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IEA
SOLAR R&D

INTERNATIONAL ENERGY AGENCY
Solar Heating and Cooling Programme

Task III: Performance Testing of Solar Collectors

SUMMARY OF NATIONAL APPROACHES TO SHORT-TERM TESTING OF SOLAR DOMESTIC HOT WATER SYSTEMS

December 1987

NOTICE

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Byard D. Wood
Center for Energy Systems Research
Arizona State University
Tempe, AZ 85287
USA

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A Technical Report of the IEA Solar Heating and Cooling Programme
Task III: Performance Testing of Solar Collectors
Subtask E: Short-Term SDHW Systems Testing

Prepared by:

Byard D. Wood
Center for
Energy Systems Research
Arizona State University
Tempe, AZ 85287
USA

Brian Rogers
Department of Mechanical Engineering
and Energy Studies
University College
Cardiff CF2 1TA
UK

With contributions by participants listed with their addresses and affiliations on the inside back cover.

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INTRODUCTION TO THE INTERNATIONAL ENERGY AGENCY AND THE IEA SOLAR HEATING AND COOLING PROGRAMME

The International Energy Agency was formed in November 1974 to establish cooperation among a number of industrialized countries in the vital area of energy policy. It is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). Twenty-one countries are presently members, with the Commission of the European Communities also participating in the work of the IEA under a special arrangement.

One element of the IEA's programme involves cooperation in the research and development of alternative energy resources in order to reduce excessive dependence on oil. A number of new and improved energy technologies which have the potential of making significant contributions to global energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), supported by a small Secretariat staff, is the focus of IEA RD&D activities. Four Working Parties (in Conservation, Fossil Fuels, Renewable Energy, and Fusion) are charged with identifying new areas for cooperation and advising the CRD on policy matters in their respective technology areas.

Solar Heating and Cooling was one of the technologies selected for joint activities. During 1976-1977, specific projects were identified in key areas of this field and a formal Implementing Agreement drawn up. The Agreement covers the obligations and rights of the Participants and outlines the scope of each project or "task" in annexes to the document. There are now eighteen signatories to the Agreement:

Australia
Austria
Belgium
Canada
Denmark
Commission of the
European Communities
Federal Republic of
Germany
Finland
Greece (withdrew in 1986)
Italy
Japan
Netherlands
New Zeland
Norway
Spain
Sweden
Switzerland
United Kingdom
United States

The overall programme is managed by an Executive Committee, while the management of the individual tasks is the responsibility of Operating Agents. The tasks of the IEA Solar Heating and Cooling Programme, their respective Operating Agents, and current status (ongoing or completed) are as follows:

Task I	Investigation of the Performance of Solar Heating and Cooling Systems: Technical University of Denmark (Completed)
Task II	Coordination of Research and Development on Solar Heating and Cooling: Solar ResearchLaboratory, GIRIN, Japan (Completed)
Task III	Performance Testing of Solar Collectors: University College, Cardiff, U.K. (Ongoing)
Task IV	Development of an Insolation Handbook and Instrument Package: U.S. Department of Energy (Completed)
Task V	Use of Existing Meteorological Information for Solar Energy Application: Swedish Meteorological and Hydrological Institute (Completed)
Task VI	Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors: U.S. Department of Energy (Ongoing)
Task VII	Central Solar Heating Plants with Seasonal Storage: Swedish Council for Buildng Research (Ongoing)
Task VIII	Passive and Hybrid Solar Low Energy Buildings: U.S. Department of Energy (Ongoing) Task IX Solar Radiation and Pyranometry Studies: KFA - Jülich, F.R.G. (Ongoing)
Task X	Solar Materials Research and Development: AIST, MITI, Japan (Ongoing)
Task XI	Passive and Hybrid Solar Commercial Buildings: Swiss Federal Office of Energy (Ongoing)

TASK III PERFORMANCE TESTING OF SOLAR COLLECTORS

The overall goal of Task III is by international cooperation to develop and validate common test procedures for rating the performance of solar thermal collectors and solar domestic hot water heating systems.

Task III was initiated in 1977 with three subtasks:

Subtask A:	Standard Test Procedures to Determine Thermal Performance
Subtask B:	Development of Reliability and Durability Test Procedures
Subtask C:	Investigation of the Potential of Solar Simulations

Upon the completion of these subtasks at the end of 1982, the Executive Committee approved an extension of the Task with the following three subtasks:

Subtask D:	Characterization of the Thermal Performance of Solar Collectors
Subtask E:	Development of a Capability to Evaluate Domestic Hot Water System Performance Using Short-Term Test Methods
Subtask F:	Development of a Basis for Identifying the Performance Requirements and for Predicting the Service Life of Solar Collector System Components

At the end of 1985 a further extension was approved, with a completion date at the end of 1987.

Participants in Task III (those marked * until the end of 1985 only):

Australia*, Austria*, Belgium*, Canada, Denmark, F.R. Germany, Italy, Japan*, the Netherlands, Spain, Sweden, Switzerland, United Kingdom, United States and the Commission of the European Communities.

ABSTRACT

This technical report on the thermal performance testing of SDHW systems gives an overview of the various approaches for short-term test methods that are currently being used or are under development within the IEA Task III participating countries. The purpose is to gain experience in the range of techniques available for characterizing SDHW systems and for predicting their long-term performance. The fourteen methods summarized can be logically grouped into the following catgetories:

1. System performance for a range of weather conditions characterized by parameters determined from individual component tests.
2. System performance for a range of weather conditions determined from measurements on the whole system.
3. System performance for a range of weather conditions determined from a combination of separately-measured component parameters and whole system measurements.
4. System performance determined as a function of internal variables from measurements on the whole system.
5. System performance determined for specific test conditions only.

The methods have been designed to meet different specific requirements. An attempt has been made to describe the basic principles of the methods, to indicate the state of development, and to identify the advantages and disadvantages of each approach.

These test methods form the basis of a joint IEA Task III programme to develop common test procedures that incorporate the best features of the individual methods. This report is based on the work performed to under Subtask E: Development of a Capability to Evaluate Domestic Hot Water System Performance Using Short-Term Methods.

TABLE OF CONTENTS

1.0 *INTRODUCTION*

Conservation of nonrenewable energy resources is the primary reason that a wide variety of solar domestic hot water (SDHW) systems are marketed throughout the world. A natural consequence of this highly dispersed activity is the need to understand, predict and compare the performance of these SDHW systems. To this end Subtask E in IEA Task III was developed. The stated objective is "The participants will apply short-term system test methods in order to develop the capability to evaluate the thermal performance of domestic hot water systems. Basic system performance parameters will be identified, methods of measurement will be developed, and analytical methodologies for predicting the seasonal system performance based on the short-term test data will be developed and validated through comparisons of predicted and measured performance." Another way of stating this objective is: Use short-term test data in conjunction with analytic techniques to predict the annual performance of any SDHW system in any solar/meteorological region.

The purpose of this technical report on SDHW testing has been to give an overview of the range of methods that are used or under development within the IEA Task III participating countries, and which are the starting point for the cooperative project on SDHW testing undertaken by the task participants during the period between January 1986 and December 1987.

The review of methods was not intended to be exhaustive in its coverage; the field is too wide and the experience of the participants in the methods of other workers is limited. Nor is it the intention here to give a critical review of the methods which have been described; different approaches have generally been adopted by individual groups in response to different local requirements and constraints, and they draw on the particular experience and expertise of the groups. The intention of what follows is rather to draw lessons on the range of techniques available for characterizing SDHW systems and for predicting their long-term performance.

1.1 DESCRIPTION OF SDHW SYSTEMS

Two general categories have been used to classify SDHW systems. They can be classified according to the relationship between the solar collector(s) and storage. Or they can be classified according to their ability to be combined with other energy sources (auxiliary energy sources) in order to meet the load. It is often convenient to further classify SDHW systems according to the control strategy implemented to provide protection against freezing.

A solar system may be designed to provide solar heated water directly to the load, end use, or plumbing system without the use of any other energy source other than that required for fluid transport and control functions. This particular system is seldom used amongst the Task III participating countries.

Many solar systems are designed to supply solar heated water to another separately furnished non-solar water heater which is not part of the solar system. An example would be a solar system which preheats the water supply before entering the conventional water heater.

Additionally there are many systems that have been designed to utilize both solar and non-solar energy sources. The non-solar energy source can be integrated with the principal solar storage tank, or can be provided through a separate heat exchanger or separate water heater.

Virtually all SDHW systems that have been introduced fall into one of three classifications, according to the relationship between solar collector(s) and storage.

Integral Collector-Storage System	A system which has the storage within the collector, directly exposed to the solar irradiance.
Thermosiphon System	A system which utilizes only the change in density of the heat transfer fluid in the collector relative to the storage or heat exchanger to cause circulation of fluid between the collector and storage or heat exchanger.
Forced Circulation	A system which utilizes mechanical means requiring external power to circulate the heat transfer fluid through the collector(s).

The first two classifications above are often referred to as passive systems since no external energy source is required, whereas, the third classification is referred to as an active system since some form of external energy source is required.

SDHW systems are also described by the method of freeze protection and whether there is a heat exchanger between the collector(s) and storage.

Indirect System, Closed (Sealed) System	A solar energy system whose collectors have a sealed in quantity of heat transfer fluid. Energy is transferred from the heat transfer fluid to hot water via a heat exchanger. The heat transfer fluid is often a non-freezing fluid for freeze protection.

Direct System	A solar energy system in which the fluid flowing through the collectors is the water which will eventually be drawn out of storage and used in the load.
Drain Back	A method of freeze protection for solar energy collectors in which water is drained from the collectors back into storage or a separate reservoir.
Drain Down	A method of freeze protection for solar energy collectors in which water is drained from the collectors and disposed of.
Recirculation	A method of freeze protection for solar energy collectors in which hot water from storage is intermittently circulated through the collectors.
Open (Vented)	A solar energy system in which the store is at atmospheric pressure via a vent or opening to the atmosphere. Heat transfer fluid is pumped directly from the store to the collectors.
Heat Pipe	A solar energy system in which the solar energy collected is transferred from the absorber to the store or heat exchanger using a heat pipe.
Antifreeze Fluids	Heat transfer fluids which will not freeze in cold climates, e.g., oil or mixture of ethylene glycol and water.

1.2 DESIRABLE FEATURES OF A COMMON TEST METHOD

A test method for the performance of SDHW systems can serve a number of purposes: apart from predicting the long-term thermal performance of the system or giving the relative performance at specific test conditions, it may also be used as a diagnostic tool to identify the cause of failure in the performance, and it may also be called on to give information on how the performance can be improved by modification of the system design, or how the performance will change as a result of operating the system in a different climate, with installation modifications, or with a different load or demand profile. Other requirements for a test are ease of performance and low cost, applicability to a wide range of systems and test conditions, and reliability of the test results.

As a rule, the features of a test that are desirable are not wholly compatible, and some compromise has to be found. A choice has to be made, therefore, of what priority should be given to the following possible features:

- the shortness of the duration of the test
- the applicability of the test method to different types and classifications of systems; with different collector types, internal or external heat exchangers, auxiliary heating, for example, or with pumped or thermosiphon operation
- the ability to test outdoors (preferably in situ), under natural conditions, as well as indoors, with a solar irradiance simulator or a thermal simulator
- the reproducibility of the test results - the accuracy of the test results, having regard to the uncertainties in predicting actual performance
- the fewness and non-intrusiveness of the measurements
- the test apparatus and instrumentation required, and their cost
- the ability to predict long-term performance, and the possibility of accounting for different weather conditions, mains-water temperatures, sizes of load and load profiles, variations of installation, and so on
- the ability to identify sources of malfunction in the event that the measured performance is significantly less than might be expected

It is clear that, in the methods presented in Chapter 2, distinct differences in importance are attached to each of these characteristics.

1.3 CLASSIFICATION OF TEST ENVIRONMENTS

The test environment can be a more or less controlled laboratory environment in which the test conditions in Section 1.4 can be maintained at the specified values over time. The primary impact is, of course, the solar energy. This can be supplied by natural sunlight, by a solar irradiance simulator or by a thermal energy input equivalent to the solar irradiance absorbed.

The test environment can also be an in-situ field test for which no attempt is made to control the test conditions.

1.4 CLASSIFICATION OF TEST CONDITIONS

Test conditions for a systems test include:

- load draw rate
- load draw profile

- load (energy draw or volume draw)
- sky temperature
- ambient air velocity and direction
- storage set temperature
- solar irradiance and collector orientation
- ambient temperature
- test period
- mains water temperature
- control settings

Depending on system design, the relative importance of each condition may change. For example, the system performance of a pumped recirculation system is not as sensitive to the load draw profile as it is for an ICS system.

1.5 TEST RESULTS

The end objective is to determine energy savings or the ability of the system to fulfill its intended purpose. A number of ways have been used to meet this objective, e.g.,

Solar Fraction	The fraction of the load delivered by the system which is supplied by solar energy for a given SDHW system.
Fractional Energy Savings	The fraction of energy used by a "conventional" domestic water heating system that is saved by using the SDHW system in place of or in conjunction with the existing system.
System Efficiency	The ratio of the solar energy supplied to the load to the solar irradiance incident on the collector aperture plane.
Correlation Parameters	Dimensionless or dimensional parameters which can be used to correlate solar fraction with the test conditions.

1.6 METHOD FOR PREDICTING ANNUAL PERFORMANCE

Being able to predict long term performance of SDHW systems for any solar/meteorological region using short term test results has proven to be a formidable problem. This is an area that needs considerably more research and development to meet the current needs. Computer simulation models or system performance correlation models are proving to be the preferred technique at this time.

A number of countries have established outdoor test facilities for conducting side-by-side comparative long term testing using a prescribed load common to all the systems being tested. The long term performance test data are being used to validate the system simulation models.

2.0 *TEST METHODOLOGIES*

2.1 AUSTRALIA - INDOOR TEST METHOD

2.1.1 Introduction

Three tests are to be carried out; pre-test, average day test and no solar test. The tests will satisfy twin aims; firstly to identify the maximum amount of hot water that the system can produce, the "capacity", under the most adverse weather conditions and secondly to provide enough data to describe the systems performance under some range of average conditions. The characteristics of interest are the amount of supplementary energy used and the temperature of the hot water produced.

The pre-test identifies how much solar energy will be collected under peak summer weather conditions with no supplementary heating. For off-peak supplementary heated systems, the average weather test load is designed to run the system at its capacity, the solar energy input plus the maximum stored energy from the supplementary heating of the night before. A similar load is arbitrarily set for continuous supplementary heated systems. The no solar test load for off-peak systems is set at the estimated capacity; the maximum supplementary heated storage. For continuous systems this test load may be limited by the recovery rate under supplementary heated volume. However the load is limited to 2.5 times the average weather load.

2.1.2 Test Details

The test conditions are set out in Table 2.1.1. They are averages for the major centers across Australia. The values given above for the ambient temperature may have to be changed, depending on the design of the solar simulator and the chamber housing the hot water system. The temperatures assume that the simulator is located in a chamber where the effective environmental temperature is the same as ambient.

There are four radiation profiles given in the standard, each applicable to different types of collector and solar simulators. Table 2.1.2 gives their characteristics and applicability. Some of the profiles require varying the radiation intensity or angle of incidence. Profiles 2 and 4 are modified to take into account angle of incidence effects on single cover collectors.

2.1.3 Tests

The pre-test is used to establish what load demands are placed on the system during the average day and no solar tests. The pre-test establishes the solar capacity, with no supplementary heating, C_0. Solar capacity is obtained by measuring the total quantity of energy in the water above 30°C after two days of irradiation at 30 MJ/m^2, one of which is used for preconditioning the storage tank at the end of which the tank is drained. The draw-off in this procedure is stopped once the outlet water temperature reaches 30°C or the total volume of the system, V_T, has been withdrawn, which ever occurs first.

For the average day and no solar tests the load demand is divided into twelve draw-offs: 0.075, 0.075, 0.075, 0.075, 0.05, 0.05, 0.05, 0.05, 0.125, 0.125, 0.125, and 0.125 of the load is taken at 0800, 0830, 0900, 0930, 1000, 1100, 1300, 1400, 1600, 1700, 1800 and 1900 h respectively.

The total load demand is found by adding to 2/3 C_0 the energy which can be supplied by the supplementary power source. The value of two-thirds of C_0 used for the load demand is the expected supply from the solar part of the system under normal operating conditions and "average" weather conditions. The amount which can be supplied will depend on:

A. the recovery rate,
B. the supplementary heated volume, V_B, (L),
C. the time between load draw-offs,
D. whether the supplementary heating is continuous or time clock controlled, e.g., off-peak electricity,
E. thermostat setting, T_{set} (°C).

The total daily load demands are given in Table 2.1.3, where $L_{2/20}$ and $L_{2/10}$ are the supplementary supplied loads from 20°C and 10°C to 60°C respectively, with a 10 percent heat loss from the tank taken into account. A delivery temperature of 60°C was arbitrarily assumed for the calculation of capacities.

$$L_{2/20} = 0.153\ V_B\ \text{MJ}$$

and

$$L_{2/10} = 0.191\ V_B\ \text{MJ}$$

The second load option in the continuous no solar case of Table 2.1.3, ensures that the quantity of energy in the supplementary heated volume is adequate to meet the second and subsequent 12.5 percent draw-off. This is irrespective of whether there is an evening or morning peak demand.

If the specifications given by the manufacturer are not met in the preliminary evaluation, the manufacturer shall be consulted and the specifications amended where necessary.

From the hot water usage data available, the peak winter demand has been set at two and a half times the average day demand. If the system presented for test cannot meet this peak winter demand because of limitations on the supplementary heated volume or the recovery rate then the manufacturer shall be consulted. The manufacturer has the option of choosing under the standard to elect to use the two and a half times average day demand with consequently lower hot water temperature or even the possibility of the system failing to meet the demand by running out of warm water. Alternatively he can opt for one of the other demand strategies which will ensure that his system will always give Class A hot water, that is, always delivered water above 57°C. (Note, when further data become available on hot water usage patterns with solar hot water systems, it may be necessary to revise downwards the factor of 2.5).

The average day and no solar tests are each run for a minimum of four days, during which the required load demands are withdrawn. If at the end of the fourth day the supplementary energy and the temperature distribution of the water in each load demand are the same, within the limits of the experimental accuracy, the tests are stopped. If not the tests continue for a fifth day.

If the heat meter and supplementary energy meters readings for the third and fifth day or the fourth and fifth day are the same, again within the accuracy of the instrumentation, the system performance is found by averaging the results from the fourth and fifth days. In those cases where the fifth day's results differ from those of both the third and fourth day, the system performance is found by averaging the results from the third, fourth and fifth days.

The energy drawn off at each load is binned into three categories:

(i) $E_1 > 57°C$
(ii) $45°C > E_2 > 57°C$
(iii) $E_3 < 45°C$

2.1.4 Presentation of Results

The following quantities are derived from the test:

Supplementary energy source : e.g., Gas/electricity/ continuous/ off-peak
Supplementary energy source rating : B (kW)
Collector aperture area : A (m^2)
Storage tank volume : V_T (L)
Storage tank supplementary heated volume : V_B (L)

PRE-TEST: Energy delivered

(1) above 30°C : C_0 (MJ/d)
(2) above 45°C : *(MJ/d)

System efficiency : $\frac{C_o}{30A} = \eta_o$
Useable warm water : $\frac{(2)}{C_o} = W_o$

The tests will give the final table of results shown in Table 2.1.4, from which a minimum number of specific quantities will be selected for inclusion on the nameplate.

2.1.5 Advantages

(i) Results can be used to find out how the system that has been tested will perform under other conditions.

Morrison (1983) has shown that a system's thermal performance can be correlated by the following expression:

$$f = a_1 \frac{\overline{G}A}{L} + a_2 \left(\frac{\overline{G}A}{L}\right)^2 + b \frac{\overline{T}_w - \overline{T}_a}{L}$$

Substituting the results from the three tests gives three equations from which the unknowns a_1, a_2 and b can be found.

$$b = \frac{L_2 - B_2}{T_{w_2} - 10}$$

$$a_1 = \frac{C_o - \left(\frac{30}{19}\right)^2 \frac{L_i^*}{C_o}\left(L_i^* - B_1\right) - b\left[\left(T_{w_o} - 20\right) - \left(\frac{30}{19}\right)^2 \frac{L_i^*}{C_o}\left(T_{w_i} - 20\right)\right]}{30A\left(1 - \frac{30}{19}\frac{L_o^*}{C_o}\right)}$$

$$a_2 = \frac{C_o - \frac{30}{19}\left(L_i^* - B_1\right) - b\left[\left(T_{w_o} - 20\right) - \frac{30}{19}\left(T_{w_i} - 20\right)\right]}{30A^2\left(\frac{30}{C_o} - \frac{19}{L_i^*}\right)}$$

Note: As can be seen from Section 2.11 on the outdoor standard we are now having second thoughts about this expression. Having had a look through all the expressions being used by the various groups in Task III, the expression to be used might in fact be of the form;

$$f = \frac{1 + a\,G/L + b\,\Delta T/L}{1 + a\,G/L + c\,\Delta T/L}$$

Previous investigation of system properties by computer simulation (James and Proctor, 1983) indicated that supplementary energy consumption varies linearly with respect to both load and radiation. Since the position of the test points for an off-peak system are not colinear and surround the region of average use, interpolation from the test points into this region is expected to give accurate results. The test points for continuous systems are however nearly colinear. Care should be used when extrapolating to conditions of low load and low radiation or high load and high radiation.

(ii) The test conditions are controlled resulting in a repeatability of better than 0.5%.

2.1.6 Disadvantages

(i) Test sequence requires up to 5 days to be carried out.

(ii) Accuracy is only 4%.

2.1.7 Limits

The test is applicable to any system that can fit in under the solar simulator except those with integral storage/absorbers. Since these types are generally very poor thermally they do not constitute a real limit.

2.1.8 References

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Table 2.1.1
Test Conditions

	Pre-test	Average Day Test	No Solar Test
Irradiation on plane of collector G_1, MJ/(m^2 day^1)	30	19	0
Ambient Temperature °C	20 ± 2	20 ± 2	10 ± 2
Wind Speed m/s	3.0 ± 0.5	3.0 ± 0.5	3.3 ± 0.5
Collector Slope	30°	30°	30°
Cold Water Supply Temperature °C	30 ± 1	20 ± 1	10 ± 1

Table 2.1.2
Irradiation Profiles

	PROFILE 1	2	3	4
PROFILE CHARACTERISTICS				
Parabolic (Varying Intensity)			No	No
Square Wave (Constant Intensity)	No	No		
Angle of incidence to be varied		No	No	No
Intensity corrected for angle of incidence effects	No		No	
APPLICABILITY TO COLLECTOR TYPES				
Tracking concentrator	No	No		No
Evacuated tubular+ and other types not listed		No	No	No
Flat plate with ordinary planar glass or acrylic*			No	
Flat plate with anti-reflection coated planar cover*		No		No

+ For both diffuse and specular rear reflectors
* With or without convection suppression devices. Covers slightly domed outwards can be considered as being planar.

Table 2.1.3
Schedule for Setting Daily Load

	Supplementary Supply Continuous	Night Rate "Off-Peak"
Average Day	$L_1 + L_{2/15}$	$L_1 + L_{2/15}$
No Solar	$2.5\,(L_1 + L_{2/15})$	$L_{2/10}$

OR

$$8L_{2/10} \bullet \frac{(T_{set} - 10)}{50}$$

$$\frac{100.7\,(T_{set} - 10)}{4.8 + \frac{4609}{B\eta_B} \bullet (T_{set} - 10)}$$

whichever is least

Table 2.1.4
Table of Test Results

			AVERAGE TEST	NO SOLAR TEST
(3)	Supplementary energy requirements with solar	MJ/d	*B_1	not required
(4)	E_1 delivery	J/d	*	*
(5)	E_2 delivery	MJ/d	*	*
(6)	E_3 delivery	MJ/d	*	*
(7)	Total delivery	MJ/d	(4)+(5)+(6)	(4)+(5)+(6)
(8)	Demand	MJ/d	2/3 (1)+$L_{2/15}$	as per Table 2.1.3
(9)	Supplementary energy requirements with no solar	MJ/d	not required	B_2
(10)	System efficiency	MJ/d	$\frac{(4) + (5)}{(3) + 19A} = \eta_1$	$\frac{(4) + (5)}{(9)} = \eta_2$
(11)	Capacity	MJ/d	$(4) + (5) = C_1$	$(4) + (5) = C_2$
(12)	Solar fraction		$\frac{(8) - (3)}{(8)} = f$	$\frac{(8) - (9)}{(8)} = f_2$

		AVERAGE TEST	NO SOLAR TEST
Hot water:	$\frac{E_1}{\text{Total demand}}$	$\frac{(4)}{(8)} = H_1$	$\frac{(4)}{(8)} = H^2$
Usable hot/warm: water	$\frac{E_1 + E_2}{\text{Total demand}}$	$\frac{(4) + (5)}{(8)} = W_1$	$\frac{(4) + (5)}{(8)} = W_2$

	Capacity MJ $d=^1$	Efficiency	CLASS A Fract.	CLASS B Fract.	Supple. MJ $d=^1$
SOLAR ONLY	C_o	η_o	–	W_o	--
AVERAGE ONLY	C_1	η_1	H_1	W_1	B_1
NO SOLAR	C_2	η_2	H_2	W_2	B_2
Collector	A				
Volume total/boosted	V_T/V_B				

2.2 AUSTRALIA - OUTDOOR TEST METHOD

2.2.1 Introduction

This procedure sets out a method of determining the performance of a solar water heating system under natural outdoor conditions and prescribes a method of transforming the test results from the particular ambient/irradiation conditions of the test to long term average conditions for the test site or for other locations with similar irradiation conditions. The test is based on continuous operation of the solar system until a range of defined test conditions is experienced. Depending upon the time at which the tests are commenced and the weather at the test site, the test period will range from three to six months.

