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Results of Solar Heating Experiments

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Phil. Trans. R. Soc. Lond. A 1980 **295**, 361-373
doi: 10.1098/rsta.1980.0133

Phil. Trans. R. Soc. Lond. A **295**, 361–373 (1980)
Printed in Great Britain

Results of solar heating experiments

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Trials with full scale systems show that solar energy can make a significant contribution to the requirements for heating domestic hot water and living spaces in the United Kingdom. Results from these experiments, and others on system components, provide essential data for the development and validation of procedures for performance prediction and design optimization. The well regulated behaviour of solar heating systems has made it possible to answer leading questions on performance with increasing confidence.

Further experimentation will be required if a full economic evaluation of these systems is to be made, covering the degradation of performance and servicing requirements during the life-cycle.

Introduction

Throughout the United Kingdom, the solar energy falling annually on the external surfaces of an average dwelling far exceeds in magnitude all the energy expended within it (Brinkworth 1972). Thus, as a resource it is not ill-matched to the main energy demands of the domestic sector, which are for hot water and space heating.

Experiments on solar heating have ranged from laboratory tests on individual components to long term trials with full scale systems in everyday use. Among the immediate objectives of this work have been the development of improved components, verification of predicted characteristics, establishment of the principles of good design and demonstration of the performance of systems in routine use. Enough of this work has now been completed for a review to be made of the kind of results that it may yield and an appropriate philosophy to be established for further studies in the field.

Full scale experiments

Water heating

The first systematic observations of the behaviour of a solar heating system in Britain seem to have been those made at a site near London by Heywood (1954). Tests were made over a period of about four years with a system employing circulation by natural convection; the collector had a presented area of about 1 m^2 with a neutral black finish and was double glazed. Regrettably, the results of this pioneering work have not been fully analysed, but it is reported that over the period April to September the average collection efficiency was about 50 % (Heywood 1954, 1971). In these tests no water was drawn off until the end of the day, when the system was drained completely. It was found that boiling could occur if the total water capacity of the system was about 25 kg per m^2 of collector area but not at 50 kg/m^2. The latter value came to be used later in a design rule-of-thumb (I.S.E.S. 1975). Heywood's suggestion that the average collection efficiency of such a system for the whole year is not likely to exceed 40 % (Heywood 1971) has not been so readily remembered.

Most of the water heating systems subsequently brought into use in Britain have been of the forced circulation type and those installed during 1977 were estimated to have an aggregate collector area of 7000 m^2 (Johansson 1978). Though some large scale schemes are being mounted for the monitoring of some of these in service, few results have yet become available.

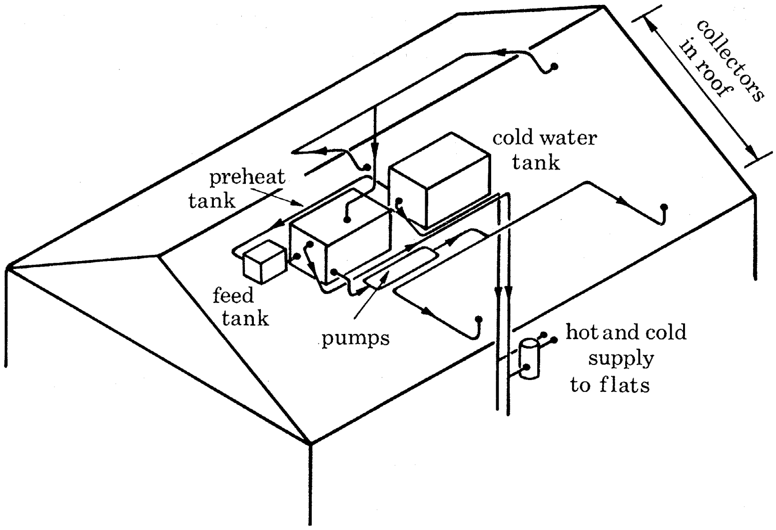

FIGURE 1. Students' flats installation: University College, Cardiff.

TABLE 1. SUMMARY OF PERFORMANCE OF WATER HEATING SYSTEMS WITH AND WITHOUT SOLAR HEATING

Student flats, University College, Cardiff
(single-glazed collectors; one bank neutral black, one bank black copper oxide, one bank black chrome finish)

period (1978)	average electricity use (MJ/man day): blocks without solar heating	block with solar heating	percentage reduction
16.1–13.2	10.34	8.56	17.2
14.2–13.3	11.30	7.53	33.4
14.3†–18.4	17.31	9.32	46.1
19.4–16.5	9.97	6.51	34.7
17.5–26.6	8.27	4.63	44.0

† Includes period of low occupancy during Easter vacation.

