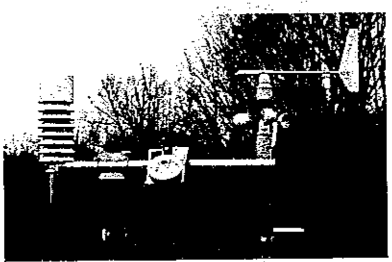
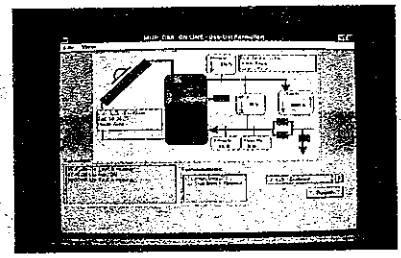
IEA ADVANCED SOLAR ENERGY SYSTEMS

INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

Dynamic Testing of Active Solar Heating Systems





Final Report of the Task 14
Dynamic Component and
System Testing Subtask

Volume B

Solar Domestic Hot Water System Testing

IEA Report no. T.14.DCST.1B

Dynamic Testing of Active Solar Heating Systems

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Solar Domestic Hot Water System Testing

Edited by:
Huib Visser

April 1997

INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

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Information on the status and availability of the standards and matching software tools mentioned in this report can be obtained from:

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Standards Australia
c/o Mr. M. Maffuci
1 The Crescent, Homebush 2140 NSW
Australia

and:

Secretarial CEN / TC 312
Centre for Renewable Energy Sources
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EXECUTIVE SUMMARY

Objectives and scope

Dynamic testing has grown into a sound method for performance characterization of solar energy components and systems. The power of dynamic data processing was demonstrated before for solar domestic hot water systems. Now, further experience has been gained for solar collectors and heat stores, both small and large in size, for outdoor laboratory tests and in situ measurements. Data processing been evaluated and test procedures for reliable and accurate performance characterization, including prediction, have been designed. This report describes experiences of the participants in the Subtask on Dynamic Component and System Testing (DCST) within Task 14 of the International Energy Agency's Solar Heating and Cooling Programme.

Work was carried out in three Groups:

I. on Dynamic Collector Testing (DCT);
II. on Dynamic System Testing (DST) of solar domestic hot water (DHW) systems;
III. (a) on Component Testing and System Simulation (CTSS) of small solar heating systems and (b) on in situ testing of large solar heating systems.

The work of these Groups constitutes the scientific basis for the present status in ISO and CEN standardization on solar energy components and systems.

General features of dynamic testing and measuring

Dynamic fitting is the inversion of dynamic simulation: simulation yields the component or system output using given model parameters, whereas dynamic fitting provides the model parameters from the measured component or system output.

The several dynamic fitting procedures, investigated by the DCST participants, all feature a black box approach in which a so-called parameter identification technique is combined with an appropriate mathematical model of the solar energy component or system. Measured output behaviour of the component or system is compared with the corresponding calculated quantity from the model. The calculated output depends on the model parameters. In an iterative optimization procedure, the deviation between calculated and measured output is minimized through adaptation of the parameter values. After dynamic fitting, the same mathematical model is commonly used for long term performance calculations for reference meteorological and load conditions.

Since no stationary test conditions have to be obtained, the measuring procedure, especially outdoor, can be shorter and less expensive. Since effects for the all day performance are taken into account, characterization can be more complete as well. Moreover, identical models for parameter identification and simulation give more accurate long term performance predictions compared to model calculations based on specifications determined from stationary tests. However, accurate and reliable characterization requires variability of component or system input sufficiently tuned into the model parameters.

Activities, results and recommendations of Group I on dynamic collector testing

Work in Group I involved investigation of various solar collector models and parameter identification techniques as well as design of a dynamic collector test procedure for outdoor laboratory testing. Main goal of the work was to investigate the extension of the present stationary ISO test standard to non-stationary testing using normal meteorological and operating conditions. Second order collector properties can be taken into account in this way so that a much wider range of collector types can be characterized accurately.

Three collector models were developed and evaluated. For one model, correction terms for diffuse irradiation, wind velocity, sky temperature, wind dependency of the zero loss collector efficiency, and possible piping heat loss were added to the terms of the stationary ISO standard, which already includes zero loss efficiency, temperature dependent heat loss coefficient, incident angle dependency of the zero loss efficiency and effective heat capacity of the collector. Local heat loss and thermal capacity have been incorporated in the other two models so that low flow collectors can be characterized more accurately. For parameter identification, both the Marquardt-Levenberg solution method has been used and a special version of the multiple linear regression method.

The test procedure includes steps up and down in collector inlet temperature together with requirements on solar irradiation and wind velocity. In order to fulfil the requirement of backwards compatibility to stationary testing, however, the most advanced possibility with rapidly varying inlet temperature has been left out so that both stationary and dynamic properties can be derived from the same test. As no continuous good weather is needed, the dynamic collector test takes only about two weeks for the average mid-European climate, which is half the time of the full stationary test. In spite of the shorter testing time, a much more complete and realistic characterization of the collector is derived.

Experimental results from dynamic collector testing show that different models and parameter identification methods show very small differences for routine testing. However, standard ISO testing has been combined now with determination of incident angle modifier and heat capacity in one single, shorter test. Moreover, a much wider range of collectors, from unglazed swimming pool collectors to concentrating collectors for high temperature applications, can be handled correctly by dynamic testing in comparison to the stationary methods needed for these varieties. Scientific work on the dynamic collector test method has finished and the method has partly been validated. Further thorough validation of the DCT method is still needed for standardization purposes.

Activities, results and recommendations of Group II on dynamic testing of solar DHW systems

Activities of Group II focused on the development and evaluation of an outdoor laboratory test procedure for small solar DHW systems including further assessment of data processing using the so-called model P. This general model contains four parameters for main characterization of solar collector and heat store, and five more parameters describe system behaviour in more detail. The procedure forces the solar DHW system to be tested in its most important system states in order to obtain accurate parameters and annual performance prediction.

Tests were carried out for solar DHW systems with spectral selective flat plate collectors, forced circulation in the collector loop and an electric element for auxiliary heating. The tests revealed accurate and reproducible results, both in identified parameters and annual performance calculations. Further investigations on solar pre-heat and solar plus supplementary systems were performed based on simulated test data. Results confirmed the power of the DST method for a wide range of factory-made systems. Preliminary boundaries of the method were determined to be the temperature dependency of the heat loss coefficient and incident angle dependency of the zero loss efficiency of the collector.

Main recommendations for standardization activities are further determination of the application range for the DST method as well as additional experimental validation.

Activities, results and recommendations of Group III on component testing and system simulation

Participants in Group III contributed to CTSS with scientific developments and investigations on heat store testing, development of a test concept to translate component testing into performance predictions for the whole system and experimental validation of the reliability and accuracy of the whole method.

Two heat store models, i.e. a multi-port and a plug flow model, have been developed and evaluated for data processing and simulation. A special indoor test procedure has been created for inducing physical effects for accurate determination of heat store characteristics from measurements of flow rates and inlet and outlet temperatures for thermal charge and discharge. Parameters include effective heat capacity, heat loss rate, heat transfer rate of heat exchangers, possible auxiliary volume, thermal stratification and vertical thermal conduction. The method, applied on twelve heat stores, yielded reliable and reproducible results.

The CTSS procedure supports thermal performance characterization of custom-built solar energy systems, and consists of four steps, (1) dynamic testing of the solar collector, heat store and controller components, (2) check of the whole system by inspection of the various components including interconnections and documentation, (3) modelling of the whole system for the relevant system configuration, and if no validated system model is available, then (4) validation by a whole system test. Component testing followed by system simulation features flexibility, both in exchanging components and in application in a large range of custom built system types, including systems for combined hot water and space heating. The CTSS method was successfully performed in practice for eleven quite different solar DHW systems. Success was also confirmed by comparison with results from DST tests on these systems.

Standardization requires further validation of the heat store test method for other store designs, refinement of the CTSS procedure to strict guidelines and extension of the scope to other system configurations such as for combined solar DHW and space heating.

Activities, results and recommendations of Group III on in situ measuring

Group IIIb focused on in situ testing for commissioning of new large scale solar water heating plants and continuous monitoring of plants in operation. The goal of the work was to apply and further develop dynamic procedures for on site testing of these systems. The method used parallels the CTSS method. The main difference is that all measured data are acquired during regular operation of the plant. Participants carried out a number of studies, mainly concentrating on the collector array. They all used data sequences of several months or longer and cross-predicted the long term performance with models fitted to monthly sequences or shorter. The time resolution of the data varied from a few minutes, which was used in most studies, to one hour, and even one day. The latter was used together with a simple regression model. One single study covered the complete procedure and predicted the yearly gain of the solar heating system.

The precision achieved in the cross-predictions of the collector array output agrees well in all of the studies. The extreme figures are ± 3% and ± 7%. This agreement is remarkable considering the large variation both with respect to models and measurements. The single study on a complete system indicates that an inaccuracy only slightly larger is possible for a complete system test. The group concludes that an in situ performance test based on the dynamic testing technique is feasible, and that an overall inaccuracy better than ± 6% is within reach for the predicted long term solar collector output.

The group recommends that the work be continued with the objective to develop an in situ test procedure for large custom built solar heating systems based on the dynamic testing technique. The cost of applying the test on a routine basis should be a major consideration.

Overview of the DCST Subtask Final Report

The results of the participants activities have been presented in two Volumes of the DCST Subtask Final Report "Dynamic Testing of Active Solar Heating Systems". Both Volumes contain a note on the IEA and the DCST Group followed by summaries of the coordinated work. Further Annexes in both Volumes present a collection of papers of the DCST Subtask participants embodying the findings of dynamic testing and measuring of solar energy components and systems in more detail. Report summaries, prepared by the coordinators of the various Groups, describe the general experience of the DCST Subtask. Participants are responsible for the contents of the papers in the Annexes. Although references have been made to the participants contributions, summaries can be understood without reading the papers.

Volume A describes the investigations, results and recommendations of Group I on dynamic collector testing as well as Group III on CTSS for small solar heating systems and in situ measuring for large systems. Experiences of the Group II participants on dynamic testing of solar DHW systems have been presented in Volume B.

INTRODUCTION TO THE INTERNATIONAL ENERGY AGENCY AND THE DYNAMIC COMPONENT AND SYSTEM TESTING GROUP

The International Energy Agency

The International Energy Agency (IEA), located in Paris, was founded in 1974 as an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) to coordinate the energy policies of its members. The 23 member countries seek to create the conditions in which the energy sectors of their economies can make the fullest possible contribution to sustainable economic development and the well-being of their people and the environment.

The policy goals of the IEA include diversity, efficiency and flexibility within the energy sector, the ability to respond promptly and flexibly to energy emergencies, the environmentally sustainable provision and use of energy, more environmentally-acceptable energy sources, improved energy efficiency, research, development and market deployment of new and improved energy technologies, and cooperation among all energy market participants.

These goals are addressed in part through a program of collaboration in research, development and demonstration of new energy technologies consisting of about 40 Implementing Agreements. The IEA's R&D activities are headed by the Committee on Energy Research and Technology (CERT) which is supported by a small Secretariat staff in Paris. In addition, four Working Parties (in Conservation, Fossil Fuels, Renewable Energy and Fusion) are charged with monitoring the various collaborative agreements, identifying new areas for cooperation and advising the CERT on policy matters.

The Solar Heating and Cooling Programme

The Solar Heating and Cooling Programme was one of the first IEA collaborative R&D agreements to be established. Since 1977, its participants have been conducting a variety of joint projects in active and passive solar and photovoltaic technologies, primarily for building applications. The present twenty members are:

Australia	France	Norway
Austria	Germany	Spain
Belgium	Greece	Sweden
Canada	Italy	Switzerland
Denmark	Japan	Turkey
European Commission	The Netherlands	United Kingdom
Finland	New Zealand	United States

The overall Programme is monitored by an Executive Committee consisting of one representative from each of the member countries. The leadership and management of the individual research projects, or Tasks, are the responsibility of Operating Agents. A total of 22 Tasks have been undertaken since the beginning of the Solar Heating and Cooling Programme of which the first 14 have been completed so far. These tasks and their respective Operating Agents are:

Task 1	: Investigation of the Performance of Solar Heating and Cooling Systems - Denmark
Task 2	: Coordination of Research and Development on Solar Heating and Cooling - Japan
Task 3	: Performance Testing of Solar Collectors - Germany/United Kingdom
Task 4	: Development of an Insolation Handbook and Instrumentation Package - United States
Task 5	: Use of Existing Meteorological Information for Solar Energy Application - Sweden
Task 6	: Solar Systems Using Evacuated Collectors - United States
Task 7	: Central Solar Heating Plants with Seasonal Storage - Sweden
Task 8	: Passive and Hybrid Solar Low Energy Buildings - United States
Task 9	: Solar Radiation and Pyranometry Studies - Canada/Germany
Task 10	: Material Research and Development - Japan
Task 11	: Passive and Hybrid Solar Commercial Buildings - Switzerland
Task 12	: Building Energy Analysis and Design Tools for Solar Applications - United States
Task 13	: Advanced Solar Low Energy Buildings - Norway
Task 14	: Advanced Active Solar Systems - Canada
Task 15	: Not initiated
Task 16	: Photovoltaics in Buildings - Germany
Task 17	: Measuring and Modelling Spectral Radiation - Germany
Task 18	: Advanced Glazing Materials - United Kingdom
Task 19	: Solar Air Systems - Switzerland
Task 20	: Solar Energy in Building Renovation - Sweden
Task 21	: Daylighting in Buildings - Denmark
Task 22	: Building Energy Analysis Tools - USA

Task 14 on Advanced Active Solar Systems

Task 14 was initiated to advance the State-of-the-Art in active solar energy systems. Many features developed during the few years before the start of the Task, when used alone or in combination, had the potential to significantly improve the performance of these systems. It was the objective of Task 14 to analyze, design, evaluate and, in some cases, construct and monitor a number of different systems incorporating one or more of these features.

The work of the Task was divided into three Working Groups, based on the type of systems studied, and one Subtask dealing with dynamic testing. The goal of the Working Groups and the Subtask was to facilitate interaction between participants with similar projects. Participants were able to identify and address issues of common interest, exchange knowledge and experience and coordinate collaborative activities.

Domestic Hot Water Systems - Working Group

The focus of this Working Group was the development of advanced DHW systems using the "low flow" concept. Participating countries contributed expertise related to different system components. The collaborative work in the Task brought this expertise together to allow participants from each country to design systems which show a significant cost/performance improvement (as high as 45%) over systems on the market in their respective countries when the Task began.

Air Systems - Working Group
Task work concentrated on further development of a commercially available concept for the preheating of ventilation air in industrial and commercial buildings. This concept is a specially designed cladding system to capture the air heated by solar radiation on the south wall of a building. Four projects, two in Canada, one in the USA and one in Germany, were constructed using a perforated version of the wall. The German project adapted the concept to preheat combustion air for a district heating plant. The practical work of these projects was complemented by theoretical work conducted at the University of Waterloo in Canada and the National Renewable Energy Laboratory (NREL) in the United States. Task work demonstrated that the cost/performance of the perforated wall is over 35% greater than earlier versions of the design.

Large Systems - Working Group
The Task also examined large scale heating systems involving temperatures under 200°C. Five large systems were studied. They were all very different but each represented important applications of active solar systems. District heating, the subject of the Swedish project, can be used in most IEA member countries to provide space and water heating for communities. The German project also involved district heating but with no storage. A tulip bulb drying installation in The Netherlands explored the staggered charging and discharging of long term storage, a strategy which may find many uses, especially in agricultural applications. Solar desalination, the subject of the Spanish project, has wide application in water starved areas of the world and could represent a major export opportunity for IEA countries. Industrial process heat was represented by a project in Switzerland. Since virtually all large systems are custom designed, cost/performance improvements for this Group was not a meaningful measure of achievement. Documentation of lessons learned is the most important product of the work.

Dynamic Component and System Testing - Subtask
Attention of the DCST Subtask was directed to research and development of dynamic test and measuring methods for characterization of solar energy components and systems on the level of long term performance prediction from short term measuring periods.

Task 14 activities began in 1989 and were completed in 1995. The following countries participated in this Task: Canada, Denmark, Germany, the Netherlands, Slovenia, Spain, Sweden, Switzerland and the United States. Canada provided the Operating Agent.

Subtask on Dynamic Component and System Testing

The Subtask on Dynamic Component and System Testing (DCST) was added to Task 14 in 1993 and provided a continuation and broadening of work completed earlier by the IEA Dynamic Systems Testing Group (DSTG). The DSTG established that dynamic fitting (or parameter identification) was a suitable tool in processing laboratory tests and on site monitoring of solar DHW systems. Final DSTG results also included preliminary versions of test and measuring procedures for solar DHW systems.

In the DCST Subtask, work on definition of the dynamic laboratory test procedure for solar DHW systems was continued, and finally led to a Committee Draft for international standardization. Broadening of the work on dynamic fitting involved development of procedures for laboratory testing of solar collectors and heat stores and the data processing tools to match as well as investigation of in situ measurements from more locations. Work was carried out in three Groups:

I. Dynamic Collector Testing (DCT);

II. Dynamic System Testing (DST) of solar DHW systems;

III. (a) Component Testing and System Simulation (CTSS) of small solar heating systems and (b) In Situ Testing of large solar heating systems.

Participants in the DCST Subtask were:

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Coordinator of the DCST Subtask was Mr. P. Bremer. His leadership was brought to a brutal end by his sudden illness and death. His enthusiasm and dedication to the work on dynamic fitting and the fine organization talents may be an inspiration for all those people working in the solar energy field.

The report on the DCST coordinated activities consists of two Volumes. Volume A describes the combined dynamic testing of components and system simulation for small solar heating systems as well as in situ measurements of large solar heating systems. Volume B presents the work on dynamic testing of solar DHW systems. Both Volumes contain summaries of the work carried out followed by a collection of papers contributed by DCST participants describing the experiences with dynamic testing and measuring in more detail.

SUMMARY OF THE DCST COORDINATED ACTIVITY ON DYNAMIC SYSTEM TESTING OF SOLAR DOMESTIC HOT WATER SYSTEMS

NOMENCLATURE

symbol	quantity	unit
A_C^*	effective collector area, solar DHW system model parameter	m^2
C	objective function	
C_S	heat capacity of the store, solar DHW system model parameter	J/K
D_L	draw-off mixing parameter, solar DHW system model parameter	-
$\vec{e}$	system input variable vector	
f_{aux}	auxiliary fraction of the store, solar DHW system model parameter	-
G_t	solar irradiance in the collector plane	W/m^2
$K_{(\alpha\tau)}$	incident angle modifier	-
n	incident angle modifier coefficient	-
$\vec{p}$	parameter vector	
P_{aux}	auxiliary power	W
P_L	power delivered to the load	W
r	residual error function, $r = y_{mod} - y_{exp}$	
R_L	thermal resistance of the load side heat exchanger, solar DHW system model parameter	K/W
S_C	collector loop stratification parameter, solar DHW system model parameter	-
$T_{aux,i}$	water temperature at the inlet of the auxiliary heat exchanger	°C
$T_{aux,o}$	water temperature at the outlet of the auxiliary heat exchanger	°C
T_{CA}	ambient air temperature of the collector loop	°C
T_{main}	cold water temperature at the inlet of the store	°C
T_S	outlet temperature of the store	°C
T_{SA}	ambient air temperature of the store	°C
u_C^*	collector loop heat loss parameter, solar DHW system model parameter	$W/(m^2K)$
$u_{C,0}$	constant part of the collector heat loss coefficient	$W/(m^2K)$
$u_{C,t}$	temperature dependent part of the collector heat loss coefficient	$W/(m^2K^2)$
U_S	overall heat loss coefficient of the store, solar DHW system model parameter	W/K
u_v	wind velocity dependency of u_C^*, solar DHW system model parameter	$J/(m^3K)$
v	wind velocity	m/s
$\dot{V}$	cold water volume flow rate at the inlet of the store	m^3/s
$\dot{V}_{aux}$	volume flow rate at the inlet of the auxiliary heat exchanger	m^3/s
y_{exp}	measured system output	
y_{mod}	modelled system output	
$(\alpha\tau)$	effective transmission-absorption product	-
$\Delta\vec{e}$	vector of errors in the input variables	
Δt_{skip}	skip time	s

Δy_{exp}	error in the measured system output	
Θ	incident angle with respect to normal of solar irradiation on the collector	°
τ_F	filter time constant	s

1 INTRODUCTION

1.1 Dynamic testing of solar domestic hot water systems

Performance test methods for solar domestic hot water (DHW) systems provide designers, manufacturers, installers and users with an objective means of measuring and comparing the output of different systems. Realistic test methods for practical use have to be able to predict from short term measurements the long term (e.g. annual) performance of a system under specified operating conditions on an arbitrary location. In order to reduce experimental effort internal measurements in the system itself should be prevented.

Several performance test methods for solar DHW systems have been proposed and developed in the past. Most of them include a more or less complicated conditioning of the system in order to simplify the subsequent analysis of measuring data, e.g., the energy content of the heat store at the end of a test day has to be equal to the one at the beginning of the day.

In dynamic testing, effort in data processing is minimized by using an appropriate mathematical model to collect as much information as possible from the measuring data. In relation to data processing, there are no principal restrictions on the measuring sequences. The method can be used not only for indoor laboratory tests, but also for outdoor tests and in- situ measurements where stationary conditions cannot be obtained. However, for an accurate long term performance characterization of the measured solar DHW system, most important system states shall be present in the measuring sequences. Hence, for laboratory tests, certain test conditions have to be fulfilled. Then, the solar DHW system model can be properly adjusted to the behaviour of the measured system, and after that, the system performance can be determined for any meteorological and load conditions.

The present dynamic system test (DST) method for solar DHW systems features:

- a black box test procedure in order to achieve the most important system states;
- dynamic fitting to obtain the parameters of a general solar DHW system model;
- long term performance prediction which uses the fitted parameters in the same model.

Advanced processing of dynamic testing has been enabled by the availability of quick computer systems. The data processing can run on a personal computer now.

1.2 Background of Group II of the Subtask on Dynamic Component and System Testing

During completion of Task III - Subtask E of the IEA Solar Heating and Cooling (SHAC) Programme ([1]), a new and promising approach to solar DHW system testing was suggested. Task III participants considered advantages of this approach to fully justify additional international effort. Thus, the Dynamic Systems Testing Group (DSTG), a limited Working Group within the SHAC Programme was formed to further develop, investigate and evaluate the so-called dynamic system test method.

Computer programs for processing the dynamic measuring data were developed by researchers at Munich University, Germany. The DSTG participants evaluated these dynamic fitting and long term performance prediction tools using both simulated and real measuring data. Conclusions were twofold: (a) the programs are suitable tools in processing dynamic laboratory tests and in situ measurements, and (b) for an accurate solar DHW system characterization, all important states shall be present in the measuring sequences. The DSTG Final Report [2] also contains preliminary versions of test and measuring procedures for solar DHW systems.

The DSTG also showed the potential of dynamic testing and measuring for characterization of solar energy components such as collectors and heat stores. This together with the need for further determination of conditions for dynamic solar DHW system testing explains the decision to continue and extend the work on dynamic testing and measuring. A place for these activities was found in a Subtask added to Task 14 on advanced active solar heating systems. Work in the Dynamic Component and System Testing (DCST) Subtask was carried out in three Groups:

I. Dynamic Collector Testing (DCT);
II. Dynamic System Testing (DST) of solar DHW systems;
III. (a) Component Testing and System Simulation (CTSS) of small solar heating systems and (b) In Situ Testing of large solar heating systems.

Activities in Group II were mainly aimed at definition of dynamic test conditions for laboratory testing of solar DHW systems and provide the basis for the Draft International Standard which will be published in the near future. The following countries participated in Group II of the DCST Subtask: Canada, Denmark, Germany, the Netherlands, Slovenia and Switzerland. The Dutch participant also coordinated the Group's activities.

1.3 Dynamic solar domestic hot water system testing in international standardization

In 1992, the International Standards Organization (ISO) adopted two new work items for Subcommittee SC4 of Technical Committee TC 180 on performance characterization of solar DHW systems based on dynamic laboratory testing:

- solar DHW system performance characterization by means of component testing and computer simulation, no. 9459 - Part 4;
- solar DHW system performance characterization by means of whole system testing and computer simulation, no. 9459 - Part 5.

Presently, Part 4 is an internal ISO Working Document (WD) and Part 5 will in the near future be published as a Draft International Standard (DIS).

Both work items cover the pre-normative research of the DCST Subtask. Volume A of this Final Report has a strong relation to work item 9459/4 whereas the present Volume B describes investigations with regard to work item 9459/5. Paper no. 1 in Annex A reports the editing work, from end of 1992 to July 1994, on the ISO Committee Draft 9459/5 dated July 28, 1994. The overview includes the main adaptations in the DST test conditions.

Since 1994, dynamic testing of solar energy systems and components is also subject to European (CEN) standardization. Technical Committee TC 312 classifies custom built solar DHW systems and factory made systems. For custom built systems, Working Group 3 of CEN TC 312 has proceeded the standardization work in ISO CD 9459/4. On the other hand, Working Group 2 on factory made systems makes use of ISO DIS 9459/5.

The importance of continuation of the work on standardization of test methods for solar DHW systems has been recognized according the approval of a proposal on validation of the DST method in the framework of the European Standards Measurements & Testing Programme. Aim of the project in which nine European countries will be represented, is to provide missing links for the DST method from its present state to CEN standardization including extensive experimental validation.

1.4 Overview of Volume B of the DCST Subtask Final Report

Chapter 2 of this Volume B report explains dynamic system testing both in general terms and for solar DHW systems in particular. The solar DHW system model used in the dynamic fitting and performance prediction procedure is explained there. For a general explanation of parameter identification, a descriptive way of presentation is chosen.

Chapter 3 describes the research on proper test conditions for dynamic outdoor solar DHW system testing. The findings are based on both simulated and real outdoor tests of solar pre-heat and solar plus supplementary systems. This chapter also contains an overview of investigated solar DHW systems with references to contributions of Group II participants in Annex A.

Conclusions and recommendations from Group II experiences can be found in Chapter 4. The features of dynamic testing and the solar DHW system model used are summarized there as well as aspects for further research.

2 DESCRIPTION OF DYNAMIC SOLAR DOMESTIC HOT WATER SYSTEM TESTING

2.1 Dynamic system fitting

2.1.1 General description

Dynamic system fitting can be interpreted as the inversion of dynamic system simulation. Simulation yields the system output using given parameters, whereas dynamic fitting yields the parameters from the measured system output; see Fig. 2.1.

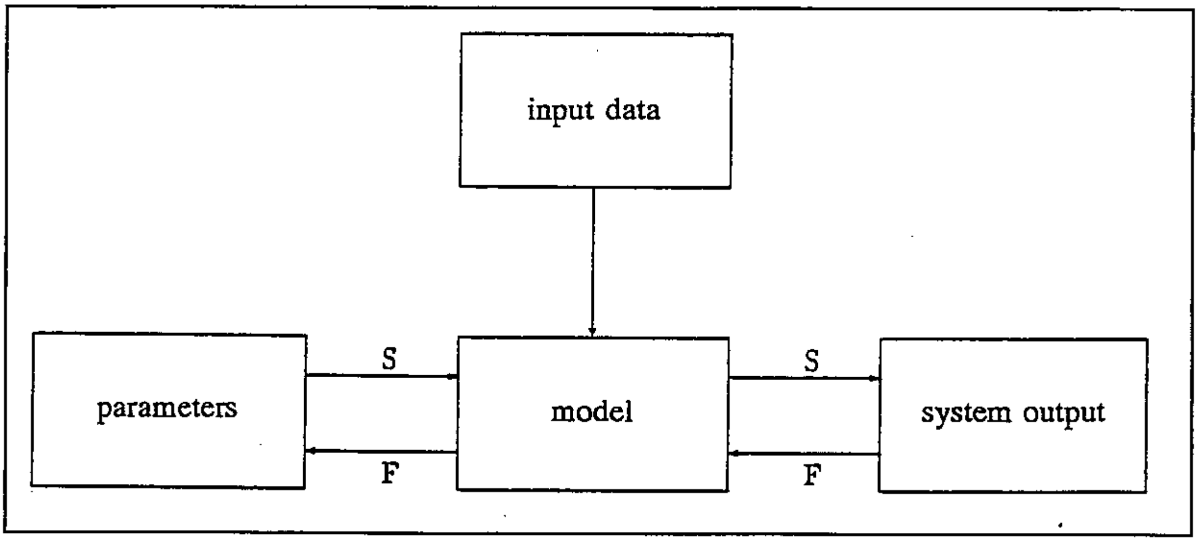

Figure 2.1: *Dynamic system fitting (F) works by the inversion of dynamic system simulation (S).*

The dynamic fitting procedure features data processing in which a parameter identification technique is combined with a system model; see Fig. 2.2. A measured quantity $y_{exp}(t)$ characterizing the performance of a system under test is compared with the corresponding calculated quantity $y_{mod}(\vec{p},t)$ from the model simulating that system. The calculated system output depends on the model parameters $\vec{p}$ and input data $\vec{e}$ which are equal to the measured conditions for the real system. The integral of the square (SI) of the filtered (F) deviation $r(\vec{p},t)$ between the calculated and measured quantities is a measure $C(\vec{p})$ for the quality of the fit. An iterative optimization procedure is used to obtain the parameters which yield the best fit. In every iteration step, the time dependent system state and consequently y_{mod} is calculated again.