2.2.2 Data Correlation Scheme

The performance of solar water heaters is expressed by the following equation

$$f = (a+b(T_d-T_a)/L)(G/L) + c(T_d-T_a)/L \qquad (2.2.1)$$

where

f = solar contribution to load
= (L-A)/L
L = daily load
G = total irradiation on the aperture of the collectors
T_d = daily average bulk mean delivery temperature
T_d = daily average ambient temperature

The primary factor G/L is used to select a range of stable test points which are averaged over ten day periods. The tests are continued until the following range of operating conditions are observed:

Table 2.2.1
Test Data Selection Criteria

G/L	Minimum number of data points
1.5	5
1.5 to 2.0	5
2.0 to 2.5	5
2.5 to 3.0	5
3.0	5

To avoid selecting data from periods when there is a significant change of internal energy in the tank, the following conditions must be satisfied for each ten day test period:

A. irradiation (G) on the day before the test period must be within 5 MJ of irradiation on the last day
B. daily loads applied every day of the period
C. system operated for two days before the test period (constant load each day)
D. f less than 1.0 every day of the test period to avoid large energy carryover from day to day

This correlation is used to compute performance under long term average conditions for the location of interest.

2.2.3 Test Details

The solar system is installed outdoors on a roof facing towards the equator and the system is operated with a daily energy load selected by the manufacturer to represent the design application of the system (the load selection is not critical as it is varied during the test).

2.2.3.1 No Solar Test

To ensure that the auxiliary heating system can supply the selected load a no solar test must show that the system is able to supply 150 percent of the energy load with less than 5 percent of the energy delivered below 45°C. If the system fails this test a lower load must be selected and the test repeated (note: a solar capacity oriented test is being considered for defining the daily load).

2.2.3.2 Test Conditions

The tests are continued until 20 periods of ten days of consecutive operation are recorded. If selection of data is based on a sliding period of ten days this first test could be finished in a minimum of 30 days; however, the stability requirements may result in some periods being rejected. The data are divided into the G/L intervals defined above. The system is then operated for a further period with a load equal to 50 percent of the standard load until ten stable ten-day periods of operation are observed. The load is then increased to 150 percent of the standard load and the tests continued until ten more test periods are observed. If the minimum spread of data given in Table 2.2.1 is not satisfied the tests are continued (with appropriate load) until the required distribution of G/L operating conditions is obtained.

2.2.3.3 Analysis of Test Results

The 22 (or more) test points are to be correlated using Equation 2.2.1. The coefficients 'a', 'b', and 'c', are evaluated using the least squares curve fitting technique.

2.2.3.4 Presentation of Results

The system performance shall be reported in the following manner:

A. Variation of monthly solar contribution

$$f = (a+b(T_d-T_a)/L)(G/L) + c(T_d-T_a)/L$$

B. Long term average solar contribution (f).

Using the above correlations the solar contribution to load may be computed for the location of interest.

C. Long term average energy savings relative to a conventional water heater (f_R). This factor is the main figure of interest to the purchaser.

D. No solar load capacity (MJ/day)

2.2.3.5 Evaluation of Long Term Average Performance

The system characteristic (Equation 2.2.1) can be used to compute the monthly performance of the system when operating under long term average irradiation and ambient temperature conditions, or for a location with similar radiation conditions to the test site. Note: the extent to which the simple characteristic (Equation 2.2.1) can be used to compute performance at other locations is currently being evaluated using a computer simulation model. A more detailed correlation scheme incorporating a radiation utilizability factor is currently being studied.

2.2.4 Advantages

(i) The system is tested under normal operating conditions, hence there are no restrictions on the type of systems that can be tested.

(ii) The correlation model allows test data to be corrected for unseasonal conditions and operation can be evaluated for locations with similar irradiation patterns to the test site.

(iii) Testing outdoors reveals design defects that will not be obvious from indoor tests, e.g., thermostat operation responding to ambient conditions for systems mounted outdoors, tracking errors in concentrating collectors, etc.

(iv) Systems incorporating collectors with biaxial incidence optical characteristics can be tested, e.g., evacuated tube systems; these systems can only be evaluated indoors if the solar simulator is tracked to simulate the correct biaxial incidence radiation input pattern.

2.2.5 Disadvantages

(i) The tests may take up to six months to complete.

(ii) Repeatability (the accuracy is obviously less than the indoor standard - see Section 2.1).

2.2.6 Limits

Test data for uncovered collectors operating as the evaporator of a heat pump cannot be evaluated using Equation 2.2.1 because these systems operate as air source systems when there is insufficient solar input.

2.2.7 Typical Test Results

2.2.7.1 Analysis of Monthly Averaged Test Data

When this method was initially devised, the data averaging period was set at one month and the only restriction on the test conditions was that the data should span a minimum of six months from mid-summer to mid-winter. The analysis of results for 16 systems tested in Sydney Australia are given in Table 2.2.2. The performance of each system was evaluated from two or three sets of six months' test data and from a twelve month set of data.

The prediction of long term average performance in the majority of the repeated test periods was within 2 percent; however, two systems showed a maximum variation of 5 percentage points.

The major problem with monthly averaged test data is that the test period must cover mid-summer to mid-winter and the minimum test period is six months. Also, the data could be biased by extended unseasonal meteorological conditions.

2.2.7.2 Analysis of Ten-Day Averaged Test Data

The concept of a shorter test period and selection of test points over a defined range of operating conditions (G/L) was developed in order to eliminate the effect of unseasonal conditions and to avoid the need for the tests to span summer and winter.

The data correlation method outlined in this document was applied to daily records of tests of a number of systems (Table 2.2.3) and a consistent prediction of long term average performance was obtained irrespective of when the tests were started. As the load was not varied in the manner described in this report, test times of eight to nine months were sometimes required to determine the specified G/L range of data. Analysis of this method using a computer simulation program has shown that when the loads are varied test periods of only three to five months are necessary.

Table 2.2.2
Analysis of Long Term Test Results Collected by the Solar Thermal Energy Laboratory

University of New South Wales
Sydney, Australia

System Number	Collector Type	Circulation Type	Tank Config	Auxiliary Boost Time	Therm Temp	Test Period Year	Test Period Mos	Annual Solar Config	Reference To Test Data
1	Flat Plate	Thermosiphon	300 L close coupled	OP	57	1980/81	12 - 05	0.59	2
						1981	06 - 11	0.57	
						1980/81	12 - 11	0.57	
2	Flat Plate	Thermosiphon	300 L close coupled	OP	57	1980/81	12 - 05	0.56	2
						1981	06 - 11	0.51	
						1980/81	12 - 11	0.51	
3	Flat Plate	Thermosiphon	300 L close coupled	C	57	1980/81	12 - 05	0.59	2
						1981	06 - 11	0.55	
						1980/81	12 - 11	0.54	
						1980/81	01 - 06	0.55	
4	Flat Plate	Thermosiphon	300 L separate tank	OP	62	1980/81	12 - 05	0.69	2
						1981	06 - 11	0.65	
						1980/81	12 - 11	0.66	
5	Flat Plate	Thermosiphon	300 L separate tank	C	62	1980/81	12 - 05	0.64	2
						1981	06 - 11	0.65	
						1980/81	12 - 11	0.60	
6	Flat Plate	Thermosiphon	300 L close coupled	OP	62	1981/82	12 - 05	0.74	2
						1982	06 - 11	0.71	
						1981/82	12 - 11	0.71	
7	Evacuated Tubes	Pumped	250 L separate tank	C	57	1981	06 - 11	0.45	3
						1981/82	12 - 05	0.47	
						1981/82	06 - 05	0.46	
8	Evacuated Tubes	Thermosiphon	250 L separate tank	C	57	1982	06 - 11	0.64	4
						1982/83	12 - 05	0.65	
						1982/83	06 - 05	0.64	
9	Evacuated Tubes	Pumped	310 L separate tank	C	57	1982/83	12 - 05	0.74	4
						1983	06 - 11	0.74	
						1982/83	12 - 11	0.74	
10	Flat Plate	Thermosiphon	300 L close coupled	C	66	1983	07 - 12	0.48	5
						1984	01 - 06	0.50	
						1983/84	07 - 06	0.49	
11	Flat Plate	Thermosiphon	300 L close coupled	C	66	1983	07 - 12	0.51	5
						1984	01 - 06	0.55	
						1983/84	07 - 06	0.53	
12	Flat Plate	Pumped	310 L separate tank	C	59	1983	07 - 12	0.59	5
						1984	01 - 06	0.60	
						1983/84	07 - 06	0.60	
13	Flat Plate	Thermosiphon	300 L separate tank	OP	63	1983	07 - 12	0.46	5
						1984	01 - 06	0.46	
						1983/84	07 - 06	0.46	
14	Flat Plate	Pumped	310 L separate tank	C	57	1983	07 - 12	0.52	5
						1984	01 - 06	0.51	
						1983/84	07 - 06	0.52	
15	Flat Plate	Thermosiphon	300 L close coupled	C	59	1983	07 - 12	0.66	5
						1984	01 - 06	0.68	
						1983/84	07 - 06	0.67	
						1982	07 - 12	0.65	
15b	Prototype of System 15								

2.2.7.3 Comparison of Tests Performed at Different Sites

The accuracy of models for correlating data evaluated at one site and that used to predict performance at a different site has been studied using test data generated by the TRNSYS 12.1 simulation program. Test data were developed for Sydney and Melbourne Australia and the correlations used to predict the long term performance at both sites. Over a period of two years of model generated data a maximum difference of 2.5 percentage points was observed in the prediction of long term performance from the correlations developed at the two sites.

Table 2.2.3
Variation of Results for Different Test Dates

Start	Finish	Result of Transformation of Test Data to Long Term Average Energy Savings
02/01/83	09/09/83	0.641
06/02/83	15/11/83	0.645
09/03/83	06/12/83	0.642
02/05/83	06/12/83	0.638
03/06/83	06/12/83	0.634
02/07/83	06/12/83	0.635
03/08/83	13/06/84	0.635
07/09/83	13/06/84	0.636
08/10/83	13/06/84	0.635
03/11/83	13/06/84	0.619
01/12/83	13/06/84	0.647
13/01/84	07/10/84	0.645
28/02/84	17/11/84	0.649
04/03/84	17/11/84	0.645
02/04/84	17/11/84	0.652
02/05/84	17/11/84	0.658
01/06/84	17/11/84	0.638
03/07/84	17/11/84	0.635

2.2.8 References

Morrison, G.L..(1982), 'Evaluation of the Performance of Solar Hot Water Systems', Proceedings ISES (ANZ) Annual Conference, Brisbane.

Morrison, G.L. and C.M. Sapsford (1984), 'Long Term Performance of Thermosyphon Solar Water Heaters', *Solar Energy*, vol. 30, pp. 341-350.

Morrison, G.L., N.H. Tran, D.R. McKenzie, I.C. Orley, G.L. Harding and R.E. Collins (1984), 'Long Term Performance of Evacuated Tubular Solar Water Heaters in Sydney, Australia', *Solar Energy*, vol. 32, pp. 785-791.

Morrison, G.L. (1984), 'Performance of Evacuated Tubular Solar Water Heaters', Proceedings ISES (ANZ) Annual Conference, Brisbane.

Morrison, G.L. (1984), 'Solar Hot Water Heaters 1984', School of Mechanical Engineering, University of NSW, Report No. 1984/FMT/8.

2.3 BELGIUM - MONS

2.3.1 Introduction

The method described in this section has been developed for "integral storage collectors" (also called integral collector-storage and further referred as ICS).

The aim is to characterize the thermal behavior of the ICS with a Hottel-Whillier look-alike equation. The long term performance prediction could then easily be done with a standard solar simulation computer code.

2.3.2 Methodology

2.3.2.1 Characterization of the Thermal Behavior of an ICS

The instantaneous behavior of an ICS can be expressed as

$$C \frac{dT_s}{d\tau} = KG\eta_o - U_s (T_s - T_a) - \dot{q}_u$$

where C : thermal capacity (J/Km^2)
T_s : mean storage temperature (°!)
τ : time (s)
K : incidence angle modifier
G : irradience (W/m^2)
U_s : global heat loss coefficient related to the storage temperature(W/Km^2)
T_a : ambient temperature (°C)
$\dot{q}_u$: energy drawn off per unit time (W/m^2)
η_o : optical conversion coefficient (including F' and ($\tau\alpha$))

$$\dot{q}_u = \left(p \cdot m_w \cdot c_w \cdot \Delta T\right) / A_a$$

where A_a : aperture area (m^2)
m_w : draw off flow rate (kg/s)
c_w : water specific heat (J/kg•K)
ΔT : temperature difference between the ICS outlet and inlet on the mains circuit (°C)
p : binary value 1 = draw off
0 = no draw off

The thermal behaviour prediction requires thus 4 parameters:

- thermal capacity
- optical conversion coefficient
- incidence angle modifier
- heat loss coefficient

If the water supply line is separated from the storage water, then a fifth parameter should be added to take into account the heat exchange efficiency.

2.3.2.2 Determination of the Five Parameters

Thermal Capacity In the past, we have done a lot of work on experimental determination of the thermal capacity of flat-plate collectors (Bougard, Boussemaere and Lagneau, 1978; Derrick and Gillett, 1980; Boussemaere, 1981).

For an ICS system, the water content is the main contribution to the thermal capacity (>10x flat-plate collector). It might be sufficient to calculate the ICS thermal capacity rather than to measure it experimentally.

Incidence Angle Modifier The incidence angle modifier is a function of the shape of the ICS. The product on which we worked is made out of a flat tank and is single glazed. A classical equation of a flatplate collector incidence angle modifier is suitable for such an ICS system.

Optical Conversion Factor η_o and Heat Loss Coefficient U_s These parameters are determined experimentally.

Without any draw-off and under near normal incidence, the ICS thermal performance equation becomes

$$C \frac{dT_s}{d\tau} = \eta_o G - U_s (T_s - T_s)$$

The irradiance, ambient and storage temperatures are recorded continuously. During the test period (>2hr) the storage temperature T_s should be a steadily increasing function of the time.

For finite Δt time intervals and if the assumption is made that η_o and U_s are constant, then the equation becomes

$$C \frac{\Delta T_s}{\Delta\tau} \cdot \frac{1}{\langle G \rangle} \approx \eta_0 - U_s \frac{\langle T_s - T_a \rangle}{\langle G \rangle}$$

where < > indicates average values.

For n time intervals, we obtain a set of n equations

$$y_i = \eta_o - U_s \cdot x_i \qquad i = 1 \rightarrow n$$

A data handling technique will allow us to determine the value of both parameters η_o and U_s.

The test period can be extended outside the near normal incidence condition period, by using the incidence angle modifier.

Heat Exchange Coefficient

The ICS is exposed to near steady state irradiance conditions until the storage temperature T_S reaches a reasonable level (>50C). A draw off is initiated and the inlet and outlet temperature of the domestic water line are recorded. The heat exchange coefficient k is calculated

$$k = \dot{m}_w \cdot c_w \cdot \ln \frac{T_s - T_i}{T_s - T_o}$$

2.3.3 Validation

This method has been developed on a couple of ICS prototypes. The heat loss coefficient obtained has been compared with the value measured during a cooling down test, as well as with a calculated one. A close agreement has been achieved.

2.3.4 Advantages, Disadvantages and Limitations

This method is limited to a specialty DHW system, the ICS. Since ICS systems are simplified systems, it is possible to characterize the thermal behaviour with few parameters.

2.3.4.1 Advantages

- easy to apply
- does not require a sophisticated test rig (compared to temperature control in ASHRAE 93-77
- provides the parameters needed to establish the instantaneous behavior which can be used for long term performance calculations

2.3.4.2 Disadvantages

- For northern latitude test locations, steady state irradiance conditions are a constraint, but this is also the case for traditional collector testing. Since most of the test labs have built a solar simulator, this is not a real problem.
- additional computer costs for long term prediction
- lack of field measurements over long periods to validate the method

2.3.5 Future Development

Future work will include:

- outdoor determination of the parameters using this method
- comparison between predicted and measured performance (field and lab) on ICS systems
- comparison with input/output methods - development of a simplified long term prediction tool based on this short term method
- temperature and flow dependence of the heat exchange efficiency

2.3.6 References

Bougard, Boussemaere and Lagneau (1978), 'Determination of the Thermal Capacity of CEC4 Collector By Several Methods', CRES Fac Polytechnique Mons.

Boussemaere (1981), 'Determination of the Thermal Capacity of a Flat-Plate Collector' ISES Congress, Brighton.

Bougard, et. al. (1984), 'Chauffe-Eau Solaire Domestique a Stockage Integre', First EC Conference on Solar Heating, Amsterdam.

Derrick and Gillett (1980), 'Recommendations for European Solar Collector Test Methods'.

Draft (1985), 'Directives Communes UEAtc Pour L'Agrement des Capteurs Solaires a Circulation de Liquide: Additif A Cas des Capteurs Stockeurs'.

2.4 CANADA - CANADIAN STANDARDS ASSOCIATION

2.4.1 Introduction

Testing of packaged solar domestic hot water systems (SDHW) in Canada is conducted according to CSA Standard F379.1 (CSA). Included in this document are safety requirements and tests for determining the thermal performance and durability of SDHW systems.

Thermal performance testing is conducted according to ASHRAE Standard 95-1981 (ASHRAE, 1981) with modifications that are designed to meet Canadian requirements and climatic conditions. The results of testing are intended for rating purposes and for estimating annual system performance.

2.4.2 Thermal Performance Test

For use in Canada, the ASHRAE "standard day" irradiance profile was modified according to the values given in Table 2.4.1. "Standard day" weather values were developed by investigation of the performance of 14 SDHW systems in four Canadian cities (Yuill). The four cities were Winnipeg, Manitoba (Prarie); St. John's, Newfoundland (Maritime); Toronto, Ontario (central); and Vancouver British Columbia (west coast).

During testing, hourly values of test irradiance are specified in both diffuse and direct components. The diffuse irradiation is set at a fixed value of 165 W/m^2 throughout the test "day". The direction of beam irradiation, is uniquely specified by both horizontal and vertical components of incident angle. The test collector, incident angle modifier may then be calculated as the product of the horizontal incident angle modifier and the vertical incident angle modifier as per ASHRAE (ASHRAE, 1986). For testing with a solar irradiance simulator or a thermal simulator an "equivalent direct normal irradiance" may be used.

2.4.3 Limitations and Validation

Values for annual performance may be estimated by multiplying the standard day performance by 365. Limitations arise in the fact that actual performance may differ from these values due to variations in load, irradiance levels, and ambient temperatures. However, the CSA tests do provide a means by which the consumer can compare SDHW systems and estimate performance.

A comparison of test results to monitored system performance is described in the paper by Beale (1986).

2.4.4 Future Developments

The development of a correlation equation that may be used with the results of "standard day" tests is currently underway to allow for the prediction of performance at a variety of operational and climatic conditions.

The development of accelerated tests to reduce the time and costs involved in the testing of SDHW systems is underway. In particular the shortening of the "daily cycle" through the use of shorter irradiation periods is under investigation.

2.4.5 References

ASHRAE Standard 95-1981, 'Methods of Testing to Determine the Thermal Performances of Solar Domestic Water Heating Systems', ASHRAE, 1791 Tulie Circle NE, Atlanta, GA 30329.

ASHRAE Standard 96-1986, 'Methods of Testing to Determine the Thermal Performance of Solar Collectors', ASHRAE, 1791 Tulie Circle NE, Atlanta, GA 30329.

Beale, S.B. (1986), 'Comparison of Short-Term Testing and Long Term Monitoring of Solar Domestic Hot Water Systems', ASME Solar Energy Conference, Anaheim, CA.

CSA F379.1 (1982), 'Solar Domestic Hot Water Systems, ('Liquid to Liquid Heat Transfer'), Canadian Standards Association, 178 Rexdale Boulevard, Toronto, Ontario, Canada M9W 1R3

Yuill, G.K. and P. Ramsay, 'Value of Standard Day Test of Solar DHW Systems', UNIES Ltd., Winnipeg, Manitoba, Canada.

Table 2.4.1.
Rating Conditions for Thermal Performance Test

Time* (h)	Average Ambient Temp.† (°C)	Incident Radiation‡ (kJ/m^2)	Hour Angle† (°)	Incident Angle† (°)	Withdrawal§ (L) at 10L/min		
					Size A (1 - 2 Persons)	Size B (3 - 4 Persons)	Size C (5 or More Persons)
0700	8.0	-	-	-	5	10	10
0800	5.5	870	-71.3	75.2	25	25	25
0900	6	1140	-56.3	61.9	0	5	25
1000	7	1360	-41.3	49.3	45	45	45
1100	7.5	2360	-26.3	38.1	0	5	25
1200	8	3510	-11.3	30.1	5	10	10
1300	9	2240	3.7	28.3	0	5	5
1400	9.5	1590	18.7	33.5	0	0	0
1500	10	1090	33.7	43.3	0	0	0
1600	11	1040	48.7	53.3	0	10	15
1700	11.5	-	-	-	5	25	25
1800	12.5	-	-	-	10	45	45
1900	13	-	-	-	30	25	25
2000	13	-	-	-	20	10	30
2100	13	-	-	-	0	5	10
2200	13	-	-	-	0	0	5
	TOTAL	15 220			150	225	300

* *This represents the time from the start of the test.*

† *This represents the value of temperature or angle as applicable during the period ending at the time listed. Accuracy shall be ± 2°C and ± 0.5°, respectively.*

‡ *This represents the total radiation on the collectors for the period ending at the time listed.*

§ *This represents the water withdrawn starting at the time listed. The rate of draw shall be made with an accuracy of ± 1 L/min. The total amount drawn during each test day shall be within 5 L of the total draw specified.*

Notes:

(1) Ambient air temperature at storage tank = 20 ± 2°C.

(2) Inlet water temperature = 8 ± 1°C.

(3) Collector tilt angle for test in solar simulator: 60° to horizontal.

(4) Wind conditions for test in solar simulator: 4.5 ± 0.8 m/s.

2.5 COMMISSION OF THE EUROPEAN COMMUNITIES JOINT RESEARCH CENTRE, ISPRA

2.5.1 Introduction

Domestic water heating remains one of the most promising applications of solar energy, since it is a typical low temperature and small scale application which enables the use of relatively simple technology. This increases the chances for more durable and reliable systems. Other advantages are related to the ease of installation, independent or implemented on existing water heating systems.

Even if these systems contribute to an energy saving for only a small part (10 to 15 percent) of the annual domestic thermal energy consumption, this is compensated by the fact that they substitute systems which have mostly a bad overall efficiency (for example, hot water delivered by a central heating system in summertime). This increases the chances for a commercial breakthrough.

Although all systems have a common goal of heating water, one can distinguish a large variety of designs. This variety renders even more difficult the choice the user has to make. He is missing information of the system performance, durability, and reliability in relation to his location and climate. This objective information serves not only the user, but can also be considered as a stimulus for the solar energy industry to develop high quality products.

The main goal of the research action set up at the Joint Research Centre on this subject, is to gain insight in the thermal behavior of the systems and to determine the main factors influencing the system performance, with the emphasis on an experimental approach, in the scope of the development of the test procedures for SDHW systems.

2.5.2 Guidelines of Approach

Although SDHW systems can be easily defined and described, there remain many possibilities to compose such a system, as described in Section 1.1.

A test procedure for the determination of the thermal performance of these systems should enable a comparison of all systems on a common basis. It should further recognize the specific demands of the manufacturers and users, before one can expect that the method will be largely recognized and accepted later.

The manufacturer is looking for a result which shows if his system achieves a good thermal performance, taking account of the limits of the system (namely the collector surface and characteristics, storage tank volume and heat exchanger).

On the other hand, the user expects a value for the yearly energy savings at a given location. The degree of precision to be achieved depends on the accuracy of the information on the hot water consumption behavior and the local climate. These data are inaccurate due to various reasons:

A. the consumption:

- total volume: there are large differences in hot water consumption between individuals, but measured average values (30-35 liters/person•day) are 40 percent less than the most general recognized design values (60 liters/person•day).

- distribution: also here, there are large differences between individuals. Next to different profiles over the day, also weekly cycles of the daily total load are measured.

- main temperature: the real cold water feeding temperature varies from location to location and over the year, and is not known.

B. climate:

- there are variations in the order of 10 percent of the total yearly irradiance level.

- the irradiance in the collector plane is mostly not measured. The solar radiation data available from the meteorological station are mostly referred to a horizontal plane, or have a different ground reflection coefficient. They do not consider shadows due to local obstacles. Also ambient temperature and wind data can differ.

These different demands from the user and the manufacturer can be handled if the problem is split up in two phases:

- a system characterization: which consists of a short term test on the whole system under various reference conditions of climate and load.

- long term performance prediction: based on the system parameters (determined in the short term test) and climatic data, one can calculate the system performance for high and low system load conditions.

2.5.2.1 System Characterization

A SDHW system has essentially two functions: first to capture the solar radiation and heat up water, and second to store this energy over a short time (should be less than one day). It is also composed of different components, which can lead to interactions which are not expected or which are difficult to describe (i.e., thermosiphon and boiling-condensing collector systems).

The determination of the thermal performance of these systems has to include a test on the whole system, at the reference conditions and with a daily (24h) cycle. The main goal of the test is to determine the system performance in extreme conditions and to demonstrate eventual defects or shortcomings in the system.

In general, the thermal performance of a system depends on the solar irradiance, ambient temperature, wind and the system load. This last factor should be eliminated as it cannot be reduced to "normalized" values, neither the volume, the distribution over the day or the main temperature. The load is eliminated by testing the system for extreme user conditions, leading to a system characterization by a few parameters which have a physical meaning and can be easily understood by users and manufacturers. These parameters can be used in simple calculation routines to estimate the long term performance. The four system paraemters are:

- * efficiency η_0
- ** efficiency without load
- *** tank stratification coefficient
- **** storage and heat loss coefficient

The first two parameters are considered on a daily basis, and with making reference to a collector aperture area.

* The first parameter "efficiency η_0" represents an upper limit of the thermal performance of the system, and summarizes in one value the optical properties of the system, including following factors or defects:

- collector incident angle effect (in case of use of reflector or concentrators, shadow, ...
- threshold value for the irradiance to start a boiling-condensing collector or a thermosiphon system.
- decrease of collector performance in a thermosiphon system due to low flowrates and fin-effects.
- bad functioning of the solar loop controller or wrong placement of the sensors.

The test is performed over one day and the system is exposed to a specified test solar day. A small continuous consumption (about 100 1/hr), with the cold water feeding temperature equal to the average daily ambient temperature, is simulated. The solar irradiance energy and the system energy output are measured and integrated over the day. The ratio of the net energy output to the total irradiation gives the "efficiency η_0" value. The experiment can be repeated for different daily irradiance levels, giving a plot of the "efficiency η_0" as a function of the daily irradiance.