The simplest level of monitoring is the recording of the energy consumption employed in water heating, preferably for comparison with that used in an otherwise identical situation without solar heating. This has been done, for example, in a four story block of student flats at University College, Cardiff. The solar heating system fitted to one block provides about 1.25 m^2 of collector area per person (Howell 1977). The collectors are integrated into the roof structure, facing in a direction dictated by the site (roughly southeast), and the demand for hot water is subject to the natural variations that occur in real use. The general arrangement is illustrated in figure 1. The system operates in a direct mode, the water itself being passed through the collectors as the heat transfer fluid and returned to the storage or pre-heat tank. Water is taken from the 1 m³ pre-heat tank to individual cylinders in each flat, where its temperature is raised to the desired delivery value by electrical heaters. Electricity consumption for this purpose is recorded for each flat in the solar-heated block and in two identical adjacent blocks. Table 1 shows the monthly average consumptions in the experimental and the control buildings for 1978 up to the time of writing.

Table 2. Summary of solar water heating test results

Don Engineering (South West) Ltd. test rigs
(single-glazed collector panels; neutral black absorbing finish)

collector area	storage mass	daily demand	percentage reduction in electricity use relative to control												
m²	kg	kg	year	J	F	M	A	M	J	J	A	S	O	N	D
3.6	164	150	74	13	23	26	36	38	44	37	42	29	22	14	12
			75	13	22	28	30	38	50	44	47	—	20	17	10
			76	13	15	—	32	37	48	46	53	—	—	—	—
3.6	164	200	76	—	—	—	—	—	—	—	—	—	—	18	12
			77	11	16	18	22	33	25	34	29	30	24	—	—
			78	13	14	17	19	30	29	28	—	—	—	—	—
3.6	246	150	75	—	—	—	—	—	—	—	—	—	—	—	8
			76	10	13	—	26	44	52	54	68	—	—	—	—
3.6	246	200	76	—	—	—	—	—	—	—	—	—	—	16	9
			77	15	21	24	31	44	36	49	37	30	24	—	—
			78	18	15	26	28	44	41	41	40	38	31	—	—
2.4	91	200	78	12	11	17	21	30	29	28	28	32	21	—	—

The most comprehensive series of trials with solar water heaters, extending over a number of years, seem to be those reported by Sharpley (1977). In these, a number of complete systems ave been run on the manufacturer's premises for extended periods with an automatic draw-off of water on a schedule intended to be roughly representative of domestic use. The delivery temperature is 62 °C. In these trials also there is a control experiment, in which a similar system is operated simultaneously, with the same draw-off but without solar heating. Results, updated to the time of writing, are summarized in table 2, by presenting the percentage reduction in conventional energy use in the solar assisted systems relative to the controls.

These very extensive trials indicate generally that systems having single-glazed neutral black collectors show a reduction in annual energy consumption of 20–30 % when serving a demand of 80–40 kg/day per m² of collector. The annual mean collection efficiency is thus about $\frac{1}{3}$.

Space heating

Not many houses have yet been built in Britain with a solar heating component incorporated in the space heating system, and very few have been monitored for any length of time. Results are available so far for one only: the house at Milton Keynes (Hodges & Horton 1978). This is a small three-bedroomed terrace house of timber frame construction, with a floor area of about 90 m². It is fitted with single-glazed collectors of 37 m² area, integrated into the structure of the roof, which has a slope of 30° and faces 10° east of south. The general arrangement of the system is shown in figure 2. Two storage tanks, each of 2.1 m³ volume, hold the heat transfer fluid, an aqueous solution of ethylene glycol. This is circulated as required through a fan-convector unit which provides warm-air heating for the living spaces. The heating unit is designed for a fluid inlet temperature of about 40 °C, and when the storage tanks are below this temperature, auxiliary heating is normally provided by a gas boiler of the type fitted to neighbouring houses. Low heating loads can be carried in full at inlet temperatures well below 40 °C. Domestic hot water pre-heating is also provided via a series of small tanks enclosed within the storage tanks and acting as heat exchangers; auxiliary heating to tap temperature is in this case provided by an electrical immersion heater in the final hot water cylinder.

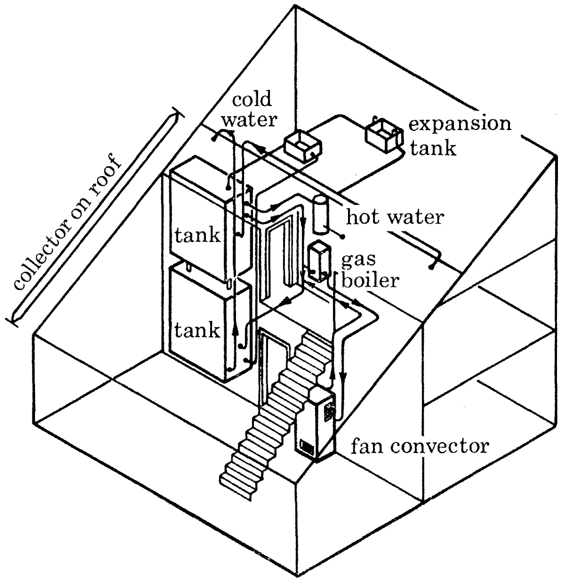

Figure 2. Solar House: Milton Keynes.