Quality of parameters depends on variability of input data which specially address the parameters. Chapter 3 describes research of outdoor test conditions which yield adequate variability of input data for accurate parameter determination for a measured solar DHW system. Paper no. 2 in Annex A describes the definition of a figure of merit for the accuracy of parameters identified in dynamic fitting in a more general sense.

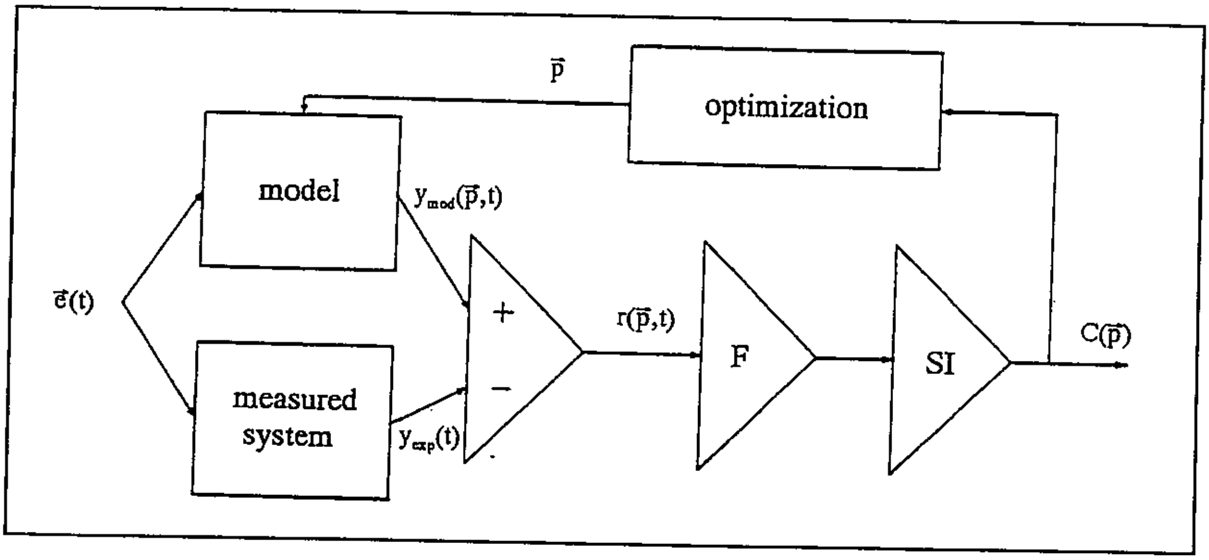

Figure 2.2: *The dynamic fitting procedure.*

2.1.2 The optimization procedure

The measure $C(\vec{p})$ mentioned above is called the objective function and incorporates the Fourier transform of the residual error function $r(\vec{p},t)$ and a low pass filter with Gaussian shape.

The filter reduces the influence of transient errors on the estimated values of the parameters. These errors generally originate from both measurements, e.g. by inertia of the sensors, and mismatch of the model. The use of a low pass filter is allowed since the effect of transient errors with zero mean on the long term performance is negligible. If the typical time scale of the measured system depends on the operating conditions, the time constant of the filter τ_F has to be time variant in order to retain significant filter effect as well as the information from the measured system output. The filter coefficient should decrease if the system state rapidly changes.

The Levenberg-Marquardt algorithm is used to minimize $C(\vec{p})$. The algorithm efficiently yields local minima. The disadvantage of this efficient local minimum search, however, is that other local minima might be overlooked. In fact, no algorithm can fully guarantee the determination of the global minimum. In order to avoid the estimation of parameter values which do not go with the global minimum, the optimization procedure is repeated several times from different starting points. At the approach of a new or old local minimum the iteration is interrupted and new starting values in a realistic parameter range are chosen. In the final search, the minimum for the best parameter vector is accurately determined.

The optimization procedure also yields estimated errors in the fitted parameter values. For the error analysis, the residual values $r(\vec{p},t)$ are used as these include measuring as well as model errors. Hence, the error estimation is fully based on the quality of the parameter fit and errors in the measured quantities are not considered separately.

The influence of errors $\Delta\vec{e}(t)$ and $\Delta y_{exp}(t)$ in respectively the input and output data on the fitted parameter values is investigated; see in Fig. 2.3. Since no distinction can be made between $\Delta\vec{e}(t)$ and $\Delta y_{exp}(t)$ all errors are taken together into $\Delta y_{exp}(t)$ which is then equal to $r(\vec{p},t)$. Only statistical errors are considered in this way, systematic errors are not taken into account.

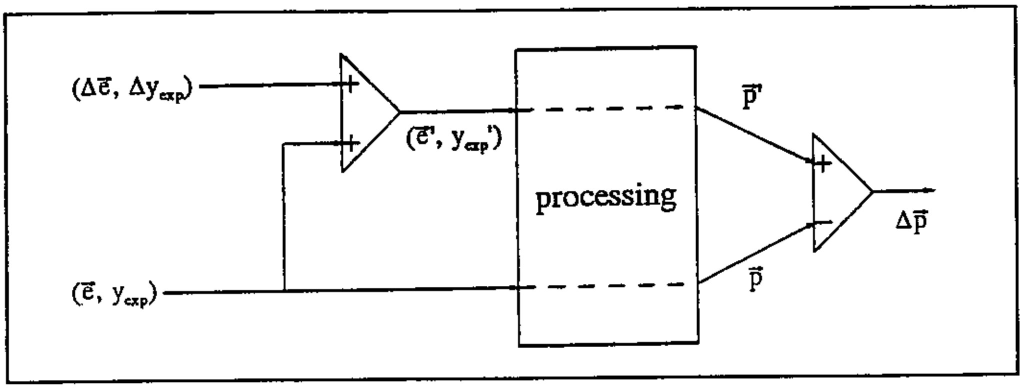

Figure 2.3: *Schematic of the error analysis.*

In general, the initial state of a measured system is unknown and not equal to the initial state of the model. When time goes by, the influence of the initial state decreases as the system state is determined more and more by the input variables. Hence, during the period that the initial state still influences the system performance, the fitting procedure should not compare the calculated and measured system output. This period is called the skip time Δt_{skip} and is only to be used to tune the calculated system state. Time Δt_{skip} depends on the difference in the initial state and on the operation of the system. If pre-conditioning of the measured system is possible, Δt_{skip} can be reduced.

Further information about the items with respect to the optimization procedure described above is given in [3, Annexes A.3 and A.2.3] and more detailed in [4, Chapter 8].

2.2 Dynamic testing of solar domestic hot water systems

The success of a test method is closely related to the general applicability of the procedure. For dynamic testing, this means that the mathematical model is capable to process measuring data from as many system types as possible. The method still gains if no internal measurements are needed and if model parameters have physical meaning and can be allocated to specific system components. The latter means that specific variability in the measuring data is needed and that the number of parameters is just sufficient to describe the most significant system behaviour. In that case, model parameters can be determined more or less uncorrelatedly. At the same time, however, these parameters will generally include more than one feature of the system components as well as certain interactions between components and even neglected effects.

Elaboration of these requirements resulted in a solar DHW system model with separate solar collector loop and heat store. The solar collector loop is characterized by at least two parameters, i.e. the effective collector area A_C^* and the collector heat loss parameter u_C^*, and so is the heat store by the overall heat loss coefficient U_S and heat capacity C_S. There are additional parameters for advanced harmonization between the model and the measured system. The model is of the black box type, i.e. no internal measurements in the solar DHW system are required. All parameters as well as the input and output of the model have been described in [3, Annexes A.2.1 and A.2.4] and more detailed in [2, Section 2.2] and [4, Chapters 4 and 8]. Table 2.1. lists the parameters including their ranges.

Table 2.1: *List of all parameters for the solar DHW system model.*

symbol	unit	range	physical meaning
A_C^*	m^2	≥ 0	effective collector area
u_C^*	$W/(m^2K)$	≥ 0	collector loop heat loss parameter
u_v	$J/(m^3K)$	≥ 0	wind velocity dependency of u_C^*
U_S	W/K	≥ 0	overall heat loss coefficient of the store
C_S	MJ/K	≥ 0.1	heat capacity of the store
f_{aux}	-	$\in$]0,1]	auxiliary fraction of the store
D_L	-	$\in$ [0,5]	draw-off mixing parameter
S_C	-	≥ 0	collector loop stratification parameter
R_L	K/kW	≥ 0	thermal resistance of the load side heat exchanger

The ISO standard only describes the requirements for the solar DHW system model to use; see [3, Annex A.4]. No reference is made to a specific model, hence, everybody is free to make his or her own data processing model. For their investigations, Group II participants used model P developed in Munich during the DSTG period. The program in which model P has been combined with the dynamic fitting procedure is called DFP.

2.3 Performance prediction of tested solar domestic hot water systems

Generally, the identified parameters described in Section 2.2 are intermediate results for short or long term prediction of the system performance; long term mainly involves annual predictions. Direct consequence of using a general model for processing of measuring data is that the model for performance prediction has to correspond. The model for long term performance prediction, including some differences with respect to the model for dynamic fitting as well as the input and output, has been described in [3, Annex A.2.5].

Group II participants used programs STP and LTPP respectively for obtaining short and long term system performance from the fitted parameters. In these programs, model P has been operated in simulation mode now. For more information on these programs is referred to [2, Section 2.3].

3 INVESTIGATION ON DYNAMIC TEST SEQUENCES FOR OUTDOOR SOLAR DOMESTIC HOT WATER SYSTEM TESTING

3.1 Introduction

The DSTG experienced that not only good data processing tools are needed to obtain an accurate characterization of the solar DHW system measured: a proper procedure to acquire suitable measuring data turned out to be just as important. Investigations of the DSTG participants yielded characteristics of measuring data needed for a good assessment of the system performance from laboratory tests and in situ measurements. Preliminary test and measuring procedures were realized.

Group II of the DCST Subtask in Task 14 continued the work on definition of the procedures, however, only for outdoor laboratory testing; in situ measurements were handled further in Group IIIb. From end of 1992 to July 1994, when the second Committee Draft 9459/5 ([3]) was sent to ISO for voting as Draft International Standard, test conditions were defined, evaluated and redefined. From mid 1994 on, CD test conditions were evaluated further in order to reveal quality and boundaries of the dynamic outdoor laboratory test procedure. The process of improvement of the test conditions can be read from the progress reports of the Subtask meetings and the various updates of the Committee Draft; see [5] - [22]. Further evaluations led to some recommendations of the Group for further improvement of the text; see [23]. These recommendations were discussed in the ISO meeting of October 1995 and will be taken into account when upgrading the CD into a DIS.

Primarily, this chapter reports on the experiences with the test procedure described in [3]. In Section 3.2, the CD test conditions have been specified briefly as well as ideas for possible improvements which resulted from the research. Sections 3.3 and 3.4 describe results of investigations on real and simulated outdoor test data, including indications for boundaries of the test procedure. In Section 3.5, a procedure has been proposed for validation of the DST method for systems not tested before. Finally, accuracy aspects have been mentioned briefly in Section 3.6.

Table 3.1 presents the solar DHW systems used for investigation of the CD test conditions. All systems consist of separate solar collector and heat store and have a collector loop heat exchanger in the store. Circulation in the collector loop is forced. Solar plus supplementary systems with electric element involve heating during off-peak hours and systems with an indirect boiler can be heated during all day. The solar collector and heat store properties indicated represent the research carried out. Main results of the investigations can be found in Sections 3.3 and 3.4; for a full description is referred to the specific papers in Annex A. Experience with the DST method for thermosyphon and Integral Collector Storage (ICS) systems from before start of the DCST Subtask and during its initial phase revealed the need for improvement of the former test conditions for these systems as well. Participants in the DCST Subtask did not have the opportunity to check the new test conditions for these systems. However, it is expected that the method is valid to a large extent for thermosyphon and ICS systems as well as test conditions have significantly improved since these first investigations.

Table 3.1: *Overview of real and simulated systems for investigation of the CD test sequences.*

system no.	solar DHW system			real/ simulated	paper no. in Annex A
	type	collector properties	store properties		
1	solar plus suppl. electric element	7.2 m^2 glazed, spectral selective	500 l, mixed charge, stratified discharge	real and simulated	3
2	solar plus suppl. electric element	4.4 m^2 glazed, spectral selective	400 l, mixed charge, stratified discharge	real	4
3	solar pre-heat	2.7 m^2 glazed, spectral selective	120 l, mixed charge, stratified discharge	simulated	5
4	solar plus suppl. electric element	2.7 m^2 glazed, spectral selective	240 l, mixed charge, stratified discharge	simulated	5
5	solar plus suppl. indirect boiler	2.7 m^2 glazed, spectral selective	200 l, mixed charge, stratified discharge	simulated	5
6	solar plus suppl. electric element	5.0 m^2 glazed, spectral selective	300 l, mixed charge, stratified discharge	simulated	3
7	solar pre-heat	4.0 m^2 glazed, spectral selective	250 l, str. charge with fixed and var. inlet, stratified discharge	simulated	6
8	solar pre-heat	4.0 m^2 glazed, spectral selective	as system 7	simulated	6
9	solar pre-heat	4.0 m^2 glazed, non-spectral selective	250 l, mixed charge stratified discharge	simulated	6
10	solar plus suppl. electric element	see system 6, with different incident angle modifiers	see system 6	simulated	3
11	solar plus suppl. electric element	5.0 m^2, glazed, high and strong T-dependent heat loss	see system 6	simulated	3
12	solar plus suppl. electric element	5.0 m^2, evacuated tubular collector	see system 6	simulated	3
13	solar plus suppl. electric element	see system 6	see system 6 with increased conduction in vertical direction	simulated	3
14	solar plus suppl. electric element	see system 6 with low flow	300 l, stratified charge, str. discharge	simulated	3
15	solar plus suppl. indirect boiler	see system 6	see system 6 with aux. heat exchanger	simulated	3

3.2 Description of sequences for dynamic testing of solar domestic hot water systems

3.2.1 Test sequences in the Committee Draft

The CD test conditions include test sequences S_{sol}, S_{store} and S_{aux}. Test sequence S_{sol} has been divided into two sequences, i.e. $S_{sol,A}$ with A-days and $S_{sol,B}$ with B-days. All test sequences have been described in the following. Before that, definition of A- and B-days, and valid A- and B-days is given. For more detailed descriptions is referred to [3].

Definition of A- and B-days:

A-days: Days with large draw-offs like in [3], Section 6.2.2.2; possible auxiliary heater "off" all day.

Valid A-days: A-days with daily irradiation exceeding 12 MJ/m².

B-days: Days with small draw-offs like in [3], Section 6.2.2.3; possible auxiliary heater "off" from 1 hour before until 1 hour after the draw-offs, unless according to the manufacturer auxiliary shall not be switched off during the day. Then, the auxiliary heater shall be "on" all day.
In order to prevent overheating the small draw-off volume is extended if tap water temperature at the store outlet exceeds a system size dependent threshold temperature, i.e. the current draw-off continues until 20 % of the store volume has been withdrawn, however, is stopped when the outlet temperature drops the threshold. The threshold temperature is larger than the set temperature of the auxiliary heater, if present.

Valid B-days: B-days with daily irradiation exceeding 12 MJ/m².

Definition of test sequence $S_{sol,A}$ and $S_{sol,B}$:

Test sequence $S_{sol,A}$ is meant to characterize solar collector performance at high efficiency. System temperature is kept low by the following test conditions:

- 1st day: pre-conditioning + operation under test A conditions.
- following days: operation under test A conditions *until at least 3 valid A-days* have been obtained.
- the number of valid A-days shall be at least one third of the days within $S_{sol,A}$.
- final conditioning.

Test sequence $S_{sol,B}$ is intended to identify store heat losses and collector performance at low efficiency. System temperature is kept relatively high by the following test conditions:

- 1st day: pre-conditioning + operation under test B conditions.
- following days: operating under test B conditions until *at least 3 valid B-days of which 2 are consecutive* have been obtained.
- the number of valid B-days shall be at least one third of the days within $S_{sol,B}$.
- final conditioning.

The number of valid B-days (in $S_{sol,B}$) shall be equal or 1 or 2 larger than the number of valid A-days (in $S_{sol,A}$).

Definition of test sequence S_{store}:

Test sequence S_{store} is meant to identify the overall store losses, i.e. by adding this test sequence to $S_{sol,B}$ store and collector heat losses are decoupled. By the following test conditions, the store can loose heat during two days without interference of solar input:

- 1st day: pre-conditioning + operation under test B conditions (but auxiliary heater "off" during all day).
- following days: operation under test B conditions (but auxiliary heater "off" during all day) *until and no more than 2 consecutive valid B-days* have been obtained.
- following 2 days (48 hours): no draw-off and no solar input by possible covering of the collector if irradiance > 200 W/m^2. In that case, the pyranometer shall be covered as well (or irradiance shall be set to zero) and outdoor ambient air temperature shall be measured under the cover (as gain can also be caused by high ambient temperatures).
- final conditioning, i.e. draw-off of three store volumes or less if temperature difference between inlet and outlet becomes lower than 2 K.

Definition of test sequence S_{aux}:

Test sequence S_{aux} is meant for identification of the heat losses and volume fraction of the auxiliary-heated part of the store. By the following test conditions, temperature of the auxiliary part is kept high whereas the solar part is kept cold:

- 1st day: pre-conditioning + operation under test B conditions, no solar input.
- 2nd + 3rd + 4th day: operation under test B conditions and no solar input.
- "no solar" means covering of the collector if irradiance > 200 W/m^2; see under S_{store} for collector covering.
- final conditioning; see under S_{store}.

Combination of test sequences:

For solar plus supplementary systems, all test sequences $S_{sol,A+B}$, S_{store} and S_{aux} shall be carried out. For solar pre-heat systems, the combination of $S_{sol,A+B}$ and S_{store} is sufficient of course.

3.2.2 Possible improvements of the test sequences

Investigations on simulated test data revealed that only minor improvement of DST parameter identification and annual system performance prediction can be expected from adaptation of the test conditions as described in Section 3.2.1; see Paper no. 5 in Annex A. However, some adaptations might simplify the test procedure. Possible improvements of the test sequences involve:

- The 12 MJ/m^2 demand for valid A- and B-days might be flexible and linked to the ratio of store volume and collector area. System temperatures during S_{sol} and S_{store} test sequences can reach higher values then, possibly reducing correlation between u_C^* and U_S, and (to a smaller extent) between A_C^* and u_C^*.
- Test sequence S_{store} or S_{aux} might be skipped for solar plus supplementary systems as only one of these may reveal the same information for decoupling identification of u_C^* and U_S.
- The strict limit of 1/3 valid days for both $S_{sol,A}$ and $S_{sol,B}$ test sequences might be more flexible. Maybe this criterion can be dropped.
- The same might be valid for the criterion that the number of valid B-days in $S_{sol,B}$ should be equal or 1 or 2 larger than the number of valid A-days in $S_{sol,A}$.

3.3 Evaluation of the Committee Draft test sequences based on real test data

The effectiveness of test condition development was checked in real testing of solar plus supplementary system 1 in Table 3.1. From twelve sequences S_{sol} and two sequences of each S_{store} and S_{aux}, twelve tests were composed in such way that seasonal dependence of the identified parameter sets and annual performance prediction could be determined. The results show good reproducibility independent from meteorological conditions both for the various parameter sets and the prediction of annual system performance. Moreover, the standard deviation as delivered by the DST data processing procedure appears to be a good indication for the spread in parameter values and performance predictions from the different sets of test sequences, i.e. if the scatter is relatively large, then, the standard deviation is relatively large. Most identified parameters and predictions coincide within their mutual rather small 2σ-bands.

Considering the general character of the DST mathematical model, quite realistic parameter values were obtained. Small underestimation of u_C^* is compensated by small overestimation by U_S. Overestimation of f_{aux} can be explained by thermal conduction and convection in the vertical direction not taken into account by the general model. For a complete overview of the parameters identified from the various tests is referred to Paper no. 3 in Annex A. The spread in the most important parameters is as follows: ± 2.8 % in A_C^* and about ± 8.8 % in u_C^* and U_S. Table 3.2 lists the predicted annual performances for various TRY (Test Reference Year) weather locations and loads. The spread in annual performance prediction remains in the range of ± 1.5 % of the hot water demand for all sets of test sequences.

Improvement of the DST procedure by addition of test sequences S_{store} and S_{aux} to test sequence S_{sol} has been demonstrated for solar DHW system 2 in Table 3.1. Figure 3.1 shows the improvement in reproducibility for f_{aux} and the solar fraction when sequences S_{aux} respectively S_{store} and S_{aux} are added to four different sequences S_{sol}.

Table 3.2: *Solar fraction (in percentages) for solar DHW system 1 with electric element as predicted from twelve sets of test sequences for various TRY weather locations, and various volumes of water heated from 10°C to 45°C.*

Location/climate	TRY Würzburg (1226 kWh/(m²a))			TRY Hannover (1042 kWh/(m²a))	TRY Stötten (1367 kWh/(m²a))
Load [litres/day]	200	350	500	350	350
Test sequence set 1	56.8	50.7	43.1	43.5	53.5
Test sequence set 2	55.9	49.6	42.0	42.3	52.1
Test sequence set 3	57.3	50.9	43.3	43.8	53.8
Test sequence set 4	56.3	50.4	43.1	43.3	53.0
Test sequence set 5	57.1	51.3	44.0	44.2	54.0
Test sequence set 6	57.9	51.7	44.2	44.6	54.7
Test sequence set 7	56.6	50.5	42.9	43.3	53.3
Test sequence set 8	55.9	49.5	41.9	42.3	52.0
Test sequence set 9	56.7	50.6	43.1	43.4	53.4
Test sequence set 10	56.4	50.4	43.1	43.3	53.0
Test sequence set 11	56.6	51.0	43.9	43.9	53.7
Test sequence set 12	57.1	51.3	44.0	44.2	54.3

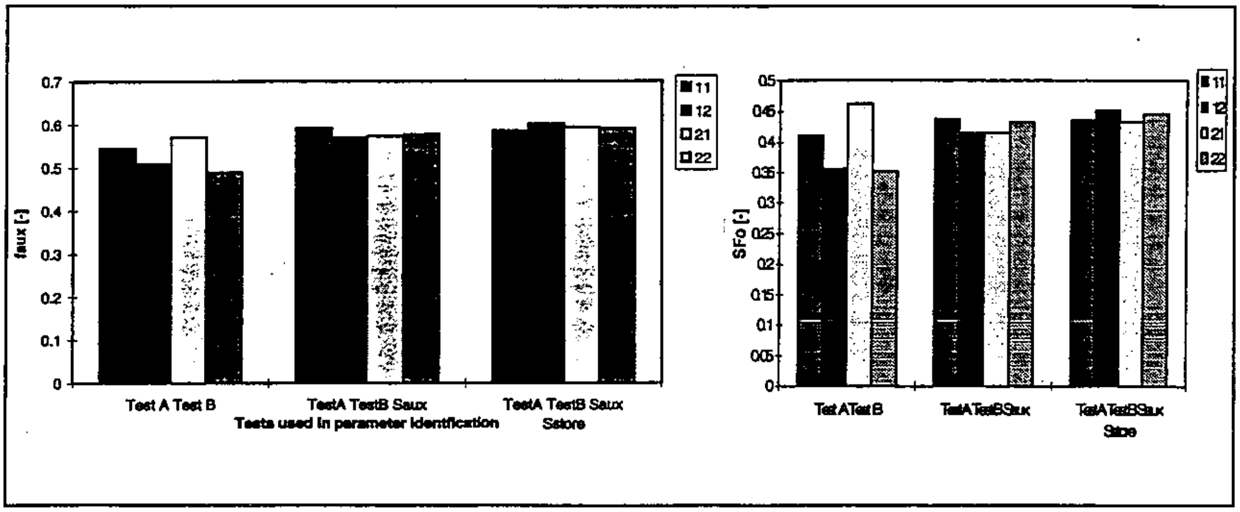

Figure 3.1: *Effect of addition of test sequences S_{aux} as well as S_{store} and S_{aux} to test sequences S_{sol} on identification of f_{aux} and prediction of the solar fraction for a load of 215 litres per day, heated from 10°C to 50°C, and for weather according to Kloten, Switzerland for solar DHW system 2 with electric element.*

Paper no. 4 in Annex A also presents reproducibility checks on two apparently identical examples of this system 2. Parameters U_S and f_{aux} seem to depend on the value of the auxiliary heater setpoint temperature which preliminary indicates the need for about the same setpoint temperature for testing and performance prediction. However, this effect should be investigated further.

3.4 Evaluation of the Committee Draft test sequences based on simulated test data

3.4.1 Investigation method

Test sequence design was extensively supported by investigation of simulated test data. Basis for these investigations was the method as presented in Figure 3.2 in which DF represents the dynamic fitting and LTP stands for long term, i.e. annual performance prediction:

- For different types of solar DHW systems, simulated test data were generated using a detailed solar DHW system model such as TRNSYS ([24]).
- The simulated test data were analyzed with program DF_P, i.e. the DST model parameters were identified.
- Subsequently, from the DST model parameter sets annual performance was predicted for various loads and locations (climates). For the predictions, program LTP_P was used.
- The annual performances for the different loads and locations were also simulated by the detailed solar DHW system model. These figures were used for comparison with the DST model predictions.

Both for test data generation and for annual performance prediction and simulation, meteorological data from TRY files were used.

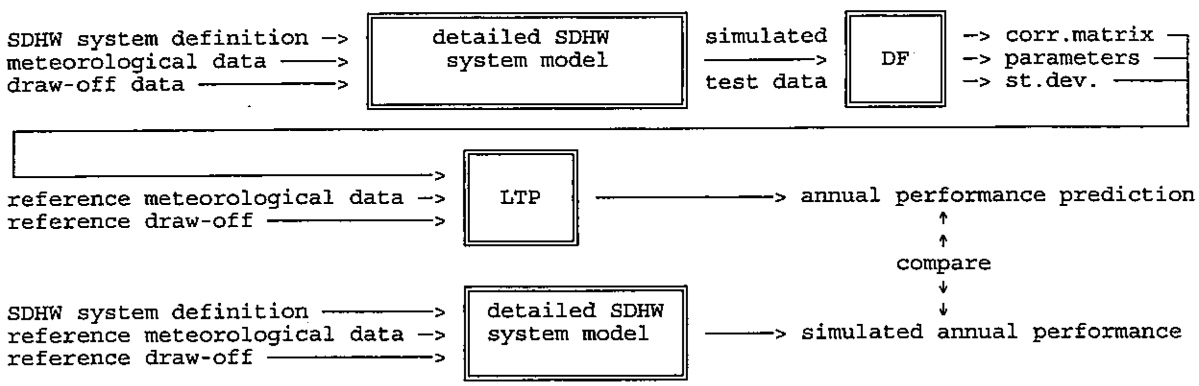

Figure 3.2: *Scheme of the investigation method comprising comparison of DST annual performance prediction with simulated annual performance.*

Participants considered the DST method to be validated if differences in all annual performance predictions from various (simulated) tests are less than 5 % with regard to the hot water demand of the system.

3.4.2 Investigations for different types of solar domestic hot water systems

Several test sequences S_{sol}, S_{store} and S_{aux} (if applicable) were generated for both solar pre-heat and solar plus supplementary systems.

