé en admettant qu'il y ait un rapport linéaire entre le rayonnement incident et le régime de séchage) est exprimé en fonction de la teneur moyenne en humidité et porté sur un graphique, la période de régime constant n'est pas réalisée et la forme générale des courbes est concave, cette concavité étant dirigée vers le haut.

Pour des courbes analogues, dans le cas du séchage à l'air, on peut prévoir que la diffusion interne détermine le régime de séchage, qui dépend de la température, varie de manière inversement proportionnelle à l'épaisseur du gîte, et ne dépend pas de la vitesse de l'air. On peut prévoir qu'il en sera de même pour le séchage par rayonnement.

Une évaluation économique approchée du processus, en admettant que l'on ait un rendement d'utilisation solaire moyen de 30 p. 100, indique que le prix par million de grandes calories, en équivalents d'eau évaporée, est de l'ordre de 1,50 dollar, la majeure partie du prix étant imputable aux opérations de manutention. Ceci représente environ un tiers de l'augmentation de la valeur des produits qui est ainsi réalisée. Bien entendu, ces évaluations reposent sur des suppositions et des approximations qu'il pourra être nécessaire de réviser à la lumière de renseignements supplémentaires quant aux conditions météorologiques, aux techniques de manutention des schistes argileux, au prix du matériel, etc. Il est clair, néanmoins, que le séchage solaire des schistes argileux, avant de les faire passer à la cornue, est assez attrayant du point de vue économique pour justifier l'évaluation complète du procédé.

THE ROLE OF SOLAR ENERGY IN THE DRYING OF VINE FRUIT

B. W. Wilson *

In Australia, the drying of vine fruit on the ground in direct sunlight has been entirely abondoned in favour of drying racks. Constructed from tiers of wire netting stretched between steel posts, the racks measure 50 metres long by 1.25 metres wide, are 2.4 metres high, and are generally covered by an iron roof 2.5 metres wide, and they are aligned in a north-south direction.

The bunches of grapes are harvested by hand into perforated metal boxes. When a number of boxes are full, the grapes are immersed in a dilute emulsion of a softening oil which promotes the loss of water during drying. After draining, the fruit is laid out on the wire racks and left for 8-10 days. Occasionally, due to unseasonal weather, prolonged exposure on the drying racks leads to serious deterioration of the fruit, and on these occasions other methods of drying have been suggested but so far nothing has been found to compete with the low cost of drying on tiered racks.

Although the physical factors involved in the drying of grapes have been reported by Martin and Stott (1) and a great deal of effort has been made to develop drying oils and other preliminary treatments, the design of racks has been purely empirical and very little has been recorded about the source of the energy for drying. The purpose of the experiments about to be described was to determine the extent to which direct solar radiation contributed to drying on racks and to examine the possibility of either modifying the racks or replacing them with some other form of solar heated air drier.

Experimental

Transmission of radiation through the skins of grapes

The skins of sultana grapes were removed and mounted in the light beam of a Hilger "Uvispeck" spectrometer fitted with a tungsten light source. The transmission of wavelengths typical of the solar spectrum was measured for natural and emulsion-dipped grapes.

Internal temperatures of grapes

If grape skins are transparent, the absorption of solar radiation by grapes should be accompanied by a rise in temperature in the interior of the grapes. A small hole was therefore cut into the interior of a grape and a "Stantel" F2311/300 thermistor enclosed in a glass sheath was inserted with the temperature sensitive element covered by a piece of aluminium foil. The opening was finally sealed with molten beeswax. The electrical conductivity was measured by the method of Herrington and Handley (2). By using a number of calibrated thermistors, simultaneous measurements were made of temperatures inside grapes exposed to the sun throughout the day.

Measurements of temperatures developed inside grapes were also made simultaneously at a number of points on a typical drying rack loaded with grapes.

Rate of rack drying of grapes

In some preliminary tests, rates of drying were measured by spreading the bunches of grapes on wire netting trays which were placed on the tiers of the racks aligned in a north-south direction and periodically removed for weighing. This method was subject to a number of errors and was abandoned in favour of a special drying rack which could be weighed throughout the drying period without disturbing the fruit. The weighing rack was constructed in such a way that its cross section was similar to a standard tiered rack. The weighed section, which measured 2 metres in length, was suspended from the roof by four large coil springs which were maintained at a constant extension throughout the experiment by transferring water into balance tanks fitted at the end of the weighing section.

At the start of each experiment, 500 kilos of dipped grapes were distributed on the wire tiers with the balance tanks empty. As the drying proceeded, water was added in weighed amounts to compensate exactly for the loss of water from the fruit. At the same time, measurements were made with a Cassella actinograph to assess the total radiation from sun and sky, and the degree of shading was estimated by the methods described by R.O. Phillips (3).

Drying rates in solar heated air driers

Closed cabinet drier with internal solar absorber

A solar drier was constructed in the form of an insulated box, 1.3 m × 1.3 m × 1.3 m, with a solar energy absorber fitted in the side facing north. The absorber consisted of a glass window above a blackened steel sheet fitted with vertical steel fins. The area of finned surface was approximately six times the area exposed to direct radiation. At 100 per

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cent efficiency, it was assumed that a temperature of 75°C would be attained from an air inlet temperature of 35°C and incident radiation at 750 m.w/cm².

The grapes were loaded onto wire-mesh trays which were arranged in tiers in the cabinet behind the absorber. During daylight, warm air circulated upwards through the finned solar heater and down through the fruit on the trays. The moisture was removed partly by condensation on the steel floor of the drier and partly by the admission of fresh air and release of humid air. Initially, it was intended to rely only on natural convection, but this was found to be impractical and a small electric fan had to be installed to maintain the circulation of the air.

Air driers with separate solar absorbers

These were essentially air driers with a solar absorber to raise the air temperature before it was passed over the drying fruit.

Because of the very large amount of air to be heated, it was necessary for the solar absorber to be very large and the cost very low. It was found that this requirement could be met by making a simple absorber of hessian (burlap) material painted with black water emulsion paint. In the first pilot model, the material was mounted over a shallow wooden box measuring 2.5 m × 1.25 m. Air was drawn through the blackened cloth at 7 m³ per minute with an electric fan and then expelled through the fruit which was arranged on wire trays in a series of nesting boxes. The best results were obtained with only a single layer of material.

A similar system of drying was installed on a much larger scale alongside one of the conventional drying racks which was covered with plastic curtains so that it formed a drying chamber. In this case, the absorber measured 15 by 17 metres and was constructed directly on the ground. Posts were driven into the ground and the jute cloth was supported on rails approximately one metre above the ground. The sides of the absorber were sealed with polythene sheet.

The solar energy absorber was connected to the drying chamber by a short length of steel duct containing an axial flow fan driven by a 2 kW electric motor. Air was drawn from the solar energy absorber at 338 m³/minute and blown through the drying chamber in a single pass. The loss of moisture was checked by weighing a number of trays of fruit at different positions in the drier.

Results and discussion

Transmission of radiation through the skins of grapes

The results of measurements made to determine the transmission of wavelengths typical of solar radiation through the skins of sultana grapes are shown in table 1. For natural grapes and emulsion-dipped grapes,[1] the maximum transmission was obtained in the range 0.70 to 0.90 μ (i.e. short infrared radiation) and the transmission of visible light was apparently much less effective. The low values for visible light could have been the result of excessive scattering of light at the surface of the skin. It is apparent that, even allowing only for the short infrared radiation, which amounts to approximately 40 per cent of the radiant energy in sunlight, quite substantial amounts of radiant energy must penetrate to the interior of grapes exposed to direct sunlight.

Table 1. Transmission of light through the skins of sultana grapes

	Wavelength, microns	Per cent transmission	
		Natural	Emulsion-dipped
Infrared	1.00	2.2	2.6
	0.95	8.0	12.5
	0.90	26.7	37.4
	0.85	39.3	55.4
	0.82	40.7	57.7
	0.80	39.9	57.2
	0.76	34.9	50.6
	0.74	30.6	44.2
Visible light	0.70	20.8	30.5
	0.66	11.5	17.1
	0.64	8.7	12.8
	0.62	6.1	9.2
	0.60	4.2	6.4
	0.58	2.8	4.2
	0.56	1.8	2.8
	0.55	—	1.8

Table 1 also shows that the treatment of grapes with dipping emulsion has a very favourable effect on the transmission of radiation, in addition to its well known action of promoting the loss of moisture through the skin.

Internal temperature of grapes during drying

The results of measurements of temperatures of grapes exposed in the open air to direct sunlight are

Table 2. Temperatures inside sultana grapes exposed without shading

Solar time (hours)	Natural grape (°C)	Dipped grape (°C)	Air (°C)
0 600	18.7	16.4	19.4
0 700	27.2	22.0	19.7
0 900	37.2	35.4	32.6
1 100	42.8	40.8	37.0
1 200	44.0	42.0	37.2
1 600	46.4	40.1	39.0
1 800	42.0	39.7	35.5
1 900	33.2	33.2	33.0

[1] Dipping emulsion is 2.0 per cent ethyl oleate and 2.5 per cent potassium carbonate and a small amount of synthetic detergent.

Table 3. Temperatures inside sultana grapes on tiered racks

Day	Solar time (hours)	Temperature inside grapes: East (°C)	Centre (°C)	West (°C)	Air temperature (°C)
1st	0 700	20.0	19.1	18.4	19.2
	0.930	34.6	24.8	23.3	29.2
	1 100	32.4	28.0	28.0	33.3
	1 200	30.2	29.8	29.8	35.8
	1 400	30.9	31.2	32.8	35.8
	1 500	32.6	33.0	40.2	35.6
	1 600	32.4	32.0	38.8	35.4
	1 800	31.8	34.7	36.2	33.9
	2 200	19.5	18.9	18.3	23.9
2nd	0 600	19.7	20.2	17.9	22.0
	0 800	37.0	34.4	28.2	28.6
	1 000	41.0	32.0	32.6	29.7
	1 200	34.6	35.2	36.0	37.2
	1 400	—	—	—	37.7
	1 600	37.8	38.3	45.0	39.0
	1 800	38.4	39.3	41.2	38.5
3rd	0 600	16.3	16.6	16.1	17.0
	0 800	28.4	26.7	20.7	22.4
	1 000	35.1	25.4	25.1	26.6
	1 200	29.4	29.0	30.0	31.6
	1 400	33.4	33.6	35.0	34.1
	1 600	33.8	34.2	39.0	33.5
	1 800	32.9	34.2	37.4	33.0
4th	0 900	30.2	23.2	20.2	22.4
	1 200	24 2	23.5	24.0	26.4
	1 400	26.4	26.2	28.4	27.5
	1 600	28.7	29.0	37.8	28.5

given in table 2. During most of the day, the temperatures inside natural grapes increased to 6.0-8.0°C above the ambient air temperatures and the rate of drying was extremely slow. By contrast, the temperatures inside emulsion-dipped grapes was seldom in excess of 4.0°C above ambient air temperature due to the rapid loss of moisture.

Table 3 shows the temperatures inside the grapes drying on tiered racks aligned north-south. The grape temperatures show a rapid response to low angle solar radiation in the early morning and late afternoon, and temperatures above the ambient air temperature were observed on all levels. During these periods, the solar energy must have been absorbed by the fruit and converted to heat at a rate in excess of that required to provide for the latent heat for the evaporation of water and heat losses by convection to the air.

Towards the middle of the day, the movement of shade across the tiers of fruit resulted in the temperature inside the fruit falling below ambient air temperature. Some of the solar energy absorbed

Table 4. Rate of loss of water from dipped sultanas on a weighed drying rack

Date	Solar insolation (W/s.cm.)	Water evaporated per meter of rack: Calculated kg.	Observed kg.
20/2	(195)	14.3	17.3
21/2	744	27.8	34.2
22/2	739	27.6	32.7
23/2	755	28.2	37.2
24/2	750	28.0	28.6
25/2	760	28.4	23.8
26/2	694	25.4	14.1
27/2	673	25.2	7.9
28/2	268	9.9	6.8
1/3	604	22.6	1.5
2/3	559	20.9	2.5

Table 5. Rate of loss of water from dipped sultanas on a weighed drying rack

Date	Solar insolation (W/s.cm.)	Water evaporated per meter of rack	
		Calculated kg.	Observed kg.
16/3	(327)	8.9	17.3
17/3	681	26.0	25.3
18/3	655	24.8	22.0
19/3	660	24.8	20.8
20/3	650	24.5	19.3
21/3	627	23.8	20.1
22/3	571	22.3	14.9
23/3	491	18.4	4.9
24/3	397	14.6	6.7
25/3			
26/3	1 843	69.3	6.0
27/3			

earlier as sensible heat was released as latent heat of evaporation at this point. A similar situation existed at night when a rapid fall in the ambient air temperature freed solar energy stored up as sensible heat during the late afternoon.

During the middle of the day, the onset of air drying is clearly indicated by temperatures below the ambient air temperatures. The latent heat required for the evaporation of moisture was absorbed by conduction from the air under conditions ideally suited to air drying. By that time, the temperature of the ground around the racks and the air temperature has been raised to its maximum by strong solar radiation from directly overhead, and the passage of thermally generated gusts of wind through the drying racks was quite frequent.

On the first day of drying, the grape temperature was 6.0°C below ambient during the period of shading at mid-day, but the temperature difference decreased to 2.0°C below ambient as the fruit dried out during the following days.

Effect of solar radiation on the drying rate

Tables 4 and 5 show the results of observations made on special weighing racks to compare the rate of loss of moisture with the theoretical drying rate based on the assumptions of 100 per cent conversion of radiation to heat inside the grapes. Both sets of observations were made over a number of days of very clear weather when the amount of diffuse sky radiation would be comparatively small and could be safely neglected.

Over the first six days of the drying cycle, when the bulk of the water has to be removed from the grapes, the observed rate of drying per unit length of rack was very closely in agreement with the ideal figures based on separate solar energy measurements and estimated shade angles. The solar energy based figures were only exceeded in the first series of results (table 4) where the fruit was picked early in the harvest and was known to contain more moisture than usual.

After six days, the drying rate decreased so rapidly that the incident solar energy appeared to be more than enough to account for all drying requirements. One reason for the sharp decline in the rate of drying at this point is that there is a rapid contraction in volume of the grapes towards the end of drying and this must result in a decrease in the area of fruit available to intercept direct solar radiation.

The close agreement between the solar energy observations and the rate of evaporation from the grapes on the tiered racks recalls a similar situation which occurs when water evaporates from the free water surface of a deep tank. It is now well known that the mechanism of evaporation is a composite effect depending both on solar radiation and heat

Table 6. Drying of dipped sultanas in a cabinet drier heated by an internal solar energy absorber (1.5m²)

Date	Solar energy (W/cm^2)	Air temp. (°C)	Drier temp. (°C)	Per cent of wet wt.		Th. Eff. (%)
				Drier	Control	
27/2	590	37°	47-53°	84	86	88
28/2	630	39°	45-57°	74	67	53
1/3	590	34°	41-54°	65	55	50
2/3	240	24°	—	60	48	75
3/3	570	25°	—	55	43	30
4/3	590	27°	39-42°	48	39	37

Table 7. Drying of dipped sultanas in an air drier heated by a solar energy absorber (3.0m²)

Date	Solar energy (W/cm²)	Air temp. (°C)	Drier temp. (°C)	Per cent of wet wt.		Th. eff. (%)
				Drier	Control	
27/2	590	37°	47-53°	69	73	61
28/2	630	39°	45-57°	52	55	31
1/3	590	34°	41-54°	39	40	25
2/3	240	24°	—	34	35	24
3/3	570	25°	—	31	30	6
4/3	590	27°	39-42°	28	23	6

derived from the air and that the total energy required for the evaporation of the water is usually identical with the calculated figure based on solar energy uptake at 100 per cent efficiency.

While the present experiments have not proceeded to the point where the quantitative measure can be made of the contribution of these two sources of energy to the drying of grapes on racks, the mechanism appears to be very similar to that controlling evaporation from a free water surface. The rate of loss of moisture from grapes on tiered racks can therefore be rated as equivalent to the rate of evaporation from a rack operating on solar energy alone at 100 per cent thermal efficiency.

Field tests of solar driers

Table 6 shows the results of field trials with a closed solar drier with the air heated by the absorption of solar radiation on blackened metal surfaces protected by a single layer of glass. Although the temperatures developed inside the drier were much higher than the outside air temperature, the grapes dried more slowly than the grapes on the tiered racks and eventually became infected by moulds and insect pests. This result was disappointing because the working efficiency of the drier was remarkably good in comparison with other solar devices such as solar stills, and even comparable with industrial drying equipment.

Table 8. Drying of sultanas in a large solar heated air drier (102m²)

Date	Solar energy (W/cm².)	Max. air temp. (°C)	Max. drier temp. (°C)	Per cent of wet wt.	
				Drier	Control
27/2.	590	37°	41°	80	86
28/2.	630	39°	45°	63	67
1/3.	590	34°	41°	54	55
2/3.	240	24°	n.d.	46	48
3/3.	570	25°	n.d.	42	43
4/3.	590	27°	29°	35	39

Table 7 shows the results obtained with a small air drying system in which the grapes were dried in a strong stream of air which had been preheated by passing it through a solar energy absorber made of blackened material. The rate of drying in this equipment was almost identical with that observed on the open racks but the grapes remained green until the completion of drying.

Table 8 shows the results obtained when the above idea was projected onto a very large scale. Once

Table 9. The performance of a 102 m² solar energy absorber for heating air at the rate of 340 m³/min

Solar time (hours)	Air temp. (°C)	Exit temp. (°C)	Heat absorbed (kW/hr)	Solar energy (kW/hr)	Th. eff. (%)
1 000	34.4	37.2	27	85	32
1 100	35.6	41.3	36	92	39
1 200	36.7	41.9	35	94	37
1 300	37.8	44.1	39	88	45
1 400	38.4	39.5	42	74	57
1 500	37.8	39.5	35	56	63
1 600	38.4	42.8	28	35	80

Table 10. Comparison of the cost of tunnel drying and natural drying *
(Basis: 34 ton/annum)

Cost item	Tunnel drying: cost per ton dried			Natural drying: Cost per ton dried		
	£	s.	d.	£	s.	d.
Cartage	2	0	0		10	0
Labour	5	2	0	10	18	0
Supplies	1	1	0	1	0	0
Power	4	11	0		—	
Fuel	8	10	0		—	
Depreciation and maintenance	10	0	6	5	0	0
Interest at 4½ per cent per annum	7	16	0	2	4	0
TOTAL COST PER TON DRIED	39	0	6	19	2	0

* *Dehydration of Vine Fruits*, Bureau of Agricultural Economics, Department of Commerce and Agriculture, Canberra, A.C.T., 1943.

again the drying rate was very close to the rate experienced on open tiered drying racks.

Table 9 shows further details of the performance of the large solar energy absorber used in these trials. For an average rise in air temperature of 5°C, the average thermal efficiency of the absorber was 50 per cent.

Table 10 shows itemized costs for producing one ton of dried fruit on the tiered racks compared with the costs for operating an oil fired tunnel drier. Under Australian conditions, the system of rack drying is not only more favourable economically but yields a grade of dried fruit which is superior in colour and flavour to the artificially dried product.

General conclusions

The vertical tiered rack, which has been developed by the Australian dried fruit industry and which operates partly by the absorption of direct radiation and partly by natural air circulation, provides a less expensive and more effective system of drying than can be devised by making use of solar energy absorbers and a supplementary source of power.

While the method is dependent on good weather, the same limitation applies to other solar devices, which would be far less efficient and a great deal more expensive to operate under unseasonal conditions.

Practical applications

A drying system based on vertical tiered racks aligned north and south may be well adapted to drying other crops and materials, particularly in arid areas and in under-developed countries where materials and power are expensive. The idea of absorbing solar radiation on a stack of horizontal absorbing surfaces is unusual and may have many other fields of application, particularly in latitudes which experience long periods of solar radiation at very low angles.

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Summary

The drying of agricultural products is one of the oldest and most widely practised uses of solar energy. Over the past 60 years, the Australian dried fruit industry has been established on the basis of a system of natural drying which is a considerable advance on the ancient method of laying the fruit out on the ground. Instead, the grapes are hung on tiered wire racks under the shelter of an iron roof. While it is generally supposed that wind is the main agent of drying, the shape, dimensions and rate of loading of these racks suggest that low angle solar radiation may play a hitherto unsuspected part in the drying processes.

In preliminary experiments, it was found that the skins of grapes are essentially transparent to the short infrared radiation in sunlight, particularly after treatment with patent dipping emulsions.

Further evidence for the absorption of solar radiation was obtained when the temperatures inside

grapes were measured electrically by thermistor elements inserted in the interior of grapes. When these grapes were exposed to solar radiation in the open air, temperatures of up to 8°C in excess of ambient air temperatures were registered. By contrast, the internal temperature of grapes shaded from the sun was 2-6°C below ambient air temperatures.

In some further experiments, a full-scale replica of a drying rack was constructed in such a way that it could be suspended on large coil springs. The loss of moisture from the fruit was measured by adding water to a balance tank to maintain a constant load on the springs during the experiment. The quantity of water lost per day was found to be in close agreement with the amount calculated from solar energy measurements and shade angles, assuming that the absorption of direct radiation was 100 per cent efficient. This situation recalled the evaporation of water from open storages where sun and wind contribute to the rate of evaporation and where the result is closely in agreement with the radiation figure alone.

The performance of the tiered drying racks was also compared with that of two types of artificial driers employing solar absorbers to heat the air. In one system, the grapes were dried in a closed insulated chamber heated by an internal solar energy absorber made of sheet metal fins under a single layer of glass. In this drier, the temperature exceeded 15°C above the ambient temperature and the average thermal efficiency was 50 per cent. However, the grapes dried more slowly than those exposed on tiered racks under identical conditions, and the quality of the final product was very poor.

This result prompted experiments with a second type of drier in which a large volume of air was preheated in a simple solar absorber made of jute fabric. As a result of initial tests, a large-scale unit capable of heating air at a rate of 330 m^3/min. was installed alongside of a drying rack which was covered with plastic sheet to form a drying chamber. This type of absorber heated the air 5-8°C above the ambient temperature, and the thermal efficiency of the absorber was 50 per cent. The rate of drying was similar to that observed on the open tiered racks under the same conditions, but the quality of the product was not as good.

For grape drying, the system of tiered racks, which operates partly by the absorption of solar radiation directly and partly by natural air drying, is particularly well adapted for clear sky conditions in low rainfall areas and is more favourable than drying chambers heated indirectly by solar energy.

With minor modifications, the system of tiered racks may prove to be well suited to the drying of other agricultural crops. The idea of using a stack of horizontal surfaces as a solar energy absorber may have other applications, particularly in high latitudes where the low angle of the sun precludes the use of other types of solar energy absorbers.

LE RÔLE DE L'ÉNERGIE SOLAIRE DANS LE SÉCHAGE DES FRUITS

Résumé

Le séchage des produits agricoles représente une des utilisations les plus anciennes et les plus répandues de l'énergie solaire. Au cours de ces 60 dernières années, l'industrie australienne des fruits secs s'est établie, puis s'est développée, autour d'un système de séchage naturel qui représente un progrès marqué par rapport à l'ancienne méthode consistant à étaler les fruits sur le terrain. Les raisins sont mis sur des claies étagées en fils métalliques, à l'abri d'une toiture en fer. Bien que l'on admette de manière générale que c'est le vent qui est l'agent de séchage principal, la forme, les dimensions et le degré de charge de ces claies donnent à penser que le rayonnement solaire aux faibles angles d'incidence joue peut-être un rôle que l'on ne soupçonnait pas jusqu'à présent dans le processus du séchage.

On a trouvé, au cours d'expériences préliminaires, que la peau des raisins est essentiellement transparente vis-à-vis du rayonnement infrarouge le plus court de la lumière solaire, particulièrement après traitement par immersion dans des solutions spéciales.

On a pu démontrer l'absorption du rayonnement solaire avec plus de clarté en mesurant la température à l'intérieur des raisins par un procédé électrique utilisant des résistances variables en fonction de la température qui sont introduites dans la masse de ces raisins. Quand ils furent exposés au rayonnement solaire à l'air libre, on enregistra des températures qui dépassaient parfois de 8 °C celle de l'air ambiant. En revanche, la température intérieure des raisins abrités du soleil était inférieure à celle de l'air ambiant de 2 à 6°.

Pour les besoins de quelques expériences ultérieures, on réalisa une maquette en grandeur naturelle d'une claie de séchage, faite de telle manière qu'il était possible de la suspendre par de gros ressorts à boudin. On mesura le degré de déshydratation des fruits en ajoutant de l'eau à un réservoir de compensation qui servait à maintenir la charge des ressorts constante pendant toute la durée de l'expérience. On observa que la quantité d'eau perdue chaque jour correspondait très sensiblement à celle qui avait été calculée à partir des mesures de l'énergie solaire et des angles d'ombre, en admettant que le rendement de l'absorption du rayonnement direct était de 100 p. 100. Cette situation rappelait celle qui se présente pour l'évaporation de l'eau des citernes ouvertes, pour lesquelles le soleil et le vent contribuent au régime

d'évaporation, donnant des résultats proches de ceux qu'indiquerait le seul chiffre du rayonnement.

Le comportement des claies de séchage étagées fut également comparé à celui de séchoirs artificiels de deux types, qui emploient des absorbeurs d'énergie solaire pour chauffer l'air. Dans l'un de ces dispositifs, les raisins sont séchés dans une enceinte fermée isolée, chauffée par un absorbeur intérieur d'énergie solaire constitué par des ailettes en tôles logées sous une seule couche de verre. La température régnant dans ce séchoir dépassait celle du milieu de 15 °C et le rendement thermique moyen était de 50 p. 100. Il est à observer toutefois que les raisins séchaient plus lentement que ceux qui étaient exposés sur des claies étagées dans des conditions identiques, et que la qualité du produit ainsi réalisé était fort mauvaise.

Ces résultats ont suggéré la réalisation d'expériences avec un séchoir d'un autre type, dans lequel on préchauffait une masse d'air considérable dans un absorbeur solaire simple en tissu de jute. A la suite des premiers essais, on installa une unité à grande échelle, capable de chauffer l'air à raison de 350 m³/min., le long d'une claie de séchage recouverte d'une plaque en matière plastique, de manière à constituer une enceinte de séchage. Ce modèle d'absorbeur permit de porter l'air à une température de 5 à 8 °C au-dessus de l'ambiante, et son rendement thermique, en tant qu'absorbeur, s'établissait à 50 p. 100. Le régime de séchage était très voisin de celui que l'on peut observer avec les claies exposées à l'air libre dans les mêmes conditions, mais la qualité du produit restait loin d'être aussi bonne.

Pour le séchage des raisins, le système de claies étagées faisant partiellement appel à l'absorption directe du rayonnement solaire, ainsi, par ailleurs, qu'au séchage à l'air libre, se prête particulièrement bien aux pays où les cieux sont clairs et la précipitation réduite, s'avérant supérieur aux enceintes de séchage à chauffage indirect par l'énergie solaire.

Avec de légères modifications, le système des claies étagées peut s'avérer très approprié pour le séchage d'autres produits agricoles. L'idée d'employer une pile de surfaces horizontales comme absorbeur d'énergie solaire peut recevoir d'autres applications, particulièrement aux latitudes élevées, où le faible angle d'incidence des rayons du soleil exclut l'emploi d'autres types d'absorbeurs d'énergie solaire.

Agenda item III.C.4

USE OF SOLAR ENERGY FOR HEATING PURPOSES: SOLAR COOKING

George O. G. Löf *

General principles

A solar cooker is a solar energy exchanger designed specifically to deliver heat to foods, for the purpose of raising their temperature and causing the chemical changes associated with the process of cooking. In supplying the required energy, the solar cooker supplements, and to a greater or less extent replaces, conventional fuels. In under-developed areas of the world, some of these fuels are wood, kerosene, charcoal, dried animal dung, agricultural refuse, and other combustible materials. The use of solar cookers can thus serve two important purposes: reduction in family cooking costs by decreasing the need for purchase or collection of fuel, and conservation of fuels for other uses, such as fertilizer in the case of dung, forest protection and erosion reduction in the saving of wood and charcoal.

Although there are almost countless ways of cooking foods, some of the principal methods may be usefully outlined. In boiling and frying, heat is transferred to the solid food from the heated liquid, whereas in baking and roasting, heat is transferred both by convection from the surrounding hot air and sometimes by radiation from hot surfaces. In all of these processes, the food must first be raised to "cooking temperature", and then it must be maintained at this temperature for a period sufficient for effecting the softening, drying, decomposing, coagulating, separating, concentrating, or other change required. The quantities of heat necessary for most of these physical and chemical changes involved in cooking are small. That is, the chemical heats of reaction or conversion are unimportant in comparison with the heat for increasing the food's temperature and the heat losses normally occurring in cooking.

Most foods contain a high proportion of water, and heating them to cooking temperatures requires nearly 1 cal per kg per °C (or 1 btu per pound per °F). The higher the heat input rate to the food and container (and to any additional cooking liquid), the faster will the food be heated to cooking temperature. Then, except where water vaporization is a necessary part of the cooking process, as in bread baking, the speed of cooking is practically independent of heat rate as long as the temperature is maintained by a heat input rate equal to the thermal losses. It is therefore generally true that differences in the time required for cooking similar quantities of food on cookers having various heat supply capacities are due mainly to the different durations of the heating-up periods. Thus cookers of low and high heat supply rates may not show large differences in the time required for foods which must be cooked several hours.

The largest of the heat losses in cooking is usually the heat consumed in vaporizing water present in the food or added for cooking — nearly 600 cal per kg or 1050 btu per pound. Next in importance are convection losses from utensils and oven walls. If the energy source has limited capacity, control of these losses by use of covers on utensils, insulation on cooking chambers (ovens), and other means becomes important. Estimating an hourly convection loss (outdoors), at boiling water temperature, of about 600 btu per sq ft of utensil, and a surface area of 0.5 sq ft per pound of container contents, the energy input for 1 hour of food boiling, if one-fourth of the water present is vaporized, would be distributed roughly as follows:

Heating materials to boiling temperature .	20 per cent
Convection losses from vessel	45 per cent
Vaporization of water	35 per cent

Although variation in the assumed conditions would materially alter this distribution, the figures would still show that most of the heat supplied in long-duration cooking is dissipated.

The great majority of family cooking throughout the world is done either in a utensil heated from below, usually by direct fire, or in an oven-type enclosure supplied with hot air from a self-contained or separate fuel-burning chamber. Most cooking involving boiling, stewing, frying and liquid heating in general is by means of direct fire from below, whereas baking and roasting are usually performed in ovens. Actual food temperatures required for most cooking do not vary widely, because the presence of water in all foods limits their own temperature to about the boiling point of water. The temperature of the heat supply, however, depends greatly on the foods and the type of cooking. Direct fire involves temperatures of a thousand degrees, and a very high thermal gradient therefore prevails in the usual surface type cooking, thus making high heat transfer rates possible. Oven-cooking involves air temperatures of only 200° to 250°C, so the heat transfer rates are lower, and longer cooking periods are generally required. In nearly all types of cooking, therefore, even though the maximum temperature

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of the food does not exceed 100°C, it is necessary to provide a heat source at a considerably higher temperature if satisfactory cooking rates are to be obtained.

A further consideration in the substitution of solar energy for fuel in cooking facilities is the customary energy supply rate. Although it is obvious that most of the energy is not usefully employed and that savings could be made by insulation and evaporation reduction, cooking habits must be reckoned with. Hence, in so far as practical, a solar cooker should provide a heat supply rate equivalent to that commonly used. Surface cooking units, using electric or gas supply, may average about 1 kW capacity, a rate capable of heating 2 litres of water to the boiling point in about 10 minutes. Automatic ovens for family baking and roasting (in the United States) have energy supply rates of 2 to 4 kW, but on an intermittent, thermostatically-controlled schedule which might place the average consumption at about 1 kW. It would appear that for performance fully equivalent to fuel cookers, a solar unit should deliver about 1 kW to the cooking vessel. If this is not done, either longer cooking times must be accepted, smaller quantities of food must be used, or heat conservation practices must be established. At 50 per cent solar collection efficiency, a solar reflector of about 2 sq m (20 sq ft) would be required for fully comparable heating rates.

The foregoing cooking principles and practices show that a practical solar cooker must be able to deliver to the food an adequate quantity of heat, within a reasonable time, at temperatures ranging from near ambient to about 200°C. To reach the middle and upper temperature ranges, solar concentrating devices must be used. Equipment design has evolved along two lines, the distinction being primarily in the manner by which concentration is achieved and the degree to which it is used. The *focusing* or *direct type* cooker uses a reflector to concentrate beam radiation onto the food or onto a cooking vessel in which the food is cooked. Solar energy is intensified by a factor typically in the range of 20 to 100 and is effectively equivalent to an open fire as a source of energy for cooking. The *oven type* cooker is an insulated box with a transparent window on the side exposed to the sun. Additional radiation reflected into the window by flat reflectors arranged around it results in a solar intensification factor of 2 to 4. It is essentially the equivalent of a fuel-fired oven. *Combinations* of the principal features of these two basic types have also been devised. In the following paragraphs, the characteristics of these types of solar cookers are outlined, and their use in cooking various foods is described. The importance of some of the sociological factors in solar cooker use is briefly mentioned.

As with all solar energy devices, the performance of solar cookers may be quantitatively evaluated by consideration of energy balances on the system. The energy required for a specific cooking operation is not always well defined, however, and may vary widely with the cooking methods used, e.g., whether evaporative losses are controlled by a cover on a cooking vessel. This variability in cooking methods and conditions makes it desirable to base solar cooker evaluation on measurements of net rate of heat delivery to the food or its container, as well as on the time required for cooking a known quantity of food. The papers of this session report energy delivery data in terms of watts, or heat energy per unit time, at some useful temperature range, and also terms of time required to cook certain quantities of foods. Most of the solar cookers described are designed to be reasonably equivalent to the other cooking methods they would replace, but usually of lower capacity.

The economic problems of using solar energy on a household scale are even more complex than those of larger scale use. Present costs of household fuel, in terms of cash, may be nil in the under-developed countries, because of the widespread use of wood and waste materials collected by the individual users. Equivalent to cash expenditures, however, is the value of the time used in gathering fuel and the economic losses due to deforestation and soil depletion resulting from excessive wood cutting and failure to fertilize the soil. Another economic problem is the poverty of the people who would be benefited most by the solar cookers but who are unable to make the initial outlay for purchasing the units. It is also true that in many areas of potential application, loans to individuals for household purchases are difficult and interest rates are very high. These factors have led most of the workers in this field to the conclusion that if solar cookers are to be of widespread significance, they must be low in cost, serviceable, and partly or completely of local manufacture.

The principal requirements for a solar cooker to be successful in a developing area can be summarized as follows:

(*a*) The unit must cook foods effectively and therefore it must be technologically satisfactory. This requires that it be capable of providing a sufficient energy rate, at the needed temperature, to the desired quantity of food.

(*b*) It must be sturdy enough to withstand rough handling and use, and to resist damage by natural hazards such as wind, for the desired lifetime.

(*c*) It must be sociologically acceptable and fit in with the cooking and eating habits of the people.

(*d*) It must be economically possible for the user to obtain a cooker at a cost which saves him money.

Solar cooker characteristics

Three of the seven papers of this session concern designs and use of focusing cookers (S/24; S/87; S/100). Two papers involve solar ovens (S/75; S/101). Comparative studies of heat delivery rates with both types are reported (S/116), and a cooker designed to combine the best features of oven and focusing systems is described (S/110). Results of field studies concerned with the practical daily use of a solar cooker are reported in S/87. All but one of the six cookers discussed have been built and tested.

In table 1, this rapporteur has attempted to outline the essential features of the six types of solar cookers discussed in the papers submitted to the United Nations Conference. In so far as possible, the tabulated data have been obtained directly from statements or figures in the papers, or they have been computed from such factual information. Some of the features, however, have required judgment and interpretation by the rapporteur, and are so indicated in the table. In certain instances, items have been omitted because of insufficient data in the papers.

Several previously developed focusing cooker variations are not represented in the contributions to this Conference. No additional information has been presented on the cookers employing the spun aluminum reflectors developed in India, the segmented aluminum paraboloid of Tarcici, conical reflectors of silvered glass developed in Japan, and a small, two-sectioned metallized plastic reflector (United States). However, the coverage here is remarkably good, including probably all of the recent significant cooker developments. The table contains data on a wide variety of cooker types, for most of which quantitative studies are reported.

It is interesting to observe that all of the cookers described in the Conference papers are different. Even the reflector materials differ from each other in almost every case. Of the practical cookers actually built, the solar collection areas vary from 0.36 m^2 to 1.07 m^2. A threefold range of solar energy collection is therefore covered. There is not much difference in the maximum size of vessel which can be heated in the various cookers, except for the combination reflector-oven of Prata which is large enough for two vessels. The solar intensification factor (concentration ratio averaged over the entire area of the receiving surface) varies from about 3 in the solar ovens to above 30 in the focusing paraboloid described in paper S/87.

Probably the most significant measure of solar cooker performance is the "effective cooking power" shown in the table in kilowatts. The tabulated values have been obtained by converting the authors' data on water heating or other use to these units. The figures refer to the rate of energy delivery to the cooking vessel and its contents under clear sky, average weather conditions. These values are seen to vary from about 0.15 kilowatt for the solar oven of Telkes and Andrassy (S/101) and the reflector-oven combination of Prata (S/110), to 0.4 to 0.5 kilowatt for the focusing paraboloid of Duffie, Löf, and Beck (S/87). The folding cooker described by Löf and Fester (S/100) has a power output slightly below the latter, in the 0.25 to 0.4 kilowatt range. Tests by the FAO (S/116) generally confirm these capacities, but because of less than ideal solar conditions, maximum outputs, of 0.12 kilowatt (S/101) and 0.38 kilowatt (S/87) were measured. The computed or measured periods required (based on authors' data) for heating one litre of water from room temperature to the boiling point are also shown in the table. These vary from about fifteen minutes for the rigid plastic paraboloid (S/87) to one-half hour for the solar oven (S/101). By comparison, the normal heating time on a wood fire or a kerosene burner should be five to ten minutes.

Appraisal of the quantity of food which can be cooked with each of these units is not readily made from the data presented. In the oven type cookers, the limiting factor is the volume of the oven enclosure. The combination unit of Prata appears to have the highest internal volume and is designed for simultaneous use of two cooking vessels. In the case of the focusing cookers, quantities are limited primarily by the area of the pot support and by the rigidity of the frame members supporting the vessel. In all of the units, there is a practical limitation imposed by the maximum acceptable duration of the cooking operation. The greater the quantity, the longer is the period for heating to cooking temperature. Also, with the focusing cookers, rate of heat loss from the walls of the vessel to the surroundings places a practical limit on the total exposed surface of the cooking vessel. All factors considered, however, it appears to this rapporteur that the approximate maximum quantities of food which can be practically cooked on these units vary from two kilograms to four kilograms as shown in the table; the smallest quantity is associated with the folding umbrella-type cooker (S/100) and the largest with the combination unit of Prata (S/110) and the rigid focusing unit (S/87). The solar oven with a window area of 0.19 m^2 (S/101) appears to have a normal capacity of about 3 kilograms. Most of these capacities are adequate for a family meal, but the one-dish limitation on all but the combination unit is a drawback. Sectional cooking vessels could be used if more than one food were to be cooked on the other units, or several small utensils might be usable. In general, it is felt that the units have adequate capacity for cooking simple meals for the average low-income family.

The table shows that weight and portability of the units vary considerably, from about three kilograms (and small collapsed volume) for the umbrella-type (S/100) to hundreds of kilograms for the masonry reflector proposed by Stam (S/24). The rigid focusing unit (S/87) has a total weight of about ten kilograms, and the large oven (S/101) and the combination unit (S/110) weigh fifteen to twenty kilograms. For some types of use, portability and compact storage are desirable features, whereas for most applications, permanent placement of the cooker is satisfactory. Damage by weather and accidents is likely to be greater for the cookers which must be permanently exposed to the atmosphere and the sun. The durability of the various cookers therefore depends on the amount of exposure as well as on usage and construction features. Most of the units

Table 1. Solar cooker characteristics

United Nations paper No.	S/24	S/87	S/100	S/75	S/101	S/110
Authors	Stam	Duffie, Löf, Beck	Löf, Fester	Abou-Hussein	Telkes, Andrassy	Prata
Cooker type	# Focusing	Focusing	Focusing	Oven	Oven	Combination
Reflector type	# Spherical	Paraboloid	Parabolicumbrella	Internal flat planes	External flat planes	Parabolic cylinder
Reflector material	# Aluminum foil on concrete or plaster	Aluminized "Mylar" plastic film on polystyrene shell	Aluminized "Mylar" laminated to fabric, on umbrella frame	Polished aluminum sheets	Anodized aluminum sheets (coated aluminum foil #)	Nickel-plated brass sheet (nickel-plated aluminum #)
Reflector dimensions	0.22 m dia # 4.5 m	1.22 m dia	1.17 m dia	(4) 1 288 cm²	(4) 43 cm sq	(2) 0.5 m × 0.8 m
Effective solar collection area	0.04 m² # ~ 10 m²	1.07 m²	1.02 m²	0.36 m²	0.56 m²	0.74 m²
Reflector focal length	# 225 cm radius	46 cm	46 cm	—	—	~ 1.05 m
Oven window	—	—	—	0.36 m² double glass	0.19 m² double glass	0.06 m² single glass
Cooking area	# (2) 30 cm dia *	~ 20 cm dia	~ 23 cm sq	~20 cm sq *	~ 25 cm sq *	20 cm × 50 cm *
Effective solar intensification	# ~ 50 *	~ 34	~ 20	~ 3 *	~ 3 *	~ 12 *
Minimum time required to heat one litre of water 20°C to 100°C	nr	15 min 15 min [a] (minimum)	22 min	nr	~ 30 min a 46 min (minimum)	26 min *
Effective cooking power, kW	nr	0.4-0.5 0.28 ave [a] 0.38 max [a]	0.25-0.4	nr	0.15-0.2 * 0.10 ave [a] 0.12 max [a]	0.15-0.25 *
Food cooking performance	nr	Good	Good	nr	Good	Good
Approximate weight, kg	# Hundreds	10	3	nr	~ 20 *	12-18
Thermal storage considered	# Yes	No	No	Yes	Yes	No
Total cooking capacity	nr	~ 4 kg *	~ 2 kg *	nr	~ 3 kg *	~ 4 kg * (2 vessels)
Portability	# None	Good *	Excellent *	Good *	Good *	Fair *
Need for positioning during cooking	# Moderate *	Frequent (15-30 min)	Frequent (15-30 min)	Occasional (30-60 min)	Occasional (30-60 min)	Moderate (25 min)
Suitability for baking and roasting	# Fair *	Poor *	Poor *	Good *	Good *	Good *
Suitability for stewing and frying	# Good *	Good *	Good *	Fair *	Fair *	Fair *
Durability	nr	Good *	Fair *	Very good *	Very good *	Good *
Use of native materials	# Good *	Fair *	Fair *	Fair *	Fair * # Good *	Fair *
Full scale cookers constructed and tested	No	Hundreds	See below	Yes	Yes	Yes
Field testing	No	Extensive	See below	No	Some	No
Commercial sale	No	No	Hundreds	No	No	No
Approx. cost or price	nr	$16 (factory)	$30 (retail)	nr	nr	~ $35 (factory)

[a] FAO tests (Paper S/116).
Proposed.
* Rapporteur's computation or estimate.
nr Not reported.
~ Approximately.

appear to have reasonably "good" durability (several years), the oven types probably being best in this regard. The folding umbrella-type is not considered as durable as the others in its present form.

Of the two principal cooker types, solar ovens appear better adapted to the use of thermal storage materials, besides having higher intrinsic storage capacity for keeping foods warm and permitting the extension of cooking a short time after sundown and during short (a few minutes) cloudy periods. In the experiments of Abou-Hussein (S/75), about one-half hour was required to increase the temperature of an empty oven from 150°C to 218°C in clear sunlight. When shaded from the sun, six or seven minutes were required for the unit to cool to 150°C. The cooker was still warm (80°C) three-quarters of an hour later. Although these tests were made with an empty oven, they show that short periods of cloudiness could be tolerated without greatly extending the cooking time for foods; the unit is also useful for keeping foods warm after cooking.

Augmented heat storage by use of heat-of-fusion and heat-of-transition materials was considered in papers S/75, S/101, and S/24. Telkes and Andrassy (S/101) have compared the heat storage capacities of several materials in the 300° to 400°F (150° to 200°C range). A mixture of alkali nitrates provides heat-of-fusion storage at 150° to 160°C, and mixtures of anhydrous alkaline sulphates undergo a solid phase transition between 191°C and 239°C, with a latent heat effect of about 60 calories per gram. An oven containing about 3 kilograms of the sulphate mixture in the form of a flat-bottom slab is described in this paper. Unless used primarily for storage during preheating of empty ovens, however, the alkali sulphate mixtures appear to have unusably high transition temperatures, because solar ovens seldom reach these levels during cooking.

Stam (S/24) has suggested the use of hydrated magnesium chloride (melting point 117°C) and magnesium palmitate (melting point 121°C) as heat storage materials in specially shaped vessels supported at the focus of the large spherical reflector proposed. He has discussed the use of a total quantity of 40 litres for effective storage and subsequent cooking. Tests with these materials are not reported, however, and this rapporteur suggests the possibility that these storage temperatures are not adequate for most types of cooking; even for boiling, the temperature driving force would be very small.

The whole subject of thermal storage for cooking appears to need further consideration. It is possible that focusing cookers could be used with some type of storage container to accumulate heat during most of the day, subsequent use then being made for evening cooking. The development and use of cheap, harmless, and dependable materials having high thermal capacity, moderate weight, and adaptability to cooker designs might greatly extend the potential of solar cooking in parts of the world.

The comparatively small focal zone of a parabolic reflector dictates the need for periodic movement of a focusing cooker if maximum heat delivery to the bottom of the cooking vessel is to be maintained. The frequency of adjustment depends on the time of day the cooker is used, the season of the year, and the size of the cooking vessel. On the average, however, small adjustment in the position of the reflector should be made at intervals ranging from 15 to 30 minutes. The table shows that oven-type cookers require less repositioning, satisfactory operation being obtained at adjustment frequencies of 30 to 60 minutes. The combination unit appears to require orientation at about the same intervals as the focusing type. Utensil adjustments required with the spherical unit proposed by Stam are not discussed, but these would probably be somewhat less frequent than with the parabolic type.

Durability of the various cookers cannot be readily appraised at this time because of inadequate data. The general characteristics of the construction materials and their assembly indicate, however, that the ovens should have excellent durability; the rigid parabolic cookers, if well made, should have good life, and the light-weight umbrella-type would probably be less durable than the others. This rapporteur believes that the durability of all these cookers could be made satisfactory by devotion of attention to this requirement.

In general, the ovens are best suited to baking and roasting, whereas the surface cookers employing focusing reflectors are best suited to stewing and frying. These uses correspond, of course, to those ordinarily involved in common kitchen practice. It is true that the ovens can also be used for boiling and frying and that the focusing type can be used for baking, provided that a small oven is placed at the focal support. The ideal uses, however, are as indicated in the table.

For applications in under-developed countries, where import of manufactured goods is often difficult, the question of whether solar cookers can be locally built, particularly by use of native materials, becomes important. None of the cookers appear to be ideally suited in this regard. All types require at least some components or materials from industrialized countries or from factories in the countries concerned. The focusing types involve metallized plastic films, molded plastic reflector shells, and shaped metal components. Ovens require glass or plastic films, polished aluminum, and (desirably) sheet metal for the oven box. Fortunately, all of these cookers could be made in small industrial establishments, using local labor and various amounts of native materials. If the unit proposed by Stam should prove practical, nearly all of the labor and materials could be individually supplied. These factors affect cooker cost, and it is clear that the maximum utilization of local components and skills is desirable.

Of the six cookers described, two of the focusing types have been built in quantities of hundreds.

Numerous solar ovens of several varieties have been constructed, but quantities are not stated. At least one of the combination cookers of Prata has been constructed, but only two small models of the large Stam spherical cooker have been built, and heat delivery tests on the very small 22 cm diameter reflector only have been reported. The table shows that five cookers described in the Conference papers have actually been tested. Only one unit, the rigid paraboloid cooker (S/87), has received extensive field evaluation; the results of several years testing under known technical and social conditions are reported. Another cooker, the folding umbrella-type (S/100) has received commercial sale in quantities of several hundred, largely for outdoor recreational use in the United States. The solar oven (S/101) is stated to have been field tested and exhibited, but data are not reported. From the information available to this rapporteur, extended use of solar cooking by numerous low-income families appears to have been limited to the rigid plastic focusing cooker described in paper S/87.

Several optimistic estimates of solar cooker costs have been made in the past, but most of these figures have been based on inadequate experience with fabrication requirements. Among the contributions to this Conference, however, the three costs shown in the table appear to be based on sound information. The two parabolic types are in the same cost range, model three of the rigid plastic paraboloid (S/87) having an estimated factory price of $16 (medium quantity production) and the folding umbrella-type (S/100) having a published retail selling price of $30 (small quantity production). Considering the customary wholesale and retail selling costs and profits, the factory price of the umbrella-type should be roughly comparable with the rigid paraboloid type. The third figure is an estimated $35 factory cost for the combination focusing oven type (S/110). It should be recognized, however, that this estimate is based on laboratory models whereas the other two are based on hundreds of cookers already made. The $35 price may therefore be more uncertain than the others, and it is possible that it might be reduced by modifications in design, materials, and fabrication methods. Previously published figures on the costs of other solar cookers include $14 to $17 for the solar cooker developed in India, $69 retail price for the collapsible paraboloid cooker of Tarcici, $25 for the "solar-chef", a small collapsible focusing type, and $4 for a two-foot diameter conical aluminized-paper reflector delivering heat to a small pan. This rapporteur has not seen any results of cooking with the "solar-chef" nor with the last mentioned cooker above, but the low rate of heat delivery to the food, below 100-watts, raises the question of the effectiveness of these units.

Further comments on individual papers

The foregoing table and discussion on the six solar cookers described in the Conference papers include most of the important characteristics, but a number of significant factors can be more fully and clearly presented by consideration of individual papers.

Focusing cookers

Paper S/24 by H. Stam

Although three types of cookers are discussed by the author, most of the paper deals with a proposed spherical concrete or plaster reflector of ten meters diameter. The cooking vessels would be suspended from overhead supports and periodically adjusted to the changing focal position. Other uses for the reflector would be in heating relatively large volumes of thermal storage materials for subsequent use in the warming of rooms on cold nights. The large focal area of a spherical reflector might permit simultaneous heating of separate cooking and heat storage vessels.

The author apparently feels that about 400 kilocalories of heat must be provided for cooking the evening meal. This is equivalent to 310 watts for one and one-half hour. With a heat of fusion of 40 kilocalories per litre, 10 litres of heat storage medium would be required for adequate heat delivery after sundown. But with a possible six hours between the heat storing process and the use of the heat for cooking, 40 litres of heat storage material should be provided to overcome losses and to supply heat when needed.

A considerable portion of the paper deals with cooking *requirements*, such as temperatures for various foods, sizes of kitchen utensils for families, and heat losses from cooking vessels. It is the author's opinion that the cookers previously developed and those which are the subjects of other papers at this Conference do not have adequate capacity for the required use. It is his belief that the unit should satisfy even the very largest household requirements.

It must be realized that the paper is based on a *proposed* design and structure, and that no prototype has been built or tested. (A small reflector twenty-two centimeters in diameter was used in measurements of the rate of heating a few cubic centimeters of oil and water). Accordingly, the effectiveness and feasibility of such a cooker have not been demonstrated. This rapporteur calls attention to the considerable difficulty of producing a smooth surface in concrete or plaster for such a large reflector, even by very skilled workers. The problems of maintaining high reflectivity on such a surface are exceptionally formidable. In appraising the merits of the design, knowledge of performance and construction cost would be essential. This rapporteur concedes the desirability of a large cooking capacity, but unless it can be shown that such capacity is obtainable at modest expense, the demonstrated utility of the smaller cookers in the preparation of a family meal appears to outweigh the author's argument.

Two other cooker designs have been suggested by the author. The first of these is an eccentric plaster paraboloid supported by the rim of a hole dug in the ground. The reflector would be about 1.6 meter diameter and the cooking vessel would be supported on a small tripod standing in the cooker shell. The unit could be turned and tilted occasionally to follow the sun. A reflective lining of aluminum foil has been suggested. Another proposal involves a parabolic cylinder on a north-south axis, rotated slowly by an hour-glass device to follow the sun. Some type of heat transfer fluid would be circulated through the hot tube to an insulated storage vessel. The heated fluid could then be subsequently used for cooking or other purposes.

The author suggests the need for local fabrication of such equipment, and the need for financial support of a program of solar cooker development.

Paper S/87 by J. A. Duffie, G. O. G. Löf and B. Beck

The rigid reflector shell of vacuum-formed or drape-formed polystyrene sheet is a remarkably smooth and cheap supporting surface for the specular material, in this case aluminized "mylar" polyester film. After reinforcement with a metal rim, this reflector has rigidity and strength. Construction details are outlined in the paper and the design criteria are presented. A study of the energy balance in solar cooking indicates that high performance requires maximum specular reflectivity and over-all shape accuracy.

The stand and frame for the cooker were modified several times. The latest "Model 3" design is believed by the authors to have the greatest durability and maximum operating simplicity. Construction costs as low as about $9 have been estimated, for large quantity manufacture of "Model 2"; an estimated factory price of $16 for "Model 3" appears possible at moderate production rates. Savings in family fuel purchases (kerosene) which could be realized by use of a solar cooker in northern Mexico should approach the total cost of a cooker in about one year.

Probably the most significant data in this paper are the results of field evaluation studies conducted over several years in Mexico. A portion of these data are presented in tabular form, showing the usage of sixteen "Model 2" solar cookers during a nine-month period. It was found that the families of these low-income agricultural workers used the cookers about two-thirds of the possible time. The later model cooker, given only a short field test prior to the date of the paper (May, 1961), received greater usage, but complete data are not yet available. Some negative indications, particularly with the "Model 2" cooker, were mechanical failures, caused primarily by wind. The authors believe that major difficulties of this sort have been eliminated by the new design. Particularly when used for the types of cooking requiring prolonged heating, such as the stewing of meats and beans, the cookers are generally considered by their users to have approximately the same speed as kerosene burners and open fires. The heat delivery of about 400 watts is considerably less than from these conventional sources, but except for a slower warming-up period, the cooking rates are the same because of equal temperatures in the utensils.

Paper S/100 by G. O. G. Löf and D. A. Fester

A characteristic of the umbrella-type focusing cooker which bears on its utility is a diffused focus. The radiation intensity is fairly uniform over the entire food-cooking area, so it is possible to cook meats and other foods directly on the grill by broiling or grilling, as over a radiant charcoal heat source. Another feature is the lightweight and compact form of the unit, when folded, permitting easy transport and storage.

Measurements of heat delivery capacity and cooking performance are reported in the paper. Heat balance studies show a solar collection efficiency of about 27 per cent and a heat delivery rate to the grill area of approximately 400 watts in clear sunlight. Fairly good closure of the heat balances was obtained, even though the optical properties of the reflector were measured by a new photographic method not involving heating performance. This technique, employing moonlight and photographic paper, appears to be a very useful and simple method for reflector quality evaluation.

Although this cooker is in commercial production and use, quantitative information from purchasers is not abundant. Reports indicate satisfactory performance for a wide variety of foods, but the authors have no data on daily use by low-income families. The authors state that certain modifications would be desirable if the cooker were to receive regular usage of this sort. The principal change would be a mounting permitting the support of larger cooking vessels and ensuring against overturning by wind.

The authors state that manufacturing costs should be reducible at greater production rates, particularly in the country of use. Cost reductions of one-half to two-thirds are considered possible.

Solar Ovens

Paper S/101 by M. Telkes and S. Andrassy

A new development of particular interest in the design of solar ovens is the use of a woven basket lined with clay or plaster as the oven body. The authors state that considerable cost reductions should be possible by use of this design and by fabrication in the country of use. The importation of such materials as plastic films or glass, aluminum sheets or foil, and heat storage materials would permit maximum economy. Performance data have not been reported, however, and the great importance of well-insulated oven walls may limit the choice and use of local materials. The authors conclude that costs of solar ovens would be excessive if they were manufactured in the United States and exported to foreign countries.

It has also been suggested that the reflective mirrors of anodized sheet aluminum be replaced with aluminum foil applied to some rigid, cheap local material. The foil would be coated with a transparent protective layer to resist oxidation. The performance of a cooker made in this way should be compared with the designs previously evaluated.

The advantages of heat storage obtainable with the solar oven are emphasized by the authors. Mixtures of anhydrous alkaline sulphates are considered to have the best performance characteristics, even though their transition temperatures are as high as 190°C to 240°C. Because the temperatures of the solar oven, even when empty, appear to reach maxima of only about 220°C, it is doubtful that this thermal storage material can be very effective unless used in the empty oven during a preheating period. The storage of solar energy during the cooking process would appear to require a lower temperature phase change because the presence of food in the oven limits the maximum temperatures to lower levels. The utility of this storage material in keeping food warm after cooking also appears dependent on whether latent heat storage during preheating remained partially unused after cooking was completed, or simply whether some sensible heat storage was involved. Data on cooker performance, with and without the heat storage element, under otherwise comparable conditions, would be of interest. In spite of this limitation, the use of storage prior to placement of food in the cooker would permit speeding the actual cooking operation, even though the total duration of oven use would have to be considerably longer than the cooking period.

This rapporteur suggests that data on the use of the alkali nitrate mixture, involving a heat-of-fusion type of storage at about 155°C, would be of considerable interest, because it would appear that in this temperature range, heat could be stored during the cooking operation for subsequent release during intermittent cloudiness or after sundown.

A useful generalization for the type of cooker used by these investigators is that if A represents the area of the double glass window, and $3A$ the total solar intercepting area of window plus reflectors, approximately $1.9A$ is a measure of the radiation actually passing to the interior of the oven chamber. Of this energy, about 300 watts, i.e., approximately one-half, is available to the food if the interior of the oven is at 150°C (for 0.19 m^2 window).

The reported cooking tests show effective oven performance. Discussion in the paper implies that prior to the placement of foods in the oven, the unit was preheated in order that the latent heat effect of the storage material could also be utilized during the cooking period. Total oven operating time therefore would be of greater duration than indicated in the cooking test results. The comparatively low instantaneous power rate of the oven, about 0.2 kilowatt, appears to be effectively supplemented by the thermal storage medium. Actual cooking duration appears comparable with conventional oven-cooking practice.

Paper S/75 by M. S. M. Abou-Hussein

A principal objective to this work was a comparison of the performance of a solar oven having reflectors external to the glass window (as in paper S/101) and one having the reflecting surfaces beneath the glass. Data reported in the previous table relate to the design with interior reflectors.

The author claims several advantages for interior reflectors such as their greater protection from damage due to mishandling, abrasion, and the wind, and the greater capture of diffuse radiation because of larger glass window area. This rapporteur could add that non-specular reflection from the internal reflectors, constituting an appreciable portion of the total reflection from aluminum, would be more completely captured inside the oven having internal reflectors. However, the larger glazed area involves the disadvantage of greater heat losses.

Measurements of total radiation received inside ovens of these two different designs are reported in the paper. Nearly equal values were observed when the incident radiation was almost all direct, whereas the unit with the inside reflectors showed about 6 per cent more energy delivery when the radiation was 30 per cent diffuse. The radiation measurement method is not explained, however, so appraisal of the figures is not possible. The oven with internal reflectors reached a temperature of 256°C whereas the other cooker showed a maximum of 248°C, while both were empty.

Data on the rate of temperature change in an empty internal-reflector oven after solar heating show a rather rapid temperature drop from 218°C to 155°C in six minutes and to 118°C in 17 minutes. Without thermal storage media or some food in the oven, heat loss rate through the large window is high.

Evaluation of these results is difficult in the absence of oven performance data such as the rate of heating quantities of water, or the rate of actual food cooking. The presence of food or water considerably alters oven temperatures, and comparisons of similar designs would have doubtful value unless such materials were used. The conclusion that a solar oven with a large window and internal reflectors is more effective than the "conventional" type described in paper S/101 therefore does not appear well supported. Moreover, in an insulated oven, most of the thermal losses are through the glazing. Therefore, tripling the glazed area would be expected to reduce the net heat available for cooking. This additional thermal loss, probably at least double than from an oven with external reflectors of equal area, should outweigh the gains due to increased capture of diffused radiation. Further investigation of the differences in the two designs by means of energy balances while heating measured quantities of water or other material appear necessary.

Combination parabolic cylinder oven

Paper S/110 by A. S. Prata

In this interesting design, a small parabolic cylinder reflector is used to focus solar radiation through a narrow glass window in a well insulated cylindrical oven supported above the reflector. In essence, this is an oven cooker with a window area considerably reduced to minimize heat loss. The solar collecting area is slightly larger than reported by Telkes and Andrassy (S/101), 0.74 m^2 versus 0.56 m^2. The net energy delivery to foods in the oven is greater by virtue of the larger collector area and the lower thermal loss.

Temperature measurements and energy transfer computations were made by the author in an evaluation of the terms in the complete heat balance. An over-all conversion efficiency from incident solar energy to heat received by water in vessels within the oven was 31 per cent. Approximately 59 per cent of the energy striking the two parabolic cylinder reflectors actually entered the oven through the glass window. It was found that single glazing resulted in maximum efficiency. The author's data on a variety of foods indicate cooking rates closely comparable to those obtained with conventional stoves and ovens. Because the shape of the oven permits placing two cylindrical vessels in the unit, simultaneous cooking of two different foods is readily accomplished.

The author has compared the performance of his reflector-oven with the "hot box" solar oven. He states that the combination unit, with a solar collection area 55 per cent greater than the comparison oven, was able to cook 2.8 times as much food. He therefore concludes that the focusing reflector oven is 1.8 times as efficient as the hot box type. This rapporteur cautions against a comparison based only on quantity of food cooked, because cooking time is also a factor. Moreover, after foods have been heated to cooking temperature, only small quantities of heat are then required to continue the cooking to completion, almost regardless of the quantity present. Comparative measurements of actual heat delivery to oven contents is the best criterion of performance.

Another advantage of the combination unit is its simple construction, the double-walled cylinder being cheap and easy to build. The reflector quality must be very good, however, because of the need for focusing. The unit must be adjusted almost as frequently as the paraboloid if maximum efficiency is to be maintained.

This rapporteur wishes to call attention to one of the items in the heat balance. Thermal radiation "through the glass" has been determined by difference, and certain anomalies were observed. These were attributed to variations in solar intensity during the testing. Because the factor is obtained by difference, it is affected by experimental errors in all the measurements, and fluctuations of moderate size would be expected. Secondly, however, there is no thermal radiation actually *through* the glass. All of this radiation originates at the glass surface itself because of its opacity to infrared wave lengths. Therefore, a measurement or estimate of the glass temperature would permit direct computation of the radiation loss. A final term in the heat balance would then be the unaccounted-for losses, which could be itemized separately. This rapporteur feels that it is unlikely the solar radiation varied as much as indicated by the adjusted values in the table, particularly when the values appear to hold constant in the somewhat foggy weather experienced during the test. During the last quarter hour of the test, for example, it would not appear reasonable to expect 1.32 Langleys (corresponding to extremely clear skies) when a value of 0.825 was measured.

The author feels that the optical efficiency and the oven efficiency are both low, and that these could be improved. In spite of his views the reported over-all efficiency of 31 per cent appears as high as any of the solar cookers discussed at this Conference, and higher than most. He also points out that if reflector surfaces of better reflectivity were used, as high as 0.80, the over-all efficiency should increase to nearly 40 per cent.

The author concludes that materials for the cooker, as now designed, would cost about $18 and that construction would require eight man-hours of labor. The total weight is 18 kilograms. The use of aluminum would permit reduction in weight to about 12 kilograms, but under the conditions encountered by the author, the cost would increase. He also concludes that the cost of a solar oven of "conventional" type, having about two-thirds the solar intercepting area and possibly slightly more than half the cooking capacity, would cost approximately the same under the conditions encountered.

This rapporteur is pleased to observe that this new design, with further simplification and economies, has some distinct advantages over both the conventional solar oven and the focusing type cookers. For oven-type cooking, preferred in some parts of the world, the design has promise.

Comparison of focusing and non-focusing cookers

Paper S/116 by the Nutrition Division, FAO

During the summer of 1959, the Food and Agriculture Organization of the United Nations made tests on two types of solar cookers. One was a focusing plastic unit, essentially Model 2 discussed in paper S/87 by Duffie, Löf, and Beck. The other was a solar oven of the type described by Telkes and Andrassy in paper S/101, but presumably without thermal storage.

The testing procedure consisted of measuring the time required for heating two litres of water from room temperature to the boiling point in each cooker on most days of the summer season. The water was contained in aluminum pans eight inches in diameter and four inches deep in one series of tests and in earthenware pans of the same size in another set of experiments.

Detailed data are tabulated in the paper, but unfortunately they do not include measurements of solar radiation. Comments on the solar and weather conditions permit inferences as to these factors. However, it was concluded from the results of about 50 tests that the average time required to bring two litres of cold water to the boiling point in the focusing cooker was 41 minutes and in the oven, 112 minutes. The most rapid heating times were 30 minutes and 92 minutes respectively. When earthenware vessels were used, both averages increased, to 76 minutes for the focusing cooker and to 142 minutes for the oven.

As shown in the table prepared by this rapporteur, the average energy delivery rates computed from the above figures show an oven power of 0.1 kilowatt and a focusing cooker power of 0.28 kilowatt. Maximum power developed was 0.12 and 0.38 kilowatt respectively. Because no perfectly clear days were noted by the investigators, it may be assumed that the performance of both units under ideal conditions would be slightly better than observed.