Table 3. Summary of solar water and space heating results

Milton Keynes house

(single-glazed collector panels; neutral black absorbing finish)

		estimated percentage reduction in energy consumption											
services	year	J	F	M	A	M	J	J	A	S	O	N	D
water heating	75	—	—	—	—	—	—	—	—	76	49	23	12
	76	22	17	39	55	78	92	100	88	78	63	38	30
	77	18	42	68	69	74	—	—	—	—	—	—	—
	78†	—	—	—	79	90	97	94	99	99	85	—	—
space heating	75	—	—	—	—	—	—	—	—	75	34	10	0
	76	4	5	41	74	—	—	—	—	—	26	8	0
	77	0	17	39	79	97	—	—	—	—	—	—	—
	78†	—	—	—	91	100	—	—	—	—	98	—	—

† After modifications.

The performance of this system has been monitored over a period of about three years by members of the design team from the Polytechnic of Central London. It has been found that the overall collection efficiency for the system was 29 % over a heating season (October–March). The useful energy collection over this period was about 0.21 GJ/m². Over the two years 1975–6 and 1976–7 the fraction of the total energy expended in space heating provided by solar energy was determined to be 17 % in both cases, while that of the water heating energy was 51 % and 63 % respectively. Modifications to the system during the winter of 1977–8 seem

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to have effected a substantial improvement in performance, but data for a complete year's operation are not yet to hand. A summary of the published results for the reduction in conventional energy consumption is given in table 3.

Philosophy of full scale experimentation

Other full scale experiments, similar to those described above, have been in hand over shorter periods, and more are planned. The early results are perhaps sufficient, however, to enable a judgement to be made of the extent to which trials of this kind can provide the answers to the questions about system performance which are needed at this time. Among these questions the main ones are probably:

(*a*) what are the leading design parameters for solar heating systems which would be best suited for operation in Britain?

(*b*) what proportion of typical heating loads could be provided by these systems in routine operation?

(*c*) what are reasonable costs for typical systems now, and what trends could be foreseen for the future?

(*d*) what would be typical lifetimes of these systems in service?

Answers to these questions are needed, so that assessments can be made of the potential contribution of solar energy as one of the optional sources available for future exploitation, and to permit the economics of its exploitation to be properly evaluated so that judgements can be made of its relative claim to development resources.

It is readily apparent that trials of the kind already described cannot themselves provide the answers to these questions. They give evidence of how particular systems performed over particular periods. Clearly, it would be impracticable to mount a sufficient number of trials to cover the effects of possible variations in system and component design, mode of operation, location and weather. Moreover, full scale tests yield results too slowly to provide the information required for development. In a rapidly advancing field, it would be unhelpful if the only guidance were to come from tests on systems representing the technology of several years ago.

This is not to say, however, that full scale experimentation is of no value. On the contrary, it has an indispensable role to play as one element in a strategy comprising three branches – component testing, computer modelling, and full scale testing. Investigation of the effects on system performance of design changes, patterns of use and weather variations can be made easily and quickly by computer modelling. Component testing provides the basic information needed to frame the system model, while full scale testing enables the model to be validated. A small number of carefully controlled and monitored experiments should be sufficient to provide the necessary data, which must be closely matched by the computer predictions if there is to be confidence in applying the system model to other situations which have not been studied at full scale.

Exercises in the validation of computer models have begun in several countries. It is already clear that the accuracy with which data can be obtained on the behaviour of full scale systems is a critical factor. A distinction is made between controlled and uncontrolled experiments. In an uncontrolled experiment, instrumentation is installed to monitor the performance of a system which is in actual use and subject to all the variation in input and demand which occurs in routine operation. The examples cited above of tests on the Cardiff student flats and the

Milton Keynes house are of this kind. Most workers engaged in this type of experimentation up to the present time have felt themselves to be still developing appropriate techniques. It has proved difficult to ensure that the data collected have been continuous and of known accuracy. This has introduced an unexpected change of timescales, so that the development of computer simulation codes has run well ahead of the availability of data having sufficiently high quality to give confidence in their use for validation.