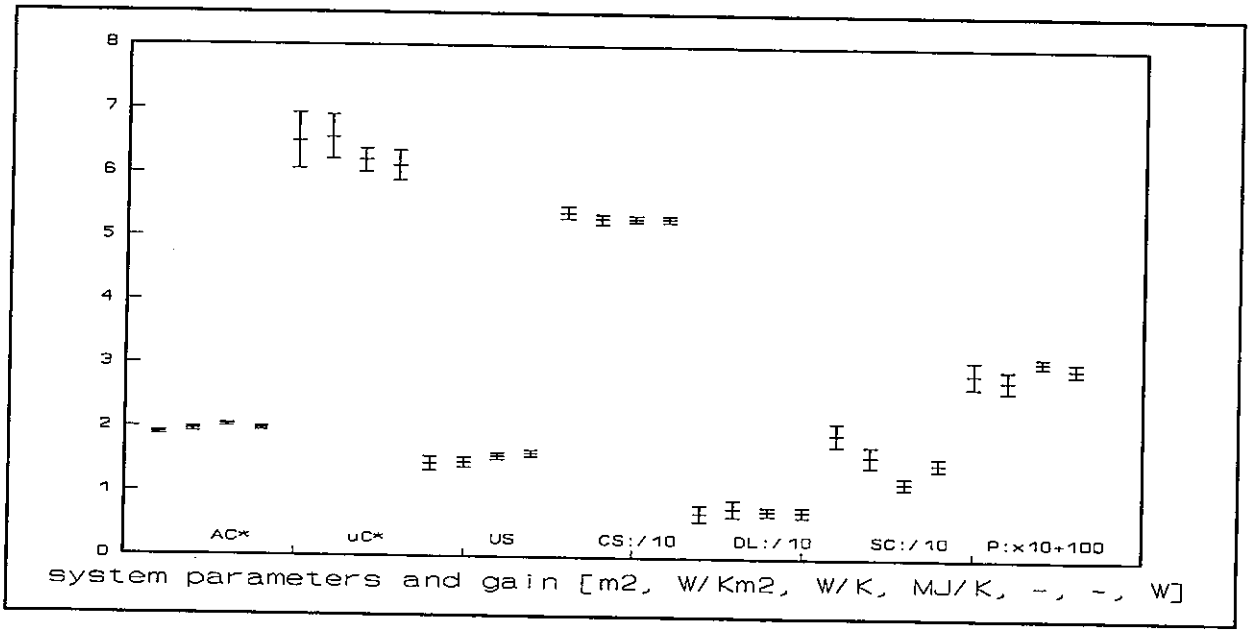

Figure 3.3: *Results of DST parameter identification and predicted annual power delivered to a load of 110 litres per day, heated from 15°C to 65°C, and for weather according to TRY-De Bilt, the Netherlands for solar pre-heat system 3.*

Figure 3.3 shows parameter sets fitted from various combinations of test sequences as well as matching annual performance predictions for solar pre-heat system 3 in Table 3.1, and so does Figure 3.4 for solar DHW system 5 with heating by an indirect boiler. Annual performance for the solar pre-heat system has been given in power P_L delivered to the load, and for the solar plus supplementary system, auxiliary power P_{aux} has been presented. More information as well as parameters fitted and performances predicted for system 4 have been given in Paper no. 5 in Annex A. Results match to a large extent with conclusions from data processing of real tests:

- Various sets of test sequences lead to very similar parameter values.
- Spread in u_C^* is relatively largest, but spread in U_S is lower than for the real tests.
- Small underestimation of u_C^* and small overestimation of U_S and f_{aux} were found again.

Table 3.3: *Range of solar fractions determined for different loads in comparison to the value calculated by TRNSYS from six simulated tests for systems 10 - 15.*

	solar fraction [%]					
	range	TRNSYS	range	TRNSYS	range	TRNSYS
load [litres/day]	50	50	200	200	1500	1500
system 6	40.5 - 44.3	43.4	47.2 - 48.1	46.4	11.7 - 12.1	14.1
system 10, n = 0.1[1)]			50.1 - 52.0	49.8		
system 10, n = 0.3[1)]			47.1 - 48.3	46.5		
system 10, n = 0.5[1)]			40.9 - 43.6	40.8		
system 11	23.1 - 30.3	27.7	38.9 - 40.7	38.7	10.4 - 10.8	12.7
system 12	62.6 - 65.8	62.5	60.7 - 61.5	59.3	15.0 - 15.4	17.9
system 13	32.2 - 36.9	35.0	44.0 - 45.5	43.6	11.3 - 11.7	13.5
system 14	45.5 - 49.6	47.0	49.2 - 50.8	49.4	12.2 - 12.5	15.0
system 15	45.6 - 52.1	46.6	48.3 - 51.2	47.0	12.3 - 12.9	12.3

1) The n-value indicates the incident angle modifier coefficient for the Ambrosetti equation, i.e. $1 - \tan^{1/n}(\Theta/2)$ for reduction of the effective transmission-absorption product ($\alpha\tau$).

- Systematic deviations between solar gain predicted according to the DST procedure and determined by data generation program TRNSYS are small and depend on the load. In general, average annual system performance has been overestimated by 1 - 2 % for the load of 200 litres per day, and it has been underestimated by 2 - 3 % for the 1500 litres per day load. For 50 litres per day, systematic deviation is around zero. For system 15, systematic overestimation is 1 - 3 %.
- Considerable seasonal bias of DST results can be expected for flat plate collectors with incident angle modifier coefficient of 0.4 and higher. For these systems, solar irradiance should be corrected as recommended in the Committee Draft.
- High and strong temperature dependent collector heat loss, i.e. 5.0 + 0.04ΔT W/(m^{2}K) in the simulations, causes an increased scattering of the results. For the load of 50 litres per day, the spread in solar fraction is about 7.2 %. However, it is much lower for the large loads.
- Quality of DST results for the system with the evacuated tubular collector is comparable with that of the reference system.

1. Performance of two full dynamic tests as described in Section 3.2.1. The tests shall be carried out in periods in which specific system characteristics different from the data processing model (see Section 2.2) are most exposed into different directions. For instance, the two tests for systems with strong temperature dependency of the collector heat loss coefficient shall be performed in a period with a relatively low respectively high ambient air temperature.
2. Evaluation of the two dynamic tests into annual performance predictions for all required meteorological and load conditions.
3. Comparison of the annual performance predictions from the two tests. The method is considered to be validated for the tested system if differences in all annual performance predictions from the two tests are less than 5 % with regard to the hot water demand of the system.
4. If validation of the method under 3 is positive, test data of both tests shall be combined and used for the annual performance prediction to be presented in the test report.

3.6 Accuracy aspects

The DST data processing procedure yields estimated errors in the fitted parameter values and the annual performance prediction. The error analysis takes into account measuring as well as model errors, however, only statistical errors are considered. In data processing, it is not possible to detect systematic errors in the sensors and systematic model errors. Nevertheless, systematic errors affect the parameter values and annual performance prediction.

For information about the systematic error in the used model P is referred to Section 3.4. However, one should be careful with the figures mentioned as the model used for generation of the test data contains systematic errors as well. The effect of systematic measuring errors on the yearly performance prediction has been investigated briefly for an earlier version of DST procedure used in the Netherlands; see [25]. Summary of investigation results has been given below.

Table 3.4: *Systematic measuring errors in the different variables, realistically for professional sensors available on the market, for investigation of their influence on annual performance prediction for solar pre-heat and solar plus supplementary systems.*

variable	systematic error	variable	systematic error
G_t	1%	$\dot{V}$	1%
T_{CA}	0.5°C	$T_{aux,i}$	0.1°C
T_{SA}	0.5°C	$T_{aux,o}$	0.1°C
T_{main}	0.1°C	$\dot{V}_{aux}$	1%
T_S	0.1°C	P_{aux} (electric)	1%

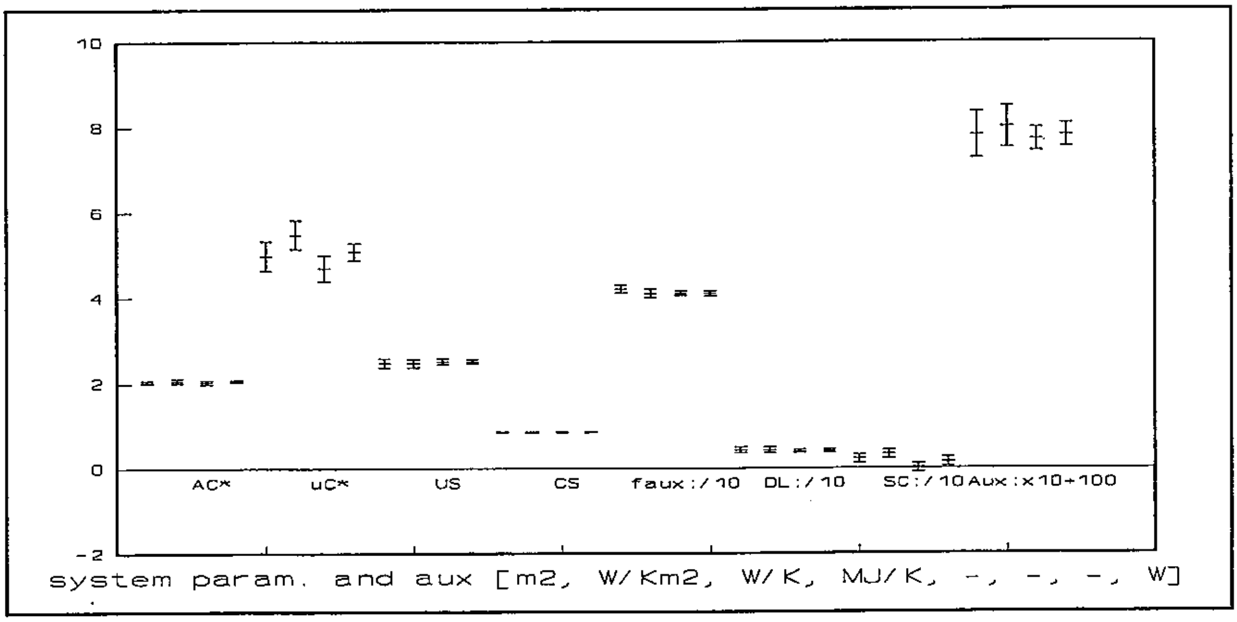

Figure 3.4: *Results of DST parameter identification and predicted annual auxiliary power for a load of 110 litres per day, heated from 15°C to 65°C, and for weather according to TRY-De Bilt, the Netherlands for solar DHW system 5 with auxiliary heating by an indirect boiler.*

- The various sets also give quite similar annual performance predictions, i.e. the spread is in the range of ± 1.5 % again.
- The DST procedure overestimates the annual system gain by several percentages (typically 2 - 4 %) with respect to determination by the data generation program.

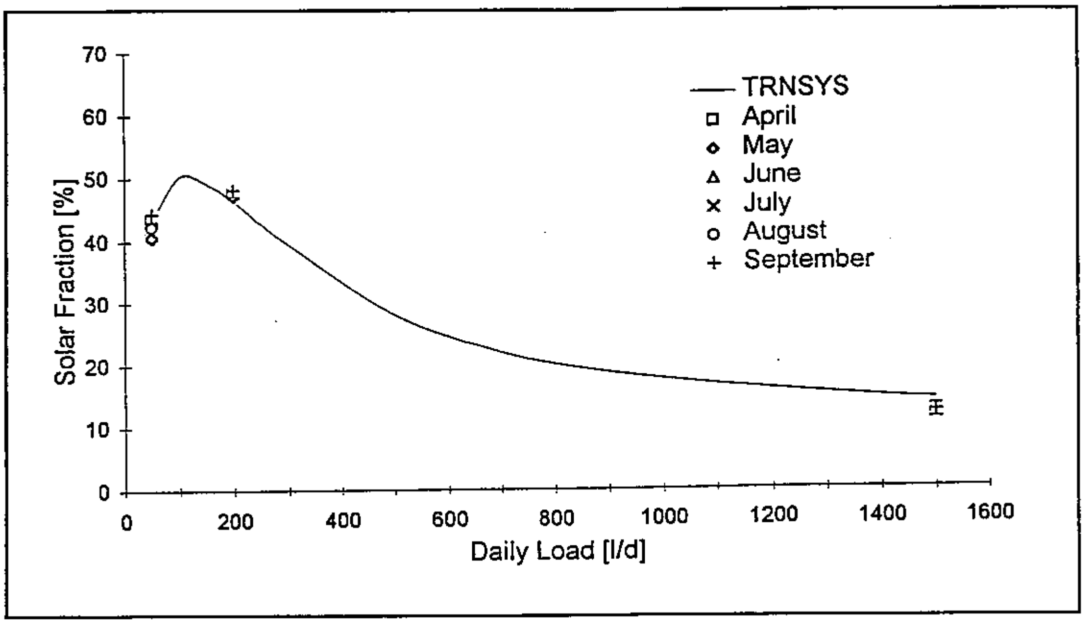

Figure 3.5: *Predicted solar fraction in comparison to the value determined by the data generation program TRNSYS for various loads and for weather according to TRY-Würzburg, Germany for solar DHW system 6 with electric element.*

- The DST standard deviation gives a good indication of the spread in parameter values and system performance predictions from the different sets of test sequences. Most identified parameters and all predictions coincide within their mutual rather small 2σ-bands.

This indicates that the different parameters and the annual performance prediction are determined quite accurately.

An example of variation in load has been presented in Figure 3.5 in which solar fraction is given as end result of DST data processing of six simulated tests for solar DHW system 6 (Table 3.1) with electric element. Largest spread is found for small draw-offs.

Identical results, i.e. very small spread in annual gain and auxiliary power, were obtained for performance predictions for locations with very different meteorological conditions than at the simulated test site; see Paper no. 5 in Annex A.

3.4.3 Investigation of the boundaries of the DST procedure

Simulated test data were also used for investigation of the boundaries of the DST procedure. Preliminary results were obtained for solar pre-heat systems, and a more systematic research was carried out starting from solar DHW system 6 with electric element.

Boundaries for solar pre-heat systems

Paper no. 6 in Annex A describes analysis of simulated test data for solar pre-heat systems 7 - 9 in Table 3.1 with spectral selective and non-selective absorber and with stratified and mixed charge of the heat store. Test sequences S_{sol} and S_{store} were generated for periods in summer, autumn and winter.

Annual performance predictions show seasonal dependency. Largest scattering was found for system 8 with a high and strong temperature dependent collector heat loss coefficient and fixed store inlet: about ± 5 % (of the hot water demand) in annual system performance for a load of 350 litres per day. Reason for the relatively large spread may be found in large scattering of the parameters identified from the various test sequences. Furthermore, a small systematic overestimation of 1 - 3 % in the DST annual system gain was found for the summer test sequences when compared with the figure determined by the data generation program TRNSYS.

These results for solar pre-heat systems should be considered as preparation for further investigations. Foremost, the differences in the parameter sets should be explained. Special point of attention is also the influence of the temperature dependency of the collector loop heat loss coefficient on the fitted parameters and the predicted performance.

Spread in parameters A_C^* and u_C^* might be due to differences in wind velocity and long wave radiation exchange for the various test sequences. These variables have not been taken into account in data processing, though might have second order influence on the system behaviour. A supplementary study

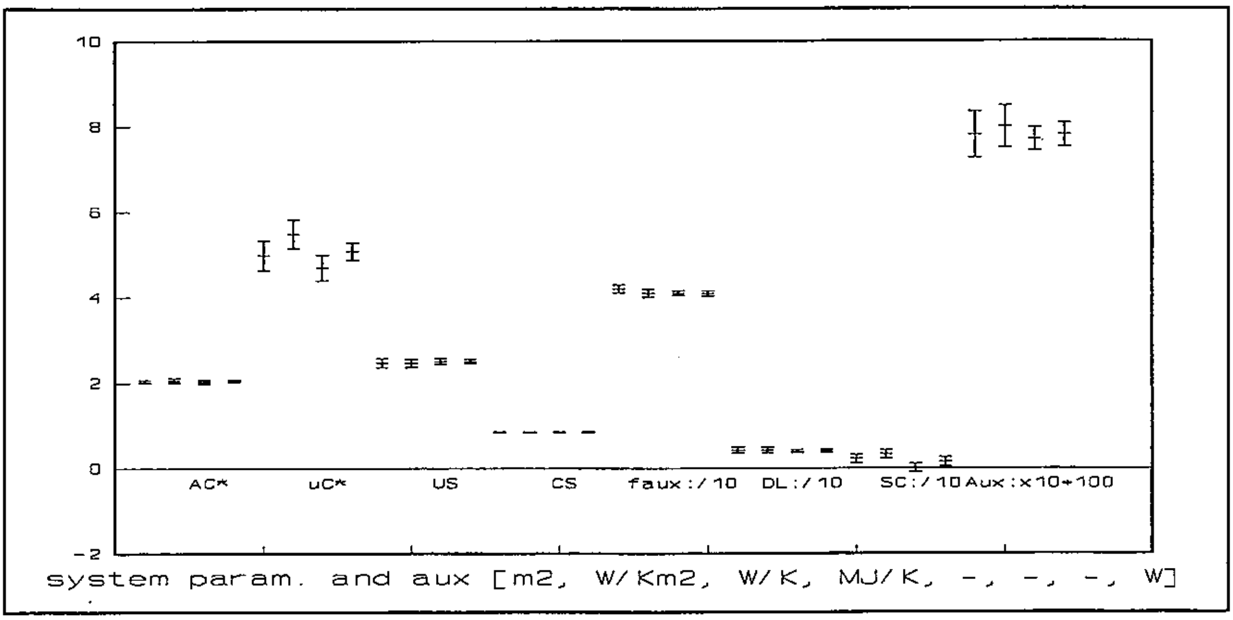

Figure 3.4: *Results of DST parameter identification and predicted annual auxiliary power for a load of 110 litres per day, heated from 15°C to 65°C, and for weather according to TRY-De Bilt, the Netherlands for solar DHW system 5 with auxiliary heating by an indirect boiler.*

- The various sets also give quite similar annual performance predictions, i.e. the spread is in the range of ± 1.5 % again.
- The DST procedure overestimates the annual system gain by several percentages (typically 2 - 4 %) with respect to determination by the data generation program.

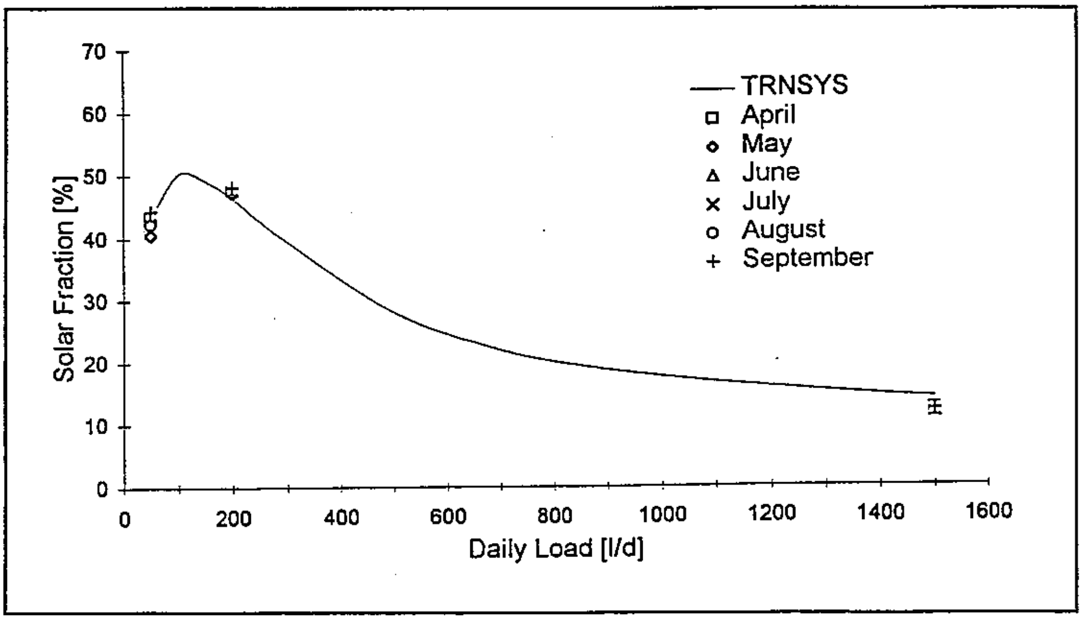

Figure 3.5: *Predicted solar fraction in comparison to the value determined by the data generation program TRNSYS for various loads and for weather according to TRY-Würzburg, Germany for solar DHW system 6 with electric element.*

- The DST standard deviation gives a good indication of the spread in parameter values and system performance predictions from the different sets of test sequences. Most identified parameters and all predictions coincide within their mutual rather small 2σ-bands.

This indicates that the different parameters and the annual performance prediction are determined quite accurately.

An example of variation in load has been presented in Figure 3.5 in which solar fraction is given as end result of DST data processing of six simulated tests for solar DHW system 6 (Table 3.1) with electric element. Largest spread is found for small draw-offs.

Identical results, i.e. very small spread in annual gain and auxiliary power, were obtained for performance predictions for locations with very different meteorological conditions than at the simulated test site; see Paper no. 5 in Annex A.

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Simulated test data were also used for investigation of the boundaries of the DST procedure. Preliminary results were obtained for solar pre-heat systems, and a more systematic research was carried out starting from solar DHW system 6 with electric element.

Boundaries for solar pre-heat systems

Paper no. 6 in Annex A describes analysis of simulated test data for solar pre-heat systems 7 - 9 in Table 3.1 with spectral selective and non-selective absorber and with stratified and mixed charge of the heat store. Test sequences S_{sol} and S_{store} were generated for periods in summer, autumn and winter.

Annual performance predictions show seasonal dependency. Largest scattering was found for system 8 with a high and strong temperature dependent collector heat loss coefficient and fixed store inlet: about ± 5 % (of the hot water demand) in annual system performance for a load of 350 litres per day. Reason for the relatively large spread may be found in large scattering of the parameters identified from the various test sequences. Furthermore, a small systematic overestimation of 1 - 3 % in the DST annual system gain was found for the summer test sequences when compared with the figure determined by the data generation program TRNSYS.

These results for solar pre-heat systems should be considered as preparation for further investigations. Foremost, the differences in the parameter sets should be explained. Special point of attention is also the influence of the temperature dependency of the collector loop heat loss coefficient on the fitted parameters and the predicted performance.

Spread in parameters A_C^* and u_C^* might be due to differences in wind velocity and long wave radiation exchange for the various test sequences. These variables have not been taken into account in data processing, though might have second order influence on the system behaviour. A supplementary study on the importance of wind velocity and long wave radiation exchange for the collector efficiency ([17]) indicates that sky temperature has more influence on the performance parameters of glazed collectors than wind velocity. Influence of sky temperature is larger for less spectral selective absorbers and higher transmission of the cover for long wave radiation. Wind velocity can be processed optionally in the DST method. There is currently no such possibility for sky temperature.

Boundaries for solar plus supplementary systems

Boundaries of the DST procedure were also investigated for solar plus supplementary systems. Starting point for the research was system 6 (Table 3.1) with electric element for heating during off-peak hours. The following aspects were investigated by changing the matching system properties with respect to this reference:

- the incident angle effect for systems with flat plate collectors (system 10 in Table 3.1);
- the effect of a high and strong temperature dependent heat loss coefficient for flat plate collectors (system 11);
- systems with an evacuated tubular collector (system 12);
- the effect of an increased effective heat conduction in the vertical direction of the store (system 13);
- low flow systems with a stratified charge of the heat store (system 14);
- systems with auxiliary heating via an immersed heat exchanger (system 15).

For all variants described above, six simulated tests were generated for meteorological conditions of TRY Würzburg, i.e. one set of test sequences for every month from April to September. Reproducibility was investigated for both identified parameters and annual performance prediction for loads of 50, 200 and 1500 litres per day, heated from 10°C to 45°C, where the 50 litres per day load has been regarded as rather unrealistically small. Moreover, deviation with respect to the annual performance calculated by data generation program TRNSYS was determined. Table 3.3 presents an overview of all investigations: the range of solar fractions determined by the DST procedure from the various simulated tests together with the solar fraction calculated by TRNSYS. For reasons of comparison, these figures have been given for system 6 as well. For more detailed information, also on the fitted parameters is referred to Paper no. 3 in Annex A.

Main conclusions from the investigations are as follows:

- Although parameters A_C^*, u_C^* and U_S show correlation effects depending on the season of testing, clear relation was observed between parameters changed in TRNSYS and matching DST parameters. Parameter U_S shows systematic overestimation.
- For all systems including the reference system, largest spread in predicted annual solar fraction was found for the small load of 50 litres per day, heated from 10°C to 45°C. This can be explained by occurrence of overheating in summer, hence, large influence of the heat loss coefficients on the thermal performance. However, the scattering remains within the validation range of 5 % for systems 6, 10 and 12 - 14. For the more realistic larger loads, the differences in annual system performance are less than 5 % for all systems 6 and 10 - 15.

Table 3.3: *Range of solar fractions determined for different loads in comparison to the value calculated by TRNSYS from six simulated tests for systems 10 - 15.*

	solar fraction [%]					
	range	TRNSYS	range	TRNSYS	range	TRNSYS
load [litres/day]	50	50	200	200	1500	1500
system 6	40.5 - 44.3	43.4	47.2 - 48.1	46.4	11.7 - 12.1	14.1
system 10, n = 0.1[1)]			50.1 - 52.0	49.8		
system 10, n = 0.3[1)]			47.1 - 48.3	46.5		
system 10, n = 0.5[1)]			40.9 - 43.6	40.8		
system 11	23.1 - 30.3	27.7	38.9 - 40.7	38.7	10.4 - 10.8	12.7
system 12	62.6 - 65.8	62.5	60.7 - 61.5	59.3	15.0 - 15.4	17.9
system 13	32.2 - 36.9	35.0	44.0 - 45.5	43.6	11.3 - 11.7	13.5
system 14	45.5 - 49.6	47.0	49.2 - 50.8	49.4	12.2 - 12.5	15.0
system 15	45.6 - 52.1	46.6	48.3 - 51.2	47.0	12.3 - 12.9	12.3

1) The n-value indicates the incident angle modifier coefficient for the Ambrosetti equation, i.e. $1 - \tan^{1/n}(\Theta/2)$ for reduction of the effective transmission-absorption product ($\alpha\tau$).

- Systematic deviations between solar gain predicted according to the DST procedure and determined by data generation program TRNSYS are small and depend on the load. In general, average annual system performance has been overestimated by 1 - 2 % for the load of 200 litres per day, and it has been underestimated by 2 - 3 % for the 1500 litres per day load. For 50 litres per day, systematic deviation is around zero. For system 15, systematic overestimation is 1 - 3 %.
- Considerable seasonal bias of DST results can be expected for flat plate collectors with incident angle modifier coefficient of 0.4 and higher. For these systems, solar irradiance should be corrected as recommended in the Committee Draft.
- High and strong temperature dependent collector heat loss, i.e. 5.0 + 0.04ΔT W/(m^{2}K) in the simulations, causes an increased scattering of the results. For the load of 50 litres per day, the spread in solar fraction is about 7.2 %. However, it is much lower for the large loads.
- Quality of DST results for the system with the evacuated tubular collector is comparable with that of the reference system.

- Increased heat conduction in the vertical direction of the heat store leads to a higher f_{aux}-value. It does not affect the quality of the annual performance prediction much.
- Low flow in the collector loop combined with a stratified charge of the heat store induces a S_C-value different from zero. It does not have much influence on the quality of the DST results.
- Despite the fact that the general DST mathematical model does not fully support the way the simulated immersed heat exchanger of system 15 operates (fully mixed charge versus stratified charge of the auxiliary part), quality of annual performance prediction is only affected a little by a larger difference of 6.5 % in annual solar fraction for the 50 litres per day load.

Summary of systems for which the DST method can be applied directly

Based on the results of real tests as described in Section 3.3 and the investigation of simulated test data reported above, DCST Subtask participants composed a preliminary list of systems for which the DST method has been validated and consequently can be applied directly:

- Systems with forced circulation in the solar collector loop, with glazed flat plate collectors which are further characterized by:
  - constant part of the collector heat loss coefficient $u_{C,0} \leq 5.0$ W/(m²K);
  - temperature dependent part of the collector heat loss coefficient $u_{C,t} \leq 0.04$ W/(m²K²);
  - incident angle dependency for solar irradiance limited by the following equation: $K_{\tau\alpha} = 1-[\tan(\theta/2)]^{1/n}$ with $n < 0.4$.

  Notice that test data for systems with higher incident angle dependency may be processed using corrected solar irradiance; see Committee Draft 9459/5 ([3]).
- Systems with ETC heat pipe collectors for which dry-out does not occur during testing and during normal operation.

This list resembles the state-of-the-art in May 1995. It is expected to grow due to further validation of the method, which will be taken care of in a project within the European Programme on Standardization, Measurements and Testing; see Section 4.3. In a few years, the method is expected to be validated for all system types with forced circulation in the collector loop, thermosyphon as well as ICS systems as indicated in the CD ([3]).

For systems differing from those mentioned above, validation of the DST method shall be carried out. The proposed procedure for this validation has been described in the next section.

3.5 Procedure for validation of the DST method

For systems not been mentioned in Section 3.4 above and for which previous validation has not taken place, test conditions and data processing model should be validated as well. In this case, DCST Subtask participants propose a test procedure including validation and consisting of the following steps:

1. Performance of two full dynamic tests as described in Section 3.2.1. The tests shall be carried out in periods in which specific system characteristics different from the data processing model (see Section 2.2) are most exposed into different directions. For instance, the two tests for systems with strong temperature dependency of the collector heat loss coefficient shall be performed in a period with a relatively low respectively high ambient air temperature.
2. Evaluation of the two dynamic tests into annual performance predictions for all required meteorological and load conditions.
3. Comparison of the annual performance predictions from the two tests. The method is considered to be validated for the tested system if differences in all annual performance predictions from the two tests are less than 5 % with regard to the hot water demand of the system.
4. If validation of the method under 3 is positive, test data of both tests shall be combined and used for the annual performance prediction to be presented in the test report.