The investigators obtained the best results with the focusing unit when it was repositioned every 15 to 30 minutes. The oven required less frequent orientation. The effects of wind were more serious with the focusing cooker than with the oven, and slight cloudiness had a smaller negative effect with the oven than with the focusing unit. The focusing unit was considered to have greater simplicity and lower maintenance requirements.

Although the studies reported in the FAO paper are of limited scope, they are useful in showing, for the first time to this rapporteur's knowledge, the relative net energy delivery capability of these two rather different systems under identical conditions of use. It may be argued that the rate of heating of two litres of water would not completely define relative cooking effectiveness. These figures do represent, however, in probably the most useful terms, the relative heating rates for these units. In addition, where boiling, stewing, or other cooking in water is practised, and where two litres is about the amount of material being cooked, these figures show the approximate times which must be added to the normal boiling period in appraising the total duration of the food cooking process. Thus, if one hour of boiling is required for a given food, it would be expected that under typical favorable conditions the cooking of about two kilograms (including any added water) would require approximately 1.5 hour on the focusing cooker (paper S/87, Model 2) and about 2.5 hours in the solar oven.

For baking or roasting, or for the frying of foods, the figures are not significant because each cooker is rather uniquely suited to one of these particular types of cooking.

Additional comments on comparisons of solar ovens and focusing cookers

A claimed advantage of the solar oven which appears to this reviewer to have been over-emphasized is the less frequent positioning and the elimination of food stirring. All solar cookers need to "follow the sun", but the frequency of oven adjustment can be less than that of the focusing units. This means that during two hours of cooking, the oven would have to be oriented two to four times for the best cooking performance, whereas the focusing unit should receive six or seven adjustments. The significant point with respect to stirring requirements is that reflector cooking is intended to serve a need now being met by surface cooking on direct fire from other sources. Thus, food stirring during cooking is already practised where necessary, and solar cooking in fact somewhat reduces this need because of a less intense source of heat. Field experience shows that the more nearly the solar source fits into the customary cooking ways, the more readily accepted it is. Occasional stirring of the food, along with slight adjustment of the reflector, is therefore no more demanding, and in most cases considerably less demanding, of the cook's time than the conventional means now used.

Another feature of the solar oven is its ability to use some diffuse solar radiation as well as the direct beam radiation; only the direct component can be utilized in the focusing type. In areas where atmospheric haze and thin cloudiness commonly reduce the beam radiation without greatly impairing the total, the oven might deliver more heat for cooking than the paraboloid. In most regions where solar cooking might be practical, however, clear skies usually prevail, and the utilization of diffuse radiation would not be a significant advantage of the oven.

Summary and conclusions

The papers submitted show a gratifying trend in two directions. First, there are quantitative data on cooker performance, both in terms of energy delivery to standard quantities of a reference material (calorimetric data) and in terms of the time required for cooking various types of foods under measured conditions. Secondly, there are the highly significant results of performance evaluation studies in the field; in these investigations, cookers were actually used regularly by low-income people who might become permanent users of commercially produced solar cookers.

The papers indicate the possible application of several types and modifications of solar cookers. Technical development has materially improved most of the units since they were first designed. Moderate cost reductions have been made in some units, and substantial improvements in performance have been achieved.

On the negative side of all these developments, however, is the high initial cost of the cookers, particularly in relation to the low income of the potential users. None of the developed cookers appears to meet a desirable cost maximum of a few dollars. There is a possibility that reductions in cost to this level might be effected by large usage of local materials and labor in fabrication. The results of extensive development studies show rather clearly, however, that there cannot be much compromise with product quality, otherwise cooker performance will be seriously impaired. These opposed factors suggest a solution involving well-controlled factory production of cookers in the countries of use, with maximum use of local materials and labor.

Even with maximum manufacturing economies, the first cost of a solar cooker will be a deterrent, and in many instances a prohibition, to purchase by many people of low income. It therefore appears that as soon as one or more solar cookers have been clearly shown useful, needed, and desired by families in a particular country or region, means for their purchase should be provided through extension of credit. This complicated subject is beyond the scope of this report, but the need must not be overlooked. The opportunity for improvement in the standard of living of peoples least able to take advantage of this development is great enough to justify the most careful consideration. There is ample justification for government interest in this matter because of the benefits in reducing the depletion of natural resources and, in some cases, dependence on petroleum imports.

It is evident that much more attention should be given to the field-testing phase of solar cooker development. The satisfactory use of a solar cooker, under "laboratory" conditions, by technologists or even by educated laymen, is no guarantee of acceptability and use by low-income families anywhere. All that can be definitely said in this regard is that if the cooker is *not technically* satisfactory, it cannot be useful; but the converse does not necessarily follow. Performance evaluation under completely normal family living conditions is obviously needed for the solar cookers which have not received this kind of testing. Even though extensive data of this type have been obtained on the plastic paraboloid cooker, more information of this sort is needed before consumer acceptability can be confidently predicted. And although there probably will be some correlation between acceptabilities in different regions and among different segments of the population, each national cooking pattern, climatic condition, and economic and social environment will have to be appraised.

In an over-all view, solar cooker development appears to be in an uncertain, but potentially significant, state. Several cookers appear technically capable of supplementing, to a substantial extent, the cooking needs of peoples in sunny climates. Reductions in equipment cost are prerequisite to large utilization, and means for credit purchase seem to be needed. Appraisal of the use prospects requires further field testing by large groups of potential users. New designs, materials, and fabricating techniques appear desirable both for achieving better performance and for lowering costs of manufacture.

Proposed topics for discussion

There are numerous general topics pertaining to solar cooking which merit consideration and discussion. These are in addition to specific points in the several papers presented to the Conference. Some of the subjects which should be of particular interest include the following:

(*a*) To what degree is the *use* of solar ovens and the focusing "surface" type cookers interchangeable? Are most cooking and eating habits such that the use, for example, of an oven for boiling, or a focusing unit for baking, would not be desired?

(*b*) If the uses are distinct, in what parts of the world is each type most likely usable by low-income groups?

(*c*) If it is considered unlikely that economical solar cookers of more than 500 watts net heat delivery capacity can be developed, is this a serious limitation to widespread use? Is it necessary that the heat delivery capacity of conventional cooking facilities, as much as 1 000 to 2 000 watts, be duplicated for successful solar application?

(*d*) Some investigators believe that for the successful application of solar cookers to use by low-income families in under-developed areas, the cooking and eating habits of the people must be essentially unaltered by this new device. To what extent is this assumption subject to modification?

(*e*) How low must the first cost really be, for successful application of a solar cooker? What is the likelihood that such a cost can be achieved in one or more of the cooker designs under investigation, and which design appears to have the best potential?

(*f*) To what extent can improved performance be expected among the solar cookers under development?

(*g*) How significant is the use of thermal storage in solar cooking? Is the capability of a solar oven in storing 200 kilocalories of heat an important factor in its use? Is the practicality of a solar oven impaired by the need for preheating it if high-temperature storage is used? Would it be desirable to undertake development of some type of thermal storage unit which could be used with the focusing type of cooker, the latent heat then being subsequently employed for cooking after dark?

(*h*) To what extent is portability and collapsibility of the cooking equipment important in its application? Could this feature be a determining factor in choice of equipment, other characteristics being comparable with non-portable units?

(*i*) What are the inherent size limitations on solar cookers of the focusing type and of the oven type?

(*j*) What are the costs of solar ovens, as now designed and as ultimately envisaged? How critical is the design of a solar oven, in respect to reflector performance, window characteristics, and extent of thermal insulation? What specific design criteria might be established in solar oven development and what are the best measures of performance? Is the maximum temperature achieved in an empty oven a useful measure of quality? What can be conclusively believed as to the relative merits of internal and external reflectors?

(*k*) What design criteria are important in the focusing type of solar cooker, and how can the units of this type be best appraised? To what extent do the characteristics of the cooking vessels influence the apparent effectiveness of the cookers, and how can this factor be considered in analyses of performance?

(*l*) What are the most significant sociological factors in the use of solar cookers, such as extent to which people will change their traditional patterns, the extent of applicability of cookers in areas where they meet acceptance, secondary effects of broad introduction such as on fuel gathering activities and fertilizer use, and needs for training in the use of mechanical devices?

(*m*) In field evaluation studies, what are the answers to questions such as the numbers of people, places, and days needed for obtaining significant results, the relative value of demonstrations versus regular family use, the effects of an observer on the validity of the results, and the extent of user education necessary?

(*n*) How can low-income families arrange for even a modest investment in any type of solar cooker?

(*o*) Are the potential gains in natural resource protection which might be achieved by widespread use of solar cooking sufficient to justify governmental support of solar cooking experiments and the financing of cooker purchases?

(*p*) What are the merits of possible use of very large solar cookers, not only as a means for food preparation but also as a small source of household heat when not used for cooking? What cost increases might be acceptable for the possible increased usefulness of such a heat source?

(*q*) Among all of the solar cookers discussed in this Conference and previously considered, does any one appear to have outstanding potential for widespread application? In what specific countries or regions does such a potential appear to exist, and by what means can it be reliably evaluated?

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : CUISINIÈRES SOLAIRES

(Traduction du rapport précédent)

George O. G. Löf *

Principes généraux

Une cuisinière solaire est un échangeur d'énergie solaire conçu spécialement pour donner de la chaleur aux aliments, afin d'élever leur température et de provoquer les transformations chimiques liées au processus de la cuisson. Par cet apport de l'énergie nécessaire, la cuisinière solaire complète et, dans une mesure plus ou moins grande, remplace les combustibles classiques. Dans les régions sous-développées du monde, certains de ces combustibles sont le bois, le pétrole lampant, le charbon de bois, les excréments séchés, les déchets agricoles et autres matières combustibles. L'emploi de cuisinières solaires peut donc viser un double but : réduire le coût de la cuisine familiale, puisqu'il diminue la nécessité d'acheter ou de ramasser du combustible; et conserver les combustibles pour d'autres usages; c'est ainsi que le fumier animal peut servir d'engrais; de même, l'économie de bois et de charbon de bois contribue à protéger les forêts et à diminuer l'érosion.

Bien que les procédés de cuisson des aliments soient presque innombrables, il n'est pas inutile de rappeler ici les méthodes principales. Lorsqu'on fait bouillir ou frire les aliments, la chaleur est transférée aux aliments solides à partir d'un liquide chauffé, tandis que lorsque les aliments sont cuits au four ou rôtis, la chaleur est transférée par convection de l'air chaud environnant, et parfois par rayonnement à partir de surfaces chaudes. Dans tous ces processus, la nourriture doit d'abord être portée à la « température de cuisson », puis maintenue à cette température pendant le temps qu'il faut pour amollir, sécher, décomposer, coaguler, séparer, concentrer ou opérer toute autre transformation requise. Les quantités de chaleur nécessaires pour la plupart des transformations physiques et chimiques que comporte la cuisson sont faibles. C'est-à-dire que les chaleurs chimiques de réaction ou de conversion sont négligeables par comparaison avec la chaleur qu'il faut produire pour augmenter la température des aliments et avec les pertes de chaleur qui se produisent normalement au cours de la cuisson.

La plupart des aliments contiennent une forte proportion d'eau, et leur réchauffement pour les porter aux températures de cuisson exige près d'une cal par kg par °C (1 btu par livre par °F). Plus l'apport de chaleur aux aliments et au récipient (et à tout liquide additionnel utilisé pour la cuisson) est élevé, plus vite les aliments seront portés à la température de cuisson. Après ce stade, sauf dans les cas où la vaporisation de l'eau est nécessaire au processus de cuisson, comme dans la fabrication du pain, la vitesse de la cuisson cesse d'être fonction de la chaleur, pour autant que la température soit maintenue par une source de chaleur fournissant une chaleur égale aux pertes thermiques. Il est donc vrai en général que les écarts entre les temps requis pour cuire une même quantité de nourriture sur des fourneaux ayant des sources de chaleur de puissance diverse sont dus principalement aux différences de durée de la période de réchauffement. C'est pourquoi, que le taux du débit de chaleur soit faible ou élevé, le temps requis dans l'un et l'autre cas pour cuire des aliments qui doivent être cuits plusieurs heures ne sera guère différent.

Dans la cuisson des aliments, c'est la chaleur consommée pour vaporiser l'eau présente dans les aliments ou ajoutée pour la cuisson (près de 600 cal par kg ou 1 050 btu par livre anglaise) qui constitue la plus importante des pertes de chaleur. Viennent ensuite les pertes, par convection, des ustensiles et des parois du four. Si la source d'énergie a une puissance limitée, il importe de restreindre ces pertes au moyen de couvercles placés sur les ustensiles, par l'isolement des chambres de cuisson (fours) et par d'autres moyens. Si l'on estime la perte horaire par convection (à l'extérieur) à la température de l'eau bouillante à 600 btu par pied carré d'ustensile (150 kcal par 0,09 m^2) et dans l'hypothèse d'une surface de 0,5 pied carré par livre (0,045 m^2) du contenu du récipient, l'apport d'énergie pour faire bouillir des aliments pendant une heure, si un quart de l'eau est vaporisé, se répartirait à peu près de la manière suivante :

Réchauffement des matières à la température de l'eau bouillante	20 p. 100
Pertes par convection à partir du récipient	45 p. 100
Vaporisation de l'eau	35 p. 100

Certes, une modification des conditions de l'hypothèse changerait sensiblement cette répartition, mais il n'en reste pas moins que les chiffres montreraient encore que la majeure partie de la chaleur fournie pour une cuisson de longue durée est perdue.

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Dans la grande majorité des cas, la cuisine familiale dans le monde entier se fait soit dans un ustensile chauffé par en dessous, d'ordinaire directement par un feu, soit dans un coffrage (le four en est le modèle typique) approvisionné en air chaud par un foyer faisant partie intégrante de l'ensemble ou par un foyer extérieur. Les opérations qui consistent à faire bouillir, à cuire à l'étouffée, à frire et, d'une manière générale, à réchauffer les liquides se font en majeure partie au-dessus d'un feu direct, alors que l'on utilise ordinairement les fours pour cuire le pain et pour rôtir. Les températures réelles des aliments au cours de la cuisson ne varient pas beaucoup, parce que la présence d'eau dans tous les aliments limite leur température qui se maintient à peu près au point d'ébullition de l'eau. La température de la source de chaleur, toutefois, dépend beaucoup des aliments et du type de cuisson employé. Le feu direct comporte des températures de 1 000 degrés, et l'on enregistre donc un gradient thermique très élevé dans la cuisson de surface ordinaire, ce qui permet des taux élevés de transfert de chaleur. La cuisson au four se fait avec des températures de l'air qui sont seulement de 200 à 250 °C, de telle sorte que les débits de chaleur sont plus faibles, et il faut en général cuire pendant plus longtemps. Par conséquent, dans presque tous les types de cuisson, même si la température maximale des aliments ne dépasse pas 100 °C, il est nécessaire de fournir une source de chaleur à une température beaucoup plus élevée si l'on veut obtenir des taux de cuisson satisfaisants.

Lorsqu'on envisage, pour la cuisson des aliments, de substituer l'énergie solaire aux combustibles, il faut encore prendre en considération la puissance habituelle de la source d'énergie. Bien qu'il soit évident que la majeure partie de l'énergie n'est pas employée utilement et que l'on pourrait économiser cette énergie par l'isolement et la diminution de l'évaporation, il faut tenir compte des habitudes de ceux qui cuisinent. De ce fait, il faudrait dans toute la mesure possible qu'une cuisinière solaire fournisse une source de chaleur à un taux équivalant à celui qui est utilisé normalement. Les fourneaux à surface de chauffe utilisant l'électricité ou le gaz peuvent avoir en moyenne une puissance de 1 kW, capable de porter 2 litres d'eau au point d'ébullition en 10 minutes environ. Les fours automatiques pour la cuisine familiale (aux États-Unis) ont une puissance de 2 à 4 kW, mais fonctionnent à un régime intermittent, réglé par thermostat, ce qui doit placer la consommation moyenne à 1 kW environ. Il semblerait que pour avoir un rendement équivalant tout à fait aux fourneaux à combustibles, un fourneau solaire devrait fournir à peu près 1 kW au récipient de cuisson. Si tel n'est pas le cas, il faut soit accepter une durée de cuisson plus longue, soit utiliser des quantités moindres d'aliments, soit mettre au point des procédés de conservation de la chaleur. Si le rendement de captage de l'énergie solaire est de 50 p. 100, il faudrait un réflecteur solaire d'environ 2 m² (20 pieds carrés) pour obtenir une puissance de chaleur comparable.

Les principes et les pratiques de cuisson que l'on vient d'exposer montrent qu'une cuisinière solaire pratique doit pouvoir transférer aux aliments une quantité suffisante de chaleur, dans un temps raisonnable, à des températures s'échelonnant à peu près de la température ambiante jusqu'à environ 200 °C. Pour obtenir les températures moyennes et supérieures, il faut avoir recours à des appareils solaires à concentration. Deux sortes de modèles ont été conçus, la différence résidant au premier chef dans la manière par laquelle on obtient la concentration, et dans le degré d'utilisation de cette concentration. La cuisinière, *à foyer* ou *directe*, utilise un réflecteur pour concentrer le rayonnement sur les aliments ou sur le récipient dans lequel sont cuits les aliments. L'énergie solaire est intensifiée par un coefficient qui se situe typiquement entre 20 et 100 et elle équivaut réellement à une source d'énergie fournie par un feu à foyer ouvert. La cuisinière du *modèle* « *four* » est une boîte isolée munie d'un vitrage transparent sur le côté exposé au soleil. Un rayonnement supplémentaire réfléchi dans le vitrage par des réflecteurs plans disposés autour du vitrage intensifie l'énergie solaire par un coefficient de 2 à 4. Ce fourneau équivaut pour l'essentiel à un four chauffé au combustible. On a également projeté de *combiner* les principales caractéristiques de ces deux modèles de base. Dans les paragraphes ci-après, nous avons exposé dans leurs grandes lignes les caractéristiques de ces modèles de cuisinières solaires et décrit comment on les utilise pour la cuisson de divers aliments. Nous mentionnons brièvement l'importance de certaines caractéristiques sociologiques des cuisinières solaires.

Comme dans le cas de tous les appareils d'énergie solaire, le rendement des cuisinières solaires peut être évalué quantitativement par l'étude des bilans énergétiques tout au long des stades du processus. Toutefois, l'énergie requise pour une cuisson particulière n'est pas toujours définie avec précision et peut beaucoup varier selon les modes de cuisson utilisés, par exemple dans les cas où les pertes par évaporation sont réduites au moyen d'un couvercle posé sur le récipient de cuisson. Ces différences dans les méthodes et les conditions de cuisson font qu'il vaut mieux évaluer le rendement d'une cuisinière solaire en mesurant le taux net de transfert de chaleur aux aliments ou au récipient qui les contient, ainsi que d'après le temps nécessaire pour cuire une quantité d'aliments connue. Les mémoires consacrés à cette session fournissent des données sur le débit de chaleur calculées en watts, ou en énergie de chaleur par unité de temps dans une gamme de températures utiles et aussi en temps nécessaire pour cuire certaines quantités de nourriture. La plupart des cuisinières solaires qui sont décrites ont été conçues de manière à être à peu près équivalentes aux autres méthodes de cuisson qu'elles remplaceraient, mais elles sont ordinairement d'une puissance moindre.

Les problèmes économiques que pose l'utilisation de l'énergie solaire dans un ménage sont encore plus complexes que ceux soulevés par son utilisation à grande échelle. Le coût actuel du combustible de ménage, calculé en argent, peut être nul dans les pays sous-développés, où l'on utilise le bois et les déchets ramassés par les consommateurs eux-mêmes. Néanmoins, on peut estimer que la valeur du temps passé à ramasser le combustible et les pertes économiques dues au déboisement et à l'appauvrissement du sol résultant des coupes de bois excessives et du manque d'engrais valent bien des débours d'argent. Un autre problème économique à résoudre est la pauvreté des gens qui bénéficieraient le plus de l'emploi de cuisinières solaires, mais qui sont dans l'impossibilité de faire la dépense initiale pour l'achat de ces appareils. C'est un fait également que dans de nombreuses régions où l'on pourrait les utiliser, les prêts aux particuliers pour l'achat d'appareils ménagers sont difficiles à obtenir et les taux d'intérêt sont élevés. Pour ces raisons, la plupart des chercheurs dans ce domaine ont conclu que si l'on veut répandre l'usage des cuisinières solaires, il faut qu'elles soient bon marché, pratiques et fabriquées partiellement ou totalement dans le pays même.

Les conditions principales que doit remplir une cuisinière solaire pour qu'elle puisse rendre des services dans une région en voie de développement peuvent se résumer de la manière suivante :

a) L'appareil doit cuire les aliments efficacement, et doit donc être satisfaisant du point de vue technique. Il faut donc qu'il puisse fournir une énergie suffisante, à la température voulue, à la quantité d'aliments nécessaire.

b) Il doit être assez solide pour résister pendant sa durée de vie à un maniement brutal et aux intempéries, le vent par exemple.

c) Il doit être sociologiquement acceptable et être adapté aux modes de cuisine et aux habitudes alimentaires de la population.

d) Il faut que l'utilisateur puisse se procurer une cuisinière à un prix tel que son utilisation représente une économie.

Caractéristiques des cuisinières solaires

Trois des sept mémoires rédigés pour cette session traitent de la construction et de l'utilisation des cuisinières à concentration (S/24, S/87, S/100). Deux mémoires sont consacrés aux fours solaires (S/75, S/101). Un auteur (S/116) a fait une étude comparative des taux de chaleur fournis par les deux modèles, et dans un autre mémoire (S/110), on trouve une description d'un appareil conçu pour combiner les meilleures propriétés du système à four et du système à concentration. Le mémoire S/87 expose les résultats d'études effectuées *in situ* pour évaluer l'utilisation quotidienne pratique d'une cuisinière solaire. Les six cuisinières étudiées, sauf une, ont été fabriquées et essayées.

Dans le tableau 1, le rapporteur a tenté de présenter les caractéristiques essentielles des six modèles de cuisinières solaires examinées dans les mémoires soumis à la Conférence. Dans toute la mesure possible, les données portées dans le tableau ont été obtenues directement à partir de faits ou de chiffres rapportés dans les mémoires, ou elles ont été calculées à partir de données des faits. Il a fallu néanmoins que le rapporteur apprécie ou interprète certaines caractéristiques, et il l'a indiqué dans le tableau. Dans certains cas, certaines caractéristiques ne sont pas signalées faute de renseignements suffisants dans les mémoires.

Plusieurs modèles de cuisinières à concentration, qui avaient été fabriqués antérieurement, n'ont pas été présentés dans les communications à la Conférence. Nous n'avons pas reçu de renseignements nouveaux sur les cuisinières utilisant les réflecteurs en aluminium repoussé au tour qui ont été construites en Inde, sur le paraboloïde en aluminium à facettes de Tarcici, les réflecteurs coniques en verre argenté du Japon, ni sur un petit réflecteur en deux parties fabriqué en matière plastique revêtue de métal (États-Unis). Quoi qu'il en soit, les études portent sur un champ très étendu et il est probable que tous les nouveaux modèles de quelque importance y figurent. Le tableau contient des renseignements sur toute une gamme de modèles, et pour la plupart d'entre eux, les auteurs ont fourni des études quantitatives.

Il est intéressant de noter que toutes les cuisinières décrites dans les mémoires sont d'un modèle différent. Même les matières utilisées pour les réflecteurs diffèrent dans presque chaque cas. Parmi les cuisinières d'un modèle pratique effectivement construites, la surface de captage du rayonnement solaire s'établit entre 0,36 m² et 1,07 m². On peut donc étudier une triple gamme de surfaces de captage de l'énergie solaire. Il n'y a pas de grande différence entre la dimension maximale du récipient qui peut être chauffé dans les diverses cuisinières, à l'exception de l'appareil combiné réflecteur-four de Prata qui est assez grand pour chauffer deux récipients. Le coefficient d'intensification solaire (taux moyen de concentration du rayonnement sur toute la surface de l'appareil récepteur) varie entre 3 environ dans les fours solaires et plus de 30 dans le paraboloïde à concentration décrit dans le mémoire S/87.

La mesure la plus significative du rendement d'une cuisinière solaire est probablement la « puissance effective de cuisson », indiquée en kilowatts dans le tableau. Nous avons obtenu les chiffres portés dans le tableau en convertissant en kW les renseignements donnés par les auteurs sur le chauffage de l'eau ou toute autre utilisation. Ces chiffres donnent le taux d'énergie fournie au récipient de cuisson et à son contenu par ciel clair, et dans des conditions atmosphériques moyennes. On verra que ces chiffres varient entre à peu près 0,15 kW dans le cas du four solaire de Telkes et Andrassy (S/101) et de l'appareil combiné réflecteur-four de Prata (S/110) et 0,4 à 0,5 kW pour le paraboloïde à concentration de Duffie, Löf et Beck (S/87). La cuisinière pliante décrite par Löf et Fester (S/100) a une production d'énergie légèrement inférieure à cette dernière valeur, dans la gamme 0,25 à 0,40 kW. Des expériences de la FAO (S/116) confirment

Tableau 1. Caractéristiques des cuisinières solaires

Numéro du mémoire	S/24	S/87	S/100	S/75	S/101	S/110
Auteurs	Stam	Duffie, Löf, Beck	Löf, Fester	Abou-Hussein	Telkes, Andrassy	Prata
Type de cuisinière	:: A concentration	A concentration	A concentration	Four	Four	Appareil combiné
Type de réflecteur	:: Sphérique	Paraboloïde	Parabolique type parapluie	Plaques planes intérieures	Plaques planes extérieures	Cylindre parabolique
Matière du réflecteur	:: Feuille d'aluminium sur du ciment ou du plâtre	Pellicule de matière plastique « Mylar » recouverte d'aluminium sur une coque en polystyrène	« Mylar » recouvert d'aluminium placé sur le tissu sur une carcasse de parapluie	Feuilles d'aluminium bruni	Feuilles d'aluminium ayant subi un traitement anodique (feuille d'aluminium enrobé) ::	Feuille de bronze plaquée de nickel (aluminium plaqué de nickel) ::
Dimension du réflecteur	Diamètre 0,22 m :: 4,5 m	Diamètre 1,22 m	Diamètre 1,17 m	(4) 1 288 cm²	(4) 43 cm²	(2) 0,5 m × 0,8 m
Surface effective de captage de l'énergie solaire	0,04 m² :: ~ 10 m²	1,07 m²	1,02 m²	0,36 m²	0,56 m²	0,74 m²
Longueur focale du réflecteur	:: Rayon de 225 cm	46 cm	46 cm	—	—	~ 1,05 cm
Fenêtre du four		—	—	0,36 m² verre double	0,19 m² verre double	0,06 m² verre simple
Plaque de cuisson	:: (2) 30 cm de diamètre *	~ 20 cm de diamètre	~ 23 cm²	~ 20 cm² *	~ 25 cm² *	~ 20 cm × 50 cm *
Intensification solaire effective	:: ~ 50 *	~ 34	~ 20	~ 3 *	~ 3 *	~ 12 *
Minimum de temps nécessaire pour porter un litre d'eau de 20 °C à 100 °C	n.i.	15 minutes à 15 minutes (minimum)	22 minutes	n.i.	~ 30 minutes 46 minutes ▲ (minimum)	26 minutes *
Puissance effective de cuisson en kW	n.i.	0,4-0,5 0,28 moyenne ▲ 0,34 max. ▲	0,25-0,4	n.i.	0,15-0,2 * 0,10 moyenne ▲ 0,12 max. ▲	0,15-0,25 *
Rendement de la cuisson des aliments	n.i.	bon	bon	n.i.	bon	bon
Poids approximatif en kg	:: plusieurs centaines	10	3	n.i.	~ 20 *	12-18
Accumulation thermique projetée	:: oui	non	non	oui	oui	non
Capacité totale de cuisson	n.i.	~ 4 kg *	~ 2 kg *	n.i.	~ 3 kg *	~ 4 kg * (2 récipients)
Portabilité	:: aucune	bonne *	excellente *	bonne *	bonne *	assez bonne *
Réorientation pendant la cuisson	:: rare	fréquente (15-30 min)	fréquente (15-30 min)	de temps en temps (30-60 min)	de temps en temps (30-60 min)	peu fréquente (25 min)
Possibilité d'utilisation pour la cuisson au four	:: assez bonne *	faible *	faible *	bonne *	bonne *	bonne *
Possibilité d'utilisation pour la cuisson de ragoûts et la friture	:: bonne *	bonne *	bonne *	assez bonne *	assez bonne *	assez bonne *
Longévité	n.i.	bonne *	assez bonne *	très bonne *	très bonne *	bonne *
Possibilité d'utilisation de matériaux trouvés sur place	:: bonne *	assez bonne *	assez bonne *	assez bonne *	assez bonne * :: bonne *	assez bonne *

:: *

Tableau 1 *(suite)*

Numéro du mémoire	S/24	S/87	S/100	S/75	S/101	S/110
Des cuisinières de dimensions normales ont-elles été construites et essayées?	non	des centaines	voir ci-dessous	oui	oui	oui
Essais sur place	non	nombreux	voir ci-dessous	non	quelques-uns	non
Vente dans le commerce	non	non	des centaines	non	non	non
Coût (ou prix) approximatif	n.i.	16 dollars (à l'usine)	30 dollars (magasins de détail)	n.i.	n.i.	~ 35 dollars (à l'usine)

[a] Essais de la FAO (mémoire S/116).
Projet.
* Calcul ou estimation du rapporteur

n.i. Non indiqué.
~ Approximativement.

généralement ces puissances, mais, dans certains cas, comme l'ensoleillement était inférieur aux conditions idéales, on a enregistré des débits maximaux de 0,12 kW (S/101) et de 0,38 kW (S/87). On a indiqué également dans le tableau le temps nécessaire (calculé ou mesuré d'après les renseignements fournis par les auteurs) pour porter un litre d'eau de la température de la pièce au point d'ébullition. Ce temps varie entre 15 minutes environ dans le cas du paraboloïde rigide en matière plastique (S/87) et une demi-heure dans le cas du four solaire (S/101). A titre de comparaison, le temps normal sur un feu de bois ou un réchaud à pétrole serait de cinq à 10 minutes.

Il est difficile, d'après les renseignements fournis d'évaluer la quantité d'aliments qui peut être cuite avec chacun de ces appareils. Dans les fourneaux du type four, le facteur limitatif est le volume du four. L'appareil combiné de Prata semble avoir le volume intérieur le plus grand, et il est conçu pour recevoir deux récipients à la fois. Dans le cas des cuisinières à concentration, les quantités sont limitées au premier chef par la surface du trépied supportant le récipient et par la rigidité du cadre qui soutient le récipient. Dans tous ces appareils, une limite pratique est imposée par la durée maximale acceptable de la cuisson. Plus la quantité d'aliments est grande, plus il faut de temps pour les porter à la température de cuisson. De même, dans le cas des cuisinières à concentration, le taux des pertes de chaleur des parois du récipient vers l'air environnant impose une limite pratique à la surface exposée totale du récipient. Tous ces facteurs ayant été pris en considération, le rapporteur estime que le maximum approximatif des quantités d'aliments qui peut être cuit sur ces cuisinières varie entre deux et quatre kilogrammes, ainsi que le montre le tableau; le minimum s'applique au réchaud pliant du type parapluie (S/100) et le maximum à l'appareil combiné de Prata (S/110) et à l'appareil rigide à concentration (S/87). Le four solaire avec une surface de vitrage de 0,19 m² (S/101) semble avoir une capacité normale de trois kilogrammes environ. La plupart de ces capacités sont suffisantes pour un repas familial, encore que le fait de ne pouvoir cuire qu'un plat (sauf dans le cas de l'appareil combiné) soit un inconvénient. S'il faut cuire plus d'un aliment, on pourrait, dans les autres appareils, utiliser des récipients compartimentés ou peut-être plusieurs petits ustensiles. On estime en général que ces appareils ont une capacité suffisante pour la cuisson des repas simples que consomme en général une famille ayant un revenu peu élevé.

On constatera d'après le tableau que le poids et l'encombrement des appareils varient considérablement; l'appareil du type parapluie pèse environ 3 kilogrammes et se présente sous un petit volume, une fois plié (S/100), alors que le réflecteur en maçonnerie proposé par Stam (S/24) pèse des centaines de kilogrammes. L'appareil rigide à concentration (S/87) a un poids total d'environ 10 kilogrammes, et le grand four (S/101) et l'appareil combiné (S/110) pèsent de 15 à 20 kilogrammes. Pour certains usages, il peut être utile d'avoir des appareils portatifs de faible encombrement, mais, dans la plupart des cas, on utilisera une cuisinière fixe. Les cuisinières qui doivent être exposées en permanence à l'atmosphère et au soleil sont plus susceptibles d'être endommagées par les intempéries et les accidents. La longévité des diverses cuisinières est donc fonction de la durée pendant laquelle elles sont exposées à l'air, de l'usage qu'on en fait et des caractéristiques de construction. La plupart de ces appareils paraissent avoir une longévité suffisamment « bonne » (plusieurs années), celles du type four étant probablement les meilleures de ce point de vue. Il est probable que l'appareil pliant du type parapluie n'est pas aussi durable que les autres dans sa forme actuelle.

Des deux principaux modèles de cuisinières, les fours solaires semblent les mieux adaptés à l'utilisation de matières accumulant la chaleur, outre qu'ils ont une capacité intrinsèque d'accumulation plus élevée qui permet de garder les aliments au chaud et de continuer la cuisson pendant une courte période après le coucher du soleil et pendant de courtes périodes (quelques minutes) de nébulosité. Au cours de ses expériences, Abou-Hussein (S/75) a constaté qu'il fallait environ une demi-heure pour porter la température d'un four vide de 150 °C à 218 °C par bon ensoleillement. Lorsque le soleil disparaissait, l'appareil tombait à 150 °C en six ou sept minutes. La cuisinière était encore chaude (80 °C) trois quarts d'heure après. Bien que ces expériences aient été faites avec un four vide, elles montrent que de courtes périodes de nébulosité peuvent être tolérées sans que le temps de cuisson des aliments en soit beaucoup allongé; cet appareil est également utile pour maintenir les aliments chauds après cuisson.

Les auteurs des mémoires S/75, S/101 et S/24 ont examiné la possibilité d'augmenter l'accumulation de chaleur au moyen de matières subissant des transformations à la chaleur de fusion et à la chaleur de transition. Telkes et Andrassy (S/101) ont comparé les propriétés d'accumulation de chaleur de plusieurs matières dans la gamme des températures 300 ° à 400 °F (150 ° à 200 °C). Un mélange de nitrates alcalins permet une accumulation du type chaleur de fusion à 150 ° ou 160 °C, et des mélanges de sulfates alcalins anhydres subissent une transition solide-solide entre 191 °C et 239 °C, avec un effet de chaleur latent d'environ 60 calories par gramme. Les auteurs du mémoire ont décrit un four contenant environ trois kilogrammes du mélange de sulfates sous forme d'une plaque inférieure plate. Toutefois, à moins qu'ils ne soient utilisés pour accumuler la chaleur pendant le préchauffage de fours vides, les mélanges de sulfates alcalins semblent avoir des températures de transition si élevées qu'ils ne peuvent être utilisés, du fait que les fours solaires atteignent rarement ces niveaux pendant la cuisson des aliments.

Stam (S/24) a proposé d'employer le chlorure de magnésium hydraté (point de fusion 117 °C) et le palmitate de magnésium (point de fusion 121 °C) pour servir de matières d'accumulation de chaleur, en les plaçant dans des récipients de forme spéciale disposés au foyer du grand réflecteur sphérique. Il propose l'emploi d'une quantité totale de 40 litres pour une accumulation efficace qui servira ensuite à la cuisson. Toutefois, il ne signale pas que des expériences aient eu lieu, et à notre avis ces températures d'accumulation ne sont peut-être pas suffisantes pour la plupart des cuissons; même pour faire bouillir, la force de cette température serait très faible.

Tout le sujet de l'accumulation de chaleur pour la cuisson des aliments semble appeler de nouvelles études. Il est possible que l'on puisse utiliser des cuisinières à concentration munies d'un type de récipient d'accumulation qui emmagasinerait la chaleur pendant la plus grande partie de la journée afin de la restituer le soir pour la préparation des repas. La mise au point et l'emploi de matières peu coûteuses, inoffensives et sûres qui auraient une forte capacité thermique, un poids modéré et s'adapteraient facilement aux modèles de cuisinières pourraient beaucoup augmenter la possibilité d'utiliser l'énergie solaire pour la cuisson dans certaines parties du monde.

La zone focale relativement petite d'un réflecteur parabolique impose le déplacement périodique de la cuisinière à concentration, si l'on veut maintenir un débit maximal de chaleur au fond du récipient servant à la cuisson. La fréquence de ces déplacements est fonction du moment de la journée où la cuisinière est utilisée, de la saison et de la dimension du récipient servant à la cuisson. En moyenne, toutefois, il faudrait procéder à de légères adaptations de la position du réflecteur à des intervalles allant de 15 à 30 minutes. Le tableau montre que les cuisinières du type four exigent moins de déplacements, et qu'elles fonctionnent bien si l'ajustement se fait toutes les 30 ou 60 minutes. Il semble que l'appareil combiné doive être orienté à peu près aux mêmes intervalles que l'appareil à concentration. Stam n'a pas mentionné quel serait le déplacement des ustensiles dans le cas de l'appareil sphérique dont il propose le plan, mais il est probable que ces déplacements seraient un peu moins fréquents que dans le cas du modèle parabolique.

La longévité des diverses cuisinières ne peut être estimée facilement à l'heure actuelle, faute de données suffisantes. Les caractéristiques générales des matériaux employés pour leur construction ainsi que leur montage indiquent toutefois que les fours devraient durer longtemps; les cuisinières paraboliques rigides, si elles sont bien fabriquées, devraient avoir une bonne longévité, et l'appareil léger du type parapluie serait probablement moins durable que les autres. Le rapporteur croit que les fabricants, s'ils attachent assez d'attention à ce problème, pourront donner une longévité satisfaisante à toutes ces cuisinières.

En général, les fours conviennent le mieux à la cuisson du pain et des rôtis, et les cuisinières utilisant des réflecteurs à concentration conviennent à la cuisson de ragoûts et à la friture. Ces usages correspondent naturellement aux opérations de cuisine habituelles. Il est vrai que les fours peuvent également être utilisés pour faire bouillir et frire et que l'on peut se servir des modèles à concentration pour cuire du pain, pourvu qu'un petit four soit adapté au support du foyer. Les usages idéals sont néanmoins ceux qui sont indiqués dans le tableau.

Lorsqu'il s'agit d'utiliser ces appareils dans les pays sous-développés où l'importation de produits manufacturés est souvent difficile, la question de savoir si les cuisinières solaires peuvent être fabriquées sur place, notamment au moyen de matériaux du pays, présente de l'importance. Aucune des cuisinières ne semble avoir été conçue de ce point de vue. Tous les modèles utilisent au moins certains éléments ou matériaux provenant de pays industrialisés, ou qui doivent être usinés. Les modèles à concentration nécessitent l'emploi de pellicules de matières plastiques recouvertes de métal, des armatures de réflecteur en matière plastique moulée, et des éléments de métal profilés. Pour construire les fours, il faut du verre ou des pellicules de matière plastique, de l'aluminium bruni et (si possible) du métal en feuille pour le coffrage du four. Heureusement, toutes ces cuisinières pourraient être fabriquées dans de petits établissements industriels utilisant la main-d'œuvre locale et certaines quantités de matériaux du pays. Si l'appareil proposé par Stam se révèle pratique, les pays utilisateurs pourront le fabriquer presque uniquement avec la main-d'œuvre et les matériaux locaux. Ce sont là des éléments qui influent sur le coût des cuisinières, et, de toute évidence, il est souhaitable que l'on utilise au maximum les matières et la main-d'œuvre du pays.

Des six cuisinières décrites, deux des modèles à concentration ont été fabriqués par centaines. De nombreux fours solaires de types divers ont été construits, mais les quantités n'ont pas été indiquées. Au moins un appareil combiné de Prata a été fabriqué, mais seulement deux petits modèles de la grande cuisinière sphérique de Stam ont été construits, et l'auteur ne signale des essais de débit de chaleur qu'avec le très petit réflecteur de 22 cm de diamètre. Le tableau montre que cinq cuisinières décrites dans les mémoires de la Conférence ont été effectivement essayées. Un seul appareil, la cuisinière parabolique rigide (S/87), a pu être évalué au cours de nombreuses expériences dans les conditions normales d'utilisation, et l'auteur du mémoire donne les résultats de plusieurs années d'essais dans des conditions techniques et sociales connues. Aux États-Unis, une autre cuisinière, le modèle pliant du type parapluie (S/100), a été vendue dans le commerce à plusieurs centaines d'exemplaires, surtout à titre récréatif. Le mémoire S/101 indique que le four solaire a été essayé et exposé, sans donner aucun renseignement précis. Selon les renseignements dont dispose le rapporteur, ce n'est que dans le cas de la cuisinière à concentration en matière plastique rigide, décrite dans le mémoire S/87, que de nombreuses familles à faible revenu ont cuit leurs aliments grâce à l'énergie solaire.

Plusieurs estimations optimistes du prix de revient des cuisinières ont été faites dans le passé, mais la plupart des chiffres indiqués ont été calculés sans que l'on ait suffisamment tenu compte des exigences de fabrication. Cependant, dans les mémoires soumis à la Conférence, les trois prix de revient qui figurent dans le tableau semblent avoir été établis d'après des informations valables. Les deux modèles paraboliques sont d'un prix à peu près égal, le modèle trois du paraboloïde en matière plastique rigide (S/87) ayant un prix estimé à l'usine à 16 dollars (production moyenne) et le prix de vente au détail du modèle pliant du type parapluie (S/100) étant annoncé à 30 dollars (petite production). Compte tenu des coûts et bénéfices de la vente en gros et au détail, le prix à l'usine du type parapluie devrait être à peu près comparable à celui du type paraboloïde rigide. Le troisième chiffre donné est le coût à l'usine estimé à 35 dollars dans le cas de l'appareil combiné (S/110). Il faut noter néanmoins que cette estimation a été faite sur des modèles de laboratoire, alors que les deux autres prix ont été établis pour des centaines de cuisinières déjà fabriquées. Il se peut donc que le prix de 35 dollars soit moins certain que les autres, et il serait peut-être réduit par des modifications de la conception, des matières utilisées et des méthodes de fabrication. Parmi les prix d'autres cuisinières solaires qui ont déjà été publiés, citons celui de la cuisinière solaire fabriquée en Inde (14 à 17 dollars), celui de la cuisinière paraboloïde pliante de Tarcici (69 dollars au détail), du « chef solaire », petit modèle pliant à concentration (25 dollars), et du réflecteur conique en papier aluminisé de deux pieds de diamètre fournissant la chaleur à une petite casserole (4 dollars). Le rapporteur n'a vu aucun résultat de cuisson effectuée avec le « chef solaire », ou avec le dernier appareil mentionné ci-dessus, mais le faible débit de chaleur aux aliments, moins de 100 watts, autorise à se demander si ces appareils peuvent rendre des services.

Observations complémentaires relatives aux mémoires

Le tableau et les remarques ci-dessus sur les six cuisinières solaires décrites dans les mémoires soumis à la Conférence présentent la plupart des caractéristiques importantes de ces appareils, mais un examen de chaque mémoire permettra de préciser un certain nombre d'éléments intéressants.

Appareils a concentration

Mémoire S/24 de H. Stam

Bien que l'auteur ait examiné trois types de cuisinières, la plus grande partie du mémoire est consacrée à un projet de réflecteur sphérique en ciment ou en plâtre de 10 mètres de diamètre. Les récipients de cuisson seraient suspendus à une armature placée au-dessus et seraient périodiquement déplacés en fonction de la position du foyer. Le réflecteur servirait également à chauffer un volume relativement grand de substances accumulant la chaleur qui serait utilisée par la suite pour chauffer des pièces d'habitation pendant les nuits froides. La grande surface focale d'un réflecteur sphérique permettrait le chauffage simultané de récipients de cuisson et de récipients pour l'accumulation thermique.

L'auteur estime apparemment qu'il faut à peu près 400 kcal de chaleur pour cuire le repas du soir. Cela équivaut à une puissance de 310 watts pendant une heure et demie. Avec une chaleur de fusion de 40 kcal par litre, il faudrait 10 litres du milieu d'accumulation de chaleur pour un débit suffisant de chaleur après le coucher du soleil. Mais comme il peut s'écouler six heures entre le processus d'accumulation de chaleur et l'utilisation de la chaleur pour la cuisine, il faudrait prévoir 40 litres du milieu d'accumulation pour compenser les pertes et fournir la chaleur le moment venu.

Une grande partie du mémoire traite des impératifs de la cuisson, tels que les températures nécessaires à divers aliments, la dimension des ustensiles de cuisine pour une famille, et les pertes de chaleur à partir des récipients de cuisson. L'auteur est d'avis que les cuisinières construites antérieurement et celles qui font l'objet des autres mémoires n'ont pas la capacité voulue pour les utilisations envisagées. Il pense que l'appareil devrait suffire aux besoins de la famille la plus nombreuse.

Il convient de se rendre compte que ce mémoire a été rédigé à partir d'un projet, et qu'aucun prototype n'a été construit ou expérimenté. (L'auteur a utilisé un petit réflecteur de 22 cm de diamètre pour mesurer le taux de chaleur nécessaire pour chauffer quelques centimètres cubes d'huile et d'eau.) L'efficacité de cette cuisinière et la possibilité de la construire n'ont donc pas été démontrées. Le rapporteur souligne ici combien il est difficile d'obtenir une surface lisse en ciment ou en plâtre pour un réflecteur de telles dimensions, même si l'on s'adresse à des ouvriers hautement qualifiés. Les problèmes que pose la nécessité de maintenir une réflectance élevée sur une telle surface sont exceptionnellement ardus. Pour pouvoir estimer les avantages de ce modèle, il serait indispensable d'en connaître le rendement et le coût de fabrication. Le rapporteur reconnaît qu'il est souhaitable que la capacité de la cuisinière soit grande, mais à moins que l'on ne puisse démontrer qu'il est possible d'obtenir cette capacité à peu de frais, il semble que l'utilité des petites cuisinières pour la préparation d'un repas familial, qui a été prouvée, l'emporte sur les arguments de l'auteur.

L'auteur propose deux autres modèles de cuisinières. La première est un paraboloïde excentrique en plâtre soutenu par le bord d'un trou creusé dans le sol. Le réflecteur aurait environ 1,6 mètre de diamètre et le récipient de cuisson serait supporté par un petit trépied placé dans l'armature de la cuisinière. L'appareil pourrait de temps à autre être tourné et incliné pour suivre le soleil. L'auteur suggère un revêtement réflecteur en feuille d'aluminium. L'autre projet est celui d'un cylindre parabolique monté sur un axe nord-sud, qui tournerait lentement pour suivre la marche du soleil au moyen d'un système de sablier. Un fluide de transfert de chaleur circulerait à travers le tube chauffé jusqu'à un récipient isolé où la chaleur s'accumulerait. Ce fluide chaud pourrait être utilisé par la suite pour la cuisson des aliments ou à d'autres fins.

L'auteur pense qu'il faut que ce matériel soit fabriqué localement, et il souligne la nécessité de réunir des fonds pour la réalisation d'un programme de recherches sur les cuisinières solaires.

Mémoire S/87 de J.A. Duffie, G.O.G. Löf et B. Beck

La coque rigide du réflecteur en polystyrène moulé sous vide ou drapé constitue une surface remarquablement unie et peu coûteuse pour soutenir la matière spéculaire, dans ce cas une pellicule de polyester revêtue de « mylar » aluminisé. Renforcé par un cercle de métal, ce réflecteur est rigide et résistant. Les détails de construction sont exposés dans le mémoire, de même que les principes du modèle. Une étude du bilan d'énergie dans la cuisson solaire montre que pour obtenir un rendement élevé il est indispensable d'avoir un coefficient de réflexion spéculaire le plus fort possible et un dessin très précis des formes.

Le support et l'armature de la cuisinière ont été modifiés à plusieurs reprises. Selon les auteurs, le dernier « modèle 3 » est le plus résistant et d'un fonctionnement extrêmement simple. Ils estiment à environ 9 dollars le coût de construction en série du « modèle 2 »; même si la production du « modèle 3 » ne porte que sur des nombres moyens, il semble possible de le vendre 16 dollars à l'usine. L'économie de combustible (pétrole lampant) pour une famille, grâce à l'utilisation d'une cuisinière solaire dans le Mexique du Nord devrait, en une année à peu près, représenter le coût total d'une cuisinière.

Les renseignements sans doute les plus intéressants contenus dans ce mémoire sont les résultats d'expériences pratiques menées pendant plusieurs années au Mexique. Une partie de ces données est présentée sous forme de tableau : il s'agit de l'utilisation de 16 cuisinières solaires « modèle 2 » pendant une période de neuf mois. On a constaté que les familles de ces travailleurs agricoles à faible revenu ont utilisé les cuisinières à peu près les deux tiers du temps où il eût été possible de s'en servir. Le dernier modèle, qui n'a été expérimenté que pendant peu de temps avant la rédaction de ce mémoire (mai 1961), a été utilisé davantage, mais on ne dispose pas encore de renseignements complets à ce sujet. Certains défauts signalés, particulièrement dans le cas du « modèle 2 », sont des pannes mécaniques dues principalement au vent. Les auteurs pensent que dans le nouveau modèle ils ont supprimé les principales difficultés de cette sorte. Notamment lorsqu'il s'agit d'aliments exigeant une longue durée de cuisson, comme la cuisson à la casserole de viandes et de haricots, les utilisateurs de ces cuisinières estiment généralement que la cuisson se fait aussi vite qu'avec les réchauds à pétrole et les feux ouverts. Le débit de chaleur d'environ 400 watts est sensiblement inférieur à celui de ces sources classiques, mais, en dehors d'une période de réchauffement plus lente, le taux de cuisson est le même, parce que les températures sont égales à l'intérieur des ustensiles.

Mémoire S/100 de G.O.G. Löf et D.A. Fester

Une caractéristique de la cuisinière à concentration du type parapluie qui a une incidence sur son utilité est l'emploi d'un foyer diffus. L'intensité du rayonnement est assez uniforme sur toute la surface de cuisson, de telle sorte qu'il est possible de cuire directement les viandes et les autres aliments sur le gril, comme sur un feu radiant de charbon de bois. Une autre caractéristique est la légèreté et le petit volume de l'appareil, une fois plié, ce qui facilite le transport et l'entreposage.

Ce mémoire présente des mesures de la capacité de débit de la chaleur et du rendement à la cuisson. Des études du bilan calorifique montrent que le rendement du captage de l'énergie solaire est d'environ 27 p. 100 et le débit de chaleur à la surface du gril d'approximativement 400 watts par bon ensoleillement. On a pu obtenir une assez bonne évaluation des bilans calorifiques, encore que les propriétés optiques du réflecteur aient été mesurées par une nouvelle méthode photographique sans qu'il y ait eu chauffage effectif. Cette technique, qui utilise le clair de lune et du papier photographique, semble être une méthode très utile et très simple d'estimation des qualités d'un réflecteur.

Bien que cette cuisinière soit vendue dans le commerce, on ne dispose guère de renseignements provenant des acheteurs. Les rapports indiquent que le rendement a été satisfaisant pour la cuisson d'une grande variété d'aliments, mais les auteurs n'ont pas de renseignements sur l'utilisation quotidienne par des familles à revenu faible. Ils déclarent qu'il serait bon d'apporter certaines modifications à cette cuisinière si elle doit être utilisée régulièrement. Il s'agirait surtout de construire une armature permettant de supporter des récipients plus larges et empêchant l'appareil d'être renversé par le vent.

Les auteurs estiment qu'on pourrait réduire les coûts de fabrication, si la production portait sur des quantités plus grandes, et particulièrement dans les pays où ces cuisinières sont utilisées. Il serait possible, selon eux, de diminuer les coûts de la moitié ou des deux tiers.

Fours solaires

Mémoire S/101 de M. Telkes et S. Andrassy

Une amélioration particulièrement intéressante apportée à la conception des fours solaires est l'utilisation, pour l'armature du four, d'un panier tressé revêtu à l'intérieur d'une couche d'argile ou de plâtre. Les auteurs déclarent qu'il devrait être possible de réduire sensiblement les coûts au moyen de ce modèle et par la fabrication dans le pays d'utilisation. S'il suffisait d'importer des matières telles que les pellicules de matière plastique ou le verre, des tôles ou feuilles d'aluminium et les substances pour l'accumulation de la chaleur, on pourrait réaliser de très grandes économies. Toutefois, ce mémoire ne donne pas de chiffres de rendement, et la grande importance qui s'attache aux parois de four bien isolées limitera peut-être le choix et l'utilisation de matériaux du pays. Les auteurs concluent que le coût des fours solaires serait excessif, s'ils étaient fabriqués aux États-Unis et exportés à l'étranger.

Les auteurs proposent également de remplacer les miroirs réfléchissants en tôle d'aluminium ayant subi un traitement anodique par de la feuille d'aluminium plaquée sur un matériau rigide et peu coûteux du pays. La feuille serait revêtue d'un enduit protecteur transparent pour résister à l'oxydation. Le rendement d'une cuisinière fabriquée ainsi devrait se comparer aux modèles déjà évalués.

Les auteurs soulignent les avantages de l'accumulation de chaleur possible avec les fours solaires. Ils estiment que des mélanges de sulfates alcalins anhydres ont les meilleurs indices de rendement, même si leurs températures de transition sont aussi élevées que 190 à 240 °C. Comme les températures du four solaire, même lorsqu'il est vide, semblent ne pas dépasser 220 °C environ, il est douteux que cette substance d'accumulation thermique soit très efficace, à moins d'être utilisée dans le four vide pendant une période de préchauffage. L'accumulation d'énergie solaire pendant la cuisson semblerait exiger une phase de transition à une température plus basse, parce que la présence d'aliments dans le four abaisse la température maximale. L'utilité de cette matière d'accumulation pour maintenir les aliments chauds après la cuisson semble dépendre également du fait de savoir si l'accumulation de chaleur latente pendant le préchauffage est restée partiellement inutilisée après la fin de la cuisson, ou simplement s'il s'agit d'accumulation de chaleur sensible. Il serait intéressant d'avoir des données sur le rendement de cette cuisinière dans des conditions comparables, avec et sans l'élément d'accumulation de chaleur. Malgré cette limitation, l'emploi de l'accumulation avant que les aliments soient placés dans la cuisinière permettrait d'accélérer l'opération de cuisson proprement dite, même si la durée totale d'utilisation du four devait être beaucoup plus longue que la période de cuisson.

Le rapporteur est d'avis que des renseignements sur l'emploi du mélange de nitrates alcalins, avec un mode d'accumulation à une chaleur de fusion d'environ 155 °C, seraient très intéressants, parce qu'il semblerait que, dans cette gamme de températures, la chaleur pourrait être emmagasinée pendant l'opération de cuisson pour être libérée ultérieurement pendant une période de nébulosité ou après le coucher du soleil.

Une généralisation utile dans le cas du type de cuisinière utilisé par ces chercheurs est que si A représente la surface du vitrage à verre double et $3A$ la surface totale de captage de l'énergie solaire représentée par le vitrage et les réflecteurs, $1{,}9\ A$ serait à peu près la mesure du rayonnement pénétrant effectivement à l'intérieur du four. Sur cette énergie (à peu près 300 watts), la moitié environ chauffe les aliments si la température à l'intérieur du four est de 150 °C (pour une surface de vitrage de 0,19 m²).

Les résultats des essais de cuisson donnent le rendement effectif du four. D'après l'exposé qui figure dans le mémoire, l'appareil, avant que les aliments aient été placés dans le four, avait été préchauffé afin que l'effet de chaleur latente de la substance d'accumulation puisse être utilisé pendant la période de cuisson. La durée totale de fonctionnement du four serait donc plus longue que ne l'indiquent les résultats de l'essai de cuisson. Le taux de puissance instantanée du four relativement faible, environ 0,2 kW, semble être efficacement complété par le milieu d'accumulation thermique. La durée effective de cuisson semble comparable à celle de fours classiques.

Mémoire S/75 de M.S.M. Abou-Hussein

Les travaux rapportés dans ce mémoire avaient principalement pour but de comparer le rendement d'un four solaire muni de réflecteurs extérieurs à la vitre de verre (comme dans le mémoire S/101) et celui d'un four muni de surfaces réfléchissantes sous le verre. Les données qui figurent dans le tableau précédent portent sur le modèle muni de réflecteurs internes.

L'auteur fait valoir que les réflecteurs internes présentent plusieurs avantages, tels qu'une plus grande protection contre les dommages causés par une manipulation brutale, par des frottements et par le vent; de plus, ce modèle permet de capter davantage de rayonnements diffus puisque la surface de la vitre est plus large. Le rapporteur pourrait ajouter que la réflexion non-spéculaire des réflecteurs internes, qui constitue une fraction appréciable de la réflexion totale de l'aluminium, serait captée plus complètement à l'intérieur du four muni de réflecteurs internes. Toutefois, la surface vitrée plus grande a pour inconvénient d'accroître les pertes de chaleur.

Le mémoire présente des mesures du rayonnement total reçu à l'intérieur de ces deux modèles différents. On a enregistré des valeurs à peu près égales lorsque le rayonnement incident était presque entièrement direct, alors que l'appareil muni de réflecteurs internes avait un débit d'énergie supérieur d'à peu près 6 p. 100 lorsque le rayonnement était diffus à 30 p. 100. Cependant, comme l'auteur n'explique pas la méthode qu'il a employée pour mesurer le rayonnement, il n'est pas possible de porter un jugement sur ces chiffres. Le four à réflecteurs internes a atteint une température de 256 °C alors que l'autre cuisinière parvenait à un maximum de 248 °C, le four étant vide dans les deux cas.

Les données sur la vitesse de changement de température dans un four à réflecteurs internes vide après chauffage solaire montrent une baisse assez rapide de 218 °C à 155 °C en six minutes et à 118 °C en 17 minutes. Sans milieu d'accumulation thermique ou sans aliments à l'intérieur du four, le taux de pertes de chaleur par le large vitrage est élevé.

Il est difficile de porter un jugement sur ces résultats en l'absence de renseignements sur le rendement du four, comme par exemple le temps nécessaire pour chauffer une certaine quantité d'eau ou la vitesse de cuisson effective des aliments. La présence d'aliments ou d'eau modifie sensiblement les températures du four, et les comparaisons de modèles similaires n'auraient guère de valeur si l'on n'utilisait pas ces substances. Rien ne semble donc étayer la conclusion selon laquelle un four solaire muni d'un large vitrage et de réflecteurs internes est plus efficace que le modèle « classique » décrit dans le mémoire S/101. De plus, dans un four isolé, la plupart des pertes de chaleur se font par le vitrage. On peut donc penser que tripler la surface vitrée réduira la chaleur nette disponible pour la cuisson. Cette perte thermique additionnelle, qui est sans doute deux fois plus forte que dans un four à réflecteurs externes de surface égale, devrait plus que compenser les gains dus à un captage accru du rayonnement diffus. Il semble nécessaire de poursuivre les recherches sur les différences entre les deux modèles en procédant à des bilans énergétiques au cours du chauffage de quantités connues d'eau ou d'une autre substance.

Appareil combinant le cylindre parabolique et le four

Mémoire S/110 de A.S. Prata

Dans ce modèle intéressant, on utilise un petit réflecteur cylindro-parabolique pour concentrer le rayonnement solaire à travers un vitrage étroit en verre dans un four cylindrique bien isolé placé au-dessus du réflecteur. Cet appareil est essentiellement une cuisinière à four avec une surface de vitrage très petite pour réduire au minimum les déperditions de chaleur. La surface de captage de l'énergie solaire est légèrement supérieure à celle décrite par Telkes et Andrassy (S/101) soit 0,74 m^2 contre 0,56 m^2. Le débit net d'énergie aux aliments placés dans le four est plus élevé à cause de la surface plus large du collecteur et une moindre perte de chaleur.

Les mesures des températures et le calcul des transferts de chaleur ont été faits par l'auteur dans le cadre d'une évaluation du bilan thermique complet. Le rendement global de la conversion d'énergie solaire incidente en chaleur reçue par l'eau placée dans les récipients à l'intérieur du four était de 31 p. 100. A peu près 59 p. 100 de l'énergie frappant les deux réflecteurs cylindro-paraboliques pénétraient effectivement dans le four par le vitrage. L'auteur a constaté qu'une seule plaque de verre donnait le rendement le plus élevé. Les renseignements fournis par l'auteur sur divers aliments montrent des taux de cuisson très comparables à ceux obtenus avec des réchauds ou des fours classiques. La forme du four permettant d'introduire dans l'appareil deux récipients cylindriques, il est facile de cuire à la fois deux aliments différents.

L'auteur a comparé le rendement de son four-réflecteur à celui du four solaire « boîte fermée ». Il déclare que l'appareil combiné, avec une surface de captage de l'énergie solaire 55 p. 100 plus grande que celle du four qui lui est comparé, peut cuire 2,8 fois autant d'aliments. Il conclut donc que le four à réflecteur convergent est 1,8 fois plus efficace que le modèle « boîte fermée ». Le rapporteur met en garde contre une comparaison qui ne repose que sur la quantité d'aliments cuits, parce que le temps de cuisson doit aussi entrer en ligne de compte. De plus, une fois que les aliments ont été portés à la température de cuisson, il ne faut que de petites quantités de chaleur pour terminer la cuisson, quelle que soit, en pratique, la quantité présente. Des mesures comparatives du débit effectif de chaleur aux aliments contenus dans le four constituent le meilleur critère du rendement.

Un autre avantage de l'appareil combiné est la simplicité de sa construction, le cylindre à double paroi étant peu coûteux et facile à fabriquer. Toutefois, le réflecteur doit être de très bonne qualité, à cause de la nécessité de faire converger les rayons. L'appareil doit être ajusté presque aussi souvent que le paraboloïde si l'on veut maintenir le rendement maximal.

Le rapporteur désire insister sur un des termes du bilan thermique. La radiation de chaleur « à travers la fenêtre » a été obtenue par différence et l'auteur a observé certaines anomalies qu'il a attribuées à des variations de l'intensité solaire pendant les expériences. Comme cet élément est obtenu par différence, il est entâché d'erreurs expérimentales dans toutes les mensurations, et il y a lieu de s'attendre à des fluctuations de peu d'importance. Deuxièmement, en fait il n'y a pas de radiation de chaleur *à travers* la vitre. Toutes ces radiations émanent de la surface même du verre, qui est opaque aux longueurs d'onde infrarouge. C'est pourquoi une mesure ou une estimation de la température du verre permettrait de calculer directement les pertes par radiation. Le terme final du bilan thermique serait alors constitué par les pertes inexpliquées qui pourraient être décomptées séparément. Le rapporteur pense qu'il est peu probable que le rayonnement solaire ait varié dans des proportions aussi fortes que celles qui sont indiquées par les valeurs ajustées du tableau, particulièrement lorsque les valeurs semblent rester constantes dans le temps assez brumeux rencontré pendant l'expérience. Par exemple, durant le dernier quart d'heure de l'expérience, il ne semble guère raisonnable de prévoir 1,32 Langley (correspondant à des cieux extrêmement clairs), alors qu'on a mesuré une valeur de 0,825.

L'auteur estime que le rendement optique et le rendement du four sont tous deux faibles, et qu'ils pourraient être améliorés. Malgré cet avis, le rendement global qu'il rapporte (31 p. 100) semble aussi élevé que celui de n'importe quelle autre cuisinière étudiée à cette Conférence, et plus élevé que celui de la plupart d'entre elles. Il souligne aussi que si l'on utilisait des surfaces réfléchissantes ayant un coefficient de réflexion plus élevé (atteignant 0,80), le rendement global monterait presque jusqu'à 40 p. 100.

L'auteur conclut qu'avec le modèle actuel, les matériaux nécessaires à la construction de la cuisinière coûteraient environ 18 dollars et que la fabrication nécessiterait huit heures-ouvrier de main-d'œuvre. Le poids total est de 18 kilogrammes. L'emploi de l'aluminium permettrait de ramener le poids à environ 12 kilogrammes, mais, dans les conditions exposées par l'auteur, le coût augmenterait. Il conclut également que le four solaire du type « classique », avec une surface de captage de l'énergie solaire inférieure d'un tiers à peu près et n'ayant peut-être guère plus de la moitié de la capacité de cuisson, coûterait approximativement le même prix dans les circonstances du moment.

Le rapporteur est heureux de faire remarquer que ce nouveau modèle, encore simplifié et moins cher, présente certains avantages évidents par rapport tant au four solaire classique qu'aux cuisinières du type à concentration. Ce modèle est très prometteur pour la cuisson au four, qui emporte la préférence dans certaines parties du monde.

Comparaison des cuisinières convergentes et non convergentes

Mémoire S/116 de la Division de la nutrition, FAO

Pendant l'été de 1959, l'Organisation des Nations Unies pour l'alimentation et l'agriculture a expérimenté deux types de cuisinières solaires. L'une était l'appareil convergent, en plastique, pour l'essentiel le modèle 2 étudié dans le mémoire S/87 par Duffie, Löf et Beck. L'autre était un four solaire du modèle décrit par Telkes et Andrassy dans le mémoire S/101, mais probablement sans accumulation de chaleur.

L'expérience a consisté à mesurer le temps nécessaire pour chauffer deux litres d'eau de la température de la pièce au point d'ébullition dans chaque cuisinière pendant la plupart des jours de la saison d'été. L'eau était contenue dans des casseroles d'aluminium de huit pouces (20 cm) de diamètre et de 4 pouces (10 cm) de profondeur au cours d'une série d'expériences, et, pendant une autre série, dans des pots de terre de mêmes dimensions.