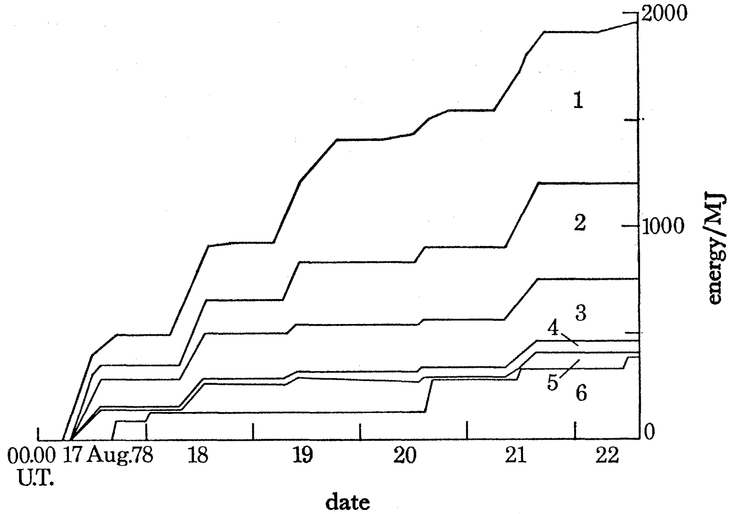

FIGURE 3. Cumulative energy account: student flats. 1, Energy incident while collector temperature ⩽ store temperature; 2, collector losses (radiation and convection); 3, collector losses (reflexion and absorption); 4, losses from store; 5, energy content of heat store; 6, energy removed from heat store.

Controlled experiments are those in which one or more of the variables may be adjusted by the experimenter. These include component tests, to which reference is made later, but many involve whole systems, in which the response is determined to controlled changes in some quantities, usually those related to the user demand. Results of such an exercise are shown, for example, in figure 3. This illustrates the changes in various elements of the energy account for the student flats installation during a period in which the demand on the system was deliberately interrupted. The comparative tests leading to the data of table 2 are also of the controlled type, since for these the hot water draw-off is made according to a standard schedule. A further example is provided by the series of substantial test stands, known as Pilot Test Facilities, which are currently under construction throughout the countries of the European Community. In these it will be possible to test a variety of systems with controlled demand and simulated heat inputs.

Relationships between experiments of this kind and the other elements of the strategy for performance evaluation are considered in the following sections. It should be noted, however, that there are other benefits to be gained by full scale testing. The construction, installation and operation of experimental systems can provide data on costs, reveal unexpected difficulties in assembly and operation, and yield information on reliability and durability which would be hard to obtain in any other way. Moreover, in the early stages of the introduction of new technology, successful demonstration at full scale is usually essential if it is to gain credibility and general acceptance. This will not be achieved unless the trials are well planned and executed, the observations minutely documented and the results widely reported. A heavy responsibility for the future course of events thus lies with those who conduct these trials.

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Computer experiments

A certain amount of performance prediction and system optimization is possible by analytical means (Duffie & Beckman 1974; Brinkworth 1975) but the number of variables and the non-deterministic character of some of the quantities involved puts strict limits on this. The main burden in providing answers to questions (*a*) and (*b*) in the previous section must, for practical reasons, fall on computer simulations. Once validated by having its predications compared with the actual behaviour of one or more real systems the computer model can be used to predict the behaviour of systems in a wide variety of situations, to determine the optimum combination of component parameters for a given duty and to explore the possible results of actual or potential changes in technology. These operations are substitutes for experimental work and may reasonably be described as computer experiments.

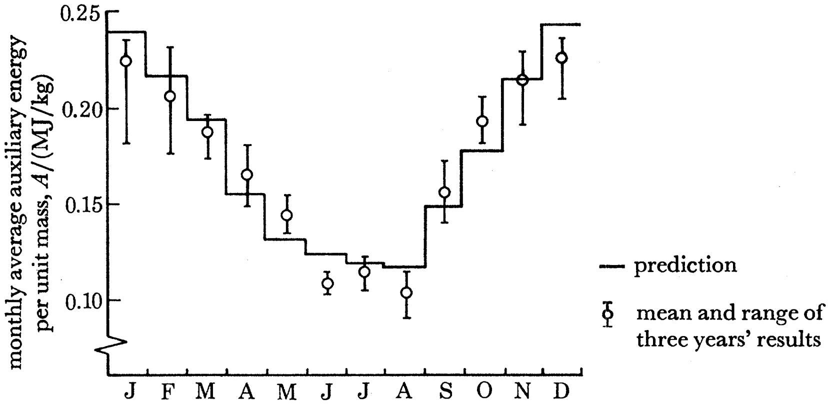

Figure 4. Validation of water heating program.