** The second parameter "efficiency without load" is determined with the system exposed to the same solar conditions as for the first parameter. The test is started with the storage tank at 5 degrees below the ambient temperature and there is no draw-off during the day. At the end of the day all sensible heat available in the system is taken out and replaced by cold water until the difference between the inlet and outlet temperature is within a given limit. The ratio of the energy output to the total irradiation gives the "efficiency without load" value. This represents the worst operating conditions of a system, although still realistic.

These two parameters are expressed as an efficiency, as it eases an evaluation of the system. For commercial reasons and for cases where a reference aperture area is difficult to define, one can express the performance in units of energy (MJ or KWh per day). Figures 2.5.1 and 2.5.2 give a graphical representation of these parameters.

*** The third parameter "stratification coefficient" represents the quality of the delivered thermal heat (determined in the second parameter). It should reflect the part of the energy delivered at high temperatures. The following formula is only a proposal and gives the ratio of the energy delivered at high temperature to the total heat delivered:

$$\frac{\text{Daily energy output above (Tamb. average +25 degrees)}}{\text{Total daily energy output}}$$

(for reference weather conditions)

**** The fourth parameter "tank heat loss coefficient" represent the tank heat losses which are expected overnight. The test is performed indoors. The storage tank is heated uniformly to 70°C. After 12 to 24 hours, the water in the tank is recirculated to realize a uniform temperature. The heat loss coefficient is calculated from the measured data. In case the storage tank has no prevention for reverse flow in the collector loop or in case the storage tank is installed outdoors, a radiative shield, at a temperature of 20 degrees below the ambient, is added in front of the collectors.

These four parameters represent the system performance in extreme user conditions, although they are still realistic. A test procedure which takes four days will be sufficient to characterize whatever system and to show eventual defects. The procedure consists of the determination of the "efficiency η_0" and "efficiency without load" for two values of the daily total irradiance energy. Values of 20 and 10 MJ/m^2•day, with 12 hours of sunshine, are representative, but it is essential to include variable and low irradiance levels (200-300 W/m^2) in the daily pattern. The highest value can have a sinusoidal profile for the solar irradiance with a decrease to 250 W/m^2 for 1 hour, from 12 a.m. to 1 p.m. The solar irradiance pattern of the low energy day should be more fluctuant. The validity and accuracy of this approach will be further investigated.

2.5.2.2 Long Term Energy Saving

The ultimate goal is to use this test procedure to quantify the energy savings of a solar water heater at a given location. To achieve this goal, one has to use the climatic data of that location and information of the consumption pattern of the user, although here remains the problem of the unpredictable behavior of the user, as mentioned before. This means that a long term performance prediction remains only valid for specified user conditions. A simple calculation method, based on the measured system parameters and climatic data in a reduced form, will give a good approximation and enables one to consider different user conditions.

The method is basically a graphical method and makes use of average yearly reference data, which are classified according to their daily irradiance values, for the whole range from cloudy to clear days, with a step of 1 MJ/m^2•day. Figure 2.5.3 shows the results for Ispra, Brussels and Hamburg. The difference in climate between the locations comes out as a difference in the number of days with high irradiance levels (20 MJ/m^2•day). A combination of these climatic data and the test results, presented in Figure 2.5.1 and 2.5.2 give a prediction of the long term performance at different locations.

The method using a dynamic computer model of the system and hourly weather data is not retained for various reasons:

- some physical phenomena are difficult to integrate in a model; i.e., thermosiphon systems and boiling-condensing collector systems.
- it requires a large effort to set up the model, is costly to run and will not be accepted by manufacturers and users.
- the physical behavior of the system has a time constant of one to two days. Long term (yearly) performance calculations with such model means that the same physical processes in the system are calculated many times for slightly different ambient temperature conditions (in contrast with the use of a detailed model to calculate the yearly performance of a seasonal storage facility).

A detailed computer model is still useful for design features, to investigate the impact of system modifications on the daily performance.

2.5.3 Advantages - Limitations

The advantages of this methodology are multiple:

- The method can be applied to all SDHW system types.
- The test method does not require a 'reference' draw-off profile. This point is of extreme importance for the manufacturer, as he retains the liberty to design a system to what he expects is the behavior of the user and is not obliged to meet certain load conditions, which are arbitrarily determined.
- The procedure requires only 4 days of testing in specified solar conditions.
- The procedure is not limited to indoor testing. Outdoor testing is allowed, although this will result in a longer testing period.
- The methodology comes up to the expectations of the users and the manufacturers.

Some disadvantages of the method are:

- The method is limited to single family systems.
- The method does not allow changes in the system without retesting; i.e., a larger collector surface.

2.5.4 Future Work

The research program at the Joint Research Centre - Ispra intends to validate this methodology and to investigate the experimental limitations. The experiments are going on for two years now, and consisted in a first phase of outdoor long term performance measurements on four commercial forced circulation systems in controlled load conditions.

The program was extended recently to include also new SDHW system types. Six commercial systems (thermosiphon systems and integrated collector storages) are added and are yet in operation.

In the mean time, measurements are carried out on a second sample of each of the systems in the solar simulator LS-1. Results obtained so far are available and are published. Pictures of the test facility are given in Figures 2.5.4-2.5.7.

2.5.5 References

Gilliaert, D., C. Roumengous and P. Tebaldi (1985), 'Analysis of Long Term Performance Measurements on SDHW Systems, In the Scope of the Development of Test Standards for European Climates', INTERSOL Conference, Montreal.

Gilliaert, D., C. Roumengous and P. Tebaldi (1983), 'Domestic Hot Water Testing at the Joint Research Centre of the European Communities, ISPRA', IEA Task III meeting.

Gilliaert, D., H. Hettinger, P. Rau, C. Roumengous and P. Tebaldi (1984), 'Investigation of Indoor and Outdoor Performance Measurements on Solar Domestic Hot Water System', First EC Conference on Solar Heating, Amsterdam.

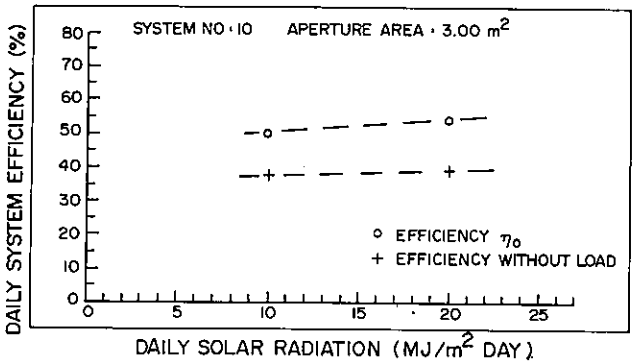


Figure 2.5.1. Two system parameters presented as an efficiency.

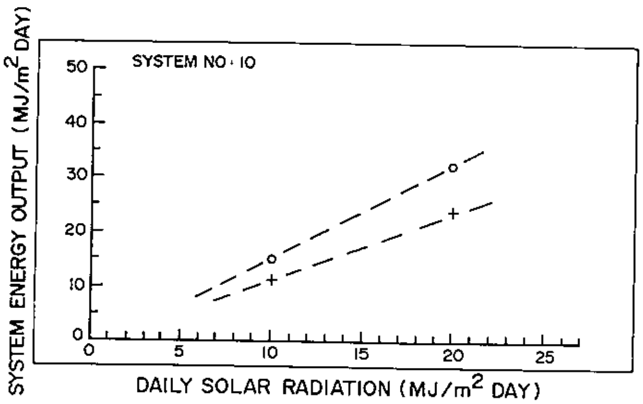


Figure 2.5.2. Two system parameters presented in units of energy.

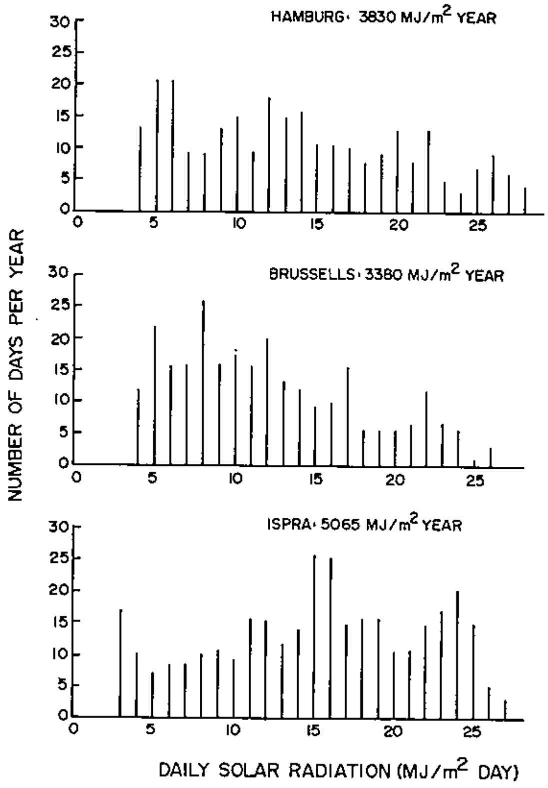


Figure 2.5.3. Climatic data for Ispra, Brussels and Hamburg

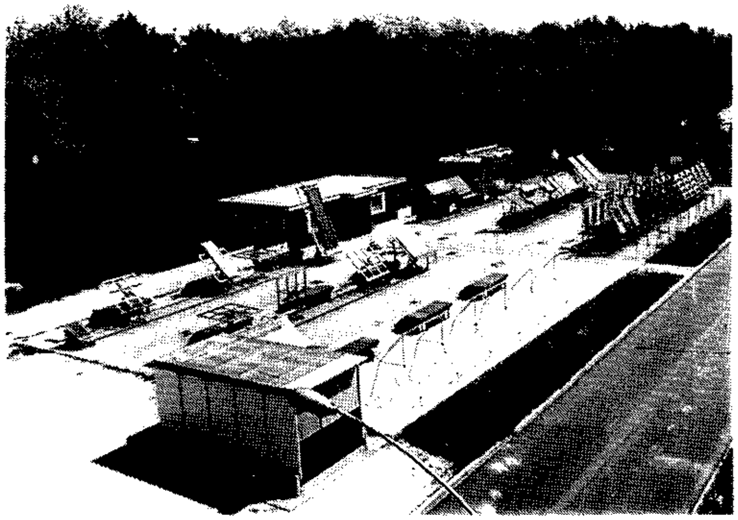


Figure 2.5.4. J.R.C. outdoor test field: general view.

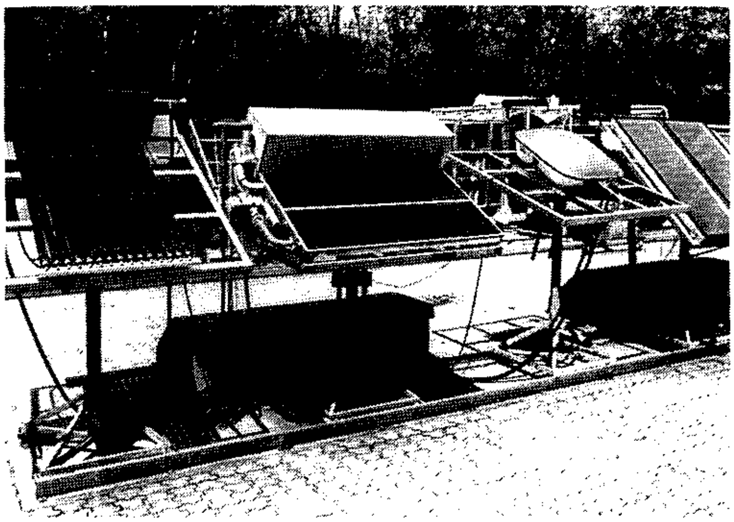


Figure 2.5.6. J.R.C. test field: two integrated collector storages and one thermosiphon system under test.

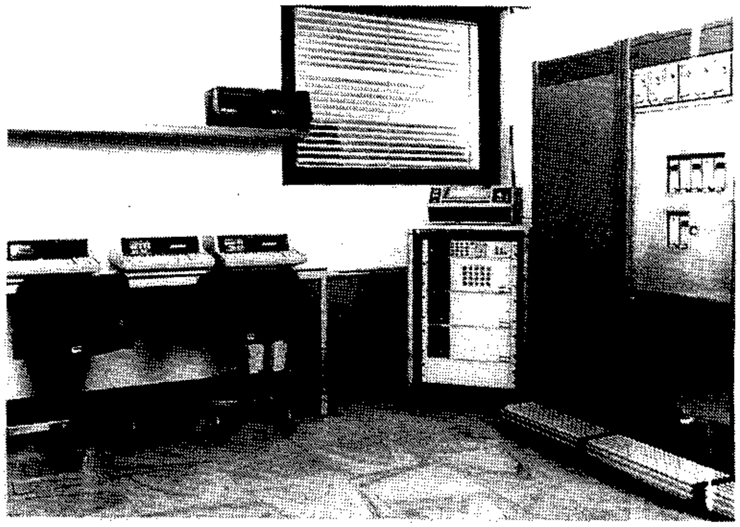


Figure 2.5.5. J.R.C. outdoor test field: data acquisition system for collector efficiency test, DHW monitoring and meteorological data.

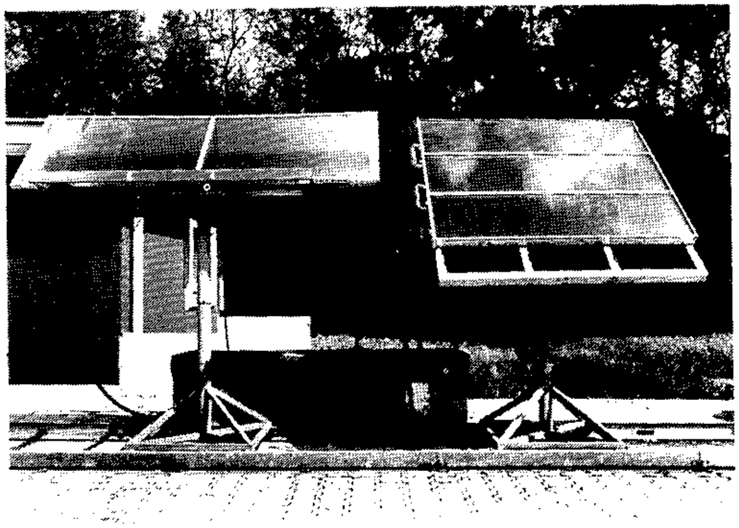


Figure 2.5.7. J.R.C. outdoor test field: one integrated collector storage and one forced circulation system under test.

2.6 DENMARK

2.6.1 Introduction

On the basis of standardized tests of solar collectors, heat storages and control systems, calculations of the performance of solar water heating systems for domestic hot water supply are carried out (Nielsen and Ravn, 1985). To check the installation, a test of one system configuration is performed. The results are:

- objective and comparable test reports for the most important components
- models for the thermal behaviour of the heat storages
- annual output of the system for different loads, system sizes and collector orientations
- suggestion for improvements of the system

2.6.2 Testing of Solar Collectors

2.6.2.1 The Test Facility

The solar simulator consists of 36 CSI lamps manufactured by THORN. The lamps are placed in a frame directing the beams towards the test rig at an angle of approximately 22.5° from horizontal. The lamps are directed individually to give a suitable high and uniform irradiance.

The test rig consists of a frame, adjustable between vertical and horizontal positions. At the lower part of the frame a cross stream fan is fitted making it possible to create a uniform air flow of approximately 5 m/s over the surface of the solar collector. A fluid system is connected to the test rig making it possible to supply the solar collector with fluid at a constant temperature.

As standard, the fluid used is 50% (weight) propylene glycol. The irradiance is measured in the centers of a network consisting of 10x10 cm squares by means of a movable pyranometer. The maximum test area which can be measured is approximately 1.4 m in width and approximately 2.5 m in length.

2.6.2.2 The Test Method

First the solar collector is exposed to solar radiation in empty condition for about six hours to ensure that the solar collector is not immediately damaged by the high temperatures which may arise. Second the solar collector efficiency is determined according to the Swedish Standard (SS, 1782). This test method has been developed jointly by the National Institute for Testing in Sweden and the Technical University of Denmark. Only a brief summary is given here.

The efficiency of solar collectors is the relation between the power gained and the solar radiation on the collector. The power gained is the absorbed power minus the heat loss which is due to the solar collector being warmer than the ambient air. With a good approximation the heat loss will increase linearly with the temperature of the fluid in the solar collector. From this the following expression for the efficiency is found:

$$\eta = \eta_o - k_o(T_f - T_a)/G - k_1(T_f - T_a)^2/G$$

where

η = efficiency
η_o = efficiency at $T_f = T_a$
k_o = heat loss coefficient at $T_f = T_a$ (W/m^2°C)
k_1 = temperature coefficient of the heat loss coefficient (W/(m^2°C)^2)
T_f = mean fluid temperature (°C)
T_a = ambient temperature (°C)
G = irradiance (W/m^2)

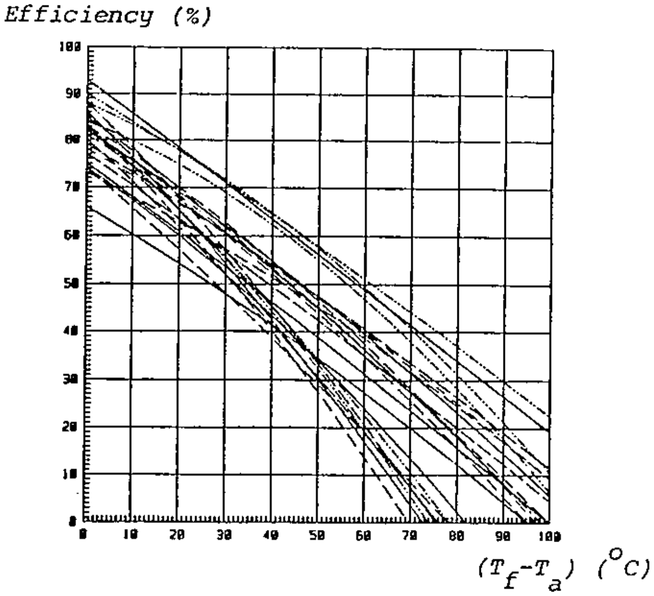


Figure 2.6.1 Solar collector test results.

The efficiency is determined at four different temperature levels of the fluid evenly spread between the ambient temperature and 100°C. Using the solar simulator giving an almost constant solar irradiance it is not necessary to correct the measured efficiency to a constant irradiance. On the basis of the corresponding values for η, $(T_f - T_a)/G$ and $(T_f - T_a)^2/G$ the values for η_o, k_o and k_1 are found by regression. As the efficiency test is carried out at a slope of

67.5° the results are normalized to 45° based on heat loss tests at different slopes.

Since 1979 a great number of solar collectors have been tested by this method. Figure 2.6.1 shows some of the test results.

2.6.3 Testing of the Thermal Characteristics of Heat Storages

2.6.3.1 The Test Facility

The test facility consists of a loop in which the solar collector fluid can be heated. The flow rate, the temperature of the solar collector entering the heat storage, and the heating power supplied to the heat storage can be controlled. Furthermore the test facility consists of a hot water tapping system in which the tapping time, the rate and the quantity can be controlled.

2.6.3.2 The Test Method

The following thermal characteristics for the heat storage are measured, according to Nielsen and Ravn (1982):

- the overall heat loss coefficient at three different temperatures during periods with the solar collector loop in operation
- the overall heat loss coefficient during a period with the solar collector out of operation
- the heat storage capacity
- the heat transfer coefficient of the heat exchanger between the solar collector fluid and the storage water at different storage water temperatures
- the temperature variations in the storage for a characteristic period of three days, in which the power from the solar collector and the water tapping are simulated (the dynamic test).

The thermal characteristics are based on temperatures, measured in different levels, inside the storage. On the basis of the static and dynamic test, mathematical models for the heat storage are set up and validated (Nielsen and Ravn, 1982). The validation is done by simulating the mentioned dynamic test using storage data and results from the static test as input parameters.

Storages have been tested using this method since 1980 and Figures 2.6.2 and 2.6.3 show some of the results.

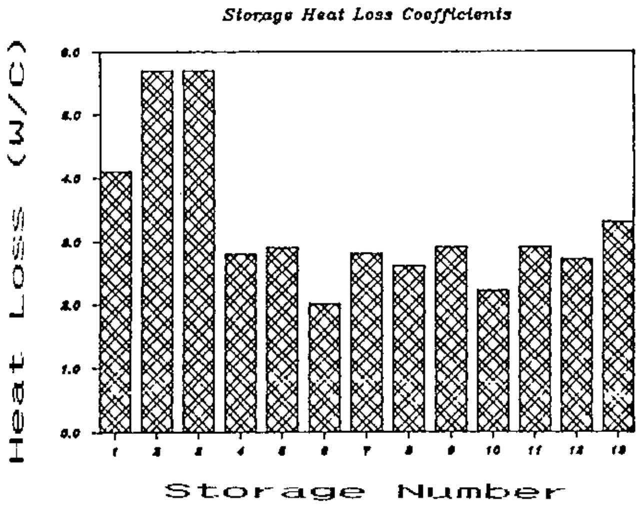


Figure 2.6.2 Storage loss coefficient.

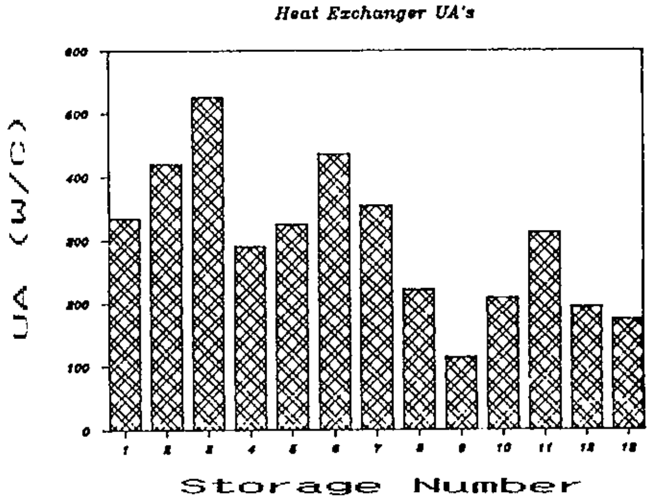


Figure 2.6.3 Heat exchanger UA (at 50°C)

2.6.4 Testing of Control Systems

For various temperature levels, it is tested if the preset start/stop difference value of the differential thermostat corresponds to the actual one. Also the accuracy of the sensors are tested at different temperature levels.

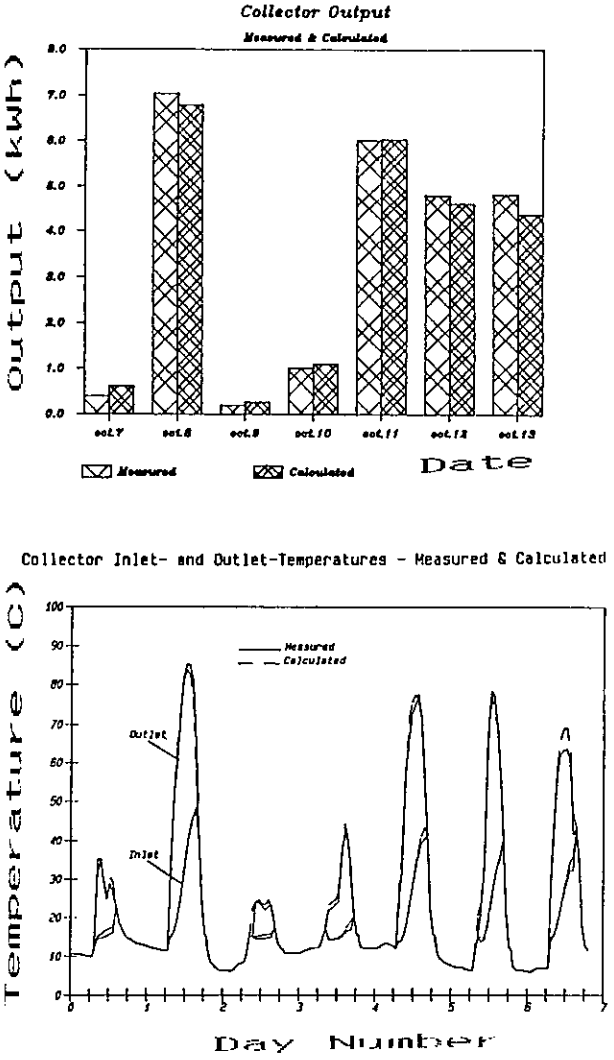


Figure 2.6.4 Examples of measured and calculated values.

2.6.5 Simulation Program for Calculation of Solar Water Heating Systems

In order to evaluate different solar water heating systems, a simulation program has been developed. Using this program one is able to compare predicted annual output of the different commercial systems.

Input to the program is test results of the components and data on system, weather and load. Data on weather (hourly values) is the Danish Test Reference Year developed by Andersen and co-workers (1982). As load data, a realistic fixed tap procedure is used.

The program is validated by measurements on one configuration of each system (installed by the dealer) in order to insure that the different mathematical models used in the program are working all right. Figure 2.6.4 shows some results from a validation. These measurements also show if the installation is done in a proper way.

The program is written in Fortran and runs on an IBM 3033 mainframe computer. In the program the solar systems are described by a number of first order nonlinear differential equations. For each timestep these equations are solved giving the temperatures in the system. The timestep varies between a few minutes and several hours depending on the dynamic behaviour of the system.

Simulation of a system for a year takes about 60 to 180 CPU-seconds, depending on the number of differen- tial equations describing the system. A detailed description of the program is given in Nielsen (1983).

Consequently, by this work one is able -- in a relatively easy way -- to support the producers and the consumers in their efforts to develop and purchase systems respectively, see Figure 2.6.5.

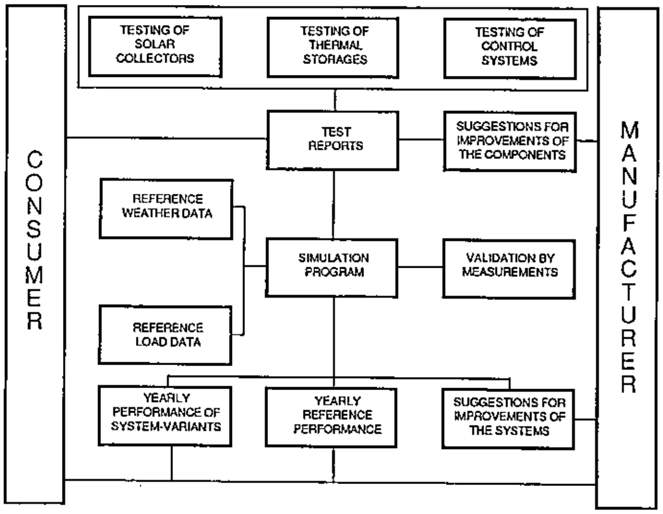


Figure 2.6.5 Information flow diagram

2.6.6 Test Results

The results of the component tests and system calculations are presented in data sheets together with a description of the component/system. Examples are shown in Figures 2.6.6-2.6.9.