3.6 Accuracy aspects

The DST data processing procedure yields estimated errors in the fitted parameter values and the annual performance prediction. The error analysis takes into account measuring as well as model errors, however, only statistical errors are considered. In data processing, it is not possible to detect systematic errors in the sensors and systematic model errors. Nevertheless, systematic errors affect the parameter values and annual performance prediction.

For information about the systematic error in the used model P is referred to Section 3.4. However, one should be careful with the figures mentioned as the model used for generation of the test data contains systematic errors as well. The effect of systematic measuring errors on the yearly performance prediction has been investigated briefly for an earlier version of DST procedure used in the Netherlands; see [25]. Summary of investigation results has been given below.

Table 3.4: *Systematic measuring errors in the different variables, realistically for professional sensors available on the market, for investigation of their influence on annual performance prediction for solar pre-heat and solar plus supplementary systems.*

variable	systematic error	variable	systematic error
G_t	1%	$\dot{V}$	1%
T_{CA}	0.5°C	$T_{aux,i}$	0.1°C
T_{SA}	0.5°C	$T_{aux,o}$	0.1°C
T_{main}	0.1°C	$\dot{V}_{aux}$	1%
T_S	0.1°C	P_{aux} (electric)	1%

Simulated test data have been used again for investigation of the effect of systematic errors in the measured variables on the annual performance prediction. For solar pre-heat system 3 and solar plus supplementary system 5 in Table 3.1, realistic systematic errors listed in Table 3.4 have been added to or subtracted from the measured variables in such a way that all changes affected DST data processing in the same direction, i.e. the solar gain increased for both systems. For explanation of the variables is referred to the Nomenclature. Influence of a systematic error in measurement of the wind velocity has not been investigated yet as these systems are not really suitable for that.

Differences between annual performance predictions for tests with and without the systematic measuring errors of Table 3.4 appeared to be 1.2 % of the hot water demand for the pre-heat system, and 3.2 % for the solar plus supplementary system. The error for solar DHW systems with an electric element is expected to be somewhat smaller. Notice that these values involve *maximum* systematic errors in the DST annual performance prediction caused by systematic measuring errors. In general, systematic measuring errors will not reinforce each other so that a realistic systematic error in the performance prediction is smaller.

4 DYNAMIC SOLAR DOMESTIC HOT WATER SYSTEM TESTING: CONCLUSIONS AND RECOMMENDATIONS

4.1 State-of-the-art in outdoor testing

A dynamic test (DST) procedure for outdoor laboratory testing of solar domestic hot water systems has been developed and evaluated. Developments were based on earlier findings of the DSTG participants who demonstrated the power of dynamic data processing. Emphasis of the two years work in the DCST Subtask was on generation of guidelines for adequate test sequences for reproducible and accurate system performance prediction, rather than on improvement of the data processing tools. Participants used available model P tools, resulting from the DSTG period, for test sequence investigations. This model contains a general description of the solar DHW system with four parameters for main characterization of solar collector and heat store, and five more parameters for specification of the system behaviour in more detail. The general character of model P implies that there is no unambiguous link between all separate physical system properties and the parameters: second order effects are taken into account by one or more of the available parameters. This means that comparison of identified model parameters with apparently corresponding system specifications determined in an other way is often hard.

The developed test procedure supports solar pre-heat as well as solar plus supplementary systems, and forces the system tested in its most important states. Three types of test sequences have been defined for solar pre-heat systems. For solar plus supplementary systems, there is one additional sequence. Test sequence $S_{sol,A}$ in which system temperature is kept low, is meant to characterize solar collector performance at high efficiency. In sequence $S_{sol,B}$, system temperature is kept relatively high for identification of store heat losses and collector performance at low efficiency. Test sequence S_{store} where the store can loose heat without interference of solar input, is specially intended to identify the overall store losses, i.e. by adding this test sequence to $S_{sol,B}$ store and collector heat losses are decoupled. For solar plus supplementary systems, the heat losses and volume fraction of the auxiliary-heated part of the store is determined from test sequence S_{aux} in which temperature of the auxiliary part is kept high whereas the solar part is kept cold.

Measuring data of real and simulated tests were used for evaluation of the test procedure. Real tests were carried out for solar DHW systems with spectral selective flat plate collectors, forced circulation in the collector loop and an electric element for auxiliary heating. Further tests were simulated for solar pre-heat systems and for solar plus supplementary systems with an electric element for heating during off-peak hours and with a heat exchanger coupled to an indirect boiler. Investigations reveal reproducible and accurate results in general, both for identified parameters and annual performance predictions. Typical scattering of the most important parameters is less than ± 3 % for A_C^* and less than ± 10 % for u_C^* and U_S whereas spread in annual performance is less than ± 1.5 %. Moreover, the standard deviation as delivered by DST data processing gives a good indication for the spread in parameter values and performance predictions. Comparison of DST annual performance prediction with results of calculation by data generation programs shows small DST overestimation, typically 2 - 4 %, for realistic loads.

Preliminary boundaries of the test procedure were determined by means of investigation of simulated test data. Results show the wide application range of the DST method. Reproducibility and accuracy in annual performance prediction better than 5 % of the hot water demand was found for solar DHW systems with spectral selective flat-plate absorbers and evacuated tubular collectors, with common and low flow in the collector loop. The DST method is also quite robust with respect to physical aspects not explicitly taken into account by the data processing tools, such as heat conduction in the vertical direction of the store and stratified charge of the auxiliary part. Considerable seasonal bias of annual performance prediction is not expected for flat plate collectors with constant and temperature dependent part of the collector heat loss coefficient of less than 5.0 W/(m^2K) respectively 0.04 W/(m^2K^2) and with incident angle modifier coefficient according to Ambrosetti of less than 0.4. For systems with larger incident angle modifier coefficients, correction of solar irradiance as recommended in Committee Draft 9459/5 ([3]) should be performed. For more details is referred to Section 3.4.

DST data processing takes into account statistical measuring and model errors. Systematic measuring errors have been investigated briefly for professional measuring sensors available on the market. Results reveal maximum systematic deviations in the annual system performance of about 1 % of the hot water demand for solar pre-heat systems and about 3 % for solar plus supplementary systems.

4.2 Recommendations for further research

Test procedure development has resulted in test sequences providing reliable characterization for a wide range of solar DHW systems. Only minor improvements can be expected from adaptations of the test sequences. Possible improvements have been presented in Section 3.2.2 and involve reduction of the correlation between the main parameters A_C^*, u_C^* and U_S leading to reduced scattering in these parameters when identified from different sequences, and a more accurate annual performance prediction. Other recommendations in Section 3.2.2 include shorter testing period and a less strict test procedure. Additionally, use of the figure of merit described in Paper no. 2, and the standard deviation in fitted parameters and performance prediction might be elaborated for criteria for termination of DST testing. Shorter test periods may further be provided by an on-line computerized test procedure which considers the operation of the system in the preceding test period together with the weather forecast for determination of the process for the days to come.

Then, the DST procedure should be checked on reproducibility aspects, also in the sense that a test carried out in one laboratory shall reveal the same results as a second test on the same system in a different laboratory. The influence of measuring accuracy, specially systematic errors in the sensors, on scattering of the resulting system performance should be part of this study. Therefore, study in Section 3.5 should be extended.

The DCST Subtask participants made up a preliminary list of systems for which the DST method has been validated; see Section 3.4. However, this summary has been based mainly on processing of simulated test data. Therefore, major recommendation is the further validation of the DST method by real testing of both solar pre-heat and solar plus supplementary systems. This means verification of the investigation results described in Section 3.4, but also validation for solar DHW systems not investigated yet, e.g. with unglazed collectors and compact systems like thermosyphon and integral collector storage systems. The method for further practical validation of the DST method has been presented in Section 3.5.

On the other hand, investigation of simulated test data remains a powerful tool in initial determination of the application range. In first instance, distinction should be made between solar pre-heat and different types of solar plus supplementary systems. Detected aspects, open for investigation are still the influence on fitted parameters and annual system performance prediction of temperature dependency of the collector heat loss coefficient, incident angle dependency of the zero loss efficiency and the setpoint temperature of the possible auxiliary part of the heat store.

Important for elaboration of results of both real and simulated tests is the way of presentation of the results. Unambiguous presentation of results facilitates efficient investigations and drawing of conclusions. The DCST participants choose to relate differences in annual system performance predictions to the hot water demand.

4.3 Outlook for dynamic testing of solar domestic hot water systems

The major recommendations described in Section 4.2 will be taken into account in a new project within the European Standards, Measurements and Testing Programme. The title of the project is 'Research and experimental validation on the DST performance test method for solar domestic water heaters'. The goal of the project is to provide the missing links from its present status to CEN standardization. Important elements are:

- comparison of the DST method to the CSTG method ([26]), leading to correspondence factors;
- fine-tuning of the present description of the test procedure;
- clear definition of the scope and boundaries of the test procedure;
- intercomparison test of the DST method in different countries;
- presentation for direct use in standardization.

These objectives are given by the present needs of the CEN TC 312 which recognizes the DST method as necessary for European standardization, but requires an experimental validation of the method as well as conversion factors to the CSTG method.

Ten recognized laboratories in nine European countries will work together in the project. All participants have strong connections with the solar energy industry in their respective countries. High level of testing expertise is present within the project team. Test sites are distributed from Scandinavia to Mediterranean countries, so that a wide range of testing climates is available. A number of industrial companies in the participating countries have shown such interest in the project and its meaning for standardization, that they have committed themselves to follow the project and comment on it.

The project activities have been structured in the following main work packages:

- calculation study to further define the scope and boundaries of the DST method;
- tests and investigations to compare the DST method with the CSTG method;
- Round Robin test in nine laboratories to validate the DST procedure.

A clear scope for the DST method will be formulated to guarantee 95 % accuracy, 90 - 95 % for extrapolation into other climates or operating conditions.

The project will be based on the work already done on the DST method. Specific information involves the second Committee Draft 9459/5 including recommendations for improvement of the text as well as the contents of the present Volume B of the DCST Subtask Final Report.

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ANNEX A: TECHNICAL PAPERS ON SOLAR DOMESTIC HOT WATER SYSTEM TESTING

Editing work on ISO draft CD9459/5 1992-1994

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1 Introduction

The development of a method to analyse short-term measurements at SDHW systems has essentially been completed in the DSTG working group of the IEA [1] and the german project VELS1 [2]. The first draft for a test standard (ISO9459-5), which has been elaborated in VELS1, proved to be not sufficient for reliable and reproducible parameter identification. These problems have been elucidated by the experimental work of the participants of the *Dynamic System and Component testing Group* (DSCG), and subsequent work has been carried out towards a reliable test standard.

From end of 1992 to August 1994, continuous efforts for improvements of the test standard formulation have been made, editored by scientists of the LMU Munich. The draft has been send out officially:

1. March 1993, for voting as DIS at the ISO meeting in Budapest in August 1993, and
2. August 1994, for the next voting as DIS [3].

The draft has not been accepted as DIS in Budapest 1993, but acceptance has been signaled if the following improvements are made:

1. The physical model and the algorithm for parameter identification shall be prescribed as mathematical rules, but not as a certain software implementation. The adequacy of a given implementation shall be checked by comparing the results with reference results for same benchmark conditions
2. The test prescription has to be augmented, such that in every case there is enough and reliable information for parameter identification.

These requirements (except the definition of the benchmark conditions and reference results) have been realized in the draft of August 1994 as follows.

2 Work on the Draft

In the draft of March 1993, the test days are partitioned into days with low and days with high load. Thus a variation of the collector inlet temperature has been achieved, which is required for separating the collector loop parameters *effective area* and *specific collector loop loss coefficient* from each other. Experiments (e.g. at ITW Stuttgart) have shown, that by this procedure the parameters can indeed by decoupled. However, not in every case it was possible to decorrelate the loss coefficients of the store and the collector loop from each other. Consequently, the draft from August 1994 contains, additionally to the solar sequence dedicated to identify the collector parameters, sequences for storage test.

2.1 Additional Testsequence for the Auxiliary Part of the Store

Measurements revealed that there was no safeguard against testing a system with integrated auxiliary under continuously sunny conditions. Under these conditions the energy delivered by the auxiliary heater is small (or zero), and thus there is not enough information to quantify the corresponding parameter, the fraction of the auxiliary store (which, at the same time, represents the fraction of losses and the fraction of volume).

In many climates the loss of the auxiliary part of the store determines performance for a significant part of the year, especially in winter. Thus it is necessary to include such situations with low solar input in the test. Such a sequence has been defined in incorporated in the draft as $\mathcal{S}_{aux}$. Store loss test sequences (this is also true for the sequence defined in the sequel) necessarily take at least one day, otherwise the resulting loss energy is too low to identify the loss coefficient.

2.2 Additional Testsequence for the Whole Store

Another, more subtle, problem is that the losses owing to the collector loop and to the store are often very similar from the viewpoint of the output quantity, the thermal load power. For a certain range of operating conditions, collector loop and store losses can compensate each other. However, only sufficiently decoupled parameters give an accurate estimate of the performance for a large class of operating conditions. Thus a separate store test sequence was sought.

In the CSTG procedure [4], a separate store loss test is performed by filling the store via the cold water inlet with hot water, and measuring the energy lost after a night. This yields the store loss coefficient in short time. However, considerable objections against this procedure have been put forward. For example, for stores with a dead zone below the inlet zone of the solar heat, the store loss coefficient may be overestimated, especially for stores with low-insulated bottoms[1]. Thus it

[1]For the same reason, an extra sequence with higher cold water inlet temperature has been discarded.

was decided to develop a sequence by which the store is loaded as in normal operation, i.e. via the solar collectors. This is obviously more demanding than the night test mentioned above, but is believed to represent better the intention of SDHW systems.

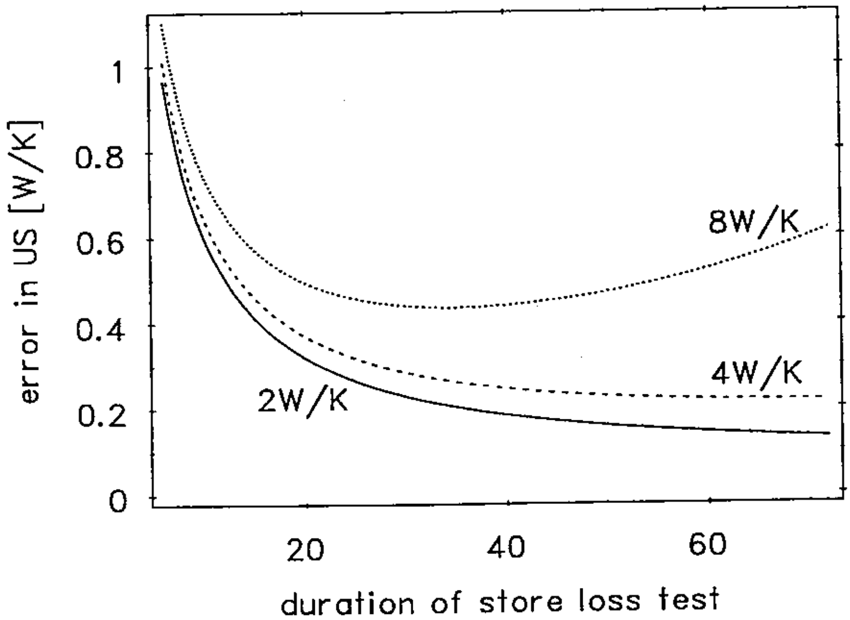

Figure 1: Accuracy of the store loss coefficient obtained from a test where the store is filled with hot water, left in stagnation for a certain period, and discharged at the end to measure the energy lost in the stagnation period, for a loss coefficient of 8 W/K, 4 W/K and 2 W/K. It was assumed that the accuracy of the measurement of the energy is 2% referred to the energy contained in the store at the beginning of the test. The store capacity has been set to 1 MJ/K.

It may be mentioned that a single night as used in the CSTG test is rather short for good stores and might yield high errors for well-insulated stores, see Fig. 1. The store loss coefficient U_S is obtained by:

$$U_S = -\frac{C}{t} \ln \left(1 - \frac{Q_i - Q_f}{Q_i}\right), \tag{1}$$

where C is the store heat capacity, t is the test duration, Q_i is the store energy at the begin of the test, and Q_f is the final energy content (both referred to the inlet temperature used in the final discharge). The error δU_S for the store loss coefficient U_S, assuming a measurement error δQ_f in Q_f is given by:

$$\delta U_S = \frac{C}{t} \exp\left(\frac{U_S t}{C}\right) \frac{\delta Q_f}{Q_i}. \qquad (2)$$

2.3 Dependence of Collector Losses on Wind

There has been considerable discrepancy about the importance of the wind-dependence of collector losses, and the right way to treat them. It has been proposed to

1. to ignore it, or
2. to restrict the wind velocity into a certain range, e.g. from 3 m/s to 5 m/s, or
3. to vary the wind in the test sufficiently such that the coefficient describing the wind-dependence may be evaluated from the test.

Option (1) may lead to large prediction errors and to non-reproducible results; Option (2) involves high effort for the artificial wind generator and underestimates the yield for certain systems, and Option (3) may be difficult to realize in regions with continuous high wind velocity. The draft from August 1994 gives the free choice to select one of the alternatives mentioned.

For converting the meteorological wind velocity to the wind velocity on collector plane, the wind velocity in collector plane shall be taken as 0.35 times the meteorological wind velocity. This factor results from the expression $(\ln(h_2/u_2)/\ln(h_0/u_2))/(\ln(h_1/u_1)/\ln(h_0/u_1))$, where $h_0 = 60$ m, $h_1 = 10$ m the height where the meteorological measurement is taken, $u_1 = 0.03$ m the corresponding ambient roughness, $h_2 = 3$ m the (effective) height where the collector is installed, $u_2 = 1$ m the corresponding ambient roughness, see [5].

3 Test Report

The report of test results has been completely revised. The results are now presented as yearly energy gain for very different operating conditions: For all combinations of test reference year weather data of the locations

1. Würzburg (Germany)
2. Edmonton (Canada)
3. Alice Springs (Australien)

and for different load volume. This complies with the intention of providing an international standard which can be used for system performance assessment all over the world.

4 Outlook

The following steps shall be undertaken in the future:

1. The scope of the draft should be reformulated according to future experience. This is important e.g. for system exhibiting collector fields with strong incidence angle effects, stratification devices or a security temperature switch with low threshold.
2. The benchmark conditions mentioned have to be formulated.
3. Computer simulation with Monte-Carlo weather data should show how the test sequences can be shortened further.

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Figure of Merit for the Accuracy of Parameters Identified in Dynamic Fitting

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Abstract

A figure of merit function is defined to quantify the expected accuracy of the parameters obtained from dynamic fitting. The function is an approximate expression for the expected average prediction error for different conditions. This function might be used to determine the optimum time for termination of measurements. Application of the theory is indicated for solar collectors.

1 Introduction

Determination of parameters in a model by adjusting them to measured data is a well established procedure. In all cases where (1) the experimental design can be chosen freely, a priori or on-line, or (2) the acquisition of data can be continued until a more or less arbitrarily chosen length, a figure of merit function indicating the information (predictive power for other data) gained from the experiment is required. This function might be used (1) to optimize decisions about the experimental design (a priori or on-line), or (2) to define a criterion to stop data acquisition.

We treat the problem in the frame of dynamic testing of solar systems [1, 2]. A stopping criterion is especially needed to for in-situ testing where there are strong restrictions on predicting or varying the input data. Hence the required length is not known in advance.

2 General

Taking into account the information available and requiring a general applicability, we define a figure of merit function as a measure of the predictive accuracy of the model in conjunction with the test data. Such a function might also be used to select between different models, e.g. to decide whether certain effects (parameters) should be included into the model or not. It would be interesting to compare such decisions with decisions resulting from general statistical criteria [3, 4].

2.1 Linear Theory

We start with measured values $\{y_n^{exp} \mid = 1 \dots N\}$ to be modeled with a linear model function $y_n^{mod}(\mathbf{p})$ with free parameters $\mathbf{p}$ which are determined by the Least Squares method, i.e. by determining the parameter set $\hat{\mathbf{p}}$ minimizing the sum Q of squares of the deviations:

$$Q(\mathbf{p}) = \sum_{n=1}^{N} \left(y_n^{mod}(\mathbf{p}) - y_n^{exp} \right)^2 . \tag{1}$$

To estimate the parameter error we assume that the measured signal y^{exp} is the modeled output for a certain *true* parameter set $\mathbf{p}^{(0)}$ plus an noise error signal Δr [5]. Hence the residue r_n is:

$$r_n(\mathbf{p}) = y_n^{mod}(\mathbf{p}) - y_n^{mod}(\mathbf{p}_0) + \Delta r_n . \tag{2}$$

It is assumed that the errors Δr_n

- are uncorrelated with each other, $\mathrm{E}\left[\Delta r_n \Delta r_m\right] = \delta_{nm} s^2$,
- are independent from the input variables $\mathbf{e}$ and the parameters $\mathbf{p}$,
- are normally distributed with root mean square s,
- have zero mean.

In this case it can be shown that for linear models $\hat{\mathbf{p}}$ is an *unbiased* estimator; i.e. the average of many different values $\hat{\mathbf{p}}$ from different measurements equals the true values $\mathbf{p}^{(0)}$, independently of the length and the kind of the measured data. The mean error is expressed by the variance-covariance matrix V_{ij}:

$$V_{ij} = \mathrm{E}\left[(\hat{\mathbf{p}}_i - \mathbf{p}_i^{(0)})(\hat{\mathbf{p}}_j - \mathbf{p}_j^{(0)}) \right] = s^2 \left(H^{-1} \right)_{ij} . \tag{3}$$

The error Δr may be interpreted as the sum of measurement uncertainties of y^{exp} and $\mathbf{e}$ as well as the model error. Note that measurement and model errors can not be separated from each other except in the special case of simulated data. Measurement errors of $\mathbf{e}$ are not explicitly taken into account, they are implicitly summarized in Δr. H is the Hesse matrix (more precisely the curvature matrix [5]),

$$H_{ij}(\mathbf{p}) = \sum_n \frac{\partial y_n^{mod}(\mathbf{p})}{\partial p_i} \frac{\partial y_n^{mod}(\mathbf{p})}{\partial p_j} . \tag{4}$$

For a linear model none of the H_{ij} depends on $\mathbf{p}$.

The covariance matrix is the appropriate measure of the uncertainty in the parameters. However, the representation by a variance vector Δp_i in conjunction with a correlation matrix R is equivalent to the covariance matrix:

$$\Delta p_i = \sqrt{V_{i,i}}, \qquad R_{i,j} = \frac{V_{i,j}}{\Delta p_i \Delta p_j}. \tag{5}$$

The covariance matrix V takes into account the variability of the data including intercorrelations. Predictions based on V according to Eq. (6) are invariant against arbitrary non-singular linear transformations of the parameters.

Potential problems with the covariance matrix are:

1. Determination of s. A low value of s might result – e.g. as the result of a low model error due to insufficient variability of $\mathbf{e}$. This could, however, be corrected in Eq. (3) by $V_{ij} \to V_{ij}\,(s^{\text{true}}/s)^2$, or in Eq. (9) by $\delta \to \delta(s^{\text{true}}/s)$, where s^{true} is a reliable a-priori lower limit for s. E.g. in a collector test s^{true} could be chosen as collector area times a certain fraction of a typical irradiance value, e.g. $A_C \cdot 0.02 \cdot 1000\,\text{Wm}^{-2}$.
2. A long measurement with low variations (e.g. in-situ) might yield low Δp_i ($\Delta p_i \propto 1/\sqrt{N}$) although the predictive power for conditions different from average measurement conditions might be pure due to model errors. Within the linear model with random errors there seems to be no general cure against this fault.

   Additional constraints on the variability of $\mathbf{e}$ (and, in principle, on their intercorrelations) might be useful.
3. In nonlinear models H depends on the parameters. Hence for insufficient data there might be parameter values with low Δp_i, e.g. at rather strange parameter values shortly after the beginning of the measurement (little data) or at a local minimum.

   If this problem is suspected it might be useful to calculate H, and thus the associated covariance matrix, for *estimated* parameter values. A rough parameter estimate is sufficient.
4. In dynamic fitting the filter weighting slightly modifies the theory [1, 2], and the number of data points N is proportional to the length of the measurement L divided by the filter time constant. However, the main difficulty is to choose the right filter constant, i.e. the right effective N.

2.2 Figure of Merit

Variability of the data, their decorrelation and the model error are all taken into account by the parameter covariance matrix V. Thus the figure of merit function should be a function of V.

For a scalar yield function $Y(\mathbf{p})$ being linear with regard to $\mathbf{p}$ the mean square prediction error σ_Y^2 is obtained from V:

$$\sigma_Y^2 = \mathrm{E}\left[\left(Y(\mathbf{p}) - Y(\mathbf{p}^{(0)})\right)^2\right] = \sum_{ij} V_{ij} \frac{\partial Y}{\partial p_i}\frac{\partial Y}{\partial p_j}. \tag{6}$$

The following inequality holds for σ_Y:

$$0 \leq \sigma_Y^2 \leq d\,(\sigma_Y')^2, \qquad (\sigma_Y')^2 = \sum_i V_{ii} \left(\frac{\partial Y}{\partial p_i}\right)^2 = \sum_i \left(\Delta p_i \frac{\partial Y}{\partial p_i}\right)^2. \qquad (7)$$

Hence σ_Y' neglecting the intercorrelation terms in Eq. (6) either overestimates σ_Y or underestimates it by a factor of not more than $\sqrt{d}$, where d is the number of parameters. In many cases σ_Y' will overestimate the error, e.g. the positive intercorrelation between the collector area term and the loss coefficient generally leads to terms partially compensating each other.

Another justification for neglecting the intercorrelation terms in Eq. (6) is that instead of the error σ_Y^2 for a single prediction the sum (average) $\sum_n \sigma_{Y_n}^2$ over different prediction errors,

$$\sum_n \sigma_{Y_n}^2 = \sum_n \sum_{ij} V_{ij} \frac{\partial Y_n}{\partial p_i} \frac{\partial Y_n}{\partial p_j} = \sum_{ij} V_{ij} \left(\sum_n \frac{\partial Y_n}{\partial p_i} \frac{\partial Y_n}{\partial p_j}\right) \qquad (8)$$

should be interesting, e.g. as the average error over all climatic zones and user behaviour patterns on earth. In this case at least a partial cancellation of the factors at V_{ij} with $i \neq j$ happens due to the summation over n. This form Eq. (8) of the figure of merit is equivalent to the function given by [6] in Eq. (6.2.6). There, alternatively the determinant of V, $|V|$, is proposed as a figure of merit. However, this criterion would accept significant deterioration in one parameter if compensated by increased accuracy in another parameter and is thus not used.

Hence the dimensionless quantity $\delta_Y = \sigma_Y'/Y$, the relative prediction error ignoring intercorrelations, is a reasonable figure of merit for the accuracy:

$$\delta_Y^2 = \sum_i \left(\frac{\Delta p_i}{\pi_i}\right)^2, \qquad \text{with} \qquad \pi_i = \frac{Y}{\left|\frac{\partial Y}{\partial p_i}\right|}. \qquad (9)$$

The stopping criterion is fulfilled if δ_Y is smaller than a certain limit δ_0. This means that each parameter p_i is determined with an accuracy of roughly $\delta_0 \pi_i$ or better.

The function δ_Y defined in Eq. (9) is invariant against linear diagonal parameter scaling, i.e. against substituting the parameters p_i by new parameters q_i via $p_i = a_i p_i + b_i$, with all a_i different from zero. However, it is not invariant against arbitrary linear transformations in the parameters – a direct consequence from neglecting intercorrelation terms. This expresses the desire to decorrelate the parameters.