An example of a validation exercise is reproduced in figure 4 (Brinkworth 1977*a*). This compares the performance predicted for a domestic water heating system with the results of three years of operation of a full scale system of the same configuration (the first set of data summarized in table 2). In this case the basis of comparison was the quantity A, the auxiliary energy used to raise the water to the desired delivery temperature, expressed per unit mass of hot water delivered. The comparison is made on the monthly averages, and the figure shows the mean value of the actual consumption and the range of variation experienced over a three year period. The predicted annual energy saving in this case was about 22 %, and the actual average saving over three years about 24 %.

The month-by-month agreement was considered to be sufficient to justify the use of the computer model to examine the effects on performance of variations in the leading system parameters of collector area and storage volume and sensitivity to the pattern of hot water demand. These exercises provided important guidelines for system design, which could not have been obtained by any practicable range of real experiments. It is found that a system of this kind is self-regulating to a remarkable degree (Brinkworth 1978 *a*). For a given hot water demand, the performance is only weakly dependent upon the storage capacity, once this exceeds a fraction of about 0.75 of the mean daily demand. It is rather insensitive to variations in the water draw-off pattern and to component characteristics such as the collector back-loss coefficient and heat exchanger effectiveness (Brinkworth 1977*a*).

For practical purposes, it is indicated that the performance in a given climate of simple open systems such as the domestic hot water heater can be expressed in terms of a single operational parameter: the daily hot water demand per unit collector area. The relative insensitivity of the performance to other factors is a consequence of the negative feedback to which the system is subject. Any change that leads to an improvement in energy collection causes a rise in temperature which is larger and more rapid; the consequences are a compensating increase in thermal losses and a termination of energy collection earlier in the day. This insensitivity makes it possible for good approximations to overall system behaviour to be obtained with procedures involving very little labour, requiring the aid of a pocket calculator only (Brinkworth 1978*b*).

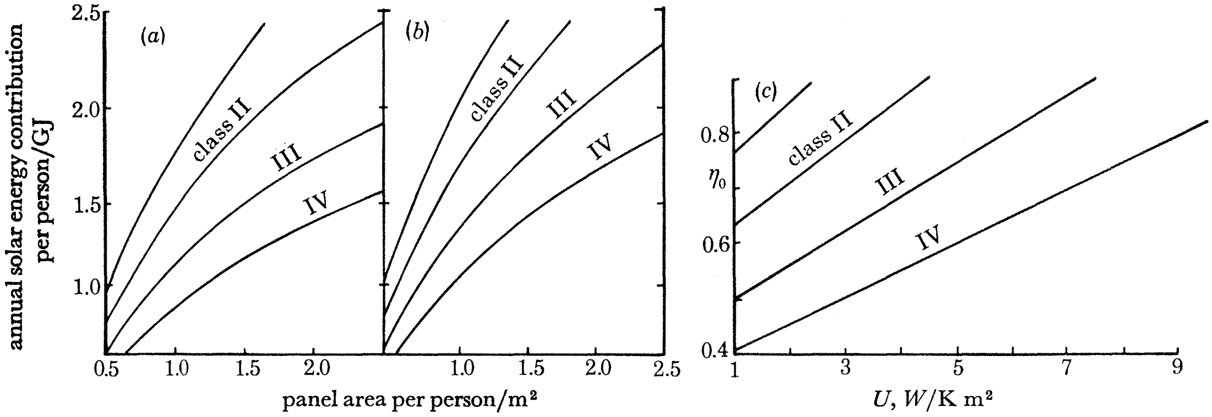

FIGURE 5. Predicted annual performance: water heating. (*a*) Hot water used at 60 °C (1 person uses 44 kg/day); (*b*) hot water used at 45 °C (1 person uses 62 kg/day); (*c*) classification of collectors.

These general conclusions about performance of solar water heaters in Britain are reinforced by new studies made in the preparation of the recent draft British Standard Code of Practice for Solar Heating Systems for Domestic Hot Water (B.S.I. 1978). In this draft computed curves are presented, which indicate the performance that might be expected from typical systems of domestic scale. Examples are reproduced in figure 5. The operational parameter is this time expressed as collector area per person in the household, one person being considered to require 44 kg of hot water per day at a delivery temperature of 60 °C, or 62 kg at 45 °C. The performance is also dependent on the type of collector employed, but the sensitivity to collector characteristics is found to be sufficiently weak for it to be possible to classify all types within only four categories. The properties of a collector which determine its category for this purpose are two parameters which are here denoted by η_0 and U. The quantity η_0 is the collection efficiency when the collector is operating with a fluid inlet temperature equal to the ambient temperature, and U is the overall conductance for heat loss from the collector to the surroundings, relative to the difference between the mean fluid temperature and the ambient temperature. Figure 5 shows the relation between the collector category and the thermal parameters used in the draft British Standards procedure.