Les données détaillées ont été présentées sous forme de tableau dans le mémoire, mais, malheureusement, elles ne comportent pas de mesures du rayonnement solaire. Néanmoins, certaines remarques sur l'ensoleillement et les conditions atmosphériques permettent de tirer certaines déductions quant à ces facteurs. On a pu conclure des résultats d'environ 50 essais que le temps moyen nécessaire pour porter deux litres d'eau froide à ébullition dans la cuisinière à concentration était 41 minutes et dans le four, 112 minutes. Les temps les plus courts furent 30 minutes et 92 minutes respectivement. Lorsqu'on a utilisé les récipients en terre, les deux moyennes ont augmenté : 76 minutes pour la cuisinière à concentration et 142 minutes pour le four.

Ainsi qu'il ressort du tableau préparé par le rapporteur, le débit moyen d'énergie calculé d'après les chiffres ci-dessus indique que la puissance du four est de 0,1 kW et celle de la cuisinière à concentration de 0,28 kW. La puissance maximale a été respectivement de 0,12 et 0,38 kW. Les chercheurs n'ayant indiqué aucune journée parfaitement claire, on peut supposer que le rendement des deux appareils dans des conditions idéales serait légèrement meilleur que celui qui a été enregistré.

Les chercheurs ont obtenu les meilleurs résultats avec l'appareil convergent quand ils le réorientaient toutes les 15 à 30 minutes. Il n'était pas nécessaire de réorienter si souvent le four. Les effets du vent sur la cuisinière à concentration étaient plus accentués que sur le four, et une légère nébulosité avait un effet négatif plus faible sur le four que sur l'appareil convergent. On a jugé que l'appareil convergent était plus simple et s'entretenait plus facilement.

Bien que les études rapportées dans le mémoire de la FAO soient de portée limitée, elles servent à montrer, pour la première fois à la connaissance du rapporteur, la puissance nette relative de débit de ces deux systèmes dans des conditions d'utilisation identiques. On peut faire valoir que la vitesse de chauffage de deux litres d'eau ne définit pas complètement l'efficacité relative de la cuisson. Ces chiffres, néanmoins, indiquent dans les termes probablement les plus utiles, le taux relatif de chauffage de ces appareils. En outre, lorsqu'on fait bouillir, cuire à l'étouffée ou que l'on pratique toute autre forme de cuisson dans l'eau, et dans les cas où deux litres représentent à peu près le volume des aliments à cuire, ces chiffres montrent le temps approximatif à ajouter à la période normale d'ébullition pour évaluer la durée totale de la cuisson des aliments. Si par exemple il faut une heure d'ébullition pour un aliment donné, on peut estimer que dans des conditions favorables typiques, la cuisson d'à peu près deux kilogrammes (y compris l'eau ajoutée) prendra à peu près 1,30 h sur la cuisinière à concentration (modèle 2 du mémoire S/87), et à peu près 2,30 heures dans le four solaire.

Pour cuire au four, pour rôtir ou pour frire des aliments, les chiffres ne sont pas concluants, parce que chacun de ces deux appareils est assez uniquement adapté à l'un de ces modes particuliers de cuisson.

Observations complémentaires sur les comparaisons des fours solaires et des cuisinières à concentration

Un avantage du four solaire qui, aux yeux du rapporteur, semble avoir été exagéré est la réorientation moins fréquente et l'élimination de la nécessité de remuer les aliments. Toutes les cuisinières solaires doivent « suivre le soleil », mais la fréquence de l'orientation du four peut être moindre que dans le cas des appareils convergents. Cela signifie que pendant deux heures de cuisson le four devra être orienté de deux à quatre fois pour obtenir le meilleur rendement, alors que la cuisinière à concentration devra être ajustée six ou sept fois. Ce qui importe, pour ce qui est de la nécessité de remuer les aliments, c'est que la cuisson au moyen d'un réflecteur doit satisfaire un besoin qui est actuellement satisfait par la cuisson de surface sur un feu ouvert. Les aliments sont donc déjà remués pendant la cuisson, si cela est nécessaire, et, en fait, la cuisson solaire réduit un peu cette obligation parce que la source de chaleur est moins intense. L'expérience acquise dans la pratique montre que plus la cuisson solaire est adaptée aux traditions culinaires, plus les populations sont disposées à l'accepter. Remuer de temps à autre les aliments, en même temps que l'on réoriente légèrement le réflecteur, n'exige donc pas plus de temps de la part du cuisinier que les moyens classiques utilisés aujourd'hui; en fait, dans la plupart des cas, ces opérations prennent beaucoup moins de son temps.

Une autre caractéristique du four solaire est son aptitude à utiliser une partie du rayonnement diffus du soleil aussi bien que les rayons directs, alors que seul l'élément direct peut servir dans l'appareil convergent. Dans les régions où une brume atmosphérique ou une légère nébulosité réduisent ordinairement le rayonnement direct sans diminuer beaucoup le rayonnement total, le four donnera peut-être plus de chaleur que le paraboloïde. Cependant, dans la plupart des régions où l'on pourrait avantageusement utiliser la cuisson par énergie solaire, le ciel est ordinairement clair, et le captage du rayonnement diffus ne constituerait pas un avantage important du four.

Résumé et conclusions

Les mémoires présentés montrent que les recherches s'orientent heureusement dans deux directions. On y trouve premièrement des données quantitatives sur le rendement des cuisinières, tant en termes d'énergie débitée à des quantités mesurées d'une substance de référence (données calorimétriques), qu'en termes de temps nécessaire pour cuire diverses catégories d'aliments dans des conditions mesurées. Deuxièmement, les mémoires présentent les résultats fort importants d'études du rendement pratiquées dans les conditions normales d'emploi; au cours de ces enquêtes, les cuisinières ont été effectivement utilisées par des personnes ayant des revenus faibles qui pourraient devenir des utilisateurs permanents de cuisinières solaires vendues dans le commerce.

Les mémoires indiquent l'application possible de plusieurs modèles et les modifications possibles des cuisinières solaires. Le progrès technique a permis de beaucoup améliorer la plupart de ces appareils depuis leur conception. Certains appareils coûtent maintenant un peu moins cher, et leur rendement a été sensiblement amélioré.

Tous ces progrès ont un inconvénient : le coût initial élevé de ces cuisinières, compte tenu notamment de la faiblesse des revenus des utilisateurs possibles. Aucune des cuisinières construites ne semble satisfaire à la nécessité d'en réduire le prix au maximum à quelques dollars. On pourra peut-être le ramener à ce niveau, en utilisant largement les matériaux et la main-d'œuvre du pays. Toutefois, les résultats d'études approfondies montrent assez nettement qu'on ne saurait admettre de compromis quant aux normes de qualité si l'on veut éviter une baisse grave du rendement. Ces éléments opposés militent en faveur de la solution qui consiste à faire fabriquer ces cuisinières sous contrôle dans des usines du pays d'utilisation, employant au maximum de la main-d'œuvre locale et des matériaux locaux.

Même si l'on réussit à fabriquer le moins cher possible, le prix initial de ces cuisinières solaires dissuadera, ou même empêchera, de nombreuses personnes à faible revenu de les acheter. En conséquence, dès que, dans un pays ou dans une région, les ménages ont reconnu l'utilité d'une ou de plusieurs cuisinières solaires, qu'ils en admettent la nécessité et souhaitent les utiliser, il faut leur donner les moyens de se les procurer en accordant des crédits. Ce sujet complexe ne relève pas du présent rapport, mais il ne faut pas négliger cette nécessité. Cette possibilité d'améliorer le niveau de vie de populations qui sont le moins en mesure de profiter de ce progrès est assez grande pour qu'il soit justifié de l'étudier soigneusement. Les gouvernements se doivent de s'intéresser à cette question, ne serait-ce que parce qu'ils pourront ralentir l'épuisement de leurs ressources naturelles et, dans certains cas, être moins tributaires des importations de pétrole.

Il est évident qu'il convient d'accorder beaucoup plus d'attention aux essais pratiques des nouveaux modèles de cuisinières solaires. L'emploi satisfaisant d'une cuisinière solaire, dans des conditions de « laboratoire », par des techniciens ou même par des profanes instruits, ne garantit nullement que des familles à faible revenu accepteront et utiliseront cet appareil. Tout ce que l'on peut affirmer à cet égard est que si la cuisinière n'est *pas satisfaisante du point de vue technique* elle ne peut rendre de services; mais le contraire n'est pas nécessairement vrai. L'évaluation du rendement dans les conditions de vie absolument normales d'une famille est indispensable dans le cas des cuisinières solaires qui n'ont pas encore été soumises à cette épreuve. Bien que de nombreux renseignements de cet ordre aient été obtenus sur la cuisinière paraboloïde en plastique, il faut en rassembler davantage avant qu'on puisse prédire en toute confiance que les consommateurs l'accepteront. Et s'il doit y avoir probablement une certaine corrélation entre l'acceptabilité entre régions différentes et fractions différentes de la population, il faudra tenir compte dans chaque cas des traditions culinaires, du climat et du milieu économique et social.

D'un point de vue très général, il semble que les progrès soient encore hésitants, mais gros de promesses. Plusieurs cuisinières semblent capables techniquement de constituer un important appoint pour satisfaire aux besoins des populations dans les climats ensoleillés. Il est indispensable de réduire le coût initial si l'on veut que l'usage de ces cuisinières se répande largement, et il faut prévoir des moyens d'achat à crédit. L'évaluation des perspectives d'emploi exige de nouvelles expériences par d'importants groupes d'utilisateurs potentiels. Il semble souhaitable de créer des modèles nouveaux, de trouver des matières nouvelles et de renouveler les méthodes de fabrication, à la fois pour améliorer les rendements et pour abaisser les prix de revient.

Sujets de discussion proposés

Nombreux sont les sujets d'ordre général relatifs à la cuisson des aliments par l'énergie solaire qui méritent d'être étudiés et discutés, en plus de points particuliers soulevés dans les divers mémoires présentés à la Conférence. Citons ici certains sujets qui devraient susciter beaucoup d'intérêt :

a) Dans quelle mesure l'*emploi* de fours solaires et de cuisinières solaires du type convergent est-il interchangeable? Est-ce que la plupart des habitudes de cuisson et d'alimentation sont telles qu'il ne serait pas utile d'employer, par exemple, un four pour faire bouillir des aliments, ou un appareil à concentration pour cuire du pain?

b) Si l'on n'emploie pas indifféremment l'un ou l'autre type, dans quelles parties du monde chaque modèle a-t-il le plus de chances d'être utilisé par les groupes à revenus faibles?

c) Si l'on juge improbable que l'on puisse fabriquer des cuisinières solaires économiques d'une puissance de débit de chaleur net supérieure à 500 watts, est-ce là un élément qui doive en limiter beaucoup l'usage général? Est-il nécessaire, pour que les applications de l'énergie solaire soient satisfaisantes, d'obtenir la même puissance que celle fournie par les appareils de cuisine traditionnels, c'est-à-dire 1 000 à 2 000 watts?

d) Selon certains chercheurs, l'adoption des cuisinières solaires par les familles à faible revenu dans les régions sous-développées ne se fera que si ce nouvel appareil ne change pas essentiellement les habitudes de cuisson et d'alimentation de ces populations. Dans quelle mesure ce postulat est-il susceptible de modification?

e) Quel est le maximum de coût initial que l'on peut réellement admettre, si l'on veut répandre avec succès l'emploi de la cuisinière solaire? Dans quelle mesure peut-on espérer parvenir à ce prix de revient dans le cas des modèles actuellement à l'étude, et quel est le modèle qui semble offrir les meilleures chances de succès?

f) Dans quelle mesure peut-on espérer améliorer le rendement des cuisinières solaires actuellement mises au point?

g) Quelle importance présente l'accumulation de chaleur en matière de cuisson des aliments par l'énergie solaire? La capacité pour un four solaire d'emmagasiner 200 kilocalories de chaleur est-elle un facteur important de son emploi? L'utilité d'un four solaire est-elle diminuée par la nécessité du préchauffage si l'on utilise l'accumulation à température élevée? Serait-il souhaitable de fabriquer un type d'appareil d'accumulation de chaleur qui pourrait être employé avec le modèle de cuisinière à concentration, la chaleur latente servant ensuite à cuire les aliments après le coucher du soleil?

h) La possibilité de porter facilement et de plier l'appareil de cuisson est-elle une caractéristique importante de son emploi? Cette caractéristique peut-elle être le facteur déterminant du choix de l'appareil, si ses autres caractéristiques sont comparables à celles de l'appareil non portatif?

i) Quels sont les facteurs intrinsèques des cuisinières solaires du modèle convergent et des fours solaires qui peuvent limiter leurs dimensions?

j) Quels sont les prix de revient des fours solaires, tels qu'ils sont conçus aujourd'hui ou envisagés pour l'avenir? Quel est le maximum que l'on peut atteindre, dans la conception du four solaire, quant au rendement du réflecteur, aux caractéristiques de la fenêtre, et à l'isolement thermique? Quels principes spécifiques peut-on fixer pour la construction des fours solaires et quelles sont les meilleures mesures du rendement? La température maximale obtenue dans un four vide est-elle une mesure utile de la qualité de ce four? Quelles conclusions peut-on tirer quant aux avantages relatifs des réflecteurs internes et externes?

k) Quels sont les critères importants qui doivent régir la conception des cuisinières solaires du type à concentration, et comment peut-on le mieux juger de la valeur de ces appareils? Dans quelle mesure les caractéristiques des récipients de cuisson influencent-elles le rendement apparent des cuisinières et comment peut-on tenir compte de ce facteur lors de l'analyse du rendement?

l) Quels sont les facteurs sociologiques les plus importants qui interviennent en matière d'emploi des cuisinières solaires, par exemple la mesure dans laquelle les populations accepteront de changer leurs habitudes, la mesure dans laquelle on peut utiliser ces cuisinières dans les régions où les populations sont disposées à les accepter, les effets secondaires qu'aurait leur utilisation sur une grande échelle, tels que le travail du ramassage du combustible et l'emploi d'engrais, et la nécessité d'apprendre aux populations à se servir d'appareils mécaniques?

m) En matière d'expériences pratiques, quelles sont les réponses aux questions suivantes : quel est le nombre de personnes, de lieux et de jours nécessaires pour obtenir de bons résultats? Quelle est la valeur relative des démonstrations par comparaison avec l'emploi régulier dans le ménage? Quel effet a la présence d'un observateur sur la validité des résultats? Dans quelle mesure faut-il former les utilisateurs?

n) Comment les familles à faible revenu peuvent-elles envisager un investissement même modeste pour l'achat d'un type quelconque de cuisinière solaire?

o) Les gains qu'il serait possible d'obtenir en matière de protection des ressources naturelles grâce à un usage très répandu de la cuisson par l'énergie solaire justifient-ils que les gouvernements soutiennent les expériences de cuisson solaire et financent l'achat des cuisinières?

p) Quels avantages présente l'utilisation possible de cuisinières solaires de très grandes dimensions, non seulement pour la préparation des repas, mais aussi en tant que petite source de chaleur pour la maison quand elles ne sont pas utilisées pour la cuisson des aliments? Quelle augmentation de coût pourrait-on accepter si l'on pouvait ainsi accroître l'utilité d'une telle source de chaleur?

q) Parmi toutes les cuisinières solaires examinées à cette Conférence ou étudiées antérieurement, en est-il une qui semble posséder des avantages remarquables qui permettraient d'envisager une application générale? Dans quels pays ou dans quelles régions cette possibilité d'utilisation existe-t-elle, et par quel moyen peut-on l'évaluer avec assez de certitude?

USE OF SOLAR ENERGY FOR HEATING PURPOSES: SOLAR COOKING

Rapporteur's summation

In reviewing the papers and discussions on solar cooking (agenda item III. C. 4), it is desirable that we be reminded of the principal requirements for the successful use of a solar cooker in an under-developed area. These may be summarized as follows:

(*a*) The unit must cook foods effectively; it must therefore provide energy at a sufficient rate and temperature for the desired quantity of food.

(*b*) It must be sturdy enough to withstand rough handling, wind, and other hazards.

(*c*) It must be sociologically acceptable and fit in with the cooking and eating habits of the people.

(*d*) It must be possible for the user to obtain a cooker at a sufficiently low cost for him to make financial savings by its use.

The current status of solar cooker development may be summarized by reference to the preceding general report on this subject, supplemented by the further discussions at the Conference. Upwards of two dozen variations of workable solar cookers have been made, eight of which have been described at the meeting. Several modifications of the focusing type for surface cooking, and two types of solar heated ovens for baking have been described. Concentration ratios have ranged from 3 to about 35. Performance data are available on most of these units. The heat delivery covers a range of 150 to 400 watts, corresponding to the heating of one litre of cold water to the boiling point in 15 to 40 minutes.

Extensive field testing results are available for the rigid plastic paraboloid cooker, in a fuel-scarce region of northern Mexico. Another focusing type, a portable umbrella-like unit, is in commercial production and is being sold in the United States. Of the two cookers produced in sizable quantity, costs (in small-scale production) are about $15. Reduction in this figure appears possible, especially with factory production and the use of native materials in under-developed countries. New designs may reduce the costs further. A Fresnel-type segmented reflector cooker has interesting possibilities along this line.

The needs for solar cooker development and application have been amply cited. In short, they are the result of the scarcity of cooking fuels in many regions, their high cost, and their wasteful use. Although cooking requires only a very small portion of the world's energy consumption, the aggregate individual and family impact of substantial cooking fuel replacement in under-developed areas could be great. Major benefits could be derived from the use of dried animal wastes for fertilizer rather than fuel, conservation of trees and other ground cover, and the reduced outlay of limited funds for fuel purchases.

Although at least one or two cookers, and possibly others, appear to meet the needs, the present costs of about $15 are too high for the average user in the areas of greatest usefulness. Hence, there should be further determined efforts to reduce manufacturing costs. Effective measures may comprise material substitutions, design simplifications, labor reduction, mass production, and the use of locally available materials and labor. When fully proven, from technical and economic standpoints, it then will probably be necessary to provide some sort of credit arrangement for individual and family purchases of solar cookers.

On the developmental side, it is essential that a high thermal output be achieved. Experience shows that a marginal output cannot succeed. It appears that about half a kilowatt of heat delivery capacity should be provided. Sturdiness and long life must also be assured. Continued effort in developing new designs and materials, several of which have been reported at the Conference, for the first time, appears highly desirable.

From the sociological standpoint, the cooker must fit the cooking techniques and schedules of the people using it. This point has been heavily stressed by several speakers. It is possible it has been overstressed, because there is a danger that technical inadequacy in a particular cooker may be blamed on some social factor or other. It is my contention that a cooker of eminently sound design and modest cost will succeed in many areas of the world, where customs do not have to be extensively modified. Notice the immediate acceptance of electricity in developing areas — and the substitution of tractors and diesel pumps for horses and human power. These are probably even greater social revolutions than solar cooking will be. I do not mean that the social factor is not important in solar cooking development, but I caution against mistaking a technical failure for a social rejection.

Another subject demanding further study is the storage of day-time heat for delayed cooking, even into the evening. Methods have been suggested, and tested to a limited extent, but it appears that the demand for this feature has not been well assessed, and that heat storage systems have not been adequately developed. Both phases of this problem warrant attention.

It was recommended that consideration of the use of solar cooking in a particular area involve the following procedure :

(*a*) Survey the type of cooking done, the time of meal preparation, and related cooking and eating customs.

(*b*) Select an existing cooker, or design and develop one, to meet the particular requirements.

(*c*) Conduct extended experimentation and field testing or trial use, under natural conditions.

(*d*) After successful conclusion of the above steps, consider sources and means for commercial supply.

It was urged by one speaker that it should be recognized that the criterion of acceptability or excellence of a design should not be on a basis of total heat output, or heat output per unit area, but rather on the ratio of efficiency to cost. More properly, this ratio should be net thermal output or useful heat delivery per unit of cost. At equivalent levels of convenience, durability, and such factors, the best cooker would show the maximum value of this ratio.

In an over-all view, solar cooker development appears to have reached a point where practical application is imminent. Several cookers appear technically capable of supplementing, to a substantial extent, the cooking needs of peoples in many climates. Reductions in equipment cost are prerequisite to large utilization, and means for credit purchase seem to be needed. Appraisal of use prospects requires further field testing by large groups of potential users. New designs, materials, and fabricating techniques appear desirable, both for achieving better performance and for lowering costs of manufacture.

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : CUISINIÈRES SOLAIRES

Résumé du rapporteur

Il y a lieu, en analysant les mémoires qui ont été présentés et les discussions qui ont eu lieu sur les cuisinières solaires (point III.C.4. de l'ordre du jour), de garder présentes à l'esprit les conditions principales de succès de l'emploi d'une cuisinière solaire dans une région sous-développée. Ces conditions sont, en quelques mots, les suivantes :

a) L'appareil doit cuire les aliments efficacement; il doit par conséquent fournir de l'énergie avec un débit et à une température suffisants pour la quantité d'aliments voulue;

b) Il doit être assez robuste pour résister aux manipulations brutales, au vent, etc.;

c) Il doit être acceptable du point de vue sociologique et être adapté aux habitudes culinaires et diététiques des populations;

d) L'usager doit pouvoir se procurer une cuisinière solaire à un prix assez bas qui lui permette de réaliser une économie.

On peut avoir une idée d'ensemble de la situation en ce qui concerne les cuisinières solaires en se référant au précédent rapport général sur le sujet complété par ce qui a été dit en séance. Plus d'une vingtaine de cuisinières solaires de types divers capables de fonctionner ont été construites et huit d'entre elles ont été décrites au cours de la séance. On a également décrit plusieurs variantes de la cuisinière parabolique à plaque et deux types de fours solaires. Les rapports de concentration des rayons solaires vont de 3 à environ 35. On peut en général se procurer les caractéristiques de ces appareils. Le débit de chaleur varie entre 150 et 400 watts et permet de porter un litre d'eau froide à ébullition dans un temps variant de 15 à 40 minutes.

On connaît les résultats de nombreuses expériences sur la cuisinière paraboloïde en matière plastique rigide effectuées dans une région pauvre en combustible du nord du Mexique. Un autre appareil parabolique portatif ayant la forme d'une ombrelle est fabriqué en série et vendu aux États-Unis. Chacune des deux cuisinières construites en assez grand nombre (petite série) coûte environ 15 dollars. On doit pouvoir abaisser ce prix notamment par la production en série de ces appareils et l'emploi de matériaux locaux dans les pays sous-développés, et peut-être aussi par la mise au point de modèles nouveaux. Une cuisinière à réflecteur segmenté du type Fresnel offre à cet égard d'intéressantes possibilités d'emploi.

On a très souvent parlé de la nécessité de mettre au point et de construire des cuisinières solaires. Cette nécessité tient, en quelques mots, à la pénurie de combustibles dans de nombreuses régions, à leur prix élevé et au gaspillage qu'on en fait. Bien que l'énergie utilisée pour la cuisson ne représente qu'une très petite fraction de la consommation totale d'énergie dans le monde, la substitution, dans une mesure appréciable, de l'énergie solaire au combustible normalement utilisé pour la cuisson des aliments par les particuliers et les familles dans les régions sous-développées pourrait avoir des conséquences notables. C'est ainsi que l'utilisation des excréments desséchés des animaux comme engrais plutôt que comme combustibles, la conservation des arbres et de la végétation et la diminution des crédits déjà limités destinés à couvrir l'achat de combustibles seraient extrêmement avantageuses pour ces régions.

Si une ou deux cuisinières au moins, et quelques autres peut-être, semblent correspondre aux besoins, leur prix actuel (environ 15 dollars) est trop élevé pour l'usager moyen des régions où ces appareils pourraient être le plus utile. Il faut donc redoubler d'efforts pour réduire les coûts de fabrication. L'emploi de matériaux nouveaux, la simplification des modèles, la diminution du temps de façon, la production en série et l'utilisation de matériaux et de main-d'œuvre locaux seraient notamment des mesures efficaces. Une fois que la fabrication sera justifiée du point de vue technique et économique, il faudra probablement prévoir des mesures de crédit afin que les particuliers et les familles puissent acheter des cuisinières solaires.

En ce qui concerne la mise au point, il est essentiel d'obtenir un rendement thermique élevé. L'expérience montre qu'un rendement passable ne garantit pas le succès. Il faudrait arriver, semble-t-il, à un débit thermique d'environ 0,15 kilowatt. L'appareil doit également être robuste et durable. Il paraît très souhaitable de poursuivre les efforts de mise au point de modèles et de matériaux nouveaux, dont plusieurs ont été signalés à la Conférence pour la première fois.

Du point de vue sociologique, la cuisinière doit être adaptée aux techniques et aux habitudes culinaires de l'usager. Plusieurs orateurs ont fortement insisté sur ce point. Il se peut cependant que son importance ait été exagérée, car on court toujours le risque d'imputer à un facteur ou à un autre les défauts d'un appareil particulier. J'estime pour ma part qu'une cuisinière bien conçue et d'un prix abordable connaîtra le succès dans de nombreuses régions du monde, où il n'y a pas lieu de modifier sensiblement les coutumes. Je n'en veux pour preuve que le fait que l'électricité a été acceptée immédiatement dans les régions en voie de développement, comme l'a été la substitution du tracteur et de la pompe Diesel au cheval et à l'énergie humaine. Ce sont là probablement des révolutions sociales encore plus grandes que ne le sera la cuisson solaire. Loin de moi la pensée que le fait social ne joue aucun rôle dans le développement de la cuisson solaire, mais je tiens à mettre le public en garde contre l'erreur qui consiste à prendre un échec sur le plan technique pour un refus sur le plan social.

La conservation de la chaleur accumulée pendant la journée aux fins d'une cuisson ultérieure, même le soir, est une autre question qui demande à être étudiée plus avant. Quelques techniques ont été proposées, et expérimentées dans une certaine mesure, mais il apparaît que la demande dans ce domaine n'a pas été bien évaluée et que les systèmes de conservation de la chaleur ne sont pas au point. Ces deux phases d'évaluation et de mise au point justifient qu'on s'intéresse au problème.

On a recommandé de suivre, pour étudier l'utilisation de l'énergie solaire en vue de la cuisson dans une région donnée, la procédure ci-après :

a) Étudier le type de cuisson effectuée, la durée de préparation des repas et les autres coutumes culinaires et diététiques;

b) Choisir une cuisinière, ou en concevoir et en mettre au point une qui soit capable de répondre aux besoins des usagers intéressés;

c) Expérimenter longuement et mettre à l'épreuve ou à l'essai, dans des conditions normales d'utilisation, les appareils en question;

d) Étudier les moyens de production commerciale.

Un orateur a demandé instamment de ne pas admettre que le critère de convenance ou d'excellence d'un modèle soit établi en fonction du rendement thermique total ou unitaire (rendement par unité de surface), mais bien en fonction du rapport rendement-prix. Plus précisément, ce rapport devrait être le rendement thermique net, c'est-à-dire le débit thermique utile par unité de coût. A niveaux équivalents de commodité, de durabilité et d'autres facteurs de ce genre, la meilleure cuisinière serait celle qui donnerait le rapport maximal.

Dans l'ensemble, la mise au point de la cuisinière solaire semble avoir atteint un stade où son application pratique est imminente. Plusieurs appareils paraissent bons, techniquement, pour fournir un appoint substantiel aux besoins des habitants des régions ensoleillées. Une diminution du prix d'achat est indispensable si l'on veut généraliser l'emploi des cuisinières solaires, et des mesures de crédit à l'achat sont, semble-t-il, à prévoir. Pour évaluer les perspectives d'emploi, il faut faire expérimenter encore les appareils par des groupes nombreux d'usagers éventuels. Il paraît souhaitable de mettre au point des modèles, des matériaux et des techniques de fabrication nouveaux, tant pour améliorer le rendement que pour abaisser le coût de fabrication.

TEMPERATURE-DECAY CURVES IN THE BOX-TYPE SOLAR COOKER

M. S. M. Abou-Hussein *

History of the box-type solar cooker

Calver, in 1899, used a heat insulated box housing a flat oven on which the solar energy fell reflected by plane mirrors through the oven glass doors (1).

Baker, in 1901, used a series of pivoted mirrors supported on an external adjustable stand to reflect solar energy to the oven (2).

De la Garza, in 1902, made use of lenses to concentrate solar radiation to the cooking pot (3). The lenses and the pot were moved to follow the sun. Boone used the same principles (4).

Chevrier, in 1915, designed a moderate temperature solar oven with rays admitted to the box through glass panes (5).

Several other cookers have been patented during recent years in Japan by Sugimoto (6), Watanabe (7) and Goto (8), and in India by Ghai (9).

Telkes uses heat insulated solar boxes with a glass window through which is reflected, using plane reflectors making 60° with the window plane, direct solar energy (10). The reflectors themselves receive solar radiation at 30° incidence. The percentage of solar radiation flowing through the glass window and reaching the stove through two glass panes amounts to 180 per cent for glass reflectors with intercepting areas equal to double the glass window area.

Solar oven

In this design, four aluminium reflectors of total areas of about 5150 cm^2 were placed inside the oven making a 60° angle with the 2-pane glass window as shown in figure I. The plane *aa* area is about 900 cm^2. The glass used was water-white, 3 mm thickness, and one cm air-spaced. The pot, of the appropriate shape, was made of copper of about 0.25 mm thickness or less. The inner surface of the oven round the pot was inclined to concentrate all reflected rays on the pot. The insulation was glass wool 10 cms thickness.

By this design we have:

(*a*) The solar energy intercepting area of the four reflectors is about three times the area of plane *aa*.

(*b*) The reflectors are weather-proof but neither light nor heat proof.

(*c*) The heat loss between the hot pot and the heated metal reflectors inside the oven is less than the corresponding value between the pot and the less heated insulated walls of the oven in case the metal reflectors are outside the oven; this is of course true assuming equality of oven volume and its contents including wall areas in both cases, and also with the two ovens having the same nature of materials.

(*d*) The indirect solar radiation reaching the oven is increased with this design because its glass window area receiving this radiation is about four times that of the oven with outside reflectors.

(*e*) The reflectors are enclosed inside the oven and so are less subject to mishandling than when they are outside.

(*f*) The heat-dissipation area inside this furnace is greater than the corresponding area with outside reflectors.

(*g*) A part of the heat reaching the inside of the oven is used to heat the reflectors themselves.

(*h*) Difficulties due to rotation with the sun exist with reflectors inside or outside the oven.

Experiments were then conducted on two ovens with almost identical dimensions of : reflectors, pots, insulating materials and air space between the inside oven walls and the plane *aa*. One oven however, had its reflectors inside and the other outside.

The number of glass panes in each type was two, with one cm air spacing, and the reflectors were made of highly polished aluminium.

Some results are given below:

Table 1. Per cent of total solar radiation at plane aa = R_{aa}; per cent incident radiation at plane bb = 400 R_{aa}

Per cent direct solar radiation	*Per cent of total solar radiation at plane aa = R_{aa}*	
	Reflectors outside	*Reflectors inside*
70	198	210
80	192	202
90	206	214
95	230	237

The increase in the value of the percent total solar radiation at plane aa in the inside-reflector type compared with the outside-reflector type is pronounced at higher percent values of indirect radiation. This is due to the increased value of this indirect radiation in the inside-reflector type by its increased glass window area.

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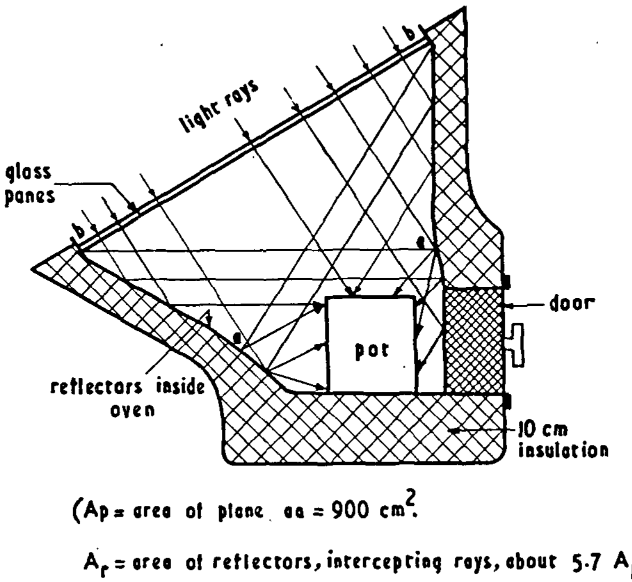

Figure 1a. Solar oven with reflectors inside

Tests on the black plate temperature in both ovens were made, and the results are given in table 2.

Table 2. Black plate temperature
(2 glass panes, 10 cms insulation, aluminium reflectors)

Reflectors outside oven		*Reflectors inside oven*	
Sun radiation btu/sq ft hr	*Temp °C*	*Sun radiation btu/sq ft hr*	*Temp °C*
280	248	280	256

Heat necessary for cooking

Most foods have nearly unity specific heat. It is known that about 150 btus are needed to boil one lb (0.445 kgm) of water from about 22°C in a covered pot.

A solar oven with a solar energy intercepting area equal to A square feet and with an over-all efficiency, at working conditions, of η will receive the following amount of solar radiation per hr:

$$R_o = R_i \eta A \text{ btu/hr}$$

where : R_i is the incident (or input) solar radiation on one square foot area of oven per hr. It follows that the weight of food cooked per hr under assumed conditions will be:

$$R_i \eta A/150 \text{ lb/hr}$$

As an example, if the sun radiation R_i is 300 btu/sq ft hr and the area A is one square foot, $\eta = 0.5$ then the weight of the food cooked per hr will be:

$$\frac{300 \times 0.5 \times 1}{150} = \text{one lb/hr or } 0.445 \text{ kgm/hr}$$

This weight can be increased with higher values of efficiency.

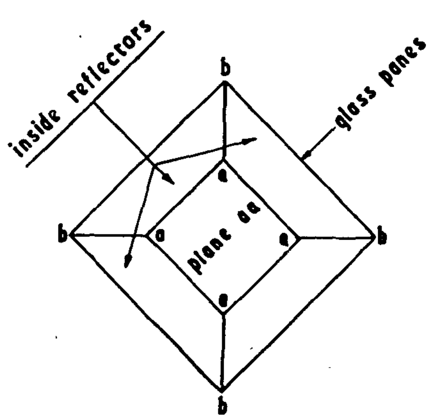

Figure 1b. Reflectors view in rays direction

Heat storage

Heat stored inside the oven is important since it indicates the accumulated heat that can be used later to speed cooking during the intermittent cloudy periods or after sun set.

Heat may be stored as latent heat of fusion or as specific heat.

If heat is stored as of fusion, then this requires a liquid tight container. Also the dripping and waste of the heat storage material should be avoided. The materials must be cheap and easily obtainable.

The heat of transition of solids may be used. Heat is stored in some materials as sensible heat and their heat of transition as latent heat. A mixture of sulphates of potassium, sodium and calcium may be used with ratios determining the transition temperatures between 191°C to 239°C.

In this respect a curve with the black-plate temperature as ordinate and time as abscissa with the oven subjected to solar radiation for some time and then removed to a place with no direct radiation, will indicate:

(*a*) The behaviour of the oven during cloudy periods or after sun set.

(*b*) The rate of heat gain during the presence of the oven in the sun light, which is equal to the slope of the curve during this interval.

(*c*) The rate of heat loss after the removal of the oven to a place with no direct radiation is equal to the slope of the curve during this period.

(*d*) The possibility of the short-term heat storage which may have the rate of heat loss as a measure.

(*e*) The stability of operation of the oven depends on both the rate of heat gain and heat loss.

Such a curve was plotted for an oven with reflectors inside and the results are given in table 3 and curve drawn in figure 2.

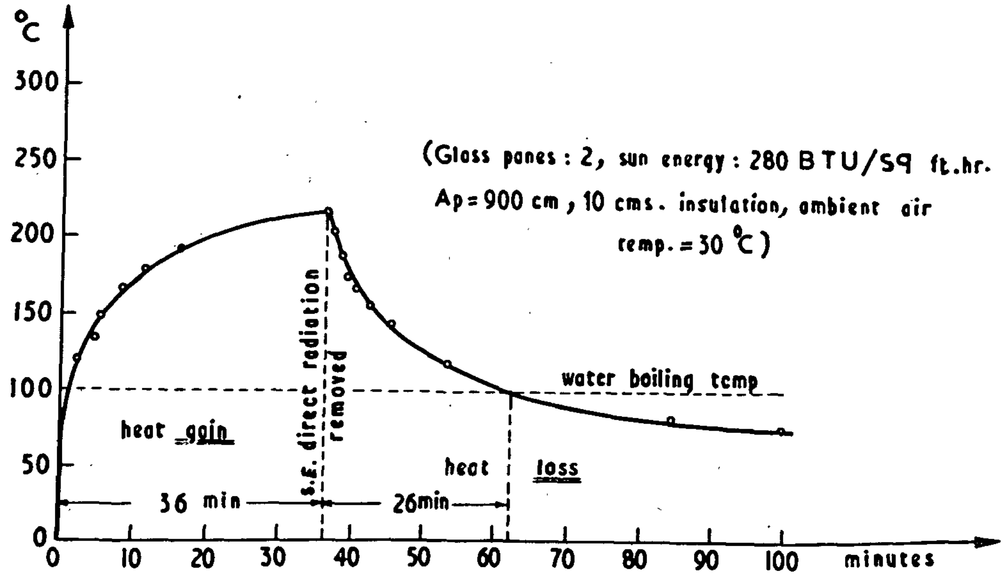

Figure 2. Temperature-decay curve of box-type solar oven

Some economical and sociological aspects and suggested improvements

An estimate is made for the price of a solar oven of solar energy intercepting area of 5 150 cm² and with aluminium reflector inside the oven; the cooking pot is made of thin copper. The estimate comes nearer to £8 (Egiptian) or about U.S. $18.2. Such an oven is capable of cooking about 5.7 lb of foods per hr under conditions assumed above.

Table 3. Temperature-decay curve

(Lat. 30° north, glass panes 2, sun rad. 280 btu/sq ft hr glass panes tilt 30° with horizontal, 7.5 cm insulation, reflectors intercepting area *twice* area of plane *aa*)

Time after first placing oven in sun, minutes		*Black plate temperature °C*
0	Heat *gain* (temp rise)	30
1		100
2		119
3		132
5		150
8		167
11		180
16		191
36		218
Removal of sun direct radiation		
37	Heat *loss* (temp decay)	205
38		187
39		177
40		167
42		155
44		144
53		118
84		80

Although this oven proves very inexpensive and cannot be compared with the high cost paid for the electric or gas cookers, it cannot find its way to public use to any considerable extent. This is probably due to some traditions of employing vegetable and animal refuse as fuels in villages. Cotton-stalks, corn-cobs and dried animal dung form the major fuels used at present in cooking and baking. At the same time, the ovens used are considered as sources of heating the house.

If an easy method is employed to make the whole oven follow the sun, then this may considerably increase the efficiency of the oven and probably spread its use and improve the heat stage.

Conclusions

An inexpensive solar oven with inside reflectors may be used. It is capable cooking about one pound of foods per hr per one square foot solar energy intercepting area. This weight of cooked food can be increased for oven efficiencies higher than 50 per cent.

A temperature-decay curve is essential to know the degree of the operation of the oven stable without direct radiation incident on the oven glass window.

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Summary

The reliability of the operation of the box-type solar cooker depends, amongst other factors, on the rate of heat gained in the sun and the rate of heat lost during cloud presence and after sun-set. A curve expressing the black plate temperature, under the assumed conditions, as ordinate and the time from first placing the cooker in the sun, as abscissa is called the temperature time curve. If the temperature is increasing, it is the temperature-rise time curve; but if it is decreasing it is the temperature-decay time curve or simply the temperature-decay curve.

In this paper the temperature-decay curve of a solar oven of the box-type is found. The oven itself has all its plane reflectors inside.

It is shown that the temperature-decay curve can be taken as a measure of the initial heat stored, the rate of heat gain or loss, the suitability of the thermal insulation, the possibility of the short term heat storage and the stability of the operation of the cooker.

Other performance characteristics of this new solar oven with all plane reflectors inside are given showing a slight increase in the black-plate temperature from the corresponding oven with outside reflectors. This is due probably to the increased indirect solar radiation. This is absorbed in the new type due to its increased glass window area.

Some economical and sociological factors are given indicating the cheapness of the oven as well as the difficulty of using the oven amongst the inhabitants of undeveloped countries, due to some traditions.

Technical improvements relating to minimising the rate of temperature decay or increasing the time of short-term heat storage are suggested.

COURBES INDIQUANT LE RÉGIME DE LA BAISSE DE TEMPÉRATURE DANS LES FOURNEAUX SOLAIRES DU TYPE A ENCEINTE FERMÉE

Résumé

La régularité de fonctionnement des fourneaux solaires du type à enceinte fermée est conditionnée, entre autres, par le régime d'acquisition de la chaleur pendant l'exposition au soleil et le régime de perte de chaleur en présence de nuages et après le coucher du soleil. On peut tracer une courbe dite « température/temps », qui donne en ordonnée la température d'une plaque noire dans les conditions admises pour l'expérience, et en abscisse le temps écoulé depuis la mise de l'appareil au soleil. Si la température augmente, la courbe est donc une courbe qui donne le régime de la montée de température mais, si elle descend, il s'agit d'une courbe de baisse ou de dégradation de la température.

Dans le présent mémoire, on examine la courbe qui donne le régime de la baisse de température pour un fourneau solaire du type boîte. Tous les réflecteurs plans sont intérieurs au fourneau.

On démontre que la courbe de baisse de température peut être considérée comme étant une mesure de la quantité initiale de chaleur mise en réserve, du régime d'augmentation ou de perte de chaleur, de la valeur du calorifugeage, de la possibilité d'une mise en réserve de la chaleur à court terme, et de la stabilité de fonctionnement du dispositif.

On donne également les caractéristiques de rendement de ce nouveau fourneau solaire. Elles révèlent une légère augmentation de la température de la plaque noire par rapport aux valeurs que l'on trouve pour un fourneau dont les miroirs ou réflecteurs sont à l'extérieur. Ceci s'explique probablement par l'augmentation du rayonnement solaire indirect. Celui-ci est absorbé, dans le nouveau type, en raison de l'augmentation de la surface qu'occupent les fenêtres en verre.

L'auteur donne certaines considérations économiques et sociologiques, desquelles il ressort que le four est d'un prix modique, mais qu'il est assez difficile de le mettre en œuvre dans certains pays sous-développés, eu égard aux coutumes de la population de ces pays.

Des améliorations d'ordre technique, ayant trait à la réduction au minimum de la baisse de température, ou à l'augmentation de la durée d'emmagasinage à court terme, sont recommandées.

LABORATORY AND FIELD STUDIES OF PLASTIC REFLECTOR SOLAR COOKERS

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Cooker design

Laboratory and field studies of reflective-type solar cookers have been in progress for several years; the results of these studies are summarized in this paper. Reflective-type cookers utilizing 48-inch aperture, 18-inch focal length molded plastic reflectors, mounted on frames adjustable in altitude and azimuth, have been used in these experiments. Two basic mounting frames have been designed and used, as shown in figures 1 and 2. The reflectors and mounting designs will be discussed below; they have evolved from laboratory studies and from results of field experience by anthropologists.

The reflective-type cooker is particularly well suited to operations of boiling, stewing, and other wet cooking. It can, with the use of metal plates of good conductivity to distribute the energy over the cooking surface, be used for frying. It can also be adapted to baking by the addition of an insulated oven over the pan support. Like any other reflective solar exchanger, proper use is mandatory if adequate energy delivery is to be achieved; with proper use these cookers can deliver a maximum of 600 watts, depending on beam radiation intensity and the condition of the reflector.

Cooker designs

The reflectors used in the solar cookers are fabricated of plastics (2). Recent models use a drape-formed high impact polystyrene shell of a thickness of 0.060 inches, stiffened at the rim with a ring of thin-wall aluminum tubing of about one-half inch diameter. These shells are light in weight, are sufficiently stiff to retain their shape, and are resistant to damage by bending. They are readily formed in the compound curvatures required by simple forming techniques.

A reflective lining of aluminized Mylar polyester film is applied to the shells with an adhesive, so that the clear film forms a protective covering over the specular surface. The new-condition specular reflectivity of this material is in the range of 75 to 80 per cent; the reflectivity decreases with time at a rate dependent on film weathering and deterioration. This reflective material has the advantage of good protection of the reflective surface and easy cleaning of the chemically inert polyester film, and relatively simple replacement of the lining. However, it must be emphasized that the best expected life of this reflective material on reasonably regular use is about two years, and while it is convenient and useful in the research programs, more durable reflecting materials are considered necessary for successful long-time, low-cost use.

The cooker design has evolved through several stages, the earliest of which was devised by D. Dunham, (1). The first model subjected to extensive study was similar to that of figure 1, but with lighter construction and a 42-inch aperture reflector; it is designated as Model 1. The cooker of figure 1 is designated as Model 2. The basic feature of these two models, other than the use of plastic reflectors, is a frame constructed of thin-wall tubular steel, formed so that the portion to which the reflector rim is secured is an arc with its center on the horizontal line of support of the reflector. This permits a simple sliding ring adjustment for solar altitude. Azimuth adjustment is achieved by pivoting the whole frame on a peg set in the ground or on a cross-stand. The reflector is pivoted about a horizontal axis at the pan support (the "grid"); this general arrangement has the advantage of providing support for the pan independently of motion of the reflector.

Model 3 of the Wisconsin cooker, a 1960 development by W. W. Schaerff, is shown in figure 2. It

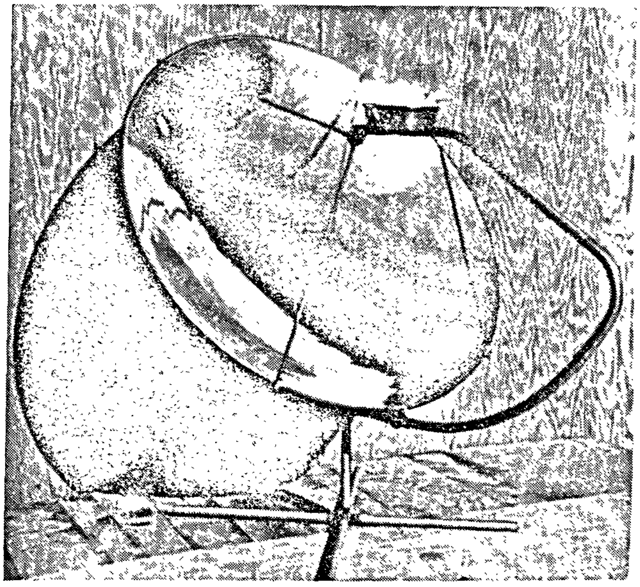

Figure 1. The Model 2 Wisconsin Solar Cooker. Reflector aperture 48", *focal length 18"*

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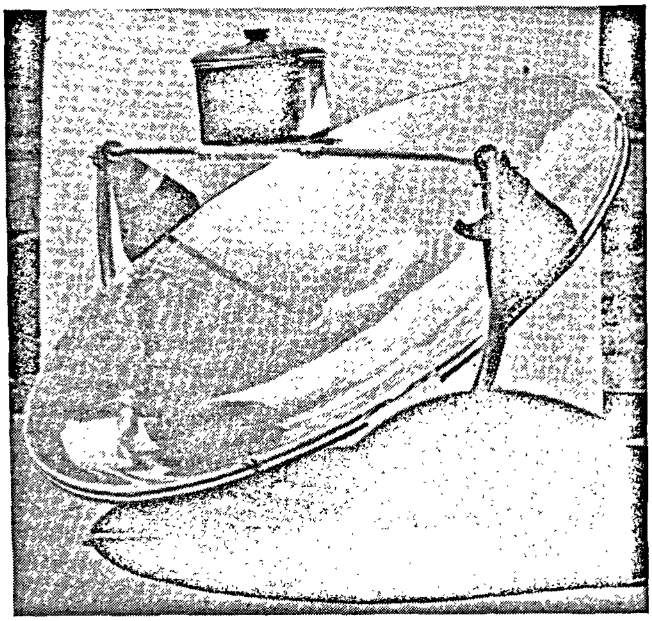

Figure 2. The Model 3 Wisconsin Solar Cooker

is similar to the earlier models in having adjustments for solar altitude and azimuth. However, the azimuth adjustment and vertical stability are provided by two spun discs at the base which fit one within the other and turn with respect to one another; this results in a much lower and more stable cooker. Adjustment in altitude is provided by a locking device on a sector attached to the reflector, and the grid is supported from each side for additional stability. The frame members of this cooker are of thin-wall steel tubing and 19-gauge sheet metal formed by stamping or (for the base discs) spinning.

The reflectors and frames of these cooker models are of simple construction, fabricated by standard techniques of readily available materials, and no great degree of precision of manufacture is required. Standard metalworking shops would be capable of the welding, brazing, forming and spinning operations required for the frames. Model 3 was specifically designed with the object of widely available materials and inexpensive, easily reproduced forming operations.

The major design criteria leading to the development of these cookers, and evolving from field studies of the use of the various models, can be summarized as: the provision of adequate capacity to deliver energy, which is generally met by the 48-inch reflector properly used; the provision of adequate mechanical strength of the frame to support heavy loads of water, etc.; provision of adequate stability in wind to prevent overturning and damage, met best by the low design of Model 3; ease of assembly and use by technically unskilled persons and reflector construction of sufficiently low precision to avoid very high reflected energy flux and subsequent burning; low cost.

Cooker performance

As with any reflective system, the delivered energy depends on the method of operation as it affects the heat balance. This balance, which has been studied extensively for other solar exchanger systems (3), can be written for steady operation, as follows:

$$H_b A_r r \gamma \alpha = q_u + q_{th}$$

Here H_b is the intensity of beam radiation, fixed by weather and time, A_r is the unshaded area of the reflector, and r is the specular reflectivity of the reflector. γ is an intercept factor which denotes the fraction of the specularly reflected radiation which is intercepted by the cooking vessel; it is a function of the accuracy of the reflector shape, the precision of orientation of the system and the size of the vessel, and in a good system properly used is near unity. The absorptivity of the vessel for solar radiation is α. Useful heat delivered to the contents of the vessel is q_u, and thermal losses from the vessel by convection, radiation and evaporation are denoted by q_{th}.

Good operation is dependent, then, on maximizing the left side of the equation, which represents the energy absorbed by the cooking vessel, and minimizing the thermal losses. Good operation is thus dependent on good beam radiation, adequate reflector area, a clean specular reflector properly oriented, and a black vessel for solar radiation. Reduction of thermal losses is most effective, for wet cooking, by covering the vessel to reduce evaporative losses.

The performance of cookers depends, to some extent, on the characteristics of the particular unit at hand, as the precision of manufacture of the reflectors has not been completely reproducable, resulting in some variation of γ. Performance also depends on the temperature of the vessel, which affects the thermal losses, and to a lesser extent on the ambient temperature. Typical of a large number of measurements with model 1 cookers, having an effective reflector area of 8.5 ft², are the following data : heating 1.0 quart of water, 2.08 pounds, from 80°F to 177°F, 10 minutes, in a covered blackened aluminum pan, on a January day when the ambient temperature was 31°F and beam radiation was 1.2 cal/cm² min; average energy delivery to water was 355 watts. The time to heat to 210° and boiling was 15 minutes, for an average energy delivery of 315 watts.

Model 2 and 3 cookers, having effective areas of about 11.5 ft², will deliver 40 to 55 per cent of the incident beam radiation to a cooking vessel 7″ in diameter, for maximum delivery rates of 400 to 550 watts at an incident beam total energy of 1.0 kW on the unshaded reflector. A cooker with a reflector several years old and used intermittently in the laboratory, with average beam radiation of 1.35 cal/cm² min, heated 2 pounds of water from 90°F to boiling in 13 minutes, 4 pounds from 90° to boiling in 28 minutes, and 8 pounds of water from 90° to boiling in 62 minutes.

It should be noted that the rate of heat delivery of the 48-inch cookers have proven satisfactory for most cooking operations. It should also be noted that in long-time cooking operations, energy delivery is more than adequate for maintenance of quantities of cooking foods at the boiling temperature for extended periods of time, and that the heating period is relatively unimportant in these slow processes.

Cooker costs

The costs of cookers, like any other manufactured item, is dependent on the volume of production. W. Schaerff (4) has estimated the costs of a first lot of 10 000 of the model 3 units to be as follows:

	$
Materials (including packaging)	7.70
Labor, at $2.00/hr	2.00
Factory overhead	5.00
Profit, at 10 per cent of above	1.47
TOTAL	16.17

The major items of cost are materials for the reflectors, based on the present practice in experimental models, and factory overhead, which includes tooling costs, supervision, warehousing, etc. Reductions may be possible by use of other reflector materials or fabrication techniques, on larger production, or by use of less expensive labor and overhead. This first estimate is considered to be realistically and probably subject to some reduction.

(Another estimate made on the costs of producing a modified version of model 2, at the high production rate of one million units per year, included the following:

	$
Materials	6.33
Labor and overhead	.48
Freight, selling expense, etc	1.26
Return on investment	.59
TOTAL	8.66

This figure probably represents a lower limit on the cost of the model 2 unit.)

The costs of manufacture of the few cookers constructed in the laboratory for experimental use has been substantially higher than either of the above estimates. Accurate cost figures are not available, and would not be meaningful because of methods used in the shops and development costs; the approximate cost of the last of the model 1 units was $25 each.

It should be pointed out that the cost per square foot of the manually operated focusing exchanger, excluding the receiver (the cooking vessel) which is provided by the user, is $1.40 by the first estimate, (paragraph 14), and $0.76 by the estimate based on production of a million units per year.

These cookers have a potential useful lifetime which depends on the model (i.e., on how much "ruggedness" is built into them), on the care of the user, and on the material used for the reflector. The metal parts of the later cookers, particularly model 3, should have a lifetime of 5 to 10 years with reasonable care on the part of the users; many of the earlier models experienced mechanical failures within a year. The lifetime of the reflectors is highly dependent on materials, care and amount of use, as noted above.

The transportability of the rigid reflectors 48 inches (1.2 meters) in diameter represents little problem; in large numbers, they can be readily nested for shipping. The cooker frames are designed to be disassembled readily for packing in a flat package. Portability of cookers by individuals, on the other hand, is not easy with the rigid reflectors. The units are light in weight, with the reflectors weighing 5.2 pounds, the model 2 frame weighing 11.6 pounds, and the model 3 frame weighing 15.6 pounds. The reflectors are readily removable from the frames for overnight or bad-weather storage.

Field studies

Over a period of four years, field studies of the use of several models of these cookers have been carried out, for the most part in northern Mexico; and some 200 cookers of various models have been used as the designs have evolved. The general plan of the field studies was to make cookers available to low-income agricultural workers, observe their use, and on the basis of the results, modify the cooker for subsequent trials. The studies started on a very small scale, involving only a few families and occasional visits to the field by laboratory personnel; in 1958 a more extensive program was started, with the co-operation of cultural anthropologists. These studies in Mexico have been made possible through the co-operation of the Rockefeller Foundation, which has made available both financial support and assistance in the Mexican field activities.

The present studies are centered largely in a village in the state of Coahuila, Mexico, near Torreon. Some studies have also been carried out in Tlaxcala, Sonora and other locations, but on a less extensive and intensive basis; this discussion refers largely to the results obtained in Coahuila during the past two years.

Conduct of experiments

On the basis of early experience in field studies, it was concluded that careful planning of field studies and careful observation of results were necessary to obtain significant information. Thus in the later studies of models 2 and 3 cookers, anthropologists went to live in the village where the studies were made; they observed reactions to the cookers and also studied a variety of economic and cultural aspects of village life which affected the reactions of the people to the innovation. As relatively few cookers were available, it was also necessary for the anthropologists to plan the experiments so as to yield results which could be generalized as far as possible, i.e., which would represent the reactions of a cross-section of the population of the village.

In these experiments, the occupations, approximate incomes, attitudes on change, size of families, sources of fuel for conventional cooking, etc., of the users were observed. Cookers of model 2 were made available (in a village in Coahuila) to sixteen families, without charge; ownership of the cookers was considered to be with the families. With transfers of cookers among the families, 20 families were involved in this study, in a community of 266 families. The heads of most of the families involved had no regular employment, but earned variable amounts in agricultural labors. An estimate placed the cost of a solar cooker at an average of two weeks' pay for a worker.

The use of the cookers was observed by frequent (usually daily) visits with the families, with the anthropologist assisting with any needed education for the user in the techniques of use, and in making any repairs on the cookers.

In the winter of 1961, five cookers of model 3 were put into use by families in the Coahuila village. The results of experience with these two models, 2 and 3, are summarized in the following sections.

Use of model 2 cookers

The use of the 16 model 2 cookers noted in paragraph 23 is summarized in table 1, as a function of the time of year and the weather (as it dictated the possible use of the cooker). The major conclusions to be drawn from these, and other supporting data, can be summarized as follows:

(*a*) Through the period January through August for which data are available, the 16 cookers were in use about $\frac{2}{3}$ of the days on which use was possible. This use included cooking and also heating of irons and heating of water for washing.

(*b*) The frequency of use, relative to days of possible use, apparently dropped during the summer months; however, the data are not complete for these months as indicated by the high number of "unknown cooker days" indicated in the last column. During the spring months when observations were relatively complete, the use stayed in the range of $\frac{2}{3}$ to $\frac{3}{4}$ of the total possible cooker days, even though mechanical failures of some of the cookers began to be significant.

(*c*) In spite of successful and trouble-free use in the laboratory, considerable mechanical troubles developed in field use. These resulted from wind damage and breakage of minor parts. (On the basis of these mechanical troubles, the model 3 cooker was designed.) This breakage resulted in non-acceptance of the cooker for some families, who suffered loss of valuable food from the cooker on its failure. Wind damage was particularly significant, and any cooker design must be made to withstand moderate winds if damage is to be avoided. After a total of 14 months, three of the original 16 cookers are in use with 13 unusable due to mechanical failures, two of the three in use are in excellent condition.

(*d*) The reactions of the families to the cookers varied. Classifying the cookers as "successful" or "unsuccessful" (a subjective rating by the anthropologist based on the family reaction, extent of use, care for cooker, etc.), the initial reactions were successful at the beginning of the study for 13 of 19 users, with 5 of the initial successes becoming unsuccessful later in the period of cooker use. Some of this loss of acceptance was due to mechanical failure.

(*e*) The usual cooking fuels of the people of this village are wood and oil, with some families using wood exclusively (gathered or purchased), and some using a combination of wood and oil. The success of the families in cooker use was about the same for both groups, and in this relatively small sample success with the cooker did not appear to correlate with need for it or financial success.

Use of model 3 cookers

Five of the model 3 cookers were introduced into the village in early February, 1961 and all five have been in constant use since that date through May 2, (the date of last reports). Three of the five families previously had the model 2 cookers, and two of these were considered successful users of the model 2. The two new families having cookers represent a range of economic status; one family is quite poor, the other successful by village standards. The new model has so far been satisfactory from the mechanical point of view, is more wind resistant, and easier to use. The frequency of use is better than with the model 2 cookers, with the purposes of use the same (cooking meals, heating water, and heating irons).

It has been observed that the users have adjusted to the idea that the cooker is a supplemental cooking device and not a complete substitute for conventional methods; the stock complaints of lack of success of use in cloudy weather are no longer heard. It is felt that many of the problems encountered in the first year of use of the model 2 cookers would have been avoided with the model 3 units, and that given a reasonable need for the cooker, and a climate conducive to its use, acceptance should be good. All of the users of the new model are considered successful users.

During the two months of these experiments, work in this village has been very scarce, and on some days no food was available. Thus the cookers were at times out of use even when the housewives would have liked to use them. With these difficulties taken into account, it was found that four of the new cookers have been used almost 100 per cent of the possible days since introduction, and the fifth about 75 per cent of the possible days.

Conclusions

On the basis of laboratory experiments and field studies as outlined above, several tentative conclu-

Table 1. Summary of use of 16 solar cookers, by month and weater conditions, Coahuila, Mexico, 1960

Month	*Weather conditions*																								*Totals by month*					
	Good weather [1]						*Partially good weather* [2]						*Poor weather* [3]						*Weather unknown*						*All weather*					
	A	*B*	*C*	*D*	*E*	*F*	*A*	*B*	*C*	*D*	*E*	*F*	*A*	*B*	*C*	*D*	*E*	*F*	*A*	*B*	*C*	*D*	*E*	*F*	*A*	*B*	*C*	*D*	*E*	*F*
January	9	144	90	0	0	35	4	32	22	6	0	27	4	0	7	5	0	11	1	0	0	0	0	16	18	176	119	11	0	89
February	17	272	192	0	0	5	3	24	36	0	0	0	8	0	0	16	0	0	1	0	0	0	0	16	29	296	228	16	0	21
March	27	432	334	0	18	48	3	24	39	0	2	2	1	0	0	3	0	13	0	0	0	0	0	0	31	456	373	3	20	63
April	16	256	172	0	36	22	3	24	22	7	9	0	3	0	0	0	0	0	8	0	0	0	0	128	30	280	194	7	45	150
May	9	144	86	0	29	6	4	32	31	1	12	3	4	0	5	2	6	16	14	0	0	0	0	224	31	176	122	3	47	249
June	No data																													
July	7	112	9	0	1	102	1	8	0	0	0	16	6	0	0	0	0	80	17	0	3	0	0	269	31	120	12	0	1	467
August	7	112	21	0	1	69	1	8	3	0	0	10	6	0	0	0	0	80	17	0	2	0	0	272	31	120	26	0	1	431
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	20	1	0	171	13	0	20	1	0	171
TOTALS BY WEATHER	92	1 492	904	0	85	287	19	152	153	14	23	58	32	0	12	26	6	200	71	0	25	1	0	1 096	214	1 624	1 094	41	114	1 641

[1] Good weather: over 4 hours of sustained sun during a day.

[2] Partially good weather: 1 to 4 hours of sustained sun during a day.

[3] Poor weather: less than 1 hour of sustained sun during a day, or too much wind to allow effective cooking.

A. Total number of days of the type noted in the group heading.
B. Possible cooker days:
(*a*) In good weather = good weather days × 16;
(*b*) In partial weather = partial weather days × 8;
(*c*) In poor weather = poor weather days × 0.
C. Actual cooker days: successful use of cooker observed during the day.
D. Ineffective cooker days: unsuccessful use of the cooker on any day is an ineffective cooker day.
E. Broken cooker days: when a cooker is specifically labeled as broken its days are counted as broken cooker days.
F. Unknown cooker days: when the use of cooker is unknown on any day, it is counted as one unknown cooker day.

sions can be drawn regarding these reflective-type solar cookers and their potential utility.

(*a*) A reflective-type cooker with a 4-foot diameter reflector, properly used, can deliver sufficient energy to perform many cooking operations, and is best adapted to wet cooking. The rate of delivery of energy to a blackened vessel under good conditions of use is typically 400 to 500 watts.

(*b*) These cookers are useful and have been used for preparation of a wide variety of foods, including beans, stews, soups, meat, tortillas, eggs, etc. They are particularly well adapted to long, slow cooking processes, in contrast to those requiring high energy delivery rates for short periods of time. They are also useful for heating water, and heating irons.

(*c*) In climates of good beam radiation availability, and in locations of reasonable need where the reflective type cooker adapts itself reasonably well to the cooking and eating habits of the people, there appears to be good prospects for successful use of the cookers. They must, however, be of adequate mechanical design to withstand handling, wind damage and other mechanical failures.

(*d*) A limited number of families in northern Mexico have been "successful" users of the Wisconsin cookers for periods of time ranging from two months to fourteen months. The inherent limitations of the device are appreciated, and it is accepted as a supplemental rather than substitute cooking method, and recent models are in regular daily use.

(*e*) Further developmental studies on the cooker are desirable, particularly insofar as the reflecting material is concerned; the laboratory materials and techniques used in the small number of units produced for experimental work are not considered adequate for long time use.

(*f*) Further field studies of cooker use are in progress and in planning, to consider cooker applicability in other cultures and economic atmospheres, and to determine any effects of the experimental methods used in these field studies on cooker acceptance. There are many diverse opinions as to the best method of introducing cookers and determining acceptability; the Wisconsin field programs have had the additional objective of provision of guidance for laboratory developments, and the techniques used in these studies will be varied in future field work.

(*g*) The economic gain on solar cooker use is difficult to determine and varies widely with location, with existing cooking habits and with the economic status of the individual family using the cookers. In Coahuila, for example, some of the cooker users gather wood for cooking and thus save time rather than money; the value of this time, in an area of low employment, is questionable. Oil users in this village pay $0.32 per litre for oil, and on a weekly basis most spend from $0.33 to $0.78 for oil. If a solar cooker were to result in an average savings of $0.25 per week (quantitative data on these savings are not available), a "payoff time" would be about one year for units purchased at prices noted in the cost estimates of paragraphs 14 and 15.

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Summary

Over a four-year period of experimental studies in the laboratory and in field applications, several models of reflective-type solar cookers have been evolved. These cookers use reflectors fabricated of plastic materials, mounted on frames adjustable in altitude and azimuth and constructed of thin-wall tubing and sheet metal parts. The reflectors of recent models are of 48-inch (1.2 meter) aperture, and 18-inch focal length; they deliver a maximum of about 600 watts of energy to the contents of a cooking vessel.

The reflectors of the cookers are fabricated of high-impact polystyrene, formed to the necessary compound curvatures by drape molding techniques, and stiffened at the rim by hoops of thin-wall tubing. The reflector shells thus manufactured are light in weight, adequately stiff and resistant to damage. The shells are lined with a metallized Mylar polyester film applied with an adhesive in a manner so that the film forms a washable protective layer over the specular surface. The specular reflectivity of this material when new is 75 to 80 per cent. Film weathering and deterioration reduce the reflectivity and limit the life of this material, which has been ex-

tremely useful in experimental work; more durable specular materials are being sought for reflector lining for long-time application.