3 Collector Model

Table 1: Values of π_i for the collector model. Reference values used for the third column are: $\langle G \rangle = 500\,\mathrm{Wm^{-2}}$, $\langle \Delta T \rangle = 50\,\mathrm{K}$, $\langle \Delta v \rangle = 3\,\mathrm{ms^{-1}}$.

p_i	π_i	
A'_C	A'_C	A'_C
u_0	$\langle u \rangle$	$10\,\mathrm{Wm^{-2}K^{-1}}$
u_T	$\frac{\langle u \rangle}{\langle \Delta T \rangle}$	$0.2\,\mathrm{Wm^{-2}K^{-2}}$
u_v	$\frac{\langle u \rangle}{\langle \Delta v \rangle}$	$3\,\mathrm{Jm^{-3}K^{-1}}$
r	$\left[\max_{0<\theta<\frac{\pi}{2}} \left\lvert\frac{\partial K_{\alpha T}(\theta,r)\cos(\theta)}{\partial r}\right\rvert\right]^{-1}$	2
c_C	c_C	c_C

For the dynamic collector model described in [7, 2] the parameters and expressions for the π_i are listed in Table 1. For the stationary parameters (i.e. all except c_C) the yield function

$$Y = A'_C[K_{\alpha\tau}(r)G - u_0\Delta T - u_T\Delta T^2 - u_v v\Delta T] \tag{10}$$

is inserted into Eq. (9). The expression for $\pi_{A'_C}$ is exact. For u_0, u_T and u_v $\langle G \rangle$ represents the value of the term in square brackets in Eq. (10), and $\langle u \rangle = \langle G \rangle / \langle \Delta T \rangle$. The derivative required to get π_r is used under the assumption of beam radiation only and is roughly 0.5 for all r values up to $r = 0.5$.

4 Conclusions

The figure of merit function introduced should be used intensively to gain experience. Any empirical criterion for sufficient data collection should be justified by a similar relation to the covariance matrix as was shown here for the figure of merit function defined.

The reliability of the covariance matrix is crucial and should be verified whenever possible. The correct adjustment of the filter constant in parameter identification is important for a realistic error estimation. The expressions for the reference parameter deviations π, which are used to express the figure of merit function, should be generalized to other systems such as SDHW systems.

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Experimental and Theoretical Validation of the Dynamic System Test for Solar Domestic Hot Water Systems According to ISO/CD 9459, Part 5

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Dynamic system testing **(DST method) is a test method used to determine the thermal performance of solar domestic hot water systems. In order to investigate the DST method several experimental tests were carried out with one typical German forced circulation system. Comparing the results of twelve tests, a high reproducibility was achieved with regard to parameter identification and the predicted energy gain. The parameters of the collector and the storage were determined by component testing. The yearly energy gain was calculated by TRNSYS simulation. The results of both methods differ only in a range of few percents. In addition to the experimental investigations simulated tests were performed for variants of the tested system. Especially critical effects were introduced that cause inaccuracy or a seasonal bias of the DST test results. For all cases the good reproducibility and accuracy of the test results obtained from the experimental tests were confirmed. A powerful tool for testing and certification of solar domestic hot water systems is implemented by the ratification of the DST method as an international standard.**

1 Introduction

The DST method /1/ was developed as a short term performance test for solar domestic hot water (SDHW) systems within the German joint research projects VELS[1] I and VELS II.

The goal of the method is to predict the yearly energy gain of a SDHW system on the base of a short term test. Therefore the thermal behaviour of the system is measured over a period of approximately three weeks. Using a numerical model, performance parameters are derived for the SDHW system, which then are used to predict the yearly energy gain of the system for reference weather data and a given load profile.

The test method is currently investigated with respect to its accuracy and reproducibility by several European test institutes. Different system types are considered by experimental testing and simulation. At the ITW experimental and theoretical investigations were carried out with a forced circulation system, which is typical for the German market.

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[1] VELS: Verfahren zur Ermittlung der Leistungsfähigkeit von solaren Brauchwassererwärmungsanlagen

In section 2 of this report the basic principles of the method are summarised. The results of the experimental and theoretical validation are presented in Section 3 and 4, respectively. Conclusions and recommendations based on these results are given in section 5.

2 Test Method

The test method is based on three steps:

Short Term Test: The thermal behaviour of the SDHW system is measured under natural weather conditions and a defined load profile within an outdoor test. The test is designed in a way, that the system is driven in all relevant system states (e.g. low collector temperatures for the determination of the optical efficiency, high collector and storage temperatures for the determination of the heat loss coefficients). The input quantities such as the meteorology and the load have to be varied in a wide range, to cover most system states of a real system operation during the test. Thereby it is important that the input quantities are varied independently from each other, otherwise the performance parameters cannot be separately determined. A sufficient and uncorrelated variability of the input quantities is ensured by three different test sequences which are part of the current test procedure. These are[2]:

S_{sol} - **Test Sequence for Solar Operation:** Test sequence S_{sol} consists of several consecutive days of measuring, where the system is operated under natural weather conditions. There are two types of days: At Test A days a load is applied, such that the system is operated on low temperatures. At Test B days the whole system (collector and storage) is kept at high temperatures by applying a low load. The measurements are continued until a minimum number of valid Test A and Test B days is reached. The substantial requirement for a valid day is, that an insolation of 12 MJ/m^2 in collector plane is reached.

S_{aux} - **Test Sequence for Auxiliary Operation:** The system is heated to a great extent by the auxiliary heater over a period of 4 days. Therefore days of low solar irradiance are required or the collector is covered.

S_{store} - **Store Loss Test Sequence:** First the system is heated up during a series of days, where a low load is applied. Then again the system is operated under low solar irradiance or the collector is covered for ca. 48 hours without any draw-off (stand-by).

All three sequences are to be applied on SDHW systems with auxiliary heater. For systems without auxiliary heater S_{aux} is left out.

Identification of Performance Parameters: During the measurements all relevant input quantities as well as the thermal power of the system during draw-offs are measured and recorded as a function of time. The performance parameters of the system are obtained using a parameter identification algorithm, which is implemented in a computer program /3/. The program minimises an objective function, which is a measure for the difference between simulated and measured system performance. The quality of the parameter identification mainly depends on the variability and a low correlation of input quantities.

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[2]The test sequences are briefly described. A more detailed discussion is found in /2/.

Low standard deviations of the parameters in conjunction with a low objective function indicate a good quality of the measurements. The performance parameters are:

A_C^*	[m²]	Effective collector area $A_C^* = A_C F_R^* (\tau \alpha)$, where F_R^* is the heat removal factor of the collector loop
u_C^*	[W/(m² K)]	Effective collector loop loss coefficient
U_S	[W/K]	Total storage heat loss coefficient
C_S	[MJ/K]	Total storage heat capacity
f_{aux}	[-]	Fraction of the storage volume used for auxiliary heating
D_L	[-]	Mixing constant, describing mixing effects during cold water inlet
S_C	[-]	Stratification parameter (for storage charging)

Long Term Performance Prediction: Using the same simulation model and the prior determined performance parameters, the thermal behaviour of the system can be simulated. Thus the yearly energy gain can be predicted for reference weather data and a standard load profile. An error of the energy gain is estimated using the standard deviations and the correlation coefficients of the system parameters.

3 Experimental Results

Experimental investigations were carried out with a typical German forced circulation SDHW system. The collector has an aperture area of 7.2 m², single glazing and a selective Rollbond absorber. The hot water storage has a volume of 500 l; it is equipped with an immersed heat exchanger for the collector loop and an electrical auxiliary heater. The measurements were carried out according to the DST method. Additional sensors were placed in the collector loop. Thus, the performance parameters of the whole system as well as the parameters of the collector and the storage could be determined.

During summer 1993 six independent tests were carried out. These tests were based on the test procedure as given in the draft of ISO 9459, Part 5 of may 1993 /4/, where only test sequences for solar operation were required. During winter 93/94 as well as in spring 94 the system was tested according to the test sequence for auxiliary operation S_{aux} and the test sequence for the determination of the store losses S_{store}. Table 3.1 shows the test sequences and the corresponding measuring periods.

3.1 Determination of Parameters with the DST Method

The test sequences were evaluated for test 1 to test 12. Table 3.2 shows the parameters with their standard error. The results show a good reproducibility independent from the meteorological conditions. Further the standard errors turn out to be a realistic measure for the scatter of the parameter values. The standard errors of the collector loop parameters A_C^* and u_C^* are still to be improved.

Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12
sol93_7 29.05. - 6.06.93	sol93_10 17.06. - 24.06.93	sol93_11 29.06.- 04.07.93	sol93_12 13.07. - 22.07.93	sol93_13 02.08. - 17.08.93	sol93_14 10.08. - 15.08.93	sol93_7 29.05. - 06.06.93	sol93_10 17.06. - 24.06.93	sol93_11 29.06.- 04.07.93	sol93_12 13.07. - 22.07.93	sol93_13 02.08. - 17.08.93	sol93_14 10.08. - 15.08.93
aux93_1 28.12. - 31.12.93						aux94_2 15.04. - 19.04.93					
sto94_1 06.04. - 09.04.94						sto94_2 02.05. - 05.05.94					

Table 3.1: Data base for test 1 to test 12 with one test sequence S_{sol}, S_{aux} and S_{store} each.

	A_C^* [m²]	u_C^* [W/(m² K)]	U_S [W/K]	C_S [MJ/K]	f_{aux} [-]	D_L [-]	S_C [-]
Test 1	5.07 ± 0.14	8.81 ± 0.94	4.19 ± 0.08	2.15 ± 0.014	0.6 ± 0.0044	0.0047 ± 0.0008	0 ± 0.021
Test 2	5.08 ± 0.16	9.59 ± 0.27	3.92 ± 0.09	2.13 ± 0.019	0.6 ± 0.0058	0.0087 ± 0.0013	0 ± 0.033
Test 3	4.99 ± 0.11	8.64 ± 0.34	4.10 ± 0.11	2.19 ± 0.015	0.59 ± 0.0052	0.0066 ± 0.0013	0 ± 0.018
Test 4	5.26 ± 0.26	9.68 ± 0.27	4.08 ± 0.09	2.18 ± 0.014	0.59 ± 0.0044	0.0077 ± 0.0011	0 ± 0.039
Test 5	5.26 ± 0.11	9.12 ± 0.31	4.23 ± 0.1	2.21 ± 0.012	0.58 ± 0.0044	0.0062 ± 0.0012	0 ± 0.016
Test 6	5.04 ± 0.016	8.22 ± 0.51	4.30 ± 0.12	2.21 ± 0.015	0.58 ± 0.0051	0.0057 ± 0.0012	0 ± 0.021
Test 7	5.01 ± 0.13	8.58 ± 0.36	4.321 ± 0.12	2.11 ± 0.0129	0.59 ± 0.0055	0.005 ± 0.0013	0 ± 0.018
Test 8	5.08 ± 0.18	9.50 ± 0.26	3.89 ± 0.13	2.09 ± 0.017	0.60 ± 0.0072	0.012 ± 0.0023	0 ± 0.035
Test 9	4.99 ± 0.2	8.62 ± 0.42	4.28 ± 0.17	2.16 ± 0.016	0.58 ± 0.0083	0.0065 ±0.002	0 ± 0.018
Test 10	5.20 ± 0.25	9.39 ± 0.32	4.14 ± 0.14	2.14 ± 0.015	0.58 0.0067	0.0095 ± 0.0019	0 ± 0.042
Test 11	5.27 ± 0.16	9.10 ± 0.39	4.45 ± 2.19	2.19 ± 0.014	0.57 ± 0.0076	0.0057 ± 0.0020	0 ± 0.026
Test 12	5.08 ± 0.19	8.26 ± 0.64	4.57 ± 0.18	2.18 ± 0.014	0.57 ± 0.0081	0.0051 ± 0.0017	0 ± 0.025

Table 3.2: System parameters for twelve tests

3.2 Comparison with Parameters from Component Testing

Alternatively to the evaluation with the DST method component parameters are determined for collector and storage by a separate evaluation of the data base. The appropriate methods are described in /5/. The system parameters of the DST method can be derived from the component parameters.

Collector Loop: The effective collector area A_C^* and the effective collector loss coefficient u_C^* were determined by a direct evaluation of the approximation of the collector loop power

$$P_C = A_C^* \, [G_t - u_C^* \, (T_S - T_{amb})]^+$$

The storage temperature T_S, which is relevant for the collector losses, was measured by an additional sensor at the lower end of the solar loop heat-exchanger. A fit of the measured collector loop power to the equation above yields $A_C^* = 5.0$ m² and $u_C^* = 6.5$ W/(m² K). Taking the influence of the collector loop controller into account $A_C^* = 5.1$ m² and $u_C^* = 10.3$ W/(m² K) are obtained. The parameter S_C marks the ability of the system to build up a thermal stratification in the storage during charging. For the system under test the storage is charged fully mixed via a heat-exchanger immersed at the bottom. Thus an estimation of $S_C = 0$ is correct.

Storage: The heat loss rate of the storage was determined to $(U\,A)_S$ = 3.9 W/K, the heat capacity to C_S = 2.1 MJ/K. The fraction of the storage capacity, which is heated by the auxiliary heater can be calculated to f_{aux} = 0.49 based on the geometric position of the heating element. However, the temperature profile within the storage shows that - depending on the mode of operation - heat is transferred to a certain extent to regions below the heating element by conduction and convection. A best fit between measurement and simulation is obtained for f_{aux} = 0.56.

3.3 Long Term Performance Prediction Using the DST Method

Using the parameters obtained with the DST method the yearly energy gain is predicted for subsequent reference conditions:

- TRY Würzburg (FRG)
- A daily load of 350 l/d at 45 °C and 3 draw-offs (7 h, 12 h, 19 h)
- storage ambient temperature 15 °C, cold water temperature 10 °C

Table 3.3 shows the results of 12 tests. The yearly system gain q_{use} and the auxiliary consumption q_{aux} (both based on collector aperture area) as well as the solar fraction f. Further the deviation δf from its mean value was calculated (absolute deviation in %).

Also for the long term performance prediction a good agreement of the results is obtained. The scatter of the solar fraction is in the range of ± 1 %. Provided that all tests are tainted with the same measuring and modelling error, this range marks the reproducibility of the method (obtained with the system in question). Also for the system gain the standard error turn out to be a good measure for the scatter of the results.

	q_{use} [kWh/(m² a)]	q_{aux} [kWh/(m² a)]	f [%]	δf [%]
Test 1	366 ± 0.8	357 ± 0.8	50.7 ± 0.1	0.04
Test 2	358 ± 1.3	365 ± 1.3	49.6 ± 0.2	-1.06
Test 3	369 ± 2.4	354 ± 2.4	50.9 ± 0.3	0.24
Test 4	364 ± 2.4	359 ± 2.4	50.4 ± 0.3	-0.26
Test 5	371 ± 2.2	352 ± 2.2	51.3 ± 0.3	0.64
Test 6	374 ± 2.8	349 ± 2.8	51.7 ± 0.4	1.04
Test 7	365 ± 2.2	358 ± 2.2	50.5 ± 0.3	-0.16
Test 8	358 ± 2.6	365 ± 2.6	49.5 ± 0.3	-1.16
Test 9	366 ± 3.3	357 ± 3.3	50.6 ± 0.5	-0.06
Test 10	364 ± 2.3	359 ± 2.3	50.4 ± 0.3	-0.26
Test 11	369 ± 2.8	354 ± 2.8	51 ± 0.4	0.34
Test 12	371 ± 3.7	352 ± 3.7	51.3 ± 0.5	0.64

Table 3.3: Results of the long term performance prediction of 12 tests

In order to investigate the influence of a variation in climate and load on the scatter of the predicted energy gain, a second performance prediction was carried out for changed boundary conditions. Table 3.4 shows the solar fraction f for TRY Hannover and TRY Stötten (lowest and highest insolation for Germany). For the TRY Würzburg the daily load was varied from 200 l to 500 l per day. Although the standard errors of the collector loop parameters A_C^* and u_C^* seem rather high, the error in the long term performance prediction remains quite small, also for a variation of loads and climate. The maximum deviation for the solar fraction remains in the range of ±1.5 %.

3.4 Comparison with Long Term Performance Predictions Using TRNSYS

In a further step the performance prediction according to the DST method is compared with TRNSYS simulations. Therefore the system was modelled in detail. The performance parameters for collector and storage were determined by component tests. The first and second order heat loss coefficients of the collector are $U_0 = 4.0$ W/(m² K) and $U_T = 0.02$ W/(m² K) (based on the aperture area). The optical efficiency was determined to $\eta_0 = 0.81$. To simulate the storage the parameters mentioned above are used. The heat capacity rate of the heat exchanger was determined to $(U\ A)_{hx} = 419$ W/K. The collector loop including the controller was modelled as close as possible to the real system. The TRNSYS simulation was carried out for the reference conditions given in the previous section.

To compare the results of the TRNSYS and DST simulation, the results of data base 2 are used, because it shows the lowest correlation between the parameters. Table 3.5 shows the results of the performance prediction for the DST method and the TRNSYS simulation. In Figure 1 the results are plotted on a monthly base.

On a yearly base the results show a very good agreement, whereas the maximum deviation on a monthly base amounts to 4 %.

	TRY Würzburg (1226 kWh/(m² a))			TRY Hannover (1042 kWh/(m² a))	TRY Stötten (1367 kWh/(m² a))
	200 l/d	350 l/d	500 l/d	350 l/d	350 l/d
Test 1	56.8	50.7	43.1	43.5	53.5
Test 2	55.9	49.6	42.0	42.3	52.1
Test 3	57.3	50.9	43.3	43.8	53.8
Test 4	56.3	50.4	43.1	43.3	53
Test 5	57.1	51.3	44.0	44.2	54
Test 6	57.9	51.7	44.2	44.6	54.7
Test 7	56.6	50.5	42.9	43.3	53.3
Test 8	55.9	49.5	41.9	42.3	52
Test 9	56.7	50.6	43.1	43.4	53.4
Test 10	56.4	50.4	43.1	43.3	53
Test 11	56.6	51	43.9	43.9	53.7
Test 12	57.1	51.3	44	44.2	54.3

Table 3.4: Results of the long term performance prediction for a variation of climate and load

	q_{use} [kwh/(m² a)]	q_{aux} [kWh/(m² a)]	f [%]
DST	358	365	49.6
TRNSYS	361	362	49.9

Table 3.5: Results of the long term performance prediction for the DST method and for TRNSYS simulation

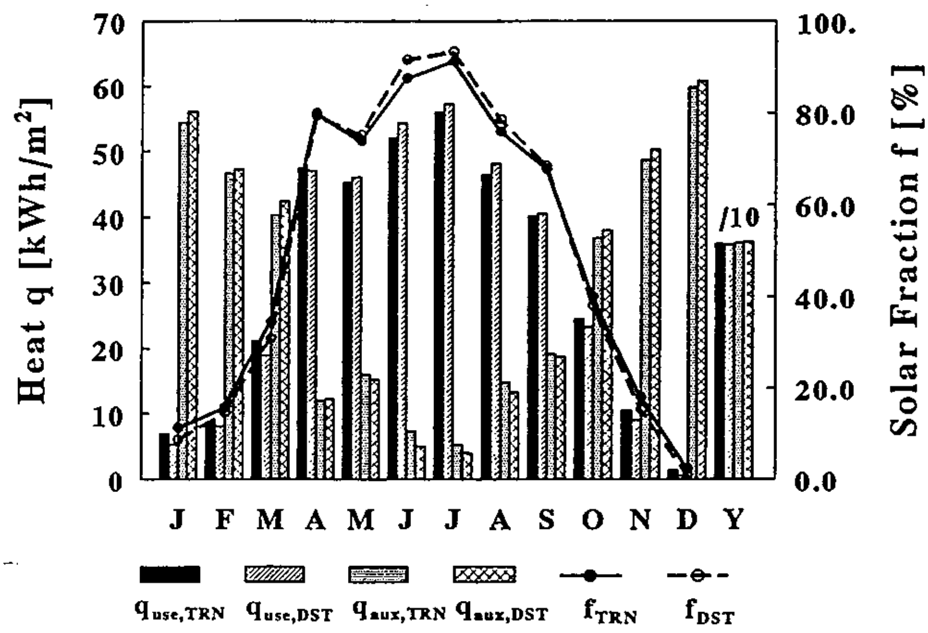

Figure 3.1: Results of the long term performance prediction for the DST method and for TRNSYS simulation on a monthly base

4 Simulation Study

The results from experimental testing presented in the previous sections show a high reproducibility and accuracy of the DST method. The question arises, whether the conclusions remain valid when components of the system are changed and with those the thermal behaviour of the system. For an analytical study of the applicability of the DST method on other system types a series of **simulated tests** were carried out. Starting from a reference system that represents the system type measured on the test stand following effects were investigated:

- Seasonal bias of the test results caused by the incident angle effect for systems with flat-plate collectors

Reproducibility and accuracy of the test results for

- systems with a flat-plate collector with a high and strongly ΔT-dependent heat loss coefficient
- systems with an evacuated tubular collector
- systems with an increased effective heat conductivity in vertical direction of the storage
- low-flow systems with a stratified charged storage
- systems with external auxiliary heater, i.e. the upper part of the storage is heated via an immersed heat exchanger by an external heat source.

The method for validating the DST method for these variants of a standard forced circulation system as well as the results of the simulated tests are presented in the following sections.

4.1 Validation of the DST Method with Simulated Tests

The method for validating the DST method with simulated tests was chosen following the proposal of Visser /7/. The principle of the method is shown in Figure 4.1.

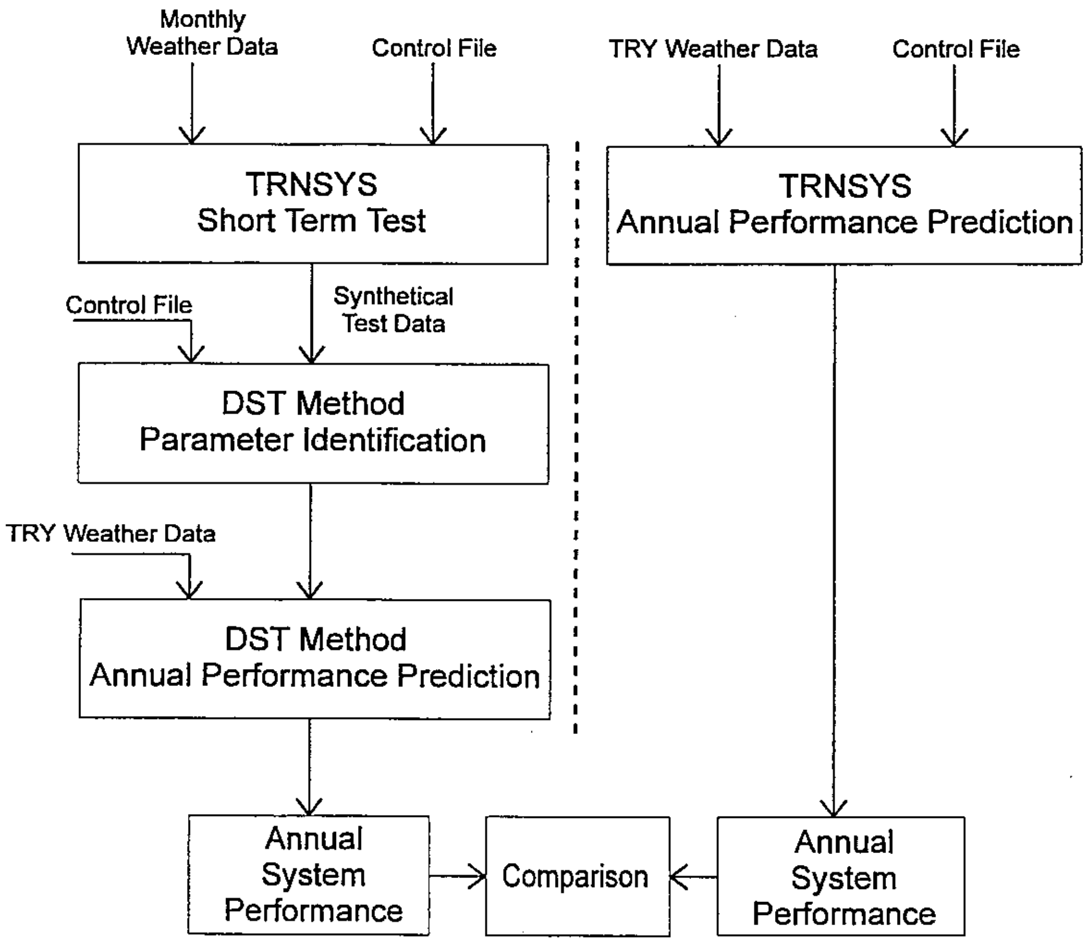

Figure 4.1: Principle of the validation of the DST method with simulated tests

It comprises 4 steps:

1. Performance of 6 full simulated dynamic tests as described in the test standard. The tests are carried out with the TRNSYS program using reference weather data of Würzburg. One test per month is performed for the period from April to September. During the period from October to March there is not sufficient insolation available.

2. Evaluation of the 6 dynamic tests into annual performance predictions for weather data of Würzburg and three selected load conditions (50, 200 and 1500 l/d).

3. Annual performance predictions with the simulation program TRNSYS for the same weather and load conditions as described in 2. The identical system configuration (TRNSYS deck file) as for the simulated tests is used.

4. Comparison of the annual performance predictions of the 6 tests and the TRNSYS simulations. The method is considered to be validated for the tested system if differences in all annual performance predictions are less than 5 % with regard to the hot water demand of the system.

Table 4.1 shows the time schedule for the test sequences. Numbers on grey background are valid test days.

April			May			June			July			August			September		
	TEST	H [kJ/(m²d)]		TEST	H [kJ/(m²d)]		TEST	H [kJ/(m²d)]		TEST	H [kJ/(m²d)]		TEST	H [kJ/(m²d)]		TEST	H [kJ/(m²d)]
1	Sol A	5261	1	Sol B	8435	1	Sol A	5462	1	Sol A	22988	1	Sol A	16816	1	Sol B	25183
2	Sol A	24983	2	Sol B	9109	2	Sol A	5474	2	Sol A	10198	2	Sol A	25357	2	Sol B	25687
3	Sol A	9581	3	Sol B	4794	3	Sol A	8882	3	Sol A	24584	3	Sol A	15833	3	Sol B	21591
4	Sol A	10125	4	Sol B	14190	4	Sol A	27124	4	Sol A	17013	4	Sol B	16667	4	Sol A	24863
5	Sol A	4778	5	Sol B	24976	5	Sol A	22503	5	Sol B	24444	5	Sol B	11672	5	Sol A	25162
6	Sol A	24464	6	Sol B	23772	6	Sol A	19247	6	Sol B	10855	6	Sol B	19724	6	Sol A	11561
7	Sol A	13370	7	Sol A	27222	7	Sol B	14693	7	Sol B	15054	7	Sol B	26106	7	Sol A	10838
8	Sol B	16375	8	Sol A	19418	8	Sol B	14529	8	Sol B	25081	8	Sto B	6778	8	Sol A	3738
9	Sol B	13869	9	Sol A	26074	9	Sol B	20116	9	Sto B	23359	9	Sto B	25687	9	Sol A	11699
10	Sol B	25820	10	Sto B	26217	10	Sto B	15204	10	Sto B	23360	10	Sto B	25902	10	Sol A	8134
11	Sto B	25331	11	Sto B	24034	11	Sto B	23951	11	Sto B	22799	11	Sto B	25688	11	Sol A	21734
12	Sto B	22885	12	Sto B	23400	12	Sto B	20869	12	Sto B	24993	12	Sto B	24321	12	Sto B	22854
13	Sto B	24331	13	Sto B	24695	13	Sto B	23469	13	Aux B	21915	13	Aux B	18571	13	Sto B	4888
14	Sto B	10727	14	Aux B	5283	14	Aux B	23603	14	Aux B	25305	14	Aux B	12971	14	Sto B	23191
15	Aux B	22129	15	Aux B	13016	15	Aux B	19018	15	Aux B	16488	15	Aux B	5205	15	Sto B	5081
16	Aux B	20572	16	Aux B	21426	16	Aux B	18445	16	Aux B	21946	16	Aux B	12011	16	Sto B	3454
17	Aux B	17996	17	Aux B	20580	17	Aux B	23372	17		20822	17		15818	17	Sto B	17193
18	Aux B	24869	18		22080	18		25592	18		18653	18		4587	18	Sto B	23559
19		24379	19		12721	19		26271	19		15786	19		19752	19	Sto B	17516
20		24904	20		21878	20		9000	20		9588	20		4519	20	Sto B	15833
21		26794	21		26512	21		16675	21		12305	21		4396	21	Aux B	7635
22		25755	22		12971	22		24191	22		17899	22		4365	22	Aux B	5863
23		21876	23		25369	23		16787	23		25488	23		7213	23	Aux B	3142
24		5546	24		26178	24		23249	24		12464	24		10994	24	Aux B	6485
25		12026	25		6798	25		22573	25		16066	25		23845	25		15486
26		19510	26		5360	26		23774	26		16034	26		25685	26		8665
27		22082	27		9083	27		22419	27		14763	27		4183	27		16805
28		24874	28		5937	28		13599	28		25254	28		4479	28		2950
29		13177	29		5456	29		25515	29		26395	29		18461	29		14590
30		4702	30		21391	30		25877	30		24995	30		14319	30		19973
			31		10562				31		24898	31		24160			

Table 4.1: Time schedule for the simulated tests for the period from April to September

4.2 Description of the Reference System

The similar system type as used for the experimental investigations on the test stand was modelled in TRNSYS as the reference system. The models for the collector and the storage are described in /8, 9/. Following data were used for modelling:

Collector:	collector aperture area: 5 m² optical efficiency[3]: $\eta_0 = 0.8$ collector heat loss coefficients: $U_0 = 3.5$ W/(m² K), $U_T = 0.02$ W/(m² K²) collector heat capacity: 7 kJ/(m² K) incident angle modifier coefficient[4]: r = 0.3 orientation: south, collector tilt angle equals latitude
Collector Loop:	flow-rate: 250 l/h total pipe length: 30 m inner pipe diameter: 16 mm pipe insulation 25 mm, $\lambda = 0.04$ W/(m K)

[3]Reference for collector performance parameters: aperture area

[4] According to the equation of Ambrosetti /10/

Storage:	volume: 300 l storage capacity: 1.25 MJ/K heat loss rate: 2.2 W/K storage ambient temperature: 15 °C stratification number: 30 effective vertical heat conductivity 2 x λ_{water}
Heat Exchanger: (Solar Loop)	immersed heat exchanger $(UA)_{hx}$ = 9 W/(m² K) x aperture area x $\Theta^{0.6}$ (Θ = mean value of hx-inlet temperature and local storage temperature)
Auxiliary Heater:	immersed electric heating element maximum heating power: 8 kW volume of the auxiliary heated part: 135 l set temperature of the auxiliary heater controller 60 °C

Table 4.2: Model parameters of the reference system

4.3 Simulated Tests

In the following sections the results of the simulated tests for the reference system and its variants are presented.