In the computations leading to these curves, further studies were made of the sensitivity of overall annual performance to variations in a comprehensive range of component and system characteristics. The low sensitivities found lend support to the view that the behaviour of solar water heating systems can be modelled simply and reliably today. It is found that essentially similar predictions of performance are obtained with programs which differ substantially in detail and embody different assumptions and computational algorithms. This experience is reflected in the findings of independent studies in several countries and in two major international collaborative exercises being run under the auspices of the Commission of the European Communities and the International Energy Agency.

Table 4. Summary of typical predictions for solar water and space heating

house at Hamburg

(single-glazed collector panels; neutral black absorbing finish)

	estimated percentage reduction in energy consumption											
	J	F	M	A	M	J	J	A	S	O	N	D
water heating	24	32	53	53	78	98	90	99	84	48	38	32
space heating	5	12	49	68	93	—	—	—	94	49	26	12

In the first of these, part of Project A: Solar Energy Applications for Dwellings – Modelling and Simulation, results from the use of nine different programs originating in eight countries have been compared, with common load profiles and weather data for three locations: Carpentras (France, lat. 44°), Hamburg (F.R.G., lat. 53½°) and Valentia (Eire, lat. 52°). The second exercise is part of the I.E.A. Solar Heating and Cooling Program – Task 1: Investigation of the Performance of Solar Heating and Cooling Systems. This involves comparisons employing a wider range of weather data from Denmark, Germany (F.R.G.), Japan and the U.S. Agreement in the predicted performance within a small percentage has been found in the majority of cases (O.E.C.D. 1978). The initial comparisons of the simulation codes in the programmes of the C.E.C. and I.E.A. are to be followed by validation exercises in which the recorded performance of certain systems will be compared with the computer predictions. No predictions are yet to hand for specifically British conditions, but some typical figures for Hamburg (lat. 53½°) are given in table 4. With due reservations, these may be compared with those of table 3 for the house at Milton Keynes (lat. 52°). They are made for a building constructed according to the Danish regulations BR 77 having a somewhat higher insulation standard, but the solar heating system is of comparable scale. The ratio of collector area to floor area is about 0.4 and the storage mass is around 100 kg/m^2 in both cases. The general similarity of the monthly variation in the results is clear. The Hamburg calculations predict a higher proportion of the space heating load provided by solar energy (38 %), though the contribution to domestic water heating is about the same (61 %) and over the period October–March the useful energy collected is similar at about 0.24 GJ/m^2.

Component tests

Tests on components such as collectors and heat exchangers, and experiments to determine likely ranges of operational variables such as solar irradiance and water supply inlet temperatures, are required so that these elements may be satisfactorily represented in computer models. The variety of these tests has been so great that only a few typical examples can be cited here. These are taken from the work of the Solar Energy Unit at Cardiff.

Radiation characteristics

National meteorological services record solar irradiance for horizontal surfaces (and in a few cases vertical surfaces) but for performance prediction it is necessary to know the irradiance for surfaces of arbitrary orientation. Theoretical methods based on assumed spatial distributions of the scattered radiation are available, but there are few reliable measurements (Kondratyev 1977).