2.6.7 Conclusion

Testing components and calculating performance in the way described in this paper has several advantages:

- testing the components only is easier, quicker, and cheaper than testing all system configurations. Only one configuration has to be tested to check the installation
- calculating the yearly performance is a good basis for comparing the different systems
- both the component testing and the simulation program give you a good help in developing components and systems

2.6.8 References

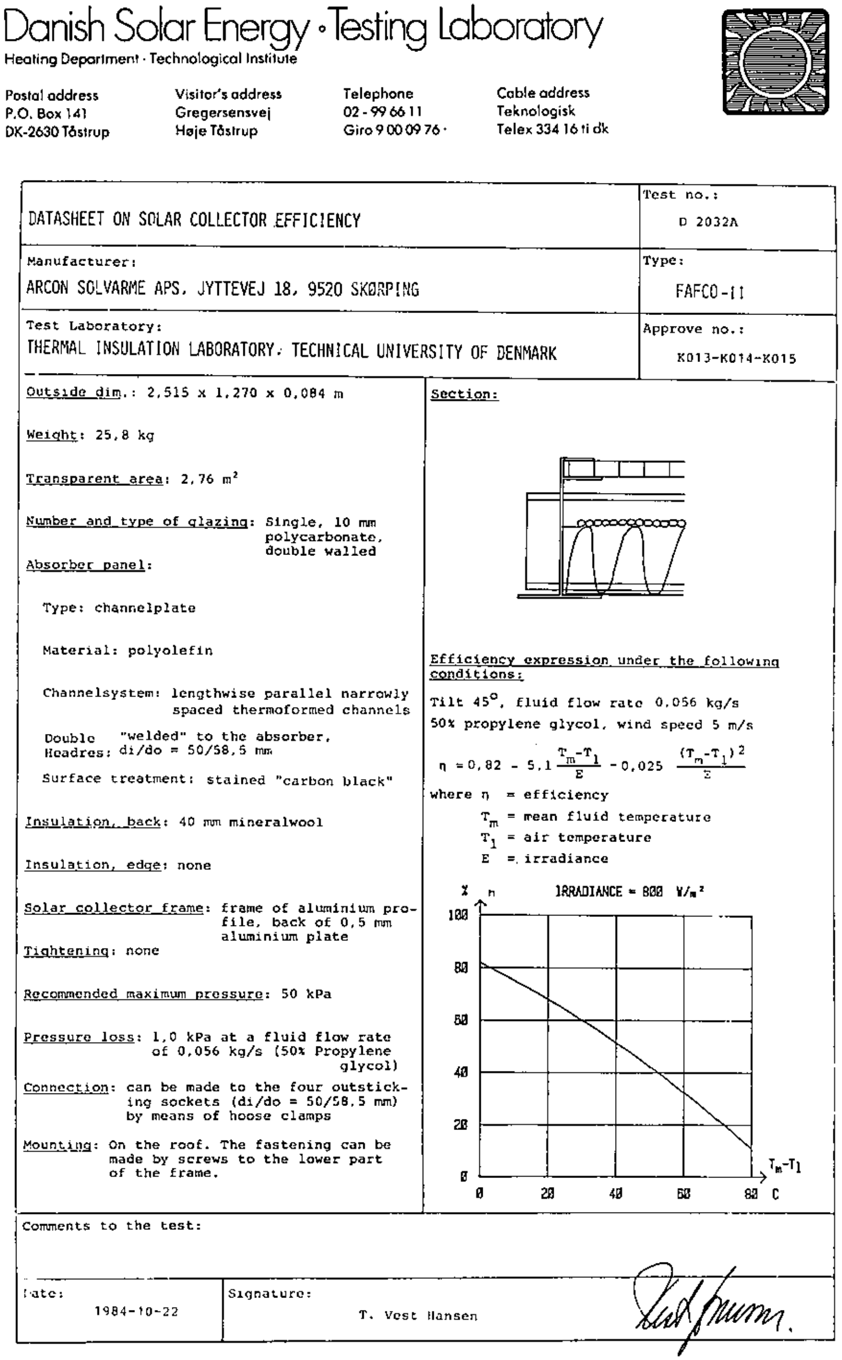
Nielsen, J.E. and O. Ravn (1985), 'Performance Testing of Domestic Hot Water and Space Heating Solar Systems'.

Swedish Standard, SS 1782. (In Swedish)

Nielsen, J.E. and O. Ravn (1982), 'Description and Validation of Mathematical Models, Simulating the Thermal Performance of Heat Storages'. (In Danish)

Andersen, B., S. Eidorff, L. Hallgreen, H. Lund, E. Pedersen, S. Rosenorn, and O. Valbjorn (1982), 'Meteorological Data for HVAC and Energy Danish Test Reference Year TRY'. (In Danish, English Summary)

Nielsen, J.E. (1983), 'Documentation of BSOL Program for Calculation of Solar Heating Systems for Hot Water Supply'. (In Danish)



Danish Solar Energy · Testing Laboratory
Heating Department · Technological Institute

Postal address
P.O. Box 141
DK-2630 Tåstrup

Visitor's address
Gregersensvej
Høje Tåstrup

Telephone
02 - 99 66 11
Giro 9 00 09 76

Cable address
Teknologisk
Telex 334 16 ti dk

DATASHEET ON SOLAR COLLECTOR EFFICIENCY	Test no.: D 2032A
Manufacturer: ARCON SOLVARME APS. JYTTEVEJ 18. 9520 SKØRPING	Type: FAFCO-II
Test Laboratory: THERMAL INSULATION LABORATORY. TECHNICAL UNIVERSITY OF DENMARK	Approve no.: K013-K014-K015

Outside dim.: 2,515 x 1,270 x 0,084 m

Weight: 25,8 kg

Transparent area: 2,76 m²

Number and type of glazing: Single, 10 mm polycarbonate, double walled

Absorber panel:

Type: channelplate

Material: polyolefin

Channelsystem: lengthwise parallel narrowly spaced thermoformed channels

Double Headres: "welded" to the absorber, di/do = 50/58,5 mm

Surface treatment: stained "carbon black"

Insulation, back: 40 mm mineralwool

Insulation, edge: none

Solar collector frame: frame of aluminium profile, back of 0,5 mm aluminium plate

Tightening: none

Recommended maximum pressure: 50 kPa

Pressure loss: 1,0 kPa at a fluid flow rate of 0,056 kg/s (50% Propylene glycol)

Connection: can be made to the four outsticking sockets (di/do = 50/58,5 mm) by means of hoose clamps

Mounting: On the roof. The fastening can be made by screws to the lower part of the frame.

Section:

Efficiency expression under the following conditions:

Tilt 45°, fluid flow rate 0,056 kg/s
50% propylene glycol, wind speed 5 m/s

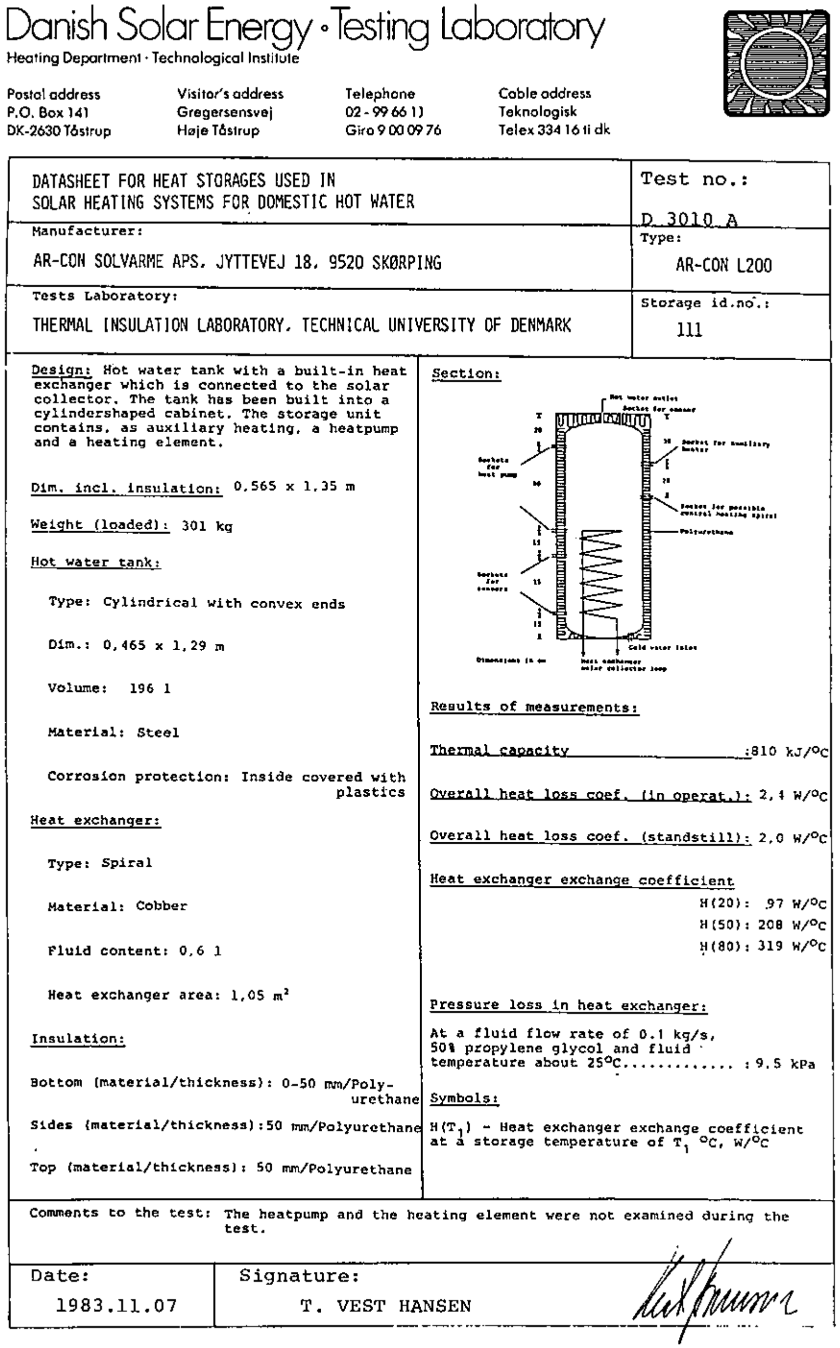
$$\eta = 0,82 - 5,1 \frac{T_m - T_1}{E} - 0,025 \frac{(T_m - T_1)^2}{E}$$

where η = efficiency
T_m = mean fluid temperature
T_1 = air temperature
E = irradiance

Comments to the test:

Date: 1984-10-22	Signature: T. Vest Hansen

Figure 2.6.6. Data Sheet for collector.



Danish Solar Energy · Testing Laboratory
Heating Department · Technological Institute

Postal address
P.O. Box 141
DK-2630 Tåstrup

Visitor's address
Gregersensvej
Høje Tåstrup

Telephone
02 - 99 66 11
Giro 9 00 09 76

Cable address
Teknologisk
Telex 334 16 ti dk

DATASHEET FOR HEAT STORAGES USED IN SOLAR HEATING SYSTEMS FOR DOMESTIC HOT WATER	Test no.: D 3010 A
Manufacturer: AR-CON SOLVARME APS. JYTTEVEJ 18. 9520 SKØRPING	Type: AR-CON L200
Tests Laboratory: THERMAL INSULATION LABORATORY. TECHNICAL UNIVERSITY OF DENMARK	Storage id.no.: 111

Design: Hot water tank with a built-in heat exchanger which is connected to the solar collector. The tank has been built into a cylindershaped cabinet. The storage unit contains, as auxiliary heating, a heatpump and a heating element.

Dim. incl. insulation: 0,565 x 1,35 m

Weight (loaded): 301 kg

Hot water tank:

Type: Cylindrical with convex ends

Dim.: 0,465 x 1,29 m

Volume: 196 l

Material: Steel

Corrosion protection: Inside covered with plastics

Heat exchanger:

Type: Spiral

Material: Cobber

Fluid content: 0,6 l

Heat exchanger area: 1,05 m²

Insulation:

Bottom (material/thickness): 0-50 mm/Polyurethane

Sides (material/thickness): 50 mm/Polyurethane

Top (material/thickness): 50 mm/Polyurethane

Section:

Results of measurements:

Thermal capacity : 810 kJ/°C

Overall heat loss coef. (in operat.): 2,4 W/°C

Overall heat loss coef. (standstill): 2,0 W/°C

Heat exchanger exchange coefficient
H(20): 97 W/°C
H(50): 208 W/°C
H(80): 319 W/°C

Pressure loss in heat exchanger:

At a fluid flow rate of 0.1 kg/s, 50% propylene glycol and fluid temperature about 25°C............ : 9.5 kPa

Symbols:

$H(T_1)$ - Heat exchanger exchange coefficient at a storage temperature of T_1 °C, W/°C

Comments to the test: The heatpump and the heating element were not examined during the test.

Date: 1983.11.07	Signature: T. VEST HANSEN

Figure 2.6.7. Data Sheet for storage.

Danish Solar Energy • Testing Laboratory
Heating Department · Technological Institute

Postal address
P.O. Box 141
DK-2630 Tåstrup

Visitor's address
Gregersensvej
Høje Tåstrup

Telephone
02 - 99 66 11
Giro 9 00 09 76

Cable address
Teknologisk
Telex 334 16 ti dk

DATASHEET ON SOLAR DOMESTIC HOT WATER SYSTEM

Test no.: D 6301 A

MANUFACTURER:
Ar-Con Solvarme ApS, Jyttevej 18, 9520 Skørping

Type: 13

The calculations are carried out using system measurements as validation basis.

Approve no.: K 013

Specifications

Collector
Manufacturer : Ar-Con
Type : Fafco-II
Test no. : D 2032
Number of units : 2
Aperture Area : 5,52 m^2

Storage
Manufacturer : Ar-Con
Type : Fønix L 200
Test no. : D 3010
Volume : 196 l
Electrical Heater: No

Control system
Manufacturer : Ar-Con
Type : TC-S3
Test no. : D 5003

Pump
Manufacturer/Type: SMC 180-40
Power : 58 W

Circulation fluid
Manufacturer/Type: BP solar collector fluid

Pipework

	Headers	In/Out
Material	-	Cupper
Dimensions	-	18/22 mm
Length	0 m	15,3 m
Insul.Mat.	-	Foam
Insul.thickn.	-	10 mm
Heat loss coef.	-	6,0 W/°C

Assumptions for the calculations

Load
Litres pr.day (10°C-45°C): 200 l/d
Corresponding to : 2920 kWh/y

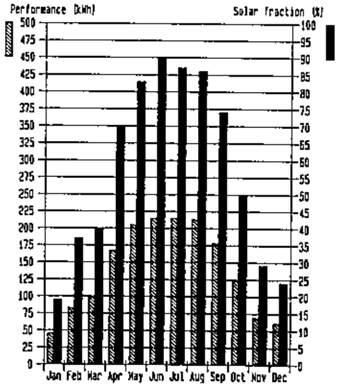
Weather data
Danish Test Reference Year
Solar radiation (45°, south): 1190 kWh/m^2

Collector orientation
Tilt : 45°
Deviation from south : 0°

Storage
Ambient temperature : 20°

Control system
Starting differential : 4°C
Stopping differential : 1,5°C

Results
Yearly performance : 1675 kWh
Yearly performance pr.m^2 coll.: 304 kWh/m^2
Solar fraction, yearly : 57% *)
Solar fraction, summer : 84%**)
Consumption of pump : 132 kWh
Consumption of elec.heater : -
Heat loss from storage : 71 kWh
Heat loss from pipes : 243 kWh



Monthly performance and solar fraction

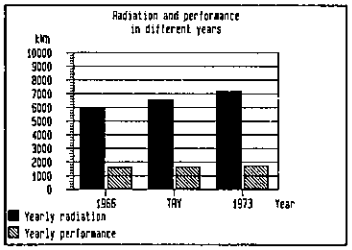
Comments: *) Solar fraction is the ratio between performance and load.
**) Summer period: 9/5-24/9 (no spaceheating demand in this period).
Performance and solar fraction for the system with elec.heater is stated on datasheet D 6303 A.

Date: 1985-10-15
Signature:
T.Vest Hanse

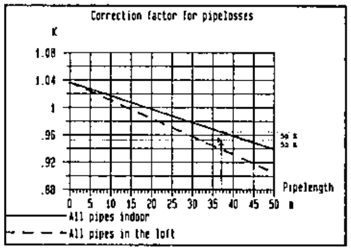
Figure 2.6.8. Data Sheet for system ("Standard Configuration.

Load l/day	Load kWh/year	1 (2.76 m²) P	S_y	S_s	2 (5.52 m²) P	S_y	S_s	3 (8.28 m²) P	S_y	S_s	
100	1460	880	60	85	1040	71	96	-	-	-	
150	2190	1130	52	76	1400	64	90	-	-	-	
200	2920	-	-	-	1680	57	84	1840	63	90	
250	3650	-	-	-	1910	52	79	2110	58	85	

Performance and solar fraction for different loads and collector areas. P: Yearly performance in kWh/y, S_y: Yearly solar fraction in %, S_s: Solar fraction in % in the summer (i.e. the period with no space heating demand, (9/5-23/9).



Performance and solar radiation in different years (1966 is the "worst" and 1973 the "best" year in the period 1959-1973).



Correction factor for different pipelengths. Performance and solar fraction is multiplied by the factor for the actual pipelength. The arrows illustrate an example using 37 m pipe, 50% indoor and 50% in the loft (unheated room).

Tilt \ Orientation	south			southsoutheast or southsouthwest			southeast or southwest			eastsoutheast or westsouthwest			east or west		
	60%	70%	80%	60%	70%	80%	60%	70%	80%	60%	70%	80%	60%	70%	80%
15°	0.87	0.86	0.85	0.86	0.85	0.85	0.84	0.84	0.84	0.81	0.81	0.80	0.77	0.76	0.76
30°	0.95	0.94	0.94	0.94	0.94	0.94	0.90	0.90	0.90	0.84	0.84	0.84	0.77	0.77	0.77
45°	1.00	1.00	1.00	0.98	0.99	0.99	0.93	0.94	0.94	0.86	0.87	0.88	0.77	0.77	0.77
60°	1.01	1.01	1.02	0.99	0.99	1.00	0.93	0.95	0.95	0.85	0.86	0.87	0.78	0.79	0.81
75°	0.97	0.98	1.00	0.95	0.96	0.99	0.90	0.93	0.95	0.82	0.84	0.86	0.72	0.74	0.78
90°	0.84	0.89	0.95	0.84	0.89	0.95	0.81	0.85	0.91	0.75	0.77	0.82	0.66	0.68	0.72

Correction factor for different orientations and tilts of the collector. S_y is the solar fraction for a solar system with a collector facing south and having a tilt of 45°. Tilt is the angle between the collector and horizontal. (Performance and solar fraction is multiplied by the factor for the actual orientation).

Figure 2.6.9 Data Sheet for system ("Other Configurations'

2.7 FEDERAL REPUBLIC OF GERMANY LUDWIG-MAXIMILANS UNIVERSITY, MUNICH

2.7.1 Introduction

A standardized test method is to be formulated for solar DHW systems allowing, after short test periods, the prediction of annual yields with adequate accuracy. The procedure should be applicable to various types of commercial systems. The values for the parameters of the system obtained by the test procedure should be the same under outdoor and indoor conditions. The method should be applicable for the investigation of installed solar systems as well. The prediction of the annual yield should be possible for arbitrary weather conditions and load profiles.

2.7.2 Definitions

All time dependent values (e.g. radiation, temperature, state of pumps, actual load) are defined as variables. Values which characterize the solar system independent of external influences are defined as parameters. Three groups of factors which are principally independent of each other determine the annual yield of a solar thermal system:

- Parameters of the solar system
- Load, e.g., in form of a load profile
- Meteorological input variables

2.7.3 Course of Action for Developing the Test Procedure

In developing a short term test method, it should be based on the physical processes in the solar system (physical method). It should separate clearly parameters of the solar system, effects of load profile, and influences of the meteorological variables. The method will be tested with data from the test campaign of TUV Bayern* (8 month test period from August 1985 to April 1986 on 18 commercial systems.)

*Technischer Uberwachungsverein Bayern is an official and independent inspection and approval institution.

2.7.4 Physical Method

2.7.4.1 Mathematical Representation of a Solar System

The method is based on a mathematical description of the behaviour of the system using linear differential equations. These equations are the basis of the evaluation program for determining the system parameters, and of the simulation program for calculating the annual yield. The scheme in Figure 2.7.1 shows the interconnection of the various steps.

For simple boundary conditions, differential equation systems with constant coefficients yield analytical solutions. The constant coefficients are derived from the parameters of the solar system. With such analytical models the performance of a solar system with a storage tank of uniform temperature (mixed storage) can be described. Our improved version of this method permits the treatment of thermally linearly stratified storage tanks (stratified storage) too. The simulation program distinguishes four operating modes (Table 2.7.1). Each operating mode is related to a different differential equation system. In non-linear processes, i.e., a change of mode, the program switches from one to another linear equation system.

A constant draw off rate with a storage temperature T_S lower than the set temperature Tset means constant flowrate through the storage. If the storage temperature is higher than the set temperature, the draw off rate from the storage is reduced and cold water is added and mixed for producing the set temperature.

2.7.4.2 Validation of the Simulation Program

Special emphasis is laid on validating the model. For that purpose the data from the tests of TUV-Bayern will be used. According to the locations of temperature and flowrate measuring points the solar systems can be divided into subsystems. The program modules related to these subsystems are submitted to separate validation procedures, i.e., at the intersections the simulated values of the variables and their time sequences are compared to the real test data (10-minute instantaneous values). Subsystems are:

- solar collector array
- heat transfer system
- heat storage tank

2.7.4.3 Sensitivity Analysis

The validated simulation model is used for performing a sensitivity analysis to the parameters and variables. Its results specify the dominating system parameters and the important measuring variables. In particular, the difference between the annual yield in systems with stratified storage and systems with mixed storage is investigated.

2.7.4.4 Development of An Experimental Test Procedure

To each operating mode a particular measuring code is applied. The measurements are undertaken with a well instrumented system. With the measured data a multilinear regression program (Stoer, 1983) is performed determining the coefficients (and their variances) of the differential equations. The steps are modified in interaction with experience gained from the test and the evaluation in such a way that the variances of the coefficients become minimal. The load profile run in the test procedure can differ from a real load profile regarding volume and time sequence. The single steps of the procedure are defined by limits of the meteorological variables and specifications for the operating parameters.

2.7.4.5 Testing the Method for Determining the Characteristic Parameters

The parameters are determined by the multilinear regression program with data taken from the TUV-test campaign. During the test campaign the components of all systems are tested separately. Comparing the values of characteristic parameters obtained in this way to those extracted from the data set permits a qualification of the multilinear regression program.

2.7.4.6 Testing the Accuracy of the Prediction of the Annual Yield

The TUV-test covers 8 months. Extrapolation to annual yields is possible with good accuracy. With measured weather data, the load profile of the TUV- test, and the characteristic parameters of the solar system, known from component tests, the annual yields are calculated using the analytical simulation model. These yields are compared to the measured annual yields.

2.7.5 Test Measurements

During the test period all sensitive variables and the temperature of the room housing the storage are recorded. It is obvious that at least the following operating parameters have to be recorded:

- flowrate in the load loop
- inlet and outlet temperature of the storage
- temperature of tapped water
- auxillary energy into the storage.

In addition to meteorological and operating data, variables have to be recorded which indicate the state of the system for identifying the operating mode. In forced circulation systems these are the control signals. In thermosiphon systems, this information is to be taken indirectly from temperature measurements.

2.7.6 Conclusions from the Investigations

The physical method should be compared to the correlation method regarding computing time, accuracy, quantity and quality of required data. For this purpose F-CHART version 4.1 (Solar Energy Laboratory, 1981) is programmed on the same computer system as the analytical model. The advantages of the analytical method are obvious. If the time sequence of the variables is constant, sinusoidal or a rational power function, the differential equation system yields an analytical solution. With simple boundary conditions a characteristic curve can be calculated directly. Arbitrary time sequences can be approximated by small time intervals. The accuracy of the calculation of the annual yield can be adjusted within the same program. The judgement on the performance of the method is based on the comparison of the results of the TUV-tests to the results gained with the well instrumented solar DHW-system. Results from the sensitivity analysis (validation of simulation of subsystems) can be used for statements on accuracy, applicability and limits of correlation methods. In particular, it can be stated to what extent results from correlation methods can be converted to situations with different load profiles and meteorological conditions.

2.7.7 State of Development of the Procedure

- The well instrumented solar system is installed and tested.

- The analytical simulation model is programmed in MODULA-2 and is working on mini-computers of the institute.

- The multilinear regression program according to Stoer (1983) was applied to dynamic test sequences. Numerical instability can occur; a more robust procedure is looked for.

- The correlation method F-CHART 4.1 with variable time base (3 to 30 days) is being programmed on an 8-bit mP-system.

- Since September 1985 the TUV-test campaign produces data sets as instantaneous values of temperatures and flowrates in 10 minute intervals. The transfer of data into the minicomputers with 9-track tapes has been successfully tested.