The frames are designed for easy adjustment for altitude and azimuth angles, and are so arranged as to support the cooking vessel and reflector independently. They are fabricated of thin-wall tubing and sheet-metal by standard metalworking techniques not requiring special tooling or high precision of manufacture. The frame design has evolved through this study to provide mechanical strength, stability in wind, and durability, as proven necessary in field use. Two basic designs have been used, and are described and pictured in the paper.

Cooker performance has been measured in the laboratory, and interpreted in terms of the energy balance for the units. Energy delivery to the contents of a cooking vessel runs typically in the range of 300 to 600 watts, depending on weather, conditions of use and age condition of the reflector. This rate of energy delivery is adequate for many cooking operations, and the units are particularly well suited for long, slow cooking operations. The reflective cookers are best adapted to wet cooking, such as boiling and stewing; they can be used for frying and also for baking by addition of a small oven over a heat absorber plate.

Two cost estimates for the cookers have been made, for two designs and differing quantities of production. One estimate places the cost of factory produced units, in an initial quantity of 10 000, at $16.17 each. The other places the unit cost of a modified cooker at $8.66 when manufactured at the rate of one million per year. These estimates include materials, labor, tooling costs, factory overhead, packaging and warehousing, factory profit and allowance for selling expense. These tentative cost figures are subject to variation and interpretation, and serve mainly as an index to the possible ultimate costs; they do not take into account the possible local manufacture of part or all of the components of the cookers.

Design evolution has been based on results obtained in field experiments, which have turned up problems not encountered in laboratory use. In particular, the mechanical design has evolved, until recent models are more rugged and more resistant to wind damage and tipping.

Recent field studies on solar cooker use have been conducted by anthropologists, largely in Mexico, and have considered cooker use by low-income agricultural workers. The significant results of one of these studies, in a village in Coahuila, Mexico, are reviewed in the paper. Two models of the cooker have been introduced in this village, one of them 14 months prior and the other 3 months prior to preparation of this paper. The acceptance of the first model (designated as Model 2) is described as initially successful in 13 of 19 families, with a loss of acceptance by 5 of the 13 after several months of use and after some mechanical failures. During this period, the cookers were in use about two-thirds of the total time in which use was possible. The acceptance of the second model (designated as Model 3) has been excellent, and the major problem of the Model 2 cooker appears to have been solved. The model 3 has mechanical improvements, is lower and less subject to wind damage, is easier to use, and in the first three months of use the units have been used on more than 90 per cent of the days on which use was possible.

There has been acceptance of the solar cookers by the users as a useful household implement. The limitations of the cooker (i.e., its utility as a supplement to and not complete substitute for conventional cooking methods in the northern Mexico climate) are recognized, but extensive use is made of them. The economic gain to the user families is difficult to determine, as many of them use wood gathered and not purchased. Some users ordinarily burn oil for cooking, and "pay off" times of one or two years are probably realistic in these areas, if the cookers can be obtained for prices as noted above.

ESSAIS EN LABORATOIRE ET SUR PLACE DE FOURNEAUX SOLAIRES A RÉFLECTEURS EN COMPOSITION PLASTIQUE

Résumé

Au cours d'une période de quatre années d'études expérimentales faites en laboratoire et d'applications sur place, on a mis au point plusieurs modèles de fourneaux solaires du type à réflecteurs faits de composition plastique montés sur des cadres réglables en hauteur et en azimut, constitués par des tubes à parois minces et des pièces en tôle. Les réflecteurs de modèle récent ont une ouverture de 48 pouces (1,2 m) et une distance focale de 18 pouces (46 cm); ils fournissent un maximum d'environ 600 W d'énergie au contenu du récipient servant à la cuisine.

Les réflecteurs sont faits de polystyrène à grande résistance aux chocs, auquel on donne les courbures complexes nécessaires par des techniques spéciales de moulure. Leurs bords sont renforcés par des cerceaux faits de tubes à parois minces. Les cadres de réflecteurs ainsi fabriqués sont légers, résistants et peu sujets à être endommagés. Les enveloppes sont revêtues intérieurement d'une pellicule de polystyrène (Mylar) métallisé appliquée avec une substance adhésive de telle sorte que la pellicule forme une couche protectrice lavable sur la surface du miroir. La réflectivité spéculaire de ce matériau, lorsqu'il

est neuf, est de 75 à 80 p. 100. Les intempéries et autres avaries réduisent la réflectivité et limitent la durée du matériau, qui a été extrêmement utile pour les travaux expérimentaux. On cherche à se procurer comme revêtement de réflecteurs un matériau spéculaire plus durable et capable de donner de longs services.

Les cadres sont conçus de manière à se prêter à un réglage facile en hauteur et en azimut, et sont disposés de telle sorte qu'ils soutiennent indépendemment le récipient de cuisson et le réflecteur. Constitués par des tubes à parois minces et de la tôle, ils sont réalisés par les techniques métallurgiques classiques, qui n'exigent ni outillage spécial ni une grande précision de fabrication. Ce type de cadre a été mis au point pendant la présente étude, pour assurer résistance mécanique, stabilité dans le vent et grande durée de service, ainsi qu'il s'est avéré nécessaire dans les applications faites sur place. On s'en est tenu à deux conceptions de base, et elles sont décrites et représentées dans le mémoire.

Le rendement de ces fourneaux a été mesuré en laboratoire et interprété en fonction du bilan énergétique. La fourniture d'énergie au contenu d'un récipient de cuisine s'inscrit en général dans la gamme de 300 à 600 W, suivant le temps, les conditions d'emploi, l'âge et l'état du réflecteur. Ce taux de livraison d'énergie est suffisant pour nombre de méthodes de cuisson, et le matériel se prête particulièrement bien aux cuissons lentes et prolongées. Il est idéal pour la cuisine dans laquelle intervient un liquide (mets bouillis ou ragoût), mais on peut s'en servir pour les fritures et rôtis en ajoutant un petit four sur une plaque absorbante de chaleur.

On a fait deux évaluations du prix de revient de ces fourneaux, pour deux conceptions et deux quantités de production. Une des évaluations donne le prix des unités produites en usine en quantités initiales de 10 000 à 16,17 dollars par unité. L'autre établit le prix unitaire d'un dispositif modifié à 8,66 dollars quand on le fabrique au rythme d'un million par an. Ces évaluations comportent les matériaux, la main-d'œuvre, les frais d'outillage, les frais généraux de l'usine, l'emballage et l'entreposage, les bénéfices de l'usine et certains frais de ventes. Il s'agit de chiffres provisoires, sujets à certaines variations et à des interprétations, et ils servent essentiellement d'indices pour les prix définitifs possibles; ils ne tiennent pas compte de la possibilité de la fabrication locale d'une partie ou de tous les éléments de ces appareils.

L'évolution de la conception de ces appareils repose sur les résultats obtenus à la suite d'expériences faites sur place. Celles-ci ont soulevé des problèmes qui ne se sont pas présentés en laboratoire. En particulier, les caractéristiques mécaniques ont évolué jusqu'à ce que les modèles actuels soient plus solides et plus résistants aux dégâts par le vent, ainsi que moins sujets à basculer.

Des recherches faites sur place récemment sur les fours solaires ont été menées par des anthropologistes principalement au Mexique. Ils ont étudié la question de l'emploi de ce dispositif par des travailleurs agricoles qui gagnent fort peu d'argent. Les résultats significatifs de l'une de ces études faite dans un village situé dans l'État de Cohuila sont passés en revue dans le présent mémoire. Deux modèles ont été établis dans le village, l'un d'eux quatorze mois, et l'autre trois mois, avant la préparation du mémoire. Le succès du premier modèle essayé (qu'on appelle modèle 2) a été bon au départ dans treize familles sur dix-neuf, avec un fléchissement auprès de cinq familles parmi ces treize après plusieurs mois d'usage et après quelques défauts mécaniques. Au cours de cette période, les fourneaux ont fonctionné pendant les deux tiers environ du nombre total de jours pendant lesquels il était possible de s'en servir. Le succès du deuxième modèle essayé (appelé modèle 3) a été excellent, si bien que le problème principal soulevé par le modèle 2 semble avoir été résolu. Le modèle 3 bénéficie de perfectionnements mécaniques, il est plus bas et moins sujet à être endommagé par le vent, son emploi est plus facile et, au cours des trois premiers mois d'usage, on s'est servi de ces appareils pendant plus de 90 p. 100 des journées pendant lesquelles l'utilisation en était possible.

Les usagers ont accepté le fourneau solaire comme étant un article ménager utile. Ses limitations, à savoir son utilité en tant que supplément et non pas comme remplaçant intégral pour les méthodes classiques de la cuisine dans le climat du Mexique du nord, ont été reconnues, mais on s'en sert abondamment. Les gains économiques, pour les familles qui en font usage, sont difficiles à déterminer, car nombre d'intéressés utilisent le bois qu'ils ramassent au lieu de l'acheter. Certains usagers consomment habituellement du pétrole pour la cuisine, et il est probable que des temps d'amortissement de un ou deux ans seront raisonnables pour ces régions, si on peut se procurer les appareils pour les prix mentionnés ci-dessus.

DESIGN AND PERFORMANCE OF FOLDING UMBRELLA-TYPE SOLAR COOKER

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The concept of utilizing the sun's heat for cooking food is not new. In the latter part of the eighteenth century, a few solar cookers were constructed but were used mainly by the inventor (1). More recently, solar cookers have been the subject of wide-spread attention for use in sunny, fuel-scarce areas. The rapid depletion of natural resources used for cooking fuel in these areas can be decreased and time spent in gathering this "natural" fuel can be reduced when solar cookers are employed.

Although many cookers employing a wide range of designs have been constructed, only a few have received even small scale field testing and/or use. Economics and social customs are the two most important factors affecting the marketing and widespread use of solar cookers.

Solar cookers can be logically divided into two types : those employing optical concentration and those without optical concentration. The Telkes solar oven is probably the most widely known cooker of the latter type (2). (This cooker employs a small amount of concentration, however, due to reflection from extended polished metal surfaces). Cookers employing optical concentration can be further subdivided into two groups : those with rigid reflectors and those utilizing collapsible reflectors.

The Indian solar cooker (3) developed by the National Physical Laboratory in New Delhi and the University of Wisconsin solar cooker (4) employ rigid reflectors. The Indian cooker, utilizing a polished metal reflector, was reported to have been manufactured commercially and sold to Indians for $14-$17. The cookers did not obtain wide scale acceptance, however, as they were too expensive for the average villager and traditional cooking methods were preferred (5). A modest field test program has been carried out with the Wisconsin cooker in rural Mexico. This cooker utilizes a polystyrene reflector shell with aluminized Mylar reflective lining. No cost data are available since this cooker has not been commercially produced. Both of these paraboloidal cookers were developed primarily for use in sunny, under-developed, fuel-scarce countries.

A few of the collapsible concentrating cookers have been produced and marketed. One of these is the Tarcici cooker which employs wedge-shaped, polished metal segments that fold in a manner similar to the flash buld reflectors used in photography (6). When opened, the segments form a paraboloidal reflector. Another cooker named the Solar-Chef utilizes two rectangular segments of a paraboloid as the reflector (7). A thin coating of vapor-deposited aluminum on the plastic segments forms the reflective lining. This cooker was marketed primarily for recreational use.

Differing from these two cookers is the Umbroiler which is a folding, umbrella-type solar cooker. The Umbroiler combines the function of a solar reflector with a readily portable and collapsible umbrella frame and a flexible reflective fabric. By this combination, a compact, portable and efficient solar cooker is obtained. Although developed primarily for intermittent recreational use, this cooker could also be adapted for day-to-day cooking in under-developed regions. A description of this cooker and data on its performance are presented in the following sections.

Description of cooker

The assembled solar cooker ready for use, is shown in figures 1 and 2. Figure 3 shows the disassembled umbrella-type cooker. One of the advantages of this type cooker is its compactness and portability. The entire cooker, including reflectors, support stand, and cooking surface weighs about 4 pounds and can be folded into a carrying case 4 inches deep, 10 inches wide, and 30 inches long. To assemble the unit, the folding tripod is placed on the ground, the reflector is opened like an umbrella and attached to the tripod, and the grill is connected to the main umbrella shaft.

Reflector

The reflector is composed of a framework, similar to a standard umbrella frame, covered with a metallized plastic film laminated to cloth. When opened, the reflector has the appearance of an umbrella with a highly reflective lining.

The reflecting material is made of aluminized Mylar polyester film laminated to a rayon fabric. Standard umbrella-making techniques are employed in fabrication. Material for the 16 segments is die-cut from roll goods according to pattern, assembled by machine stitching, and mounted on an umbrella frame having sixteen 24-inch ribs. The material segments are cut to special shape in order to provide a parabolic profile in the assembled reflector. The final shape is dictated entirely by the pattern of the material since the umbrella ribs are straight pieces

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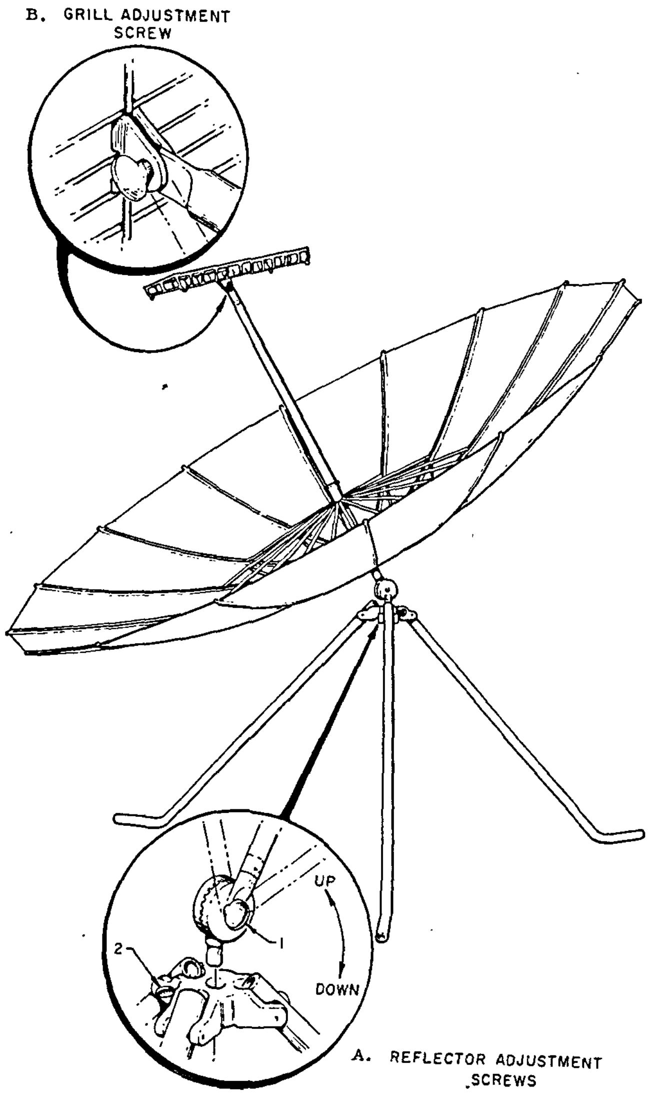

Figure 1. Diagrammatic sketch of folding, umbrella-type solar cooker

of spring metal which flex only as forced by the fabric.

Having an aperture of 46 inches, the opened reflector presents a gross interception area of 11.5 square feet and an effective area of 11.0 square feet (after deducting for the shaded area of the grill). The shape of the umbrella-type reflector is not paraboloidal in nature and does not have a compound curvature. Instead, it is curved in only the radial direction, from the umbrella center. Circumferentially, the surface consists of flattened, straight portions between adjacent ribs. Eight small portions of parabolic cylinders with wedge-shaped sides are thus formed. The effect of this departure from a true paraboloid is to diffuse the focus from a very small, intensely hot spot to a larger and less intensely, but more uniformly, heated area. This proves to be advantageous for broiling since meat can be uniformly cooked instead of being burned in one spot and left raw in another. Also, burned food in pan bottoms is eliminated.

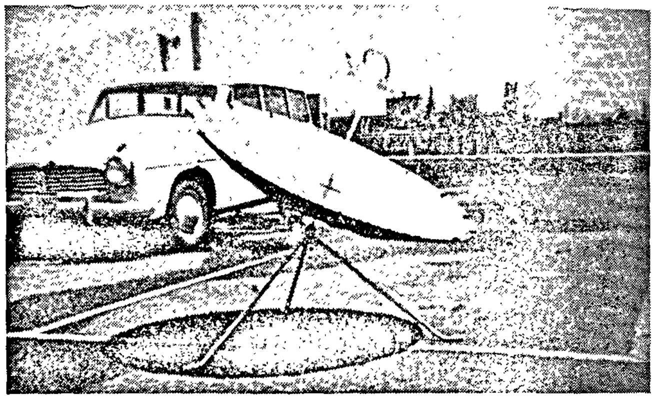

Figure 2. Assembled cooker in operation

Supporting stand

As can be seen in figure 1, the cooker stand is composed of a simple, folding tripod constructed of $\frac{5}{8}$-inch aluminum tubing hinged from a central aluminum casting, which forms the apex of the tripod. A hole in this apex casting accommodates a metal peg attached to the main "umbrella" or reflector shaft through an arrangement of matched serrated aluminum discs. This peg, firmly held in the casting opening by means of thumbscrew 2 (shown in expanded view A of figure 1), provides support for the reflector. The 9-inch square wire grill cooking surface (or vessel support) is rigidly held at the correct position in the hot focal zone by a thumbscrew-tightened fitting which attaches to the main $\frac{1}{2}$-inch aluminum rod reflector shaft.

Orientation mechanism

Orientation is accomplished by three separate adjustments which include altitude and azimuth positioning for correct reflector alignment and an angle adjustment for obtaining the desired tilt position for the grill. The reflector altitude is adjusted by means of thumbscrew 1 which firmly holds the serrated discs at the desired altitude position (expanded view A of figure 1). Reflector azimuth position is adjusted by either loosening thumbscrew 2, turning the reflector support peg in the aluminum casting, and retightening the thumbscrew or else turning the entire support stand. The former is the

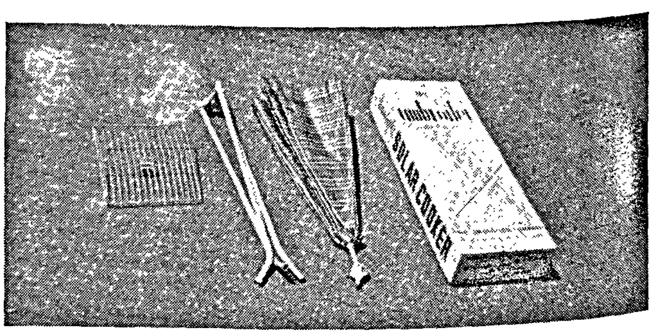

Figure 3. Folded cooker components shown beside container

recommended azimuth positioning procedure. Grill tilt is fixed by tightening the grill adjustment screw shown in figure 1, expanded view B. For the cooking of food in pots and pans, the grill must be practically horizontal, but if meats are being broiled, the grill may be tilted more nearly parallel to the reflector aperture to obtain greater energy interception on the grill area.

A small white cloth circle located at the reflector center provides a focusing target. Proper cooker alignment is obtained when the grill shadow is centered on this cloth circle; solar energy reflected from all portions of the reflector surface then reaches the focal zone.

Performance data

Optical measurements

Specular reflectivity

Average specular reflectivity of the aluminized Mylar was found to be 0.75. An Eppley normal incidence pyrheliometer was used to measure incident and reflected radiation. Specular reflectivity equals the ratio of specularly reflected to incident direct radiation.

Shape factor

A photographic technique, utilizing radiation reflected from the moon as the source, was employed to determine the distribution of reflected radiation in the focal zone of the cooker. The focal zone of interest was arbitrarily chosen as the area occupied by the grill; the zone was thus 9 inches square, centered on the theoretical focus. A 9-inch square sheet of slow speed, low contrast photographic paper (Velox F-1) was exposed at the focus for a time interval of 30 seconds. A test sheet of the photographic paper was also exposed to direct moonlight (no concentration) for periods of one to 10 minutes in one minute increments. The exposed sheets were developed in one part Dektol developer to 2 parts water at about 70°F for a period of 1½ minutes.

By a density comparison of the focal zone picture and the test sheet, isolines of concentration ratio from 4 to 12 were drawn on the focal zone picture. Maximum concentration ratio of the cooker was found to be 12. With the focal zone pattern known, it was possible to determine the fraction of specularly reflected radiation falling in the 9-inch square focal zone. By multiplying the areas between isolines by the average concentration ratio, values representative of the amount of radiation falling on each area were obtained. Their sum equalled the radiation received in the focal zone. Specularly reflected radiation was equal to the unshaded reflector area times the specular reflectivity of the aluminized Mylar. It was found that 45 per cent of the specularly reflected radiation was intercepted by the 9-inch square focal zone and 31 per cent fell inside a 7-inch diameter circle centered on the theoretical focal point. The product of reflectivity, r, and shape factor, γ, is the optical efficiency of the concentrator for a particular sized target. Thus, $0.45 \times 0.75 = 33.7$ per cent optical efficiency for the 9-inch square grill area and $0.31 \times 0.75 = 23.2$ per cent optical efficiency for the 7-inch diameter circle.

Calorimetric tests

Many experiments on heating one quart of water have been performed with cookers chosen at random. An aluminum whistling tea kettle with its 7-inch diameter bottom painted dull black was employed as the vessel. The empty kettle weighed ½ pound and had a heat capacity of 0.18 btu/lb°F and a surface area of 0.59 ft^2. Effective absorptivity of the black coating was 0.90. The combined convection and radiation heat loss coefficient was approximately 2.0 btu/hr ft^2 °F. For all tests, the grill was aligned parallel to the reflector aperture and supported the tea kettle which was centered on the grill. Results of three experiments performed at Denver, Colorado, latitude 40°N, are tubulated below.

Test No.	*1*	*2*	*3*
Direct solar radiation (btu/ft^2 hr)	320	299	273
Wind velocity (mph)	3.0	3.3	3.4
Ambient air temp (°F)	70	50	52
Amount of water (qt)	1.0	1.0	1.0
Initial water temp (°F)	70	62	62
Final water temp (°F)	202	202	202
Time required to boil water (minutes)	20	23	27
Incident radiation on 11 ft^2 of unshaded reflector (btu)	1 172	1 260	1 350
Heat transferred to water, q_u (btu)	275	291	291
Heat loss from kettle, q_l (btu)	32	45	53
Heat retained by kettle, q_v (btu)	12	13	13
Collection efficiency (per cent)	27.2	27.7	26.5
Net efficiency, solar to water (per cent)	23.5	23.1	21.6

The figures for net efficiency (efficiency of converting incident solar radiation to heat in the water) are confirmed by the results of Gunnar Pleijel (8). He tested one of the cookers in central Sweden and obtained an over-all efficiency for heating water of 24 per cent.

Heat balance

The heat balance for the cooker can be written as follows:

$$\Omega = H_D A \theta \nu \gamma \alpha = q_u + q_l + q_v \qquad \text{(A)}$$

where

Ω = Solar radiation absorbed by bottom of vessel, btu.
H_D = Incident direct solar radiation, btu/ft^2 hr.
A = Effective or unshaded reflector area, ft^2.
θ = Time, hr.
ν = Specular reflectivity of reflecting surface, dimensionless.
γ = Shape factor, the fraction of specularly reflected radiation intercepted by the vessel or object being heated, dimensionless.
α = Solar absorptivity of black coating on vessel being heated, dimensionless.

q_u = Useful heat transferred to liquid or other object being "cooked", btu.
q_l = Heat loss by convection and radiation from heated object to surroundings, btu.
q_v = Heat retained by vessel containing liquid, btu.

The results obtained from the optical measurements and the calorimetric tests can be combined in the heat balance. As previously noted, reflectivity of the reflecting surface was 0.75 and reflector shape factor for striking a centered target 7 inches in diameter was 0.31. By substituting these values and those obtained from the calorimetric tests in equation (A), the relative importance of the several variables and the reliability of the measurements can be evaluated:

From Calorimetric Test No. 1:

By radiation measurement,

$$\Omega = H_D A \theta \nu \gamma \alpha$$

$$= 320\,(11)\left(\frac{20}{60}\right)(0.75)\,(0.31)\,(0.90) = 245 \text{ btu}$$

By calorimetric measurement,

$$\Omega = q_u + q_l + q_v = 275 + 32 + 12 = 319 \text{ btu}$$

From Calorimetric Test No. 2:

By radiation measurement, Ω = 264 btu
By calorimetric measurement, Ω = 349 btu

From Calorimetric Test No. 3:

By radiation measurement, Ω = 282 btu
By calorimetric measurement, Ω = 357 btu

The heat absorbed, Ω, determined from the calorimetric measurements is always higher than Ω determined from radiation measurements and is considered the more reliable of the two. The discrepancy is therefore thought to be on the radiation side of the heat balance and is believed attributable to the shape factor determination. A shape factor of 0.40 instead of 0.31 would close the heat balance within the limits of random experimental error and is thought to be more representative of the reflector at the time the calorimetric tests were performed. The fact that the optical shape factor measurements were made at low ambient air temperature (during a winter night at about 35°F) probably resulted in a somewhat poorer reflector shape than when the calorimetric experiments were performed. The laminated reflector material is rather stiff when cold, and the folded surfaces are therefore not stretched flat between ribs, under these conditions. It should also be noted that these measurements were not all made with the same cooker and that a certain amount of variability does exist between cookers.

Food cooking

A variety of foods have been satisfactorily cooked on the cooker and in some cases the time required was less than that needed for merely building a cooking fire. Taste and quality of the solar cooked foods are excellent. Listed below are some of the foods which have been cooked and the approximate length of time required when cooking with bright sunshine.

Type of food	*Cooking time*
Grilled frankfurters	8-12 minutes
Grilled hamburgers (ground meat patties)	10-15 minutes
Grilled beef-steaks (1 inch thick)	15-20 minutes
Grilled trout (fish)	10-15 minutes
Potatoes in black-bottom pressure cooker (for average family of 5)	30 minutes
Eggs fried in black-bottom pan	5 minutes
Coffee (1 quart):	
Boiled	20 minutes
In percolator	25 minutes

A report on operation of the cooker in Sweden has been made by Gunnar Pleijel (8) He reports that eggs and sausages were fried in a black-bottom frying pan in a total time of 10 minutes (5 minutes were allowed for heating the pan and 5 minutes were required for cooking). Wieners (frankfustess) were cookeddirectly on the grill in 12 minutes. Of further interestis a portion of his translated report:

"The family had several picnics. The cooker proved itself excellent at heating water in a teakettle while the table was being set. When the water was boiling we placed the pot on a fibre mat under a heat insulated top and the temperature stayed steady. Then we fried large sausages, eggs, and wieners that we ate with sandwiches. When we were through frying, we again put the hot tea kettle on the grill and in a few minutes it was again boiling at just the right time to coincide with the time when we were through eating. Then we made coffee in another vessel, using the boiling water. Soon we had delicious coffee of a good quality. Coffee and sweet-rolls finished the lunch. Water boiled in the tea kettle by our sun-grill was then used for dish water. The whole party took less than one hour."

These results, secured at a latitude of about 60°N, are in good agreement with those obtained by the authors and by others.

Durability

As with any manufactured item, durability or expected life of the cooker depends, to a great extent, on the care or treatment given the cooker by its user. The manufacturers of the Weatherable Mylar, E. 1. du Pont de Nemours, state a life of a few years with continuous outdoor exposure. It is believed that the plastic-fabric laminated material composing the reflecting cover will have a similar life expectancy of a few years. The aluminized Mylar surface has an advantage over exposed metal reflecting surfaces as the Mylar side is uppermost and provides protection against reflecting surface deterioration by oxidation, weathering, etc. Given proper treatment, the metal parts of the cooker, comprising reflector framework and cooker support stand and grill, should outlast the fabric covering. When the fabric cover does eventually become unuseable, either through deterioration or accidental damage, a replacement cover may be obtained for use with the same framework.

Cost considerations

At the present time, the complete packaged solar cooker is being sold in the United States at a retail price of approximately 30 dollars. This price includes manufacturing cost, overhead, selling expense, distribution costs, and profit. The material for the reflector surface represents about 20 per cent of the total cost; adding the labor of cutting and sewing the material, about one-third of the total manufacturing cost is associated with the reflector surface. When assembled on the umbrella-type frame, the reflector unit comprises approximately one-half the total cost, the balance being in the stand, grill, packaging material, and general assembly. About two-thirds of the total manufacturing cost is in materials and one-third in labor.

The possibilities for cost reduction lie along three lines. These are increases in production volume, changes in materials and methods of construction, and manufacture in other countries. The first of these, particularly significant in the United States, might be brought about through cost reductions associated with purchase of materials in larger quantity and lower labor requirements if production were increased sufficiently to permit simple, repetitive steps in fabrication.

Some of the possible design simplifications are also dependent on production in larger quantity. In place of fairly expensive metal castings, cheap sheet-metal stampings could be used if production volume justified the initial cost of stamping dies. Expensive aluminum tubing could be replaced by flat strip metal formed into round, triangular, or rectangular tubing shapes. Minor design changes in reflector framework and support arrangements could also permit cost reductions.

Because labor cost is such a large item in this country of high wage rates, substantial savings could be effected by manufacture in countries where lower labor costs prevail. Cost reductions of one-third should be possible in many areas. Moreover, the design is suited to small scale manufacture, so large volume need not be a requirement for economical fabrication in these circumstances. This situation is in contrast to that in the United States. It is possible that cookers could be manufactured in other countries and shipped to the United States for sale at lower costs than possible with domestic production. In appraising the potential for use of this solar cooking unit in the under-developed areas, perhaps with some design modifications, the possibilities for low cost manufacture in the countries of use are a favorable factor. Without more detailed information and consideration, it is not possible to present a reliable figure for a selling price under such circumstances. However, it is estimated that the present price could be reduced by a factor of at least one-half, and possibly even as much as two-thirds, under ideal conditions. The changes in cooker design which are considered desirable for daily use in family food preparation in fuel-scarce areas are indicated in the following section.

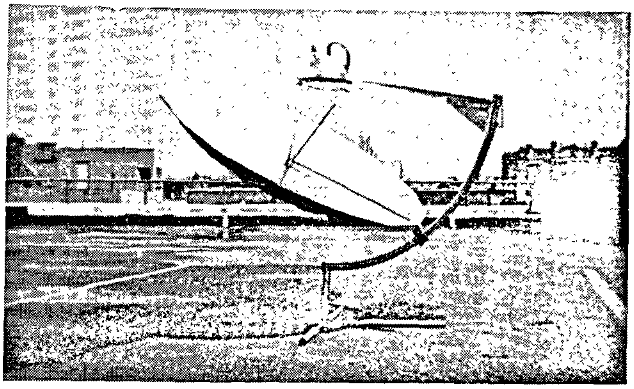

Figure 4. Collapsible, umbrella-type reflector with modified support stand

Modifications for routine cooking

There are changes which might be made in the present cooker design that would make the unit more serviceable for every-day use in areas where it might be the primary food-cooking unit. The present cooker, while considered excellent for its original purpose, should probably be strengthened to meet more severe use, such as that accompanying the cooking of meals for large families in heavy utensils. This could be accomplished in two ways: (1) by simply employing stronger structural members in the present design, or (2) by changing the design of the support. The first possibility is self-explanatory. The second point merits further consideration. In the present design, the stand supports the reflector which in turn supports the cooking surface and cooking vessel. The stand could be redesigned to support the cooking surface and cooking vessel directly and at the same time also support the reflector. Heavier cooking loads could thus be accommodated. Figure 4 shows one possible modification of the type discussed.

Moderate improvements in the existing reflector will, in all likelihood, be possible as improved materials become available. Plastic films possessing higher specular reflectivities are a distinct possibility. Also, flexibility and surface smoothness of the laminated combination material might be increased, thus providing a closer approach to perfect parabolic curvature.

Any plans for adapting the cooker to routine cooking would of course include studies on simplification and cost reduction along with increasing durability. A reduction in the cost of a modified cooker for day-to-day use from the cost of the present model is possible, even though more structural materials may be required. Most, if not all, of the parts could be manufactured and the entire cooker assembled in the country of use.

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Summary

One of the few solar cookers in modest commercial production and use employs a parabolic reflector of aluminized plastic film supported on an umbrella framework. Since its first public use about 2½ years ago, several improvements in design and construction materials have been made, and performance and durability are now considered satisfactory.

The tripod-mounted cooker has 16 intersecting wedge-shaped portions of parabolic cylinders, aggregating approximately 11.5 square feet of concentrating surface. The erected unit has a 46-inch diameter and an 18-inch focal length. A 9-inch square grill may be secured to the end of the axial shaft near the theoretical focus. Movable joints permit periodic adjustment for solar alignment. Design details are presented in the paper.

Recently secured performance data show gross heat delivery rates to the grill area of slightly over 1 300 btu per hour in full sunshine (320 btu/ft² hr). This is nearly equivalent to 400 watts. The results of cooking several types of food by boiling, frying, and broiling are reported.

Designed principally for recreational use, sale of the cooker has been limited by comparatively high manufacturing costs. Small production has not yet permitted mass-production economies. It is anticipated that as demand increases, price can be materially reduced. This in turn may place the cooker in the potentially large market of the under-developed countries where shortages of cooking fuel are a problem.

CONSTRUCTION ET RENDEMENT DES CUISINIÈRES PLIANTES DU TYPE PARAPLUIE

Résumé

L'une des rares cuisinières solaires en production commerciale à une échelle modeste et en service fait usage d'un réflecteur parabolique constitué par une pellicule en composition plastique revêtue d'aluminium et portée sur un support en forme de parapluie. Depuis sa première utilisation en public il y a environ deux ans et demi, elle a bénéficié de plusieurs améliorations dans sa conception et ses matériaux, si bien que son rendement et sa durée de service sont maintenant considérés comme satisfaisants.

La cuisinière, montée sur un trépied, est dotée de 16 éléments de cylindre parabolique en forme de coin, dont la surface totale de concentration est de 11,5 pieds carrés (très sensiblement 1 m²). L'unité une fois montée a un diamètre de 46 pouces (1,17 m) et une distance focale de 18 pouces (46 cm). Un gril carré de 9 pouces de côté (23 cm) peut être fixé à l'extrémité de l'arbre monté axialement, près du foyer théorique. Des articulations mobiles permettent des réglages périodiques en vue de l'alignement du dispositif avec le soleil. On présente des détails de construction dans la présente communication.

Les données récemment recueillies sur le rendement de ce matériel indiquent un débit brut de chaleur, à la surface du gril, d'un peu plus de 1 300 btu à l'heure (environ 325 calories) en plein soleil (320 btu/pieds carrés/h), ce qui est presque équivalent à 400 W. On décrit les résultats obtenus dans la cuisson de plusieurs genres d'aliments que l'on a fait bouillir, frire ou griller.

Conçues principalement à des fins récréatives, ces cuisinières ont été vendues en nombre limité à cause de leurs frais de fabrication relativement élevés. La première série produite, portant sur de petits nombres, n'a pas encore permis de réaliser des économies telles que celles qu'assure la production en grande série. Avec l'augmentation de la demande, on prévoit que les prix seront sensiblement réduits. Ceci, à son tour, peut ouvrir à la cuisinière le gros marché possible que représentent les pays sous-développés, où le manque de combustibles pour la cuisson constitue un problème.

REPORT ON TESTS CONDUCTED USING THE TELKES SOLAR OVEN AND THE WISCONSIN SOLAR STOVE OVER THE PERIOD JULY TO SEPTEMBER 1959

Nutrition Division, Food and Agriculture Organization of the United Nations

The use of the energy of the sun to supply heat for the cooking of food has been adapted to the design of several types of solar cookers. The principle involved is the concentration of solar radiation by a reflecting surface with the result that heat is applied and accumulated at a cooking position. The efficiency of solar cookers is dependent upon several factors such as the nature and design of the reflecting surfaces, the alignment of the stove to the direction of the sun, and the cooking utensil used.

During the months of July-September, two types of solar-cookers, the Telkes oven and the University of Wisconsin solar stove, were tested on the terrace of the FAO building. The first of these was developed by Dr. Telkes at New York University under a grant from the Ford Foundation. It consists of an insulated cabinet of approximately 2 cubic feet capacity with a double glass window at the front and a hinged door at the back. Arranged around the window are four flat aluminium reflectors approximately square in shape and each of an area of about 350 to 400 square inches. These reflectors make an angle of about 110 to 120 degrees with the glass front and reflect the solar energy into the cabinet. The cooker developed by engineers at the University of Wisconsin Solar Energy Laboratory is a parabolic type. The reflecting surface is circular, about 4 ft in diameter and shaped like a saucer with the deepest part at the center about 3 inches below the rim. A grill for holding a cooking utensil is fixed at the center about 16 inches above the deepest section of the parabola and directly over the point of focus. The parabolic reflective surface is made of aluminium foil bonded onto plastic.

The criterion used for testing these two types of solar cookers was the time required to heat 2 litres of water in a closed container from a temperature of 15-20°C to 100°C and throughout this report this is referred to as the "water-heating time".

The tests reported here using the two stoves were, in general, conducted simultaneously. The stoves were set out each morning at approximately 9 am. The area in which they were placed was a relatively confined terrace and open to direct sunlight during the hours 9 am to 4 pm. The area was not, however, sheltered from the wind.

At the beginning of each test and during the day as necessary, the reflecting surfaces of both stoves were carefully wiped free of dust and dirt. The stoves were oriented to the sun as soon as they were set out, and in most tests every 15-30 minutes thereafter.

Two types of cooking utensils were used. Aluminium pans 8 inches in diameter and 4 inches deep and painted black for maximum absorption of heat were tested in both stoves. Earthenwere pans of the same size were also used in a limited number of tests with either an aluminium cover painted black or another earthenware pan as a cover.

During the period of July-September, day temperatures in Rome ranged from 22 to 34°C, the daily variation being from 2°C to 7°C. In general the weather during the day was fair and sunny, though usually there was a slight haze with slight to moderate cloud cover and a light wind.

Results and discussion

TELKES OVEN

Data concerning the time required to raise the temperature of 2 litres of water through 80 to 85°C (i.e., from 15-20°C to 100°C) when using a covered aluminium pan painted black are given in table 1. It will be seen that in 14 separate tests representing days on which there was uninterrupted sunlight during the tests, the "water heating time" ranged from 92-140 minutes. The mean time was 112 minutes.

In six other trials, on days when the sun was obscured by clouds for varying periods of time (15-51 minutes), the "water heating time" ranged from 115-165 minutes.

In table 2 data are given for "water heating times" using an earthenware pan covered with an aluminium cover painted black or with another earthenware pan. There are results for only four tests with the black cover and two with the earthenware cover during periods of continuous sunshine and with the stove orientated at frequent intervals. The mean "water heating times" were 141 and 142 minutes respectively. From these results it is clear that the "water heating time" for the earthenware pans is approximately 30 minutes longer than for the aluminium pans painted black. The initial heating of the pan material itself could largely account for the increased time, since the heat capacity of earthenware is considerably greater than that of aluminium pans.

In table 3 limited data are given of the effects of infrequent positioning of the oven as well as the

Table 1. Telkes oven. Time required for 2 litres of water to reach 100°C using a covered aluminium pan painted black

Air temperature (range)	*Oven temperature (range)*	*Temperature rise of water (to reach 100°C)*	*Time to reach 100°C (min)*	*Weather*	*Remarks*
30-34	109-117	83	100	Slightly cloudy and windy	
30-34	105-110	83	120	Slightly cloudy and windy	
31-34	100-117	83	110	Slightly cloudy and windy, haze	
32-33	110-113	83	115 *	Very cloudy, moderate wind	Sun covered 15 min
28-32	80-110	83	150 *	Cloudy, moderate to strong wind	Sun covered 21 min
28-32	60-110	83	140 *	Cloudy, moderate to strong wind	Sun covered 17 min
26-31	35-115	83	120	Calm, haze to slightly windy, slightly cloudy	
27-34	110-112	81	120	Calm, haze to slightly windy, slightly cloudy	
27-34	95-120	84	120	Calm to slightly windy, haze	
27-30	90-110	84	145 *	Cloudy, slightly windy	Sun covered 43 min
27-30	103-117	81	105	Cloudy, slightly windy	
26-32	97-117	83	105	Calm, slightly cloudy	
27-32	95-115	85	120	Calm, slightly cloudy	
27-32	95-100	84	150 *	Calm, slightly cloudy	Sun covered 30 min
26-30	80-115	85	105	Bright sun, north wind, slightly cloudy	
26-30	105-120	82	92	Bright sun, north wind, slightly cloudy	
26-30	95-110	83	108	Slightly windy and cloudy	
23-30	63-105	85	165 *	Cloudy	Sun covered 51 min
22-28	85-118	84	100	Calm, haze, slightly cloudy	
22-27	36-115	85	140	Calm, slightly cloudy	
			Average (14 tests) — 112 min		

* Not included in average.

effect of the weather. These data, combined with those in tables 1 and 2, show that continual positioning of the stove is not a critical factor. It appears that the oven may be left in one position for periods up to 60-70 minutes without affecting its performance. Enough heat is trapped by the oven so that the average "water heating time" is maintained at about 112 minutes. However, when the sun is obscured by clouds for many minutes the "water heating time" is increased by an amount approximately equal to the time the sun had been covered.

Telkes ovens have been sent by FAO for studies in Thailand and in Trinidad. The work undertaken in Thailand was mainly concerned with the prepara-

Table 2. Telkes oven. Time required for 2 litres of water to reach 100°C using a covered earthenware pan

Air temp (range)	*Oven temp (range)*	*Temperature rise of water (to reach 100°C)*	*Time to reach 100°C (min)*	*Type of cover*	*Weather*	*Remarks*
27-32. .	50-115	83	165	Earthenware	Calm or slightly windy	Sun covered 30 min
27-33. .	100-120	84	150	Aluminium painted black	Haze	
27-33. .	70-117	79	135	Aluminium painted black	Slightly windy and cloudy	Sun covered 15 min
27-33. .	100-107	76	130	Aluminium painted black	Slightly windy, haze	
26-33. .	86-112	83	165	Aluminium painted black	Sky not bright, haze, slightly windy	
22-26. .	95-119	85	135	Earthenware	Slightly cloudy and windy	Stove moved every 15 min
22-26. .	100-115	77	165	Earthenware	Slightly cloudy	Stove not moved 75 min Sun covered 7 min
21-28. .	74-120	85	150	Earthenware	Haze, slightly windy	Stove moved every 15 min
21-28. .	95-105	75	150	Earthenware	Haze, slightly windy	Sun covered 1 min
22-28. .	100-120	83	120	Aluminium painted black	Calm, haze	Stove moved every 15 min
22-28. .	55-118	85	150	Aluminium painted black	Sky not bright, haze	Stove moved every 15 min
22-28. .	107-95-107	80	165	Aluminium painted black	Sky not bright, haze	Stove not moved 75 min Sun covered 11 min
24-31. .	84-105	79 (did not reach 100°C)	180	Aluminium painted black	Slightly windy and cloudy	Sun covered 20 min

Table 3. Telkes oven. Time required for 2 litres of water to reach 100°C using a covered aluminium pan painted black, with infrequent orientation of the stove and/or cloudy weather

Air temperature (range)	*Oven temperature (range)*	*Temperature rise of water (to reach 100°C)*	*Time to reach 100°C (min)*	*Weather*	*Remarks*
31-34	107-115	80	100	Slightly windy and cloudy, haze	Stove not moved 70 min
26-31	109-117	81	105	Calm or slightly windy, haze	Stove not moved 75 min
27-34	100 —	81	140	Cloudy	Sun covered 45 min
27-30	90-105	81	115	Slightly cloudy and windy	Stove not moved 65 min
26-32	104-110	84	100	Cloudy	Stove not moved 70 min
27-29	110-84-99	85	180	Slightly windy	Sun covered 40 min Stove not moved 70 min
26-30	75-100	85	245	Calm, haze	Sun covered 35 min

tion of a number of traditional dishes and apparently all of these were quite successfully cooked in the oven. The work in Trinidad has been confined mostly to a record of oven temperatures on a number of days during which the weather was suitable for solar cooking.

In Rome, the studies were primarily concerned with the heating of water, but on three days observation were made of the maximum temperatures that could be obtained in the empty oven and values of 170°C, 152°C and 165°C were recorded.

In Thailand, comparable values could also be derived from the data relating to the initial heating-up period of the empty oven, prior to the cooking tests, and the values so obtained were 171°C, 182°C and 204°C. In thirty trials in Trinidad, maximum oven temperatures varied from 134°C to 204°C, with an average of 176°C. Air temperatures during these tests ranged from 26 to 33°C.

It is interesting to note that even with reasonably good weather in Rome during July-September, the highest oven temperature observed was much lower than the maximum oven temperatures recorded in Thailand and Trinidad.

However, for practical purposes, this type of test is only of limited value since it gives little indication of the performance of the stove when used for cooking. Under favourable conditions, relatively high oven temperatures may be reached in the empty oven within a period of about an hour, but as soon as a cooking utensil containing water is put into the oven, the oven temperature falls through 30 to 50°C and thereafter the rate of increase in temperature is slow. This is not simply a matter of the small amount of heat required to heat air in the empty oven. Rather it is an indication of the low heat input into the cabinet and the low heat losses through the well insulated structure of the cabinet. What is really of interest is the level of total heat input not only to balance heat losses from the system, but also to provide heat for cooking. This information is only obtained by cooking tests.

Wisconsin solar stove

Data obtained for the Wisconsin solar stove "water-heating times" when using a covered aluminium pan painted black are presented in table 4. An average of 39 tests gave a value of 41 minutes for "water-heating times". This represents only about 37 per cent of the time required to heat the same quantity of water in the same pan in the Telkes oven. As in the case of the Telkes oven, this figure refers to those tests conducted under the most favourable conditions of weather.

Only a limited number of values is available for "water-heating times" in earthenware pans. The same two types of covers were used and again it is not possible to say if there is an effect due to the different covers. The average "water-heating times" for earthenware pans are much greater than for aluminium pans painted black. The average value for seven trials with the earthenware pan having the black aluminium cover is 78 minutes and for five trials using the earthenware pan with an earthenware cover is 72 minutes.

As with the Telkes oven the effect of cloud cover over the sun is to increase the "water-heating time". This effect is illustrated in tables 4, 5 and 6. Here again it appears that the "water-heating time" is increased by an amount approximately equal to the time the sun had been obscured by clouds. It should be noted that since the "water-heating time" is so much shorter for the Wisconsin stove, the proportional effect of cloud-cover is greater.

The only data available on the effect of leaving the stove in the same position for an hour or longer were obtained during a period when there was frequent cloud cover. From these data, it would appear that, in contrast to the Telkes oven, it is important to orientate the Wisconsin solar stove every 15-30 minutes. This could well be explained by the fact that in the Wisconsin solar stove, the heating area is small and the maximum concentration of heat in this area is only obtained when the sun rays are parallel to the axis of the parabolic reflecting surface. By contrast, the reflecting surfaces of the Telkes oven are flat and the nature of reflection from these surfaces into the oven is such that the orientation of the oven to the sun is not so critical. Another point to note is that the whole surface of the cooking utensil on the Wisconsin stove is freely exposed and loss of heat from it is considerably increased so that the "water-heating times" are also

Table 4. Wisconsin solar stove. Time required for 2 litres of water to reach 100°C using a covered aluminium pan painted black

Air temperature (range)	*Temperature rise of water (to reach 100°C)*	*Time to reach 100°C (min)*	*Weather*	*Remarks*
30-34	83	39	Slightly cloudy and windy	
30-34	83	65	Slightly cloudy and windy	
31-33	83	50	Slightly cloudy and windy, sky not bright, haze	
31-33	83	52	Slightly cloudy and windy, sky not bright, haze	
29-33	84	45	Calm or slightly cloudy and windy, haze	
31-33	84	47	Slightly cloudy and windy, haze	
31-34	84	35	Calm and slightly cloudy and windy, haze	
31-34	82	38	Calm and slightly cloudy and windy, haze	Stove sways in wind
31-34	82	36	Calm and slightly cloudy and windy, haze	Stove sways in wind
31-34	82	33	Calm and slightly cloudy and windy, haze	
31-32	83	45 *	Particularly cloudy and windy	Sun covered 10 min
31-32	83	40 *	Particularly cloudy and windy	Sun covered 6 min
31-32	81	45 *	Particularly cloudy and windy	Sun covered 10 min
28-31	82	57 *	Particularly cloudy, moderate wind	Sun covered 23 min
28-31	81	65 *	Particularly cloudy, strong wind	Stove sways in wind; sun covered 5 min
28-31	81	75	Particularly cloudy, strong wind	
25-31	84	45	Calm to slightly cloudy and windy, haze	
25-31	81	38	Calm to slightly cloudy and windy, haze	
25-31	81	34	Calm to slightly cloudy and windy, haze	
25-31	81	30	Calm to slightly cloudy and windy, haze	
25-31	81	45	Calm to slightly cloudy and windy, haze	
27-34	83	45	Slightly cloudy and windy, haze	
27-34	81	40	Slightly cloudy and windy, haze	
27-34	81	32	Slightly cloudy and windy, haze	
27-34	81	40	Slightly cloudy and windy, haze	
27-34	81	40	Slightly cloudy and windy, haze	
27-34	80	55 *	Slightly cloudy and windy, haze	Sun covered 3 min
31-33	82	45	Very cloudy and windy	
28-30	84	40	Very cloudy, calm to slightly windy	
28-30	81	50	Very cloudy, calm to slightly windy	
28-30	81	32	Very cloudy, calm to slightly windy	
28-30	81	45 *	Very cloudy, calm to slightly windy	Sun covered 3 min
26-32	83	35	Calm to slightly or moderately cloudy	
26-32	82	30	Calm to slightly or moderately cloudy	
26-32	81	30	Calm to slightly or moderately cloudy	
26-32	83	32	Calm to slightly or moderately cloudy	
26-32	84	71 *	Calm to slightly or moderately cloudy	Sun covered 25 min
26-32	81	50	Calm to slightly or moderately cloudy	
27-32	84	50	Slightly cloudy and calm to slightly windy	
27-32	81	31	Slightly cloudy and calm to slightly windy	
27-32	81	45	Slightly cloudy and calm to slightly windy	
27-32	84	45	Slightly cloudy and calm to slightly windy	
27-32	81	72 *	Slightly cloudy and calm to slightly windy	Sun covered 30 min
24-31	85	38	Slightly cloudy to cloudy, north wind	
24-31	81	30	Slightly cloudy to cloudy, north wind	
24-31	82	33	Slightly cloudy to cloudy, north wind	
24-31	81	31	Slightly cloudy to cloudy, north wind	
24-31	82	35	Slightly cloudy to cloudy, north wind	
24-31	81	100 *	Slightly cloudy to cloudy, north wind	Sun covered 55 min
22-29	85	80 *	Haze, moderate wind, slightly cloudy	Sun covered 27 min
23-29	85	45 *	Calm to slightly windy, cloudy	Sun covered 12 min
		Average (39 tests) — 41 min		

* Not included in average.

Table 5. Wisconsin solar stove. Time required for 2 litres of water to reach 100°C using a covered earthenware pan

Air temperature	*Temperature rise of water (to reach 100°C)*	*Time to reach 100°C (min)*	*Type of cover*	*Weather*	*Remarks*
24-31	80	55	Aluminium painted black	Haze, sky not light; cloudy, slightly windy	
24-31	81	150	Aluminium painted black	Haze, sky not light; cloudy, slightly windy	Sun covered 21 min
26-32	84	107	Aluminium painted black	Haze, sky not light, cloudy, slightly windy	Sun covered 25 min
26-32	77	68	Aluminium painted black	Haze	Sun covered 4 min
26-33	83	89	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	81	55	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	82	75	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	84	90	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	78	80	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	80	105	Aluminium painted black	Haze, calm to slightly windy and cloudy	
22-28	84	80	Earthenware	Haze, calm to slightly windy and cloudy	Stove moved every 15 min
22-28	82	60	Earthenware	Haze, calm to slightly windy and cloudy	Stove moved every 15 min
22-28	78	55	Earthenware	Haze, calm to slightly windy and cloudy	Stove moved every 15 min
22-28	85	90	Earthenware	Haze, slightly windy and cloudy	
22-28	78	75	Earthenware	Haze, slightly windy and cloudy	

increased when there is a wind. By contrast, in the Telkes oven which has an insulated cabinet to house the cooking utensil, the effect of wind on its performance is not so marked.

One very important consideration with the Wisconsin solar stove is the necessity for a firm anchoring of the legs, since it sways readily with the wind.

Summary and conclusions

Two solar stoves, one an oven type (Telkes) and the other a parabolic reflector type (Wisconsin) were tested at FAO Headquarters during July, August and September 1959. In general the weather was sunny and warm, sometimes slightly cloudy and usually there was a slight to moderate wind.

Table 6. Wisconsin solar stove. Time required for 2 litres of water to reach 100°C using a covered aluminium pan painted black, with infrequent orientation of the stove and/or cloudy weather

Air temperature (range)	*Temperature rise of water (to reach 100°C)*	*Time to reach 100°C (min)*	*Weather*	*Remarks*
28-31	81	150	Particularly cloudy, moderate wind	Stove not moved 70 min; sun covered 40 min
27-34	81	114	Haze, slightly cloudy and windy	Stove not moved 70 min; sun covered 30 min
31-33	83	205	Very cloudy and windy	Stove not moved 70 min; sun covered 90 min
28-30	82	90	Calm to slightly windy, very cloudy	Sun covered 43 min
26-28	84	55	Slightly cloudy and windy	Stove not moved 45 min
24-30	84	90	North wind, slightly cloudy, slightly windy	Stove not moved 60 min
24-30	83	83	North wind, slightly cloudy, slightly windy	Stove not moved 60 min; sun covered 33 min
24-30	81	100	North wind, slightly cloudy, slightly windy	Stove not moved 70 min; sun covered 30 min
24-30	81	80	North wind, slightly cloudy, slightly windy	Stove not moved 60 min; sun covered 26 min

The average time required to heat two litres of water from 15 to 20°C to 100°C (termed "water-heating time") was determined for each stove. The cooking pot used in most of these tests was a covered aluminium pan painted black, but some comparisons were also made with earthenware pans.

For the Telkes oven, it was observed that when using a covered aluminium pan painted black, the mean "water-heating time" was 112 minutes. When earthenware pans were used, the mean time was 142 minutes.

For the Wisconsin solar stove, it was observed that when using a covered aluminium pan painted black, the mean "water-heating time" was 41 minutes. When earthenware pans were used, the mean time was 76 minutes.

The performance of both types of stoves is directly affected by clouding of the sun, and under such conditions the "water-heating time" is increased by an amount approximately equal to the time the sun is obscured. The performance of the Wisconsin solar stove is considerably influenced by wind, but for the Telkes oven the effect of wind is not so marked. To obtain the best results, the Wisconsin solar stove has to be orientated towards the sun at least every 15-30 minutes. In the case of the Telkes oven, such frequent orientation is not necessary.

The efficiency of these two stoves can be judged according to two criteria observed here:

(1) The time required for cooking;

(2) The amount of handling needed for the best performance of the stoves.

In these tests it has been shown that water can be boiled considerably faster on the Wisconsin solar stove than in the Telkes oven. However, performance of the Telkes oven is less affected by infrequent positioning of the stove, by clouding of the sun and by wind.

In addition, it is necessary to consider that the Telkes oven is more expensive as well as more complicated than the Wisconsin solar stove with greater risk of mechanical difficulties and more need for repairs and spare parts.

UNE CUISINIÈRE SOLAIRE CYLINDRO-PARABOLIQUE

Salgado Prata *

Les modèles de cuisinières solaires essayés jusqu'à présent appartiennent essentiellement, à l'un des deux types : parabolique ou « boîte fermée ».

Les modèles paraboliques ont été traités notamment par Ghai (2, 3), Burda (4), J. A. Duffie (5), J. R. Jenness (6). Les modèles « boîte fermée » ont été étudiés et mis au point par M. Telkes (1).

Avec les cuisinières paraboliques, on obtient un haut degré de concentration, mais l'ustensile de cuisine, parce qu'il est exposé, perd beaucoup de sa chaleur par convection et radiation vers l'atmosphère, surtout s'il y a du vent. Les modèles « boîte fermée » sont plus chers, plus lourds et possèdent un faible degré de concentration, mais ils abritent les ustensiles de cuisine et permettent de tenir les aliments chauds pendant quelques heures après leur cuisson, pourvu qu'ils y soient conservés.

Dans un nouveau modèle, on a cherché à combiner les deux caractéristiques fondamentales citées.

Ce rapport donne les résultats d'essais et d'études concernant le nouveau modèle de cuisinière solaire, ainsi que les résultats d'une comparaison entre la nouvelle cuisinière et un modèle « boîte fermée » (figure 4).

Description et principe de fonctionnement

Un miroir cylindro-parabolique constitué par deux éléments (figures 1, 2 et 3)[1] est tourné vers le soleil. Le four cylindrique, par la fente-fenêtre duquel pénètrent les rayons solaires réfléchis, est placé au foyer du miroir. Les ustensiles de cuisine, contenant les aliments à cuire, sont placés dans le four. Les deux éléments du cylindre parabolique et le four lui-même sont supportés par quatre pieds contreventés.

Chaque réflecteur, construit en feuille de laiton nickelée est fixé à une structure en bois traversée par un axe de sustentation autour duquel elle peut tourner. Cet axe permet d'obtenir la focalisation du réflecteur. Son immobilisation à la position convenable peut être obtenue grâce à des coulants (figure 1).

Le four est construit en feuille double d'aluminium formant un cylindre, qui est garni extérieurement avec de la laine de verre. Il ne possède pas d'autres éléments structuraux. Sa propre forme en « coque » lui donne la rigidité longitudinale nécessaire. La tendance à l'ovalisation est contrariée par les couvercles, qui servent aussi de portes. A sa partie inférieure et selon une génératrice, le cylindre présente une fenêtre de forme allongée, qui permet l'entrée de la radiation solaire concentrée. Pour réduire les pertes par convection et radiation à travers la fenêtre, celle-ci est garnie intérieurement d'un

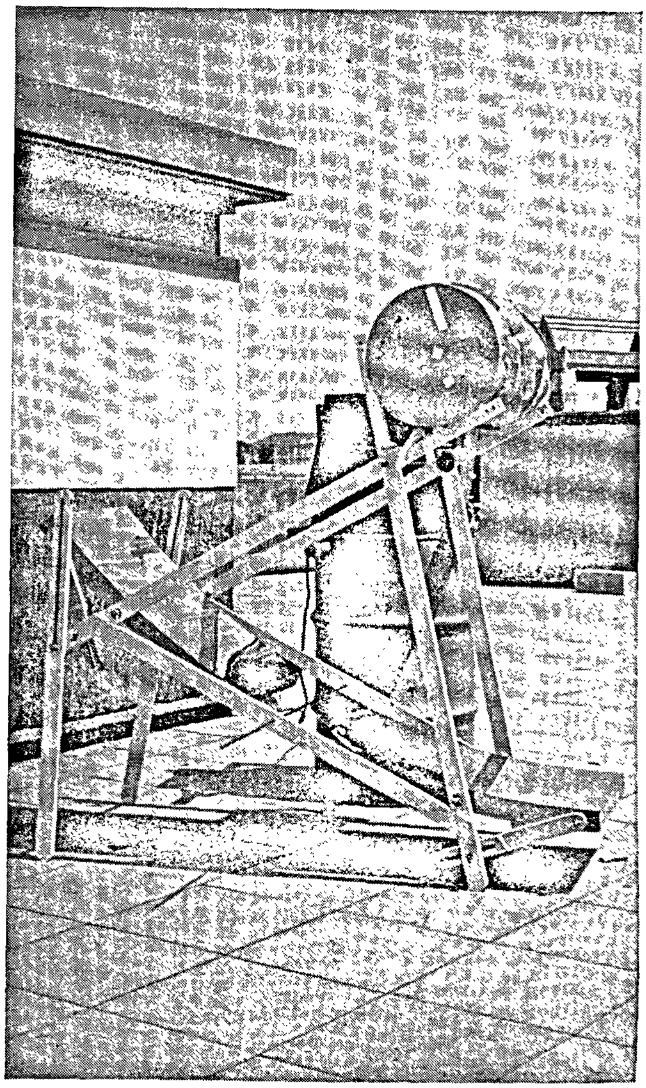

Figure 1. Cuisinière solaire cylindro-parabolique vue du côté des coulants

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[1] On doit noter que la figure 3 montre un modèle qui diffère de celui construit du fait qu'il est entièrement métallique.

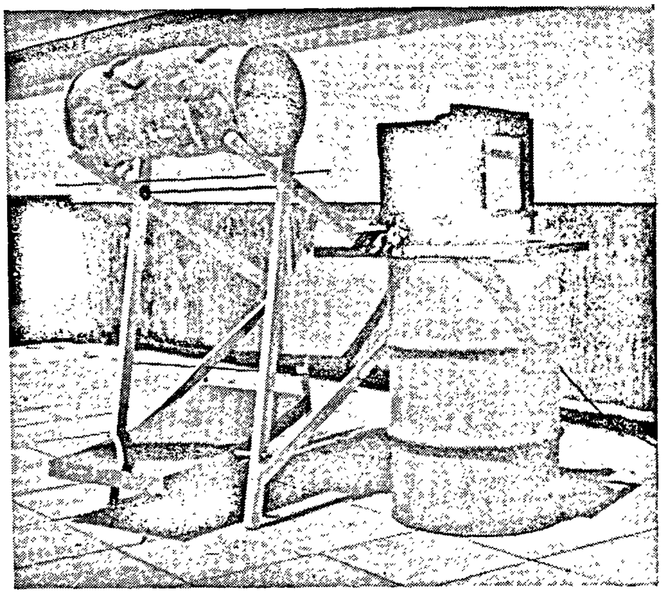

Figure 2. Cuisinière solaire cylindro-parabolique vue du côté porte d'usage. A côté de la cuisinière, on voit l'appareil mesureur-enregistreur de température Honeywell

panneau de verre et extérieurement d'une plaque de film plastique « Mylar » collée à même le cylindre.

Les miroirs sont décentrés relativement à la fenêtre, afin d'augmenter l'intervalle de temps entre chaque ajustement de position de l'appareil nécessaire pour compenser la variation de l'azimut solaire.

Dans cet appareil, on a cherché à intercepter un maximum de radiation solaire avec un minimum de surface réflectrice.

La construction des miroirs en forme de parabole ouverte satisfait cet objectif. Pratiquement, la parabole se confond avec une circonférence. En outre, avec un grand rayon de courbure, les angles d'incidence que les rayons réfléchis par les zones les plus éloignées des miroirs font avec le verre de la fenêtre ne sont pas exagérés, de sorte que les pertes par réflection sont faibles. On doit observer aussi que cette construction permet de placer le four à une hauteur commode pour l'utilisateur.

La conception de ce modèle de cuisinière solaire fait prévoir que les pertes par radiation à travers la fenêtre seront faibles, puisqu'elle a une surface relativement réduite. Il en est de même pour les pertes par convection; comme le flux calorifique est descendant, ces pertes seront pratiquement nulles. Quant aux pertes par conduction, elles seront minimes.

Essais typiques d'utilisation avec le modèle cylindro-parabolique

Les heures indiquées dans la description suivante sont des heures solaires. Les essais ont été effectués à Lisbonne (38° de latitude nord).

Les résultats les plus importants sont les suivants :

Aliments cuits	*Radiation solaire directe (cal/cm².min)*			*Durée*	*Observations*
	9 h	*12 h*	*15 h*		
3,76 kg de pommes de terre cuites à l'eau	1,122	1,224	—	10 h 25-12 h 25	Quantité la plus grande d'aliments qu'on ait pu introduire dans le four
2 kg de pommes de terre cuites à l'eau	1,122	1,224	—	10 h 20-11 h 38	
1 l de haricots et 1 l de maïs cuits à l'eau	1,214	1,295	1,132	12 h 25-14 h 05	
1 l de maïs rôti	1,214	1,295	1,132	14 h 10-14 h 40	
Gâteau de 0,710 kg cuit au au four	0,92	0,978 (brume)	0,851	10 h -11 h 15	
Friture de poisson et d'œufs	0,92	0,978 (brume)	0,851	11 h 32-11 h 47	
Poulet de 2 kg rôti.	0,690	0,805 (brume)	0,736	14 h -16 h	Le poulet était parfaitement cuit et savoureux

On trouvera dans l'annexe des précisions supplémentaires sur ces essais.

Essais d'utilisation réalisés avec le modèle « boîte fermée »

Le 6 mai 1961, jour où la radiation solaire directe a été exceptionnellement forte (1,203, 1,334 et 1,242 cal/cm².min, respectivement à 9, 12 et 15 heures), on a cuit 1,5 kg de pommes de terre dans un pot contenant 1 l d'eau, en 2 h 30 min (11 h 50 à 14 h 20). Ce résultat a été le meilleur obtenu avec ce modèle.

Un jour d'intensité de radiation semblable à celle du 6 mai 1961, il faut deux heures et demie pour cuire 1 l de haricots dans un pot contenant 1 l d'eau.

On a aussi vérifié, en septembre 1960, que le modèle « boîte fermée » cuit des gâteaux en 2 h 15 et de la viande en 2 h 45.

Il n'a pas été possible, toutefois, de rôtir du maïs ni de la viande.