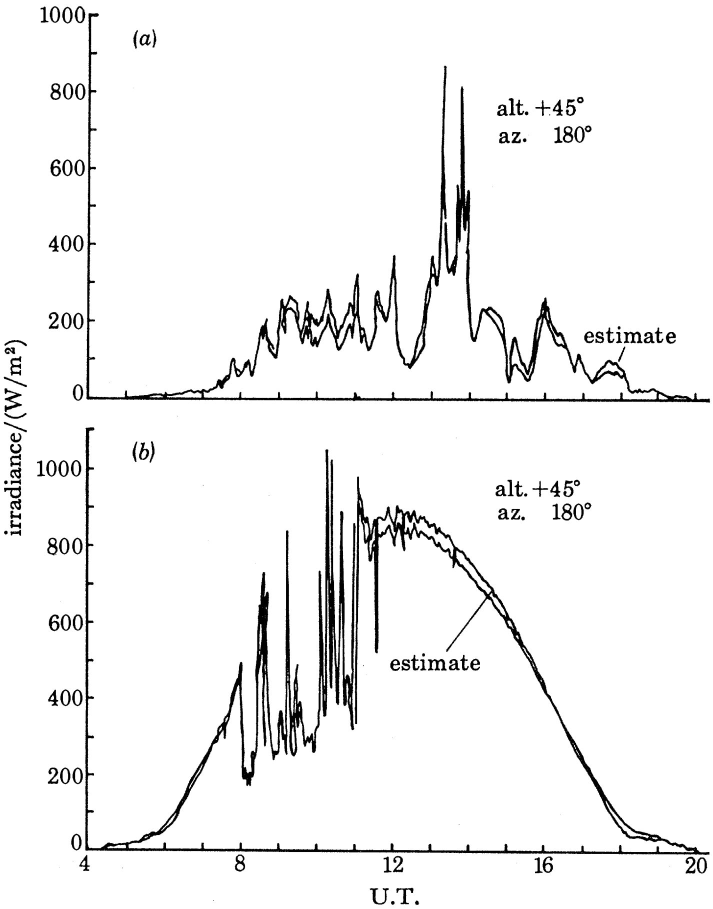

FIGURE 6. Estimated and measured irradiance. (*a*) Cardiff, 2 August 1978; (*b*) Cardiff, 16 July 1978.

A scanning pyranometer has been developed which repeatedly samples the radiation at 26 angular positions over cycles of 60 s duration (Svendsen 1977). The data are recorded on magnetic tape and can be deconvoluted numerically to give estimates of the irradiance for surfaces of any orientation. Examples of the output are shown in figure 6, where the estimated irradiance is compared with that determined by fixed instruments.

As seen in figure 6, the temporal variation in the irradiance is very large and rapid at inland sites in the U.K. The relatively slow response of systems of the kind considered here suggest that a general daily variation embodying only the low frequency components might be determined, to serve as an input for system models. Appropriate shapes have been proposed (Brinkworth 1978*b*, *c*). It is further shown that day-to-day variation in the total irradiation for the U.K. may be adequately represented as a Gaussian–Markov process having a simple first order

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regressive autocorrelation (Brinkworth 1977 *b*). The parameters of this process have been used in the generation of synthetic day-to-day sequences for modelling purposes and in the selection of real irradiance data representative of the long term sequential characteristics of the U.K. insolation. These were employed, for example, in the validation exercise which led to figure 4.

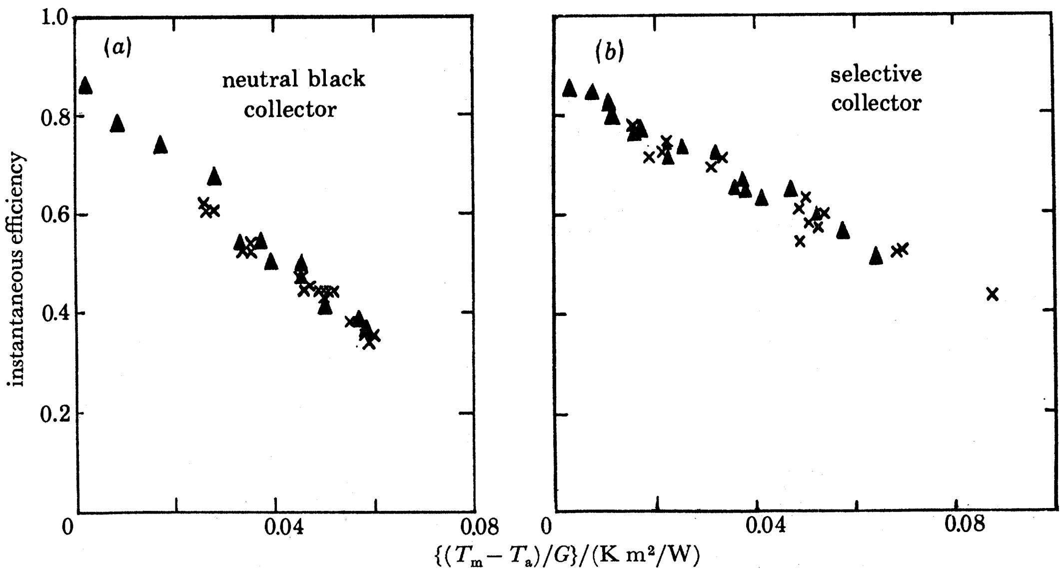

FIGURE 7. Indoor/outdoor test comparisons. T_m = Mean fluid temperature; T_a = ambient temperature; G = global irradiance; ×, Outdoor data, 700–900 W/m²; ▲, simulator data, 800 W/m².

Collector characteristics

The Unit has a substantial Outdoor Test Facility for the measurement of collector thermal characteristics and for the study of long term durability. Outdoor testing is frustrated in the U.K. climate by the infrequency of periods of steady conditions of sufficient duration. The commissioning of the S.R.C. Solar Simulator has made it possible to test collectors and other devices indoors in a perfectly steady state at any time. This machine provides an irradiance of up to 800 W/m² with an appropriate spectral distribution of energy and reasonable uniformity over a working area more than 2 m in diameter with complete angular variation (Gillett 1977). For full simulation it is necessary also that the test cell should provide an appropriate background of long wavelength radiation. The degree to which this has been achieved is illustrated in figure 7, which compares the results of tests outdoors and indoors on two collectors, one having a neutral absorbing finish and the other one which is strongly selective.