2.7.8 References

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Table 2.7.1
Operating Modes of Solar System

	State of Solar Loop	State of Load Loop
mode A	pump on	constant draw off rate ($T_S < T_{set}$)
mode B	pump on	constant heating load ($T_S > T_{set}$)
mode C	pump off	constant draw off rate ($T_S < T_{set}$)
mode D	pump off	constant heating load ($T_S > T_{set}$)

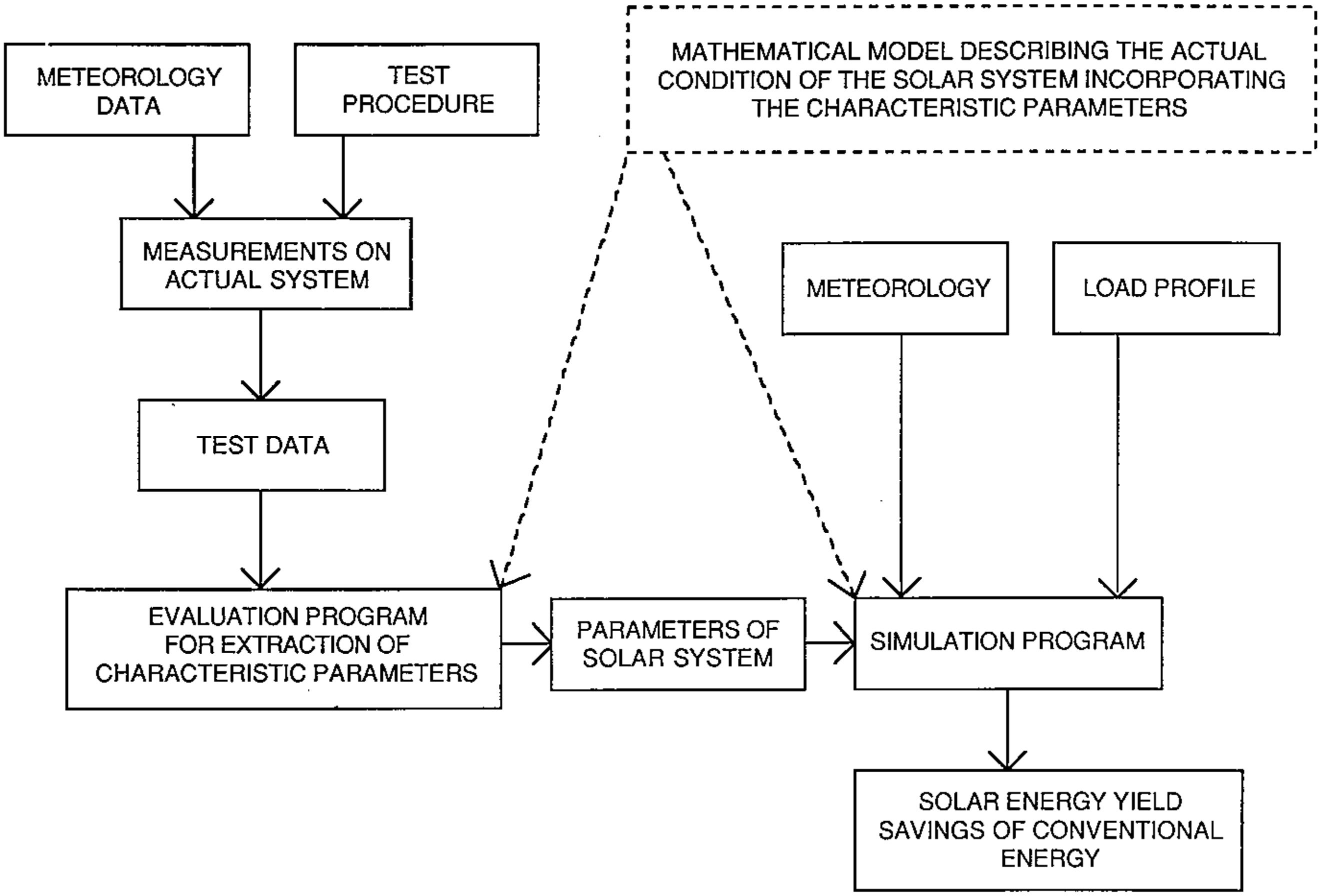

Figure 2.71. Interconnection of test procedure and simulation program

2.8 THE NETHERLANDS - TECHNISCH PHYSISCHE DIENST TNO-TH TNO INSTITUTE OF APPLIED PHYSICS

2.8.1. Introduction

The performance of solar domestic hot water systems under actual weather conditions is often less than expected. Accurate testing is needed to determine the origin of the problem. At first it must be established whether the system is fundamentally correct, then the design of the components is a matter of interest. The performance of the components is influenced by their design and by the operating conditions, so it is important to test under realistic conditions.

When a system has been operational for several years, it must be checked if it is still functioning correctly, a test of the durability of the functioning. Therefore, testing of DHW-systems at the TNO Institute of Applied Physics (TPD) will consist of a sequence of several steps:

A. Testing and characterization of new systems under actual weather conditions or under a solar irradiance simulator.

B. Check of the functioning of installed DHW-systems.

2.8.2. Indoor Tests Under the Solar Simulator

The test of a DHW-system starts with a short term test under the solar simulator, in which two steps can be discerned:

- Diagnosis
  At first, the system is checked to see if it works as designed by the manufacturer and in accordance with the installation instructions. This is meant as a "trouble-shooting" test (e.g. leakage detection). After the well-functioning of the system has been established, a test sequence is performed.

- Test Sequence
  This test consists of a fixed irradiation during several hours, followed by a period of rest of about 16 hours or more (cooling down of the storage due to heat losses) and a draw-off until the tap temperature is constant (emptying the storage).

  The irradiation and the draw-off of water are separated in time to avoid interaction. During the test, collector inlet and outlet temperatures, storage temperature(s), flows, ambient temperature and insolation level are measured.

From this test, the main characteristics of the system (collector parameters, heat loss of the storage, stratification of the storage, effectiveness of heat exchangers, etc.) are determined. The parameters are input for the TPD computer simulation model, which gives an indication for the expected output of the system.

The general form of this test will be the same for all DHW systems, but it is, of course, possible to adjust the test to a specific system. Until now the method has been used to test forced circulation systems and an experimental boiling/condensing collector system, thermosiphon system and a forced circulation system with a hot top.

2.8.3. Outdoor Tests Under Actual Weather Conditions

2.8.3.1 Interpretation Method

For the interpretation of outdoor tests under actual weather conditions for all kinds of solar energy systems (not only DHW systems) an interpretation method has been developed (van Galen, 1982).

The aim of the method is to equip solar energy researchers with a tool which enables them to carry out system tests and system development studies. The ultimate goal of this type of study is to determine and explain the performances of all system components and the resulting system performance in relation to system design and as a function of weather conditions. Therefore, the method has to establish the thermal characteristics of the solar energy system in operation.

The thermal characteristics of, e.g., a solar thermal collector conversion factor and heat loss coefficient, are determined by series of steady-state tests under well-defined conditions. The result is that the collector characteristics are given as a function of variables, describing these test conditions.

The basic idea behind the interpretation method discussed hereafter is that the thermal characteristics of a solar energy system should be established on the analogy of such a component test. This means that some kind of "steady state" must be obtained for the total system in operation, for which the conditions are well defined and known. The main problem is then to find a definition for "steady state" for solar systems.

Analogous to the commonly used collector efficiency curves the overall system efficiency curves which result from this interpretation method can be used to compare and classify different (DHW) system types.

If an appropriate weather descriptive parameter has been chosen these curves are independent of the climate.

2.8.3.2 Definition for "Steady State" for Solar Energy Systems

Apart from the design parameters, which have a constant value, independent of the system operation, there are a number of variables in the sytem, which depend on input and output conditions, such as the temperatures in the various system components and the energy flows between components.

Input and output conditions are directly related to the weather conditions.

"Steady state" for a solar energy system is supposed to be reached when all interdepending variables in the system attain to "steady state" within their own system and climate depending operating ranges.

So first of all the conditions are to be defined for which each single variable attains to this "steady state" independently to the other variables.

The conditions are made upon the cumulative average of the variable and the standard deviation of the cumulative average based on all values of the variable in the preceding period. For instance:

- Fluctuations of cumulative average values will be less than 2% of the range of possible values in the system under consideration.
- The time-dependent standard deviations will be less than 10% of the range of possible values in the sytem under consideration.

For each interdependent variable conditions are to be made. A period for which the conditions for each variable are met, i.e. "steady state" for all variables is attained, shall be called a characteristic period (see van Galen [1982]) for more detailed information).

Once a number of characteristic periods has been found, a system performance study can be carried out. Presentation of results in the form of time dependent relations between physical variables is then possible. This type of presentation has the advantage that comparisons can be made between interdependent variables independent of the way the results are obtained and therefore valid for different locations and climates.

Each of these variables is represented by the cumulative average value over the period of determination, the characteristic period and the standard deviation giving information concerning the actual values of the variable during this characteristic period.

Because the weather condition is one of the variables and performance as a function of weather conditions is one of the most interesting results of system studies, it is obvious that a weather descriptive parameter shall often be chosen as one of the variables in the relations presented.

2.8.3.3 An Example of the System Interpreting Method for a Solar Heating System

The system interpreting method has been theoretically tested for the reference system (SS1) of the European Solar pilot Test Facilities. Calculations have been done with the simulation programme EMPG. In van Galen (1982) and van Galen and den Ouden (1982) there is more detailed information about this example. A number of characteristic periods have been determined. The following efficiences are defined:

- the collector efficiency η_1 = SCG/CGR
- the efficiency of the storage system η_3 = IL/SSG
- the performance of the system, i.e. the solar contribution to the heat demand η_4 = IL/HP
- the total system efficiency η_5 = IL/CGR

in which:

CGR = <u>C</u>ollector <u>G</u>lobal <u>R</u>adiation
SCG = <u>S</u>olar <u>S</u>torage <u>G</u>ain
IL = <u>I</u>nterface <u>L</u>oss, discharged energy
HP = <u>H</u>eating <u>P</u>ower required

All these quantities are integrated over the period considered. The efficiencies are plotted as a function of a dimensionless parameter that, for a given situation (installation and house) is entirely determined by the weather conditions and the heating demand of the house, namely CGR/HP.

Figure 2.8.1 shows the collector efficiency. This efficiency is a linear function slightly decreasing for higher CGR/HP values. Figure 2.8.2 shows the storage efficiency. This plot shows a maximum near CGR/HP = 2.5.

Figure 2.8.3 shows the solar contribution.

Figure 2.8.4 gives the system efficiency.

Efficiencies of single components under working conditions can be derived by the described method, showing weak spots in the design. The functioning of the components under different climatic conditions is understood. This is a very important result to judge the economic viability of the components and to optimize their dimensions.

Analogous to collector efficiency curves, overall system efficiency curves can be used to compare different types of systems.

To predict the yearly performance of the system, for a chosen location and climate, a frequency distribution of the operating conditons (expressed as weather descriptive parameter) has to be calculated.

With this frequency distribution, the expected output can be calculated from the system efficiency curve. This method allows the user to calculate the output of a solar heating system for different locations and climates. For one location and climate different types of systems can be compared.

2.8.3.4 Domestic Hot Water Testing

In the latest report of the Dutch solar pilot test facility (Amerongen and van Galen, 1984) the system test method is used to interpret the results of the measurement at the SS2 installation. This installation consists of a collector field, a thermal storage unit and a simulated heating demand of a family house. It is shown in this report that the system test method works out well.

Further experimental and theoretical verification studies of the system test method are being carried out. For the experiments a new System Test Facility has been built which has been in operation since late 1985.

So far the test method has only been used for solar heating systems. The applicability of this test method for testing DHW systems will be studied. Experiments are planned for the second half of 1986.

It is expected that a DHW system test works out in the same manner as shown in the previous paragraph. The weather descriptive parameter will be the ratio of the collector global radiation and the heating demand for domestic hot water.

For DHW systems the so-called characteristic period is expected to be 24 hours. The expected period for testing a DHW system is about 2 months.

2.8.3.5 Check On Installed DHW Systems

After some time of operation a DHW-system should be checked on its proper functioning. The user of the system will generally not notice any bad functioning because the auxiliary heat always helps to provide enough hot water. A test sequence has been outlined that is based on the same idea as the indoor short term test described above.

The test is simulated with the computer model to investigate the effects of various parameters on the measured variables. A method is chosen for which the sytem is affected as little as possible. The chosen procedure is: at the beginning of a test day hot water is drawn off without use of auxiliary heater until the tap temperature equals the main temperature. The heat content of the water is measured. During the day no hot water must be used, so no interaction between irradiation and draw-off will occur.

The following quantities will be measured:

- irradiance G, ambient temperature, temperature of storage (if possible at several levels to register stratification), temperature of mains, temperature of drawn-off water, flow during draw off.

This will result in information about:

A. during daytime:	functioning of collector and primary circuit
B. during nighttime:	heat loss of storage
C. during draw-off :	functioning of heat exchanger (if present)

This sequence must be done during several days to obtain sufficient data. The results from the test will be compared with calculations with the simulation model for the test sequence. The inputs for this calculation are reference data either from the manufacturer or obtained from earlier measurements (e.g. under solar simulator).

This test will give an indication of problems and where they will occur. If any bad functioning is detected a more extensive monitoring will be needed to determine the actual cause of it. When some experience is gained with this test method it may be possible to extend the test also to the auxiliary heater.

2.8.4 References

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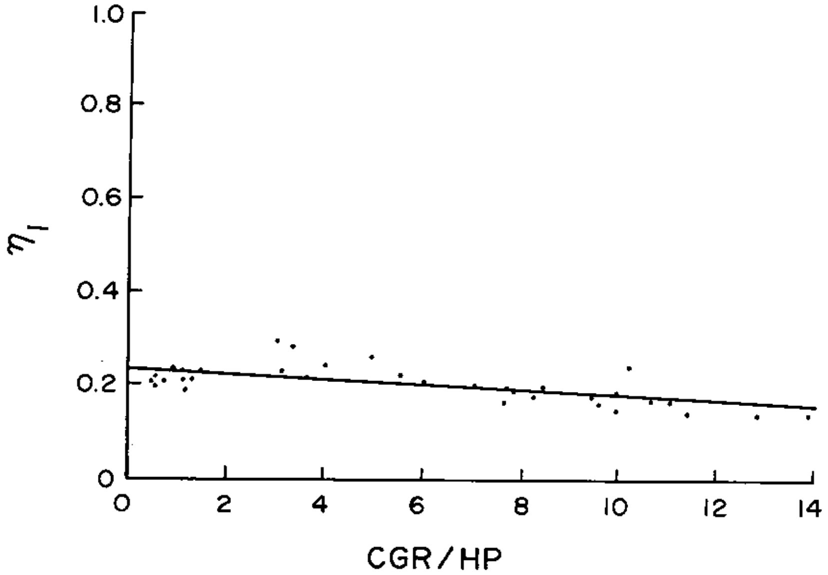

Figure 2.8.1. Collector efficiency as a function of the weather descriptive parameter.

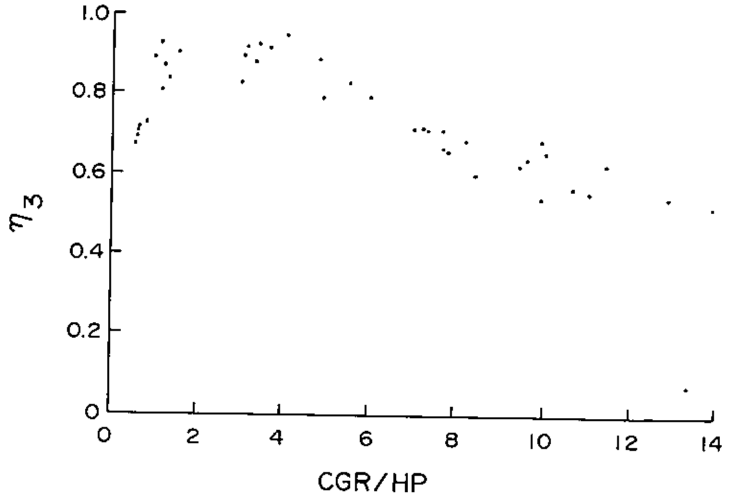

Figure 2.8.2. Storage efficiency as a function of the weather descriptive parameter.

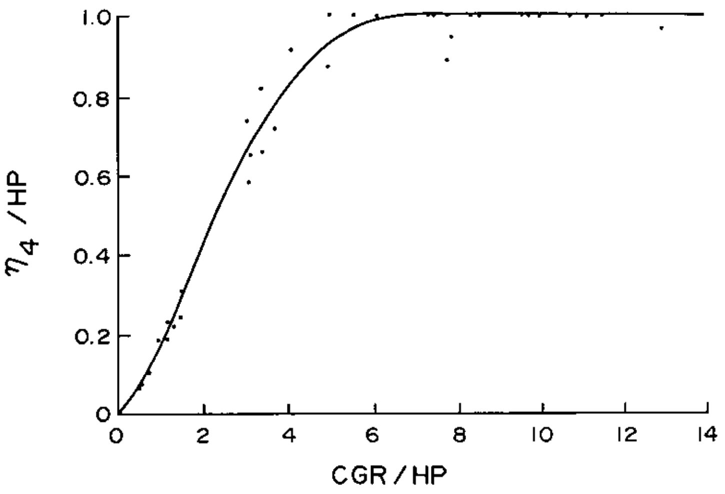

Figure 2.8.3. Solar contributions as a function of the weather descriptive parameter.

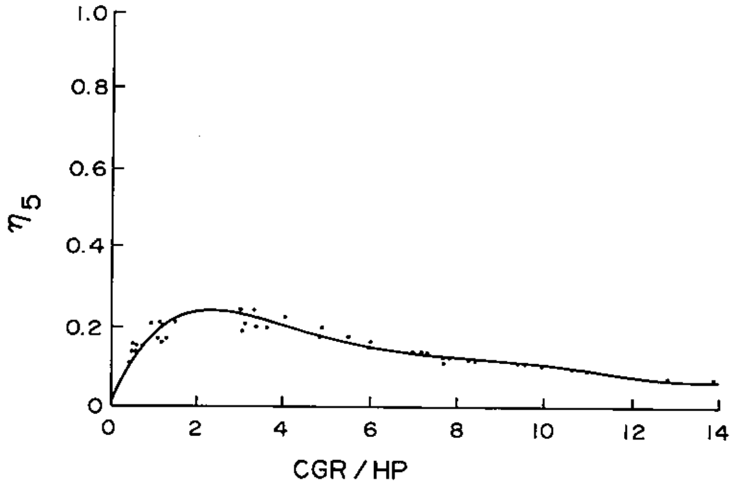

Figure 2.8.4. System efficiency as a function of the weather descriptive parameter.

2.9 SWEDEN/FRANCE

2.9.1 Introduction

This method has been developed at Centre Scientifique et Technique du Batiment at Sophia Antipolis, Valbonne, France and is now being introduced and evaluated at the National Testing Institute in Boras, Sweden.

In the method, two parts may be distinguished: one experimental procedure to determine five parameters, which are independent of the operating conditions, and one simulation model (OSOL), where input parameters are system parameters, meteorological data and domestic hot water demand, and the output is yearly performance of the system.

The method can be applied to complete systems for the production of domestic hot water. The systems may be pumped systems as well as thermosiphon systems. Even ICS systems can be tested.

2.9.2 Principles of the Method

The following five parameters are measured.

η_o	Collector conversion factor
K_o	Collector loss coefficient
η_p	Collector loop efficiency
M_s	Storage thermal mass
K_s	Storage loss coefficient

The significance of the parameters may be explained as follows. Four additional parameters are introduced.

η	Collector efficiency
A	Collector area
G	Solar irradiance
ΔT	Collector overtemperature

The collector efficiency, η, is given by

$$\eta = \eta_o - K_o \cdot \Delta T/G \qquad (2.9.1)$$

where in this case K_o is a mean value of the loss coefficient in the overtemperature range $\Delta T = 0 - 60°C$ at an irradience level of $G = 800\ W/m^2$.

If $G.A.\eta$ is the useful power from the collector then $G.A.\eta.\eta_p$ is the useful power into the storage.

The storage thermal mass, M_s, is the temperature weighted mass of hot water that can be drawn off the tank above a given temperature. Thus this mass is a measure both of the obtainable stratification in the tank and of the efficiency of the hot water draw off technique.

In applications where necessary, the quotient of the loss coefficient, K_o, to the conversion factor, η, may be used in place of the parameters themselves.

The main input parameters to the computer program are the following.

η_o	Collector conversion factor
K_o	Collector loss coefficient
K_s	Storage loss coefficient
M_s	Storage thermal mass
$A.\eta_p$	Product of collector area and solar loop efficiency.

- Collector tilt angle and azimuth
- Yearly meteorological data for the system site given as hourly data
- Domestic hot water demand given as daily profiles

The main output data are as follows:

- Solar fraction on a yearly basis
- Back up energy consumption
- Mean temperature of the DHW supplied, in order to verify that the size of the installation is sufficient.

2.9.3 Experimental Procedures

Two types of measurements are performed: loss measurements where no solar radiation is present and efficiency measurements where the solar radiation is supposed to remain constant over an extended period of time.

Collector efficiency and loss coefficient are measured using standard test procedures and are therefore not discussed here.

2.9.3.1 Loss Measurements

Loss Coefficient for the Water Storage Tank K_s. It is first ensured that no water can be circulated between the collector and the tank. The water in the tank is heated to 60°C. The temperature of the water in the tank is made constant throughout the volume by recirculation of the water. The tank is left overnight and the water is recirculated once more. The cooling of the tank is supposed to follow an exponential pattern and a loss coefficient is computed from measured data.

Loss Coefficient for the Complete System. The above procedure is followed except that the connection between the collector and the tank is open during the cooling period. This loss coefficient is compared to K_s. It is only used as a check of a possible energy consuming recirculation to the collectors during night conditions.

2.9.3.2 Efficiency Measurements

The system is installed following the instructions given by the producer. The nominal value of the solar irradiance should be 800 W/m^2. In case the test is performed outdoors, the mean value of the irradiance should be 800 ± 100 W/m^2. In this case the integrated irradiation during a 4h period should be between 3.15 and 3.25 kWh. The ambient temperature should be between +5°C and +30°C and remain stable within ±5°C. The temperature of the incoming cold water should be close to ambient temperature (±3°C).

At the beginning of the experiment the temperature of the water in the tank should be that of the incoming cold water to within ±2°C. The collector is then radiated during a 4h time period.

After the radiation period, a draw off test is performed. The flow speed during that test should be two times the volume of the tank per hour and the temperature of the incoming water should be close to ambient. The temperature of the draw off water is measured every second minute and the draw off is continued until the difference between the inlet and outlet temperatures is less than 2°C. The maximum temperature of the draw off water is noted.

The storage thermal mass given as the integral of the draw off water weighted to the difference between its outlet and inlet temperatures is computed using Equation 2.9.2.

$$M = (\int_i (T_i - T_o) \cdot dM_i)/(T_m - T_o) \qquad (2.9.2)$$

where

T_o is the inlet water temperature (approximately equal to ambient temperature),

T_m is the maximum outlet water temperature.

The data thus obtained contain enough information for the calculation of the collector loop efficiency of the system. The energy balance of the system during the radiation period is employed for the calculation.

When there are no heat losses from the collector loop, the power transferred from the solar collector to the heat exchanger of the tank can be expressed with the following equation using coefficients η_o and K_o.

$$P1(t) = A \cdot \eta_p(\eta_o G - K_o(T_u(t) - T_{amb})) \qquad (2.9.3)$$

where		
	K_o	is the collector overall heat loss coefficient.
	T_{amb}	
	$T_u(t)$	is the output water temperature.

The heat losses of the tank can for every moment be expressed with the relationship

$$P2(t) = -K_s(T_u(t) - T_{amb}) \qquad (2.9.4)$$

The power corresponding to intermediate drawings of domestic hot water is given by

$$P3(t) = -\frac{E_s}{\Delta t} \qquad (2.9.5)$$

The power supplied by back-up energy

$$P4(t) = \frac{E_a}{\Delta t} \qquad (2.9.6)$$

with E_s defined as

$$E_s = \frac{4180}{3600 \cdot 1000} \sum_{i=1}^{n} \int_{t_i}^{t_{i+1}} (T_u(t) - T_{cw}) \cdot Q2 \cdot dt \qquad (2.9.7)$$

where		
	$(t_{i+1} - t_i)$	is the duration of the intermediate drawings.
	n	is the number of intermediate drawings
	Q2	is the weight of the water drawn
	T_{cw}	is the input water temperature.

For the tank, the energy balance is given by

$$(P1(t) + P2(t) + P3(t) + P4(t))dt = 4180 \cdot M \cdot dT_u(t) \qquad (2.9.8)$$

This equation can be expressed in the following manner

$$\frac{dT_u(t)}{dt} = \qquad (2.9.9)$$

$$\frac{\eta_p \cdot A \cdot \eta_0 \cdot G}{4180 \cdot M} - \frac{\eta_{p\phi} \cdot A \cdot K_0 + K_s}{4180 \cdot M}\left(T_u(t) - T_{amb}\right) + \frac{E_a - E_s}{\Delta t \cdot 4180 \cdot M}$$

as a linear differential equation of the first order with constant coefficients, where the solution contains the temperature conditions at the start.

$$T_u(t) = (a + T_{amb}) - (T_{amb} - T_{cw} + a) \cdot e^{-b \cdot t} \qquad (2.9.10)$$

with $$a = \frac{G + \frac{E_a - E_s}{\Delta t \cdot A \cdot \eta_o \cdot \eta_p}}{\frac{K_L}{\eta_o} + \frac{K_s}{A \cdot \eta_o \cdot \eta_p}}$$

$$b = \frac{\frac{K_L}{\eta_o} + \frac{K_s}{A \cdot \eta_o \cdot \eta_p}}{4180\ M/(A \cdot \eta_o \cdot \eta_p)}$$

The result is

$$T_{um} = (a+T_{amb})-(T_{amb}-T_{cw}+a) \cdot e^{-bt} \qquad (2.9.11)$$

The solution of this imlicit equation determines the efficiency of the collector loop, η_p.

2.9.4 Simulation Model (OSOL)

The simulation model works for DHW systems, either solar only systems or systems including an electric heater. The time step of the simulation is one hour.

2.9.4.1 Meteorological Data

The parameters used are

- Air temperature
- Global radiation on a horizontal surface
- Diffuse radiation on a horizontal surface.

The radiation in the collector plane is computed using solar position, height of obstacles, ground albedo, collector orientation and global and diffuse radiation as measured on a horizontal plane. A coefficient for non-isotropic is put to 0.2, which means that 80 percent of the diffuse radiation is assumed isotropic while 20 percent is supposed to originate from the direction of the sun.

2.9.4.2 Domestic Hot Water Load

Daily profiles for the DHW demand are introduced. Those profiles are obtained from statistical data.

2.9.4.3 Storage Simulation Model

The tank is divided into a number of layers, usually five. All controllers are presumed to work ideally.

Each layer is subject to the following heat transfer:

- Heat losses to the environment
- Contribution from the solar loop (only for the position of the heat exchanger)
- Possible contribution from electric heater
- Heat transfer from a high temperature layer to a low temperature layer.