4.3.1 Test of the Reference System

The reference system was modelled as described in the previous section. Table 4.3 shows the system parameters obtained with simulated tests performed with reference weather data of Würzburg from April to September.

The parameters are compared with the expected parameters, which were used as inputs for the TRNSYS simulation program (see table 4.2). The collector loop parameters A_C^* and u_C^* are difficult to compare with standard collector parameters. The product of collector loop heat removal factor and transmittance-absorptance-product amounts to $F_R^* (\tau\,\alpha) \approx 0.65$, which is within the range of values obtained from experimental tests of a similar system configuration. The heat loss coefficient for the collector loop can be estimated to

$$F_R^*\,U = F_R^*\,(\tau\,\alpha) \cdot u_C^*$$

which leads to a range for $F_R^*\,U$ of 3.5 to 4.5 W/(m² K). The storage heat loss rate is overestimated by 0.5 to 0.9 W/K. The storage heat capacity is determined within its error band. Also the fraction of the auxiliary heated part is determined as expected with a slightly higher value as given by the geometrical position of the heating element. Since the system is charged fully mixed an identification of $S_C = 0$ is correct.

The collector loop parameters A_C^* and u_C^* as well as the storage heat loss coefficient show a seasonal dependence. The scatter of all other parameters can be estimated in most cases by 3 times the standard deviation σ delivered by the error analysis of the DST method.

Table 4.4 and figure 4.2 show the results of the annual performance predictions with the DST method and TRNSYS for weather data of Würzburg and daily loads of 50, 200 and 1500 l/d. The lowest and highest results obtained with the DST method are printed bold.

	A_C^* [m²]	u_C^* [W/(m²K)]	U_S [W/K]	C_S [MJ/K]	f_{aux} [-]	D_L [-]	S_C [-]	Obj. [W]
April	3.33 ± 0.04	6.84 ± 0.2	2.78 ± 0.11	1.27 ± 0.008	0.48 ± 0.0064	0.0242 ± 0.0026	0 ± 0.008	25.8 -
May	3.31 ± 0.04	6.49 ± 0.33	3.01 ± 0.13	1.28 ± 0.014	0.48 ± 0.0074	0.0237 ± 0.0013	0 ± 0.008	23.5 -
June	3.17 ± 0.04	5.75 ± 0.21	3.01 ± 0.11	1.27 ± 0.009	0.48 ± 0.0076	0.0272 ± 0.0033	0 ± 0.007	27.2 -
July	3.14 ± 0.04	5.47 ± 0.27	3.11 ± 0.12	1.27 ± 0.009	0.48 ± 0.0081	0.0237 ± 0.0037	0 ± 0.009	28.3 -
August	3.14 ± 0.03	5.75 ± 0.25	3.03 ± 0.12	1.23 ± 0.009	0.48 ± 0.0082	0.0215 ± 0.0034	0.001 ± 0.008	27.2 -
Sept.	3.3 ± 0.02	6.48 ± 0.21	2.76 ± 0.09	1.28 ± 0.008	0.499 ± 0.0054	0.026 ± 0.0026	0 ± 0.005	18.7 -

Table 4.3: System parameters identified for the reference system

Daily load [l/d]	Results of the long term performance prediction Solar fraction [%]						
	TRNSYS	DST					
		April	May	June	July	August	Sept.
50	43.4	43.4	**40.5**	42.1	41.5	42.2	**44.3**
200	46.4	47.8	**47.2**	47.7	47.8	47.9	**48.1**
1500	14.1	**12.1**	12	12	**11.7**	11.8	12

Table 4.4: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the reference system

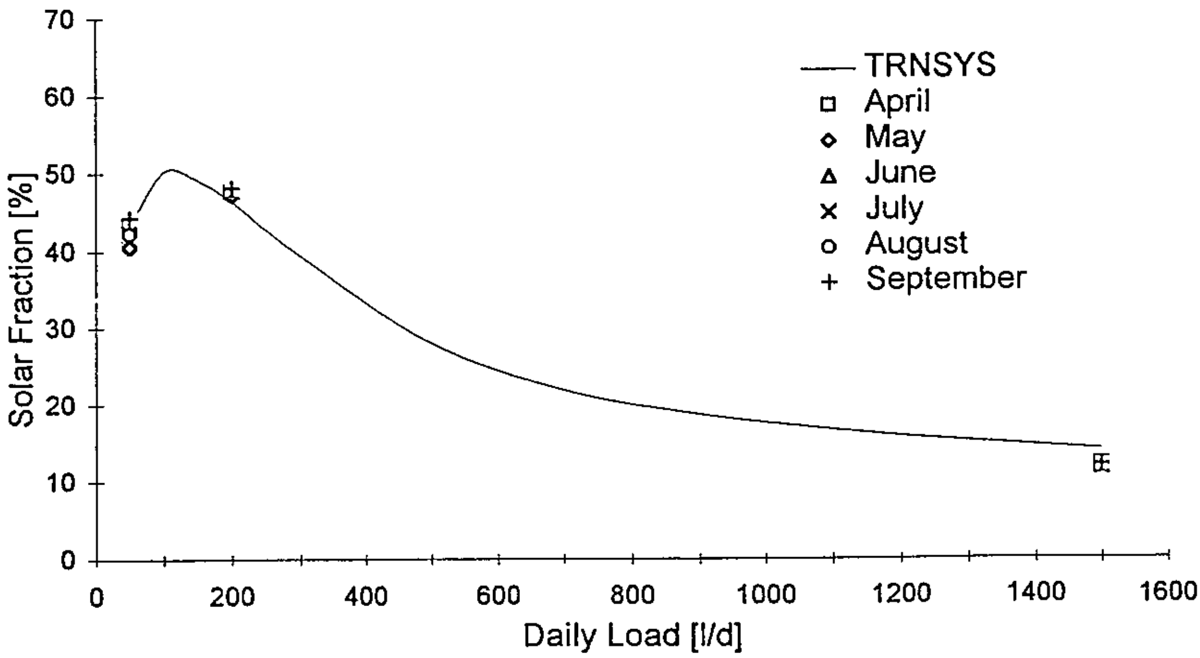

Figure 4.2: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the reference system (plotted)

Although a scatter of the system parameters was observed an excellent agreement of the DST performance predictions is obtained. For the load of 50, 200 and 1500 l/d the values for the solar fraction differ 3.8, 0.9 and 0.4 % respectively. The maximum deviation from the results of the TRNSYS simulations is 2.9 %.

4.3.2 Seasonal Bias of the Test Results Caused by Incident Angle Effects

In general the absorptance and transmittance of a collector depends on the angle of incidence of the incident radiation. This effect is not taken into account by the DST method. However, in the test standard a recommendation for correcting is given: The measuring data shall be pre-processed by multiplying the irradiance in the data files by an appropriate incident angle modifier prior to parameter identification. The results presented in this clause show the seasonal bias of the test results if the data are not pre-processed in this way.

The TRNSYS collector model used for this investigations describes the dependence of the optical efficiency on the incident angle with the equation formulated by Ambrosetti /10/:

$$K_{(\tau\alpha)}^{beam} = 1 - \tan^{1/r}\left(\frac{\theta}{2}\right)$$

Typically the incident angle modifier coefficient of a single glazed flat-plate collector is in the range from r = 0.25 to 0.4.

It is expected that testing in spring and autumn will lead to predictions of higher annual performance: The collector tilt angle of the collector equals the local latitude of the test site, the incident angle in longitudinal plane caused by the altitude angle of the sun is systematically smaller in spring and in autumn than in winter and in summer. This seasonal bias is investigated by simulating tests for a range of incident angle modifier (IAM) coefficients from r = 0 (no dependency on the angle of incidence) to r = 0.7. For each IAM coefficient tests were simulated from April to September. The tests were evaluated into annual performance predictions using the DST method. The results were compared with results of the annual performance prediction using the TRNSYS program. The results for a daily hot water load of 200 l/d are shown in table 4.5 and figure 4.3.

The results show that a significant seasonal bias occurs for IAM coefficients of r = 0.4 and higher. The scatter of the solar fraction amounts to 2.3 % for r = 0.4 and 4.4 % for r = 0.7 for a load of 200 l/d.

It is recommended to apply the pre-processing of the measuring data prior to parameter identification, if the IAM coefficient of the collector is r = 0.4 or higher. If the pre-processing is applied in any case a reduction of the scatter to 1.2 % can be expected (see results for r = 0).

IAM coefficient	Results of the long term performance prediction Solar fraction [%]						
	TRNSYS	DST					
		April	May	June	July	August	Sept.
0	49.9	51.1	51	**50.6**	51.7	**51.8**	51
0.1	49.8	50.9	**50.1**	51.4	51.4	**52**	50.9
0.2	48.6	50.1	**51.3**	**49.9**	50.1	50.7	**49.9**
0.3	46.5	47.5	**47.1**	47.7	47.9	**48.3**	48
0.4	43.8	45	**43.9**	44.9	44.6	45	**46.2**
0.5	40.8	42.5	**40.9**	41.4	41.5	41.6	**43.6**
0.6	37.9	40.7	**37.6**	38.3	37.8	39.2	**41.5**
0.7	35.1	37.9	**34.7**	35.3	34.9	36.3	**39.1**

Table 4.5: Results of the annual performance predictions with the DST method and the TRNSYS simulation for a variation of the incident angle modifier coefficient from r = 0 to 0.7

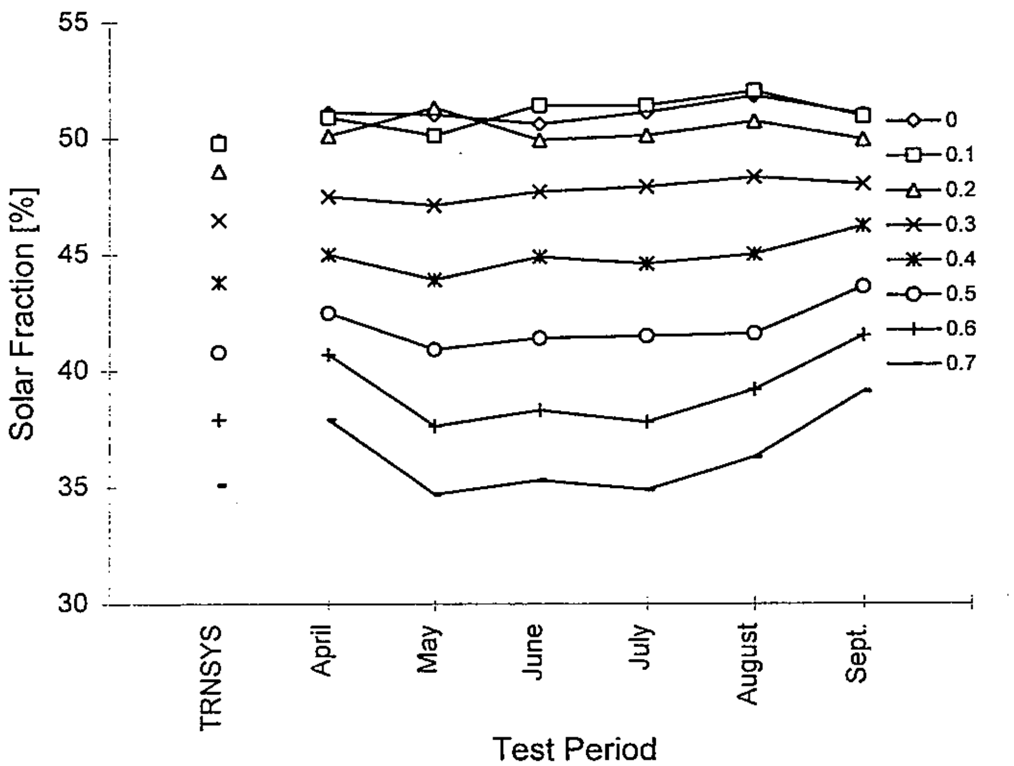

Figure 4.3: Results of the annual performance predictions with the DST method and the TRNSYS simulation for a variation of the incident angle modifier coefficient from r = 0 to 0.7 (plotted)

4.3.3 Effect of a High and Strongly ΔT-dependent Heat Loss Coefficient of the Collector

In order to investigate the seasonal dependence of the test results caused by an increased and strongly ΔT-dependent heat loss coefficient of the collector the reference system is tested with the collector heat loss coefficients $U_0 = 5$ W/(m² K) and $U_T = 0.04$ W/(m² K²).

Table 4.6 shows the parameters determined from the simulated tests. Table 4.7 and Figure 4.4 show the results of the annual performance prediction obtained by the evaluation with the DST method and obtained with the TRNSYS simulation program.

The collector loop heat loss coefficient u_C^* increases approximately by the same factor as it was increased for the TRNSYS simulation. All other parameters remain the same. The scatter of the results of the annual performance predictions increases compared to the reference case: For a load of 50 l/d the values for the solar fraction differ 7.2 %. For a load of 200 and 1500 l/d a difference of 1.8 and 0.4 % is obtained. The maximum deviation from results of the TRNSYS simulation is 4.6 %.

4.4.4 Test of a System with Evacuated Tubular Collectors

The optical and thermal behaviour of an evacuated tubular collector (ETC) differs in two aspects from that of a flat-plate collector. These are (1) a lower heat loss coefficient and (2) a biaxial incident angle modifier. The performance parameters of the ETC used for simulation are shown in table 4.8:

optical efficiency:	collector heat loss coefficients:	heat capacity:
$\eta_0 = 0.789$	$U_0 = 1.37$ W/(m² K); $U_T = 0.005$ W/(m² K²)	C = 10.9 kJ/(m² K)

incident angle modifier:	Θ	0	10	20	30	40	45	50	60	70	90
	$K_{\tau\alpha}^{beam}(\Theta_l)$	1	1	0.998	0.992	0.976	0.961	0.940	0.868	0.731	0
$K_{\tau\alpha}^{diffu} = 0.95$	$K_{\tau\alpha}^{beam}(\Theta_t)$	1	1.015	1.032	1.052	1.075	1.085	1.098	1.005	0.826	0

Table 4.8: Performance parameters of the evacuated tubular collector used for the simulated tests

Table 4.9 shows the parameters determined from the simulated tests. Table 4.10 and Figure 4.5 show the results of the annual performance prediction obtained by the evaluation with the DST method and with the TRNSYS simulation program.

A higher effective collector area A_C^* and a lower collector loop heat loss coefficient u_C^* is obtained for the system with ETC. The storage heat capacity increases about 0.4 MJ/K.

A slightly lower scatter of the results of the annual performance prediction as for the reference case is observed. For the load of 50, 200 and 1500 l/d the values for the solar fraction differ 3.2, 0.8 and 0.4 % respectively. The maximum deviation from results of the TRNSYS simulation is 3.3 %.

	A_C^* [m²]	u_C^* [W/(m²K)]	U_S [W/K]	C_S [MJ/K]	f_{aux} [-]	D_L [-]	S_C [-]	Obj. [W]
April	3.2 ± 0.05	9.37 ± 0.32	2.74 ± 0.12	1.24 ± 0.008	0.5 ± 0.0071	0.02 ± 0.002	0.0024 ± 0.01	28.0 -
May	3.2 ± 0.05	9.27 ± 0.38	3.13 ± 0.15	1.27 ± 0.013	0.48 ± 0.0086	0.022 ± 0.0036	0 ± 0.015	25.8 -
June	3.1 ± 0.05	8.13 ± 0.37	3.0 ± 0.12	1.23 ± 0.01	0.49 ± 0.0085	0.024 ± 0.003	0.002 ± 0.01	29.7 -
July	3.0 ± 0.05	7.97 ± 0.36	3.09 ± 0.13	1.26 ± 0.012	0.49 ± 0.01	0.026 ± 0.004	0 ± 0.015	31.2 -
August	3.0 ± 0.05	8.06 ± 0.33	3.22 ± 0.14	1.26 ± 0.011	0.49 ± 0.009	0.022 ± 0.0036	0 ± 0.013	28.5 -
Sept.	3.2 ± 0.03	8.94 ± 0.27	2.9 ± 0.11	1.27 ± 0.009	0.5 ± 0.006	0.025 ± 0.0031	0 ± 0.007	19.8 -

Table 4.6: System parameters identified for the system with a high and strongly ΔT-dependent heat loss coefficient of the collector

Daily load [l/d]	**Results of the long term performance prediction Solar fraction [%]**						
	TRNSYS	**DST**					
		April	May	June	July	August	Sept.
50	27.7	**30.3**	**23.1**	28.7	27.1	24.4	28
200	38.7	**40.7**	**38.9**	40.5	39.9	39.3	40.2
1500	12.7	**10.8**	10.7	10.7	**10.4**	**10.4**	10.7

Table 4.7: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the system with a high and strongly ΔT-dependent heat loss coefficient of the collector

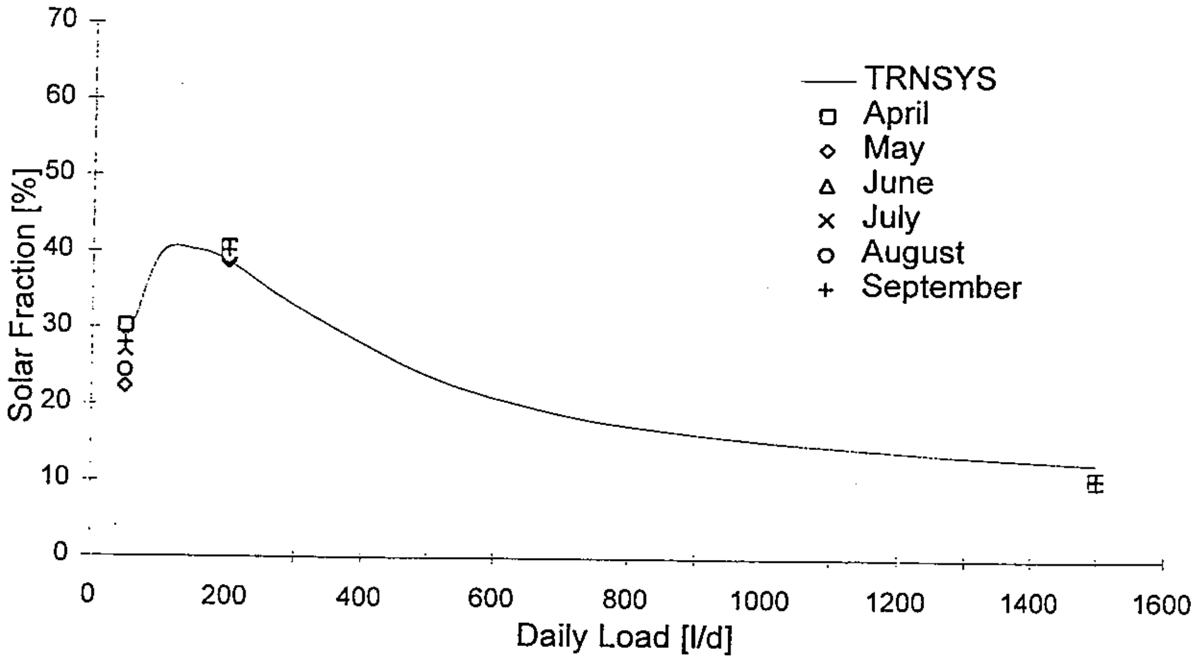

Figure 4.4: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the system with a high and strongly ΔT-dependent heat loss coefficient of the collector (plotted)

	A_C^* [m²]	u_C^* [W/(m²K)]	U_S [W/K]	C_S [MJ/K]	f_{aux} [-]	D_L [-]	S_C [-]	Obj. [W]
April	3.7 ± 0.03	3.35 ± 0.08	2.55 ± 0.06	1.32 ± 0.005	0.48 ± 0.0045	0.024 ± 0.002	0.0009 ± 0.003	19.2 -
May	3.7 ± 0.02	3.09 ± 0.14	2.83 ± 0.09	1.31 ± 0.007	0.47 ± 0.005	0.022 ± 0.002	0 ± 0.003	18.1 -
June	3.6 ± 0.03	2.75 ± 0.15	2.8 ± 0.09	1.31 ± 0.008	0.47 ± 0.006	0.027 ± 0.003	0 ± 0.003	23.8 -
July	3.6 ± 0.03	2.56 ± 0.15	2.94 ± 0.1	1.31 ± 0.008	0.47 ± 0.007	0.023 ± 0.003	0 ± 0.003	25.9 -
August	3.6 ± 0.03	2.47 ± 0.16	2.92 ± 0.1	1.32 ± 0.007	0.47 ± 0.007	0.023 ± 0.003	0 ± 0.003	23.9 -
Sept.	3.7 ± 0.02	3.16 0.12	2.64 ± 0.07	1.31 ± 0.005	0.486 ± 0.004	0.026 ± 0.0019	0 ± 0.002	16.3 -

Table 4.9: System parameters identified for the system with ETC collector

Daily load [l/d]	**Results of the long term performance prediction Solar fraction [%]**						
	TRNSYS	**DST**					
		April	May	June	July	August	Sept.
50	62.5	**65.8**	**62.6**	63.8	62.7	63.6	64.6
200	59.3	61.3	**60.7**	61.1	61	**61.5**	61
1500	17.9	**15.4**	15.3	15.2	**15**	15.1	15.2

Table 4.10: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the system with ETC collector

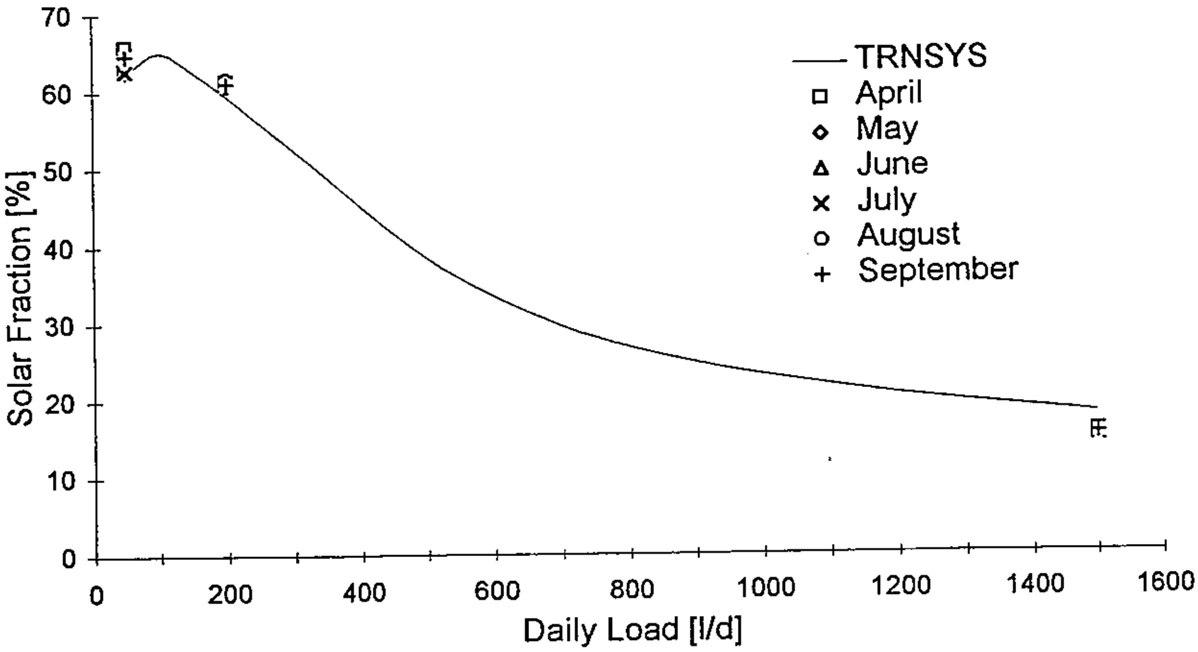

Figure 4.5: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the system with ETC collector (plotted)

4.4.5 Effect of an Increased Heat Transfer in Vertical Direction in the Storage

Vertical heat transfer by conduction and convection in hot water storages have an impact on the performance of a SDHW system. An effective heat conductivity was measured in a range from 0.6 W/(m K) for storages made of stainless steel to about 3.2 W/(m K) for storages made of normal steel with an enamel layer. For the latter a decrease of the annual performance by more than 5 % is determined compared to the stainless steel tank. This is caused by two negative effects: (1) The heat which is lost to the lower part of the storage has to be compensated by the auxiliary heater and (2) the collector efficiency decreases due to the temperature raise in the lower part of the storage.

For the simulated tests the effective heat conductivity in the storage is increased to 3 W/(m K). Table 4.11 shows the parameter determined from the simulated tests. Table 4.12 and Figure 4.6 show the results of the annual performance prediction obtained by the evaluation with the DST method and with the TRNSYS simulation program.

The parameters show that an increase of the conductivity within the storage is identified as a higher fraction of the auxiliary heated part f_{aux} by the DST method. The parameter f_{aux} increases by 4 % (absolute).

The results of the annual performance predictions show good agreement. For the load of 50, 200 and 1500 l/d the values for the solar fraction differ 4.7, 1.5 and 0.4 % respectively. The maximum deviation from results of the TRNSYS simulation is 2.8 %. This fairly good agreement shows that the effect of different heat conduction in vertical direction of the storage can be compensated by an extension of its auxiliary heated fraction.

4.4.6 Test of a Low-Flow System

For the simulation of a low-flow system the reference system was modified in following points:

- The flow-rate in the collector loop is reduced to 60 l/h.
- The hot water tank is equipped with a mantle heat exchanger for the solar loop instead of an immersed heat exchanger. The mantle heat exchanger enables stratified charging of the storage. The mantle covers the lower 50 % of the storage height.

Since a thermal stratification is build up during the charge process, the temperature profile differs significantly from that of a fully mixed charged storage. The DST method indicates the ability of stratified charging with a stratification parameter $S_C > 0$.

Table 4.13 shows the parameters determined from the simulated tests. Table 4.14 and Figure 4.7 shows the results of the annual performance prediction obtained by the evaluation with the DST method and with the TRNSYS simulation program.

For all simulated tests a stratification parameter S_C different from zero is identified. The values are lying in the range between 0.03 to 0.1. The annual performance predictions for the loads of 50, 200 and 1500 l/d differ 4.1, 1.6 and 0.3 % respectively. The maximum deviation from results of the TRNSYS simulation is 2.8 %.

4.4.7 Test of a System with External Auxiliary Heater

The electric heating element of the reference system is exchanged by an external auxiliary heater, i.e. the upper part of the storage is heated via an immersed heat exchanger by an external heat source. The heat exchanger for the auxiliary heater loop is designed in a way that a thermal stratification can be built up in the upper part of the storage during the charge process. The heat exchanger inlet enters the storage at its top. The heat exchanger outlet is located at 60 % and the controller sensor at 70 % of the total height of the storage.

The thermal stratification in the auxiliary heated part of the storage can lead to problems during the parameter identification process of the DST method, since the model used by the DST method charges the auxiliary heated part in all cases fully mixed.

Table 4.15 shows the parameter determined from the simulated tests. Table 4.16 and Figure 4.8 show the results of the annual performance prediction obtained by the evaluation with the DST method and with the TRNSYS simulation program.

The parameter f_{aux} is identified to approximately 0.41, which corresponds to the geometrical data of the upper heat exchanger. The annual performance predictions for the loads of 50, 200 and 1500 l/d differ 6.5, 2.9 and 0.6 % respectively. The maximum deviation from results of the TRNSYS simulation is 5.5 %. The annual performance of the system is overestimated by the DST method.