Radiative selectivity is a desirable property for collector surfaces. The finish should have a high absorptance for solar radiation but a low emittance for thermal radiation at operating temperatures. Apparatus has been developed for the measurement of these properties as a matter of routine (Morgan & Gillett 1977). Table 5 shows some typical values for a range of surface finishes.

These are the total hemispherical values. Recent studies have shown that the greater selectivity of thin-film semiconductor finishes, relative to that of paint films, is accompanied by a different form of angular variation of emittance (Hutchins 1978). Some representative patterns are shown in figure 8. Methods are being explored for using diagnostic measurement of optical properties to monitor the durability of surface films in long term exposure trials.

Table 5. Total hemispherical optical properties of surface films

category	film	solar absorptance ±0.03	thermal emittance ±0.02
non-selective	epoxy	0.95	0.90
	alkyd	0.95	0.77
	acrylic	0.94	0.90
	polyester	0.95	0.86
selective films	black chrome	0.96	0.16
	copper oxide	0.87	0.10
	chromated zinc	0.95	0.28
	blue stainless	0.93	0.18

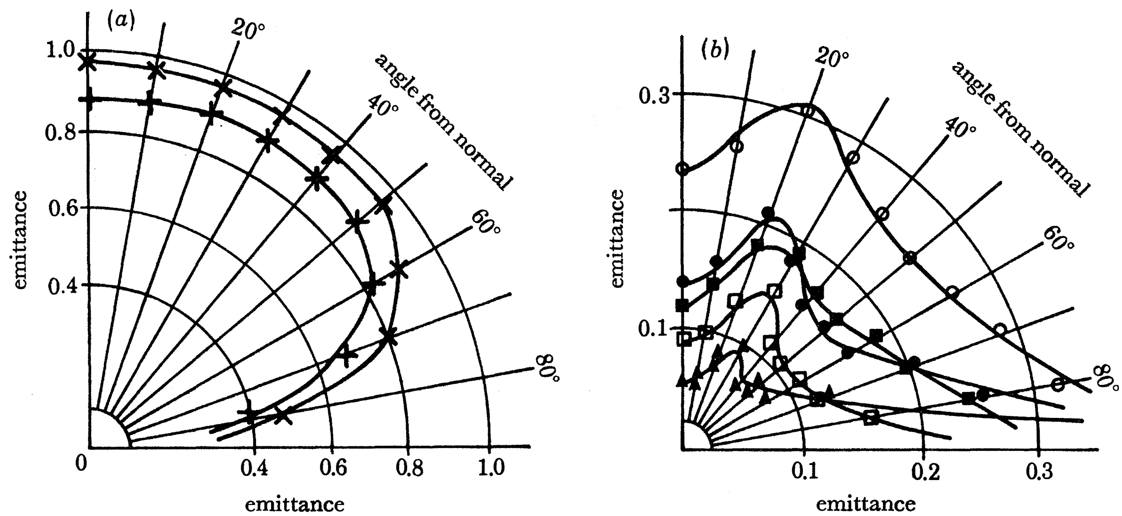

Figure 8. Total directional emittance of surface films. (*a*) Paint films; (*b*) semiconductor films.

Thermal storage

All solar heating systems need storage capacity and in those described above this has been as much as 100 kg of water per m² of collector area. For space heating systems the requirement is inconveniently large. Two ways of alleviating the difficulty are being studied: outdoor siting of the store, possibly involving community sharing but still employing sensible heat storage, and internal storage in media which undergo a physical change of phase. In the latter case the large enthalpy change in some transitions makes it possible to use much smaller volumes of material (Pillai & Brinkworth 1976). Experimental thermal stores are now being assembled, but performance figures are not yet to hand. The design of these stores has called for a substantial programme of theoretical and experimental work on convective mixing (Marshall 1977, 1978; Hawlader 1978; Brinkworth 1978*d*).

Conclusion

It has been seen that the results of experimental work provide two of the three necessary inputs to procedures for determining system performance and design optimization. While much remains to be done, experience with water heating systems indicates that an appropriate strategy has been established for the development of these procedures, which will be applicable

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also to space heating systems. There will be a need to supplement them with others for determining degradation of performance and life-cycle servicing requirements if full economic evaluations are to be made. This will call for further experimentation, probably extending over long periods.

Permission to include the following material is gratefully acknowledged: figure 2 and table 3 (A. Horton, Polytechnic of Central London); table 2 (D. E. Sharpley, Don Engineering (South West) Ltd.).

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