2.9.4.4 Simulation Output

Solar Only System. Yearly solar fraction, which is available solar energy compared to energy demand (maximized to one when the temperature from the heater exceeds the reference temperature).

Solar and Electric Heated System. Hot water production above reference temperature. Yearly electric energy divided into

- low load hours at night
- full load hours
- wintertime
- summertime

Execution time on a VAX minicomputer for a one year period is about 30 seconds.

2.9.5 Advantages and Limitations

- Short term testing, long term predictions.
- Measured data are solely system parameters.
- The simulation model connects climate, system and load.
- Control system not included.
- At present stage only useful for one family DHW systems.

2.9.6 Experimental Validation

At CSTB at Sophia Antipolis a study was performed where the same system was run on six different days for measuring the collector loop efficiency, η_p. The mean value of the irradiance was in the range of 858 to 928 W/m^2, the ambient temperature ranged from +16 to +27.5°C while the running time was varied from 2h to 6h. The measured values of η_p was 0.90, 0.91, 0.93, 0.90 and 0.90 respectively.

A parametric study is being performed at the Testing Institute at Boras where irradiance level, test duration and draw off pattern are varied. Comparison will be made with computed performance from the indoor test.

2.9.7 Future Development

At CSTB work is in progress for introducing effects of the control system and the thermal inertia of the collector loop.

At the Testing Institute an extension of the method is planned to include systems which also contribute to the space heating of the house.

2.9.8 References

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2.10 SWITZERLAND - SOFAS

2.10.1 Introduction

2.10.1.1 General

The Swiss Professional Association of Solar Energy Firms (SOFAS) carried out a preliminary study about short-term solar energy systems tests in order to clarify the methodology (Schläpfer and Schneiter, 1986). The most adequate approach had to be selected to meet the requirements of Swiss Solar energy firms.

This work has been realized in the framework of the cooperation in the field of research and development projects of the International Energy Agency (IEA). It has been supported by the Swiss Federal Office of Energy (BEW). The conclusions and opinions expressed in this paper are only binding for the authors. If the authors refer to a commercial company or product, it does not mean that other companies or products fulfilling the same requirements are excluded.

2.10.1.2 Purpose

In Switzerland a short-term test method should be applicable in situ, the system under test being operated without interruption of the heat supply to the user. The test should yield the yearly auxiliary energy saving with a typical accuracy of 10%. The test should also give information about subsystems performance in order to identify possible malfunctions. The test costs should be at max. SFr. 2500.-(~US $1500). The test period should not exceed 4 weeks.

Systems tests are thought to be applied as quality controls, comparison between design and real data (especially the actual heat load), stimulator of owner's confidence in solar energy technology and tool for improvement of the experience level of designers and installers of solar energy systems. The tests should be performed by qualified engineers using a portable instrument package and a personal computer.

Short-term system tests should be applicable to the majority of solar energy systems installed in Switzerland for domestic hot water and, optionally, space heating. Variations in system configuration include the type of auxiliary energy (electricity, oil, gas, wood), the number of storage vessels, the type of heat exchanger (internal or external), the circulation mode between collectors and storage (thermosiphon or forced circulation) and the organization of the heat transfers between collectors, storage and load (heat management concept). Variations occur also in systems size (from a few m^2 collector area to about 100 m^2).

2.10.2 Methodology

2.10.2.1 Long Term Performance Prediction

In a first step of the preliminary study a few simplified system models (correlations) have been analyzed and their suitability as a procedure to predict the long-term system performance has been evaluated. The alternate approach considered was the use of a detailed simulation programme. It was concluded that the simplified system model approach is <u>not</u> appropriate. The arguments supporting this conclusion were:

- The simulation approach was felt more sure than the simplified model approach; simulation programmes running on personal computers are available, simplified models are still under development.
- The simulation approach was judged as more qualified to predict accurately the long-term performance of the great variety of systems involved. Especially, concern was expressed on the accuracy of simplified model predictions when the system or component parameters not explicitly considered in the simplified model strongly deviate from their standard values (such a situation may happen in the practice). Therefore, simplified models were thought to be more convenient to system design (sizing) than to short-term system testing.
- Simplified models are not able to give sufficient information about subsystems performance in order to identify possible malfunctions. Additional tests would be necessary in such a case, leading to increased test costs.
- With the simplified model approach the measurement results cannot be reproduced by calculation as well as can be done with the detailed simulation. This requirement was felt to be necessary to improve the credibility of the test method.

It was thus decided to select the <u>detailed simulation programme approach</u>.

2.10.2.2 Experimental Procedure

Another part of the preliminary study cleared up the experimental procedure to be used for short-term tests. Several approaches have been considered:

1. <u>Immersed sensors</u>

Temperature and flow sensors are placed in the piping, directly in contact with the heat transfer liquid. The measurements are performed in the same way as in a long-term monitoring programme, except that the measurement period does not exceed 4 weeks. The monitored quantities include the energy flows within the system, the meteorological data, the heat load(s) and some operation temperatures. Selected intervals of the monitoring period are then used to calculate from the measurement results the component and subsystem parameters required as input to the simulation programme.

The SOFAS study concluded that this approach fulfills the accuracy requirements set. However, the test goal cannot be reached: a test costs between SFr. 2900.- and 3200.-, depending on system configuration, and even SFr. 4700.- to 5100.- if the amortization of instrument package and personal computer (within 50 system tests) is included. Another severe disadvantage of this approach is the perturbation of the heat supply during sensor mounting and removing. In new systems the places for mounting the sensors could be prepared already when the system itself is installed. Then, test costs would be reduced by about SFr. 700.- and heat supply to users could be undisturbed by tests.

2. Integral storage temperature sensor as only indicator for heat flows

This approach tries to minimize the costs for instruments and sensors. A long resistor wire is used as unique indicator for heat flows. The sensor is placed in a flexible tube. This tube is introduced into the storage vessel (one per vessel if several vessels are present). The vessel must have a free connection pipe at the top for this purpose. The sensor, which still has to be developed and tested, is placed vertically and measures the average temperature of the storage vessel. The time variation of its indication is proportional to the difference of the heat flow rates leaving the store and those coming into it.

This approach has several severe limitations. 1) The heat flows to and from the store have to be interrupted successively (all flows but one) and for relatively long periods (several hours) in order to measure their rates individually. This is a major concern for the user of the system. The heat flow control unit is added to the system at the beginning of the test. 2) This approach is applicable to only a few number of system types and its accuracy needs to be studied experimentally. 3) A cross-check of the monitored data is difficult since they are recorded successively instead of simultaneously. However, the test cost goal may be reached.

3. Clamp-on sensors

Principally, this approach is identical to #1, except that clamp-on temperature and flow rate sensors (mounted on the piping) are used in place of immersed sensors. In this way, sensor mounting and removing does not disturb the heat supply to the users. However, use of clamp-on flow meters is not so easy as that of immersed flow meters and approach #3 is expected to be less accurate than approach #1. Hence, an additional store heat loss test is necessary. Because of the high acquisition cost for clamp-on flow meters, only the test costs without amortization are lower than in approach #1: SFr. 2300.- to 2500.-, depending on system configuration. The test costs with amortization amount to SFr. 5700.- to 6300.-.

4. Integral storage temperature sensor, minimal number of additional clamp-on sensors plus one heatmeter for collector loop heat output.

This approach was studied in order to take advantage of the positive aspects of approaches #1, #2 and #3 and simultaneously reduce the test costs. In particular, the separate store heat loss test is performed using the integral storage temperature sensor. The remaining measurements are performed without disturbing the heat supply to the users.

This approach is applicable to the numerous system configurations required. However, the test costs are still beyond the goal (SFr. 2700.- to 3600.- without/SFr. 4700.- to 6400.- with amortization) and the accuracy is poorer than with approach #1.

The SOFAS preliminary study concluded that none of the approaches #1 to #4 of the experimental procedure meets all the severe requirements listed in the Introduction. Hence, some of the goals have to be loosened:

- A first way is the exclusion of the amortization costs from the test costs, the instrument package and the computer being financed on another way. Under these conditions the approaches #1, #3 and #4 may be considered and further optimized.
- Another approach is a kind of "black-box" monitoring: only the input (solar/ meteorological and auxiliary energy) and output (heat loads) data are measured, thus reducing drastically the test and acquisition costs. The goal of SFr. 2500.- per test including amortization should be achievable. However, such a procedure does not give information about subsystems performance and possible malfunctions. Only the auxiliary energy consumption is calculated using a simulation programme. All input data for the simulation programme except the few measured quantities are taken from the design sheet of the system. The calculated auxiliary energy consumption during the test period is compared with the measured one. In the case of a satisfactory agreement, the system works properly and the yearly auxiliary energy needs may be calculated. In the opposite case, additional investigations

(not included in the test costs goal) are required to identify the origin of the discrepancy. The black-box monitoring approach is thought to be applied with clamp-on sensors to minimize the perturbation of the heat supply to the users.

2.10.3 Experience/Validation

The SOFAS preliminary study was based on the experience gained by the participating firms and institutions during the course of other research projects or commercial activities. Let us mention in particular*:

- E. Schweizer AG, Zurich/Hedingen (monitoring activity within SOFAS research project 'Guidelines for Optimal Planning and Construction of Solar Energy Systems' (Schläpfer, 1986)).
- TNC Consulting, Chur (energy analysis of buildings and heating systems (Nordmann et al., 1982)).
- FATRA SA, Prahins (IEA research programme 'Energy Conservation in Buildings and Community Systems' (Elsinore, 1981)).
- Swiss Federal Institute for Reactor Research (EIR), Würenlingen (monitoring programme on 29 commercial solar heating systems (Suter et al, 1984), investigation of the applicability of clamp-on sensors for in situ measurements (Impulsprogramm Haustechnik, in press)).
- Burgdorf School of Engineering (computer simulation programmes and correlation model for solar domestic hot water systems (Zogg and Rieder, 1986)).
- Rapperswil School of Engineering (IEA solar heating and cooling programme, Task III, research project 'Reliability and Durability of Solar Energy Systems.'(Frei, 1983-84)).

2.10.4 Future Work Needed

The follow-up programme (main project) will now be started. The most promising approaches identified during the course of the preliminary study will be investigated in detail (experimental programme and validation) and the instrument and software packages will be developed and implemented. At the end of the project a practical tool for in situ testing at acceptable costs of most solar energy systems types of Switzerland without serious perturbation of the heat supply to the users should be available.

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*The parentheses indicate activities from which experience was gained.

2.11 UNITED KINGDOM - SEU

2.11.1 Introduction

From parametric studies of open-loop solar heating systems J. P. Kenna (1981 and 1984) has shown that the monthly solar fraction of a SDHW system with a fixed daily draw-off pattern depends on the monthly values of four dimensionless 'system parameters', which he denoted by M, K, R, and L_s. Each of these parameters can be given a physical interpretation: M is a measure of the energy which the system can collect, the inverse of K a measure of the maximum temperature at which energy can be collected, R a measure of the storage capacity of the system, and L_s a measure of the storage losses.

The motivation for Kenna's study was the development of a simple design method for SDHW systems. He assumed that any well-designed system would have well-insulated storage, so that the influence of L_s on the solar fraction could be ignored. He then fitted formulae to the correlation between the monthly solar fraction and the remaining parameters M, K and R, for different forms of draw-off pattern. The design method based on these correlations Kenna called the 'SEU Design Method.'

At the SEU an investigation is planned to establish the feasibility of developing this approach into a test method for SDHW systems.

2.11.2 Notation

A'	effective normalized collector area (including the effects of any heat exchanger and pipe losses)
A_sU_s	product of store surface area and store loss coefficient
f	monthly solar fraction
G*	monthly average daily maximum possible rate of energy input into store
$\bar{H}$	monthly average daily energy input into store
$\bar{L}$	monthly average daily load
M_sC_p	product of mass of water in store and water specific heat capacity
T_m	monthly average daily mains water temperature
T	DHW demand temperature (assumed constant)
U'	effective normalized collector loss coefficient (including the effects of any heat exchanger and pipe losses)
Δt	constant time period having a value of 24 h

2.11.3 Definitions

For a SDHW system the system parameters M, K, R and L_s are defined as follows:

$$M = A'H/L \qquad (2.11.1)$$

Thus M is the ratio of the monthly average daily energy collected (solar + ambient) to the monthly average daily load.

$$K = U'(T_w-\bar{T}_m)/G^* \qquad (2.11.2)$$

Through its dependence on G*, K indicates the quality of energy that can be collected by the system. It is one of the advantages of Kenna's correlation that it can take this into account. More insight into the significance of K can be obtained by noting that G*/U' is equal to the monthly average daily maximum possible temperature gain from solar, i.e., the monthly average daily maximum difference between the temperature of water entering the store and the mains water temperature. Therefore, K can be interpreted as the ratio of the storage capacity of the system at the demand temperature to the monthly average daily maximum possible storage capacity, each capacity specified relative to the temperature of the mains water supply.

$$R = M_sC_p(T_w-\bar{T}_m)/L \qquad (2.11.3)$$

Thus R is the ratio of the storage capacity at the demand temperature to the monthly average daily demand.

$$L_s = U_sA_s\Delta t/M_sC_p \qquad (2.11.4)$$

Thus L_s is the NTU of the store for a discharge time of exactly one day.

2.11.4 Monthly Correlations

From the results of detailed computer simulations Kenna found that the monthly solar fraction for a SDHW system with a well-insulated store was strongly correlated with M, K and R. The correlation curves can be used directly to predict f, but for convenience Kenna fitted the data to a formula of the type

$$f = aM/(b+MK^*) \qquad (2.11.5)$$

with

$$K^* = K/(1+0.11K) \text{ for } K > 0.65 \qquad (2.11.6)$$

$$K^* = (K+cM)/(0.69+0.87K) \text{ for } K < 0.65 \qquad (2.11.7)$$

It was assumed that whenever the store temperature exceeded the demand temperature the demand would be met by mixing mains water with water from the store. Equation 2.11.7 takes into account the reduction in volume of hot water which would then be supplied by the system. If there is no mixing, then Equation 2.11.6 is appropriate for all values of K.

In general, the constants a, b and c are functions of R which depend on the demand pattern. These too are found by fitting the results of a large number of detailed computer simulations, and examples are given in Kenna (1984) for specific demand patterns.

2.11.5 Basis for SDHW Test Method

The performance of a SDHW system can generally be described by equations containing physical variables which can be measured directly, as well as constant parameters that are characteristic of the system. The performance of the system can thus be predicted for a specific set of conditions provided estimates can be found for the values of the system parameters. To estimate these parameters from measurements of the physical variables, methods of system identification can be used. This approach can form the basis of a system test.

To base a test method of the system-identification type on the parametric studies described above, a number of problems need to be overcome.

Firstly, it should be noted that the correlations 2.11.5, 2.11.6 and 2.11.7 were deduced under the assumption that the system under consideration has a well-insulated store. A test should establish whether this is true rather than assume it. Thus, either these correlations need to be generalized to include the effect of L_S on the performance, or the assumption of low losses has to be established separately.

Secondly, Kenna's so called system parameters M, K and R are not true system parameters, but depend on the conditions under which the system is operating. It is easy to separate constant system parameters from measurable variables in R, but in M and K the variables H and G* are each dependent on collector incident angle modifiers, whose values depend on both the system and the test conditions. The simplest way of overcoming this problem is to assume that the modifiers are constants and to identify effective values for them from the data; alternatively, it may be possible to calculate them or measure them separately.

Thirdly, and more seriously, there is a problem arising from the time-scale of the correlations. As the equations were developed they are formulated in terms of monthly average daily values of the variables. To gather sufficient data to identify up to six independent system parameters from these correlations could require many months of data, which is clearly impractical. A formulation using variables in something like the form of daily average hourly values is needed, but correlations appropriate for short-term values -- if they exist -- need to be established. It may be that correlations of the same form are also valid for short-term data, and that only the constants are affected by a difference in time-scale and demand pattern. A more likely possibility is that more parameters are needed to model the thermal performance of the system in the short term.

2.11.6 Likely Form of Test Method

Assuming that correlations using hourly data can be found, the test method that could be envisioned might consist of the following steps:

- A short-term demand pattern would be specified for the test, and computer simulations would be used to find the coefficients (analogous to a, b and c in equations 2.11.5 and 2.11.7 that occur in the short-term correlation appropriate for this demand pattern.

- The system parameters A', U', M_SC_p, A_SU_S, and the collector incident angle modifiers would be estimated by best fit of test data to the short-term correlation functions. (Some, of course, may be determined separately by more direct methods.)

- A long-term demand pattern would be specified either by the user or according to test specifications.

- Coefficients would be determined for the long-term correlations, given either by equations 2.11.5, 2.11.6. and 2.11.7 or by a generalization of them that included the dependence on L_S. These coefficients would normally be known, but in the case of a novel demand pattern they would have to be evaluated specially using computer simulations.

- The long-term performance of the system would be predicted using the long-term correlations together with the values for the system parameters that were estimated from the short-term test.

2.11.7 Experimental Validation

The correlations contained in Equations 2.11.5, 2.11.6 and 2.11.7, which would be used to predict the long-term system performance from the estimated values of the system parameters, have been validated against detailed computer simulations using data from a wide range of localities (Kenna, 1984). The short-term correlations, on which the test would be based, are likely to be generated by a similar method, and would therefore also be validated against detailed computer simulations. The experimental validation of the test method depends therefore on the validation of the detailed-simulation computer program.

2.11.8 Future Development

Clearly the approach outlined above remains somewhat speculative, and much needs to be done to develop it into a practical and reliable SDHW test method. Among the steps which need to be taken are to

- establish short-term correlations
- determine from the scatter about these correlations the quantity of data needed to identify the system parameters with sufficient accuracy,
- determine the test conditions required and the necessary accuracy and precision of the measurements,
- determine the most appropriate numerical method for the system-parameter identification,
- specify a format for reporting the results of the test.

Two research projects at the SEU, one to study short-term correlations as a basis for a test method and the other to study appropriate methods of system identification, are in progress.

2.11.9 Potential Advantages of the Method

- The method could be used in situ.
- A few, simple measurements would be required.
- It would be easy to predict the long-term performance for different locations and demand profiles.

It may be possible to take account of different control strategies in the same way as different demand patterns, and the possibility should also be investigated of using the same or other correlations to extend the approach to non-conventional systems, such as thermosiphon systems or integrated systems.

2.11.10 Potential Disadvantages of the Method

- The identification of grouped system parameters does not permit diagnosis of individual component failures.
- The test method is not fully developed, and its practicability is not yet certain.

2.11.11 References

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2.12 UNITED STATES - ARIZONA STATE UNIVERSITY

2.12.1 Introduction

A proposal is made that commercial SDHW systems be rated by their annual fractional energy savings under site-specific solar/meteorological conditions, the method of estimation to be interpolation between indoor test points by means of the f-Chart 4.0 performance correlation (Beckman and Klein, 1977) and the indoor test method to be ASHRAE Standard 95-81.

The concept of a performance correlation for solar domestic water heating systems is analogous to the concept of an instantaneous efficiency curve for a collector. The efficiency curve of a collector is, generally speaking, a straight line relationship between the collector efficiency and a parameter involving insolation, ambient temperature and inlet water temperature. This line characterizes the thermal performance of the collector. We envision a performance correlation for SDHW systems to be a linear relationship between the solar fraction carried by a system and a correlation parameter involving average solar/weather data and collector/storage parameters. Such a correlation could capture the thermal performance of a system in much the same manner an efficiency curve captures the thermal performance of a collector.

2.12.2 Scope

Promising correlation parameters have been derived by others from computer simulated performance of SDHW systems. Most notable among these stands the f-Chart version 4.0 correlation for solar fraction which employs long-term collector utilizability statistics. The validity of the correlation for monthly performance figures of actual systems remains to be shown. Linearities may appear in simulation results owing to linearity assumptions rather than physical fact. The major thrust of investigation in this area has been to determine the degree of linearity actually existing between two selected correlation parameters and actual monthly performance of four generically different SDHW systems.

2.12.3 Results

Initial consideration for a correlation variable went to one proposed by Liu and Hill (1979) based on TRNSYS simulation of long-term SDHW system performance. Their correlation variable, labelled F, is formed by multiplying total insolation on the aperture plane by the collector optical factor, $F_R(\tau a)_{e,n}$ and subtracting a figure for collector heat losses to a reference temperature. The difference correlates with useful energy gain of the system and when ratioed to the hot water load correlates with the solar fraction carried by the system.

A more refined correlation parameter is the estimated solar fraction defined by the following formula:

sf(estimate)=

$$[AF_R(\tau\alpha)\ G\ \emptyset - (UA)(\bar{T}-\bar{T}(env))\Delta t - C_s(\bar{T}_f - T_i)]/Q(load)$$

where the symbols have the following meanings:

$\emptyset$ = A statistical insolation parameter defined as the fraction of radiation during a specified interval which is above the utilizability threshold of the collector in question.
G = Total solar irradiation per square area on the collector aperature integrated over the time interval in question.
$(\tau\alpha)$ = An estimated time averaged value of the collector transmittance-absorptance product (τa).
F_R = The collector heat removal factor according to ASHRAE standard 93-77 testing.
A = Gross area of the array.
(UA) = Storage overall heat transfer coefficient.
$\bar{T}$ = An estimate of average storage temperature.
$\bar{T}(env)$ = Average temperature of the storage tank environment.
Δt = Length of the time interval.
C_s = Thermal capacity of the storage tank.
T_f = Final storage temperature.
T_i = Initial storage temperature.
Q(load) = The hot water thermal load on the system.

The parameter sf(estimate) will follow variations in system performance more closely than F because 1) the utilizability concept more accurately reflects how systems operate and thereby gives better estimates of useful energy collection, 2) diurnal variation in optics of collection are accounted for in $(\tau\alpha)$, 3) storage losses are taken into account, and 4) changes in stored thermal energy are figured into the monthly energy balance.

Figure 2.12.1 shows the correlation of sf (actual) vs sf (estimate) for a double tank direct system monitored by the National Bureau of Standards (Wood, 1981) for a period of 11 months. The coefficient of determination for this correlation is 0.97 -- a significant improvement over the correlation of the same data using the F parameter which yielded $r^2 = 0.91$.

Figure 2.12.2 shows the performance correlation for a Drain Down system based on the data gathered in the long-term evaluation experiment. (Balon and Wood, 1980) The ten monthly data points are represented as circles. The data point on performance obtained by ASHRAE Standard 95-81 testing of the system is shown as a cross.

Figure 2.12.3 shows the performance correlation for a concentrator system. The points designated by an F represent months in which the system experienced a significant freeze-protection burden. The system employs recirculation freeze-protection so freeze-protection activity appears as additional heat loss. The correlation line drawn in Figure 12.2.3 excludes consideration of the points designated F.

2.12.4 Discussion

The extension of the utility of the correlation to a variety of generic types is important if the correlation is to be used for rating of commercial systems. Cognizance must be given to factors which change performance such as the burden of freeze protection. As evidenced by the data for the concentrator system which used a significant amount of energy for freeze protection pose some difficulty for the proposed rating method or any rating method. A reasonably accurate method of estimating freeze-protection losses will be necessary to resolve this problem. The indirect type of system should present no difficulty since the effect of the heat-exchanger can be modelled as a change in the collector performance parameters.

A second source of encouragement on the proposed rating method is the accurate prediction of outdoor performance by the indoor test method, ASHRAE Standard 95-81. The cross in Figure 2.12.2 represents a laboratory test point on performance of the Drain Down system obtained in four days of testing. The close proximity of the indoor data point to the performance line established in outdoor testing encourages the belief that the performance of this system could have been established with indoor testing alone.

Thus the proposed rating method as illustrated in Figure 12.5.4 consists of two ASHRAE 95-81 tests for two different rating days. One of the days could be a non-solar day. A computer algorithm such as f-Chart 4.0 can then be used to interpret these data in a variety of ways. For example, the sensitivity of annual system performance to various hot water loads can be determined for any location as illustrated in Figure 2.12.5. Moreover, the change in annual system performance for various cities is also readily available as illustrated in Figure 2.12.6.

2.12.5 Summary and Conclusions

A proposal has been made that SDHW systems be rated by their estimated annual energy savings under location-specific solar/meteorological conditions, the method of estimation to be interpolation between laboratory test points by means of the f-chart 4.0 performance correlation, and the laboratory test method to be ASHRAE 95-81. Evidence for the workability of the proposed rating method has been gathered, including a demonstration of the correlation on Drain Down and Concentrator systems. In one case a laboratory test point was available to compare with the outdoor performance correlation and good agreement was shown. The data correlations show that heat loss due to freeze-protection was substantial for two of the systems examined and poses a difficulty for rating the systems. Nevertheless, the evidence encourages a belief in the workability of the proposed rating method.

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Liu, Stanley T. and James E. Hill (1979), 'Proposed Technique for Correlating the Performance of Solar Domestic Water Heating Systems', ASHAE Transactions, vol. 85, part I, pp. 96-103.

Wood, B.D. (February 1981), Private communication from Mary Jane Orloski, Active Thermal Solar Group at the Natonal Bureau of Standards to Dr. Byard D. Wood, Director of the Center for Energy Systems Research, College of Engineering and Applied Sciences, Arizona State University, regarding detailed data from the performance monitoring of four generic SDHW systems.

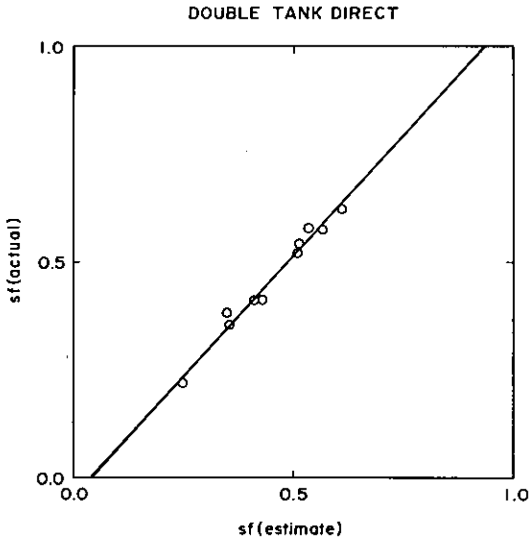


Figure 2.12.1. Correlation of Actual Monthly Solar Fractions with the Parameter sf(estimate) for the NBS Double Tank Direct System.