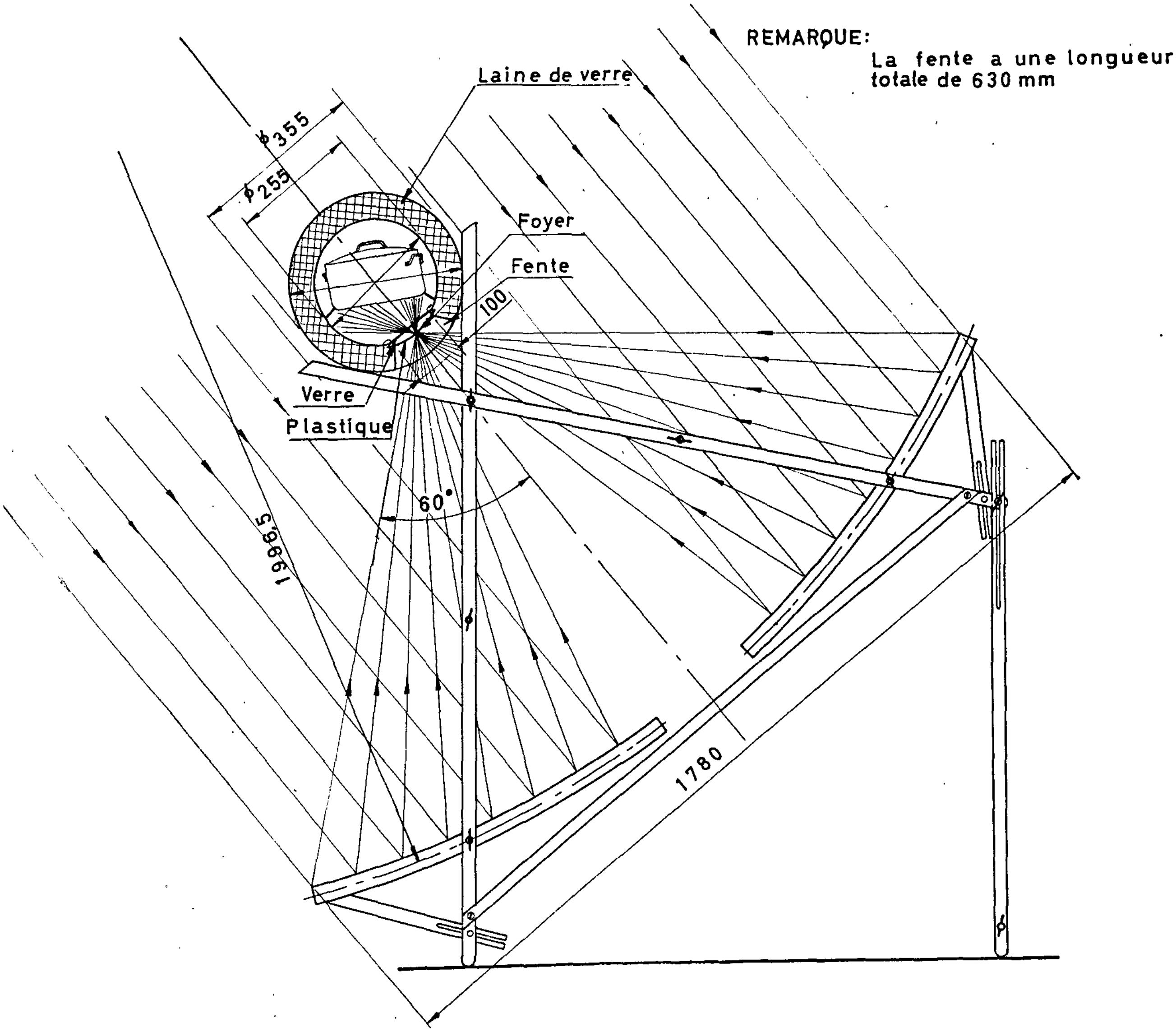

Figure 3. Représentation schématique, dimensions principales et principe de fonctionnement

Conclusions des essais d'utilisation

a) La cuisinière cylindro-parabolique permet de cuire des quantités d'aliments deux fois et demie plus grandes que le modèle « boîte fermée », et ceci dans un espace de temps plus court. En outre, elle permet de rôtir du maïs et de la viande, ce qui n'a pas été possible avec l'autre modèle.

b) Un ajustement périodique de la position de l'appareil doit être fait pour compenser la variation du zénith et de l'azimut solaire. L'ajustement azimutal est constant et doit être fait chaque 22,5 min. Le besoin d'ajustement zénithal varie selon l'heure considérée. De 10 h 30 à 13 h 30, cet ajustement peut être fait à des intervalles de 22,5 à 40 min. Cela signifie que si l'on commence à 10 h 30 la préparation d'aliments qui demandent 1 h 30 pour cuire complètement, on doit faire seulement trois ajustements de position, avec des intervalles de 22,5 min., chacun d'eux consistant en un réglage du zénith et un réglage de l'azimut de l'appareil. Il en va de même pour l'intervalle de 12 h à 13 h 30.

Par conséquent, on peut préparer deux repas par jour exigeant chacun 1 h 30 de cuisson, pourvu que la position de l'appareil soit réglée de cette façon. Les aliments préparés pendant la seconde période, qui normalement seront destinés au dîner, peuvent être conservés chauds pendant quelques heures pourvu qu'ils soient laissés dans le four de la cuisinière solaire.

On doit noter que quand on fait un ajustement de la position du four, il ne faut pas toucher les ustensiles de cuisine à moins qu'ils ne soient trop pleins. D'ailleurs, il est facile de prévoir un gril qui peut glisser sur les parois du four et rester toujours horizontal.

Si on veut cuisiner avant 10 h 30 ou après 13 h 30, avec le même intervalle entre chaque ajustement

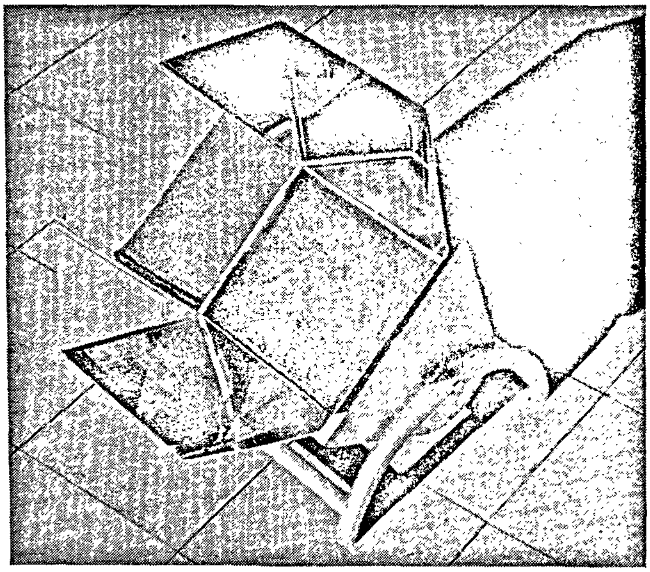

Figure 4. Cuisinière solaire « boîte fermée »

de position, on devra agrandir la fenêtre, ce qui amènera une diminution du rendement du four.

Si vers midi on veut espacer au-delà de 22,5 min les ajustements de position, lesquels sont conditionnés par la variation de l'azimut, il faudra augmenter la longueur de la fenêtre, et par conséquent celle du four, ce qui diminuera également le rendement. Dans ce cas, la diminution du rendement est plus importante, à cause de l'accroissement non seulement de pertes par radiation, malgré l'augmentation de longueur de la fenêtre, mais aussi des pertes par conduction, puisque la longueur du four est augmentée. On peut également diminuer la fréquence des ajustements azimutal et zénithal, en diminuant la distance focale du miroir cylindro-parabolique, ce qui, toutefois, conduit à une construction plus chère, puisque à égale surface interceptée les miroirs, ayant une courbure plus marquée, auront besoin d'une quantité plus grande de matériau réflecteur.

c) On a constaté que l'efficacité était supérieure sans le film plastique de Mylar, qui dans la conception primitive était collé extérieurement au cylindre d'aluminium et couvrait la fenêtre.

En d'autres termes, l'énergie calorifique que le plastique retenait, ne compensait pas l'énergie solaire dissipée par absorption et réflexion. Dans tous les essais décrits, le cylindre parabolique a donc utilisé un four avec une fenêtre de 10 cm de largeur, couverte seulement par un panneau de verre.

d) On a estimé qu'il conviendrait de peindre en noir toute la surface extérieure des ustensiles de cuisine.

e) On a constaté qu'il est préférable de poser les ustensiles de cuisine sur des grils plutôt que sur une plaque continue de longueur égale à celle de la fenêtre, peinte en noir sur la face inférieure et exposée à la radiation solaire concentrée. De ce fait, il semble légitime de conclure que si on avait employé pour la construction du four une plaque d'aluminium poli au lieu d'une plaque d'aluminium ordinaire, les résultats seraient supérieurs à ceux obtenus. L'emploi de la plaque sera seulement indiqué lorsque les dimensions de l'ustensile de cuisine sont suffisamment petites par rapport à celles du four, ou quand il faut répandre un certain aliment dans une surface relativement étendue — par exemple, quand on souhaite rôtir du maïs.

f) A moins d'employer des marmites à pression, il convient de prévoir un échappement pour la vapeur d'eau formée, faute de quoi elle se condense dans les zones les plus froides du verre. La meilleure méthode consiste à trouer les pots et, au moyen d'un tuyau, à mettre ces trous en communication avec l'atmosphère. De cette façon on évite la perte vers l'atmosphère, de l'air chauffé contenu dans le four.

g) Dans le modèle type « boîte fermée », on n'a fait que des ajustements d'azimut, et ceci moins fréquemment que dans le nouveau modèle.

Coût de la cuisinière

Le présent calcul estimatif suppose une construction métallique, entièrement démontable.

Le four pourra être conçu comme celui qui a été décrit plus haut.

Les pieds et les contreventements pourront être faits avec du barreau en acier doux 20 × 3, pourvu que des éléments d'assemblage (voir figure 3) soient prévus à mi-portée entre les axes des réflecteurs

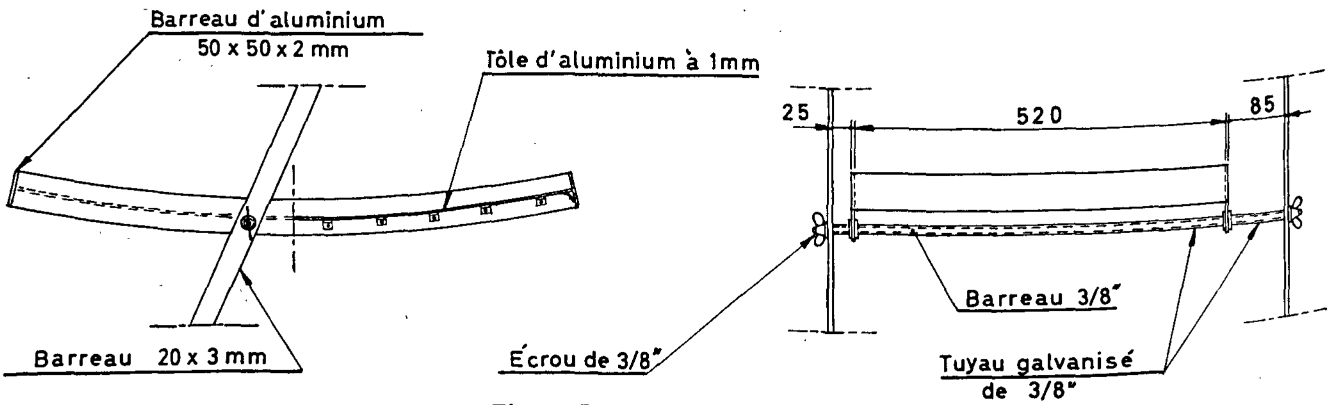

Figure 5. Détail des réflecteurs

et l'axe commun des quatre pieds. Les éléments d'assemblage relieront les pieds, en évitant ainsi le flambage.

Les réflecteurs pourront être en aluminium nickelé. Les châssis qui les supportent, aussi en aluminium, pourront être constitués comme on l'indique dans la figure 5.

De cette façon et en supposant une construction en série moyenne, il faudra 18 dollars de matériaux (y compris le coût du nickelage) et 8 heures-ouvrier de main-d'œuvre. L'appareil pèsera 18 kg.

Si la construction est entièrement en aluminium, l'appareil sera plus cher mais son poids tombera à 12 kg environ.

Les matériaux et la main-d'œuvre nécessaires pour un modèle « boîte fermée » avec les mêmes dimensions que celui qui a été essayé, c'est-à-dire ayant 0,48 m^2 de surface normale aux rayons solaires, sont à peu près les mêmes que ceux indiqués pour le modèle cylindro-parabolique. Le poids du modèle « boîte fermée » est de 22 kg.

Conclusions

L'appareil présenté peut cuire des quantités assez importantes d'aliments de toutes sortes, en certains cas dans un espace de temps peu supérieur à celui demandé par les cuisinières domestiques ordinaires.

La surface collectrice effective, normale aux rayons solaires, est, dans le modèle parabolique construit, de 0,74 m^2. La surface correspondante du modèle « boîte fermée » décrit dans ce rapport est de 0,48 m^2. En outre, le rapport entre la quantité des aliments cuits et le temps nécessaire pour les cuire est, pour le premier modèle, 2,8 fois plus grand que pour le second. Ceci signifie que la cuisinière solaire cylindro-parabolique est $2{,}8 : \left(\frac{0{,}74}{0{,}48}\right) = 1{,}8$ fois plus efficace que la « boîte fermée ». Pour une égale surface collectrice effective, le modèle cylindro-parabolique est le moins cher. La fréquence avec laquelle, dans cette cuisinière solaire, l'ajustement de position doit être fait, encore qu'elle est acceptable, est plus grande que celle demandée dans la cuisinière type « boîte fermée ».

Le modèle cyclindro-parabolique, quoiqu'il soit démontable et plus léger que celui de « boîte fermée », n'est pas encore complètement adéquat pour une vie nomade.

Le nouveau modèle demande un entraînement plus grand par les utilisateurs que le modèle « boîte fermée ».

Remerciements

A l'ingénieur investigateur J. Laginha Serafim, pour les suggestions présentées lors de l'élaboration de ce rapport. A Alfredo Mendes et ses collaborateurs pour leurs déterminations de réflectivité, transmittance et radiation solaire. A l'ingénieur Esteves Ferreira pour ses suggestions. A Pedro V. Pereira pour sa collaboration à la réalisation de ce travail.

ANNEXE I

ESSAIS TYPIQUES D'UTILISATION EFFECTUÉS AVEC LA CUISINIÈRE SOLAIRE CYLINDRO-PARABOLIQUE

Le 1er mai 1961

Conditions météorologiques :

Radiation solaire directe. . . .	9h	1,122 cal/cm^2.min
	12h	1,224 cal/cm^2.min
	15h	1,224 cal/cm^2.min
Température . .	22°	
Vent	vitesse moyenne	

Durée

De 10 h 25 à 12 h 25.

Description :

Deux pots d'aluminium (chacun pesant 0,849 kg) et une forme en fer-blanc, sans couvercle, ont été introduits dans le four. Chacun des pots contenait 1,5 kg de pommes de terre et 1 litre d'eau. La forme contenait 0,76 kg de pommes de terre et 0,5 litre d'eau.

Les plus hautes températures atteintes ont été 97° dans l'eau des pots et 110° dans l'air contenu dans le four. Il y a eu formation de vapeur. Les pommes de terre contenues dans les pots étaient parfaitement cuites. Celles de la forme étaient mal cuites, peut-être parce qu'elle était découverte. La quantité d'aliments utilisée dans cet essai a été la plus grande qu'on ait pu introduire dans le four de la cuisinière. L'ajustement de la position de l'appareil a été fait cinq fois, le premier à la fin de 20 min, et les autres chaque 22,5 min.

Le 5 mai 1961

Conditions météorologiques :

Température	20,3°
Vent	faible vitesse

Durée

De 10 h 20 à 11 h 38.

Description :

Les deux pots avec 1 kg de pommes de terre et 1 litre d'eau chacun ont été introduits dans le four.

Les plus hautes températures atteintes ont été 85,5° et 91 °C dans les pots, et 101° dans l'air contenu dans le four.

Les pommes de terre étaient parfaitement cuites.

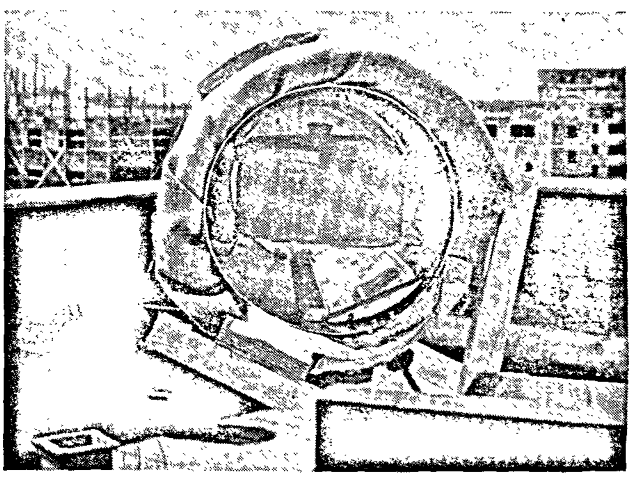

Figure 6. Four de la cuisinière dans lequel sont placés deux pots

Le 7 mai 1961

Conditions météorologiques :

Radiation solaire directe. . . .	9^h	1,214 cal/cm².min
	12^h	1,295 cal/cm².min
	15^h	1,132 cal/cm².min
Température . .	26°	
Vent	brise légère	

Durée

De 12 h 25 à 14 h 5.

Description :

Un des pots contenait un mélange de 0,5 litre de haricots blancs et 0,5 litre de haricots rouges, et 1 litre d'eau. L'autre pot contenait 1 litre de maïs et 1 litre d'eau (voir figure 4).

A la fin de l'essai, les deux pots étaient à 100° et il y avait beaucoup de vapeur d'eau dans le four.

Les haricots et le maïs étaient parfaitement cuits.

Pendant l'essai, on a fait quatre ajustements de la position de l'appareil, chaque 22,5 min.

Le 7 mai 1961

Conditions météorologiques :

Radiation solaire directe. . . .	9^h	1,214 cal/cm².min
	12^h	1,295 cal/cm².min
	15^h	1,132 cal/cm².min
Température . .	26°	
Vent	brise légère	

Durée

De 14 h à 14 h 40.

Description :

On a répandu 1 litre de maïs sur une plaque d'aluminium de longueur égale à celle du four, la face inférieure étant peinte en noir (voir figure 7).

A la fin de 30 min, la plaque était à 135 °C et l'essai a été arrêté parce que le châssis en bois qui retient le verre commençait à flamber. On a vérifié que presque tout le maïs était parfaitement rôti; quelques grains étaient même torréfiés.

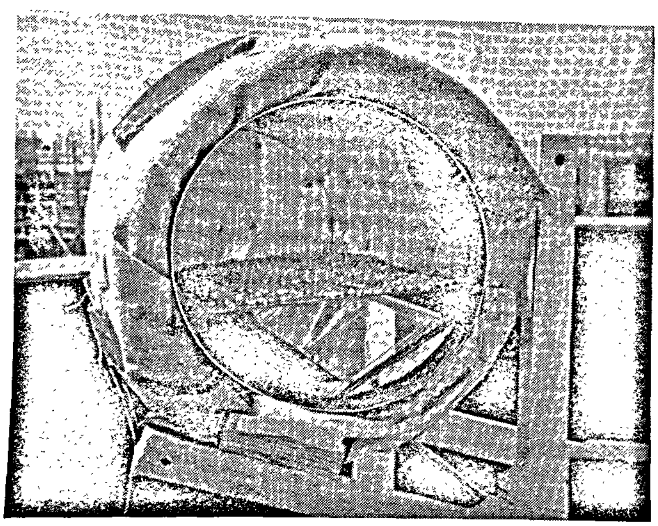

Figure 7. Four avec du maïs

Le 8 mai 1961

Conditions météorologiques

Radiation solaire directe. . . .	9^h	0,920 cal/cm².min
	12^h	0,978 cal/cm².min (brume)
	15^h	0,851 cal/cm².min
Température . .	30°	
Vent	vitesse moyenne	

Durée

De 10 h à 11 h 15.

Description :

Une forme contenant un gâteau de 0,7[illegible] kg a été placée au milieu du four sur une plaque d'aluminium semblable à celle utilisée dans l'essai antérieur, mais avec deux ouvertures circulaires de 120 mm de diamètre.

L'air contenu dans le four a atteint la température de 130 °C. L'utilisation de la plaque d'aluminium indiquée a permis une concentration de la chaleur dans le four. Le gâteau était parfaitement et uniformément cuit.

On doit observer que le jour n'a pas été des meilleurs pour des appareils utilisant la radiation solaire directe.

Le 8 mai 1961

Conditions météorologiques

Radiation solaire directe. . . .	9^h	0,920 cal/cm².min
	12^h	0,978 cal/cm².min (brume)
	15^h	0,851 cal/cm².min
Température . .	30°	
Vent	vitesse moyenne	

Description :

Une poêle à frire contenant 0,350 kg de poisson et une autre contenant 4 œufs ont été placées de 11 h 32 à 11 h 47 dans le four.

Une troisième poêle, contenant 0,25 kg de pommes de terre, a été placée dans le four de 11 h 32 à 12 h.

Au bout de 15 min, quand la température dans le four était de 95°, on a enlevé le couvercle pour vérifier l'état des aliments. Les œufs et le poisson étaient complètement cuits. Les pommes de terre ne l'étaient pas, et il a fallu quelque temps de plus pour qu'elles soient cuites.

Les conditions météorologiques laissaient encore une fois à désirer.

Le 9 mai 1961

Conditions météorologiques

Radiation solaire directe. . . .	9^h	0,690 cal/cm².min
	12^h	0,805 cal/cm².min (brume)
	15^h	0,736 cal/cm².min
Température . .	30°	
Vent	brise légère	

Durée

De 14 h à 16 h.

Description :

Un poulet de 2 kg, après avoir été préparé, a été mis sur une broche appuyée sur les couvercles, dont chacun porte un trou pour la recevoir.

Le poulet était parfaitement cuit et savoureux. La broche a été tournée périodiquement. On doit observer que le jour n'a été relativement faible en radiation directe et que l'essai n'a pas été fait à la meilleure heure.

ANNEXE II

BILAN THERMIQUE

On a fait l'essai complet pour déterminer les pertes de chaleur dans les différents éléments de l'appareil, le rendement et aussi pour obtenir des conclusions concernant l'influence de modifications éventuelles à introduire dans la cuisinière solaire.

L'essai a consisté dans le chauffage de 4 litres d'eau, également distribués par deux pots, et dans la mesure des températures en plusieurs points de l'appareil.

Des couples *thermo-électriques ont été installés* sur les points où l'on souhaitait mesurer la température.

Seize thermocouples ont été installés, avec la distribution suivante :

Deux dans les parois latérales des pots, à mi-hauteur;
Deux plongés dans l'eau, un dans chaque pot;
Quatre dans la paroi intérieure du four, dont un installé sur le couvercle;
Quatre extérieurement au four, sur la laine de verre;
Quatre sur le verre : deux à l'intérieur et deux à l'extérieur.

Les thermocouples installés sur le verre ont été protégés par de petites feuilles d'étain, afin d'éviter des erreurs dues à la radiation solaire ou calorifique agissant sur les thermocouples eux-mêmes.

Les températures ont été mesurées et enregistrées d'une façon presque continue par un appareil Honeywell.

Dans les calculs, on a employé la nomenclature suivante :

A = surface interceptée (mesurée perpendiculairement aux rayons solaires) (0,74 m^2).
I = intensité de la radiation solaire directe à l'heure considérée (calg/cm^2.min).
γ = réflectivité du laiton nickelé (p. 100).
α = transmittance du verre de la fenêtre (p. 100).
E = énergie solaire directe incidente sur le réflecteur cylindro-parabolique, dans un certain intervalle de temps (kcal).
t_i = température moyenne intérieure du four (°C).
t_a = température moyenne extérieure du four, mesurée sur la laine de verre (°C).
r_1 = rayon intérieur du cylindre d'aluminium du four (0,1275 m).
r_2 = rayon extérieur du même cylindre (0,1285 m).
r_3 = rayon extérieur moyen de la laine de verre (0,175 m).
K_A = conductibilité de l'aluminium (195 kcal $h^{-1}m^{-1}°C^{-1}$).
K_l = conductibilité de la laine de verre (0,035 kcal $h^{-1}m^{-1}°C^{-1}$).
L = longueur du four, mesurée entre les faces internes des couvercles (0,65 m).
Δ_t = intervalle de temps (h).
e_A = épaisseur de l'aluminium du cylindre (0,001 m).
e_c = épaisseur de l'aggloméré de liège incorporé dans les couvercles (0,05 m).
e_b = épaisseur de l'aggloméré de copeaux de bois, appliqué dans les couvercles (0,01 m).
K_c = conductibilité de l'aggloméré de liège (0,06 kcal $h^{-1}m^{-1}°C^{-1}$).
K_b = conductibilité de l'aggloméré de copeaux de bois (0,10 kcal $h^{-1}m^{-1}°C^{-1}$).
S = surface de la fenêtre (0,063 m^2).
e_v = épaisseur du verre (0,002 m).
K_V = conductibilité thermique du verre (0,7 kcal $h^{-1}m^{-1}°C^{-1}$).
m = masse de chaque pot d'aluminium (0,849 kg).
C = chaleur spécifique de l'aluminium (0,0696 kcal/kg°C).
t_{fn} et t_{in} = températures finale et initiale du pot n dans l'intervalle de temps Δ_t considéré (°C).
M = masse de l'eau contenue dans le pot (2 kg).
C_a = chaleur spécifique de l'eau (1 kcal/kg°C).
t'_{fn} et t'_{in} = températures finale et initiale de l'eau contenue dans le pot n dans l'intervalle de temps Δ_t considéré.
t_{tt} = température moyenne intérieure du couvercle (°C).
t_V = température moyenne intérieure du verre (°C).
t_e = température moyenne extérieure du verre (°C).
q_c = pertes de chaleur par conduction à travers les parois du four, dans l'intervalle de temps Δ_t considéré (kcal).
q_f = pertes de chaleur par conduction à travers le verre de la fenêtre, dans l'intervalle de temps Δ_t considéré (kcal).
q_r = pertes de chaleur par radiation à travers la fenêtre pendant l'intervalle de temps Δ_t (kcal).
q_i = quantité de chaleur employée dans le chauffage du four (kcal) pendant le temps Δ_t.
$t_{im} = \dfrac{t_i + t_{tt}}{2}$ (°C).
q_u = chaleur utile, reçue par l'eau et par les pots pendant l'intervalle de temps Δ_t (kcal).

Expressions à employer et calculs

Énergie qui entre dans le four = énergie utilisée + pertes

$$E\gamma\alpha = q_u + q_c + q_i + q_r + q_f$$
$$E = A \times I \times 10 \times 15$$

Pour le calcul du produit $\gamma\alpha$, on a considéré que chaque réflecteur était divisé en cinq bandes (parallèles à l'axe du cylindre) d'égale surface projetée. On a déterminé les angles d'incidence des rayons lumineux moyens avec le réflecteur et avec le verre de la fenêtre.

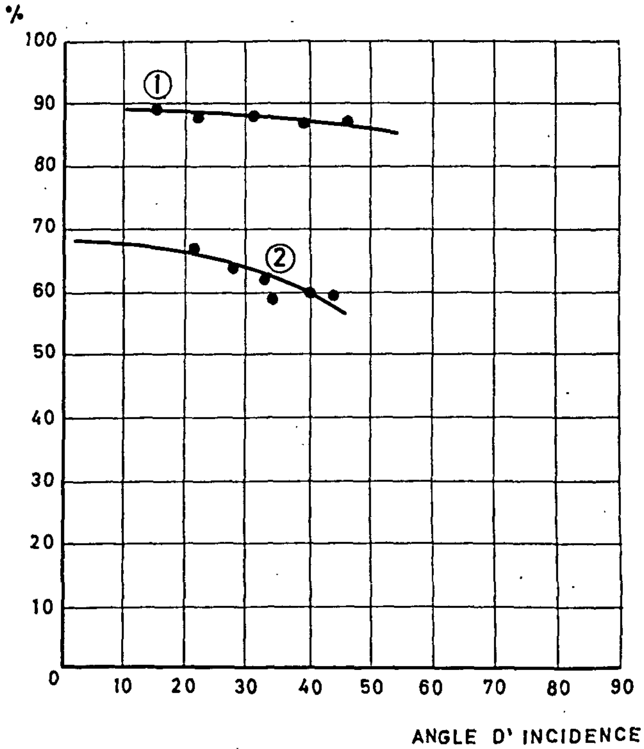

Figure 8. 1. Transmittance d'un verre ordinaire; 2. Réflectivité d'une feuille de laiton nickelé

Du graphique représenté dans la figure 8, on a extrait les valeurs de la réflectivité et de la transmittance correspondantes :

Rayon moyen incident sur la zone n°	Angles d'incidence		Réflectivités	Transmittances
	Sur le réflecteur	Sur le verre		
I (la plus éloignée du four) . .	24°	48°	65,5 p. 100	86,1 p. 100
II	20°	40°	64,4 p. 100	87 p. 100
III	16°	32°	67 p. 100	88 p. 100
IV	12°	24°	67,6 p. 100	88,4 p. 100
V	7,5°	15°	68 p. 100	89 p. 100

La valeur de $\gamma\alpha$ a été calculée par moyenne pondérée, en obtenant 58,7 p. 100.
Alors

$$E\alpha\gamma = 65{,}1 \times I$$

En outre

$$q_c = \left(1 - \frac{S}{2\cdot\pi\cdot r_1\cdot L}\right)\frac{2\cdot\pi\cdot(t_i - t_a)\cdot L\cdot\Delta_t}{\dfrac{l_n\, r_2/r_1}{K_A} + \dfrac{l_n\, r_3/r_2}{K_1}} + \frac{2\cdot\pi\cdot r^2{}_1\cdot\Delta_t\cdot(t_{it} - t_a)}{\dfrac{e_A}{K_A} + \dfrac{e_c}{K_c} + \dfrac{e_b}{K_b}} + 0{,}54\cdot 2\cdot\pi\,\frac{r_2 + r_3}{2}\,K_l\,(t_{lm} - t_a)$$

où

$$\left(1 - \frac{S}{2\cdot\pi\cdot r_1\cdot L}\right)\frac{2\cdot\pi\cdot(t_i - t_a)\cdot L\cdot\Delta_t}{\dfrac{l_n\, r_2/r_1}{K_A} + \dfrac{l_n\, r_3/r_2}{K_1}}$$

représente les pertes par conduction à travers les parois latérales du four,

$$\frac{2\cdot\pi\cdot r_1^2\cdot\Delta_t\,(t_{it} - t_a)}{\dfrac{e_A}{K_A} + \dfrac{e_c}{K_c} + \dfrac{e_b}{K_b}}$$

représente les pertes à travers les couvercles,
et

$$0{,}54\cdot 2\cdot\pi\,\frac{r_2 + r_3}{2}\,K_l\,(t_{lm} - t_a)$$

représente les pertes par conduction à travers les espaces annulaires extrêmes (les diamètres intérieur et extérieur sont les mêmes que ceux du four, et l'épaisseur est égale à celle des couvercles).

Pour les pertes par conduction à travers le verre de la fenêtre, on obtient :

$$q_j = \frac{S\,(t_v - t_e)\,\Delta_t}{\dfrac{e_v}{K_v}}$$

La chaleur récupérée par l'eau et les pots sera

$$q_u = mc\,(t_{f1} - t_{i1}) + mc\,(t_{f2} - t_{i2}) + Mc_a\,(t'_{f1} - t'_{i1}) + Mc\,(t'_{f2} - t'_{i2})$$

En considérant $\Delta_t = 0{,}25$ heure et en substituant des valeurs on obtient :

$$\begin{aligned}
q_c &= 0{,}09767\,(t_i - t_a) + 0{,}0273\,(t_{it} - t_a) + 0{,}018\,(t_{lm} - t_a)\\
q_j &= 5{,}5\,(t_v - t_e)\\
q_u &= 0{,}059\,(t_{f1} + t_{f2} - t_{i1} - t_{i2}) + 2\,(t'_{f1} + t'_{f2} - t'_{i1} - t'_{i2})\\
q_i &= 0{,}14\,\Delta\,(t_{it} + t_a) + 0{,}291\,\Delta\,(t_i + t_a) + 0{,}178\,\Delta\, t_i + 0{,}065\,\Delta\,(t_v + t_e)
\end{aligned}$$

Dans la dernière expression, les termes ont la signification suivante :

$0{,}14\ \Delta\,(t_{it} + t_a)$: chaleur accumulée par l'aggloméré de liège.
$0{,}291\ \Delta\,(t_i + t_a)$: chaleur accumulée par la laine de verre.
$0{,}178\ \Delta\, t_i$: chaleur accumulée par l'aluminium et le châssis du verre.
$0{,}065\ \Delta\,(t_v + t_e)$: chaleur accumulée par le verre.

Dans tous les termes où le Δ précède une température ou addition de températures, on veut dire qu'il s'agit de la variation de cette température ou de la somme de températures dans l'intervalle de temps considéré.

Une fois les valeurs de q_c, q_j, q_u et q_i calculées et la valeur de I connue, la valeur de q_r peut être obtenue par calcul :

$$q_r = 65{,}1 \times I - q_u - q_i - q_c - q_j$$

Le tableau résume les résultats des calculs.

Comme on a considéré $\Delta_t = 0{,}25$ heure, l'essai, dont la durée a été de deux heures, a été partagé, à cause du calcul, en huit intervalles, sur chacun desquels on a fait le bilan thermique tel qu'on vient de le montrer.

Les températures instantanées ne nous intéressent pas pour le calcul. Donc t_{it}, t_i, t_a, t_v et t_e sont pris en moyenne à l'intervalle de temps considéré. Mais on prend déjà la différence, par exemple, pour $\Delta\,(t_{it} + t_a)$ entre la valeur $t_{it} + t_a$ à la fin de l'intervalle de temps considéré, et la valeur correspondante au commencement du même intervalle. Il en est de même, par exemple, pour $t_{f2} - t_{i2}$.

Des valeurs obtenues pour q_r, il y en a quatre qui ne sont pas logiques parce que trop petites. Ce sont justement les valeurs correspondant aux intervalles de temps II, VI, VII et VIII.

Résumé des calculs

Intervalle de temps	$t_i - t_a$ °C	$t_{ii} - t_a$ °C	$t_{im} - t_a$ °C	$t_v - t_e$ °C	$t_{f_1} + t_{f_2} - t_{i_1} - t_{i_2}$ °C	$t'_{f_1} + t'_{f_2} - t'_{i_1} - t'_{i_2}$ °C	$\Delta(t_{ii} + t_a)$ °C	$\Delta(t_i + t_a)$ °C	Δt_i °C	$\Delta(t_v + t_e)$ °C
I 11 h-11 h 15	2,3	—1,4	0,5	0,4	17	16,1	10,8	16,9	14,6	33,9
II 11 h 15-11 h 30 . . .	15,5	5,5	10,5	0,75	18,5	18,7	11,5	17,9	15,9	23,3
III 11 h 30-11 h 45 . . .	23,1	10,1	16,6	0,9	15,9	17,2	8,0	7,7	4,5	2,8
IV 11 h 45-12 h	26,6	16,0	20,3	0,3	17,3	18,2	6,5	5,8	5,7	— 10,1
V 12 h-12 h 15	31,2	22,2	25,4	0,5	16,5	16,1	5,3	2,6	3,1	3,7
VI 12 h 15-12 h 30 . . .	35,1	23,1	29,4	2,3	16,3	17,3	3,1	5,7	5,1	16,8
VII 12 h 30-12 h 45 . . .	39,4	26	33,1	2,5	17,8	17,8	5,9	7,0	5,9	12,5
VIII 12 h 45-13 h	41,3	34,5	35,9	3,2	10,6	10,6	12,9	8,2	3,8	12

Intervalle de temps	I cal/cm².min	$E\alpha\gamma$ kcal	q_c kcal	q_j kcal	q_u kcal	q_i kcal	q_r kcal
I 11 h-11 h 15	0,835	54,3	0,19	2,2	33,2	12,28	6,43
II 11 h 15-11 h 30.	0,84 0,96*	54,7 62,5*	1,85	4,12	38,49	11,16	— 0,9 7,0*
III 11 h 30-11 h 45.	0,84	54,7	2,82	4,95	35,34	4,34	7,25
IV 11 h 45-12 h	0,84	54,7	3,40	1,65	37,42	2,95	9,32
V 12 h-12 h 15	0,837	54,5	4,11	2,75	33,17	2,07	12,4
VI 12 h 15-12 h 30.	0,835 1,14*	54,3 73,83*	4,59	12,6	35,56	4,09	— 2,54 17,0*
VII 12 h 30-12 h 45.	0,83 1,27*	54,0 82,69*	5,16	13,7	36,65	4,71	— 7,1 23,0*
VIII 12 h 45-13 h	0,825 1,32*	53,8 86,54*	5,62	17,6	21,83	5,65	3,01 26,3*

On donne l'explication suivante de cette anomalie : la valeur de la radiation solaire, I, a été déterminée d'après les points de la courbe, tandis que les valeurs intermédiaires (voir figure 9) ont été obtenues par interpolation. Or il se peut que précisément pendant les intervalles II, VI, VII et VIII la radiation solaire ait été élevée, dépassant les valeurs interpolées. Cette hypothèse est vraisemblable, car le jour était brumeux lors de l'essai. Il serait suffisant que I ait pris les valeurs marquées par un astérisque pour que les valeurs correspondantes q_r prennent des valeurs acceptables, marquées elles aussi par un astérisque et obtenues par évaluation. Ce sont ces dernières valeurs qu'on considère pour le calcul du rendement.

Calcul du rendement total pendant deux heures de fonctionnement

$$\gamma\alpha = 58{,}7 \text{ p. } 100$$

Quantité de chaleur reçue par l'eau et les pots :

$$\sum_{I}^{VIII} q_u = 275{,}66 \text{ kcal}$$

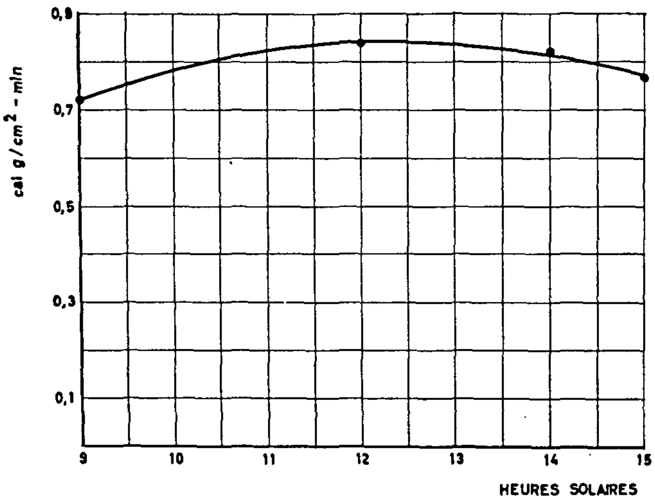

Figure 9. Radiation solaire directe

Énergie solaire totale qui entre dans le four :

$$\sum_{I}^{VIII} E\,\gamma\alpha = 523{,}76 \text{ kcal}$$

Énergie solaire reçue par les miroirs :

$$\sum_{I}^{VIII} E = \frac{523{,}76}{0{,}587} = 892 \text{ kcal}$$

Énergie calorifique perdue par radiation à travers le verre :

$$\sum_{I}^{VIII} q_r = 108{,}7 \text{ kcal}$$

Énergie calorifique perdue par conduction à travers le verre :

$$\sum_{I}^{VIII} q_f = 60{,}57 \text{ kcal}$$

Énergie calorifique utilisée pour chauffer le four :

$$\sum_{I}^{VIII} q_i = 47{,}25 \text{ kcal}$$

Énergie calorifique perdue à travers les parois du four :

$$\sum_{I}^{VIII} q_c = 30{,}10 \text{ kcal}$$

Énergie utilisable :

$$\frac{275{,}66 \times 100}{892} = 31 \text{ p. } 100$$

Pertes optiques :

$$100 - 58{,}7 = 41{,}3 \text{ p. } 100$$

Pertes par radiation :

$$\frac{108{,}7 \times 100}{892} = 12{,}2 \text{ p. } 100$$

Pertes par conduction à travers le verre :

$$\frac{60{,}57 \times 100}{892} = 6{,}8 \text{ p. } 100$$

Pertes dues à l'inertie thermique :

$$\frac{47{,}35 \times 100}{892} = 5{,}3 \text{ p. } 100$$

Pertes par conduction à travers les parois du four :

$$\frac{30{,}10}{892} = 3{,}4 \text{ p. } 100$$

Le rendement du four sera :

$$\frac{31}{0{,}587} = 52{,}8 \text{ p. } 100$$

Conclusions tirées des bilans thermiques

Par les raisons déjà citées, et quoique certaines températures, par exemple la température des verres, aient été obtenues par moyenne des valeurs mesurées d'après un nombre insuffisant de points, les valeurs présentées pour les rendements et les pertes ne donnent qu'un ordre de grandeur.

Le rendement optique et celui du four sont faibles.

Le rendement donné n'est pas un indice des possibilités les plus grandes de l'appareil, puisque l'essai a été fait un jour brumeux.

On doit observer que si, au lieu du laiton nickelé ($\gamma = 0{,}67$), on utilise un matériau ayant un pouvoir réflecteur $\gamma = 0{,}80$, le rendement optique change de 58,7 à 70 p. 100 et le rendement global changera de 31 à 37 p. 100.

Parce que les pertes par conduction à travers les parois du four sont supérieures à celles dues à l'inertie thermique, on peut conclure qu'il convient de réduire l'épaisseur de l'isolant, qui est l'élément ayant la plus grande capacité calorifique.

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Résumé

Ce mémoire présente un modèle de cuisinière solaire d'une nouvelle conception.

Les rayons solaires sont captés dans un réflecteur cylindro-parabolique qui les transmet à une fenêtre vitrée mince dans la partie inférieure de la boîte cylindrique à axe horizontal, placée au foyer du paraboloïde. Les aliments à préparer sont placés dans la boîte, qui est isolée.

Cette conception permet d'augmenter le degré de concentration et de réduire les pertes du four.

L'auteur donne les résultats obtenus dans les essais d'un modèle, et présente des remarques sur la nécessité d'ajustements de position, et sur le prix et l'utilisation de la cuisinière solaire.

Ce modèle est comparé à tous points de vue avec l'autre type existant.

On calcule ses pertes et son rendement.

A CYLINDRO-PARABOLIC SOLAR COOKER

(Translation of the foregoing paper)

Salgado Prata *

The models of solar cookers tried up to now belong essentially to one of two types, parabolic or "hot-box".

Parabolic models have been discussed by Ghai (2,3), Burda (4), J. A. Duffie (5), J. R. Jenness (6) and others. "Hot-box" models have been studied and developed by M. Telkes (1).

Parabolic cookers give high concentration, but the cooking utensil is exposed and thus loses a good deal of heat to the atmosphere, especially if there is wind. The "hot-box" models are more expensive, heavier, and provide only low concentration, but they shelter the cooking utensils and can keep the food hot for several hours after cooking, provided the food is left in them.

We have sought in the new model presented in this paper to combine these two basic features.

In this paper we give the results of tests and studies of this new cooker model, and compare its results with those of a "hot-box" model, figure 4.

Description and principle of operation

A cylindro-parabolic mirror composed of two elements (figures 1, 2 and 3)[1] is turned to the sun. The oven, of cylindrical shape, with a slit window through which the solar rays enter, is placed at the focus of the mirror. The cooking utensils containing the food to be cooked are placed in the oven. Both elements of the parabolic cylinder, and the oven itself, are supported by four legs, properly braced.

Each reflector, made of nickel-plated brass sheet, is attached to a wooden structure traversed by a supporting shaft, about which it may be rotated. This shaft permits the reflector to be focused. It may be fixed in any desired position by means of slip rings (figure 1).

The oven is built of doubled aluminium sheet, forming a cylinder, protected on the outside by glasswool. Its own "shell" shape gives it the necessary longitudinal rigidity. The tendency to ovalization is counteracted by the covers, which also serve as doors. In its lower part, the cylinder has an elongated window along one generatrix to admit the concentrated solar radiation. To reduce the radiative and convective losses through the window, a glass pane is installed on the inside, and on the outside a plate of Mylar plastic film is glued onto the cylinder itself.

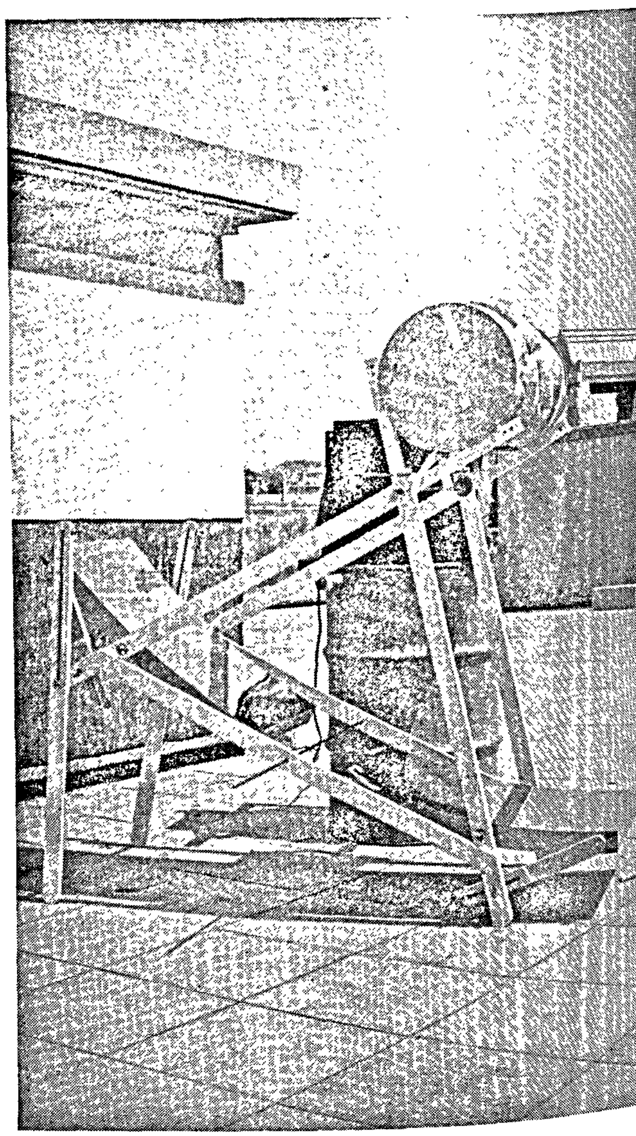

Figure 1. Cylindro-parabolic solar cooker viewed from the side of the slip rings

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[1] It should be noted that the model sketched in this figure differs from that actually built. The model sketched is all metal.

The mirrors are eccentrically positioned relative to the window, so that the position of the apparatus need not be so frequently adjusted to the changing azimuth of the sun.

Interception of the maximum of solar radiation by means of the minimum reflecting surface has been sought in this design.

This object is realized by designing the mirrors as open parabolas. The parabola practically merges into a circumference. Moreover, with a great radius of curvature, the angles of incidence of the rays reflected by the most distant zones of the mirror on the glass of the window are not too great, so that the reflection losses are low. It should also be noted that this design permits placing the oven at a level convenient for the user.

The conception of this cooker model allows the prediction that the radiative losses through the window will be small, since its surface is relatively small. The situation is the same for the convective losses. Further than that, the heat flux travels downward, so that there will be practically no convective losses; there will, however, be conductive losses. However, these will be smaller.

Typical utilization tests with the cylindro-parabolic model

The times indicated throughout the description refer in all cases to solar time. The tests were run at Lisbon (38° N. Lat.).

The following are the most important results.

Food cooked	*Direct solar radiation (cal/cm² min)*			*Duration*	*Remarks*
	9 h	*12 h*	*15 h*		
Boiling 3.76 kg of potatoes .	1.122	1.224	—	10.25 h-12.25 h	Largest amount of food that would go into the stove
Boiling 2 kg of potatoes . .	1.122	1.224	—	10.20 h-11.38 h	
Boiling 1 ltr of string-beans and 1 ltr of cornmeal . .	1.214	1.295	1.132	12.25 h-14.05 h	
Roasting 1 ltr of cornmeal .	1.214	1.295	1.132	14.10 h-14.40 h	
Baking a cake, 0.710 kg . .	0.92	0.978 (fog)	0.851	10.00 h-11.15 h	
Frying fish and eggs	0.92	0.978 (fog)	0.851	11.32 h-11.47 h	
Roasting a 2 kg chicken . .	0.690	0.805 (fog)	0.736	14 h-16 h	The chicken was perfectly cooked and delicious

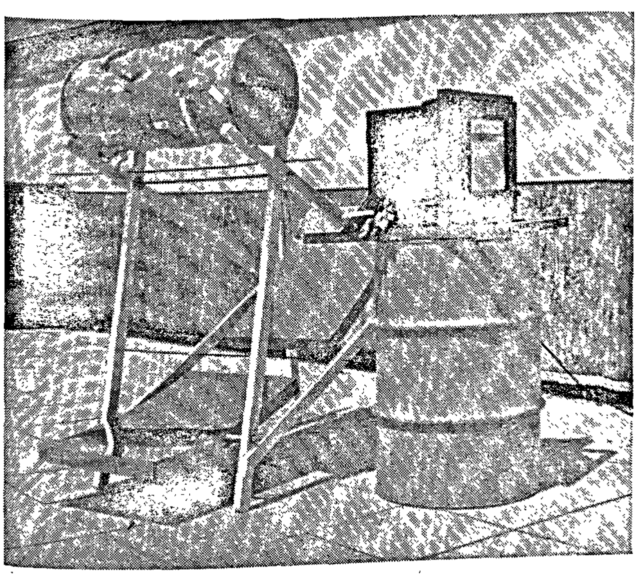

Figure 2. Cylindro-parabolic solar cooker, viewed from the side of the food door. The Honeywell recording thermometer will be seen beside the cooker

More details on these tests will be found in the annex.

Utilization tests on a "hot-box" model

On 6 May 1961, a day of exceptionally strong direct solar radiation (1.203, 1.334 and 1.242 cal/cm² min at 9, 12 and 15 h respectively), 1.5 kg of potatoes were cooked in a pot with 1 litre of water, in 2 h 30 min (from 11.50 h to 14.20 h). This gave the best result obtained with this model.

On a day when the radiation was as intense as on 6 May 1961, it took two and a half hours to cook 1 litre of string-beans in a pot with 1 litre of water.

In September 1960 it was also found that the "hot-box" model baked cakes in 2 h 15 min and cooked meat in 2 h 45 min.

Cornmeal or meat, however, could not be roasted.

Conclusions from the utilization tests

(*a*) The cylindro-parabolic cooker cooks two and a half times as much food as the "hot-box" type,

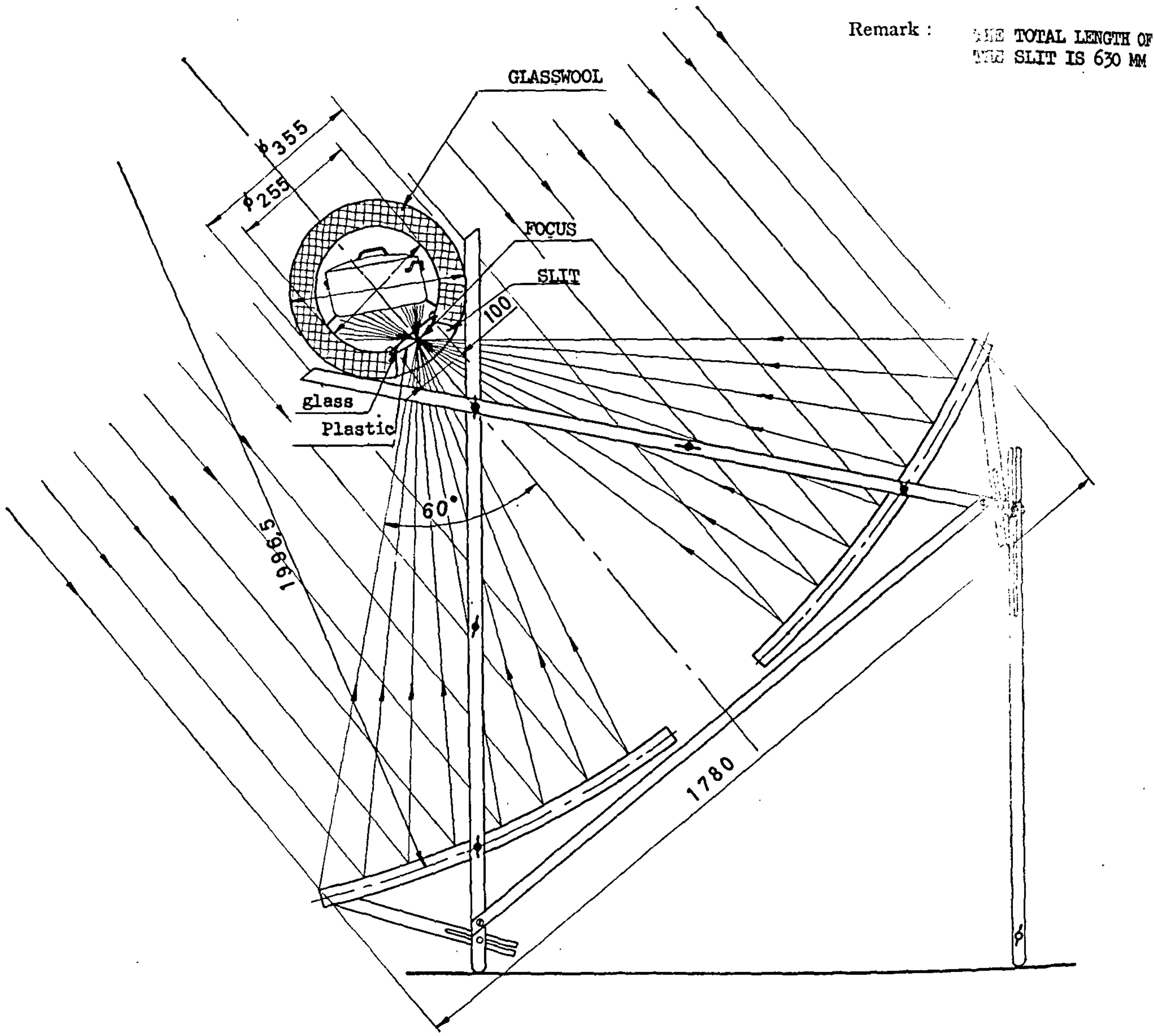

Figure 3. Schematic diagram, principal dimensions, and operating diagram

and in a shorter time. It also roasts corn and meat, which cannot be done with the other model.

(*b*) The orientation of the apparatus must be periodically adjusted to compensate for the change in the solar zenith angle and azimuth. The azimuthal adjustment is constant, and must be made every 22.5 min. The required frequency of azimuthal adjustment varies with the hour of the day. From 10.30 h to 13.30 h, it may be made at intervals of 22.5 to 40 m. This means that if the preparation of food that takes 1 h 30 min to cook completely is at 10.30 h, only three adjustments of position will be needed, at intervals of 22.5 min, each adjustment comprising one change of the zenith angle of the collector and another change in its azimuth. The same applies for the period between 12 h and 13.30 h.

Consequently, two meals a day can be cooked, the cooking time of each being 1 h 30 min, provided the position of the apparatus is adjusted in this way. The food cooked during the second period, normally used for dinner, may be kept hot for several hours provided it is kept in the oven of the solar cooker.

It must be noted that when the position of the stove is adjusted, the cooking utensils should not be touched, if they are not too full. Moreover, it is easy to design a grill to slide along the stove walls while always remaining horizontal.

If the user desires to cook before 10.30 h or after 13.30 h, with the same interval between each adjustment of position, the window will have to be enlarged and the efficiency of the stove diminished.

If a longer interval is desired between the adjustments near noon, which are due to the changes in solar azimuth, the window will have to be lengthened and consequently the stove as well, likewise with an adverse effect on efficiency. In this case, the loss in efficiency will be greater, owing not only to the increased radiative losses, in spite of the increased

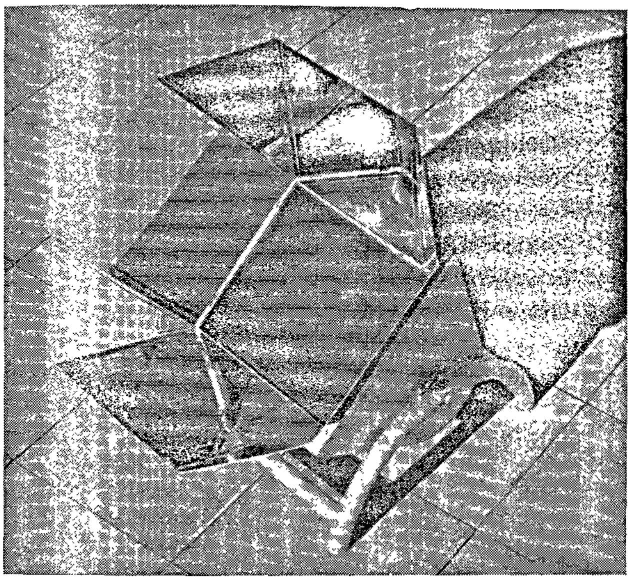

Figure 4. "Hot-box" solar cooker

length of the window, but also the increased conductive losses, since the length of the stove is also increased. The frequency of the azimuthal and zenithal adjustments may also be decreased by shortening the focal length of the cylindro-parabolic mirror. But this would increase the cost since, for equal intercepted surface, the curvature of the mirrors would be greater, thus requiring a larger amount of reflecting material.

(*c*) The efficiency was found to be higher without the Mylar plastic film which, according to the initial design, was pasted on the outside of the aluminium cylinder and covered the window.

In other words, the thermal energy retained by the plastic did not compensate the solar energy dissipated by absorption and reflection. In all the tests described, the parabolic cylinder utilized an oven with a single window 10 cm wide, covered by only a single thickness of glass.

(*d*) We conclude that it would be appropriate to paint the entire outside surface of the cooking vessels black.

(*e*) It was also found to be preferable to rest the cooking utensils on grills instead of on a continuous plate as long as the window, painted black on the inner surface, and exposed to the concentrated solar radiation. It seems legitimate to conclude from this that, if a polished aluminium plate had been used to build the stove instead of a plate of ordinary aluminium, the results would have been better than those actually obtained. The use of the plate would be advisable only if the dimensions of the cooking utensil were small enough by comparison to those of the stove, or when a certain food had to be spread over a relatively extended area, as when corn is roasted.

(*f*) Unless pressure cookers are used, there should be an outlet for the steam formed. Otherwise it will condense on the coldest parts of the glass. The best way of doing this is to make holes in the pots and put them in communication with the atmosphere by means of a duct. This will prevent the loss to the atmosphere of the heated air in the oven.

(*g*) In the "hot-box" model, only the azimuth was adjusted, and that less frequently than in the new model.

Cost of the cooker

This estimate assumes a metal structure that can be completely dismantled.

The oven design may resemble the above- described model.

The legs and the cross bracing may be made of mild steel bars 20 × 3, provided framing members (see figure 3) are placed half way. The framing members connect the legs, thus preventing buckling.

The reflectors may be made of nickel-plated aluminium. The frame supporting them, also of aluminium, may be constructed as indicated in figure 5.

In this way, assuming manufacture in medium-scale series, it would cost $18.00 for materials (including the cost of the nickel-plating) and 8 man-hours of labour. The apparatus would weigh 18 kg.

If the construction is all-aluminium, the apparatus would cost more, but it would now weigh only about 12 kg.

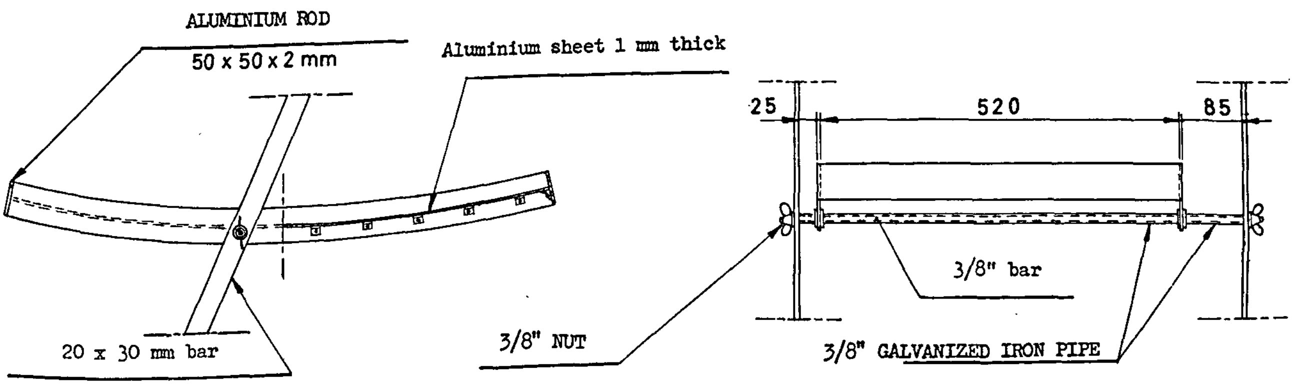

Figure 5. Detail of the reflectors

The materials and labour required for a "hot-box" model of the same dimensions as that tested, that is, with 0.48 m^2 of area normal to the solar rays, would be about the same as that indicated for the cylindro-parabolic model, and it would weigh 22 kg.

Conclusions

The cooker here presented can cook comparatively large amounts of food of any kind, in some cases requiring only little longer than conventional domestic cookers.

The effective collector surface, normal to the solar rays, is 0.74 m^2 in the parabolic model we have built. The corresponding surface of the "hot-box" model referred to in this paper is 0.48 m^2. Further than that, the quantity of food cooked in the same time is 2.8 times as great for our model as for the "hot-box". This means that the cylindro-parabolic solar cooker is $2.8: (0.74/0.48) = 1.8$ times as efficient as the "hot-box". For equal effective collector surfaces, the cylindro-parabolic model is cheaper. The required frequency of position adjustment of this solar cooker is acceptable, but greater than for the "hot-box" type of cooker.

The cylindro-parabolic model can be dismantled and is lighter than the "hot-box" model, but is still not entirely adequate for nomad life.

The new model requires more position adjustment by the user than the "hot-box" model.

Acknowledgements

The author wishes to express his gratitude to Research Engineer J. Laginha Serafim, for suggestions in working out this paper, to Alfredo Mendes and his associates for their help in the determinations of reflectivity, transmittance and solar radiation, to Engineer Esteves Ferreira for his suggestions and to Pedro V. Pereira for his collaboration in this work.

ANNEX I

TYPICAL UTILIZATION TESTS ON THE CYLINDRO-PARABOLIC SOLAR COOKER

(a) *On 1 May 1961*

Meteorological conditions.

Direct solar radiation	9 h	1.122 Cal/cm^2min
	12 h	1.224 Cal/cm^2min
	15 h	1.224 Cal/cm^2min
Temperature	22°C	
Wind	Moderate breeze	

Duration of test from 10.25 h to 12.25 h

Description:

Two aluminium pots, each weighing 0.849 kg, and a galvanized iron coverless mould, were placed in the oven. Each pot contained 1.5 kg of potatoes and 1 ltr of water. The mould contained 0.76 kg of potatoes and 0.5 ltr of water.

The highest temperatures attained were 97°C in the water of the pots and 110°C for the air in the oven. Steam was formed.

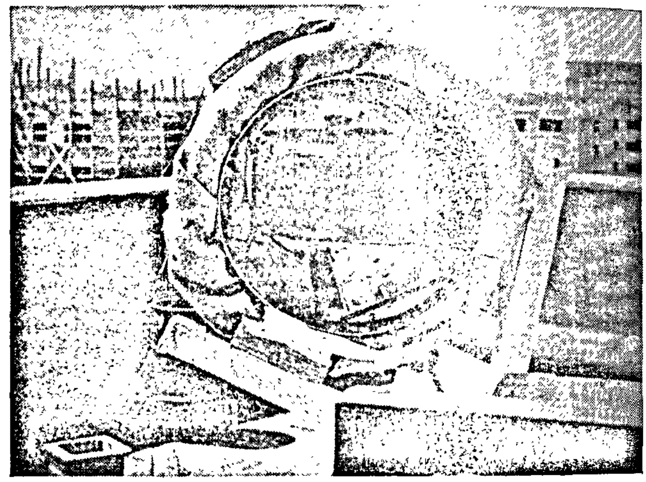

Figure 6. Oven of the cooker, which holds two pots

The potatoes in the pots were cooked perfectly. Those in the mould were under-cooked, perhaps because it was open. The amount of food used in this test was the greatest that could be accomodated in the oven of the cooker. The position of the apparatus was changed five times, the first time after 20 min, and the other times at 22.5 min intervals.

(b) *On 5 May 1961*

Meteorological conditions.

Temperature	20.3°C
Wind	Gentle breeze

Duration of test from 10.20 h to 11.38 h

Description:

The two pots, each with 1 kg of potatoes and 1 ltr of water, were placed in the oven.

The highest temperatures attained were 85.5°C and 91°C in the pots and 101°C in the air in the oven.

The potatoes were perfectly cooked.

(c) *On 7 May 1961*

Meteorological conditions.

Direct solar radiation	9 h	1.214 Cal/cm^2min
	12 h	1.295 Cal/cm^2min
	15 h	1.132 Cal/cm^2min
Temperature	26°C	
Wind	Light breeze	

Duration of test from 12.25 h to 14.05 h

Description:

One of the pots contained a mixture of 0.5 ltr of white string-beans, 0.5 ltr of red string-beans, and 1 ltr of water. The other pot contained 1 ltr of cornmeal and 1 ltr of water (see figure 4).

At the end of the test both pots were at 100°C, and there was much steam in the oven.

The string-beans and cornmeal were perfectly cooked.

Four adjustments of the collector position were made during the test at intervals of 22.5 min.

(d) *On 7 May 1961*

Meteorological conditions.