	A_C^* [m²]	u_C^* [W/(m²K)]	U_S [W/K]	C_S [MJ/K]	f_{aux} [-]	D_L [-]	S_C [-]	Obj. [W]
April	3.4 ± 0.05	6.77 ± 0.23	3.01 ± 0.106	1.29 ± 0.008	0.52 ± 0.0067	0.03 ± 0.003	0.002 ± 0.007	26.3 -
May	3.4 ± 0.04	6.69 ± 0.32	3.23 ± 0.14	1.3 ± 0.013	0.51 ± 0.008	0.032 ± 0.004	0 ± 0.01	24.9 -
June	3.2 ± 0.05	6.12 ± 0.3	3.23 ± 0.12	1.28 ± 0.01	0.52 ± 0.008	0.034 ± 0.0038	0.0015 ± 0.08	28.7 -
July	3.2 ± 0.04	5.38 ± 0.3	3.31 ± 0.13	1.29 ± 0.011	0.52 ± 0.0086	0.031 ± 0.004	0 ± 0.008	28.8 -
August	3.2 ± 0.04	5.49 ± 0.27	3.33 ± 0.128	1.3 ± 0.01	0.52 ± 0.0085	0.029 ± 0.0039	0 ± 0.009	27.4 -
Sept.	3.3 ± 0.03	6.2 ± 0.25	3.04 ± 0.116	1.31 ± 0.01	0.53 ± 0.007	0.039 ± 0.0039	0 ± 0.007	22.5 -

Table 4.11: System parameters identified for the system with an increased heat transfer in vertical direction of the storage

Daily load [l/d]	Results of the long term performance prediction Solar fraction [%]						
	TRNSYS	DST					
		April	May	June	July	August	Sept.
50	35.0	36.2	32.2	33	35.1	34.4	36.9
200	43.6	45.1	44.1	44	45.5	45.2	45.5
1500	13.5	11.7	11.6	11.6	11.3	11.3	11.6

Table 4.12: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the system with an increased heat transfer in vertical direction of the storage

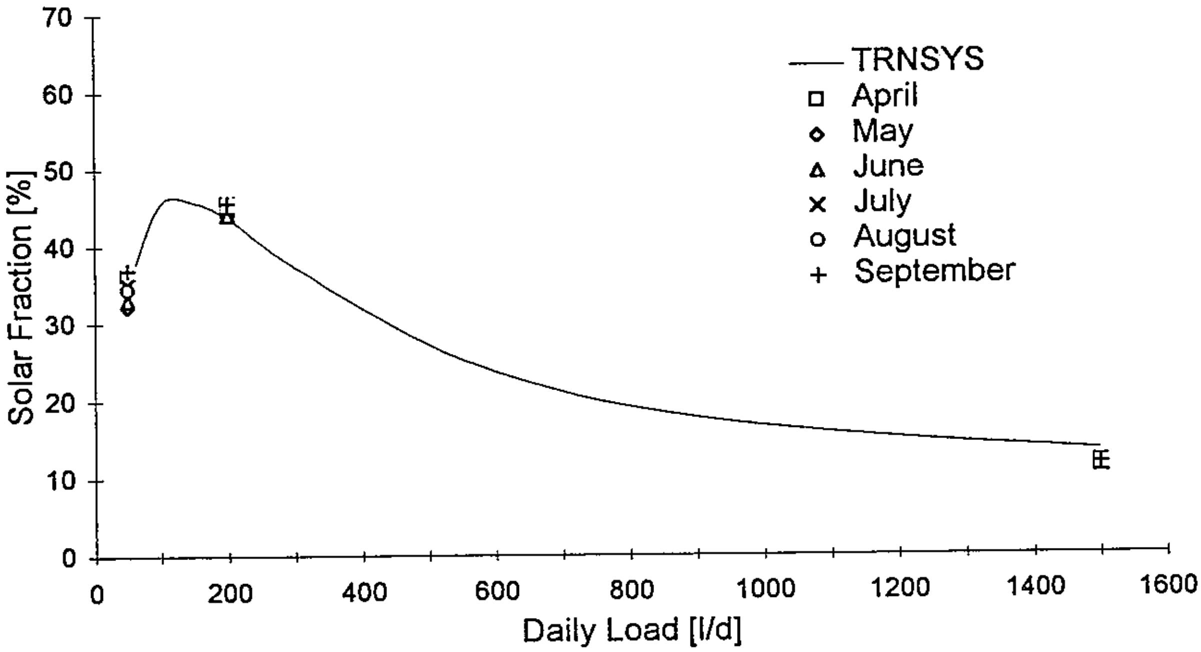

Figure 4.6: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the system with an increased heat transfer in vertical direction of the storage (plotted)

	A_C^* [m²]	u_C^* [W/(m²K)]	U_S [W/K]	C_S [MJ/K]	f_{aux} [-]	D_L [-]	S_C [-]	Obj. [W]
April	3.3 ± 0.03	6.15 ± 0.16	2.67 ± 0.09	1.23 ± 0.008	0.51 ± 0.007	0.027 ± 0.003	0.034 ± 0.006	28.1 -
May	3.2 ± 0.04	6.55 ± 0.26	2.56 ± 0.14	1.26 ± 0.015	0.49 ± 0.01	0.027 ± 0.005	0.104 ± 0.0076	31.9 -
June	3.3 ± 0.03	5.88 ± 0.18	2.96 ± 0.1	1.26 ± 0.01	0.49 ± 0.007	0.026 ± 0.003	0.055 ± 0.0059	26.7 -
July	3.3 ± 0.03	5.94 ± 0.17	2.71 ± 0.1	1.25 ± 0.009	0.5 ± 0.009	0.026 ± 0.004	0.036 ± 0.0067	28.4 -
August	3.2 ± 0.04	5.58 ± 0.19	2.74 ± 0.12	1.25 ± 0.01	0.5 ± 0.009	0.023 ± 0.004	0.029 ± 0.0067	29.6 -
Sept.	3.4 ± 0.03	6.43 0.2	2.49 ± 0.1	1.24 ± 0.011	0.51 ± 0.0085	0.035 ± 0.0046	0.042 ± 0.0065	30.5 -

Table 4.13: System parameters identified for the low-flow system

Daily load [l/d]	**Results of the long term performance prediction Solar fraction [%]**						
	TRNSYS	**DST**					
		April	May	June	July	August	Sept.
50	47.0	47.4	49.4	**45.5**	47.7	48.7	**49.6**
200	49.4	49.8	50.2	**49.2**	49.8	**50.8**	50.2
1500	15.0	12.3	**12.5**	12.2	**12.2**	12.3	12.5

Table 4.14: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the low-flow system

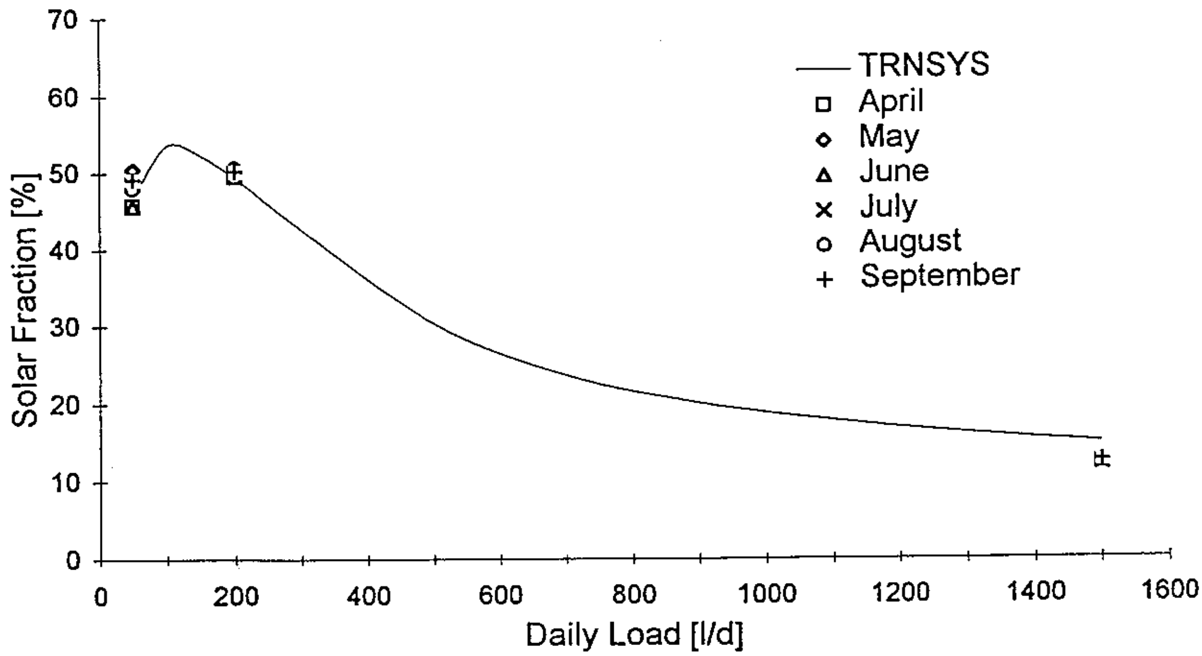

Figure 4.7: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the low-flow system (plotted)

	A_C^* [m²]	u_C^* [W/(m²K)]	U_S [W/K]	C_S [MJ/K]	f_{aux} [-]	D_L [-]	S_C [-]	Obj. [W]
April	3.2 ±0.05	9.16 ±0.3	2.79 ±0.13	1.28 ±0.01	0.42 ±0.0066	0.023 ±0.0026	0 ±0.016	29.8 -
May	3.2 ±0.05	9.17 ±0.41	3.02 ±0.15	1.31 ±0.014	0.4 ±0.007	0.027 ±0.0035	0 ±0.015	26.8 -
June	3.1 ±0.05	8.3 ±0.42	3.0 ±0.14	1.27 ±0.011	0.41 ±0.0078	0.026 ±0.0033	0.002 ±0.01	32.6 -
July	3.1 ±0.05	8.3 ±0.43	3.0 ±0.14	1.27 ±0.011	0.41 ±0.0078	0.026 ±0.0033	0.002 ±0.011	32.6 -
August	3.0 ±0.05	7.5 ±0.3	3.22 ±0.16	1.3 ±0.012	0.41 ±0.0084	0.025 ±0.0039	0.002 ±0.01	30.8 -
Sept.	3.2 ±0.03	8.8 ±0.28	2.88 ±0.112	1.31 ±0.009	0.42 ±0.0052	0.029 ±0.0026	0 ±0.007	19.7 -

Table 4.15: System parameters identified for the system with external auxiliary heater

Daily load [l/d]	Results of the long term performance prediction Solar fraction [%]						
	TRNSYS	DST					
		April	May	June	July	August	Sept.
50	46.6	49.8	47.8	45.6	46.2	48	52.1
200	47	50.6	50	48.3	49.4	50.5	51.2
1500	12.3	12.9	12.9	12.3	12.4	12.5	12.9

Table 4.16: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the system with external auxiliary heater

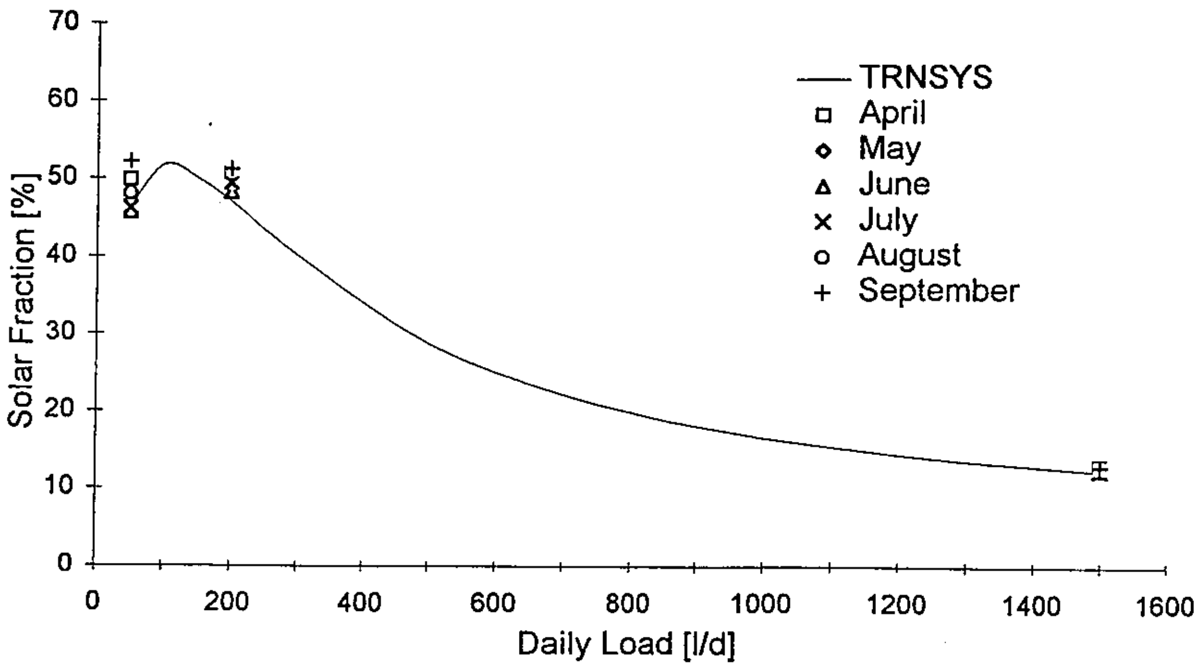

Table 4.8: Results of the annual performance predictions with the DST method and the TRNSYS simulation for the system with external auxiliary heater (plotted)

4.5 Discussion of the Results from Simulated Tests

Simulated tests were carried out for variants of a standard SDHW system. Especially critical effects were introduced that either cause a seasonal bias of the DST test results or lead to inaccurate performance predictions due to physical effects that are not taken into account by the DST method. For all cases the good reproducibility and accuracy of the test results obtained from the experimental tests were confirmed. Subsequently the results are summarised and discussed:

- Due to the simplicity of the model used by the DST method a scatter of the system parameters identified from different tests can be observed. Especially the parameters A_C^*, u_C^* and U_S show correlation effects depending on the season in which the test is performed. The parameters obtained are close to the expected parameters that were used as input to the TRNSYS simulation. Changes of specific parameters in the TRNSYS model for testing lead to changes of the corresponding parameter of the DST model. A systematic overestimation of the storage heat loss coefficient U_S was observed. In most cases the DST parameters should not be interpreted as physical parameters.

- For all cases the annual performance prediction delivered very reproducible and accurate results for loads of 200 l/d and 1500 l/d. For these cases the predicted system performance scatters at maximum 2.9 %. The maximum difference to the results of the TRNSYS performance prediction amounts to 4.2 % for the system with external auxiliary heater and between 1.4 and 2.2 % for all other systems.

  For a load of 50 l/d the scatter of the predicted system performance increases. For the system with the high and strongly ΔT-dependent heat loss coefficient of the solar collector and the system with the external auxiliary heater the required 5 % are exceeded. However the performance prediction for 50 l/d seems to be critical for all system variants, since overheating occurs during summer and thus the heat losses strongly dominate the thermal performance of the systems.

- Most of the model errors due to the simplified model used for parameter identification can be compensated by the DST method:

  A significant seasonal bias of the DST test results occurs for IAM coefficients of r = 0.4 and higher. For these cases it is recommended to apply a pre-processing method on the measuring data prior to parameter identification. This correction as proposed in the test standard improves the reproducibility of the test results remarkable.

  For systems with high and strongly ΔT-dependent heat loss coefficient of the collector and the system with an external auxiliary heater predictions of the annual system performance for very small loads (overheating of the system in summer) should be omitted since the required accuracy of 5 % is not achieved. It is considered as useful to skip unrealistic load conditions for all types of systems.

  For systems with an external auxiliary heater that is able to charge the upper part of the storage stratified, the DST method systematically overestimates the system performance for several percent (typically 2 %). It is recommended to correct for this bias in case a higher accuracy of the test results is required. A correction factor can be calculated by using detailed simulation models.

A reproducibility and accuracy better than the required 5 % was obtained for following cases:

- standard SDHW system (reference system)
- systems with ETC
- low-flow systems
- systems with an increased heat transfer in vertical direction of the hot water storage.

5 Conclusions and Recommendations

The DST method as it is recently implemented in the ISO/CD 9459, Part 5 was experimentally validated by real tests of a forced circulation SDHW system. With regard to reproducibility and accuracy of the system parameters as well as the prediction of the yearly energy gain DST turned out to be a reliable testing method. Also variation of the climatic conditions and the load for the performance prediction did not cause significant changes of the quality of the test results. Merely the identification of the collector loop parameters A_C^*, u_C^* and U_S are still subject of improvement.

Simulated tests showed that also for other system types than the standard system under test the method delivers reproducible and accurate test results. Only in two cases the method did not fulfil the requirement of a reproducibility better than 5 % for the very low load of 50 l/d. In general the investigations show that performance predictions for these unrealistic conditions are critical for all system types. Further the seasonal bias caused by incident angle effects could be quantified. It is recommended to correct for this effect for incident angle modifier coefficients of r = 0.4 and higher. The method is robust with respect to special system designs (ETC, low-flow) and physical effects that are not explicitly taken into account by the DST method.

Comparing the existing performance test methods for SDHW systems the DST method turns out to be the most flexible and accurate method which further allows for testing of a wide range of system types. A powerful tool for testing and certification of solar domestic hot water systems is implemented by the ratification of the DST method as an international standard.

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REPRODUCIBILITY OF THE COMMITTEE DRAFT ISO/CD 9459 PART 5 BY PRACTICAL APPLICATION

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NOMENCLATURE

A_c^*	Effective collector loop area $A_c^* = F_R^*(\alpha\tau)A_c$	[m^2]
$(\alpha\tau)$	Effective transmission-absorption product	[-]
A_c	Collector aperture area	[m^2]
u_C^*	Collector heat loss fitting parameter $u_C^* = u_C/(\alpha\tau)$	[Wm^{-2}K^{-1}]
u_C	Specific loss coefficient of the collector loop	[Wm^{-2}K^{-1}]
U_S	Loss coefficient of the store	[WK^{-1}]
C_S	Thermal heat capacity of the store	[MJK^{-1}]
f_{aux}	Auxiliary fraction of the store	[-]
D_L	Draw-off mixing parameter	[-]
S_C	Solar loop stratification parameter	[-]
obj	Objective function of parameter identification	[W]
SF_o	Output oriented solar fraction $(Q_{load} - Q_{aux})/Q_{load}$	[-]
Q_{load}	Useful energy subtracted from the system	[MJ]
Q_{aux}	Energy delivered by auxiliary to the system	[MJ]
T_{cw}	Cold water temperature	[°C]
T_s	Outlet temperature of store	[°C]
T_{sa}	Ambient temperature in vicinity of the store	[°C]
T_{CA}	Ambient temperature in vicinity of the collectors	[°C]
V_s	Volumetric flow rate through the store	[lmin^{-1}]
v	Surrounding air velocity in the plane of the collector	[ms^{-1}]
G_t	Solar irradiation in the collector plane	[Wm^{-2}]
T_{SET}	Set temperature of auxiliary heater	[°C]
C_F	Filter time constant with regard to the load draw-off	[MJK^{-1}]
τ_F	Filter time constant	[hr]
C_S	Thermal heat capacity of the store	[MJK^{-1}]

1. INTRODUCTION

In the performance certification of solar domestic hot water (SDHW) systems the draft ISO/CD 9459 part 5 [1] was applied to 2 identical SDHW systems. The test described by [1] consists of 4 test sequences designed to operate the SDHW test subject in a wide range of system states. Two of which focus on identifying heat storage parameters.

This paper will investigate the improvement of the reproducibility of parameter identification and long term predictions caused by the application of the storage test sequences. In addition we will compare and contrast the results of the two identical systems.

2. INVESTIGATION METHOD

2.1. Overview of test site

The test faculty is located on the roof of the Rapperswil School of Engineering. SDHW systems are housed in 2 air conditioned huts. The water supply to all 4 systems is regulated to 10°C. Collectors are mounted on an open structure facing south at an angle of inclination of 45°. All measurements made comply with [1] and are logged by an event driven data logger.

Both the investigated SDHW systems are located in the same hut, with there collectors mounted next to each other.

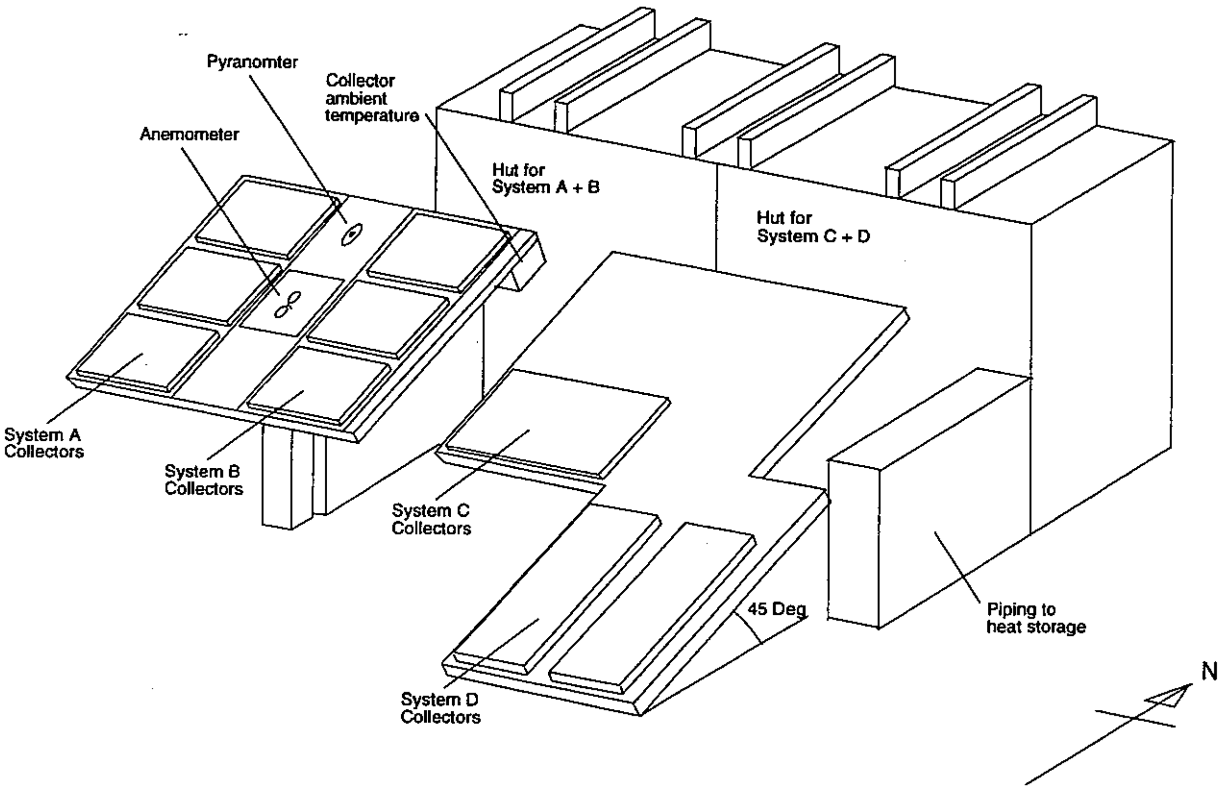

Figure 1: SPF Test Site

2.2. Test sequence description

During the Summer of 1995 two identical systems where tested twice, in unison, in accordance to the draft ISO/CD 9459 part 5. This consists of 4 tests:

Test A is designed to acquire data with a cold heat store and collector, thus information over the system at high efficiencies is gained. In this test a high demand is achieved by 7 substantial hot water draw-offs. During this test auxiliary heating is disabled.

Test B is the opposite of Test A; hot collector and heat storage temperatures are accomplished by 5 small hot water draw-offs, during which an auxiliary electrical heater is enabled.

In order to decouple the collector loop heat losses from the heat storage losses two storage tests S_{aux} and S_{store} are implemented. These tests involve periods of low solar irradiation, which, in the interests of reproducibility, where made by covering the collectors with a suitable material.

S_{aux} is intended to gain more information about the heat losses and the fraction of auxiliary heated storage volume. This is done by running 4 Test B days with the covered collectors, thus, the heat storage is exclusively heated by auxiliary energy.

S_{store} is designed to determine overall store loss information. This test consists of 3 phases; firstly the storage is heated up by 2 consecutive Test A days (without auxiliary heating). Secondly a cooling down period during which the collectors are covered and no draw-off is made. Finally a series of large draw-offs are made to determine how much energy remains in the store.

Before and after each test a series of large draw-offs are made, thus emptying the store of energy and providing a common starting point for all tests. This process is called conditioning.

2.3. Identification method

The Dynamic Fitting (DF) algorithm [1] works by finding minima in an objective function. In order to avoid being caught in a local minima the algorithm finds a minima, and then tries to escape that minima by making a random jump followed by a renewed search for a minima. In order to be sure of finding the global minimum, that is, the minimum of minima it is necessary for the DF algorithm to search a number of times. This process is called parameter identification.

All parameter identifications carried out in this report have been done in 2 phases. Firstly, starting with default parameter values, the DF algorithm is run looking 5 times for the global minima. Secondly, the result from the first phase is taken as starting point, and the DF algorithm is run looking 10 times for the global minima. SPF Rapperswil has had good experience with this method. The filter time constants where fixed to τ_F =4 hrs and C_F = 0.1 MJK^{-1}.

2.4. Long term prediction method

The yearly performance of a SDHW system was simulated using LTP_P.EXE (a part of the DF simulation package [1]). We used hourly data from Kloten 1968 and used a draw-off profile designed to simulate the demand of a typical Swiss family, see Table 1.

Table 1: Simulated demand for a typical Swiss family

Daily load volume	215 l	Store ambient temperature (T_{SA})	20 °C
Mains temperature (T_{CW})	10 °C	Demand temperature (T_S)	50 °C
Auxiliary heating:			
Set temperature (T_{SET})	60* °C	2 kW Enabled between 22:00 and 7:00	
Draw-off profile:			
Time		Quantity [kWh]	
07:00		1.50	
08:00		1.50	
11:00		1.00	
13:00		1.25	
18:00		1.25	
20:00		1.25	
22:00		1.25	

* The set temperature at which the auxiliary heater is enabled (T_{SET}) is adjusted, to the nearest 1°C, until the SDHW system just meet the specified demand. Naturally, the performance of a SDHW system is strongly dependent on T_{SET}, and inaccuracies in the identification will be magnified when examining the simulated output orientated solar fraction.

2.5. Comparison method

Two complete ISO/CD 9459 sequences have been measured for both SDHW systems. In order to compare the effects of the store sequence parameter identification and long term simulations have been carried out for the following test sequences.

1. 1 Test A, 1 Test B
2. 1 Test A, 1 Test B, 1 S_{aux}
3. 1 Test A, 1 Test B, 1 S_{aux}, 1 S_{store}

Both SDHW systems where tested in unison. That means, each test was carried out on both systems at the same time. In so doing, effects due to different weather conditions can be eliminated, and since we keep the same filter constants we can also compare the objective function for parameter identifications over the same time periods.

Test A and Test B where carried out twice, therefore each system has a total of 6 test sequences. The following naming convention is used in this report:

Table 2: Test A and Test B naming convention

	Test A period	Test B period
11	9 June - 15 June 1995	16 June - 22 June 1995
12	9 June - 15 June 1995	28 June - 2 July 1995
21	23 June - 28 June 1995	16 June - 22 June 1995
22	23 June - 28 June 1995	28 June - 2 July 1995

3. SOLAR DOMESTIC HOT WATER SYSTEM TEST SUBJECT

The system under test is a typical Swiss forced circulation system with a 4.4 m^2 selective flat plate collector and a 400 l storage with an immersed finned coil heat exchanger at the bottom and an immersed auxiliary heater mounted horizontally in the top half of the storage. See Figure 2.

The set temperature is set by a large plastic knob on the control panel. There is some play between the knob and the potentiometer controlling the set temperature making precise specification of the set temperature difficult.