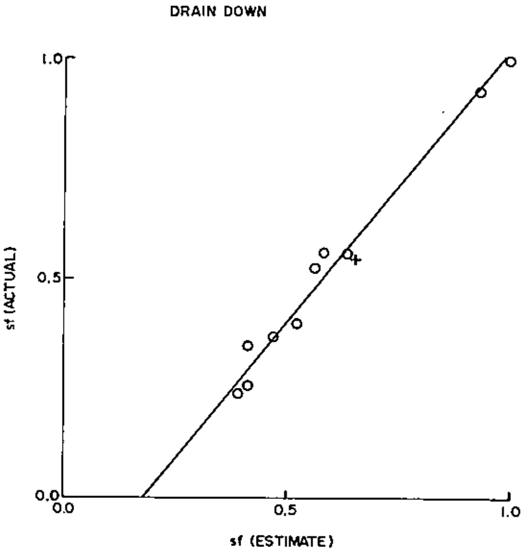


Figure 2.12.2. Correlation of Actual Monthly Solar Fractions with the Parameter sf(estimate) for the Drain Down System.

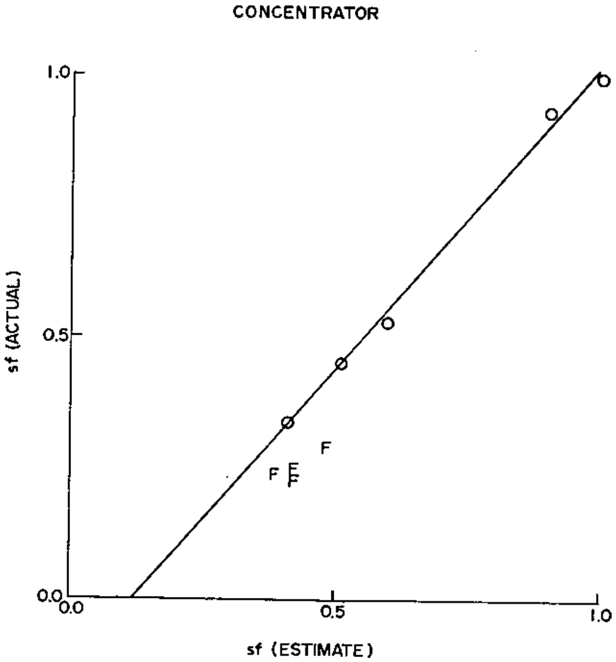


Figure 2.12.3. Correlation of Actual Monthly Solar Fractions with the Parameter sf(estimate) for the Concentrator System.

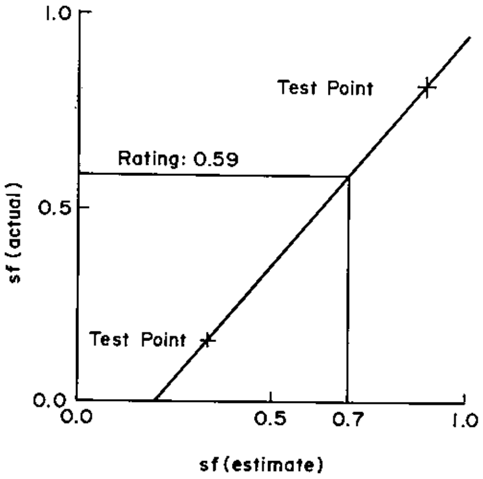


Figure 2.12.4. Example of Proposed Rating Based Upon Two ASHRAE 95-81 Tests But for Two Different Rating Days, e.g., Winter and Summer.

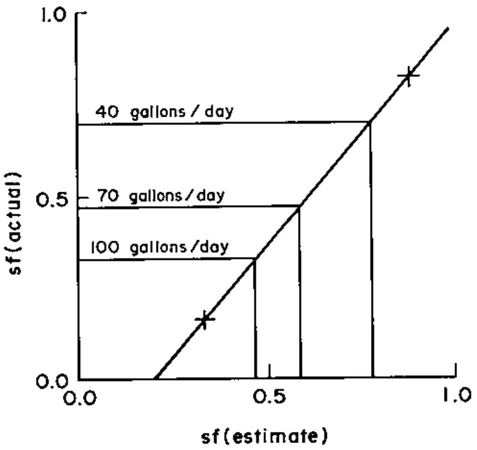


Figure 2.12.5. Example of How the Proposed Rating Can Be Used in Conjunction With f-Chart 4.0 to Evaluate the Effects of Various Loads on SDHW System Performance.

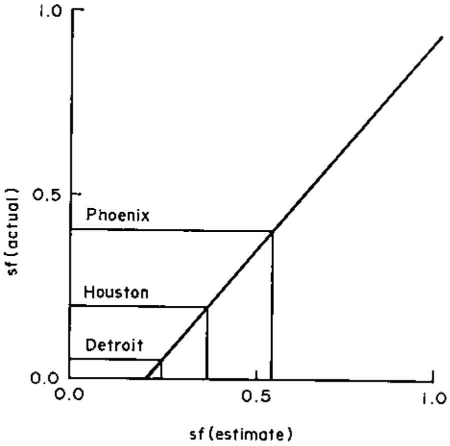


Figure 2.12.6. Example of How the Proposed Rating Can Be Used to Determine System Performance for Various Solar/ Meteorological Regions.

2.13 UNITED STATES - ASHRAE 95

2.13.1 Introduction

A repeatable test method, independent of outdoor environmental conditions and laboratory geographical location, was developed to provide a means by which SDHW systems could be tested and compared. Two methods were employed. One uses a solar irradiance simulator to irradiate the solar collectors which are part of the SDHW system being tested. The other requires that the energy normally furnished by an outdoor irradiated solar collector array be replaced by an equivalent amount of energy supplied by a conventional energy source such as an electric resistance heater.

2.13.2.1 Test Apparatus

A representative test configuration is shown in Figure 2.13.1 for the case where a non-irradiated collector array is used and the collector loop heater is downstream of the non-irradiated collector array. The purpose of the by-pass loop is to circulate the transfer fluid through the collector loop heater during those times when solar irradiation occurs but the solar domestic hot water system controller does not require the collector loop pump to be on. The by-pass loop pump should not operate when the collector loop is on. For the case where a solar irradiance simulator is used, the heater and by-pass loop shown in the solar collector loop of Figure 2.13.1 shall not be used.

The test is done by assembling the complete system in the laboratory and testing it under a prescribed set of conditions until its performance is the same for two successive days and then data are taken for rating purposes. For all system, either the solar fraction, sf, or the fractional energy savings, e, can be determined. In addition, a test to determine the energy delivery capability of the system during a continuous draw-down is conducted.

2.13.3 Test Procedure

For the thermal test method, the solar collector shall have been previously tested according to ASHRAE Standard 93 and the following determined:

1. a value of the collector time constant,
2. a curve of collector efficiency as a function of $(t_{f,i}-t_a)/G_t$ with the collector operating at near-normal incidence to the beam of the sun,
3. a curve of incident angle modifier as a function of incident angle θ,
4. the mass flow rate and the specific heat of the fluid used during the 93 tests.

The fluid used in the solar water heating system shall be the same as that used in the 93 tests.

The storage device(s) shall be filled with water at a specified temperature, t_{main}, on the morning of the first day. The system shall be energized, including integral heaters and controls, and shall be allowed to operate in its normal mode during the day and each successive day of the test. The time for the beginning of the first and subsequent 24 hour test days shall be specified in an associated rating standard. Any device which is intended to limit or control the operation of the solar energy collection equipment shall be set as recommended by the manufacturer. If the system is designed so that the temperature of the delivered water is controlled by a thermostatic control on the auxiliary energy delivery system, this thermostat shall be set to deliver water at t_{set}. If the system is designed so that the temperature of the delivered water is controlled by a mixing valve, the mixing valve shall be set to deliver water at t_{set} and the control of the auxiliary heating system shall be set as recommended by the manufacturer. On each test day, water shall be withdrawn from the system at times, rates, duration, and temperature, t_{set}, as specified in an associated rating standard. If the outlet water temperature from the system is not maintained at t_{set}, an energy integrator may be used and the length of time of the draw adjusted so that the same total amount of thermal energy output, measured above t_{main}, is delivered. The energy content of the water withdrawn shall be determined. Although the use of an installed flow meter and temperature sensors is allowed, a preferred method is to collect the water in an insulated container of known thermal capacity and tare weight. The water in the container is thoroughly mixed during the withdrawal period and its temperature, t_{wj}, measured within 30 seconds after withdrawal is complete. The reported value should account for the thermal capacity of the weigh tank and/or the time constant of the temperature sensor. The weight of the collected water is measured. If an installed flow meter and temperature sensors are used, the delivery temperature shall be measured and recorded at no greater than 4.5 kg (10 lb) intervals throughout the withdrawal period.

The test shall be performed until the daily system supplemental energy required (Q_{AUX}) is within three percent of the value on the previous test day.

2.13.4 Measurements

During the test periods, measurements of the daily energy consumed by the circulation system (pumps, controls, solenoid valves, etc.) and the energy consumed every 30 minutes for auxiliary heating shall be made. The energy consumed by the bypass loop controls, pump, fan, and valves if measured, shall be obtained separately form the energy consumed by the solar domestic hot water system components. The daily thermal energy output from the collector loop heater (if used) shall also be determined from measurements. All daily quantities shall be recorded at the end of each test day. During the withdrawal periods, the mixed temperature of the incoming water and the mass and mixed temperature of each withdrawal shall be measured. If the collector loop heater is used, the thermal energy output from the heater, the mass flow rate through the collector array, and the entering fluid temperature to and temperature increases across the collector loop shall all be recorded for each 30 minute time period when the collector loop is in operation.

2.13.5 Calculations

The daily system hot water load shall be calculated as:

$$Q_L = \sum_{j=1}^{n} c_{p,w} \left(t_{wj} - t_{main}\right) m_j$$

The daily net energy supplied by solar energy shall be calculated as,

$$Q_S = \sum_{j=1}^{n} c_{p,w} \left(t_{sj} - t_{main}\right) m_j$$

The fraction of the daily system hot water load supplied by solar energy shall be calculated by

$$sf = \frac{Q_s - Q_{PAR}}{Q_L}$$

All measurements used in this calculation shall be those for the final test day.

2.13.6 Test Day

The test day is generally specified by a rating and certification organization such as SRCC (see second reference).

Variable	Setting
Tilt angle of collectors	a. 45° if collectors are non-irradiated. b. 45° for irradiated collectors, unless manufacturer requires an alternate tilt angle for normal operation and so specified in writing.
Solar conditions	Table 2.13.1
Average air temperature surrounding the system	A single ambient temperature of 22°C (±2°C), 71.6°F (±3.6°F), will be maintained.
Input water temperature (t_{main})	22°C (±1°C) 71.6°C (±1.8°F)
Water draw	Three times daily at 0800, 1200, and 1700, at a draw rate of 0.2kg/s (3.17 gpm) for a variable time period until for each draw:

Q_{DEL} is energy load delivered.

$$Q_L = \int m_j c_{p,w} (t_i - t_{main}) d(\text{time}) = 14{,}000 \text{ kJ/draw } (13{,}373 \text{ Btu/draw}, 3.92)$$

Q_{DEL} is equal to Q_L for Solar Plus Supplement or Solar Only.

$$Q_S = \int m_j c_{p,w} (t_S - t_{main}) d(\text{time})$$

Q_{DEL} is equal to Q_S for Solar Preheat Systems	where t_s is equal to temperature at outlet of preheat systems. Unless and until t drops below 35°C (95°F) at which time the draw is terminated and the total energy is recorded. Q_L shall be measured, in the case of solar plus supplemental and solar preheat systems, at the outlet of the supplemental tank. Thus, for a solar preheat system, a load as defined as Q_L, is withdrawn from and measured at the outlet of the specified supplemental tank. The delivered load from the preheat system is concurrently measured at the outlet of the preheat system and is defined as Q_S.
Set Temperature	T_{set} shall not be less than 48.9°C (120°F), but can otherwise be set in accordance with manufacturer's instructions.
Preheated water temperature of solar system (t_{pre})	Up to and including 45°C (113°F)
Time considered for beginning of first and subsequent test days for energy calculations	1700
Mass flow rate during draw (m_j)	0.2 kg/s (3.17 gpm)
Wind Requirement	The requirement for wind speed shall be 3.4 m/s (±0.8 m/s, 7.6 mph (±1.8 mph), across (parallel

to) the aperture of the collector
during the simulation period.

2.13.7 References

'Methods of Testing to Determine the Thermal Performance of Solar domestic Water Heating Systems, ASHRAE Standard 95-1981', The American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., 1791 Tullie Circle NE, Atlanta, GA 30329

'Test Methods and Minimum Standards for Certifying Solar Water Heating Systems', Standard 200-82, Solar Rating and Certification Corporation, 1001 Connecticut Ave. N.W., Washington, D.C. 20036, Revised Nov. 1984

Table 2.13.1

SOLAR INSOLATION CONDITIONS
Solar Irradiance Profile

Time	Total Irradiance $W.h/m^2$	Total Irradiance $Btu/ft^2.hr$	Incident* Beta
0800-0900	315	100	60
0900-1000	470	150	45
1000-1100	570	180	30
1100-1200	660	210	15
1200-1300	700	220	0
1300-1400	660	210	15
1400-1500	570	180	30
1500-1600	470	150	45
1600-1700	315	100	60
	4,730 $W.H/m^2$	1,500 Btu/ft^2	

*For solar simulation incident angles with respect to 45° reference plane.

B (Beta) - the angle between the direct beam of the radiation source and the normal to the 45° reference plane

45° reference plane - a plane at 45° to the local horizontal intersecting the collector aperature along a horizontal line.

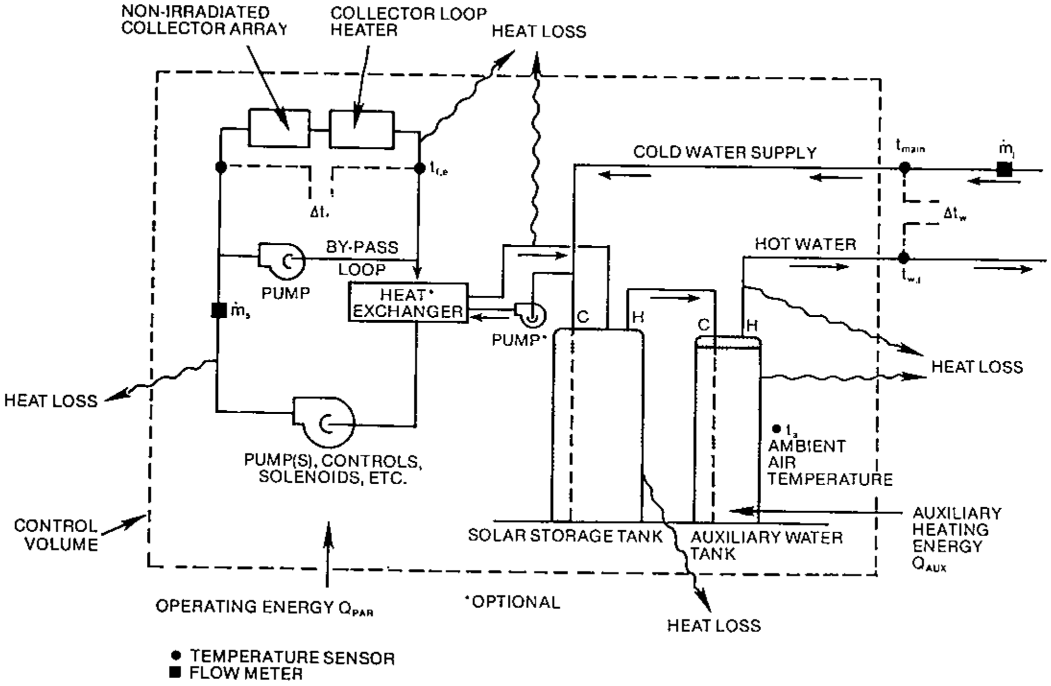


Figure 2.13.1 Schematic of SDHW system test facility using a thermal simulator for the solar energy input.

2.14 UNITED STATES - NATIONAL BUREAU OF STANDARDS

2.14.1 Introduction

A rating procedure for solar domestic hot water systems is described which combines the advantages of short-term system tests and correlations of long-term thermal performance (Klein and Fanney, 1983). The testing procedure consists of two indoor tests which are in accordance with ASHRAE Standard 95-1981, except for one additional measurement needed only for systems employing a heat exchanger between the collector fluid and the potable water. The test results are plotted in a manner in which they can be used to estimate the long-term performance of the solar water heating system for any location where site-specific, monthly-average meteorological data are available. The annual solar function obtained in this manner provides the recommended rating indicator. This method is very similar to that given in Section 2.12.

2.14.2 Theoretical Development

The basic problem faced in developing the rating procedure proposed in this paper was to devise a technique in which the ASHAE Standard 95-1981 steady periodic one-day test results could be used to estimate the long-term performance of a SDHW system. A solution to this problem was found by using the concept of solar radiation utilizability. The utilizability concept allows SDHW performance to be presented in a manner independent of meteorological conditions.

Utilizability, ϕ, is defined as the fraction of the solar radiation incident on a surface which is above a specified level referred to as the critical level, I_c. Utilizability is a solar radiation statistic, analogous to degree-days, an ambient temperature statistic. When hourly (or shorter time period) radiation data are available for the period of interest, utilizability can be calculated directly from

$$\phi = \frac{\sum^{n} \left(I_T - I_c\right)^{+}}{\sum^{n} I_T} \qquad (2.14.1)$$

In Equation 2.14.1, I_T is the average solar radiation per unit area incident on the surface of interest for a given time period, and n is the number of measurements of I_T used in the summation. The superscript "+" sign is used to indicate that only positive values of $(I_T\text{-}I_c)$ are considered; negative values are set to zero.

Using the ASHRAE Standard 95-1981 test method, the solar radiation at short intervals is known and the utilizability for any critical level can be calculated directly from Equation 2.14.1 for the test day. Long-term average values of utilizability (referred to as ϕ) depend on the distribution of solar radiation (i.e., the relative numbers of poor, average, and excellent days of sunshine which together compose the long-term average). Methods of estimating the long-term average value of utilizability without using actual hourly data have been developed on both monthly-average (Klein, 1978; Mitchell, Theilacker and Klein, 1978; Evans, Rule, and Wood, 1982) and annual (Rabl, 1981) bases.

2.14.3 Correlations of Steady Periodic One-Day Thermal Performance

Solar fraction is used as the index of system thermal performance. The solar fraction, f, is defined here as

$$f = 1 - \frac{Q_{AUX}}{Q_L} \qquad (2.14.2)$$

where Q_{AUX} is the auxiliary energy required including that needed to supply tank energy losses, but excluding the energy to operate pumps, blowers and controls, Q_L is the energy required to heat the require amount of water from the mains supply temperature, t_m, to the delivery temperature, t_d. Q_L is measured by summing the products of the mass of water drawn, m, the specific heat, C_p, and the difference between the delivery and mains supply temperatures over the test day as indicated in Equation 2.14.3. Tank energy losses and parasitic energy consumption are not included in Q_L.

$$Q_L = \Sigma m C_p \left(t_d\text{-}t_m\right) \qquad (2.14.3)$$

Both an energy balance and previous investigations (Klein and Beckman, 1979; Liu and Hill, 1979) suggest that the solar fraction can be correlated to the product of ϕ and a dimensionless parameter, Y. Y is defined as

$$Y = \frac{A_g \frac{A_a}{A_g} F_R \left(\tau\alpha\right)_{e,n} \Sigma\left(I_T K_{\tau\alpha}\right)\Delta\tau}{Q_L} \qquad (2.14.4)$$

where

A_g = the gross collector area

$\frac{A_a}{A_g} F_R(\tau\alpha)_{e,n}$ = the intercept of the collector efficiency curve determined in accordance with ASHRAE Standard 93-77 (ASHRAE, 1978)

$\Delta\tau$ = the time period over which I_T is measured.

$K_{\tau\alpha}$ = the incidence angle modifier averaged over the hourly period.

The product of I_T and $K_{\tau\alpha}$ is summed over the test day. Physically, Y is related to the ratio of the total energy absorbed on the collector surface to the total load during the test period.

The utilizability, ϕ, for the test day can be calculated from Equation 2.14.1 once the critical level, I_c, is specified. Collector theory (Duffie and Beckman, 1980) indicates that the critical level should be defined as follows:

$$I_c = \frac{\frac{A_a}{A_g} F_R U_L}{\frac{A_a}{A_g} F_R (\tau\alpha)_{e,n}} \qquad (2.14.5)$$

where

$\frac{A_a}{A_g} F_R U_L$ = the magnitude of the slope of the collector efficiency curve determined in accordance with ASHRAE 93-77 (ASHRAE, 1978).

$\bar{t}_s$ = a daily average system operating temperature.

$\bar{t}_a$ = a daytime-average ambient temperature.

The final choice for $\bar{t}_s$ is the daily average temperature of the water in the solar-heated portion of the storage tank during the period in which the collector pump is operated. The solar-heated portion of the storage tank is defined as that portion of the tank which can be heated by solar energy, but is not heated by an auxiliary energy supply. In a double-tank system, the solar-heated portion constitutes the entire preheat tank, but excludes the auxiliary tank. In a single-tank system having an electric heating element in the upper section, the solar-heated portion of the tank consists of that portion of the tank located below the electric heating element. $\bar{t}_s$ can be measured in either of two ways. For system configuration in which water is pumped from the tank to either a collector array or a heat exchanger, $\bar{t}_s$ is the average temperature of the water exiting the tank during the period in which the collector pump is operated. For indirect heat exchanger systems, $\bar{t}_s$ must be determined by measuring the temperatures at several representative positions within the solar-heated portion of the tank and averaging these over the period in which the collector pump is operated. Thus, for all systems employing heat exchange between the collector fluid and the potable water, a measurement of the average temperature in the solar-heated portion of the storage tank is required in addition to those measurements specified in the ASHRAE Standard 95-1981 test method.

2.14.4 Correlation of Long Term Thermal Performance

The monthly and annual performance calculated using the steady periodic one-day results is compared with the performance predicted by TRNSYS simulations for a yearly period.

The monthly solar fraction, f, is defined as in Equation 2.14.2, except that in this case Q_{AUX} and Q_L represent the monthly auxiliary energy use and water heating load. A monthly value of the dimensionless factor Y is defined analogously to Equation 2.14.4 as follows:

$$Y = \frac{A_g \frac{A_a}{A_g} F_R (\tau\alpha)_{e,n} \bar{H}, \bar{R}, \bar{K}_{\tau\alpha}}{\bar{Q}_L} \qquad (2.14.6)$$

where

$\bar{H}$ = the monthly-average daily radiation per unit area on a horizontal surface

$\bar{R}$ = the ratio of the monthly radiation on the collector plane to that on a horizontal surface

$\bar{K}_{\tau\alpha}$ = the monthly-average incidence angle modifier

Q_L = the monthly-average daily hot water load

Monthly-average daily horizontal radiation data are available for more than 200 locations in North America (Knapp, Stoffel and Whitaker, 1980). $\bar{R}$ can be estimated (when tilt radiation data are not available) as described in Klein and Theilacker (1981). A method of calculating $\bar{K}_{\tau\alpha}$ can be found in Klein (1979).

Methods in estimating ϕ, the monthly-average solar radiation utilizability, are available (Klein, 1978; Mitchell, Theilacker and Klein, 1981; Evans, Rule and Wood, 1982); in the results which follow, the algorithm of Mitchell, Theilacker and Klein (1981) is applied. In order to estimated, a monthly-average critical level, $\bar{I}_c$ must be specified. $\bar{I}_c$ is defined in analogy with I_c in Equation 2.14.5.

$$\bar{I}_c = \frac{\frac{A_a}{A_g}F_RU_L}{\frac{A_a}{A_g}F_R(\tau\alpha)_{e,n}}\left(\bar{t}_s-\bar{t}_a\right) \tag{2.14.7}$$

where

$\bar{t}_s$ = a monthly-average system operating temperature

$\bar{t}_a$ = the monthly-average ambient temperature. (As indicated by Evans et al. (1982), using the daytime-average in place of the 24-hour monthly-average ambient temperature has little effect on the calculated value of ϕ.)

The system operating temperature for the short-term tests is measured during the test procedure as described in Section 2.14.3. On a monthly-average basis, however, measurements are not available. A monthly-average system operating temperatures, $\bar{t}_s$, is needed in order to evaluate the utilizability and thereby use the steady periodic one-day test results to estimate monthly performance. An appropriate definition of $\bar{t}_s$, for this purpose is the monthly-average temperature of stored water heated by solar energy. $\bar{t}_s$ was calculated in the TRNSYS simulations. For single-tank systems, $\bar{t}_s$ was taken to be the monthly-average value of the average temperature in the lower three sections of the storage tank. (The top section is maintained at the delivery temperature by the heating element). For double-tank systems, $\bar{t}_s$ was simply the monthly-average temperature in the preheat tank.

This procedure for estimating the long-term average thermal performance from the steady periodic one-day test results is as follows:

Step 1: $\bar{Y}$ is evaluated using Equation 2.14.6.

Step 2: A guess is made for $\bar{t}_s$.

Step 3: $\bar{I}_c$ is calculated using Equation 2.14.7.

Step 4: ϕ is evaluated at a critical level of $\bar{I}_c$ using the algorithm in either Mitchell, Theilacker and Klein (1981) or Evans, Rule and Wood (1982).

Step 5: The product of ϕ and $\bar{Y}$ is calculated and used (in place of ϕY) to obtain a value of f from the correlation based on short-term ASHRAE Standard 95-1981 test results.

Step 6: $\bar{t}_s$ is calculated using Equation 2.14.12. If this value of t_s differs significantly from that used to calculate $\bar{I}_c$ in Step 3, steps 3-6 through six are repeated until convergence is obtained. Convergence can be achieved by successively substituting the newly calculated value of $\bar{t}_s$ back into Step 3; however, at high solar fractions, the use of an iterative solution technique such as Newton's method greatly reduces the number of iterations required.

Step 7: The annual solar fraction, F, is calculated from

$$\frac{\bar{t}_s-t_m}{t_d-t_m} = 0.688\left(\bar{f}+f_o\right) + 0.201\left(\bar{f}+f_o\right)^2 \tag{2.14.12}$$

$$F = \frac{\sum_{i=1}^{12}\overline{f\,Q_L}}{\sum_{i=1}^{12}\bar{Q}_L} \tag{2.14.13}$$

The annual solar fraction should be used (along with a consideration of parasitic energy consumption reported with the short-term test results) as the basis for rating SDHW systems.