Direct solar radiation	9 h	1.214 Cal/cm^2min
	12 h	1.295 Cal/cm^2min
	15 h	1.132 Cal/cm^2min

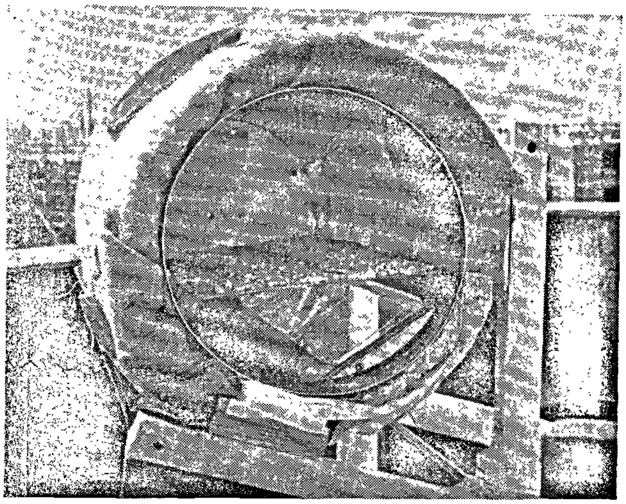

Figure 7. Oven with corn

Temperature	26°C
Wind.	Light breeze

Duration of test from 14 h to 14.40 h

Description:

One litre of cornmeal was spread on an aluminium plate as long as the oven, with its lower face painted black (see figure 7).

At the end of 30 min the plate had reached 135°C and the test was stopped because the wooden frame holding the glass was beginning to buckle. Almost all the cornmeal was perfectly roasted, and some of it was even parched.

(e) *On 8 May 1961*

Meteorological conditions.

Direct solar radiation. .	9 h	0.920 Cal/cm²min
	12 h	0.978 Cal/cm²min
	15 h	0.851 Cal/cm²min (fog)
Temperature	30°C	
Wind.	Moderate breeze	

Duration of test from 10 h to 11.15 h

Description:

A mould containing a cake weighing 0.710 kg was placed at the centre of the oven on an aluminium plate similar to that used in the preceding test, but with two circular openings, each 120 mm in diameter.

The air in the oven reached 130°C. The use of this aluminium plate permitted a concentration of heat in the oven. The cake was perfectly and uniformly baked.

It should be noted that the day was not one of the best for utilizing direct solar radiation.

(f) *On 8 May 1961*

Meteorological conditions.

Direct solar radiation. .	9 h	0.920 Cal/cm²min
	12 h	0.978 Cal/cm²min (fog)
	15 h	0.851 Cal/cm²min
Temperature	30°C	
Wind.	Moderate breeze	

Description:

A frying-pan with 0.350 kg of fish; another with 4 eggs	*From 11.32 h to 11.47 h*
Another frying-pan with 0.25 kg of potatoes was placed in the oven .	From 11.32 h to 12.07 h

At the end of 15 min, when the oven temperature was 95°C, the cover was removed to check the condition of the food. The eggs and the fish were both completely cooked. The potatoes were not, and they were therefore left a little longer in the oven, after which they were found to be cooked.

The meteorological conditions were likewise not very good

(g) *On 9 May 1961*

Meteorological conditions.

Direct solar radiation. .	9 h	0.690 Cal/cm²min
	12 h	0.805 Cal/cm²min (fog)
	15 h	0.736 Cal/cm²min
Temperature	30°C	
Wind.	Fresh breeze	

Duration from 14 h to 16 h

Description:

A 2 kg chicken was first prepared, after which a spit was passed through it. Each of the covers had a hole to receive the spit.

The chicken was perfectly cooked and delicious.

The spit supporting it was periodically rotated. It should be noted that the direct radiation was relatively low that day and that the test was not performed at the best hour for it.

ANNEX II

Heat balance

A complete test was run to determine the heat losses in the various components of the apparatus and the efficiency, and also to obtain data for drawing conclusions on the effect of possible changes that might be made in the solar cooker.

The test consisted in heating 4 litres of water, equally distributed in two pots, and in measuring the temperature at a number of points of the cooker.

Thermocouples were installed at the points where the temperature was to be measured.

Sixteen thermocouples were installed, distributed as follows:

Two in the side walls of the pots, half-way to the top;
Two immersed in the water, one in each pot;
Four in the inside oven wall, one of them on the cover;
Four outside the oven, on the glasswool;
Four on the glass: two of them inside, the other two outside.

The thermocouples on the glass were protected by small leaves of tinfoil to prevent errors due to the radiation of the sun or heater on the thermocouples themselves.

The temperatures were measured and recorded semi-continuously by a Honeywell recording thermometer.

The following notation was used in the calculations:

A = Intercepted surface (measured perpendicular to the solar rays) (0.74 m²).
I = Intensity of direct solar radiation at the given time (kcal/cm²min).
γ = Reflectivity of nickel-plated brass (per cent).
α = Transmittance of the glass of the window (per cent).
E = Direct solar radiation incident on the cylindro-parabolic reflector during a certain time interval (kcal).
t_i = Mean internal temperature of oven (°C).
t_a = Mean external temperature of oven (measured on the glasswool) (°C).
r_1 = Inside radius of aluminium cylinder of oven (0.1275 m).
r_2 = Outside radius of the same cylinder (0.1285 m).

r_3 = Mean outside radius of the glasswool (0.175 m).
K_A = Thermal conductivity of the aluminium (195 kcal $h^{-1}m^{-1}{}^\circ C^{-1}$).
K_1 = Thermal conductivity of the glasswool (0.035 kcal $h^{-1}m^{-1}{}^\circ C^{-1}$).
L = Length of oven measured between inside faces of the covers (0.65 m).
Δ_t = Time interval (h).
e_A = Thickness of the aluminium of cylinder (0.001 m).
e_c = Thickness of the cork composition incorporated in the covers (0.05 m).
e_b = Thickness of the composition of wood shavings applied in the covers (0.01 m).
K_c = Thermal conductivity of the cork composition (0.06 kcal $h^{-1}m^{-1}{}^\circ C^{-1}$).
K_b = Thermal conductivity of the wood-shavings composition (0.10 kcal $h^{-1}m^{-1}{}^\circ C^{-1}$).
S = Surface of the window (0.063 m^2).
e_v = Thickness of the glass (0.002 m).
K_V = Thermal conductivity of glass (0.7 kcal $h^{-1}m^{-1}{}^\circ C^{-1}$).
m = Mass of each aluminium pot (0.849 kg).
C = Specific heat of aluminium (0.0696 kcal/kg°C).
t_{fn} and t_{in} = Final and initial temperatures of the pot n during the time interval Δ_t considered (°C).
M = Mass of the water in the pot (2 kg).
C_a = Specific heat of water (1 kcal/kg°C).
t'_{fn} and t'_{in} = Final and initial temperatures of the water in the pot n during the time interval Δ_t considered.
t_{it} = Mean inside temperature of cover (°C).
t_V = Mean inside temperature of glass (°C).
t_e = Mean outside temperature of glass (°C).
q_c = Heat losses by conduction through the oven wall, during the time interval Δ_t considered (kcal).
q_j = Heat losses by conduction through the glass of the window, during the time interval Δ_t considered (kcal).
q_r = Heat losses by radiation through the window during the time interval Δ_t considered (kcal).
q_i = Quantity of heat used in heating the oven (kcal) during the time interval Δ_t considered (kcal).
$t_{im} = \frac{t_i + t_{it}}{2}$ (°C).
q_u = Useful heat received by the water and the pots during the time interval Δ_t considered (kcal).

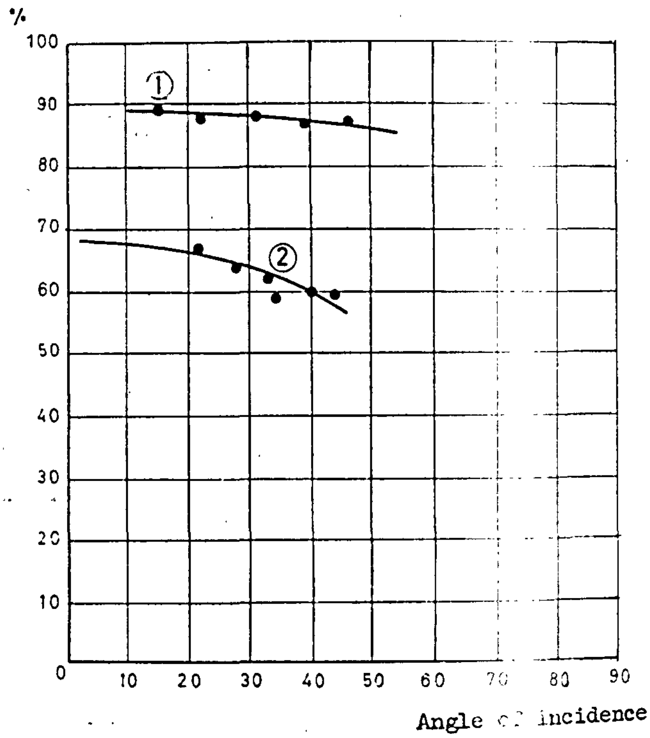

Figure 8. 1. Transmittance of ordinary glass; 2. Reflectivity of nickel-plated brass sheet

Expressions used in the calculations

Energy entering the oven = energy utilized + losses

$$E\gamma\alpha = q_u + q_c + q_i + q_r + q_j$$
$$E = AI \cdot 10 \cdot 15$$

In calculating the product $\gamma\alpha$, each reflector is considered as divided into five bands (parallel to the axis of the cylinder) of equal projected surface. The angles of incidence of the central light rays in the reflector and on the glass of the window are determined.

From the graphs of figure 8 we find the corresponding values of the reflectivity and transmittance

Central incident ray on zone No.	Angle of incidence		Reflectivity	Transmittance
	On the reflector	On the glass		
I the farthest from the oven . .	24°	48°	65.5 per cent	86.1 per cent
II	20°	40°	64.4 per cent	87 per cent
III	16°	32°	67 per cent	88 per cent
VI	12°	24°	67.6 per cent	88.4 per cent
V	7.5°	15°	68 per cent	89 per cent

The weighted mean of $\gamma\alpha$ was calculated, and found to be 58.7 per cent.
Then

$$E\alpha\gamma = 65.1 \times I$$

Moreover,

$$q_c = \left(1 - \frac{S}{2\cdot\pi\cdot r_1\cdot L}\right)\frac{2\cdot\pi\cdot(t_i - t_a)\cdot L\cdot\Delta_t}{\frac{l_n\, r_2/r_1}{K_A} + \frac{l_n\, r_3/r_2}{K_1}} + \frac{2\cdot\pi\cdot r^2_1\cdot\Delta_t\cdot(t_{it} - t_a)}{\frac{e_A}{K_A} + \frac{e_c}{K_c} + \frac{e_b}{K_b}} + 0.54\cdot 2\cdot\pi\,\frac{r_2 + r_3}{2}\,k_l\,(t_{im} - t_a)$$

whence

$$\left(1 - \frac{S}{2\cdot\pi\cdot r_1\cdot L}\right)\frac{2\cdot\pi\cdot(t_i - t_a)\cdot L\cdot\Delta_t}{\frac{l_n\, r_2/r_1}{K_A} + \frac{l_n\, r_3/r_2}{K_1}}$$

representing the losses by conduction through the side walls of the oven.

$$\frac{2 \cdot \pi \cdot r^2_1 \cdot \Delta_t (t_i - t_a)}{\frac{e_A}{K_A} + \frac{e_c}{K_c} + \frac{e_b}{K_b}}$$

representing the losses through the covers

and

$$0.54 \cdot 2 \cdot \pi \frac{r_2 + r_3}{2} K_l (t_{im} - t_a)$$

representing the losses by conduction through the extreme annular spaces (the inside and outside diameters of which are the same as those of the oven, and the thickness of which is equal to that of the covers).

For the losses by conduction through the glass of the window, we find:

$$q_j = \frac{S (t_v - t_e) \Delta t}{\frac{e_v}{K_v}}$$

The heat collected by the water and the pots will be:

$$q_u = mc (t_{f1} - t_{i1}) + mc (t_{f2} - t_{i2}) + Mc_a (t'_{f1} - t'_{i1}) + Mc_a(t'_{f2} - t'_{i2})$$

Taking Δ_t as 0.25 hours, and substituting the values, we get:

$$q_c = 0.09767 (t_i - t_a) + 0.0273 (t_{it} - t_a) + 0.018 (t_{im} - t_a)$$
$$q_j = 5.5 (t_v - t_e)$$
$$q_u = 0.059 (t_{f1} + t_{f2} - t_{i1} - t_{i2}) + 2 (t'_{f1} + t'_{f2} - t'_{i1} - t'_{i2})$$
$$q_i = 0.14 \Delta (t_{it} + t_a) + 0.291 \Delta (t_i + t_a) + 0.178 \Delta t_i + 0.065 \Delta (t_v + t_e)$$

The terms in the last expression have the following meanings:

$0.14 \Delta (t_{it} + t_a)$: the heat accumulated by the cork composition.
$0.291 \Delta (t_i + t_a)$: the heat accumulated by the glasswool.
$0.178 \Delta t_i$: the heat accumulated by the aluminium and the framing of the glass.
$0.065 \Delta (t_v + t_e)$: the heat accumulated by the glass.

In all terms in which the Δ precedes a temperature or sum of temperatures, it implies that we are dealing with the variation of this temperature or temperature-sum in the time interval under consideration.

Once the values of q_c, q_j, q_u and q_i have been calculated and the value of I is known, the value of q_r may be found by calculation:

$$q_r = 65.1\, I - q_u - q_i - q_c - q_j$$

The table gives the results of these calculations.

Since Δ_t has been taken as 0.25 hours, the test, two hours in duration, is divided for calculation into eight intervals. The heat balance is drawn up for each of these intervals, as we shall now see.

The instantaneous temperatures are of no interest for this calculation. Therefore, the mean values of t_{it}, t_i, t_a, t_v and t_e are taken over the interval of time considered. But we do take the difference, for instance for $\Delta\ (t_{it} + t_a)$ between the value of $t_{it} + t_a$ at the end of the time interval considered and the corresponding value at the commencement of the same interval. It will be the same, for instance, for $t_{f2} - t_{i2}$.

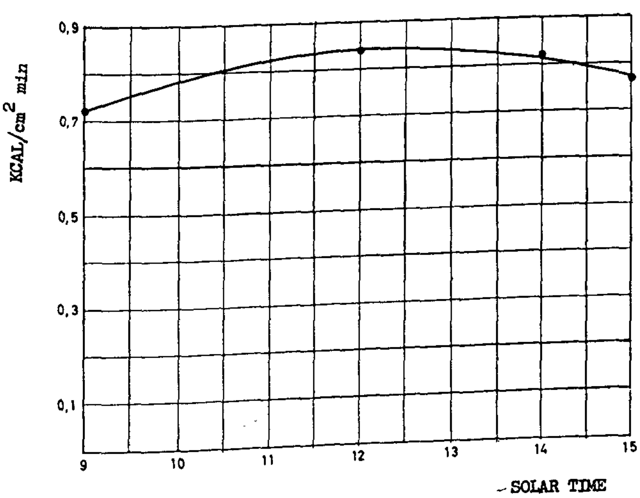

Figure 9. Direct solar radiation

Among the values found for q_r, there are four that are illogical, because they are too small. They are precisely the values corresponding to the time intervals II, VI, VII and VIII. The following explanation is given for this anomaly. The value of the solar radiation *I* was determined from the points of graph, while the intermediate values were found by interpolation (see figure 9). But it might just have been that the solar radiation was high in the intervals II, VI, VII and VIII, exceeding the interpolated values. This hypothesis is probable, since the day of the test was foggy. It would have been sufficient for *I* to have taken the values marked by an asterisk for the corresponding values of q_r to take acceptable values, likewise marked by an asterisk and obtained by evaluation. It is these latter values that are considered in calculating the efficiency.

Calculation of over-all efficiency in two hours of operation

$$\gamma\alpha = 58.7 \text{ per cent}$$

Quantity of heat received by the water and the pots:

$$\sum_{I}^{VIII} q_u = 275.66 \text{ kcal}$$

Total solar energy entering the oven:

$$\sum_{I}^{VIII} E\gamma\alpha = 523.76 \text{ kcal}$$

Solar energy received by the mirrors:

$$\sum_{I}^{VIII} E = \frac{523.76}{0.587} = 892 \text{ kcal}$$

Thermal energy lost by radiation through the glass:

$$\sum_{I}^{VIII} q_r = 108.7 \text{ kcal}$$

Summary of the calculations

Time interval	$t_i - t_a$ °C	$t_{ii} - t_a$ °C	$t_{im} - t_a$ °C	$t_v - t_e$ °C	$t_{f1} + t_{f2} - t_{t1} - t_{t2}$ °C	$t'_{f1} + t'_{f2} - t'_{t1} - t'_{t2}$ °C	$\Delta (t_{ii} + t_a)$ °C	$\Delta (t_i + t_a)$ °C	Δt_i °C	$\Delta (t_v + t_e)$ °C
I 11 h-11 h 45	2.3	—1.4	0.5	0.4	17	16.1	10.8	16.9	14.6	33.9
II 11 h 15-11 h 30 . . .	15.5	5.5	10.5	0.75	18.5	18.7	11.5	17.9	15.9	23.3
III 11 h 30-11 h 45 . . .	23.1	10.1	16.6	0.9	15.9	17.2	8.0	7.7	4.5	2.8
IV 11 h 45-12 h	26.6	16.0	20.3	0.3	17.3	18.2	6.5	5.8	5.7	—10.1
V 12 h-12 h 15	31.2	22.2	25.4	0.5	16.5	16.1	5.3	2.6	3.1	3.7
VI 12 h 15-12 h 30 . . .	35.1	23.1	29.4	2.3	16.3	17.3	3.1	5.7	5.1	16.8
VII 12 h 30-12 h 45 . . .	39.4	26	33.1	2.5	17.8	17.8	5.9	7.0	5.9	12.5
VIII 12 h 45-13 h	41.3	34.5	35.9	3.2	10.6	10.6	12.9	8.2	3.8	12

Time interval	I cal/cm².min	$E\alpha\gamma$ kcal	q_c kcal	q_j kcal	q_u kcal	q_i kcal	q_r kcal
I 11 h-11 h 15	0.835	54.3	0.19	2.2	33.2	12.28	6.43
II 11 h 15-11 h 30.	0.84 0.96*	54.7 62.5*	1.85	4.12	38.49	11.16	—0.9 7.0*
III 11 h 30-11 h 45.	0.84	54.7	2.82	4.95	35.34	4.34	7.25
IV 11 h 45-12 h	0.84	54.7	3.40	1.65	37.42	2.95	9.32
V 12 h-12 h 15	0.837	54.5	4.11	2.75	33.17	2.07	12.4
VI 12 h 15-12 h 30.	0.835 1.14*	54.3 73.83*	4.59	12.6	35.56	4.09	—2.54 17.0*
VII 12 h 30-12 h 45.	0.83 1.27*	54.0 82.69*	5.16	13.7	36.65	4.71	—7.1 23.0*
VIII 12 h 45-13 h	0.825 1.32*	53.8 86.54*	5.62	17.6	21.83	5.65	3.01 26.3*

Thermal energy lost by conduction through the glass:

$$\sum_{I}^{VIII} q_j = 60.57 \text{ kcal}$$

Thermal energy utilized to heat the oven:

$$\sum_{I}^{VIII} q_i = 47.25 \text{ kcal}$$

Thermal energy lost through the oven walls:

$$\sum_{I}^{VIII} q_c = 30.10 \text{ kcal}$$

Utilizable energy:

$$\frac{275.66 \cdot 100}{892} = 31 \text{ per cent}$$

Optical losses:

$$100 - 58.7 = 41.3 \text{ per cent}$$

Radiation losses:

$$\frac{108.7 \cdot 100}{892} = 12.2 \text{ per cent}$$

Losses by conduction through the glass:

$$\frac{60.57 \cdot 100}{892} = 6.8 \text{ per cent}$$

Losses due to thermal inertia:

$$\frac{47.35 \cdot 100}{892} = 5.3 \text{ per cent}$$

Losses by conduction through the oven walls:

$$\frac{30.10}{892} = 3.4 \text{ per cent}$$

The efficiency of the oven will be:

$$\frac{31}{0.587} = 52.8 \text{ per cent}$$

Conclusions from the heat balances

For the reasons given above, and since certain temperatures, for instance those of the glass, have been found from values measured at an insufficient number of points, the values we have presented for the efficiencies and the losses give *only* the order of magnitude.

The optical efficiency and that of the oven are low.

The efficiency we have presented is not an indication of the maximum possible performance of the apparatus, since the test was made on a foggy day.

It should be noted that if instead of nickel-plated brass ($\gamma = 0.67$) a material of reflectivity $\gamma = 0.80$ is used, the optical efficiency changes from 58.7 per cent to 70 per cent and the over-all efficiency from 31 per cent to 37 per cent.

Since the conduction losses through the oven walls are greater than those due to thermal inertia, we may conclude that the thickness of the insulation — the member with the highest specific heat — should be reduced.

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Summary

A solar cooker of a new type is presented.

The solar beams are collected by a parabolo-cylindrical reflector and routed to a narrow glass window in the lower portion of an insulated cylindrical box with a horizontal axis, placed at the focus of the paraboloid. The food to be cooked is placed inside this box.

This design makes it possible to increase the degree of concentration and to reduce the heat losses in the oven.

The author reports results obtained in tests of the cooker and discusses its need for position adjustments while operating, its cost and its utilization.

It is compared in several respects with another type of cooker.

Losses and efficiency are computed.

CHEAP BUT PRACTICAL SOLAR KITCHENS

H. Stam *

In arid regions, the common use of desert scrub and dung for household cooking deprives the land of fodder on which animals might be maintained, and of essential fertilizer. The successful application of solar cooking in such areas would, therefore, bring direct benefits in increased food production.

Basic conditions for solar kitchens

There are good reasons why in these regions wood, straw, charcoal and dung continue to be used as fuel. They are well adapted to all the needs of a housewife, from boiling an egg or cooking some potatoes to roasting a whole camel. The gathering of scrub and dung for these needs may require no more than a few hours' work by children a day. Despite their saving in fuels which are scarce, solar kitchens cannot easily compete with these ancient and simple methods of cooking. It is quite understandable that the varied American, Indian and Russian domestic solar stoves have had very meagre success among the people of desert zones. They are far too small.

Solar kitchens must meet the following conditions:

(*a*) They must be cheap, even for families with a yearly income of $150;

(*b*) At noon, bread must be baked and, in addition, sufficient heat must be supplied to a heat accumulator, also cheaply;

(*c*) From shortly after sunrise till before sunset, the kitchen must provide hot water for washing and must enable the housewife to cook breakfast and lunch and to make tea and coffee;

(*d*) A heat-accumulator should make it possible to cook dinner after sunset and even supply some warmth during the cold nights, common in arid regions;

(*e*) The eyes and the hands of the housewife should be made safe from concentrated solar radiation;

(*f*) Standard kitchen practice of industrialized countries must be adopted.

Solar-radiation cookers in comparison with fuel-burning kitchens

Figure 1 shows the amount of insolation due to the direct radiation of the sun, neglecting the scattered radiation from the sky. The differences between favourable sites, such as Chile or [illegible]ukkaro, and the norm for clear weather conditions are notable. In desert regions, aerial dust may diminish insolation to a ratio comparable with the absorption by cirrus clouds. Drifting clouds are, moreover, a normal occurrence during a great part of the year in India and Pakistan. To satisfy the housewives with solar kitchens on all the days of the week, not on sunny days *only*, one can calculate safely on the basis of half the insolation norm of the American Society of Ventilating and Heating Engineers (1 and 2).

Table 1 summarizes the heat capacities of fuel-burning and electrically operated kitchen equipment and compares the capacities of solar kitchens as needed for different domestic uses. The comparison for clear weather and cloudy conditions is very superficial indeed, and the conclusion is that solar kitchens need areas of 2½ to 5 square metres. But it is the primary purpose of this paper to make a closer analysis of kitchen practice and to propose improvements in solar kitchens that can satisfy housewives in arid zones with different living standards.

Kitchen practices

Temperatures required in food processing

The total heat needed by food during preparation amounts roughly to 1½ times the net heat accumulated from a cold start-up to the cooking or baking stage, provided that evaporation is limited.

Temperatures vary widely. Eggs are easily baked at 80°C, though it is desirable to process them above cooking temperature to prevent typhoid. Fresh vegetables and soups, as well as laundry, boil at sea level at 100°C, but during the steaming of such foods as rice, potatoes and beans, the cooking pan shows wall temperatures normally reaching 110° to 140°C.

Figure 2 shows the duration of heating and the danger of scorching such easily burnt foods as mashed potatoes and macaroni. For short periods, say 10 minutes, temperatures as high as 160°C are allowable and are often common practice. Rice starts to stick to the pan at 120°C, and begins to scorch disagreeably at 170°C. This is established from data collected by Professor van Staveren (3). In the above-mentioned cases, scorching must be avoided, but during baking, higher wall temperatures are necessary to obtain the desired caramelled crust. In domestic baking ovens, the ambient air temperatures vary

* Stichting Dienst Ontwakende Wereld, Amsterdam.

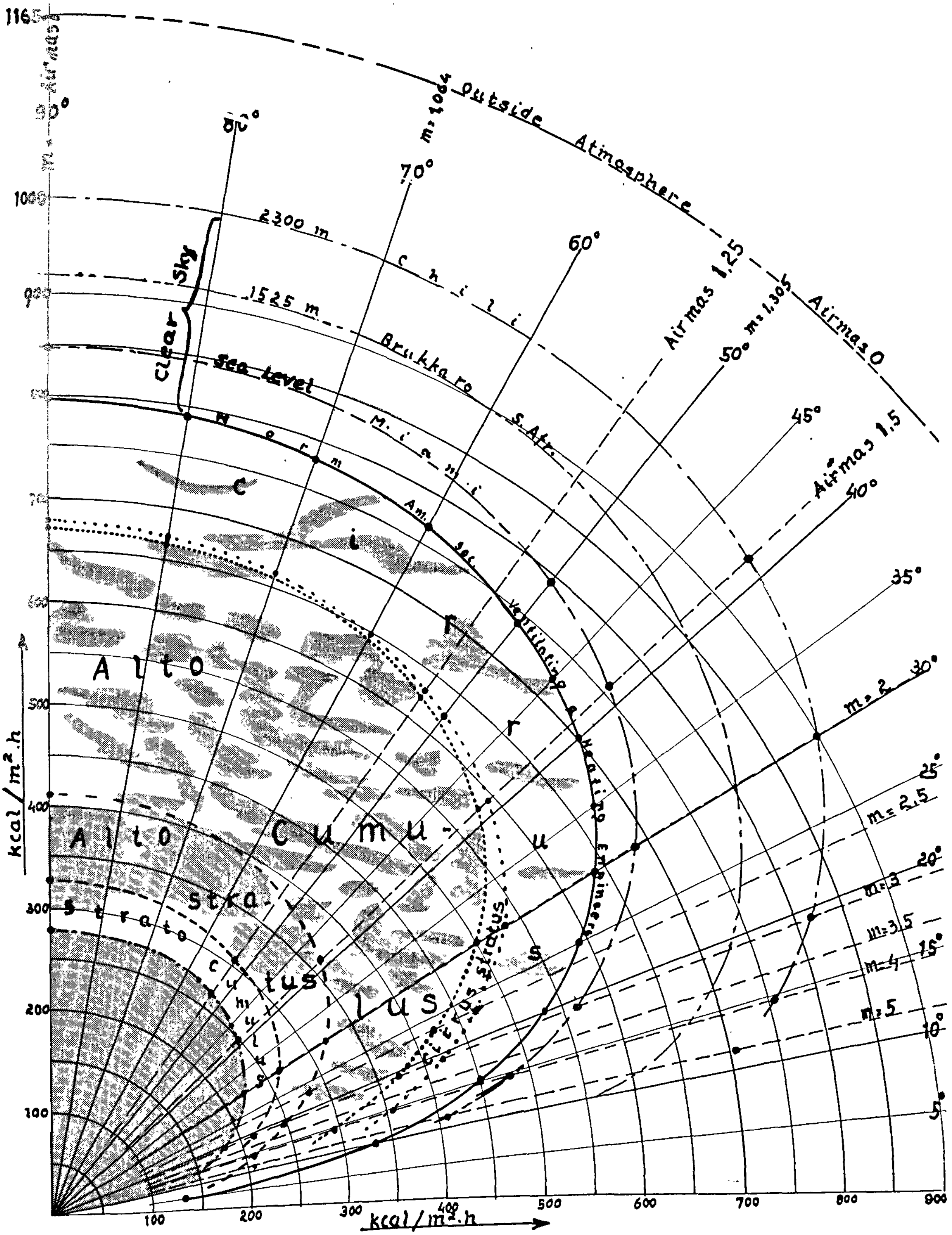


Figure 1. Sun energy due to direct radiation on perpendicular plane as a function of solar altitude and cloudiness of the sky

Table 1. Comparison of standard-kitchens with solar-kitchens

	Town gas		*Oil products*			*Solar reflector (spheroidal)*		
Burner size	*l/h*	*kcal/h*		*l/h*	*kcal/h*	*kcal/h*	*Necessary sq m*	
Simmering	84	350						
	112	475				360	1.50-[illegible]	Keeping warm
	140	600						
Normal	400	1 600-1 800	Pet. cooker	0.24	2 000	1 800	2.50-5	Meals
Large.	600	2 400-2 700	3-wick	0.30	2 700	2 700	3.75-7.50	Bread-baking
Largest	900	3 600-4 000				3 600	5	Laundry (accumulator)
Daily consumption .	1.0 m³	4 000-4 500 kcal		1.50 litre	4 500 kcal	710 kcal/h.m²	360 kcal/h m²	Insolation
Daily costs (U.S.)		5 cents; in Europe : 3 cents				Normal	Alto-cumulus	Clouds

	Electro-heat			*Solar reflector (paraboloid)*		
Burner size	*Plate diameter*	*Watt*	*kcal/h*	*kcal/h*	*Necessary sq m*	
Simmering		300	260	250	0.37-0.70	
Normal	14.50	850-1 000	730-860	800	1.10-2.25	Meals
Large.	18	1 200	1 050	1 200	1.75-3.50	Bread-baking
Largest	22	1 800	1 550	1 600	2.2[illegible]-[illegible].50	
Daily consumption		2.50 kWh	2 200 kcal	2 000 kcal Meals, laundry only		
				8 000 kcal With accumulator		
Daily costs (U.S.)		5 cents, Europe 14 cents, Cairo 40 cents, Dakar	Without bread-baking	Nil		

Notes:

This comparison is only very superficial.

In electro-cooking, heat losses at the pans are smaller than in gas-cooking; in solar-cooking, heat losses in electro-plates expire.

from 125° to 200°C; in industry, from 140° to 250°C, depending on the kind of product, e.g. soft cakes or crusted bread. The crust temperatures of the batch itself will not exceed 140° to 175°C. Finally, frying in oil requires 180°C.

Sizes of normal kitchen utensils

The laundry of an ordinary family can be boiled in pails with a content of 10 to 15 litres, but it is quite normal to place a bucket of 36 to 45 litres on two normal burners at once to obtain a heating time of little more than an hour. Pans of 4 to 6 litres are normally heated to cooking temperature in 20 to 35 minutes.

Soups and meals need pans of 4 litres. Steaming, after reaching the cooking temperature, varies from 10 minutes to some hours. Baking also shows the same variation in the time needed, depending on the kind of bread. Wheaten bread needs a long baking:

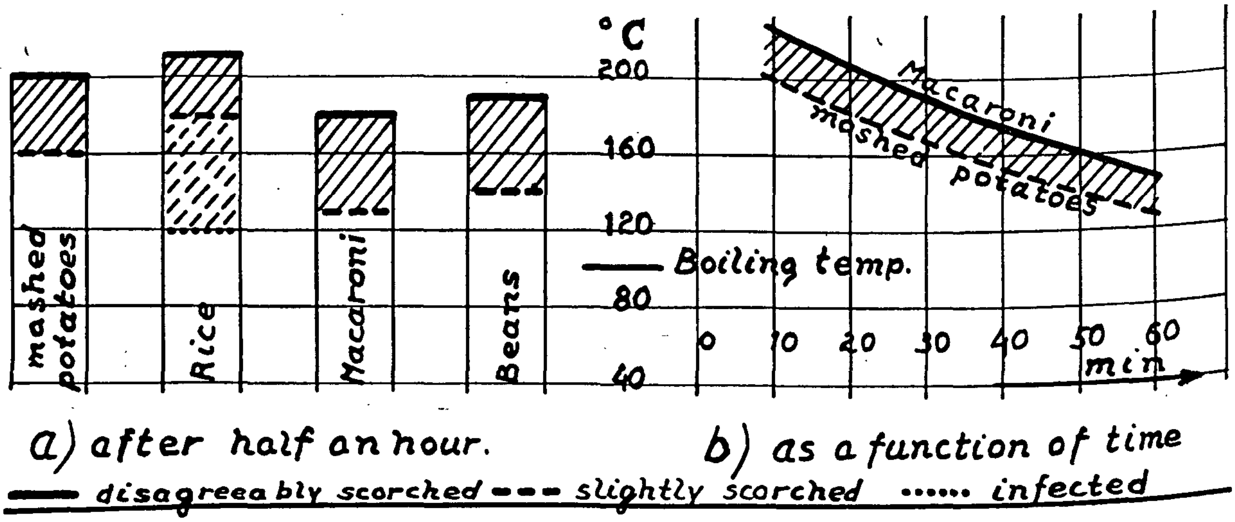


Figure 2. Burning temperatures of different foodstuffs

thus the daily bread of a small family, $1\frac{1}{2}$ kg when ready, is made in one or two loaves only. But short-baking kinds of bread, i.e. those made from corn, are divided up into pieces, each 200 to 400 grams.

Some foods, such as tortillas, are first cooked and later baked. Those easily and quickly baked pancakes of corn meal, used as daily food by the Indians in Mexico and the United States, are favoured for the demonstration of solar stoves of small area. But in the literature on cultivated plants (4), it is stated that the flour for tortillas is made from corn, which is cooked with lime for several hours and then pounded. In these cases, the pre-cooking requires a larger kitchen than the baking itself. Regardless of all variations, the need of warm water for washing requires the same capacity all over the world.

Experiments on heat losses of pans used in the open air

We made a series of time-temperature tests with European kitchen utensils of varied sizes and shapes in still air and with $1\frac{1}{2}$, 3 and 6 m/sec wind velocity. Only metal containers were used and all were well sooted. Figure 3 shows the heat losses at 100°C as a function of volume.

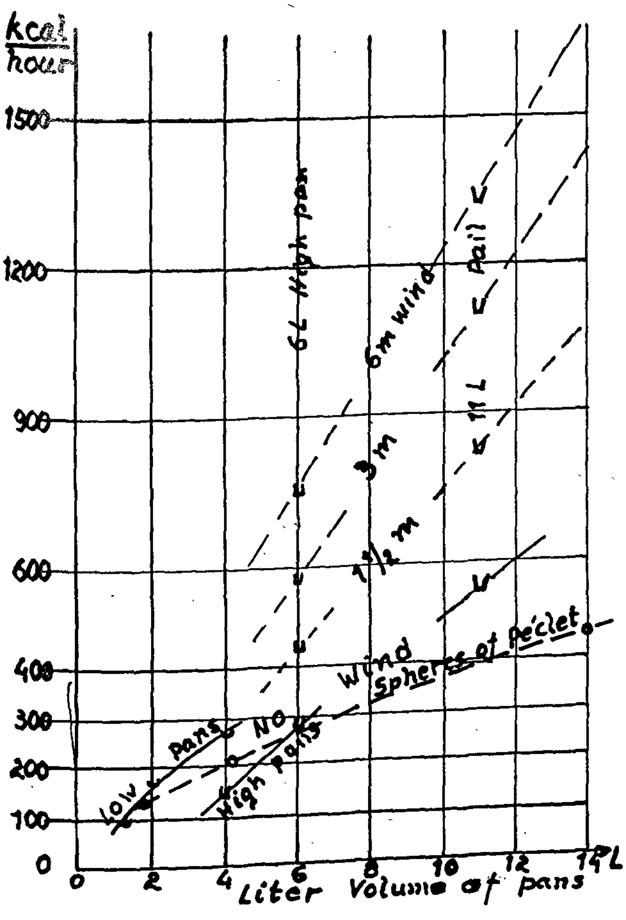


Figure 3. Total losses at 100°C

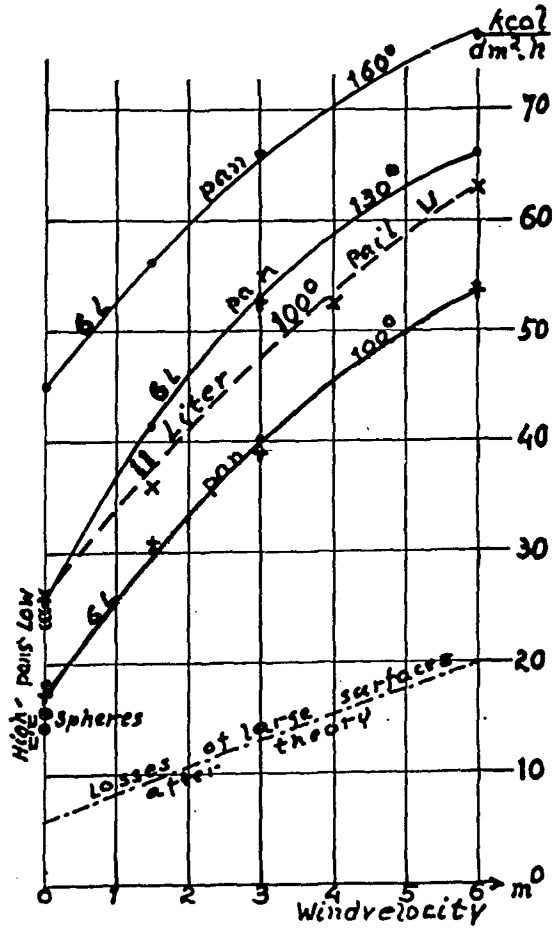


Figure 4. Surface losses at 100°, 130° and 160°C

The influence of shape on heat loss is remarkable. High-shaped pans and pails have considerably lower losses in still air. The typical pans produced by domestic handicrafts and sold on the markets of Africa and Asia, not available for our tests, are estimated to show characteristics lying between the curves of the sphere and the low, rectangular form.

Figure 4 shows the influence of the wind as measured in reality and in comparison with some formulae for heat transfer. In this figure, heat losses are given per square decimetre, emphasizing the fact that the influence of the shape of the pan on natural convection is far more important than the size. We measured total losses. In theory, the influence of the wind increases proportionally with temperature difference as well as with velocity, while natural convection losses increase at the 1.25 power of temperature difference (5).

No measurements were made with black-oxydized copper pots or with pyrex glass vessels.

Mirror material

For both cylindrical and spheroidal reflectors, the cheapest and one of the best insolation-concentrating materials is aluminium foil, anodized to give it an

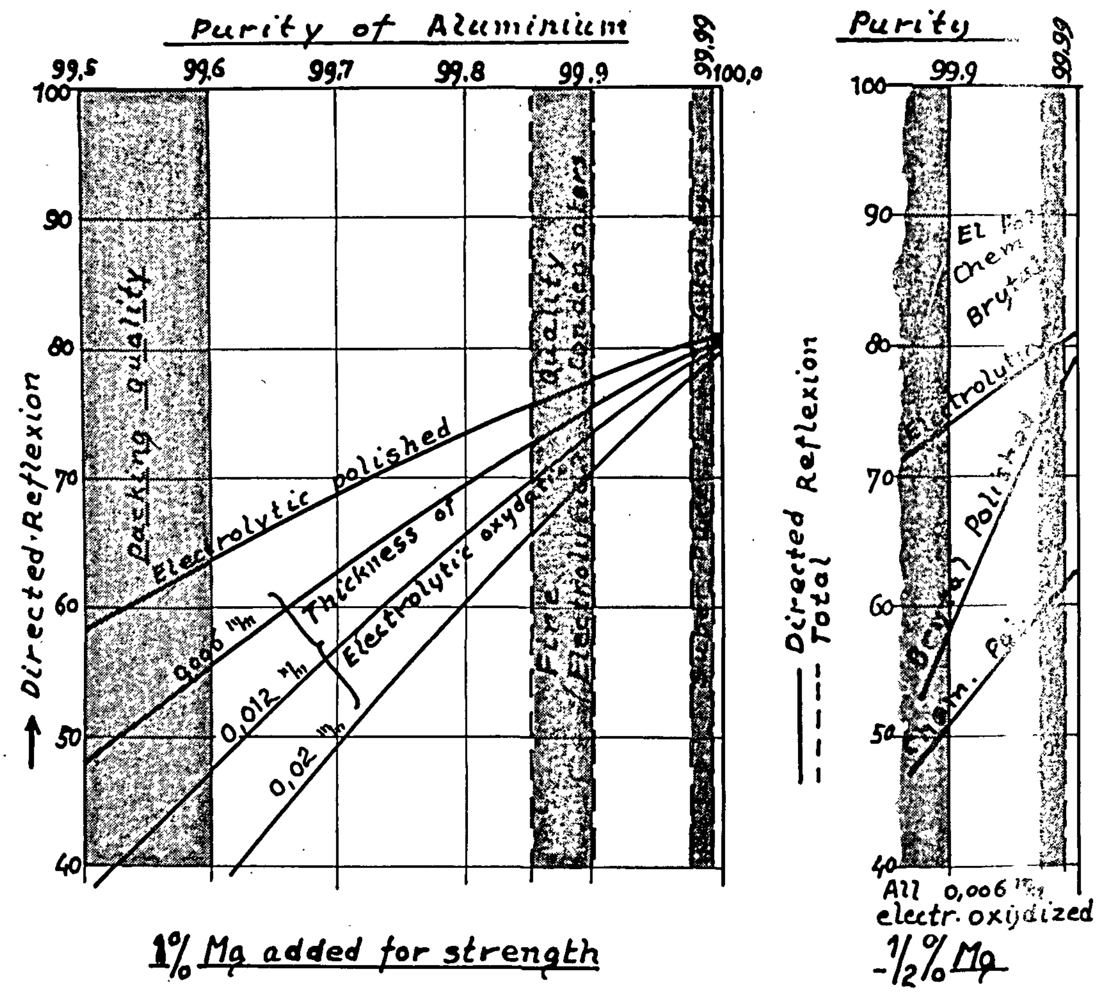


Figure 5a and b. Influence of impurities and surface treatment on aluminium

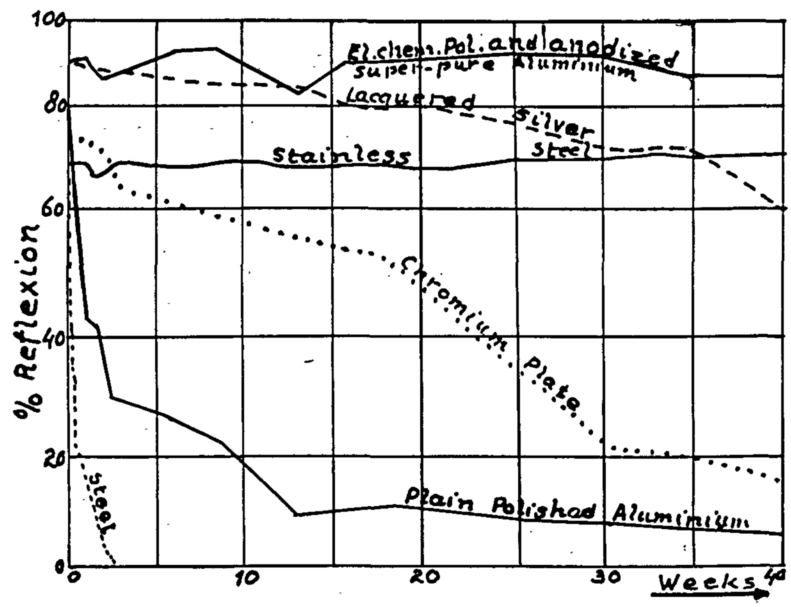


Figure 5c. Endurance of reflexion

emerald-hard surface. It is important to emphasize the diminishing effect minor impurities possess, above all Fe and Si.

In the hope that material specialists will provide more data on the subject, the role which super-pure aluminium (99.992 per cent pure), now gradually entering the world market, may play with regard to solar kitchens is underlined. From the literature (6), figures 5a, b and c were collected, demonstrating that super pure aluminium possesses the highest and longest lasting direct reflection figure of 80 per cent, uncontaminated by the relatively thick oxide layer, needed for the protection of the finish. Super-pure aluminium sheets are now available; foils can be bought, but only in large quantities. At the moment, however, the price is prohibitive: U.S. $46 per lb. For foils of 0.0012 mm thickness, the price is $3/m². Figure 5 shows, however, that the next best normal fine-quality (99.85 to 99.9 per cent), with 70 per cent direct reflection, can be used where the super-pure quality may be too costly. It will deteriorate more rapidly, but costs only $0.10 per square metre.

Needed capture of solar heat

With regard to these reflection figures and with absorption coefficients for well-sooted cooking utensils of 95 per cent, the normalized value of insolation from figure 1 must be reduced to three-fourths or even two-thirds. Thus, under good weather conditions, each square metre of mirror, reflecting on the pots, will deliver to heat their contents, and as heat losses, 500 to 550 kcal/hour. But, as already mentioned, the heat delivery to the pots will be frequently halved. The greatest challenge will come from washing utensils and from the needed heat accumulator. With unfavourable insolation, washes can be divided up into some smaller portions, say 15-litre pails. One pail placed in the open air, and exposed to a wind of 6 metres per second, demands for cooking within one hour under slight clouds, a concentrating surface of 8 square metres. Thus table 1 did not exaggerate.

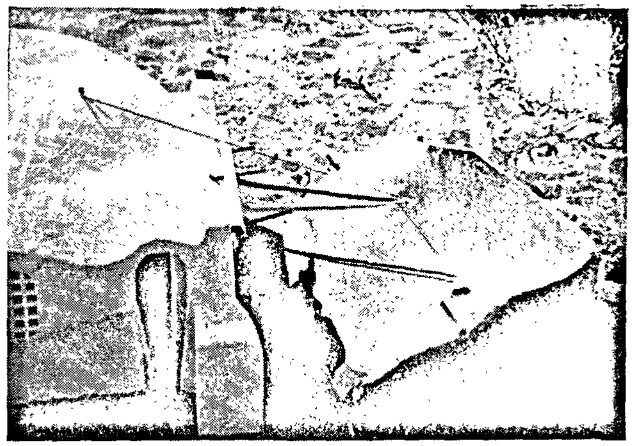
Proposed improved solar kitchens

It is obvious that the solar kitchens which have been made to date, in sizes of 1.0 to 1.3 metres across, are too small. There are different ways to improve on them.

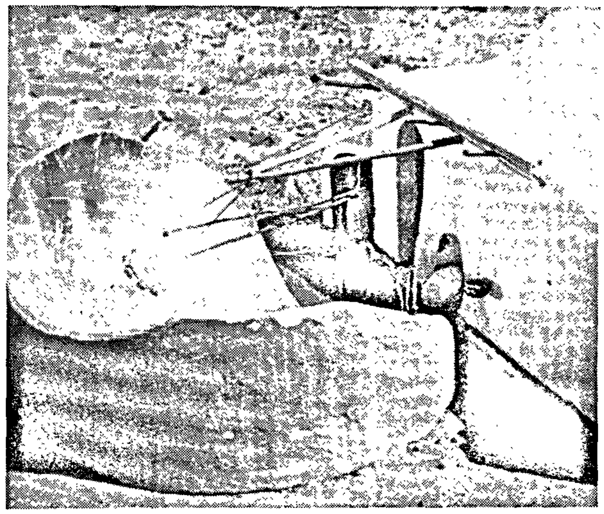
One way is simply to enlarge the reflecting surface till it is able to warm up one pot and to maintain cooking or baking temperature in another one, both heated pots being in the open air. This leads to the spheroidal reflector, in our opinion the best and cheapest solution for rural conditions.

A second way is to prevent the influence of the wind, thus diminishing heat losses and simplifying the moving mechanism of traditional reflectors and so leading to the use of the shell-type reflector.

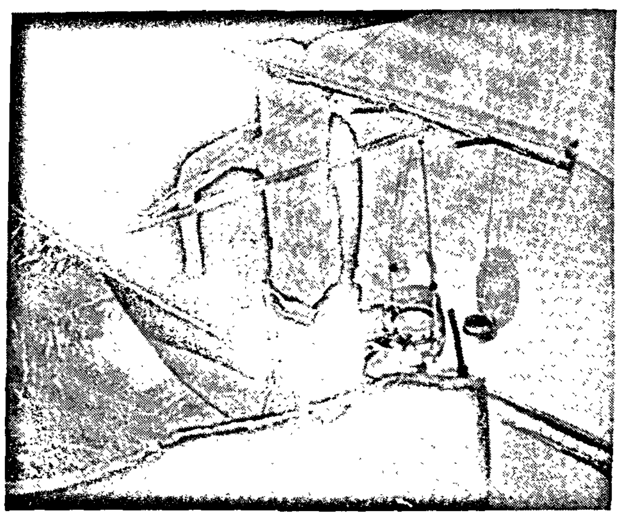
Another way is to continuously heat an accumulator, so that during cooking more heat can be



Bread baking, cooking, laundering, by day



Heating the accumulator



Dinner cooking in accumulator, by night

Figure 6. Spheroidal solar kitchen in use

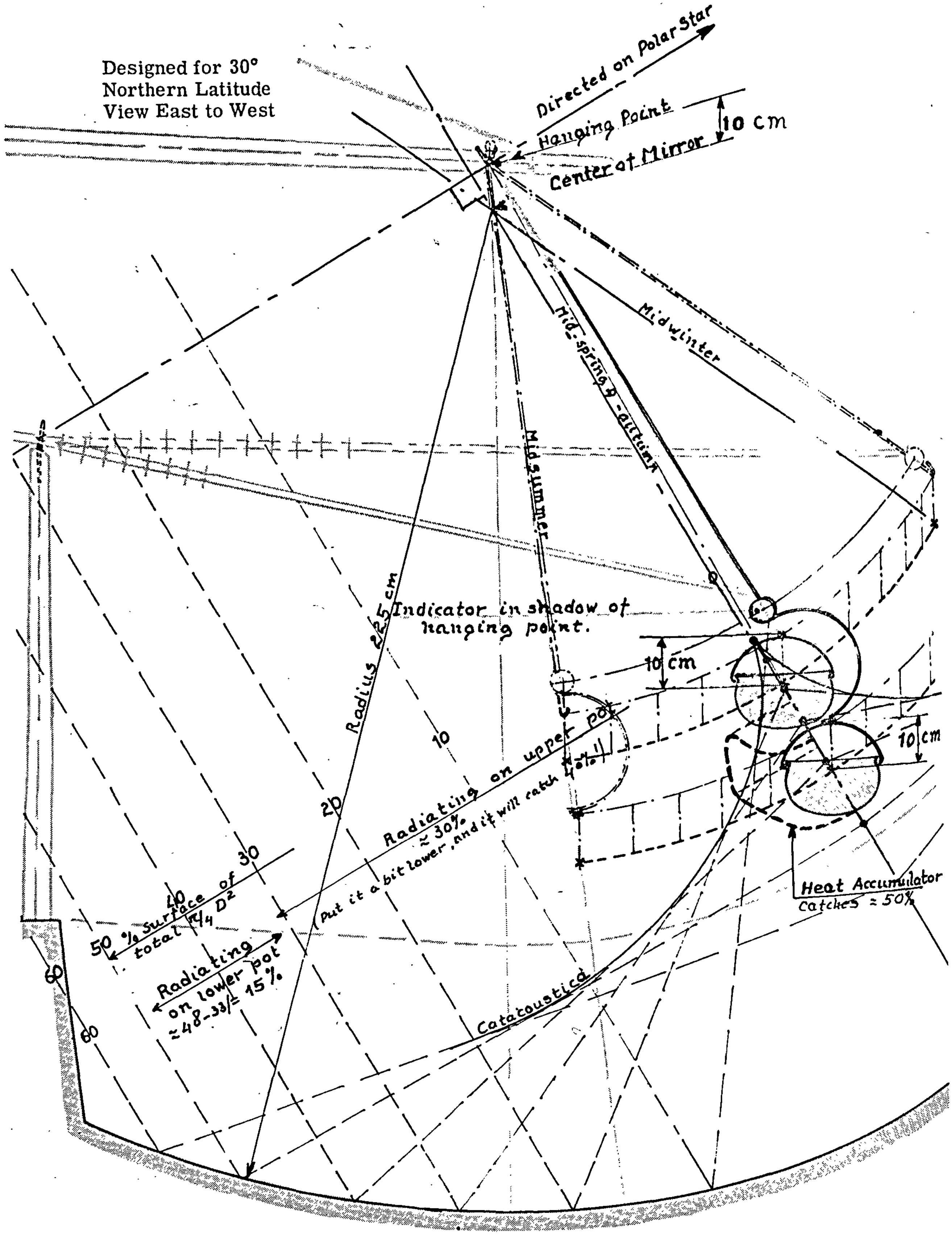


Figure 7. Arrangement for pots or heat accumulator in spheroidal solar kitchen

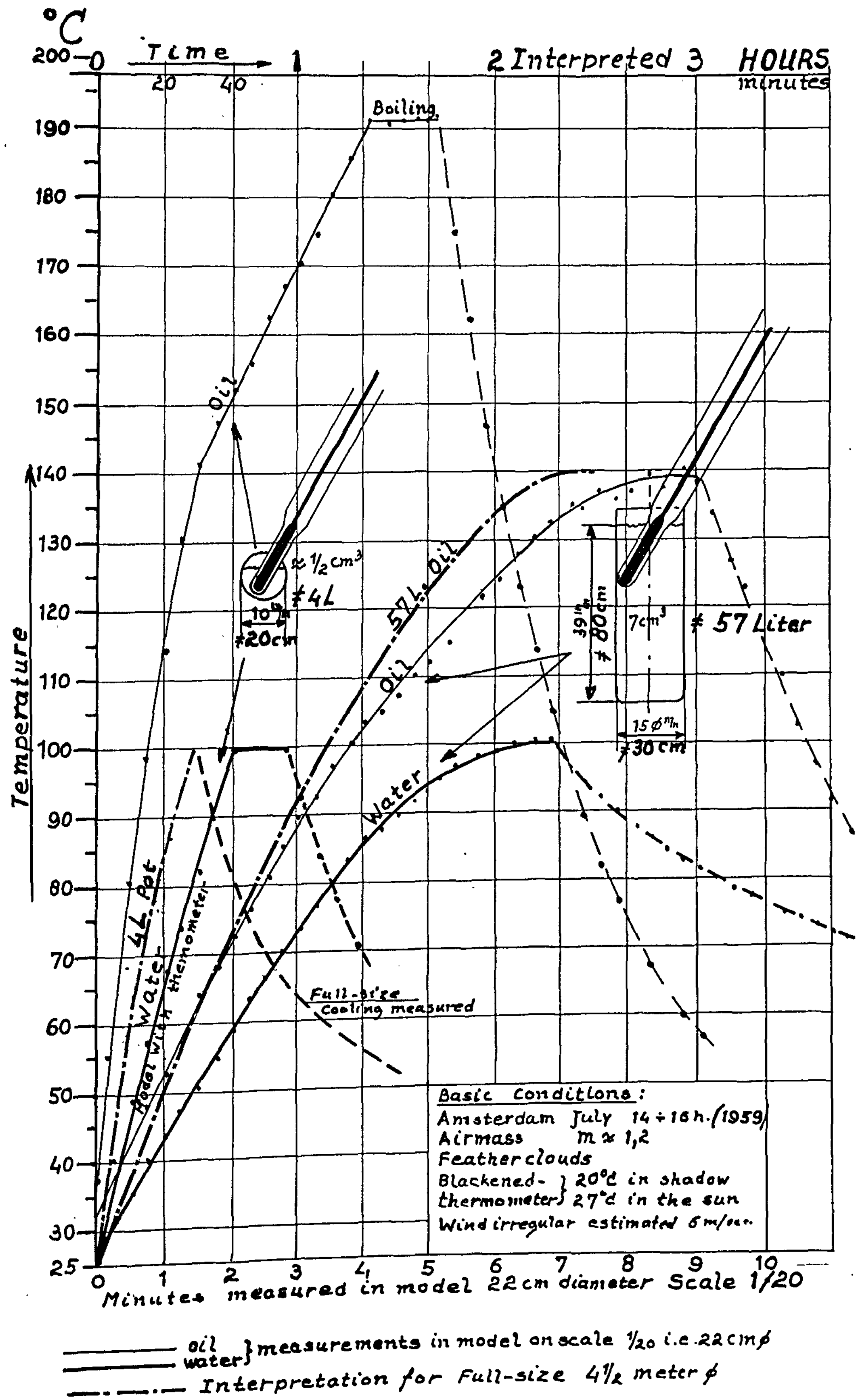


Figure 8. Results of spheroidal solar stove clad with aluminium foil

used than is supplied by the sun during the cooking period. This principle needs automatic following of the sun's course. Although it is the most practical solution, it is also the most expensive.

Spheroidal solar kitchen

The photographs of figure 6 give an over-all impression of cooking with this kitchen during the day and at night. Figure 7 shows the arrangement of two pots which allows them to be handled independently of each other or to be changed for the heat accumulator during its warming-up. Both the large reflecting surface, needed for a pail in the open air, and the necessary distance between two pots in the focusing stretch, lead to a diameter of 4½ metres. This is quite wide in comparison with the size of houses. The housewife sits in the shade of the house. It is impossible for her to burn her hands in the focusing stretch, but for stirring the pots she must bring them into her direct neighbourhood. Judging the cooking at such instances is difficult, but help can be obtained from an inlaid small plate, hammered on the inside of the pot when cooking starts. Baking in an oven is mostly done out of visual observation and is based on experience.

The following of the sun's daily course is done by means of ropes; it is a kind of "sailing the pots". The "booms" make it possible to follow the diurnal displacements of the sun's course. The building of the spheroidal reflector is a rather easy technique, if done with a chain joining the centre at the pole and trowel. The aluminium foil glued with a bitumastic solution gives a remarkably smooth surface and the folds cause little loss of the direct reflection.

The heat accumulator

Concentrating the insolation reflected by a 10 square metre foil, the accumulator catches, under cloudy conditions, roughly 3 000 kcal per hour, and under clear weather, double this. But the losses during heating cause wide variations in heating time. In the designed vessel, the cooking pan is enclosed in the accumulator in order to diminish heat losses during cooking of the food and for cheap construction. A good average value for many of the melting materials fitted for the job is obtained if the content of the accumulator-pan is 4 litres and the accumulator-content has a fusion heat of 40 kcal per litre. Then 10 litres of the accumulator content coagulates while the dinner is cooking in the evening.

Taking into account the unfavourable conditions that often occur in India, and estimating that the warming up of the accumulator must be done at noon, at maximum insolation, a duration of 6 hours will lie between the end of accumulator-heating and its use for dinner purposes. A total content of 40 litres fusing material is then needed to supply the heat losses during that period and for some additional hours. Good heat insulation is obtained with aluminium foil and a layer of cotton or kapok between two baskets of rushes. Given more favourable normal weather conditions, the accumulator may be made much smaller and can be heated up in the afternoon.

The fusing content can be collected by the rural population if resins, rubbers or sugars are used. But it is estimated that these will be too viscuous for the purpose. Thus magnesium chloride crystallized with 12 H_2O (melting point, 117°C) or magnesium palmitate (melting point, 121°C) will be better suited and costs, in impure state, less than \$0.30 per litre. But the chloride requires a vessel carefully lead-plated on the inside, though some reports suggest that aluminium is suited for the accumulator as well.

Actual results

Though the Netherlands, both in latitude and climate, is exceptionally badly suited to try out

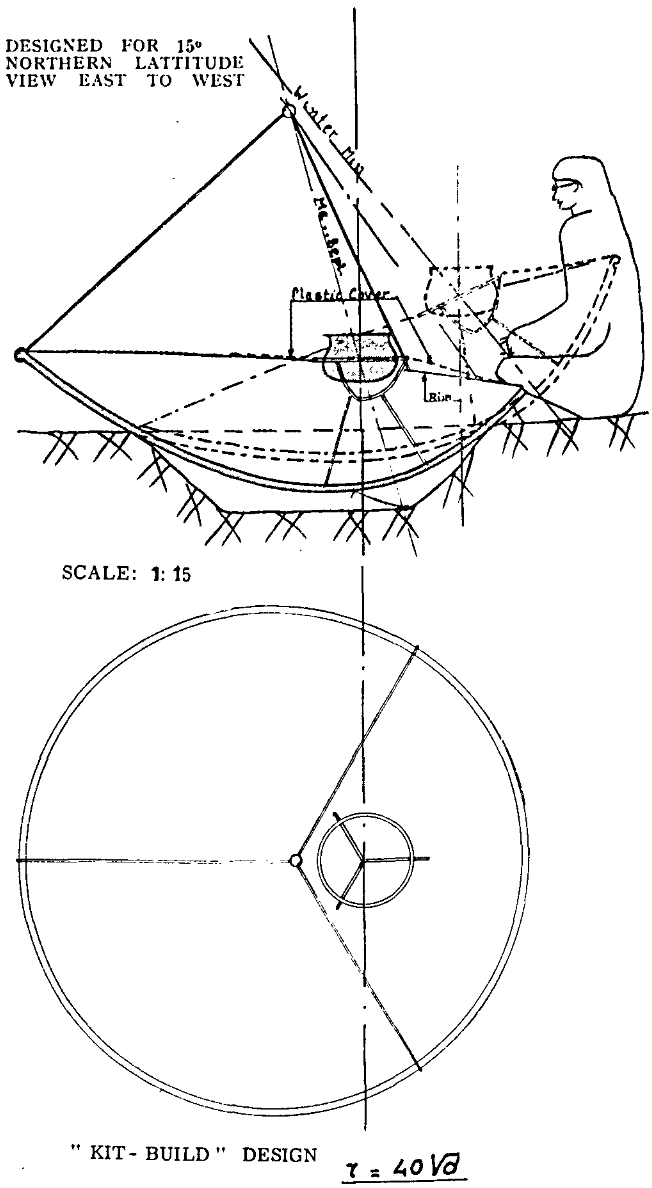


Figure 9. "Oyster-shell" paraboloid solar kitchen

solar kitchens, some measurements on a spheroidal reflector with pots and bucket were made during 1959 on a small scale. The results are given in figure 8. The extremely bad summer of 1960 did not permit the measurements to be repeated with the bigger model, made for the purpose and fitted also with an accumulator.

The plastic-covered "oyster shell" reflector (figure 9)

The American, Indian and Russian solar stoves of paraboloidal form, mentioned above, have a support to follow the sun's course. The costly construction makes it uneconomic to enlarge them, and the wind forces on them demand rather high weight. But the same paraboloidal form cut by an oblique, rather than a perpendicular, plane enables the resultant "shell" to be put on the rim of a hole in the earth. Catching so little wind, it can easily be enlarged to 1.6 metres across, or more if desired. A plastic covering will ensure that its behaviour will be reasonably stable, even under windy conditions, and the diameter allows the housewife to stir the pots during cooking. The plastic cover will serve to reduce the insolation on her hands. The nonsymmetrical form of the reflector allows it to follow the sun's course for 6 hours a day by simple turning and towing. The figure explains the way in which the pots are held in position on a ring and the method of directing the reflector axis towards the sun.

Under favourable climatic conditions, it must be possible to use a heat accumulator with this solar kitchen too; this affords the opportunity of cooking in one pan and at the same time in the accumulator during the day.

In our opinion, the reflector can best be made as a basket, plaited from twigs, the inside lined with plaster and covered with aluminium foil.

The heat-storage solar kitchen (figure 10)

Any tube held parallel with the earth's axis can collect a great deal of insolation by means of a paraboloidal reflector, the line of focus of which coincides with the tube. The diurnal variations of the eliptic do not matter, so long as the sun's daily course is followed by the reflector.

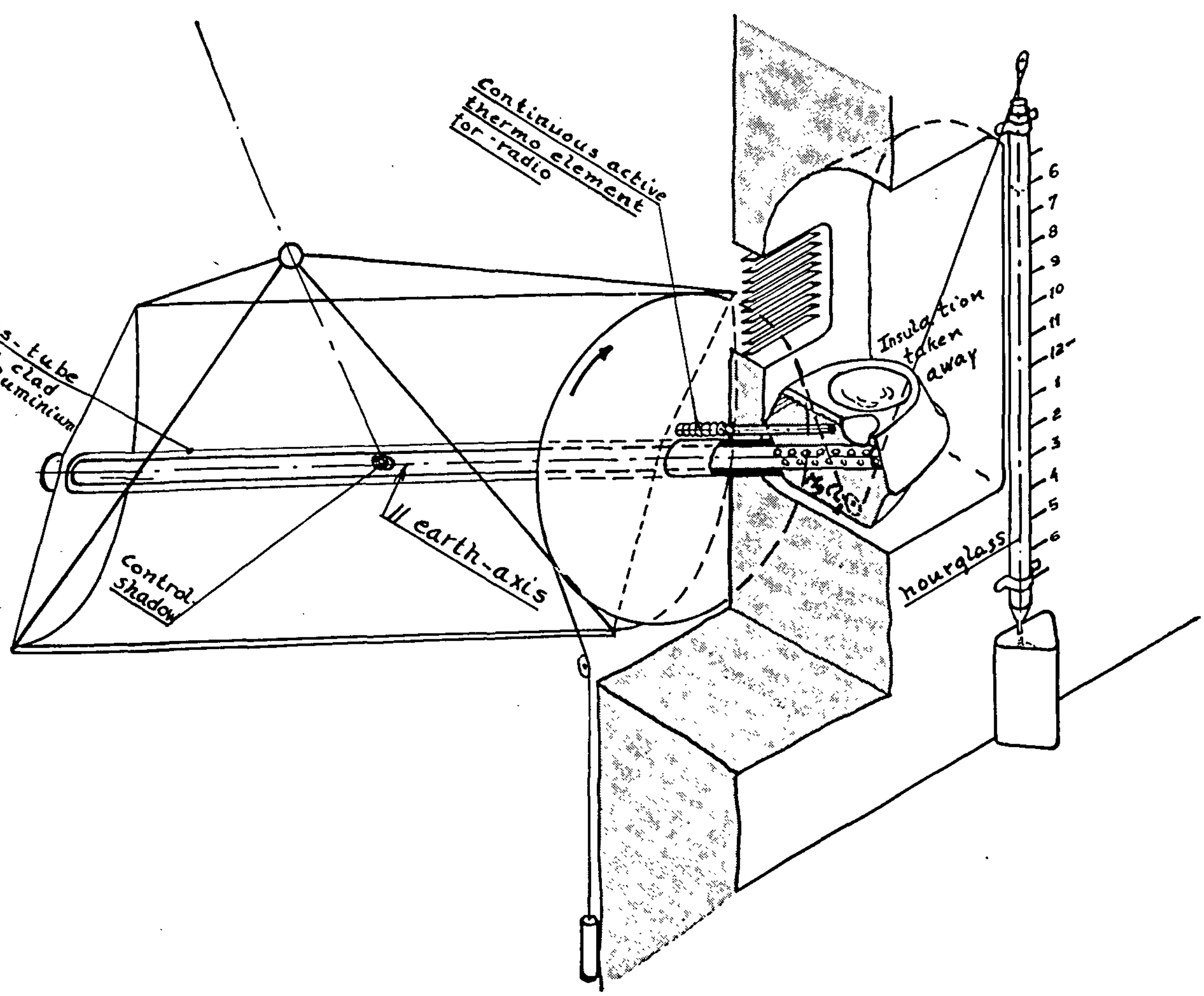


Figure 10. Solar kitchen using accumulated heat

Figure 10 shows such a tube in use as the lower part of a heat accumulator, with some pans sunk in, simulating industrial kitchen ovens in common practice.

By insulating the tube against heat with a glass tube-covering, the heat losses throughout the day will be limited to such an extent that the fusing accumulator content will never coagulate entirely under normal domestic use.

An essential point in the design is an inexpensive feature for following the sun's daily course, bearing in mind that the reflector catches a great deal of wind. The simplest turning device is a big size hour glass, a 5-cm diameter tube with exceptionally well selected sand so as to maintain sufficiently regular descent of the weight supported by the sand column. A smaller counterweight keeps the reflector turning cord tightly stretched. The reflector turns only during the day. The hour glass has to be refilled every morning. Minor adjustment of the reflector position relative to the sun may be necessary.

The upper part of the accumulator can contain a thermo-electric element supplying some electricity during day and night for a transistor radio. (To obtain light for bulbs by this method would require a large reflector.)

Handicraft adaptation to production and use of solar kitchens

It is impossible to design, in detail, solar kitchens for the less industrialized zones without close contact with craftsmen in order to form a link between modern knowledge and the basic needs of the rural masses. Moreover, these solar kitchens need actual practical testing by housewives to improve any faults which may be found.

The spheroidal reflector, in particular, is suited for such rural processing as sugar cooking, fruit canning, and even for lime burning, ore melting and fertilizer production.

A scientific institute and the support of the governments concerned may be needed, however, to back up handicraft co-operatives. The proper use of semi-manufactured products is also needed to inspire rural handicraft development in a way that can compete with industry.

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Summary

In arid regions, the common use of desert scrub and dung for household cooking deprives the land of fodder on which animals might be maintained, and of essential fertilizer. The successful application of solar cooking in such areas would, therefore, bring direct benefits in increased food production.

Basic conditions for solar kitchens

The fires of scrub, charcoal and dung-cakes are well adapted to all the needs of a housewife. The gathering of such fuel is easy. On the other hand, the varied American, Indian and Russian solar stoves have had very meagre success, mainly because they are too small.

Solar kitchens must meet the following conditions :

(*a*) They must be cheap, even for a yearly family income of $150;

(*b*) At noon bread must be baked and sufficient heat supplied to a heat-accumulator, also cheaply;

(*c*) During daytime, the kitchen must provide hot water for washing and for cooking breakfast and lunch, tea and coffee.

(*d*) The heat-accumulator should cook dinner after sunset, as well as supply some warmth during cold nights;

(*e*) Neither eyes nor hands should be hurt by solar radiation;

(*f*) Standard kitchen practice of industrialized countries must be adopted.

Solar-radiation cookers in comparison with fuel-burning kitchens

Figure 1 shows the direct radiation, influence of clouds and the norm for clear weather (1 and 2). Aerial dust may be comparable with cirrus clouds, a normal occurrence in India and Pakistan. Calculation from half of the norm must be made in order to be safe.

Table 1 compares superficially the capacities of kitchens commonly used with those of solar kitchens and concludes that solar kitchens need areas of $2\frac{1}{2}$ to 5 square metres. Closer analysis indicates that solar kitchens can be truly satisfactory.

Kitchen practices

Temperatures required in food processing. The heat needed amounts to $1\frac{1}{2}$ times the net heat which has been accumulated by the time normal cooking temperature in reached. Steamed foods like rice, potatoes and beans show pan temperatures of 110° to

140°C. Figure 2 shows the danger of scorching. For short durations, 160°C is often common practice. Rice starts to stick at 120°C and is scorched disagreeably at 170°C (3). In baking, oven temperatures vary from 125° to 250°C, but temperatures in the crust will not exceed 140° to 175°C. Frying in oil requires 180°C.

Sizes of normal kitchen utensils. Laundry is boiled in pails of 10 to 15 litres, or in a bucket of 36 to 45 litres. With pans of 4 to 6 litres, soups or meals cook in 20 to 35 minutes. Steaming and baking vary from 10 minutes to some hours. Long-baking wheaten bread ($1\frac{1}{2}$ kg for a small family) is made in one or two loaves. Short-baking corn is divided up into pieces of 200 to 400 grams. Tortillas, the quickly baked corn cakes and daily food of the Indians in Mexico and the United States, are suitable for cooking in solar stoves with small area. Tortillas are made from corn, which is cooked for many hours and then pounded (4). Washing requires the same capacity all over the arid zones.

Experiments on heat losses of pans used in the open air

Time-temperature curves were made with varied European utensils in still air and with wind velocities of $1\frac{1}{2}$, 3 and 6 metres per second, respectively. Only well-sooted metal containers were used. Figure 3 shows the heat losses at 100° as a function of volume. Figure 4 shows the influence of the wind as measured and in comparison with accepted formulae for heat transfer. Through an omission, neither black-oxydized copper pots nor pyrex glass vessels were tested.

Mirror material

For cheap reflectors, the best material is aluminium foil, emerald-hard anodized. Figures 5 a, b and c (6) demonstrate that 99.992 per cent super-pure aluminium possesses the highest and most long-lasting direct reflection of 80 per cent. The foils can be bought, but at the moment the price is prohibitive: \$3 per square metre. But next-best quality, 99.85 to 99.9 per cent pure with 70 per cent reflection, can be used too. It deteriorates more rapidly, but costs only \$0.10 per square metre.

Needed capture of solar heat

Efficiency of reflection and absorption for well-sooted cooking utensils (95 per cent) reduces insolation (figure 1) to three-fourths or even two-thirds of the input. Under good weather conditions, each square metre of mirror directs onto the pots 500 to 550 kcal/hour, but frequently this is halved by clouds or dust. The challenge comes from washing utensils and heat accumulator. A 15-litre pail, when exposed to a wind of 6 m/sec, needs, for cooking within an hour under slight clouds, a concentrating surface of 8 square metres. The same surface in bright weather and still air cooks a 36-litre bucket within an hour and charges a heat accumulator in some hours.

Improved solar kitchens

Obviously, solar stoves 1.3 metres across are too small. They may be improved by: (*a*) simply enlarging the reflecting surface; (*b*) screening the wind; (*c*) continuously heating an accumulator, automatically following the sun's course.

Spheroidal solar kitchen. Figure 6 shows cooking during day and night, and figure 7 shows the arrangement of two pots, independently handled. The large surface requirement and distance between the pots necessitate a diameter of $4\frac{1}{2}$ metres. The heat accummulator (figure 7) contains 40 litres magnesium chloride + 12 H_2O, or, alternatively, Mg. palmitate, costing, impure, \$0.3 per litre. Actual results are given in figure 8, though the Dutch climate and latitude allowed measurements over a small range only.

The plastic-covered shell reflector (figure 9). The paraboloidal form cut by an oblique plane enables the shell to be put directly on the earth. The non-symmetrical form allows 6 hours following of the sun. The shell is a basket.

Heat-storage solar kitchen (figure 10). A heat-collecting tube mounted parallel to the earth's axis requires a cylindrical reflector, turning with the sun. A large hourg-lass achieves the movement. The heating tube can contain a thermo-element for a radio.

Practical testing of solar kitchens

This is impossible under the Dutch climate. It needs close contact with the housewives, as well as with the craftsmen, of the regions concerned, and the backing of a scientific institute. Ample instructions, covering the whole subject, are available at our secretariat.

CUISINIÈRES SOLAIRES ÉCONOMIQUES MAIS PRATIQUES

Résumé

Dans les régions arides du monde, l'emploi généralisé de broussailles et d'excréments pour fournir la chaleur qu'impose la tenue d'un ménage prive le pays d'aliments qui pourraient être consommés par les animaux et d'engrais essentiels. Une judicieuse application de la cuisine solaire aux besoins de ces régions pourrait donc présenter des avantages directs prenant la forme d'une augmentation de la production d'aliments.

Conditions fondamentales applicables aux cuisinières solaires

Les feux constitués par des broussailles, du charbon de bois et des excréments se prêtent bien à tous les

besoins d'une ménagère. Il est facile de se procurer ces combustibles. En revanche, les diverses cuisinières solaires américaines, indiennes et russes n'ont eu que peu de succès, en général parce que trop petites.

Les cuisinières solaires doivent satisfaire aux conditions suivantes :

a) Elles doivent être peu coûteuses, même pour une famille dont les revenus annuels ne dépassent pas 150 dollars;

b) A midi, elles doivent pouvoir assurer la cuisson du pain et fournir assez de chaleur à un accumulateur de chaleur, le tout à bon compte;

c) Pendant la journée, la cuisinière doit fournir de l'eau chaude pour la lessive et assurer la cuisson du petit déjeuner, du déjeuner et, au besoin, du thé et du café;

d) L'accumulateur doit pouvoir faire cuire un dîner après le coucher du soleil et fournir quelque chaleur pendant les nuits froides;

e) Ni les yeux, ni les mains des usagers ne doivent être blessés par le rayonnement solaire;

f) On doit adopter les pratiques de cuisine standard applicables dans les pays industrialisés.

Comparaison des cuisinières à rayonnement solaire avec les dispositifs classiques à combustible

La figure 1 donne le rayonnement direct, l'influence des nuages et la norme applicable aux temps clairs (1 et 2). La poussière que l'on trouve dans l'air doit avoir des effets comparables à ceux des nuages cirrus, situation qui se présente normalement en Inde et au Pakistan. Il faut calculer sur la moitié de la norme pour avoir une marge de sécurité.

Le tableau 1 donne une comparaison superficielle de la capacité des cuisinières d'emploi commun avec celle des cuisinières solaires, et aboutit à la conclusion que les cuisinières solaires exigent des surfaces comprises entre 2,5 et 5 m². Une analyse plus serrée indique que les cuisinières solaires peuvent être vraiment satisfaisantes.

Pratiques observées en cuisine

Températures nécessaires à la cuisson des aliments. La chaleur nécessaire représente 1,5 fois la chaleur nette accumulée au moment où la température normale de cuisson est atteinte. Les aliments faits à la vapeur, comme le riz, les pommes de terre et les haricots, accusent des températures, à la sole du four, allant de 110 à 140 °C. La figure 2 signale le danger de brûler. Pour de brèves périodes, l'emploi de 160 °C est chose commune. Le riz commence à attacher à 120 °C et il est désagréablement brûlé à 170 °C (3). Dans la cuisson au four, les températures varient entre 125 et 250 °C mais, dans la croûte, ces températures ne dépasseront pas 140 ° à 175 °C. La friture à l'huile exige 180 °C.

Dimensions des ustensiles de cuisine standard. La lessive est bouillie dans des lessiveuses ayant une capacité de 10 à 15 litres, ou dans un seau de 30 à 45 litres. Avec des casseroles de 4 à 6 litres, les soupes ou les repas sont cuits en 20 à 35 minutes. La cuisson à la vapeur et la cuisson au four varient entre 10 minutes et quelques heures. Le pain de blé à cuisson lente, à raison de 1,5 kg pour une petite famille, se fait en une ou deux miches. Le maïs en cuisson rapide est divisé en morceaux de 200 à 400 g. Les galettes dites « tortillas », qui sont des gâteaux de maïs rapidement cuits et la nourriture quotidienne des Indiens du Mexique et des États-Unis, se prêtent à la cuisson dans des cuisinières solaires avec une petite surface. Elles sont préparées avec du maïs cuit pendant plusieurs heures, puis broyé (4). La lessive exige la même capacité dans toutes les régions arides.

Expériences sur les pertes de chaleur des casseroles utilisées en plein air

Nous avons établi des courbes temps-température, pour divers ustensiles européens, à l'air calme et avec des vitesses de vent de $1\frac{1}{2}$, 3 et 6 mètres par seconde respectivement. On ne s'est servi que de récipients en métal bien couverts de suie. La figure 3 donne les pertes de chaleur à 100 °C en fonction du volume. La figure 4 donne l'influence du vent, telle qu'on la mesure, et en comparaison avec les formules qui donnent la transmission de la chaleur. En raison d'une omission, on n'a pas fait d'essais sur les casseroles en cuivre traitées à l'oxyde noir ou les récipents en pyrex.

Matériaux pour les miroirs

Pour les réflecteurs peu coûteux, le matériau idéal est la feuille de papier d'aluminium traitée anodiquement et dure comme de l'émeraude. Les figures 5 a, b et c (6) indiquent que l'aluminium ultra-pur à 99,992 p. 100 fournit la proportion de réflexion directe la plus élevée et la plus durable à 80 p. 100. On peut acheter ces feuilles d'aluminium mais, pour le moment, le prix en est prohibitif, étant de 3 dollars par m². La qualité immédiatement inférieure, d'une pureté de 99,85 p. 100 à 99,9 p. 100, avec 70 p. 100 de réflexion, peut être utilisée également. Ce matériau se détériore plus rapidement mais ne coûte que 0,1 dollar par m².

Quantité de chaleur solaire à récupérer

Le rendement de la réflexion et de l'absorption, pour les ustensiles de cuisine bien enduits de suie (95 p. 100), réduit l'ensoleillement (figure 1) aux trois quarts et même aux deux tiers de la quantité fournie. Dans de bonnes conditions météorologiques, chaque mètre carré de miroir concentre de 500 à 550 kcal/h sur les casseroles, mais il arrive souvent que ceci soit réduit de moitié par les nuages ou la poussière. La difficulté est créée par les ustensiles à lessive et l'accumulateur de chaleur. Un seau de 15 litres exposé à un vent de 6 m/sec. exige une surface de concentration de 8 m² pour la cuisson en une heure avec un peu de nuages. La même surface, par temps brillant et en air calme, assure la cuisson dans un seau de 36 litres en une heure et charge un accumulateur de chaleur en quelques heures.

Cuisinières solaires perfectionnées

Il est évident que les cuisinières solaires de 1,3 m de diamètre sont trop petites. On les améliorera comme suit : *a*) en augmentant simplement leur surface réfléchissante; *b*) en les protégeant contre le vent; *c*) en chauffant continuellement un accumulateur qui suit automatiquement la trajectoire du soleil.

Cuisinières solaires sphéroïdes. — La figure 6 montre comment on fait la cuisine de jour et de nuit. La figure 7 montre la disposition à deux casseroles maniées indépendamment. Le besoin d'une grande surface et d'une distance suffisante entre les casseroles exige un diamètre de 4,5 m. L'accumulateur de chaleur (figure 7) contient 40 litres de chlorure de magnésium + 12 H_2O ou, au choix, du palmitate de magnésium, qui coûte, à l'état impur, 0,3 dollar par litre. Les résultats effectivement obtenus sont donnés par la figure 8, bien que le climat et la latitude des Pays-Bas n'aient permis les mesures que sur une petite gamme.

Réflecteurs à coquille recouverte de produit plastique (figure 9). — La forme paraboloïde coupée par un plan oblique permet que la coquille soit posée directement sur le sol. Son caractère asymétrique permet de suivre le soleil pendant 6 heures. La coquille est constituée par un panier.

Cuisinière solaire à accumulation de chaleur (figure 10). — Un tube d'accumulation de chaleur monté parallèlement à l'axe de la terre exige un réflecteur cylindrique qui tourne avec le soleil. Un gros sablier assure ce mouvement. Le tube chauffant peut contenir un élément thermique qui sert à un appareil de radio.

Essais pratiques sur les cuisinières solaires

Ils sont impossibles à exécuter avec le climat hollandais. Ils exigent un contact serré avec les ménagères ainsi qu'avec les artisans des régions en cause, et l'appui d'un institut scientifique. Notre secrétariat tient à la disposition des intéressés d'amples instructions portant sur l'ensemble du sujet.

PRACTICAL SOLAR COOKING OVENS

Maria Telkes and Stella Andrassy *

Interest in solar cooking has increased rapidly during the past ten years, primarily for two reasons.

First, the peoples of sun-rich countries can easily "reach for the sun" and use it as fuel because it is practically overhead. They can avoid the tedious labor of collecting twigs or cow dung, often the only fuel resource that is available in arid lands. In such regions, fuel wood is scarce and usual fuels — charcoal or kerosene — are expensive. In most of these regions, dinner is prepared at noon or during the late afternoon, when the sun is available. On the relatively few rainy days, people could return to their traditional ways of cooking, saving fuel during clear days.

Secondly, interest in outdoor cooking during mild weather has increased rapidly in the United States. This fad or hobby has captivated the suburban population. Low-cost gas or electricity is available in practically all American kitchens, but in spite of this, some forty million charcoal-burning outdoor cookers have been sold during the past ten years and are in frequent use during warm days. If solar cooking ovens could be fabricated and marketed at competitive prices, they could gain considerable popularity as useful devices in outdoor living, on camping trips and for field use.

Solar cooking devices

It is hardly necessary to mention the fact that two cooking devices are used in most kitchens, the range and the oven. The cooking range with one or more burners or heaters is used for boiling water and for cooking foods in pots or skillets. The oven is used for roasting, baking and for the preparation of casserole dishes of most foods. This "division of labor" between cooking range and oven has been established during centuries of natural evolution and it is to be expected that solar cooking devices will be used in the same way.

The parabolic reflector-type solar cooker concentrates solar radiation on a relatively small spot on the bottom of pots or skillets resembling in operation the burner or heater of the kitchen range. Food must be stirred, to prevent scorching, and for this reason the pot must be easily accessible. Well-designed indoor kitchen burners transfer about 40 to 50 per cent of the heat of the burner to the contents of the pot. But when the cooking is out-of-doors, influenced by wind, considerable heat loss may occur. According to experience, on windy days it is difficult to heat the contents of larger pots with parabolic solar cookers. Attempts have been made to cover the pot with heat insulation, but when this is done it is difficult to stir the food. In addition, the parabolic cooker must be adjusted frequently to keep the radiation of the sun concentrated on the bottom of the pot.

Solar cooking ovens consist of a well-insulated oven body, capable of holding larger volumes of food in several cooking utensils. The insulated oven prevents the loss of heat from pots or pans to a considerable degree. Solar energy is admitted to the interior of the oven through a "window" and is augmented by flat reflectors. Adjustment in orientation to "follow the sun" is less frequently needed, once every half-hour or hour being sufficient. Heat from the sun can be stored inside the oven, accumulating heat when the oven is not used for cooking. The stored heat is released when food is placed into the oven and cooks it more rapidly, or keeps the food warm for some time when clouds intervene, or even after sunset. Solar ovens can cook larger quantities of rice or vegetables and are able to roast meats and bake bread. This cannot be done with the parabolic reflector-type solar cooker.

The intercepted amount of solar energy is directly proportional to the projected area of the window and reflectors, or of the parabolic concentrating device. Larger areas intercept more solar radiation.

Development of solar cooking ovens

A previous article (1) and an extensive report (2) describe the history of solar cookers and ovens, as well as the results of measurements of reflection, transmission and heat loss characteristics of various oven designs. Several solar ovens have been designed, built and tested. These models were different in construction features, costs and convenience in food handling and orientation.

Field tests have been carried out with several designs and the most convenient model has been selected for further use. Ovens of this type (figures 1 and 2) have been exhibited at several trade fairs and at the world fair in Brussels. The United Nations Food and Agriculture Organization has acquired several ovens for field tests. The Caribbean Commission has operated an oven for more than two years — in Trinidad — after the oven was personally introduced and demonstrated to the Commission by one of the authors.

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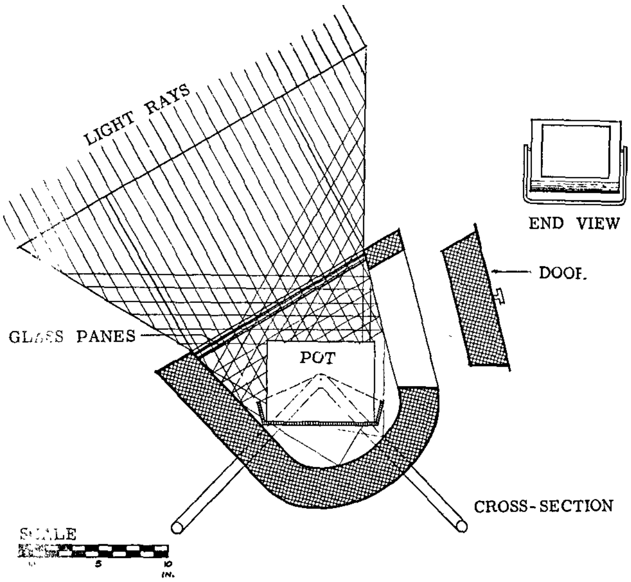

Figure 1. Solar cooking oven, cross-sectional view

Figure 2. Solar cooking oven with tubular stand

Technical details of the solar cooking oven

The oven design used most extensively in tests is shown in figures 1 and 2. Recent work results in simplification in design and increase in convenience (figures 3, 4 and 5), incorporating the best features of previous designs.

The oven body consists of a well-insulated semi-cylindrical form, made of sheet aluminum, sheet steel, galvanized iron, or basket-work (figures 4 and 5). Two shells are made and the space between them is filled with insulating materials. The interior shell is painted black, using heat resistant paint. Sheet aluminium does not have to be coated, because it is sufficiently reflective and concentrates solar radiation to the pot. A door is part of the oven body and is made of similar materials.

The window of the oven consists of two air-spaced transparent layers. Glass panes have been used successfully, but heat-resistant plastic materials can be used, especially when the window is hinged (figure 5) and used as a door to introduce food.

The reflectors, made of silvered glass mirrors, are heavy and brittle. Equally good results are obtained with anodized sheet aluminum of the type known as "Alzak." Reflectors of this type have been used for several years without tarnishing or diminishing in reflectivity. Bright aluminum foil, or sheet, tarnishes very rapidly when used out-of-doors in rain, wind and dust. Bright aluminum foil, coated or laminated with sun-resistant plastic finish, has become recently available. Protected aluminum foil can be laminated to low-cost, rigid backing to decrease the cost of reflectors.

The stand and orienting device can be made of tubular metal (figure 1 or 2) with pivoting axle for rotating the semi-cylindrical oven part. The position of the oven is fixed by using a pin which engages into openings on the side of the oven-body. This construction has been simplified greatly in figures 3, 4 and 5, where a cradle-like holder is shown for moving the oven. The cradle-holder can be made of wood or other materials.

The cooking platform provides a firm horizontal base for the cooking utensils and for absorbing and accumulating heat from the sun before food is placed into the oven. In figures 1 and 2, the platform is attached to the pivots in a horizontal position. In later models (figures 3, 4 and 5), the construction

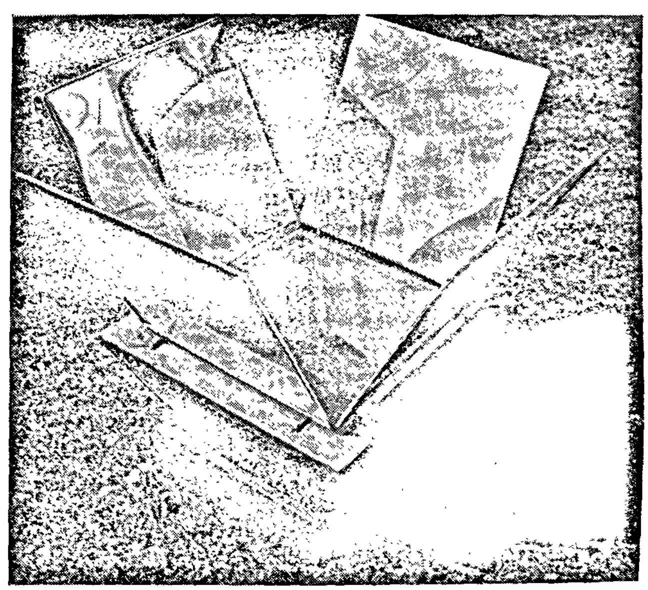

Figure 3. Solar cooking oven with cradle support

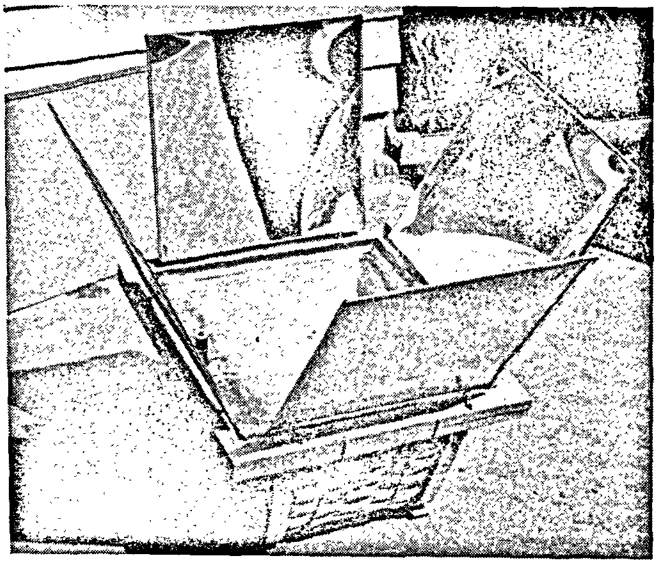

Figure 4. Solar cooking oven with basket body and clay inner coating

has been simplified by using a movable platform, adjusted when the orientation of the oven is changed. The movable platform eliminates the need for pivots and their bearings in the walls of the oven, thus simplifying construction. The cooking platform is preferably made of hollow sheet metal shell, filled with heat storage material. It should be black to absorb solar radiation.

Heat storage material is necessary to accumulate heat before food is placed into the oven and to increase the cooking rate, by transferring stored heat to pots when these are placed on the preheated platform. The usual cooking temperatures are in the 300-400°F (about 150-200°C) range and it is desirable to store heat in this range. Heat is usually stored as specific heat, but this can be augmented by using the latent heat of fusion, or heat of transition of materials which change phase in the desired temperature range. The specific heat of bricks, stones or sand can be used and in this case the entire platform could be made of suitably shaped blackened bricks or rocks. The use of the latent heat of fusion requires a cooking platform that is liquid tight and sturdy enough to prevent the possibility of damage during use and leakage of the contents when they melt. Relatively few materials melt in the 300-400°F temperature range. One of these materials has been used for many years in the heat treatment of metals and consists of a mixture of 20 per cent sodium nitrate, 30 per cent sodium nitrate and 50 per cent potassium nitrate. The mixture melts at 310°F. It is possible to change the melting point of this mixture by slight variations in the amount of components. Another mixture consists of equal parts of sodium hydroxide and potassium hydroxide, which must be entirely free of water. Due to possible leakage and to the corrosive and hygroscopic nature of this mixture, it is definitely not recommended. Another comparatively safe material is a mixture of anhydrous alkaline sulfates (3) which changes in crystal form, without melting (solid-solid transition), thus avoiding the danger of puncture and leakage through the walls of the platform. The following data compares the heat storage capacity of these materials, including specific heat and heat of fusion or transition, in the 300-400°F range:

Material	*Heat storage capacity in the 300-400°F range*
Bricks or stones (spec. heat)	20 btu/pound
Nitrate mixture	96 btu/pound
Anhydrous sulfate mixture	105 btu/pound
Hydroxide mixture	113 btu/pound

In actual use, the platform was built in the form of a flat slab about one inch thick containing 6 pounds of the sulfate mixture. This could be used repeatedly without any difficulty.

Cooking utensils were selected to cover the platform area and for this reason rectangular pans ("bread pans") or oval roasters were used, as shown in figure 5. The utensils were preferably black or of dark color to absorb the maximum possible amount of solar radiation. All utensils had tightly fitting covers which also were black or of dark color.

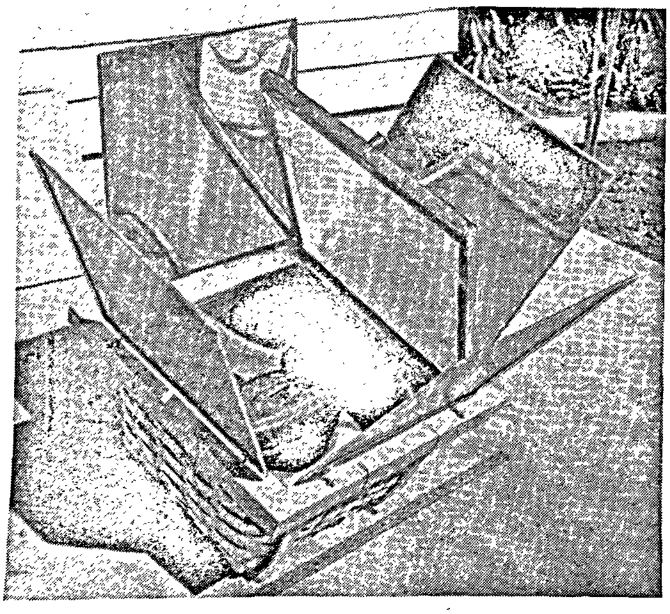

Figure 5. Solar cooking oven, as shown in figure 4, with opened window-door

Improvements in design

Numerous requests have been received for a solar cooking oven that could be fabricated in countries which would use the oven, employing local labor and materials. Based on this request, our new design (figures 4 and 5) separates the component parts of the oven into easily available parts and key-parts. The body of the oven is constructed of basket-weave material, an art that is known universatility. The double walls of the oven are filled with locally available heat insulation and the inner shell is coated on the inside with clay or cement to form a hard smooth finish when dry and baked by the sun. The cradle for orienting the oven can be easily made of wood. The window-frame can also be made of wood and coated with heat resistant cement.

The key parts are: (*a*) heat resistant plastic for the hinged window; (*b*) reflector material, preferably plastic-coated aluminum foil; and (*c*) the heat storage platform. These materials can be obtained from manufacturers and assembled locally to complete the oven.

The new design could be perfected during field tests with the help of people most interested in its use, determining its most preferred dimensions. Several models could be distributed to local shops, with the necessary patterns and key-parts for fabrication. In this way, small local industries could progress by introducing the oven to local inhabitants. The work of demonstrating and marketing the oven could progress at the local level, with increased probability of success.

Temperature and heat transfer

The ovens shown in the illustrations intercept solar radiation directly through their windows and by reflection from the mirrors. As the projected area of the mirrors is twice the window area, as the intercepted solar radiation is three times the window area. This radiation is transmitted through the double window at normal incidence, when 80 per cent is transmitted through glass of low iron content. Special heat-resistant plastics may transmit 90 per cent. The mirrors reflect only the direct part of solar radiation, while the diffuse part is mostly scattered. Even on the clearest days, not more than 90 per cent of the incident radiation is direct; it is reflected from the mirrors and transmitted through the window at 60 degree incidence. At such angles, both reflection and transmission are somewhat less than at normal incidence. The net result is that A sq ft window and its reflectors intercept $3A$ sq ft solar radiation, and $1.9\ A$ reaches the interior of the oven, on clear days.

The semi-cylindrical shape of the oven body has an interior heat-losing area of $2.3A$ sq ft for each A sq ft window area. The heat loss through the insulating layer of the oven body and its window can be calculated but, in addition, measurements have been carried out to control the calculation. In these tests, the cooking platform was replaced with a thin, flat electric heater, of the same area, painted black on its top surface. The oven was operated out-of-doors after sunset, heating it with a measured amount of electrical energy. The temperature within the oven was measured until temperature equilibrium was obtained. At this point, the heat loss was equal to the heat input. This method is quite useful to determine the merit of various designs, insulating materials and construction details and can be used equally well to determine the cooking time required for various foods. The results are shown for an oven with 2 sq ft window area (17″ × 17″ double glass) intercepting 6 sq ft of solar radiation with 3.8 sq ft of radiation reaching the interior of the oven:

Temperature inside the oven (°F)	*Electric heating delivered to the platform area (in btu)*
80	0
200	280
250	420
300	580
400	980

On clear days, 300 btu sq ft hour solar radiation can be expected and, therefore, the oven can intercept 1 800 btu/hour, and 1 060 btu/hour reaches the interior. The actual maximum temperature attained by this oven with clear day sunshine (in the vicinity of New York) was 410-430°F. Higher temperatures could be obtained in the clearer atmosphere of the country, where occasionally 460°F was reached during the noon hours.

Food placed in the solar heated oven (with 2 sq ft of window area) absorbed 560-600 btu/hour, on reasonably clear days. This amount of heat is sufficient to raise the temperature of 4 pounds of the usual foods from 70°F to the boiling point, during one hour. It is obvious that larger ovens of the same design are capable of absorbing more solar radiation and can cook larger quantities of food.

The same oven with 2 sq ft of window area was used to test the efficiency of the heat storage slab, filled with 6 pounds of anhydrous sulfate mixture. After the oven was exposed to the sun for 2 hours, the mirrors were removed and the window was covered with 2-inch thick heat insulation.

Time (minutes)	*Temperature inside the oven (°F)*
0	350
30	350
60	350
90	280
120	250

This result shows that the temperature can be kept at baking level (350°F) for one hour and above 250°F for another hour, if the oven window is covered with insulation.

Cooking tests

The aim of the cooking tests was to determine the cooking capacity of the oven, selecting primarily staple foods of tropical countries. The tests were made on clear days in the New York area.

Rice. One pound and 1.2 pounds of water in a flat pan cooks in 45 minutes, without stirring or other attention. Water is absorbed completely and rice is perfectly cooked.

Lentils. One pound requires 4 pounds of water. The mixture was standing at room temperature for 12 hours to soften the lentils and cooked for 2 hours, until done.

Dry peas and black beans. One pound requires 4 pounds of water and was softened for about 12 hours. Peas and beans must be cooked for 3 to 4 hours until they are sufficiently tender.

Roasts. The oval roaster (figure 5) can hold up to 8 pounds of meat (beef, veal, pork, etc.). Roast beef, 8 pounds, required 3 hours. Roast pork, 7 pounds, required 3.2 hours. Two chickens — 4 pounds — were completely roasted in one hour. On clear days, the roasting time is approximately the same as in conventional ovens.

Stews. Stews, containing meat and vegetables, required about 2 hours cooking until the meat was sufficiently tender.

Bread, rolls and cakes. Two loaves of bread — 2 pounds — baked in 45 minutes; rolls required about 30 minutes; cake — 3 pounds — one hour. The baked food was uniform in texture, and the results comparable to baking in conventional ovens.

Fruit preserves. Two pounds of fruit were mixed with one pound of sugar and 0.5 pound of water. Cooking time was 3 hours, producing preserves which were filled into containers and sterilized in the oven, in the usual way. These tests indicate that the solar oven can be used for the preparation of preserved and "home-canned" foods.

The conclusions derived from these cooking tests clearly indicate that baking, roasting, stewing and other forms of cooking can be carried out in the oven in the same way as in conventional fuel-heated ovens. On clear days, the cooking time is the same as in conventional ovens. On hazy or partly cloudy days, the cooking time may be somewhat longer, but with the help of the pre-heated heat storage platform, the foods are completely cooked.

The major advantage of the solar cooking oven is that it requires practically no attention. The orientation of the oven is adjusted when the food is placed into it, and the oven is closed and can be left out in the sun, while the cook retires into the shade. An adjustment every half hour to one hour is all the attention that is needed.

Economical considerations

In arid tropical countries, the major economical aspect of the solar cooking oven is in saving fuel and the labor needed to collect and transport fuel. Solar energy replaces animal dung, which can be used with greater advantage as an agricultural fertilizer to improve crop yield. The yearly fuel consumption of various countries has been estimated by the Statistical Office of the United Nations in 1952. The non-commercial, *per capita* consumption in tropical countries is rather uniform, being the equivalent of 0.2-0.25 tons of coal yearly. Most of this fuel is used for cooking and for heating water which, therefore, require the equivalent of nearly one pound of coal per person daily, corresponding to 10 000 btu. This amount of fuel is burned rather inefficiently in open cooking hearths. According to estimates (4), only 6 per cent of the heating value of fuel, or 600 btu per person daily, is actually used in the pot. This amount is plausible, because it is sufficient to cook about 4 pounds of food, including water used in cooking and for warm beverages. This amount is sufficient for one person daily. As was outlined above, a solar cooking oven with two sq. ft of window area is capable of furnishing the same cooking output during one hour. An oven of this type, operated daily for 4 to 6 hours, would be sufficient to prepare food for a family of 4 to 6 persons. Larger ovens with a window area of 4 sq ft, forming a rectangular opening of 24 inches (or 60 centimeters) on edge, should be sufficient for a family of 8 to 12 persons.

The value of the estimated *per capita* fuel saving, the equivalent of 0.20 ton of coal per year, may be established by using the local value of coal or the local value of the equivalent fuels that are actually used. In India the value of fuel, including agricultural waste, is around $5.00 per ton (5). On this basis, the *per capita* fuel saving may be around $0.75 per year. Other estimates range from $1 to $6 per person as the equivalent cost of cooking fuel consumed yearly, based on potential agricultural benefits that may be derived if the present cooking fuel were to be used as fertilizer.

Economical considerations clearly lead to the unavoidable conclusion that solar cooking ovens must be low in initial cost. At the same time, the ovens must be simple in operation, must cook enough food and must be durable. It is essential that the ovens be acceptable, and accepted by the people who need them most. Fabrication in the United States — if competitive with the charcoal outdoor cooker — may easily result in their widespread use. Fabrication in an industrialized country for export to arid, tropical countries would be precluded, due to high shipping and distributing costs. Local fabrication in arid, tropical countries may progress rapidly, if the distribution of special key parts, materials and patterns and the necessary indoctrination could be organized.

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Summary

The authors' previous work on designing, constructing and testing solar cooking ovens has been published. Practically all foods have been baked, roasted or otherwise cooked in such ovens and detailed results are presented.

Parabolic reflector-type cookers concentrate solar energy on a pot and are suitable for boiling water or for cooking food with continuous stirring to prevent scorching of the food. The reflector must be adjusted frequently to keep the focus image of the sun at the center of the pot. In the solar cooking oven, it is not necessary to stir foods, because they cannot be scorched. Adjustment in orientation is required only once every half hour, or hour, and is very simple. Staple foods, such as peas, beans, lentils and rice, can be cooked, without any attention. Relatively large quantities of foods can be cooked in several pots or pans at one time. Solar cooking ovens can be used to prepare fruit and vegetable conserves and for sterilizing foods for preserving in containers.

New models have been developed with the aim of simplifying construction and of using materials available in arid, tropical countries. The semi-cylindrical body of the oven is supported by a cradle holder for convenience in orientation. Basket material can be used for the construction of the double-walled oven body — a fabrication method that is well-known in most countries. The inside surface of the basket material is coated with clay or cement and after drying it is baked by the sun.

The door of the oven is replaced by a hinged window unit, made of coated wood framing and heat-resistant plastic film, replacing the air-spaced double glass used in previous models.

The flat reflector mirrors originally made of anodized sheet aluminum ("Alzak") can be replaced by aluminum foil, coated with sun-resistant plastic, or laminated to a thin plastic film. The coated foil can be reinforced with locally available rigid sheet material.

Heat storage is desirable, because it can prolong the cooking period when passing clouds intervene, can extend cooking for an hour after sunset and can keep food warm for an additional hour. Heat can be stored as the heat of transition of a mixture of alkaline sulfates, which store heat by solid-solid phase change. This heat storage slab eliminates the danger of leakage (when heat-of-fusion type materials are used) and is otherwise harmless.

It is not practical to fabricate solar cooking ovens in the United States for export to arid, tropical countries, because shipping and distribution costs are prohibitive. The new design can be fabricated by using simple materials, available in most arid countries, and only "key-parts" have to be obtained elsewhere. These parts include sun-resistant plastic film, plastic-covered aluminum film and the heat storage slab.

The daily fuel savings that could be attained through the use of solar ovens have been estimated as the fuel equivalent of one pound of coal *per capita* daily. The value of this fuel can be variously estimated at a low of U.S. $0.75 *per capita* yearly, or as high as $5.00 if the agricultural benefit is considered by using cow dung as fertilizer, instead of burning it.

On the basis of extensive studies and field tests, we recommend that solar cooking ovens should be fabricated locally where they are most needed. Models, patterns and key parts should be made available to those interested in fabricating ovens; they would be most competent to demonstrate and introduce the ovens to those who need them the most.

CUISINIÈRES SOLAIRES PRATIQUES

Résumé

Les auteurs ont publié leurs travaux antérieurs sur la mise au point, la construction et les essais des cuisinières solaires. On a cuit au four, rôti, grillé, etc. tous les aliments concevables dans de telles cuisinières et le présent mémoire donne les résultats détaillés de ces essais.

La cuisinière du type à réflecteur parabolique concentre l'énergie solaire sur un récipient qui se

prête à l'ébullition de l'eau, ou à la cuisson des aliments avec une agitation continue, pour éviter qu'ils ne brûlent. Le réflecteur doit être ajusté fréquemment pour tenir l'image solaire de son foyer au centre du récipient. Dans le four solaire, il n'est pas nécessaire d'agiter les aliments, car il est impossible de les brûler. Le réglage en orientation n'a besoin de se faire qu'une fois toutes les demi-heures ou toutes les heures, et il est très simple. Les aliments de base, tels que les pois, les haricots, les lentilles et le riz, peuvent être cuits sans la moindre surveillance. Des quantités d'aliments relativement importantes peuvent être cuites dans plusieurs récipients à la fois. Les fours solaires peuvent être utilisés pour préparer des conserves de fruits et de légumes et pour stériliser les aliments en vue de leur mise en conserve dans des récipients appropriés.

On a mis au point de nouveaux modèles, dans le but de simplifier la construction et pour se servir des matériaux disponibles dans les pays tropicaux et arides. Le corps semi-cylindrique du four est supporté par un berceau pour la commodité de l'orientation. On peut se servir de matériaux du type employé pour les paniers, pour la construction d'un corps à doubles parois, méthode de fabrication bien connue dans la plupart des pays. La surface intérieure du panier est revêtue d'argile ou de ciment et, après séchage, on la cuit au soleil.

La porte de la cuisinière est remplacée par une fenêtre à charnières faite d'un cadre en bois recouvert de produit plastique, avec une pellicule résistant à la chaleur qui remplace le double verre avec espace d'air dont on se servait dans les modèles antérieurs.

Le miroir réflecteur plat, qui était fait à l'origine de feuilles d'aluminium anodisées (Alzac) peut être remplacé par de la feuille d'aluminium revêtue d'un composé plastique résistant au soleil ou laminé de manière à former une pellicule plastique mince. La feuille ainsi enduite peut être renforcée par de la tôle rigide disponible sur place.

L'accumulation de chaleur est souhaitable, car elle peut prolonger la période de cuisson quand des nuages interviennent et permettre de pousser la cuisson pendant une heure après le coucher du soleil et de tenir les aliments au chaud pendant une heure de plus. On peut mettre en réserve de la chaleur sous forme de chaleur de transition d'un mélange de sulfate alcalin qui accumule la chaleur par des changements de phases solide-solide. Cette plaque d'accumulation de chaleur élimine le danger de fuites (lorsqu'on se sert de matériaux du type chaleur de fusion) et ne présente aucun danger.

Il n'est pas pratique de construire des cuisinières solaires aux États-Unis en vue de leur exportation dans les pays arides tropicaux, car les frais d'envoi et de distribution sont prohibitifs. On peut fabriquer le nouveau modèle en se servant de matériaux simples, disponibles dans la plupart des pays arides, et on ne doit importer que les pièces essentielles. Ces pièces comportent une pellicule en composition plastique résistant au soleil, une pellicule en aluminium couverte de composition plastique et une plaque d'accumulation de chaleur.

Les économies journalières de combustible que l'on peut réaliser par l'emploi du fourneau solaire ont été évaluées comme étant l'équivalent, en combustible, d'une livre de charbon par tête et par jour. La valeur de ce combustible peut être évaluée à plus de 0,75 dollar par tête et par an, ou même jusqu'à 5 dollars, si l'on considère les avantages réalisés dans l'agriculture en se servant de bouse de vache comme d'engrais au lieu de la brûler.

Sur la base d'études poussées et d'essais faits sur place, nous recommandons que les cuisinières solaires soient fabriquées à pied d'œuvre là où le besoin s'en fait le plus sentir. Des modèles, des maquettes et des pièces essentielles devraient être mis à la disposition des personnes qui s'intéressent à la fabrication de ces fours. Ces personnes seraient le plus compétentes pour faire la démonstration des cuisinières et les présenter à ceux qui en ont le plus besoin.

Agenda item III.C.5

USE OF SOLAR ENERGY FOR HEATING PURPOSES: HEAT STORAGE

Kailash N. Mathur *

Any improvements in the present methods of storing solar energy will have wide applications and open the way to extensive and more economic utilization of the sun's heat. Space heating is one of the most important fields which offer the simplest direct utilization of solar energy, since only a relatively small increase in temperature is needed here. Among the many domestic uses of energy, perhaps the most important are cooking, lighting, hot water supply and house heating in winter and cooling in summer. These requirements are of some significance, since they constitute a large proportion of demand on conventional energy resources. It has been estimated that nearly one-third of the total fuel consumed in the United States is used for heating of buildings alone. It is not surprising, therefore, that considerable attention has been given during the last several years to the important problem of storing the sun's heat, when it is available, for later use for supplying vital heat when it is not so available. The storage problem for some localities may be for short periods only, i.e. storage during daytime and use during the night. Many localities may need long-term storage, such as storing during the long hours of summer sunshine for use during the following winter months.

The designs tried so far include a flat plate collector, a storage system and a means of transporting heat from collector to storage. For reasons of economy, the collector is usually designed to act also as the roof of the building, which brings in the problem of proper architectural design so as to give the roof the most favourable angle of tilt and the correct orientation to take the maximum advantage of the sunshine hours.

Since space heating is most needed in the winter months, when the days are short and sunshine undependable, it follows that efficient means should be available for collecting and storing whatever energy may be available. During the winter months, the solar collectors have to operate within a rather restricted temperature level, in the range of 120°-150°F on clear days. For comfort conditions, room temperatures have normally to be maintained around 70°F, which sets a limit of minimum 80°F on the storage temperature.

A major problem in the design of a storage system is the selection of material in which the heat energy is to be stored, since it determines the capacity of the system. The selection of material has been the subject of considerable experimentation. The materials tried can be divided into two broad types: (*a*) those that store energy in the form of sensible heat; and (*b*) those that undergo a change of state or physico-chemical change at some temperature within the practical range of temperature provided by the solar heat collectors, namely, 90°-120°F.

In the first category of materials, water and rock pebbles have been found to be the most practical storage materials, heat being absorbed here as their specific heat. Thus, one cubic foot of water can store 62.5 btu per °F rise in temperature, while one cubic foot of rock can store about 36 btu/°F. Taking as an average a temperature rise of 30°F, the heat storage capacity of 1 cubic foot of water comes to 1 880 btu and that of rock, to about 1 080 btu.

According to an estimate made by Maria Telkes, for an "average house" with a cubic content of 10 000 cubic feet and having reasonably good insulation, the average daily winter heat loss may be around 300 000 btu per day, with twice this loss on exceptionally cold days. This "average house" will require about 160 cubic feet of water weighing about 5 tons, or 280 cubic feet of rock weighing about 25 tons. After allowing for additional room for circulation of hot air or water from the solar collector, a space of about 400 cu. ft. is needed for storing the heat requirement for about 2 average days when using water, and about 1.3 days when using rock pebbles. If a longer period of heat storage is necessary, especially in localities where winter sunshine is very uncertain, the storage space necessary will have to be much larger.

The use of materials that undergo physico-chemical change has been largely dictated for the purpose of reducing storage space. A number of low-cost salt hydrates were tried by Maria Telkes in her early experiments, a typical example being sodium sulphate deca-hydrate which almost melts in its water of crystallization when heated to its transition temperature at 90°F. The stored heat in this case is recovered as the material recrystallizes. A great drawback when using this type of material is that considerable super-cooling can take place, during which period the substance does not part with its stored heat until either some nuclei are introduced or stirring is done. Although largely discarded for this reason, these substances nevertheless offer the means of reducing storage space. It is from this angle that Martin Goldstein of the National Physical Laboratory of Israel undertook a survey of materials that could possibly be used. His aim has been to find

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such chemical systems as will give the greatest storage of heat per unit mass or unit volume — more especially volumes, since heat losses and insulation costs will depend on the volume of the enclosure rather than on the mass of the substance contained in it. In his paper (S/7), Goldstein has surveyed many groups of substances selected from standard reference sources such as Perry's *Chemical Engineers' Handbook* and the *International Critical Tables*, and has classified his study somewhat as follows : (*a*) inorganic and organic substances with large heats of fusion, having their melting points within the temperature range 30° and 200°C; (*b*) eutectic mixtures of inorganic salts; (*c*) change of phase class of substances; (*d*) solid-to-solid transitions; (*e*) heats of solutions; (*f*) heats of vaporization; (*g*) storage by chemical reaction in solution.

Goldstein's study, based on purely thermodynamic grounds, deserves to be followed up with detailed investigation of some of the more promising lines, such as the vaporization process.

In his paper entitled "Solar Buildings in Temperate and Tropical Climates" (S/8), Edward Speyer has made a critical study of the six important parameters — cost, space requirements, capacity, efficiency, level and rate — in the design of a solar energy system. In using solar energy for space heating and cooling, the important over-all problem, according to him, is to make a solar house pay for itself in terms of fuel saving. The cheapest form of energy storage is as sensible heat in rocks or water, and the storage capacity needed for long-term storage, i.e., summer heat for winter use, does not, according to him, require more than a small percentage of the volume of the space being heated or cooled. Even less space was needed for short-term storage. This space can be further reduced if chemical storage methods are adopted, though at a higher cost. The efficiency of storage required for a solar house is based on two superimposed duty cycles, namely, the daily variations in temperature over the seasonal variations from summer to winter. Speyer considers that, for long storage, at least 50 per cent of the energy put into storage must be available some three months later.

Storage capacity is inversely related to collector capacity, but if storage efficiency is high, then the collector capacity, i.e. area, can usually be reduced. Collector efficiency is, however, an important factor in determining the optimum functioning of the solar house. The rate of storage or withdrawal is not considered of importance unless the storage is done as heat of fusion. In summing up, Speyer concludes that solar collectors can only be economically comparable to fossil fuels if the cost does not exceed U.S. $3 or $4 per square foot, and for all areas which can be readily reached, whether by truck, train or ship, he considers that fossil fuels will continue to remain the cheapest and most dependable source of energy. He even considers that, for remote regions, it may be better economic investment to build roads rather than make a large investment in solar devices.

Speyer argues that the main hope for solar energy utilization lies in making cheaper solar energy collectors of high efficiency. He estimates that if efficient large capacity storage could be made 80 per cent cheaper, i.e. by a factor of 5, it would minimize the required collector area and make the system economically competitive. On the other hand, if collectors could be made cheaper by only a factor of 2 or 3 and their efficiency improved, the over-all performance could be vastly better. Realizing the importance of solar collectors, Speyer has designed a flat collector using the principle of the Dewar flask, i.e. using evacuated chambers for insulating above and below the absorbing layers of the collector. This is briefly described in the paper, though no estimates of cost are given.

Allcut and Hooper, of the University of Toronto, have examined the special problems of solar energy utilization in Canada in their paper entitled "Solar Energy in Canada".[1]

In the higher altitudes of northern parts of Canada, conditions for solar energy use are difficult : the mean annual hours of bright sunshine are about 1 400-1 600, and during the month of December there may be fewer than 25 hours of sunshine. The southern part of Canada is a highly industrialized region but, besides the large industrial power needs, there is the field of residential and commercial space heating which accounts for some 25 to 30 per cent of total energy consumption. This in 1958 consumed the equivalent of 34.5 million tons of coal and may reach a figure of 81 million tons in 20 years' time.

Allcut and Hooper have examined in some detail the region of southern Ontario. They find that if the heating system is to be entirely independent of auxiliary sources, it would be essential to have a long-term storage system to carry over the heat collected during summer, otherwise the size of the collector area would have to be very large and would exceed the projected south-facing area of a normal house.

After analysing several designs, they conclude that a solar heated house, fitted with a panel heating system which could effectively utilize heat at a temperature of 80°F, would be economically feasible if a large reservoir with heat storage at 145°F and with only limited amount of insulation could be provided.

The paper reports upon the results obtained with scale models of basement heat storage reservoirs filled with water to predict the behaviour of complete full-scale systems, including the house, the solar collector and storage characteristics, over periods of several years. Their equipment consisted essentially of a sand box in which they placed a small-scale model of the underground heat reservoir. A typical time scale was one minute in the model equal to 2 days of real time. The conditions in the house they had taken as typical were : a collector area of 600 sq ft

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[1] *Proceedings of the United Nations Conference on New Sources of Energy, 1961*, vol. 4, agenda item III.A, paper S/20.

tilted at an angle of 60° to the horizontal, a heat load of 775 btu/°F and a storage of 50 000 gallons. The main value of the model scale experiments lies in the ease with which information can be provided for interrelations between angle of tilt and the incidence of direct, indirect and total radiation; sequences of clear, partly cloudy or overcast hours; small changes in the orientation, etc. Typical results obtained have been presented in the form of curves. While they cannot entirely replace full-scale trials, the model experiments have the great merit of being able to forecast long-term behaviour under predetermined conditions.

Impressive work has been done on house heating in America. Mention may be made here of the two houses at M.I.T.; of the Dover (Mass.) house by Telkes, Raymond and Peabody; of the houses built by George Löf in Boulder, Colorado; by Bliss near Tuscon; and more recently by Harry Thomason.[2] It would appear that for most applications, the minimum cost heating system will be one in which entire dependence is not placed on storage alone but in which provision is made for auxiliary heat. If such a compromise could be accepted, then the cost of storage could be brought within economic limits.

[2] See paper S/67, S/114, S/30 and S/3, under agenda item III.C.2 above.

Suggested topics for discussion

1. Whether sufficient data exists to justify the conclusion that a reasonably cheap storage system can be installed to enable solar energy to be used exclusively for the purpose of house heating or both heating and cooling.

2. Whether, in the present state of development, it would be economically feasible to fully replace conventional heating systems by roof-type solar energy collectors and underground storage with water or rock pebbles as storing media.

3. Whether a long-term storage system is a practical proposition and, if so, whether it would be more economical to adopt a solar energy storage system in which conventional methods of heating are employed to supplement solar heat storage, thereby enabling the capacity of the storage system to be reduced.

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : ACCUMULATION DE CHALEUR

(Traduction du rapport précédent)

Kailash N. Mathur *

Toutes les améliorations apportées aux méthodes actuelles d'accumulation de l'énergie solaire sont susceptibles de vastes applications et ouvrent la voie à une utilisation extensive et plus économique de la chaleur solaire. Le chauffage des locaux est l'un des domaines les plus importants où l'on puisse directement utiliser l'énergie solaire par les procédés les plus simples, puisqu'il suffit dans ce cas d'élever la température dans des proportions relativement faibles. Parmi les nombreux usages domestiques de l'énergie, les plus importants sont peut-être la cuisson des aliments, l'éclairage, la fourniture d'eau chaude, le chauffage des maisons en hiver et leur climatisation en été. Ces besoins ne sont pas négligeables, puisqu'ils entrent dans une forte proportion dans la demande de ressources d'énergie classiques. On estime que près d'un tiers du total des combustibles utilisés aux États-Unis sert au seul chauffage des immeubles. Il n'est donc pas surprenant que depuis plusieurs années on accorde une grande attention à l'important problème que constitue l'accumulation de la chaleur solaire, quand elle est disponible, afin de l'utiliser ultérieurement lorsqu'elle est nécessaire pour fournir la chaleur nécessaire à la vie. Dans certaines régions, il ne s'agit d'emmagasiner la chaleur que pendant de courtes périodes, par exemple, accumuler la chaleur pendant le jour pour l'utiliser durant la nuit. Nombreuses sont les régions où il faut emmagasiner la chaleur solaire pendant de longues périodes, c'est-à-dire l'accumuler pendant les longues heures d'ensoleillement en été afin de l'utiliser pendant les mois d'hiver qui vont suivre.

Les modèles expérimentés jusqu'ici comprennent un insolateur à plaques plates, un système d'emmagasinage, et un moyen de transport de la chaleur de l'insolateur au système d'accumulation. Pour des raisons d'économie, l'insolateur est habituellement conçu de façon à faire également office de toit pour l'immeuble, ce qui pose le problème d'une architecture appropriée afin de donner au toit l'angle le plus favorable et la bonne orientation qui permettront de profiter au maximum des heures d'ensoleillement.

Comme le chauffage des maisons est le plus nécessaire pendant les mois d'hiver où les jours sont courts et l'ensoleillement imprévisible, il s'ensuit qu'il faut disposer de moyens efficaces pour amasser et emmagasiner toute l'énergie disponible. Pendant les mois d'hiver, les insolateurs doivent fonctionner à un niveau de température assez faible qui se situe entre 120 °F (49 °C) et 150 °F (65 °C) par temps clair. Pour qu'une pièce soit suffisamment chauffée, la température doit normalement être maintenue aux environs de 70 °C (22 °C), ce qui impose que la température du système d'accumulation soit au minimum de 80° F (27 °C).

Un des problèmes les plus difficiles que pose la construction d'un système d'accumulation est le choix de la matière dans laquelle l'énergie de la chaleur va être accumulée, puisque ce choix détermine la capacité du système. Le choix de la matière a fait l'objet de très nombreuses expériences. Les matières essayées peuvent être divisées en deux grandes catégories : *a*) celles qui accumulent l'énergie sous forme de chaleur sensible; et *b*) celles qui subissent un changement de nature ou une altération physico-chimique a un degré de température qui se situe dans la gamme pratique des températures fournies par les insolateurs, c'est-à-dire 90 à 120 °F (32 à 49 °C).

Parmi les matières de la première catégorie, on a constaté que l'eau et les pierres de petites dimensions sont les plus pratiques pour l'accumulation, la chaleur étant absorbée sous forme de chaleur spécifique de la matière. Par exemple, si la température s'élève de 1°F (1/2 °C), un pied cube (0,028 m^3) d'eau peut accumuler 62,5 btu (15,7 kilocalories), alors qu'un pied cube (0,028 m^3) de cailloux peut emmagasiner 36 btu (9 kcal/1/2 °C). Si l'on prend en moyenne une hausse de température de 30 °F (15 °C), la capacité d'accumulation de chaleur de un pied cube (0,028 m^3) d'eau s'élève à 1 880 btu (473 kcal) et celle des cailloux à 1 080 btu (272 kcal) environ.

Selon une estimation de Maria Telkes, dans le cas d'un « type moyen de maison » d'un volume de 10 000 pieds cubes (283 m^3) normalement isolée, la perte moyenne de chaleur par jour d'hiver est d'environ 300 000 btu (75 600 kcal), cette perte pouvant être doublée les jours exceptionnellement froids. Il faudra pour cette « maison moyenne » environ 100 pieds cubes (2,83 m^3) d'eau pesant environ 5 tonnes, ou 280 pieds cubes (7,85 m^3) de cailloux pesant environ 25 tonnes. Si l'on tient compte de l'espace supplémentaire nécessaire pour la circulation de l'air chaud ou de l'eau chaude venant de l'inso-

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lateur, il faut environ 400 pieds cubes (11,20 m³) d'espace pour accumuler la chaleur nécessaire pour environ deux jours de température normale, lorsqu'on utilise l'eau, et pour 1,3 jour lorsqu'on utilise les cailloux. Si une période plus longue d'accumulation de chaleur est indispensable, notamment dans les régions où l'ensoleillement d'hiver est très incertain, l'espace nécessaire à l'emmagasinage devra être beaucoup plus grand.

C'est surtout pour réduire l'espace nécessaire à l'emmagasinage que l'on préconise l'emploi de matières qui subissent une transformation physico-chimique. Dans ses premières expériences, Maria Telkes a essayé un certain nombre d'hydrates de sel de coût peu élevé, un exemple typique étant le décahydrate de sulfate de sodium qui fond presque dans son eau de cristallisation lorsqu'il est porté à sa température de transition : 90 °F (33 °C). Dans ce cas, la chaleur accumulée est libérée lorsque la matière se recristallise; un grand inconvénient que présente l'emploi de cette matière est qu'il peut se produire beaucoup de surfusion, et pendant cette période la matière ne libère pas la chaleur accumulée tant qu'on n'a pas projeté une parcelle solide ou agité la solution. On a dû pour cette raison renoncer presque toujours à l'emploi de ces substances, qui offrent néanmoins le moyen de réduire l'espace d'emmagasinage. C'est sous cet angle que Martin Goldstein du Laboratoire national de physique d'Israël a entrepris l'étude des matières qui pourraient être utilisées. Il s'est proposé de trouver des systèmes chimiques qui permettent l'accumulation de chaleur la plus grande par unité de masse ou unité de volume, de préférence par unité de volume puisque les pertes de chaleur et les frais d'isolement sont fonction du volume de l'enceinte plutôt que de la masse de la substance qu'elle contient. Dans cette étude, Goldstein a étudié de nombreux groupes de substances choisis dans les ouvrages de référence classiques, tels que Perry's Chemical Engineers' Handbook, les Tables critiques internationales, etc., et il les a classés de la manière suivante : *a*) Substances inorganiques et organiques avec de grandes chaleurs de fusion, dont le point de transition se situe dans la gamme des températures de 30° à 200 °C; *b*) Mélanges eutectiques de sels inorganiques; *c*) Catégories de substances formant de nouvelles phases; *d*) Transitions solide-solide; *e*) Chaleurs de solution; *f*) Chaleurs de vaporisation; *g*) Accumulation par réaction chimique en solution.

L'étude ci-dessus, établie sur des bases purement thermodynamiques, mérite d'être suivie de recherches approfondies sur les aspects les plus prometteurs, comme par exemple le processus de vaporisation.

Dans son mémoire intitulé « Bâtiments utilisant l'énergie solaire sous les climats tempérés et tropicaux » (S/8), Edward Speyer a fait une étude critique des six importants paramètres (frais, espace nécessaire, capacité, rendement, niveau et débit) dont il faut tenir compte lors de la construction d'un système d'utilisation de l'énergie solaire. Lorsqu'on utilise l'énergie solaire pour le chauffage ou le refroidissement des immeubles, Speyer estime que ce qui importe, c'est que les coûts de construction de la maison solaire soient amortis par l'économie de combustible. La forme la moins chère d'accumulation d'énergie est l'emmagasinage de chaleur sensible dans des cailloux ou de l'eau, et la capacité d'emmagasinage nécessaire pour une accumulation de longue durée (par exemple la chaleur de l'été à utiliser en hiver) n'exige, selon lui, qu'un faible pourcentage du volume de l'espace à chauffer ou à climatiser. Il faut encore moins d'espace pour emmagasiner de la chaleur pendant une courte période. Cet espace peut encore être réduit si l'on adopte des méthodes d'accumulation chimique, mais les frais sont plus élevés. Le rendement de l'accumulation nécessaire à une maison solaire est fonction de deux cycles surimposés, à savoir les variations quotidiennes de température venant s'ajouter aux variations saisonnières entre l'été et l'hiver. Speyer estime que pour un emmagasinage de longue durée, il faut pouvoir disposer, trois mois plus tard, de 50 p. 100 au moins de l'énergie accumulée.

La capacité d'accumulation est fonction inverse de la capacité de l'insolateur, mais si le rendement de l'accumulation est élevé, la capacité de l'insolateur (c'est-à-dire la surface) peut être ordinairement réduite. Toutefois, le rendement de l'insolateur est un facteur important lorsqu'il s'agit de déterminer le fonctionnement optimal de la maison solaire. Speyer ne pense pas que le débit d'accumulation ou de libération présente de l'importance, sauf si l'accumulation se fait sous forme de chaleur de fusion. Speyer conclut que les insolateurs ne peuvent être rentables par rapport aux combustibles fossiles que si leur coût ne dépasse pas 3 à 4 dollars le pied carré (0,092 m²), et, à son avis, les combustibles fossiles continueront à rester la source d'énergie la moins chère et la plus sûre dans les régions facilement accessibles par camion, train ou navire. Il estime que même pour les régions écartées il est peut-être plus rentable de construire des routes que d'investir des sommes importantes pour construire des appareils solaires. Speyer est d'avis que si l'on veut utiliser l'énergie solaire il faut fabriquer des insolateurs moins chers et à rendement élevé; selon lui, si l'on pouvait abaisser de 80 p. 100 (c'est-à-dire par coefficient de 5) le prix d'un système d'accumulation de grande capacité et à rendement élevé, cela permettrait de réduire la surface de l'insolateur et ce système pourrait soutenir la concurrence des autres moyens de chauffage. D'autre part, si l'on pouvait abaisser le prix des insolateurs, ne serait-ce que d'un coefficient de 2 ou 3, et améliorer leur rendement, le fonctionnement du système serait bien meilleur. Speyer, qui reconnaît l'importance des insolateurs, a conçu un insolateur plat utilisant le principe du vase de Dewar, c'est-à-dire muni de chambres à vide pour isoler par-dessus et par-dessous les couches absorbantes de l'insolateur. Il en a donné une brève description dans son étude, sans toutefois en estimer le coût.