2.14.5 References

ASHRAE Standard 93-1977, 'Methods of Testing to Determine the Thermal Performance of Solar Collectors', American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA 30329, revised printing 1978.

de Winter, F. (1975), 'Heat Exchanger Penalties in the Double Loop Solar Water Heating Systems', *Solar Energy*, vol. 17, pp. 335-338.

Duffie, J.A. and W.A. Beckman (1980), 'Solar Engineering of Thermal Processes, Wiley-Interscience, New York.

Evans, D.L., T.T. Rule and B.D. Wood (1982), 'A New Look at Long-Term Collector Performance and Utilizability', *Solar Energy*, vol. 28, pp. 13-24.

Klein, S.A. (1978), 'Calculation of Flat-Plate Collector Utilizability', *Solar Energy*, vol. 21, pp. 393-402

Klein, S.A. (1979), 'Calculation of the Monthly-Average Transmittance-Absorpance Product', *Solar Energy*, vol. 23, pp. 547-551

Klein, S.A. and A.H. Fanney (1983), 'A Rating Procedure for Solar Domestic Water Heating System', *ASME Journal of Solar Energy Engineering*, vol. 105, pp. 430-439.

Klein, S.A. and J.C. Theilacker (1981), 'An Algorithm for Calculating Monthly Average Radiation on Inclined Surfaces', *ASME Journal of Solar Energy Engineering*, vol. 103, pp. 29-33.

Knapp, C.L., T.L. Stoffel and S.D. Whitaker (1980), 'Insolation Data Manual', Solar Energy Research Institute, Golden, CO, 80401.

Mitchell, J.C., J.C. Theilacker and S.A. Klein (1981), 'Calculation of Monthly average Collector Operating Time and Parasitic Energy Requirements', *Solar Energy*, vol. 26, pp. 555-558.

Rabl, A. (1981), 'Yearly Average Performance of the Utilizability Principal Solar Collector Types', *Solar Energy*, vol. 27, pp. 215-234.

2.15 UNITED STATES - OREGON DEPARTMENT OF ENERGY

2.15.1 Purpose

This document is a guide for determining the thermal performance of ICS and thermosiphon systems. The methods are written to be consistent with testing procedures specified in ASHRAE Standard 93-77, ASHRAE Standard 95-81, ISCC Standard 80-1 and ISCC Standard 82-3. (See Section 2.15.4.)

2.15.2 Scope

This document applies to passive solar water heating systems and is intended to provide data for determining thermal performance of those systems. Systems must also meet the design criteria and durability standards specified in ISCC 82-3. The manufacturer may submit ISCC approval or sufficient information to enable the Oregon Department of Energy to determine that the system complies. In addition, Oregon has specified requirements for freeze tolerance which must be met by all systems.

The procedure does not include a specific standard for safety. Safety must be considered and attention is directed to the following documents.

A. Underwriters Laboratory (1979), 'Underwriters Laboratory Standard for Solar Collectors: Proposed Standard UL1279'

B. The Council of American Building Officials (1980), 'Recommended Requirements to Code Officials for Solar, Heating, Cooling and Hot Water Systems', (Model document for Code Officials on Solar Heating and Cooling of Buildings [CABO])

C. Local Building and Plumbing Codes.

2.15.3 Test Methods for Solar Systems

2.15.3.1 Volume Measurement

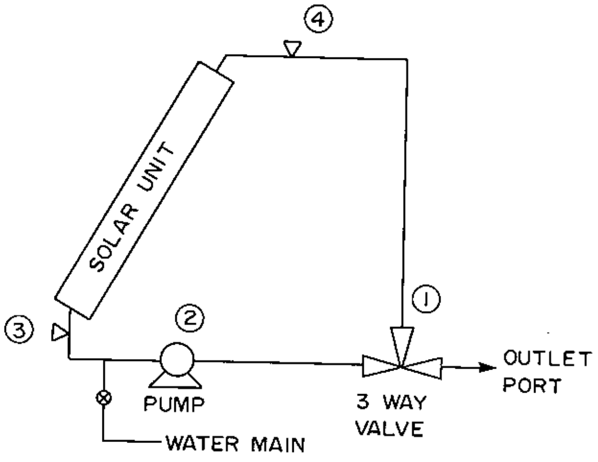
The volume of the storage unit in the solar system shall be measured. During normal operation, it is quite possible for an air bubble to fill a portion of the storage tank. The tank should be filled as if it were in normal operation at a typical installation tilt, with no attempt to dislodge a normally occurring air bubble. The volume of water in the storage tank shall be determined by draining the water into smaller containers which can be weighed. The temperature of the water shall be recorded. The volume shall be calculated as $V = (W_F - W_O)/R$ where: V = volume, W_F = filled weight, W_O = empty weight, and R = density of water at the specified temperature. The sum of all the volumes shall be reported as the storage volume. The volume is used for estimating annual performance although it is not necessary to the thermal performance test.

2.15.3.2 Thermal Performance Test

The thermal performance test determines the heating efficiency of the solar collector over a range of operating temperatures. Efficiency is defined as the ratio of collected energy to the total available solar energy falling on the collector area. Collected energy is determined by the product of the fluid thermal mass times the change in temperature of that mass. Available energy is determined by the integrated solar irradiance. Typically, two installations are set up side by side and data points of five hours duration are taken at two different starting temperatures. The collector is allowed to cool at night in order to establish the night cooling losses. The procedure is repeated for a second and third day. The test procedure is written for an outdoor test; however, it is possible to test under a solar irradiance simulator according to procedures specified in ASHRAE 95-81.

Instrumentation. Instrumentation specifications are as specified under ASHRAE 93-77. The recording pyranometer should be capable of integrating the solar irradiation over the test period. Both direct and diffuse irradiation fractions shall be reported.

Experimental Configuration. The unit to be tested shall be installed with a configuration as indicated in the figure:



To shorten the number of test periods, two solar systems are tested side by side. The collector units are covered until the start of the test. The configuration includes a 3-way diverter valve at #1, immersed thermosensors at #3 and #4, and a pump at #2. The pump must be capable of circulating the storage volume in about 10 minutes. Usually a 1/30 horsepower circulator is adequate.

The experimental set-up allows for cold water to enter through the pump with the three-way diverter valve #1 rotated to an outflow position. After the unit has been filled, three-way diverter valve #1 is rotated to permit pumped flow of the fluid from the top to the bottom of the storage tank. A temperature sensor is inserted at the storage tank outlet and the make up water inlet. All pipelines and the pump are insulated with a minimum of R-4 insulation.

Test Sequence. The thermal test sequence is as follows:

1. System inspection and inventory of all components.
2. Verify system installation as specified above and as specified in manufacturers documentation.
3. One system charged with cold water not exceeding 57°F (14°C) water initially. The other is charged with hot water at approximately 110°F (43°C). Both systems are circulated to uniform temperature and that temperature recorded before start of the test.
4. Collectors are uncovered and exposed to solar radiation for the specified measuring period from 0930 to 1430 hours relative to solar noon at 1200 hours.
5. At the end of a measuring period, recirculate the tank water in both systems by turning on the pump until the temperature is uniform (approximately 10 minutes) prior to recording a temperature measurement.
6. Record the circulated tank temperature at 0930 and 1430 hours.
7. Leave the tanks overnight to measure the cooling loss.
8. Repeat steps three (3) through six (6) for two more days. On the second day use the test period from 0800 to 1350 hours.
9. Perform the specified water withdrawal test to measure the thermal mass.
10. Report preparation.
11. Data analysis.

During the testing procedure, the ambient air temperature shall be monitored and recorded at 15 minute intervals. The use of a datalogger which will average the readings is recommended.

Document that the components are correctly and completely assembled according to manufacturer's recommendation. List and describe all components. The installation must conform to usual installation practice as described in the manufacturer's installation instructions.

Install the system with the configuration specified in 2.15.3.2 (Experimental Configuration). The solar collector unit shall be oriented due south and tilted to allow an incident angle at solar noon that is as close as possible to normal. An exception may be allowed for units whose supporting documentation specifies a different tilt. The system is tested without any external reflectors.

The pyranometer shall meet the requirements specified in ASHRAE 93-77 and shall be mounted with its sensor coplanar to the plane of the collector aperture. It shall not cast a shadow onto the collector aperture at any time during the test period. The pyranometer shall not be mounted so as to receive a percentage of reflected radiation that is disproportionate with that received by the collector. It is recommended that the pyranometer be mounted near the upper-half periphery of the collector and in the upper center of the collector array. The pyranometer should be oriented so that the emerging leads or the connectors are located north of the receiving surface or are otherwise shaded to minimize solar heating of the electrical connections. Care should be taken to minimize reflected and reradiated energy from the collector onto the pyranometer. The pyranometer must be capable of integrating readings over the test period.

Identification of the aperture plane may be difficult for curved or cylindrical collectors. Generally, the aperture plane will be the plane that contains the long axis of the collector and also faces due south.

Charge one system with cold water at a temperature of 57°F (14°C) or less entering through the pump. This requires that three-way valve #1 be rotated to allow flow from the collector to the outlet port. The method ensures that air is purged from the pump subsystem. After the unit is filled, rotate three-way valve #1 to allow flow from the collector to the pump. Circulate the fluid until the temperature is uniform (approximately 10 minutes). Stop circulation and record the initial temperature on Sensor #4. Repeat the same process to charge the other system with hot water at 110°F (43°C). The easiest method to charge the system is to fill it with water one day ahead of the test and allow it to be solar-heated. It can also be charged with hot water from a conventional hot water heater. For subsequent tests, the unit with the hottest water can be used for the hot filled unit. The cold filled unit should be filled from the water main. The purpose is to ensure that duplicate tests are performed under different inlet parameter conditions. Errors are minimized by testing two units under the same irradiance.

Initiate the test at 0930 hours relative to solar noon at 1200 hours. Uncover the collectors and expose the unit to solar radiation. Make sure that the pyranometer begins to collect integrated readings starting at the same time. Record ambient temperatures at intervals of 15 minutes.

At 1430 hours the test period ends. Cover the collectors and circulate the water until a uniform temperature is established. Record the temperature on Sensor #4. Repeat the same process for both systems.

Night Cooling. Circulate the water in the warmest tank at 1700 hours. Record the time and the temperature after it reaches uniformity. Shade the collector from any sunlight but do not cover the collector overnight. Continue to record ambient temperature at 15 minute intervals. On the next morning, circulate the water at 0800 hours or before the sun rises. Record the water temperature after it has stabilized. Record the precise duration of the cooling period.

Continue the test procedures as described in steps 3 through 5 for two more days. On the second day use the test period from 0800 to 1300 hours. On the third day, use the test period from 1100 to 1600 hours.

Thermal Mass Measurement. At the end of the last test period, use the storage unit which is filled with the hottest water and which has been circulated to achieve a uniform temperature. Cover the collector to prevent further solar gain. Rotate valve #1 to allow a draw from the collector to the outlet port. Draw approximately 10 gallons (40 liters) of water out of the unit. Rotate Valve #1 to permit flow from the pump to the collector unit. Circulate the unit again until it has reached a new uniform temperature. Record the inlet temperature on Sensor #3, the initial circulated temperature, the final circulated temperature and the precise volume of water removed.

2.15.3.3 Reporting of the Data

The raw data will be reported in the following format. List for each model tested the tank temperatures at start and end of the test period. For the same periods of time, list the solar irradiation and average ambient temperatures during the measurement intervals. List the direct and diffuse fractions as specified in ASHRAE 93-77 Section 8.3.2. For the intervening night cool-down, list the tank temperatures at the start and end of the period, the duration of the period, and the recorded hourly average ambient temperatures. For the thermal mass measurement, list the initial temperature, the final temperature, the make-up water temperature and the precise volume drawn off.

2.15.3.4 Data Analysis

Heating efficiency of the unit will be calculated by the following procedure. First, establish the thermal mass of the system. Second, establish the heating efficiency for the test intervals. Third, establish the inlet parameter for the measurement intervals. Fourth, plot the results graphically to establish the slope and intercept parameters. Fifth, establish the exponential night cooling constant.

A. Calculate the thermal mass of the unit:

$$M = \frac{V\left[\left(Cp_i T_i\right) - \left(Cp_m T_m\right)\right]}{T_i - T_F}$$

where

M = Thermal mass
V = volume of water withdrawn
$(Cp)_i$ = specific heat of water at initial temperature
$(Cp)_m$ = specific heat of water at water main temperature
T_F = final temperature
T_m = water main temperature

B. The heating efficiency is established for each of the test periods:

$$\eta = \frac{M\left(T_F - T_i\right)}{I}$$

where

η = heating efficiency
M = thermal mass
T_F = final temperature
T_i = initial temperature
I = integrated solar irradiation over the 5 hour period.

C. The inlet parameter is established for each of the test periods:

$$P = \frac{5\left(T_i - T_{amb}\right)}{I}$$

where

P = inlet parameter
T_i = initial temperature
T_{amb} = average ambient temperature during the test interval
I = integrated solar radiation during the 5 hour period.

D. Results are plotted graphically as η versus P for each test period. A least squares fit of the data points is used to establish the intercept and slope of the efficiency curve.

At least six data points must be used. No points may exhibit excessive departure from the calculated least squares line. Excessive departure will be considered as a difference in the efficiency value which exceeds the least squares line at the same inlet parameter by one or more standard deviations compared to the differences of the other data points. The test procedure may need to be repeated if at least six good quality data points are not apparent. The data points must also represent equal numbers of morning, noon, and afternoon test periods. A slight difference in efficiency may occur during these different periods and the reported result must be the equally weighted average.

E. Calculate heat loss coefficient. The exponential cooling coefficient is calculated from the natural logarithm of the initial and final temperature differences.

$$\ln \frac{\left(T_i - T_{amb}\right)}{\left(T_F - T_{amb}\right)} = kt$$

where

T_i = the temperature at the start of the cooling period
T_F = the temperature at the end of the cooling period
T_{amb} = the average ambient temperature during the night
t = the time interval, in this case 10 hours
k = the exponential cooling coefficient

The exponential cooling coefficient is related to the heat loss as follows:

$$k = (UA)_L/M$$

where

M = the thermal mass
$(UA)_L$ = the heat loss coefficient

Solve for $(UA)_L$ and report this result. This result should be very similar to L, the heat loss coefficient calculated in the test procedure ISCC 81-3. The difference is that the ISCC procedure specifies a fan to duplicate wind cooling effects. Results from the ISCC test can be substituted if a manufacturer chooses to simplify the procedure.

2.15.3.5 Use of the Solar Simulator

A similar test procedure may be followed using a solar simulator as specified under ISCC 82-3. Under these conditions, the ambient environment shall be controlled to 22.0 ±2°C (71.6 ± 3.6°F). Ambient temperatures shall be recorded at 1 hour intervals. Input water temperature shall be as specified in Section 2.15.3.2 (Test Sequence). The collector unit shall be mounted at 45° tilt and exposed to the same irradience profile as specified under ISCC 82-3. The test may be performed on a single collector unit.

The collector is initially charged with cold water. The water is circulated as previously described and the temperature recorded. The test period shall be from 0800 to 1230 hours. At the end of the test period, the water will be circulated and the temperature recorded as described in Section 2.15.3.2 (Test Sequence).

A new test period shall be started from 1230 to 1700 hours. Procedure is as described in Section 2.15.3.2 (Test Sequence).

A night cooling test is performed on the unit from 1700 to 0800 hours the next morning. Procedure is as described in Section 2.15.3.4 (Test Sequence). The manufacturer may substitute the night heat loss results from the ISCC 81-3 test procedure.

Following the cooling test, the unit should already be filled with water at a uniform temperature. A new test period is started from 0800 hours to 1230 hours as described in Section 2.15.3.2 (Test Sequence).

Thermal mass test shall be as specified in Section 2.15.3.2 (Thermal Mass Measurement).

Data analysis proceeds as described in Section 2.15.3.4 (Data Analysis). Calculations involving the length of the heating period are corrected to use a duration of 4.5 hours. The slope and intercept must be calculated from at least four data points composed of equal numbers of morning and afternoon test periods.

2.15.4 References

American National Standards Institute 'Performance Specifications and Methods of Test for Safety Glazing Material Used in Buildings', ANSI 1430 Broadway, New York, NY 10018.

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U.S. Department of Housing and Urban Development (1977), 'HUD Intermediate Minimum Property Standards Supplement', Solar Heating and Domestic Hot Water Systems, Document 4930.2

3.0 *REVIEW AND CONCLUSIONS*

3.1 SUMMARY

Section 1.1 indicated the many factors including the system design, meteorological variables, control strategies and usage, which influence SDHW system performance, and which may or may not be taken into account in a test. The form of approach adopted when developing a procedure for testing SDHW systems is largely determined by the relative importance given to these various elements. In the section that follows there is a discussion of the features which would be desirable in a general-purpose test method designed to meet the different needs of the IEA participating countries.

In Section 3.2, a brief overview is given of the different types of SDHW system testing that are presently available. The test methods described in Chapter 2 are classified according to common features that have suggested ways in which they could be synthesized into perhaps two or three distinct methods. In each case, an indication is given of the direction in which the collaborative work of Task III is intended to proceed.

Finally, in Section 3.3, the conclusions of the report are summarized.

3.2 TYPES OF APPROACH ADOPTED IN THE METHODS CONSIDERED

The methods described in Chapter 2 can conveniently be classified firstly according to whether the test measurements are made on the whole system, on individual components, or on both, and secondly according to whether the procedure results in a characterization of the system performance as a function of external (meteorological) variables, in terms of internal (thermal) variables only, or as a single-valued rating. Accordingly, we have the following types of method:

A. System performance for a range of weather conditions characterized by parameters determined from individual component tests

In this approach, the test consists of a battery of separate component tests to identify individual component parameters such as the collector efficiency with the inlet temperature equal to the ambient temperature, the collector loss coefficient, heat-exchanger effectiveness, store loss coefficient, and so on.

The prediction of long-term performance is generally by detailed simulation, but could also be by some form of simplified model whose parameters can be calculated from the measured values of the component parameters.

Measurements on the whole system are used only to verify that with the measured values of the component parameters the simulation model provides an accurate description of the system performance. The more detailed the model, and the more variables that are measured in the short-term validation, the more easily can this approach be used as a diagnostic test of system malfunction.

Examples of this kind of test are the TPD indoor method (2.8.2) (the component parameters in the TPD test are actually determined from a whole system test.), and the Danish test method (2.6). It is not always necessary to determine the component parameters from completely separate component tests. Often it is possible to get the relevant information about the component parameters out of the system test. The Danish test method can be used both indoors and outdoors. For convenience, methods of this type could be referred to as 'simulation methods'.

As a contribution to the development of simulation methods the Task III Participants have begun to draft procedures for component tests which, after careful validation, will be published as joint recommendations. It is also planned to draw up recommendations on the form of presentation of the long-term performance predictions and on requirements for the validation procedures. The detailed or simplified simulation models used in these methods will not be the subject of any collaborative development or validation, as this lies outside the scope of the Task. Clearly, however, the validity of a particular test method depends critically on the applicability of the simulation model to the system under test.

B. System performance for a range of weather conditions determined from measurements on the whole system

These are methods in which the performance of the system is characterized by a correlation or by a model, and where the form of the correlation or the values of the model parameters for the system under test can be determined directly from measurements on the whole system. The same correlation or model, suitably weighted or extrapolated, provides the method of long- term performance prediction.

Among methods of this type are the Australian indoor and outdoor methods (2.1) and (2.2), which use a simplified f-chart type correlation, the TPD outdoor method (2.8.3), which produces input-output subsystem efficiency curves, the UK SEU method (2.11), based on the correlations by Kenna, the US ASU method (2.12), based on f-chart utilizability type correlations, the CEC JRC method (2.5) which produces an input-output correlation, the Munich University method (2.7.1), in which sufficient measurements are to be taken on the system that individual component parameters of a more detailed simulation model can be identified, and the Swiss SOFAS method (2.10), in which the individual component parameters of a more detailed simulation model are calculated from in-situ measurements for a few weeks under real operating conditions. Note that it is the only possibility of using system measurements alone which characterizes these methods; in many cases partial information may be also obtainable from individually-measured component parameters. In view of the methods of data analysis required by these methods, it may be useful to refer to them as "system- identification methods".

System-identification methods have an advantage over simulation methods in that the long-term performance prediction is based directly on system measurements. The prediction will therefore reflect any difference between actual system performance and the design performance of the system. For this reason, the Task III Annex proposed the development of methods of this type as the objective of Subtask E, and this has a strong influence on the direction of the work.

C. System performance for a range of weather conditions determined from a combination of separately-measured component parameters and whole system measurements

These methods include those in which the performance of the system is characterized by correlations or model parameters that cannot be determined solely from measurements on the system. Examples are the Sweden/France method (2.9) and the US NBS method (2.14).

In the Sweden/France method, the usual collector parameters are measured using established test methods, and the storage-tank loss coefficient is measured in an overnight heat-loss test, while estimates of the storage thermal mass and a collector-store loop efficiency are obtained from indoor or outdoor measurements on the whole system. These parameters are fed into a simplified simulation program (OSOL) which predicts the long-term performance.

The US NBS method was devised to provide a means of long-term performance prediction from the measurements performed in the ASHRAE-95 procedure. The method makes use of correlations involving short- and long-term daily utilizabilities, which gives it a much wider applicability than methods based on correlations of the original f-chart type. In order to compute the utilizabilities, however, values of the collector parameters have to be determined by separate test measurements.

Variants of the system-identification methods, where some of the system parameters are calculated in terms of separately-measured component parameters, could also be included among these methods. If all the system parameters were determined in this way, of course, the method would count as a simulation method.

Because they lie somewhere in approach between the simulation methods and the system-identification methods, it will be convenient to refer to this methods as "hybrid methods".

In view of the advantages seen for system-identification test methods, it may be felt better to identify model parameters from system measurements whenever possible. When this is not possible, however, the development of a hybrid method may be amply justified by other inherent advantages. There are features of the methods described which would be of considerable advantage in any type of method, and which are likely to have a strong influence on the final outcome of the programme.

D. System performance determined as a function of internal variables from measurements on whole system

The methods of this category were developed for systems with thermosiphon operation. They are the Belgium Mons method (2.3), which is directly applicable only to integrated collector storage (ICS) systems, and the Oregon DOE method (2.15). Both can be used indoors or outdoors, and, in both, the system performance is characterized by correlation between the efficiency of operation and the operating temperature. Separate parameters describe the heat loss from the store.

Because these methods provide a partial solution to the long-term prediction of system performance, they could be described as "partial methods".

In view of the considerable and growing interest in thermosiphon systems, a study within Task III of how these methods could be developed would be of great value. In particular, correlations or simplified models that can be extended to thermosiphon systems would provide a means of predicting their performance for given demand patterns in terms of meteorological data.

E. System performance determined for specific test conditions only.

In these methods the performance of the system is measured in a specific set of conditions, and this performance is taken as a measure of the quality of the system. If the conditions are repeatable, as in a solar simulator or outdoors in a very dependable climate, then a comparison of the performances of different systems in the test can be used to compare the systems. If the conditions can be such that the test performance is representative of the long-term performance of the system in a given climate and with a specified usage, then (by simple multiplication) the method provides an estimate of long-term performance.

However, the method does not as a rule provide a means for predicting the performance in other conditions.

Examples of such methods - commonly described as "rating methods" - include the ASHRAE-95 method using a solar simulator (2.13), and the Canadian Method (2.4), which was developed from ASHRAE-95 but with test conditions typical of Canada.

Also included in this group are methods in which the performance rating is determined from a combination of separately-measured component parameters and measurements on the whole system. An example is the ASHRAE-95 method using a thermal simulator (2.13), in which the solar-collector parameters are determined, and in the test the collectors are replaced by a heater giving the same thermal output.

Because rating methods do not provide a flexible means of predicting long-term performance, they do not in themselves meet the objectives of the Task. They can, however, with additional measurements or analysis, provide an experimental basis for a more general test method - as the US ASU and the US NBS methods using results from the ASHRAE-95 method. Hence within Task III rating methods are being studied on the same basis as the other methods for the contribution they can make to the common procedures under development.

3.3 CONCLUSIONS

A variety of methods of testing SDHW system performance exist or are under development. These methods have generally been designed to meet different specific requirements. In this document the authors of a number of methods have described the principles of their methods, outlined the experimental procedures, and indicated the state of development of the method. They have also drawn attention to the possible advantages and disadvantages of each approach.

The IEA Task III participants have identified a number of common objectives in SDHW testing, and are undertaking a joint programme to develop common test procedures that incorporate the best features of the individual methods. The report has indicated the way in which this development is taking place.

During the period 1986 - 1987, following the drafting of agreed test procedures, an experimental programme of validation will be carried out within the participating laboratories. This work will culminate in the publication of joint recommendations for testing SDHW systems and reporting the results, in 1988.

CONTRIBUTORS TO THIS REPORT

Dr. H.E.B. Andersson
Swedish Council for Building Research
Sankt Goransgatan 66
S-112 33 Stockholm
Sweden

Mr. C. Boussemaere
Fac. Polytecnhique de Mons
31 Bld. Dolez
B-7000 Mons
Belgium

Mr. D. Gilliaert
Joint Research Centre, Euratom
I-21020 Ispra
Italy

Mr. S.J. Harrison
Solar Calorimetry Laboratory,
Dept. of Mech. Eng.
Queens's University
Kingston, Ont.,
Canada, K7L3N6

Dr. G. Morrison
School of Mechanical Engineering
University of South Wales
Sydney
Australia

Mr. J.E. Nielsen
Mr. O. Raun
Danish Solar Energy Testing Laboratory
Technological Institute
P.O. Box 141
DK-2640 Tästrup
Denmark

Dr. D. Proctor
Division of Energy Technology
CSIRO
P.O. Box 76
Highett Victoria 3190
Australia

Mr. W. Schölkopf
Sektion Physik
Universität München
Amalienstr. 54
D-8000 München 40
FR Germany

Dr. J.M. Suter
Eldg. Institut für Reaktorforschung
CH-5303 Würelingen
Switzerland

Mr. S. Svendsen
Thermal Insulation Laboratory
Building 118
Technical University of Denmark
DK-2800 Lyngby
Denmark

Ir E. Van Galen (dec.)
Ir J. Havinga
Institute of Applied Physics
TNO-TH
P.O. Box 115
2600 AD Delft
Netherlands

Dr. D.B. Wood, Director
Center for Engergy Systems Research
College of Engineering & Applied Sciences
Arizona State University
Tempe, AZ 85287-5806, USA