Allcut et Hooper de l'Université de Toronto ont, dans leur étude sur « L'énergie solaire au Canada » examiné le problème particulier que pose l'utilisation de l'énergie solaire au Canada[1].

Dans les hautes altitudes des régions septentrionales du Canada, les conditions d'utilisation de l'énergie solaire sont difficiles, la moyenne des heures d'ensoleillement s'établissant entre 1 400 et 1 600 par an; pendant le mois de décembre, il peut y avoir moins de 25 heures de soleil. La partie méridionale du Canada est une région très industrialisée, mais, en plus d'une importante demande d'énergie industrielle, le chauffage des immeubles résidentiels et commerciaux entre pour 25 à 30 pour cent dans la consommation totale d'énergie. Celle-ci a représenté en 1958 l'équivalent de 34,5 millions de tonnes de charbon et peut atteindre 81 millions de tonnes dans vingt ans.

Allcut et Hooper ont étudié en détail la région de l'Ontario méridional. Ils ont conclu que si l'on veut que le système de chauffage ne soit pas complété par des sources de chaleur d'appoint, il est indispensable de disposer d'un système d'accumulation à long terme afin de garder la chaleur accumulée pendant l'été, faute de quoi il faudra que la surface de l'insolateur soit très étendue et dépasse la superficie de la face d'une maison normale orientée vers le sud.

Après avoir analysé plusieurs projets, ils concluent qu'une maison chauffée par l'énergie solaire, munie d'un système de chauffage par panneaux qui pourrait effectivement utiliser la chaleur à une température de 80 °F (27 °C) est économiquement rentable, si l'on peut disposer d'un grand réservoir d'accumulation de chaleur à 145 °F (62 °C), avec un isolement modéré.

Dans le mémoire qu'ils ont soumis, les auteurs décrivent les résultats obtenus avec un modèle à échelle réduite de réservoirs d'accumulation de chaleur, remplis d'eau et placés dans le sous-sol; ces résultats permettent de prévoir le comportement pendant des périodes de plusieurs années de systèmes complets aux dimensions normales, comprenant la maison, l'insolateur et les caractéristiques de l'emmagasinage. Leur matériel consistait essentiellement en une caisse de sable dans laquelle ils plaçaient un modèle à petite échelle du réservoir de chaleur souterrain. L'échelle typique de temps était qu'une minute de fonctionnement du modèle était l'équivalent de deux jours de temps réel. Les caractéristiques typiques de la maison étaient les suivantes : un insolateur d'une surface de 600 pieds carrés (56 m²) incliné sous un angle de 60° à l'horizontale, une charge de chaleur de 775 btu/°F (195 kcal/1/2 °C) et un réservoir de 50 000 gallons (225 000 litres). Le principal avantage des expériences avec un modèle à l'échelle réside dans la facilité avec laquelle on peut réunir des renseignements sur les corrélations entre l'angle d'inclinaison et l'incidence du rayonnement direct, indirect et total; les successions d'heures de temps clair, partiellement nuageux ou couvert; les petites modifications de l'orientation, etc. Les résultats typiques obtenus ont été présentés sous forme de courbes. Si les expériences à l'échelle ne peuvent remplacer tout à fait les essais sur une maison de dimensions normales, elles ont le grand avantage de permettre de prédire le comportement sur une longue période dans des conditions prédéterminées.

Des travaux remarquables ont été effectués sur le chauffage des maisons en Amérique. Citons les deux maisons du Massachusetts Institute of Technology; la maison construite à Dover (Mass.) par Telkes, Raymond et Peabody; les maisons construites par George Löf à Boulder, Colorado, par Bliss près de Tuscon, et plus récemment par Harry Thomason[2]. Il semble que, dans la plupart de ces applications, le système de chauffage le plus économique soit celui qui n'utilise pas uniquement la chaleur accumulée, mais où il est prévu d'avoir recours à une source de chaleur d'appoint. Si ce compromis peut être accepté, le coût du système pourrait être ramené dans des limites rentables.

Sujets de discussion proposés

1. Dispose-t-on de données suffisantes pour conclure qu'il est possible de construire un système d'accumulation raisonnable et peu coûteux qui permette d'utiliser exclusivement l'énergie solaire pour le chauffage des maisons ou pour le chauffage et la climatisation ?

2. Serait-il économiquement rentable, dans l'état actuel des connaissances, de remplacer entièrement les systèmes de chauffage conventionnels par des insolateurs du type « toit » et par des réservoirs souterrains utilisant l'eau ou les cailloux pour l'accumulation ?

3. Les systèmes de chauffage par accumulation à long terme ont-ils un intérêt pratique, et, dans l'affirmative, serait-il plus économique d'adopter un système d'accumulation de l'énergie solaire utilisant les méthodes de chauffage conventionnelles pour compléter l'emmagasinage de chaleur solaire, ce qui permettrait de réduire la capacité du système d'accumulation ?

[1] *Actes officiels de la Conférence des Nations Unies sur les sources nouvelles d'énergie, 1961,* vol. 4, point III.A de l'ordre du jour, mémoire S/20.

[2] Voir plus haut les mémoires S/61, S/114, S/30 et S/3, au titre du point III.C.2 de l'ordre du jour.

USE OF SOLAR ENERGY FOR HEATING PURPOSES: HEAT STORAGE

Rapporteur's summation

The authors' report in the technical session of the Conference mentioned that the subject of heat storage had been studied mainly as a subsidiary to space heating and had therefore not received the attention it deserved. The storage problem connected with space heating discussed under agenda item III.C.5 has its own importance, but it is a comparatively simple problem since the storage temperature lies between the rather restricted range of 25° to 40°C. Water and rock pebbles have served the function admirably; the quantity of the material and the insulation needed depending on whether the storage required was for shorter or longer duration. Since most of the trials were being made in highly developed areas—mainly in the United States—the problem could be made simpler and the solution more economical by installing an auxiliary heating source using coal, oil or electricity to take care of any prolonged periods of bad weather.

The one difficulty that arises in using these materials is that their large bulk restricts the period of storage to only a few days. Thus storage space of some 400 to 500 cubic feet is needed for storing the heat requirements of an average home for two days. Much larger space is required if the aim is to tide over prolonged periods of difficult weather without auxiliary heating.

In early pioneering work on solar house heating, Maria Telkes introduced the idea of using a hydrated salt, like Glauber's salt, which on heating melted in its own water of crystallization. The heat energy supplied brings about the physical change without a sensible rise in temperatures. On cooling, the cycle reverses itself, and the material recrystallizes, releasing the absorbed latent energy which could be used for house-warming purposes. This appeared to be a very satisfactory solution of the storage problem until it was found that these materials could be very temperamental in their behaviour, and in the absence of crystal nuclei or stirring, considerable supercooling could take place before the material started to recrystallize and part with its latent heat. The heat of fusion materials was therefore discarded by the designers of the solar heated houses constructed so far, and use was made of bulky but more dependable materials, like water or pebbles.

Phase change materials, however, possess two outstanding advantages: (*a*) they offer the possibility of storage of heat at higher temperatures, and (*b*) they offer considerable reduction in the volume of storage space occupied by the material itself — the reduction in storage being as much as one-tenth.

Some of the properties of materials which could be used as heat storage materials can be summarized as follows:

(*a*) Inorganic or organic substances having large heats of fusion;
(*b*) Eutectic mixtures of inorganic salts;
(*c*) Change-of-phase materials;
(*d*) Materials with large heats of vaporization.

In the course of discussion in the technical session, reference was made to a study undertaken on heat storage materials for heat pumps. While for low temperature storage in the range 30° to 50°C, materials like water, rock pebbles and salt hydrates were found adequate, the use of materials like fire clay, ceramic oxides and fused salts was found desirable in the range 50° to 450°C. By using mixtures of metal nitrates, nitrites and chlorides various melting points could be realized in the temperature range from 120° to 500°C. In the higher temperature range of 600°C and above, the use of lithium hydride and sodium chloride was found to offer good possibilities.

In using solar energy for house heating the temperature range involved is very narrow, and flat plate collectors have been found adequate. However, when one comes to consider the problem of storage at higher temperatures, resort has to be made to the focusing type of collector—whether parabolic or cylindrical.

Perhaps an exception can be made for solar ovens where a cooking temperature of 150°C has been attained for baking purposes and a chemical storage material has been used for storing heat over several hours.

A very interesting use of storage material has been made in the engine demonstrated by the National Physical Laboratory of Israel, in which a constant temperature of 150°C is maintained for the turbine fluid despite sunshine variations; and the capacity of the storage material is such that the engine can run even during the dark hours.

Since the main purpose of this Conference is to explore possibilities of the application of the newer sources of energy to developing countries, it would be worth while, before concluding, to review the storage problem in this context.

As pointed out in the earlier part of this report, the major application of storage has been for the purpose of house heating, and a considerable amount of carefully recorded data exists on the subject. I suppose it is fairly well understood that heating of houses is not generally one of the problems of the emerging countries and, therefore, this aspect is largely of academic interest in so far as they are concerned. The very considerable work done on the subject is, however, of direct interest to the countries concerned inasmuch as the subsidiary use of solar energy could help to reduce the consumption of conventional fuels or release for industrial purposes the power consumed for house heating.

It can, however, make a major contribution to the economy of the emerging countries if a combined concentrator-storage system could effectively trap and store the sunlight so plentifully available and then make use of the power produced for providing for some of the basic needs, like lift irrigation or electric power for cottage and small-scale village industries. A promising start has been made in this direction, and one may express the hope that the deliberations of this Conference will lead to more rapid progress.

EMPLOI DE L'ÉNERGIE SOLAIRE POUR LE CHAUFFAGE : ACCUMULATION DE CHALEUR

Résumé du rapporteur

Dans notre rapport à la séance technique de la Conférence, nous avons indiqué que le problème de l'emmagasinage de l'énergie avait été étudié surtout à propos du chauffage des locaux et n'avait pas reçu, par conséquent, l'attention qu'il méritait. L'emmagasinage de l'énergie en relation avec le chauffage des locaux, dont il est question au point III.C.5 de l'ordre du jour, est un problème qui ne manque pas d'intérêt, mais qui est relativement simple, car l'énergie est emmagasinée à une température de 25 à 40 °C, marge somme toute assez restreinte. L'eau et les galets ont joué admirablement leur rôle dans ce domaine, la quantité de matières et d'isolants thermiques nécessaire étant fonction du temps pendant lequel on veut conserver la chaleur. Comme la plupart des expériences ont été réalisées dans des pays très développés — principalement aux États-Unis — on pourrait simplifier le problème et rendre la solution plus économique en installant une source thermique d'appoint utilisant le charbon, le pétrole ou l'électricité en cas de longues périodes de mauvais temps.

Le seul inconvénient de l'emploi de ces matières est leur grand volume, qui limite à quelques jours seulement la période d'emmagasinage. De ce fait, 400 à 500 pieds cubes sont nécessaires pour emmagasiner la quantité de chaleur nécessaire à une maison de dimension moyenne pendant deux jours. Si l'on doit traverser une longue période de mauvais temps sans installation de chauffage d'appoint, il faut un volume bien plus important encore.

Au début, dans les travaux sur le chauffage solaire des locaux, Maria Telkes a eu l'idée d'utiliser un sel hydraté, comme le sel de Glauber, qui, en s'échauffant, fondait dans son eau de cristallisation. L'énergie thermique dégagée provoque la réaction physique sans augmentation sensible de température. Pendant le refroidissement, le cycle s'inverse et la matière recristallise en dégageant l'énergie latente absorbée qui pourrait être utilisée pour chauffer les maisons. Cette solution du problème de l'emmagasinage est apparue très satisfaisante jusqu'au jour où l'on a constaté que les matières en question avaient un comportement très instable et qu'en l'absence de noyaux cristallins ou de brassage la matière pouvait rester en surfusion avant de se remettre à cristalliser et à dégager sa chaleur latente. Les architectes des maisons chauffées par l'énergie solaire qui ont été construites à ce jour ont donc abandonné l'idée de produire de la chaleur au moyen de matières fusibles et emploient désormais des matières volumineuses mais sûres comme l'eau ou les galets.

Les matières sujettes à changement de phase possèdent cependant deux avantages capitaux : *a*) elles permettent d'emmagasiner la chaleur à des températures plus élevées; *b*) elles permettent de réduire considérablement — jusqu'au dixième — le volume des réservoirs d'accumulation occupés par la matière même.

Quelques-unes des propriétés des matières utilisables pour emmagasiner l'énergie peuvent être résumées de la façon suivante :

a) Substances organiques ou inorganiques à température de fusion élevée;
b) Mélanges eutectiques de sels inorganiques;
c) Matières subissant des réactions chimiques;
d) Matières à température de vaporisation élevée.

Au cours de la discussion en séance technique, on a signalé une étude sur les matières utilisables pour conserver la chaleur dans les pompes à chaleur. On a constaté que les matières comme l'eau, les galets et les sels hydratés convenaient lorsqu'il s'agissait de conserver les basses températures (30 à 50 °C), mais qu'il était souhaitable d'employer des matières comme la terre réfractaire, les oxydes employés en céramique et les sels fondus pour les températures de 50 à 450 °C. En utilisant des mélanges de nitrates, de nitrites et de chlorures métalliques, on pourrait obtenir plusieurs points de fusion entre 120 et 500 °C. A partir de 600 °C, on a constaté que l'hydrure de lithium et le chlorure de sodium offraient de bonnes possibilités d'emploi.

Quand on emploie l'énergie solaire pour chauffer les maisons, la gamme des températures voulues est très réduite, et des collecteurs plans sont suffisants. Mais quand il s'agit de conserver des températures plus élevées, il faut recourir aux collecteurs paraboliques ou cylindriques.

Peut-être peut-on faire une exception pour les cuisinières solaires dans lesquelles on a obtenu une température de cuisson de 150 °C et employé un procédé chimique afin d'emmagasiner la chaleur pendant plusieurs heures.

Un emploi très intéressant de matériaux conservant la chaleur a été fait dans le moteur présenté par le laboratoire national de physique d'Israël : le fluide de la turbine est maintenu à une température constante de 150 °C malgré les variations de l'ensoleillement; la capacité d'accumulation des matériaux est telle que le moteur peut tourner même pendant la nuit.

La présente Conférence ayant principalement pour objet d'envisager les possibilités d'application des sources nouvelles d'énergie dans les pays en voie de développement, il serait utile, avant de conclure, de considérer le problème de l'emmagasinage de l'énergie à ce point de vue.

Comme nous l'avons fait observer au commencement de cet exposé, le chauffage des locaux est la principale application de la conservation de la chaleur, et il existe à ce sujet une somme considérable de données soigneusement enregistrées. On se rend assez bien compte, je pense, que le problème du chauffage des maisons n'est généralement pas de ceux qui se posent aux pays qui viennent d'accéder ou qui vont accéder à l'indépendance, et c'est porquoi il ne présente guère pour eux qu'un intérêt théorique. Les travaux considérables effectués dans ce domaine intéressent cependant directement les pays en question en ce sens que l'utilisation de l'énergie solaire comme moyen d'appoint permettrait de diminuer la consommation de combustibles classiques ou de libérer pour l'industrie l'énergie consommée aux fins de chauffage des locaux.

L'énergie solaire peut cependant aider considérablement au développement économique des pays nouveaux si l'on arrive à mettre au point une installation efficace combinant un concentrateur et un système d'accumulation capables de capter et d'emmagasiner la lumière solaire si aisément disponible et d'utiliser ensuite l'énergie produite pour satisfaire quelques besoins essentiels comme l'irrigation ou la fourniture d'électricité pour l'artisanat et la petite industrie de village. On a fait un début prometteur dans cette voie et l'on peut exprimer l'espoir que les débats de la Conférence permettront d'accélérer encore les progrès.

SOME PHYSICAL CHEMICAL ASPECTS OF HEAT STORAGE

Martin Goldstein *

We wish to consider here some physical chemical aspects of the problem of heat storage. The problem will be defined somewhat narrowly as follows. A chemical system in some kind of container is brought into thermal contact with a heat transfer medium at a higher temperature than the substance in the container. Heat flows until the rise in temperature of the substance puts an effective stop to further heat flow. At some later time, the heat transfer medium, now at a lower temperature, is brought again into thermal contact and heat flows in the opposite direction, again until some practical limit on the flow is reached. In general, we are interested in finding such chemical systems as will give the greatest storage of heat per unit mass or per unit volume. As heat losses and insulation costs are more sensitive to volume (or surface) than they are to mass, more stress will be placed on the volume criterion, although it is often easier, density data not always being available, to calculate on the basis of mass. When possible we will consider both.

In this paper, a number of possibilities that have been proposed for this purpose are examined, and estimates of the magnitudes of the storage capacity to be expected from each are attempted, both on the basis of tabulated data and on the basis of fundamental principles. Discussion is limited to the maximum possible storage to be expected when thermodynamic equilibrium is reached, and little regard is paid to kinetic, engineering, or economic aspects of processes.

The storage of heat at temperatures within the range of 30° to 200°C is considered; this covers the range of temperatures that have been proposed for various methods of utilizing solar energy directly for power generation and home heating.

In order to give the problem meaning, an allowed rise in temperature of the storage medium must be specified; this is taken to be 20°C. It will be usually assumed that the temperatures between which heat is released are the same as those between which it is stored: in a later section, a means of storage in which this restriction may be disregarded will be discussed.

General principles

Any chemical or physical change storing and yielding up heat in the manner specified should be one operating reversibly; the system should be at or near thermodynamic equilibrium at all times. In accordance with a well-known thermodynamic principle, when a system is at equilibrium, a rise in temperature tends to shift the equilibrium in such a direction as to absorb heat (1). If a substance is capable of existing in two different phases, the phase stable at the higher temperature is the phase of higher heat content. The melting of a solid to a liquid or the change of a solid from one crystal form to another are examples. In these cases, the change of state occurs abruptly at a definite temperature. In other processes to be considered, such as a chemical reaction taking place in solution, the shift of equilibrium is a gradual one. In these cases, one may imagine the process carried out with reactants and products in their standard states (1), rather than the states observed under actual experimental conditions. In this imaginary experiment, the shift of equilibrium also occurs at a sharply defined temperature, rather than over a range.

To all such abrupt transitions, real or imagined, the following thermodynamic relations apply:

$$\Delta G = \Delta H - T \Delta S$$

in which ΔG is the Gibbs free energy change of the process, ΔH the change in the heat content, T the absolute temperature, and ΔS the entropy change.

At the temperature of the transition $\Delta G = 0$ and we have

$$T_{eq} = \frac{\Delta H}{\Delta S}$$

T_{eq}, the temperature at which products and reactants are in equilibrium, is determined by the use to which the energy is to be put, rather than being a matter of choice. The problem in heat storage is to make ΔH as high as possible. It is clear then that changes of state of large ΔS are particularly to be sought for; unless ΔS is large, a large storage of heat at a specified temperature cannot be achieved.

We now proceed to the examination of some specific types of physical and chemical changes from the point of view of the above considerations.

Sensible heat

The direct storage of heat through heat capacity is conceptually the simplest possible way of doing it. Water has one of the highest heat capacities of any substances known—about 1 calorie per gram per

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degree; i.e. a litre or a kilogram of water stores 20 kilocalories for a 20°C rise in temperature. This figure is a useful reference one for comparison with other methods.

Consideration of the theory of specific heats of solids (2) gives little reason to expect any pure substance to have an appreciably higher heat capacity than those presently known. There is no complete theory as yet for the specific heat of liquids : empirically, they are somewhat greater than the solid phases of the same substances, but not more than double (3 and 4). Thus there does not seem to be much hope for the discovery of some new substance having a significantly higher heat capacity than water.

Heats of melting

Pure substances

All pure substances with melting points between 30 and 200°C listed in a table of 300 common inorganic substances (4) were examined on the basis of storage capacity per kg and per litre of the solid phase. The capacities per litre ranged from 9.0 kcal to 136 kcal (Al_2Cl_6). The distribution was as follows: below 20, 5; 20-40, 6; 40-60, 6; 60-80, 4; 80-100, 3; 120-140, 1. The high value for Al_2Cl_6 is not only anomalous but misleading. We did the calculations on the basis of the density of the solid, because data on liquid densities was, in most cases, not available, but Al_2Cl_6 doubles in volume on melting, and if storage capacity were given more realistically in terms of liquid volume, Al_2Cl_6 would store about 80 kcal/litre.

On examining a table of heats of fusion per gram of common organic substances (4), it was found that 113 melted between 30° and 200°C. Their heats of fusion in kcal/kg were distributed as follows: up to 10 kcal, 1; from 10 to 20, 10; from 20 to 30, 46; from 30 to 40, 33; from 40 to 50, 15; from 50 to 60, 8. None had higher latent heats than 60 kilocalories per kilogram, either in the 30-200°C range or elsewhere. Assuming densities of about 1 for organic substances, we estimate the maximum storage capacities to be 50-60 kcal/(litre).

It should be noted that substances of high molar latent heat of fusion are not necessarily the best storers of heat. The number of mols that fit into a kilogram or litre play a part, as can be seen by comparing the heats in kilocalories per mol, per kilogram, and per litre, of lithium metal (1.1, 159, 84.5), ice (1.4, 80, 73.5) and Al_2I_6 (8.0, 9.8, 39.0).

Entropies of fusion reflect additional degrees of freedom gained by molecules in melting. There are rough regularities predictable from the molecular nature of the material (5); however, the higher storage capacities are mostly associated with some anomalous and unpredictable effects in melting, such as shown by Al_2Cl_6. There does not seem to be any systematic way to search for such substances.

Eutectics

A eutectic will have a sharp melting point, just as does a pure compound (6) : the heat of fusion per gram is the weight average heat of fusion of the pure substances at the eutectic temperature plus the heat of mixing of the liquids. The heats of fusion will vary about as do the heats of fusion of pure substances. Eutectics should be worth investigating; there are, in principle, more of them than there are pure substances. A feature to be considered is that pure substances melting above the temperature range we have focused attention on can form eutectics melting within this range. As examples, we may cite patents on mixtures of $AlCl_3$, NaCl, and $FeCl_3$ for heat storage, melting at 150°C, and mixtures of $LiNO_3$, $NaNO_2$ and KNO_3, melting below 100°C (7). The heats absorbed on melting by these compositions are not given in the patents.

Incongruently melting substances

Hydrates of certain salts are members of a class of substances that at a sharply defined temperature "melt" to form two new phases: a solid phase, consisting of a lower hydrate or the anhydrous salt; and a liquid phase, consisting of a saturated solution of the salt in water (6). Some of these substances melt at temperatures convenient for home heating purposes, and a few have been given careful study for this reason.

A tabulation of nine common hydrates in the *Handbook of Chemistry and Physics* (3) gave values of from 25 to 67 kcal/kgm and 56 to 105 kcal/litre. These are thus comparable to the heats of fusion of pure substances.

The fact that, at the transition point, there are three phases in equilibrium, having different chemical compositions, has led to kinetic difficulties on repeated cycling of these materials : some segregation of the different species results and thermodynamic equilibrium is not readily achieved (8, 9, 10 and 11).

Solid-solid transitions

Although the heat capacity of common rocks is lower than that of water, both on a mass and on a volume basis, the self-insulating property of pebble beds has led to their use for heat storage. H. Tabor has suggested that if a pebble-bed could be made of some solid that undergoes a phase transition in the storage range, an appreciably higher storage capacity could be achieved.

A survey was made of solid-solid phase transitions listed in the Bureau of Standards tables of chemical thermodynamic properties (12).

The storage capacities in a few such transitions were in the range of heats of fusion : e.g.: Ag_2Se at 133°C, ΔH/litre of 46 kcal, FeS at 138°C, ΔH/litre of 55 kcal, V_2O_4 at 72°C, ΔH/liter of 50 kcal, KHF_2 at 196°C, ΔH/litre of 75 kcal.

Most heats of transition in solids are quite small; those cited are typical ones, in which a considerable part of the randomization normally taking place on melting occurs within the solid phase: the heats of fusion in these cases are usually lower than normal.

Some transitions taking place at higher temperatures have even higher latent heats: Li_2SO_4 has a transition at 575°C with a ΔH of 6.8 kcal/mol, storing 140 kcal/litre. Solid solution formation is known to change transition temperatures (13). It is interesting to speculate on the possibility of bringing such a transition down to the range of interest by means of solid solution formation.

Heats of solution

If a solid dissolves in its saturated solution with the absorption of heat, raising the temperature increases its solubility; if heat is evolved, raising the temperature decreases its solubility. In either case, raising the temperature results in an absorption of heat in excess of that due to the specific heats of the substances present.

Some salts are known with very large temperature coefficients of solubility and very large solubilities, so much so that on a mass basis (not necessarily on a mol basis) the saturated solution is mostly salt: the process is almost a melting of the salt, except that it can occur at a temperature somewhat lower than the melting point of the salt, and the heat absorbed per mol is not equal to (and may be greater than) the heat of melting of the salt.

The storage capacity may be calculated from such thermodynamic data as the heat of solution of the solid salt in the saturated solution at various temperatures and the change of solubility with temperature.

For survey purposes, data on solubility for about 200 common salts as given in Perry's *Handbook* (4) was examined: only three were found to have sufficient promise for further calculation — the nitrates of ammonium, potassium, and silver. Sufficient thermodynamic data was available only for ammonium nitrate (14 and 15). It was found that the heat of solution in the saturated solution was of the order of 2-5 kcal/mol at 50°C, decreasing to 1.9 at 124°C. This is somewhat higher than the heat of melting of 1.46 kcal/mol, but not so much higher as to give any significant increase of storage capacity over storage by sensible heat. For example, a system composed of solid ammonium nitrate plus just enough water to form one litre of a saturated solution of 91.4 per cent NH_4NO_3 at 100°C will, on being heated from 80°C, absorb 15 kcal due to solution of the solid salt not already dissolved at 80°C. The specific heat of the system (assuming it equal to that of the pure components, which is not far wrong) is 0.6 kcal/°C-litre, sufficient to absorb 12 kcal. The two heats added together exceed only slightly the heat stored by a litre of water undergoing the same temperature rise.

A patent exists on heat storage by this method (16), but the temperature swing is much greater than 20°C, and the potential usefulness of the invention lies in a non-reversible aspect: it is claimed that the hot saturated solution can be cooled to room temperature and stored without crystallization until the heat is needed, at which time crystallization can be induced by shaking.

Heats of vaporization

As pointed out previously, any process capable of storing appreciable energy must be a process of large entropy change. The energy and entropy changes on evaporating liquids, as is well known, are usually much greater than the changes of these quantities on the melting of solids. For example, a litre of water evaporating at its normal boiling point absorbs about 500 kcal, a litre of ice melting, 73.5 kcal.

The obvious difficulty is that if it is necessary to store the vapor, the enormous volume changes (1 700 litres for water at its boiling point) make the process useless. It has been suggested in this connection that the evaporated liquid may itself be condensed or absorbed in some manner, and thus stored in a small space. In fine, we are using a sort of absorption refrigerator as a heat storage device, and the extensive technology of such devices may be of help here.

Our storage system then requires two chambers, a "hot" chamber and a "cool" chamber, held at the temperature of the environment. The substance vaporizing must have a lower vapor pressure at a given temperature in the "hot" chamber than in the "cool" chamber. This can be achieved by having it present either as one component of a solution, the second component being relatively non-volatile, or else in a chemically bound form, such as a hydrate or ammoniate. The cool chamber may condense the liquid directly, absorb it as a hydrate of lower stability, or absorb it in a solution from which it has a higher vapor pressure at a given temperature.

The application of heat to the storage chamber distills substance to the cool chamber where it condenses, losing heat to the environment. When as a result of a temperature drop on the hot side, the vapor pressure falls below the vapor pressure on the cool side, the substance distills back into the hot chamber, supplying heat as it condenses there. In a sense, the heat is stored in the atmosphere or environment, and removed therefrom when needed, through the medium of the volatile liquid. This fact introduces some advantages and some disadvantages. Once the substance is distilled from the hot chamber, the chambers may be isolated from each other by a valve and the hot chamber allowed, at the price of the sensible heat involved, to cool to the temperature of the environment. There will therefore be no heat loss during storage, and the time of storage may be indefinitely long. Among the disadvantages are the limitation on the rate that heat can be stored or used placed by heat transfer requirements at the cold end.

In addition, if the heat is stored when the environment is warm and used when it is cool, an additional difficulty appears. During storage, the vapor pressures of the liquid on the hot and cold sides were the same. If the environment cools, the vapor pressure on the cold side drops and no heat can be regenerated until the temperature on the hot side drops sufficiently to equilibrate the pressures again. If it is necessary that the heat be regenerated within the same temperature range at which it was stored, a drop in the temperature of the environment can reduce or eliminate completely the recoverable heat. If, however, a drop in the temperature of the heat can be tolerated, all the heat can still be recovered. If, for example, a collector storage system could be charged from 50 to 70°C, a drop in environmental temperature may permit recovery of the stored heat only from 35 to 55°C; however, this might still be sufficient for home-heating purposes.

In considering this process, one non-thermodynamic but quite plausible assumption must be made: that a steady state is reached in which equilibrium exists between vapor and condensed phase in each chamber.

We were able to find sufficient data on aqueous solution of sulphuric acid (4), sodium hydroxide (17) and potassium hydroxide (18) for calculation. The heat of vaporization of water from the solutions could be calculated from the data for the hydroxide solutions; it did not differ appreciably from that of pure water.

We have assumed in our calculation that the cold side is maintained at a temperature of 20°C, at which the vapor pressure of water is 17.5 mm. The concentrations of solutions having this vapor pressure at the lower and upper temperatures of the storage range were readily calculated and, from these, the mass of water distilling could be found.

The influence of the specific heats of the substances involved on storage capacities have not been included in the table: it may be shown to have only a slight effect on the capacities.

The results are given in table 1. The decomposition of hydrates, ammoniates, etc., presents some different features. The typical reaction may be written.

$$A \cdot n\,S = A\,(n - m) \cdot S + m\,S \text{ (vapor)}$$

where A is a salt, S a volatile molecule, and n and m are usually integers. The vapor pressure over a system where both $A \cdot n\,S$ and $A \cdot (n - m)S$ are present usually obeys an equation of the form

$$\log_e P = K - \frac{\Delta H}{RT}$$

where ΔH is the heat of the reaction per mol of S vapor formed. It is usually greater per mol of S than the heat of vaporization of the pure liquid S.

Obviously, the larger m is, the greater the storage capacity tends to be. $CaCl_2$ forms [illegible] ammoniates, and the maximum number of ammonia molecules formed in the decomposition of any one of these is 4, for the reaction $CaCl_2 . 8NH_3 = CaCl_2 . 4NH_3 + 4NH_3$. The heat of this reaction is 44 kcal per mol of $CaCl_2$. $8NH_3$. $BaCl_2$ appears to form only one ammoniate, $BaCl_2 . 8NH_3$, which decomposes to $BaCl_2$ and $8NH_3$, with ΔH = 72 kcal (18 and 19).

A feature of the aqueous solutions considered in the preceding part of this section is that the pressure in the system must be maintained considerably below atmospheric pressure (vapor pressure of water at 20°C = 17.5 mm), as the presence of air would slow down tremendously the rate of transfer of water from one chamber to the other. Maintaining a system at pressures much lower than atmospheric may well be undesirable from an engineering point of view. Using solid ammoniates rather than hydrates makes it possible to do the storage at pressures near atmospheric or above it.

It should be clear that as a result of phase rule requirements (6), storage in such systems is like storage by heat of fusion in that the process occurs at a sharply defined temperature, rather than over a range, as in storage by distillation from a solution.

We have calculated storage capacities for the decomposition of nine common hydrates based on data in the Landolt-Bornstein tables (19) and the *International Critical Tables* (18).

Table 1. Storage capacity for distillation from aqueous solutions

Temp. range	*Initial concentration, weight per cent non-volatile component*	*Grams water distilling per litre*	*Mean heat of vaporization per gram*	*Storage capacity in kcal:* per litre	*Storage capacity in kcal:* per kg
Sulphuric acid					
40-60°C	54	242	625	150	104
60-80°C	65	170	675	115	74
80-100°C	73	132	740	98	59
Sodium hydroxide					
60-80°C	55.5	302	(570)	172	110
Potassium hydroxide					
40-60°C	42	302	(570)	172	122

Table 2. Storage capacity for decomposition of some solid hydrates

Reactant	Solid product	Δ H, kcal per mol of starting substance	Δ H, kcal per kgm	Δ H, kcal per litre	Storage temp., °C (vapor pressure = 17.5 mm)	Grams H_2O distilled per litre of substance
$BaCl_2.2H_2O$	$BaCl_2$.?	28	115	(360)[a]	39	...
$CaCl_2.2H_2O$	$CaCl_2.H_2O$	11.0	75	(165)[a]	70	270
$CaSO_4.\frac{1}{2}H_2O$	$CaSO_4$	5.7	39	(105)[a]	100	170
$LiBr.H_2O$	LiBr	18.4	175	(530)[a]	103	515
$Li_2SO_4.H_2O$	Li_2SO_4	13.1	105	210	56	290
$MgCl_6.6H_2O$	$MgCl_2.4H_2O$	25	123	186	73	280
$Mg(OH)_2$	MgO	12.5	204	20	45	740
$MgSO_4.7H_2O$	$MgSO_4.6H_2O$	14.0	57	95	30	122
$Na_2CO_3.H_2O$	Na_2CO_3	13.7	110	170	40	225

[a] Based on an estimate of density.

The hydrates were chosen for consideration, as there was more data on density for them than for the ammoniates. In some cases, the densities could be estimated, when they were not tabulated, by comparison with higher and lower hydrates of the same salt. The capacities per litre based on such estimates are shown in parentheses in table 2. The heats of reactions were calculated from plots of the log of vapor pressure *vs.* $1/T$ and the storage capacity per litre from the heat of reaction, density and molecular weight. A cold side temperature of 20°C was again used.

The method of storage by distillation can thus be seen, when considered purely from the point of view of capacity, to offer considerable promise. Distillation from solutions can in favorable cases store up to 200 kcal/litre of solution for the permitted 20°C rise; decomposition of a hydrate can store up to 500 kcal/litre of the hydrate. The obvious disadvantages of such a method are its complexity of construction and its sensitivity to changes in the environmental temperature.

Storage by chemical reaction in solution

We wish to consider in this section the possibility of storage by chemical reaction in solution.

If a system of reactants and products is at equilibrium and the temperature is changed, the system moves to a new position of equilibrium. A rise in temperature shifts the equilibrium in such a way as to absorb heat.

A priori estimations of heat and entropy changes in chemical reactions are very difficult to make in condensed phases. We therefore chose a particular class of reactions—oxidation-reduction reactions involving ionized species—for survey purposes. These were chosen primarily because sufficient thermodynamic data was available to determine readily the $\Delta H°$ and $\Delta S°$ of the processes. However, it is also felt that reactions involving such molecular species are likely to show high heats and entropies.

As the position of equilibrium shifts continuously with temperature, the total heat of reaction is not available for storage purposes over a limited temperature range. Rather than calculate the heat absorbed for a twenty degree rise in temperature, we assumed that half the heat of reaction could be used for storage: a rough calculation of the temperature rise necessary to accomplish this gave values of the order of 20°C or less.

It was found possible to obtain consistent thermodynamic data on fourteen half reactions taking place in neutral or acid solution (12 and 20). These half reactions could be combined with each other to give ninety-one complete reactions. Of these, eight had temperatures of "equilibrium" ($T_{eq} = \Delta H°/\Delta S°$) in or near the storage range of 30-200°C. The heats of reaction per mol of major reactant ranged from 2 to 18 kcal. If 10 mols of reagent could be fitted into a litre of water, then remembering that only a fraction of the heat of reaction is available for storage, one could expect storage capacities of the order of 100 kilocalories per litre.

The thermodynamic properties used in the calculation apply only to infinite dilution. To calculate the true storage capacities, we would need thermodynamic data in highly concentrated solutions of these substances, data which is not presently available in sufficient detail. Even in the absence of such data, there are reasons for believing that the influence of concentration on the entropy and enthalpy changes of these reactions will prevent the achievement of such high capacities.

The entropy changes are in part associated with the anomalous properties of water as a solvent, and can be accounted for on the basis of a model of water structure as an equilibrium between liquid-like and ice-like regions (21). The sizes and changes of the chemical species affect the sizes of the ice-like domains. More detailed considerations indicate that the entropy changes per molecule of reactant or product species formed must decrease in concentrated solutions as the number of water molecules per molecule of reactant decreases, and as the temperature is raised.

It seems therefore that the estimate of 100 kcal/litre for storage capacity is too high. This seems to indicate that these chemical reactions are not promising. Whether other types of chemical reactions may prove more useful can only be decided by further investigation.

Some advantages of chemical reaction in solution are that storage is entirely in a liquid phase, simplifying heat-transfer problems, and that the rate of storage of release of the heat can be almost as fast as in storage by sensible heat, as some chemical reactions have extremely rapid rates in solution.

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Summary

A number of physical and chemical processes having potential application for heat storage have been examined from the point of view of the maximum storage capacity to be expected on purely thermodynamic grounds.

The storage capacity of the sensible heat of water when a 20°C rise in temperature is allowed provides a reference figure of 20 kcal/litre or 20 kcal/kgm.

No pure substance among those considered by us storing heat by melting has a storage capacity in excess of 100 kcal per litre. There appear to be many such whose capacities lie between 75 to 100 kcal per litre. The heats of transitions of hydrates also lie in this range.

A few solid-solid transitions out of a very large number examined had storage capacities comparable to heats of fusion: the highest found was 75 kcal/litre (KHF_2 at 196°C).

Heats of solution of salts forming highly non-ideal solutions did not — on the basis of a calculation on only one salt, but that a very promising one — show much enhancement of storage capacity over systems using sensible heat.

Vaporization, being a process of higher entropy change than melting, appeared to offer greater promise, and this was found to be so. Some concentrated, highly non-ideal aqueous solutions considered gave storage capacities as high as 200 kcal/litre, and the decomposition of solid hydrates gave capacities up to 500 kcal/litre. A disadvantage, however, is that the storage system requires two chambers instead of a simple insulated tank, and the performance of the system is influenced by changes in ambient temperature.

The shift of equilibrium with temperature of chemical reactions in solution was also considered.

Capacities estimated for some aqueous oxidation reduction reactions on the basis of quite naïve assumptions were of the order of heats of fusion. However, there is good reason to believe that the actual storage capacity of these particular systems will be lower than calculated. No general statement can be made yet about such systems until much more data is available.

The above evaluations have considered only the maximum storage to be expected if thermodynamic equilibrium is readily achieved. It follows, therefore, that in addition to further thermodynamic data required to evaluate more precisely the storage capacities, data is needed on the kinetics of the chemical or physical processes occuring to ascertain if the rate at which they will store or deliver their energy is comparable to the rate required by practical considerations. Equally important are the economic and engineering considerations that were either passed over very lightly in this paper or ignored entirely.

QUELQUES ASPECTS PHYSICO-CHIMIQUES DE L'EMMAGASINAGE DE LA CHALEUR

Résumé

Nombre de processus physiques et chimiques susceptibles de recevoir des applications dans l'emmagasinage de la chaleur sont examinés du point de vue de la capacité maxima d'emmagasinage à en attendre, sur la base de considérations purement thermodynamiques.

La capacité d'emmagasinage que représente la chaleur sensible de l'eau dont on laisse la température monter de 20 °C fournit un chiffre étalon de 20 grandes calories par litre ou 20 kilocalories par kg.

Il n'existe aucune substance pure, parmi celles qu'on a prises en considération dans ce mémoire sur l'emmagasinage de la chaleur par la fusion, qui ait une capacité d'accumulation dépassant 100 kilocalories par litre. Il semble y en avoir beaucoup dont cette capacité s'échelonne entre 75 et 100 kilocalories par litre. Les chaleurs de transition des hydrates se retrouvent dans cette même gamme.

Quelques transitions solide-solide, parmi celles, fort nombreuses, qu'on a eu lieu d'examiner, avaient des capacités d'emmagasinage comparables à leur chaleur de fusion; la plus grosse valeur ainsi trouvée fut 75 calories par litre (KHF_2, à 196 °C).

Les chaleurs de solution des sels, formant des solutions très loin d'être idéales, n'ont pas révélé d'amélioration appréciable de la capacité d'emmagasinage par rapport aux systèmes qui s'en remettent à la chaleur sensible, à en juger par les calculs faits pour un sel sur lequel beaucoup d'espoir semblait pouvoir se fonder.

La vaporisation, en tant que processus dans lequel le changement d'entropie est plus grand que dans la fusion, semblait plus riche en promesses, ce qui fut confirmé. Certaines solutions aqueuses concentrées et fort loin d'être idéales ont donné des capacités d'emmagasinage allant jusqu'à 200 kilocalories par litre, et la décomposition des hydrates solides fit ressortir des valeurs atteignant 500 kilocalories par litre. Elles présentent toutefois le désavantage d'exiger deux enceintes d'emmagasinage au lieu d'un seul réservoir calorifugé, et le fonctionnement du système est influencé par les variations de la température ambiante.

On a examiné le changement d'équilibre des réactions chimiques en solution avec la température. Les capacités évaluées pour certaines réactions d'oxydation-réduction en milieu aqueux, sur la base de certaines hypothèses fort élémentaires, furent de l'ordre des chaleurs de fusion. On a cependant d'excellentes raisons de croire que la capacité d'emmagasinage réelle de ces systèmes sera inférieure à celle que donne le calcul. Il est impossible de formuler des points de vue généraux au sujet de ces systèmes avant de disposer de données beaucoup plus nombreuses.

Les évaluations passées en revue ci-dessus n'envisageaient que la capacité maximum d'emmagasinage à attendre quand l'équilibre thermodynamique peut se réaliser facilement. Il s'ensuit qu'il faut, outre les données thermodynamiques supplémentaires qui sont nécessaires pour évaluer les capacités d'emmagasinage avec plus de précision qu'aujourd'hui, des données sur la cinématique des processus chimiques ou physiques en cause, pour s'assurer que leur taux d'emmagasinage ou de débit d'énergie soit comparable au taux qu'imposent les considérations d'ordre pratique. Les aspects économiques et techniques, si rapidement traités, voire laissés totalement de côté, dans le présent mémoire, sont également très importants.

SOLAR BUILDINGS IN TEMPERATE AND TROPICAL CLIMATES

Edward Speyer *

If a solar-powered apparatus is to be operative during night-time or cloudy hours, it must draw either on auxiliary energy sources or on energy stored from previous sunny periods. Thus, in general, energy storage must be included in the design of solar energy applications; this is certainly true of solar houses.

In designing a building heated and cooled by solar energy, the major problems involve matching the parameters of solar energy collectors with those of the energy storage facility. Some, if not all, of the following six parameters will be major considerations :

(*a*) Cost : this is usually figured per unit capacity, such as dollars per square foot of collector and dollars per therm of energy storage.

(*b*) Space and/or weight of the collector and of the storage system.

(*c*) Capacity : collector capacity is the area perpendicular to the sun; storage capacity is the number of calories which can be furnished to, or withdrawn from, the house.

(*d*) Efficiency : collector efficiency is the fraction of incident solar energy which is usefully employed or put into storage. Storage efficiency is the fraction of energy previously stored which is still available after a certain specified storage period.

(*e*) Level : collector input level is the intensity of the incident sunlight; the lower limit is set by what Tabor (1) has called the cut-off intensity. If the collector is a quantum device, such as a photovoltaic cell or fuel cell, the usable range of collector input levels is a band-width in the electromagnetic spectrum. Collector output level in ordinary collectors is the collection temperature, which must be matched to the use, and to the range of storage input levels. Usually some adjustment of collection level can be obtained by controlling the gallons per minute of fluid pumped through the collector. The upper limit of input storage level will usually be determined by the phase diagram of the storage medium and by the effect on collection efficiency. The lower limit of output levels of both collector and storage are usually approximately the same.

(*f*) Rate : input rate for the collector is the insolation; it is established mostly by the altitude of the sun. Output rate for the collector is calories collected per minute; it equals the input rate times the collection efficiency. Maximum storage input rate must exceed the maximum collector output rate. The maximum storage output rate must exceed the power requirement of the end use, i.e. the rate of house heat or cooling demand.

Applications to solar houses

The over-all problem in using solar energy for space heating and cooling is to make a solar house pay for itself in terms of fuel saving, both for heating the building in cold weather and for cooling the building in hot weather. This means the substitution of solar energy for fossil fuel, i.e. the fuel which is burned in a home furnace and/or the fuel which turns the turbines at an electric power station.

The storage capacity needed for long-term storage (summer heat for winter use) does not require more than a small percentage of the volume of the space being heated and/or cooled (2). Short-term storage (night-time and a few cloudy days in succession) requires even less space, of course. The cheapest form of energy storage for houses is as sensible heat in rocks or water. Water has at least 25 per cent higher thermal capacity per unit volume than rocks; in addition, air passages must be provided for heat transfer to and from solid materials, whereas water has convection. Since the storage space must be insulated, it must be at least fairly tight, so that not much additional expense is incurred in making it water-tight.

Storing *potential* energy by pumping water into a high reservoir eliminates the need for insulation and apparently gives 100 per cent storage efficiency (more, if rainfall exceeds evaporation losses). Unfortunately, a mass of water must be pumped to the enormous height of 427 meters before the energy stored equals that of a 1°C rise in temperature. Moreover, the high efficiency is an illusion, because the conversion of solar energy into mechanical energy for pumping the water is inefficient.

If more sophisticated storage methods are used, such as heat of fusion or of solution, less storage space may be required, but costs will be higher. However, if the energy is stored in the form of heat, the efficiency depends partly on the surface-to-volume ratio of the tank and partly on the type and thickness of insulation. If chemical storage is used, the number of input-output cycles, and possibly also the per cent of depletion reached, may affect the efficiency.

The efficiency of storage required for a solar house is based on the doubly periodic duty cycle : the

* American Machine and Foundry Company, Stamford, Connecticut.

daily variations in temperature are superimposed on seasonal (annual) variations. If energy is to be stored from one season to the next, at least 50 per cent of the energy put into storage must be available three months later so that late summer heat can be used in early winter. If storage is needed for only a few cloudy days in addition to overnight, the efficiency requirements, of course, are much lower. The actual cost difference is not necessarily large, however, because all that may be involved is reducing the insulation around a tank from 12 inch thickness to 3 inch thickness.

During weeks of peak load (cold wave), the number of calories required by the house per degree day times the number of degree days during the cold wave may exceed the energy collected by an amount greater than the storage capacity times the storage efficiency. When this is true, auxiliary (non-solar) power must be used. With appropriate definition of degree day for cold, a similar relation holds also for house cooling. Gilman *et al.* (3) found that the computation of residential cooling load by the degree day method should use, as the datum temperature, 70°F (21°C). For example, a 24-hour day in which the average temperature is 85°C is to be counted as 15 degree days. For commercial rather than residential structures, a lower datum temperature is indicated.

Storage capacity is inversely related to collector capacity. If heat or cold can be stored for several weeks, that is, if storage efficiency is sufficient, collector capacity (area) can usually be reduced. Storage efficiency by itself, however, has a very slight effect on required collector area. Calculations, described in reference 2, show that the obvious advantages of higher storage efficiency tend to be nullified because it increases the required collection level (temperature) and thus reduces the collection efficiency (see figure 1).

If air conditioning (space cooling) is the major interest, short-term storage is all that will be required in most cases. The engineer has a choice, however, whether he will store energy to run the compressor, or whether he will store *cold*. In other words, during the sunny periods, the system must operate beyond the capacity for which it is being used, and the surplus stored either as heat or electricity for continuing the system after the sun has set, or else as chilled liquid which can be used as a heat sink after the sun has set. In the latter case, the pumps and fans must be powered by other means, which could be supplied by heat storage. Thus, if cold is stored, it may be desirable to provide also for simultaneous storage of some heat.

The choice made depends primarily upon storage level. The biggest problem in solar powered air conditioning, whether one uses a solar-powered compressor in a mechanical system or whether one uses an absorption cycle system, is obtaining energy at a sufficiently high level. In a mechanical system, the electric motor must be replaced by a cyclical heat engine, all of which are afflicted with what may be called the Carnot curse — the low efficiency inherent in the formula ΔT, that is to say, nothing of the much lower operating efficiency reached in

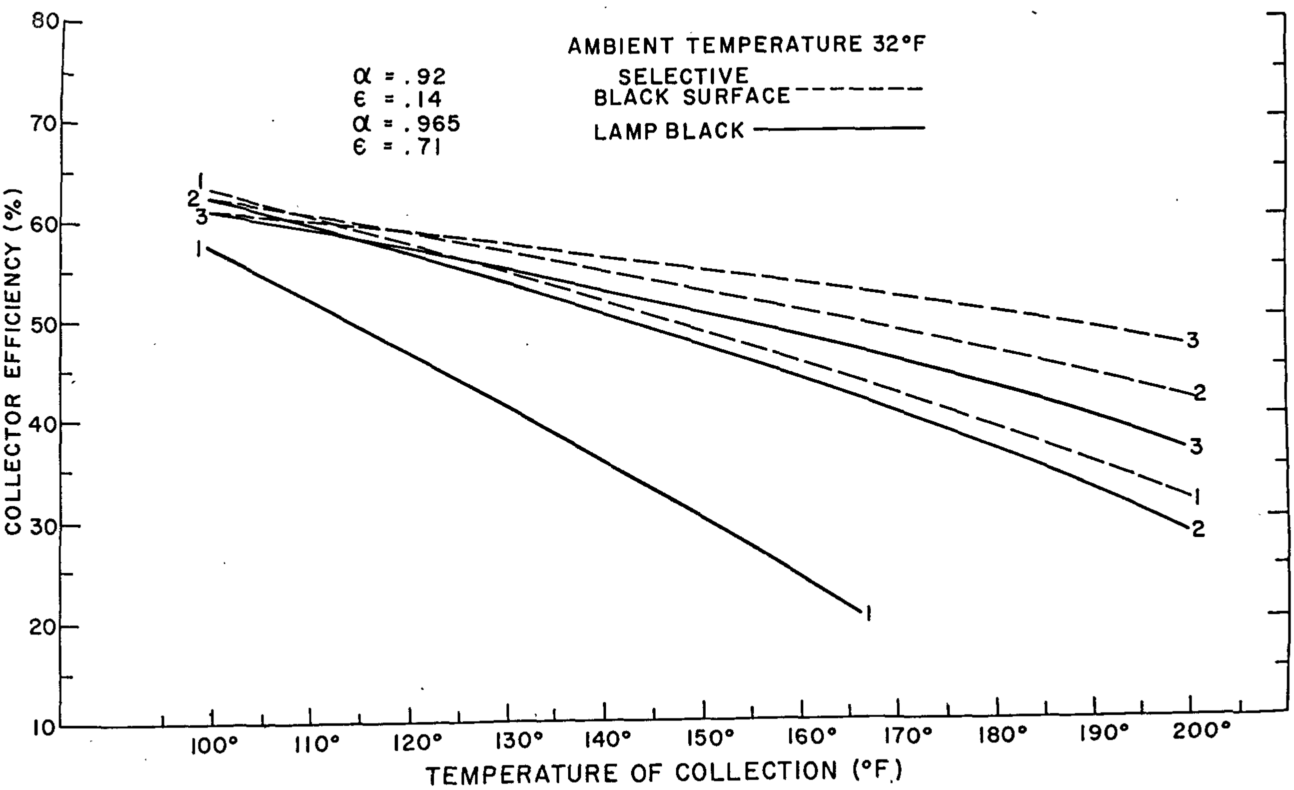

Figure 1. Efficiency of collector *vs.* collection temperature for 1, 2 and 3 glass plates

practice. In proven absorption cycles, such as that used in the Servel system, collection temperatures of at least 185°F (85°C) are needed. This means that in either case the collection temperatures required for air-conditioning systems are higher than for house-heating systems. Thus, if one elects to store heat for after-dark air conditioning, the storage level required is considerably higher than if one elects to store cold.

As can be seen from figure 1, there is a close relationship between storage level and collection efficiency. Maximizing the latter is often so important to the optimum functioning of the solar house that lowering storage levels (and even lowering storage efficiency) sometimes surprisingly turns out to improve the over-all system. A method for calculating the optimum parameters is given in reference 2.

Rate of storage or withdrawal is not usually a problem in space heating or cooling, unless heat of fusion is stored, in which case difficulty may be encountered with crystallization rates. Otherwise, storage input rate is determined by the collector, and storage output rate is determined by the size of the heat transfer device. The latter will ordinarily be liquid-to-air, because (a) hot liquid can be used down to lower temperatures (increasing the energy storage capacity) if used to heat circulating air than if piped directly into room radiators, and (b) circulating air lends itself readily to cooling, which usually will be desired in addition to heating.

Cold *vs.* hot climates

Engineering studies of space heating and cooling have centered almost exclusively around the problems of houses in temperate latitudes.

As pointed out in an earlier study (2), the economic feasibility of space heating and cooling in temperate zones stands or falls on the cost of solar collectors, rather than on storage costs. In the tropics, there is more sunshine, so that collector areas can be reduced, but as indicated above, the collection temperature (level) requirement is raised while the storage requirements, except for level, are easier to meet in warmer latitudes. Thus, the relative importance of collector costs for solar houses will be as great, if not greater, in the tropics than in the temperate zones.

An exception to this may be found in areas where the night temperatures usually go down to 75°F and/or the humidity is usually below 60 per cent. Thomason (4) has shown that house cooling is feasible under these conditions, using only the cooling of water as it runs over the roof at night. In other words, in areas where heating requirements are small and the big problem is house cooling, collectors might become a small item in the system and cool water storage the biggest expense. This would not be solar-powered air conditioning, but it could be combined with solar-powered apparatus for heating and/or pumping, and the storage system would be the same as for a fully solar-conditioned house. Thomason has devised an interesting two-stage storage system, consisting of water in a tank surrounded by a much larger mass of stones, the whole contained in an insulated bin. Heat is tranferred from or to the circulated air via the stones, which are cooled or heated by the water tank.

However, in most areas, as long as solar collectors cost more than U.S. \$3 or \$4 per square foot, installed on the site, both house heating and air conditioning will remain best approached through fossil fuels. In fact, for all areas which can be reached readily by truck, ship or train, fossil fuels remain so much the cheapest and most dependable source of energy for heat, electricity or mechanical work that remote areas are at the present time generally more justified in building roads (or otherwise increasing their accessibility) than in investing heavily in solar energy equipment which will be obsolete as soon as roads or railroads are built. The enormous energy content of a ton of oil or coal, and the relatively low cost of shipping fossil fuel almost anywhere in the world, are the justifications for this statement, discouraging as it may seem for under-developed countries. But the penalty for ignoring such facts of economic life are far worse than for taking them into account.

The main hope of overcoming such facts, as far as space heating and cooling are concerned, lies in the direction of cheaper solar energy collectors of high efficiency. A break-through in storage costs is the less promising road, because storage is a smaller fraction of the over-all cost. It is shown in reference 2 that, at prevailing prices in the United States, large capacity storage would have to become cheaper by about 80 per cent, i.e. by a factor of 5, before solar houses would be economically competitive in the United States. If such a break-through *were* accomplished, however, it would almost automatically make long-term (several months) energy storage of large capacity mandatory in solar houses. In other words, cheap, high efficiency, large capacity storage would minimize the required collector area.

Collectors, on the other hand, need to become cheaper by only a factor of 2 or 3 in order to make solar houses economically competitive. In addition, as pointed out above, collector efficiency is a critical parameter, improvement of which pays off surprisingly in the over-all performance of the solar house. Therefore, although this paper is concerned mainly with storage problems, the concluding section is devoted to describing some recent investigations of improved cheap collectors.

Cheap, high level, high efficiency collectors

The usual designs of flat plate collectors (5) do not generally provide high enough temperatures to operate efficient heat engines or absorption refrigeration cycles for air conditioning. Concentrating collectors provide such temperatures, but must be made to track the sun, i.e. must be movable, and hence are expensive. Flat plate collectors will yield higher collection temperatures if two or three glass

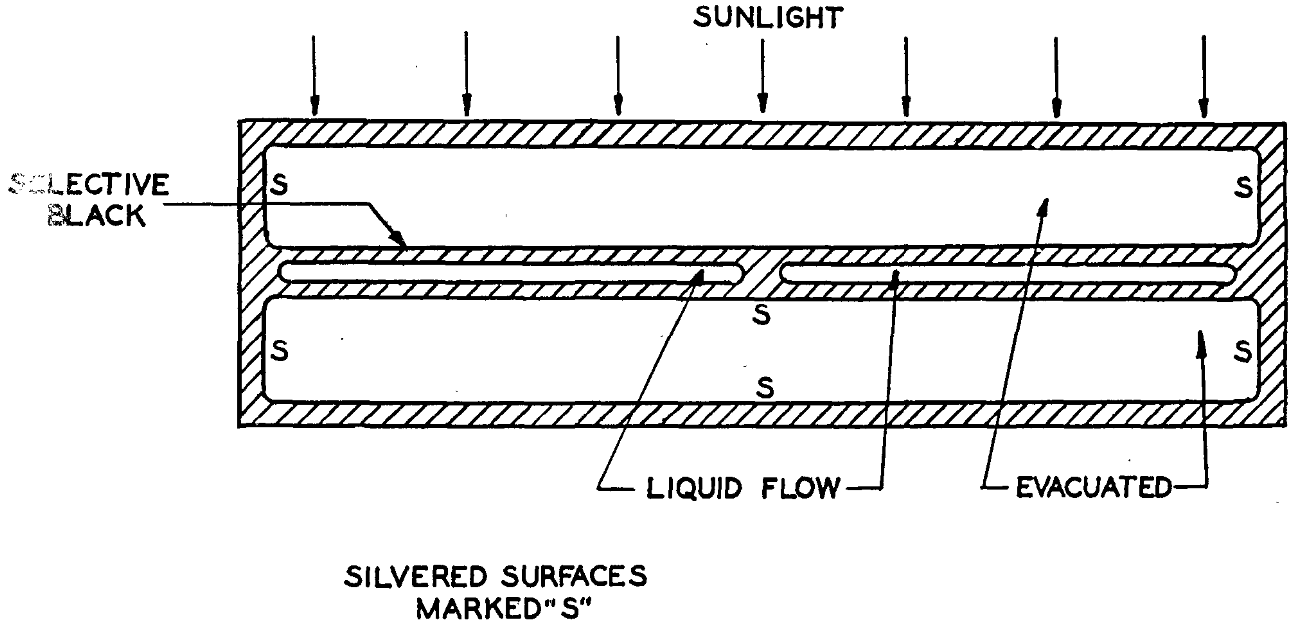

Figure 2

plates are used above the absorbing surface instead of a single glass plate. Figure 1 shows the effect of increasing the number of glass plates. The curves cross near the low temperature end of the scale where reflection losses from multiple sheets become more significant than improved insulation. The calculations for figure 1 were made on the basis of the analysis given by Hottel and Woertz (6). Details of the calculation are given in reference 7.

The curves for selective black surfaces, suggested by Tabor (1 and 8) show a significant increase in collection efficiency over conventional carbon black. The figure gives a typical absorptivity (α) for solar energy and for emissivity (ε) at normal collection temperatures for both types of surface. Substituting a selective black for lampblack has an effect similar to adding a layer (plate) of glass; however, the selective black gives the greater increase in efficiency, and does not increase reflective losses.

A further improvement in flat plate collectors can be made using the principle of the Dewar flask, that is, using evacuated chambers for insulating above and below the absorbing layers of the collector. However, collectors experience large temperature variations, and the problem of keeping air out of the evacuated chambers under such conditions, without making the cost prohibitive, has discouraged investigation.

Recently, our laboratories have been investigating evacuated flat plate collectors, using designs that permit sealing the evacuated spaces at the factory. The collectors are made principally of glass and completely avoid the necessity for pipes containing the collector fluid to pass through any surface enveloping the vacuum. Thus the plumbing problem is completely separated from that of sealing the evacuated chambers.

Figure 2 shows a design of this type. Studies are in progress on how to mass-produce such collectors cheaply, and how to install them easily on a house so that significant saving of conventional roofing materials is achieved. It is hoped to bring down the cost below $3 per square foot for collectors which will efficiently heat liquids to high enough temperatures under normal sunny-day conditions to provide solar-powered air conditioning.

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Summary

Solar energy storage must be designed for the system of which it is a part, particularly with respect to cost, space requirements, capacity, efficiency, level, and rate. The first two parameters have received much attention, but the last four have not always been optimized.

These six parameters are defined and discussed with relation to house heating and cooling. Storage capacity is the number of calories which the storage system can furnish. Storage efficiency is the fraction of energy put into storage which is still available at some later period. Storage level is ordinarily the storage temperature. Storage rate is the power (e.g. calories per minute) put in, or withdrawn from, storage. These parameters must be designed to match, or optimize, similar parameters which are defined for collectors. Some of the more important relationships between the twelve parameters are pointed out, including some which were investigated in a previously published study.

A comparison is made between the requirements of solar houses where the major need is for heat and where the major need is for cooling. The economic feasibility of solar houses stands or falls on the collector cost, both in temperate zones and in the tropics. The annual fuel (or electricity) savings must justify the total initial extra investment in solar equipment; the greater part of the latter cost is that of the collector. For all areas which can be reached readily by truck, ship or train, fossil fuels remain so much the cheapest and most dependable source of energy for heat, electricity or mechanical work that remote areas are at the present time generally more justified in building roads (or otherwise increasing their accessibility) than in investing heavily in solar energy apparatus which will be obsolete as soon as roads or railroads are built.

The most promising line of investigation for the future appears to be that of cheaper collectors. A new type of evacuated flat-plate collector, made almost entirely of glass, is described which uses the principle of the Dewar flask. The evacuated spaces are sealed at the factory; the liquid flowing through the collector does not present a sealing problem because the pipes are within, but do not penetrate through, the walls containing the vacuums. It is hoped that such collectors, mass produced, will be not only cheaper but also more efficient than previous designs.

BATIMENTS UTILISANT L'ÉNERGIE SOLAIRE SOUS LES CLIMATS TEMPÉRÉS ET TROPICAUX

Résumé

Les dispositifs servant à l'emmagasinage de l'énergie solaire doivent être organisés en accord avec l'installation dont ils font partie, particulièrement en ce qui concerne les frais, les servitudes de place, la capacité, le rendement, le niveau et le débit. Les deux premiers de ces paramètres ont reçu beaucoup d'attention, les quatre derniers n'ont pas toujours bénéficié du meilleur degré de raffinement.

Ce mémoire définit et passe en revue ces six paramètres en liaison avec le chauffage et la climatisation d'une maison. La capacité d'emmagasinage ou d'accumulation est définie comme étant le nombre de calories que le système peut fournir. Le rendement de l'emmagasinage est conditionné par la fraction de l'énergie mise en réserve qui reste disponible à une date ultérieure. Le « niveau » est habituellement identique à la température d'emmagasinage. Le débit est une puissance, par exemple un certain nombre de calories par minute, que l'on accumule ou que l'on soutire du système. Ces paramètres doivent être étudiés de manière à être comparables ou supérieurs à ceux, du même ordre, que l'on définit pour les collecteurs. L'auteur attire l'attention sur certains des principaux rapports entre les douze paramètres, dont certains ont été passés en revue dans une étude publiée antérieurement.

On procède à une comparaison entre les besoins des maisons qui font usage de l'énergie solaire et dont la principale exigence est le chauffage, d'une part, et celles, d'autre part, pour lesquelles c'est la climatisation qui compte le plus. La possibilité pratique de réaliser des maisons de ce genre est conditionnée, tant dans la zone tempérée qu'aux tropiques, par le coût du collecteur. Les économies annuelles de combustible (ou d'électricité) doivent justifier la totalité de l'investissement supplémentaire que représente le matériel d'utilisation de l'énergie solaire, dont le plus gros élément est le prix du collecteur. Pour toutes les régions qu'il est facile d'atteindre par camion, bateau ou chemin de fer, les combustibles fossiles restent si nettement la source d'énergie la plus économique et la plus sûre dont on dispose pour la production de chaleur, d'électricité ou de travail mécanique qu'il est plus judicieux en général, dans les régions peu accessibles, de construire des routes (ou autres voies d'accès) que de procéder à de gros placements au titre du matériel à énergie solaire, qui deviendrait inutile dès que l'on construit routes ou chemins de fer.

L'orientation la plus fructueuse, pour les recherches d'avenir, semble être celle qui aboutirait à la réalisation de collecteurs d'un prix plus modique que ceux dont nous disposons aujourd'hui. L'auteur décrit un nouveau type de collecteur à plaques plates et à enceinte totalement évacuée, fait entièrement de verre, qui met en œuvre le principe du vase de Dewar. Les enceintes évacuées sont scellées en usine, et le liquide qui circule dans le collecteur ne soulève pas de problème d'étanchéité parce que les tuyauteries sont logées dans les parois entre lesquelles règne le vide, sans pour autant les traverser. On espère que de tels collecteurs, produits en grande série, ne seront pas seulement plus économiques que ceux qui les ont précédés, mais aussi qu'ils auront un meilleur rendement.

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