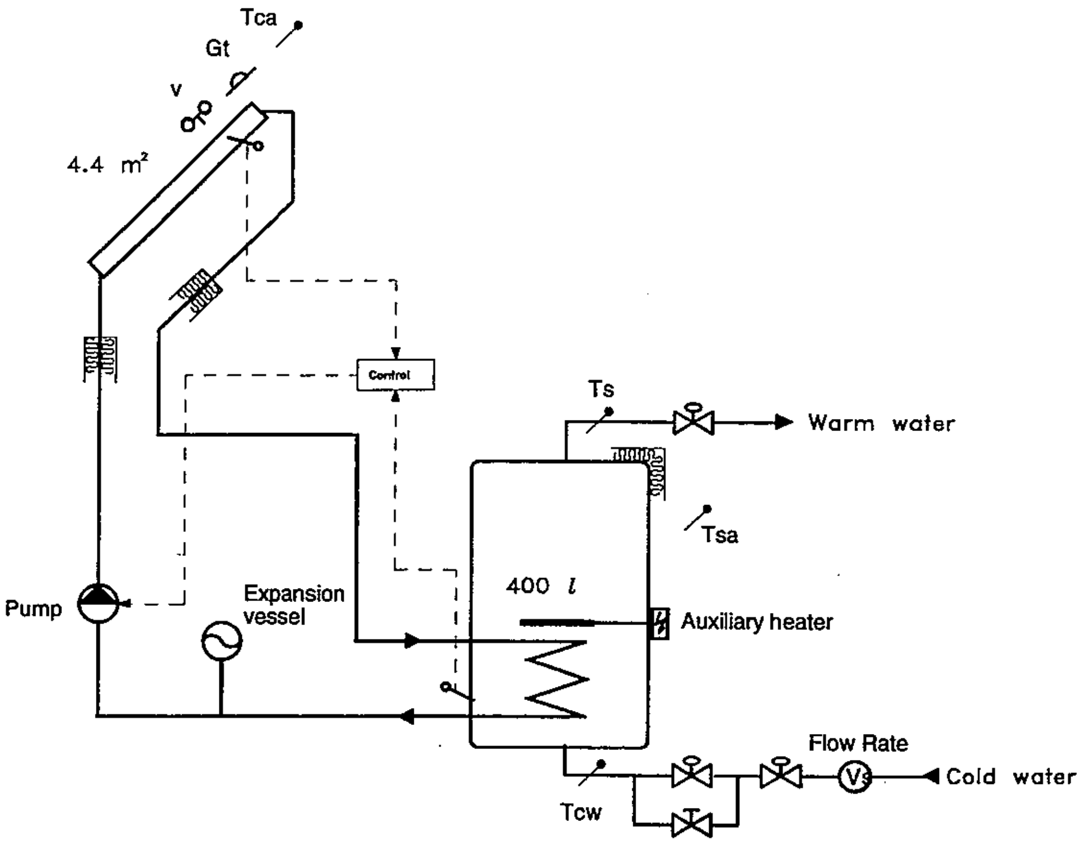

Figure 2: Swiss reference SDHW system

4. PARAMETER IDENTIFICATION AND LONG TERM PREDICTION

The identified parameters can be divided into two groups:

Parameters which are easily identified, consist of parameters such as A_c^*, CS and f_{aux}. These parameters exhibit only a small scatter, even with small quantities of data.

Parameters that exhibit a scatter, consisting of u_C^*, U_S, D_L and S_C. The scatter is caused by either having not enough data, or because of differences between the SDHW model and the real SDHW system.

The DF algorithm generates statistics including some indications of the overall figure of merit of a fit. These statistics provide a figure of merit based on the parameter covariance matrix. Using this figure of merit we were unable to determine any significant difference between data that was known to be insufficient with data that should be sufficient. For this reason, when considering goodness of fit we examine the scatter of these parameters with different data sets.

The improvement in parameter identification by the addition of storage tests is easily seen by examining the improvement in scatter of the f_{aux} fitting parameter (see Figure 2.). In this case the standard deviation of the identified f_{aux} parameter for the 4 combinations of Test A and Test B improves from 0.0605 (Test A and Test B) to 0.00645 (Test A, Test B, S_{AUX} and S_{STORE}).

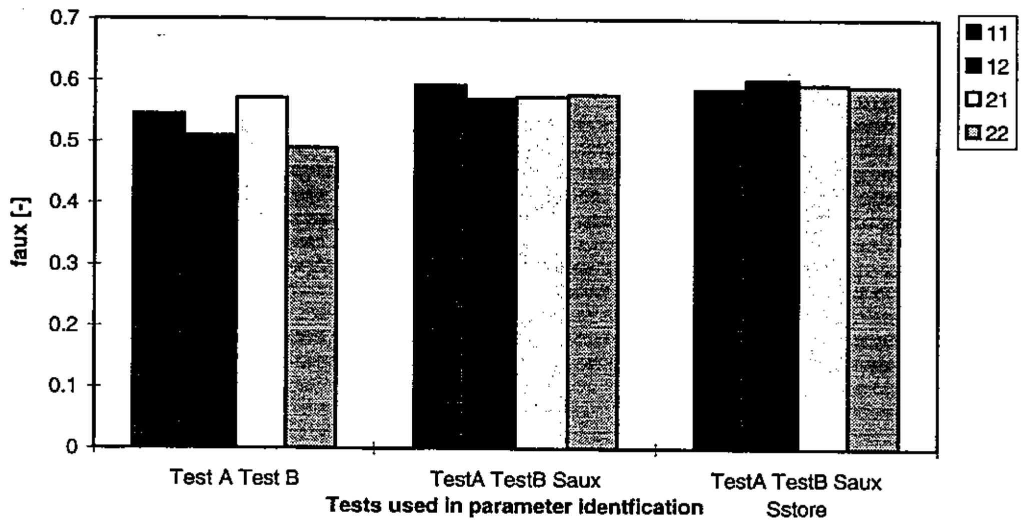

Figure 2: Improvement of f_{aux} identification by additional storage sequences

Since the store parameters have been better identified there is a corresponding improvement in longterm simulations. This can be seen by examining the minimum set temperature for the auxiliary heater ($T_{SET\,MIN}$) necessary to satisfy the standard Swiss family demand under Kloten 1968 weather data (See figure 3.). The stabilisation in output orientated solar fraction (Sf_o) is masked, since Sf_o is a strong function of auxiliary heater set temperature (see figure 4.).

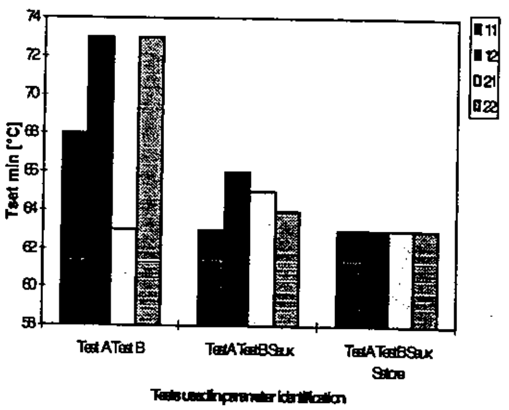

Figure 3: Improvements in Auxiliary heater set temperature

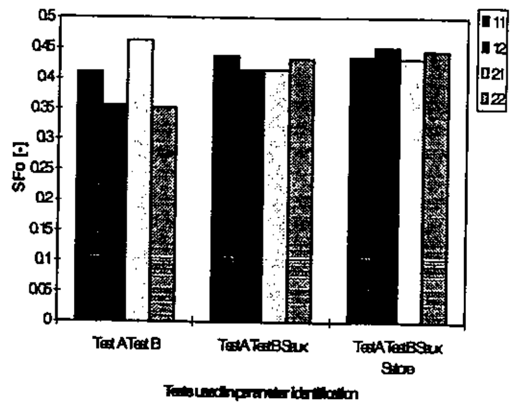

Figure 4: Improvements in output orientated solar fraction

Since the best identified parameters are identified with Test A, Test B, S_{AUX} and S_{STORE}, both reference systems will be compared for this case. There is a significant difference amongst the parameters, most notably, the heat storage losses U_S by 24%. It should be noted that the set temperature knob on the control panel cannot be set accurately, and is indeed 2.5°C lower for system B. There are two possibilities to describe this effect:

- First, there is a difference in the two systems that we have overlooked.
- Second, the set temperature has an effect on the identified parameters.

Since both systems where produced in the same batch, the first possibility is unlikely. In which case the set temperature has an effect on the identified parameters, namely the heat storage losses U_S and the auxiliary fraction of the store f_{aux}. Consequently the set temperature used in the test seems to have an effect on the longterm performance predictions. This effect can be seen in table 3, were the minimum predicted set temperature for system B is 2°C lower that system A.

Table 3: Identified parameter comparison for system A and B.

Parameter	System A	System B		Percentage difference
A_c^*	2.844	2.842	m^2	-0.10 %
u_C^*	8.219	7.768	$Wm^{-2}K^{-1}$	-5.81 %
U_S	2.793	2.272	WK^{-1}	-23.93 %
C_S	1.446	1.491	MJK^{-1}	3.05 %
f_{aux}	0.593	0.617	-	3.91 %
D_L	0.009015	0.011248	-	19.85 %
S_C	0.0147	0.02096	-	29.47 %
obj	28.509	39.93	W	28.6 %
T_{SET}	63	60.8	°C	-3.7 %
SF_o	0.442	0.485	-	8.87 %

5. CONCLUSION

These tests show that provided all 4 tests are carried out, for this type of system, the demanded reproducibility of ±5% of the fractional system gain can be achieved.
The identified parameter values should be applied in the longterm performance predictions with an auxiliary heater set temperatures close to those used in the test. This effect should be investigated further.

The additional storage tests, together with a stable store ambient temperature is necessary to decouple the effective collector loop loss coefficient u_C^* and Overall storage loss coefficient U_S.

6. REFERENCES

[1] Draft ISO/CD 9459 part 5, 'Solar Heating - Domestic water heating systems - Part 5: System performance by means of whole system testing and computer simulation', October 94

7. Appendix 1

Table 4: Parameter identification and long term simulation results for 1 Test A and 1 Test B

	System A				System B			
Seq.	11	12	21	22	11	12	21	22
A_c^*	2.87	2.847	2.873	2.806	2.899	2.866	2.905	2.896
u_C^*	8.08	5.815	10.09	6.534	7.605	5.304	7.925	5.346
U_S	3.014	4.437	1.799	4.281	3.109	4.484	2.825	4.771
C_S	1.42	1.438	1.429	1.434	1.392	1.406	1.475	1.49
f_{aux}	0.5455	0.5101	0.571	0.4902	0.557	0.5163	0.5536	0.5206
D_L	0.007245	0.01022	0.007473	0.008626	0.009388	0.01236	0.007351	0.01012
S_C	0.001832	0.001418	0.017	0.001585	2.06E-5	0.00127	0.01158	0.001424
obj	28.35	29.974	30.854	33.372	29.452	30.482	43.831	48.675
$T_{set\,min}$	68	73	63	73	68	73	64	73
SF_o	0.411	0.356	0.462	0.352	0.416	0.368	0.457	0.349

Table 5: Parameter identification and long term simulation results for 1 Test A, 1 Test B and 1 S_{aux}

	System A				System B			
Seq.	11	12	21	22	11	12	21	22
A_c^*	2.869	2.805	2.898	2.777	2.922	2.847	2.904	2.797
u_c^*	8.41	7.467	8.609	7.723	8.158	7.23	7.789	7.177
U_S	2.889	3.219	3.051	2.998	2.708	2.905	2.959	2.855
C_S	1.423	1.43	1.432	1.433	1.403	1.404	1.485	1.479
f_{aux}	0.5923	0.5705	0.5741	0.5775	0.6074	0.6044	0.5735	0.58
D_L	0.007967	0.01048	0.00867	0.008661	0.01244	0.01552	0.00695	0.009613
S_C	0.005814	0.008497	0.002101	0.01351	3.53E-5	0.002041	0.01348	0.02087
obj	26.413	28.803	27.969	31.352	27.129	28.972	38.845	42.055
$T_{set\ min}$	63	66	65	64	64	65	63	63
SF_o	0.438	0.415	0.415	0.433	0.44	0.435	0.456	0.46

Table 6: Parameter identification and long term simulation results for 1 Test A, 1 Test B, 1 S_{aux} and 1 S_{store}

	System A				System B			
Seq.	11	12	21	22	11	12	21	22
A_c^*	2.904	2.786	2.903	2.784	2.918	2.786	2.882	2.78
u_c^*	8.754	7.358	8.755	8.009	8.405	7.042	8.417	7.208
U_S	2.897	2.773	2.835	2.668	2.133	2.283	2.307	2.366
C_S	1.44	1.459	1.442	1.442	1.479	1.491	1.492	1.503
f_{aux}	0.5866	0.6013	0.5931	0.5903	0.6184	0.6109	0.613	0.6254
D_L	0.006366	0.0108	0.009014	0.009881	0.01166	0.01445	0.007782	0.0111
S_C	0.007636	0.01342	0.002076	0.036	0.01405	0.01953	0.0269	0.02336
obj	26.761	29.469	27.626	30.183	36.199	38.95	40.718	43.855
$T_{set\ min}$	63	63	63	63	61	62	60	60
SF_o	0.436	0.452	0.433	0.446	0.482	0.484	0.484	0.489

INVESTIGATION OF TEST CONDITIONS FOR ISO COMMITTEE DRAFT 9459/5 ON SOLAR DOMESTIC HOT WATER SYSTEM TESTING USING SIMULATED TEST DATA

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NOMENCLATURE

A_C^*	effective collector area, DST model parameter	m^2
C_S	heat capacity of the store, DST model parameter	J/K
D_L	draw-off mixing parameter, DST model parameter	-
f_{aux}	auxiliary fraction of the store, DST model parameter	-
P_{aux}	auxiliary power	W
P_D	power demanded by the user	W
P_L	power delivered to the load	W
S_C	collector loop stratification parameter, DST model parameter	-
u_C^*	collector loop heat loss parameter, DST model parameter	$W/(m^2K)$
U_S	overall heat loss coefficient of the store, DST model parameter	W/K

1. INTRODUCTION

Work carried out in Group II 'Solar Domestic Hot Water (SDHW) System Testing' of the Subtask on Dynamic Component and System Testing (DCST) within Task 14 of the IEA Solar Heating & Cooling Programme mainly involved determination of test conditions for dynamic testing (DST) of SDHW systems. Investigations of real and simulated test data have resulted in the description of test conditions in ISO Committee Draft 9459/5 ([1]) which was forwarded by the German Standards Organization DIN to ISO members for voting as a Draft ISO Standard. The DCST Subtask activities were a direct follow-up of the Dynamic Systems Testing Group (DSTG), a Working Group within the IEA SH&C Programme ([2]).

Determination of the ultimate test conditions described in the Committee Draft embodied an iterative process, for both researchers involved in investigation of real test data and the ones working with simulated data. Both investigation processes proceeded parallel, i.e. intermediate results often lead to same conclusions, hence, strengthened the way how to continue. Intermediate results have been described in progress reports and memoranda: [3] - [5] and [9] for the work with real test data, and

[6] - [10] for the investigations on simulated test data.

The investigations on simulated test data described in this paper only encompass the test conditions in the mentioned final Committee Draft ([1]). Another paper in this report by Pauschinger ([11]) describes results of investigations based on real data.

2. DESCRIPTION OF THE TEST CONDITIONS

The test conditions investigated include test sequences S_{sol}, S_{store} and S_{aux}. Test sequence S_{sol} has been divided into two sequences, i.e. $S_{sol,A}$ with A-days and $S_{sol,B}$ with B-days. All test sequences have been described in the following. Before that, definition of A- and B-days, and valid A- and B-days is given. For more detailed descriptions is referred to [1].

2.1 Definition A- and B-days

A-days: the days with large draw-offs like in [1], Section 6.2.2.2; possible auxiliary heater "off" all day.

Valid A-days: A-days with daily irradiation exceeding 12 MJ/m^2.

B-days: the days with small draw-offs like in [1], Section 6.2.2.3; possible auxiliary heater "off" from 1 hour before until 1 hour after the draw-offs, unless according to the manufacturer auxiliary should not be switched off during the day. Then, the auxiliary heater shall be "on" all day.
In order to prevent overheating the small draw-off volume is extended if tap water temperature at the store outlet exceeds a system size dependent threshold temperature, i.e. the current draw-off continues until 20 % of the store volume has been withdrawn, however, is stopped when the outlet temperature drops the threshold. The threshold temperature is larger than the set temperature of the auxiliary heater, if present.

Valid B-days: B-days with daily irradiation exceeding 12 MJ/m^2.

2.2 Definition of test sequence $S_{sol,A}$ and $S_{sol,B}$

Test sequence $S_{sol,A}$ is meant to characterize solar collector performance at high efficiency. System temperature is kept low by the following test conditions:

- 1st day: pre-conditioning + operation under test A conditions.
- following days: operation under test A conditions *until at least 3 valid A-days* have been obtained.
- the number of valid A-days should be at least one third of the days within $S_{sol,A}$.
- final conditioning.

Test sequence $S_{sol,B}$ is intended to identify store heat losses and collector performance at low efficiency.

System temperature is kept relatively high by the following test conditions:

- 1st day: pre-conditioning + operation under test B conditions.
- following days: operating under test B conditions until *at least 3 valid B-days of which 2 are consecutive* have been obtained.
- the number of valid B-days should be at least one third of the days within $S_{sol,B}$.
- final conditioning.

The number of valid B-days (in $S_{sol,B}$) should be equal or 1 or 2 larger than the number of valid A-days (in $S_{sol,A}$). For the investigations, the minimum requirement of three valid A-days and three valid B-days was followed.

Pre- and final conditioning:
Pre-conditioning normally means draw-off of at least three store volumes. For the investigations, test data with a pre-conditioned store were generated.
Final conditioning means draw-off of about 1.5 store volumes. For the investigations, draw-off of two store volumes was used. This draw-off was sufficient to meet a temperature difference between inlet and outlet of the store smaller than 2 K.
Conditioning should take place during hours without solar irradiation and the possible auxiliary heater should be switched off at that time.

2.3 Definition of test sequence S_{store}

Test sequence S_{store} is meant to identify the overall store losses, i.e. by adding this test sequence to $S_{sol,B}$ store and collector heat losses are decoupled. By the following test conditions, the store can loose heat during two days without interference of solar input:

- 1st day: pre-conditioning + operation under test B conditions (but auxiliary heater "off" during all day).
- following days: operation under test B conditions (but auxiliary heater "off" during all day) *until and no more than 2 consecutive valid B-days* have been obtained.
- following 2 days (48 hours): no draw-off and no solar input by possible covering of the collector if irradiance > 200 W/m^2. In that case, the pyranometer should be covered as well (or irradiance should be set to zero) and outdoor ambient air temperature should be measured under the cover (as gain can also be caused by high ambient temperatures).
- final conditioning, i.e. draw-off of three store volumes or less if temperature difference between inlet and outlet becomes lower than 2 K. For the investigations, draw-off of two store volumes was sufficient to meet the latter requirement.

2.4 Definition of test sequence S_{aux}

Test sequence S_{aux} is meant for identification of the heat losses and volume fraction of the auxiliary-heated part of the store. By the following test conditions, temperature of the auxiliary part is kept high whereas the solar part is kept cold:

- 1st day: preconditioning + operation under test B conditions, no solar input.
- 2nd + 3rd + 4th day: operation under test B conditions and no solar input.
- "no solar" means covering of the collector if irradiance > 200 W/m^2; see under S_{store} for collector covering.
- final conditioning; see under S_{store}.

2.5 Combination of test sequences for investigation

Investigations involved whether or not the combination of test sequences $S_{sol,A+B}$ and S_{store} is sufficient for solar pre-heat systems, and the combination of $S_{sol,A+B}$, S_{store} and S_{aux} is sufficient for solar plus supplementary systems.

3. DESCRIPTION OF THE INVESTIGATION METHOD

The investigation method has been presented in Figure 1.

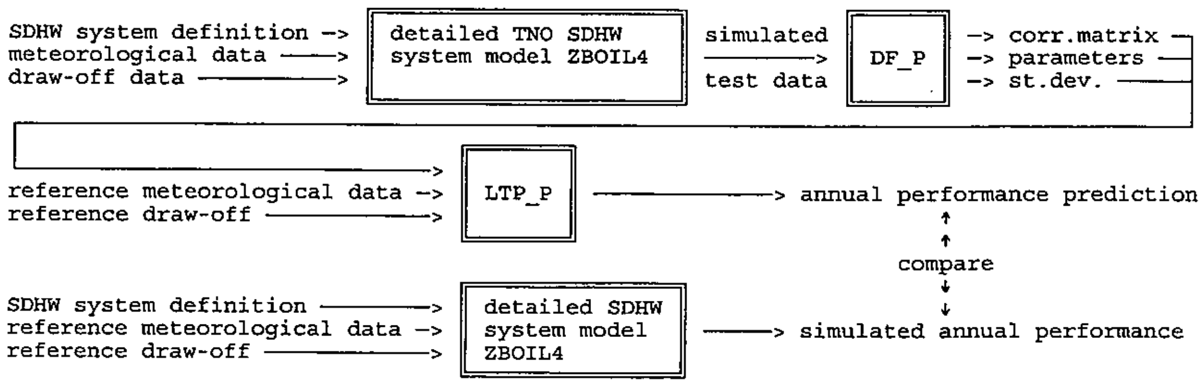

Figure 1: Scheme of the investigation method.

Investigations consisted of the following steps:

- For three different types of SDHW systems (see Section 4), simulated test data were generated for a Dutch test site (De Bilt). Detailed TNO SDHW system model ZBOIL4 was used for the test data generation.
- The simulated test data were analyzed with program DF_P Version 2.2 (September 1993), i.e. the DST model parameters were identified.
- Subsequently, from the DST model parameter sets annual performance was predicted for the Dutch location for three different loads, i.e. 50, 110 and 200 litres per day, heated from 15°C

to 65°C. Annual performance was also predicted for Trapani, Italy for 121 litres per day, heated from 20°C to 65°C. For the predictions, program LTP_P Version 2.4β (June 1994) was used.

- The annual performances for the different loads and locations were also simulated by program ZBOIL4. These figures were used for comparison with the DST model predictions.

Both for test data generation and for annual performance prediction and simulation, meteorological data from Test Reference Year (TRY) files were used.

4. DESCRIPTION OF THE SIMULATED SDHW SYSTEMS

Test data were generated for the following SDHW systems:

I. Solar pre-heat system with separate solar collector and heat store and with a collector loop heat exchanger in the store.

II. Solar plus supplementary system with separate solar collector and heat store and with a collector loop heat exchanger in the store. In normal operation, the auxiliary heater is switched on only during off-peak hours.

III. As system II, however, in normal operation, the auxiliary heater is switched on all the time.

All systems have forced circulation conventional flow in the collector loop. The solar collectors are glass-covered and have spectral selective absorbers. Tables 1 - 3 give the main characteristics of the systems. Presented auxiliary control and setpoint temperature involve values for predicted and simulated annual performance. These systems encompass the majority of Dutch SDHW systems.

Table 1: Main characteristics of solar pre-heat system I.

SOLAR PRE-HEAT SYSTEM I	
collector area	2.7 m^2
η_0 collector	0.80
heat loss collector	3.72 + 0.019ΔT W/m^2K
collector pipe heat loss	1 W/K
control collector	ΔT_{on} = 10 K, ΔT_{off} = 2 K
solar energy store volume	120 litres (no auxiliary part)
auxiliary volume	- (pre-heat system)
store heat loss	1.40 W/K
UA-value collector loop heat exchanger	260 W/K
auxiliary control	-
auxiliary setpoint temperature	-
auxiliary power	-

Table 2: Main characteristics of solar plus supplementary system II with auxiliary heating by an electric element during off-peak hours.

SOLAR PLUS SUPPLEMENTARY SYSTEM II	
collector area	2.7 m^2
η_0 collector	0.80
heat loss collector	3.72 + 0.019ΔT W/m^2K
collector pipe heat loss	1 W/K
control collector	ΔT_{on} = 10 K, ΔT_{off} = 2 K
solar energy store volume	120 litres (excluding auxiliary part)
auxiliary volume	120 litres
store heat loss	2.50 W/K
UA-value collector loop heat exchanger	260 W/K
auxiliary control	from 11 p.m. to 7 a.m. (electric element during off-peak hours)
auxiliary setpoint temperature	62.5°C
auxiliary power	1.5 kW

Table 3: Main characteristics of solar plus supplementary system III with auxiliary heating by an indirect boiler during all day.

SOLAR PLUS SUPPLEMENTARY SYSTEM III	
collector area	2.7 m^2
η_0 collector	0.80
heat loss collector	3.72 + 0.019ΔT W/m^2K
collector pipe heat loss	1 W/K
control collector	ΔT_{on} = 10 K, ΔT_{off} = 2 K
solar energy store volume	120 litres (excluding auxiliary part)
auxiliary volume	80 litres
store heat loss	2.14 W/K
UA-value collector loop heat exchanger	260 W/K
auxiliary control	all day (indirect boiler)
auxiliary setpoint temperature	65°C
auxiliary power	20 kW

5. DESCRIPTION OF SEPARATE AND COMBINATIONS OF TEST SEQUENCES

5.1 Separate test sequences

For each of the three SDHW systems, TNO model ZBOIL4 was used for generation of two $S_{sol,A}$ and two $S_{sol,B}$ sequences, one S_{store} and, for the solar plus supplementary systems, one S_{aux} sequence.

The $S_{sol,A}$ and $S_{sol,B}$ sequences have been chosen such that:

- all days within the sequence are valid days (sequences 1 and 2).
- the number of valid days is one third of the days within the sequence, hence, just meeting the '1/3 criterion' mentioned in Section 2.2 (sequences 3 and 4).

Valid days have a daily irradiation of approximately 12 - 19 MJ/m^2.

The following test sequences have been chosen (day nos. refer to the TRY file for De Bilt, Netherlands):

$S_{sol,A}$ sequence no.:

1: A period with three consecutive valid A-days: day no. 258 - 260 with daily irradiation of 12.3, 13.2 and 12.1 MJ/m^2 respectively.

3: A 9-day period with no consecutive valid A-days: day no. 64 - 72 with daily irradiation of 1.2, 12.5, 2.2, 10.3, 4.4, 16.9, 4.8, 5.5 and 14.0 MJ/m^2 respectively.

$S_{sol,B}$ sequence no.:

2: A period with three consecutive valid B-days: day no. 255 - 257 with daily irradiation of 13.0, 13.0 and 13.5 MJ/m^2 respectively.

4: A 9-day period with two consecutive valid B-days: day no. 282 - 290 with daily irradiation of 5.9, 3.3, 13.5, 5.7, 9.5, 7.8, 1.8, 17.8 and 18.9 MJ/m^2 respectively.

S_{store} sequence no.:

5: A period with two valid B-days and two following days with shielded collector: day no. 201 - 204 with (adapted) daily irradiation of 13.5, 12.2, 0.0 and 0.0 MJ/m^2 respectively.

S_{aux} sequence no.:

6: A period with a total shielding of the collector with use of outdoor ambient air temperatures of day no. 255 - 258.

In data generation of test sequences $S_{sol,B}$, S_{store} and S_{aux} for SDHW system II, the auxiliary heater can be in operation from 11 p.m. to 7 a.m, i.e. the auxiliary heater is switched on if temperature in the top of the store drops below 60°C, and delivery of heat stops if the temperature in the auxiliary part exceeds 65°C. For system III, auxiliary heat is delivered all day, if needed. For this system, the setpoint temperature of the auxiliary heater is 65°C and there is no hysteresis. The threshold temperature in test sequences $S_{sol,B}$, S_{store} and S_{aux} for B-days is set at 66°C, i.e. auxiliary heater operation can never cause the extension of the draw-off volume described in Section 2.1.

5.2 Combinations of test sequences

Test sequences described above were combined in a total of 4 sets of simulated $S_{sol,A}$ and $S_{sol,B}$ test data for each system. For the solar pre-heat system, S_{store} was added to these sets. Both S_{store} and S_{aux} were added for the solar plus supplementary systems. Table 4 shows an overview.

Table 4: Overview of combinations of test sequences.

	$S_{sol,A}$		$S_{sol,B}$		S_{store}	S_{aux} [1)]
Combination	1	3	2	4	5	6
A	x		x		x	x
B	x			x	x	x
C		x	x		x	x
D		x		x	x	x

[1)] For solar plus supplementary systems only.

6. INVESTIGATION RESULTS

For detailed information about the investigation results is referred to Appendix I which contains tables with parameter identification and annual performance prediction results from the individual combinations listed in Table 4. In this section, same results have been presented in figures. Moreover, a table displays averaged values of the four sets.

6.1 Parameter identification results

Figures 2 - 4 show for SDHW system I, II and III respectively, the results of parameter identification for the four sets indicated in Table 4. The parameters are:

- A_C^* effective collector area;
- u_C^* collector loop heat loss parameter;
- U_S overall heat loss coefficient of the store;
- C_S heat capacity of the store;
- f_{aux} auxiliary fraction of the store;
- D_L draw-off mixing parameter;
- S_C collector loop stratification parameter.

Notice that the readings of f_{aux}, D_L and S_C should be divided by 10; the same applies to C_S in Figure 2.

Each identified parameter has been provided with its standard deviation. The combination of these deviations causes the standard deviation that is related to the difference between 'measured' (simulated in this case) and predicted signal. The readings of the standard deviations have to be treated in the same way as those of the parameter values.

Further investigation ([8]) on the solar pre-heat system parameters revealed that A_C^* is the most important parameter; the second important parameter is u_C^*. For A_C^*, a 1 % parameter change introduces a 0.5 % change in the annual gain. For u_C^*, this figure is 0.25 %.

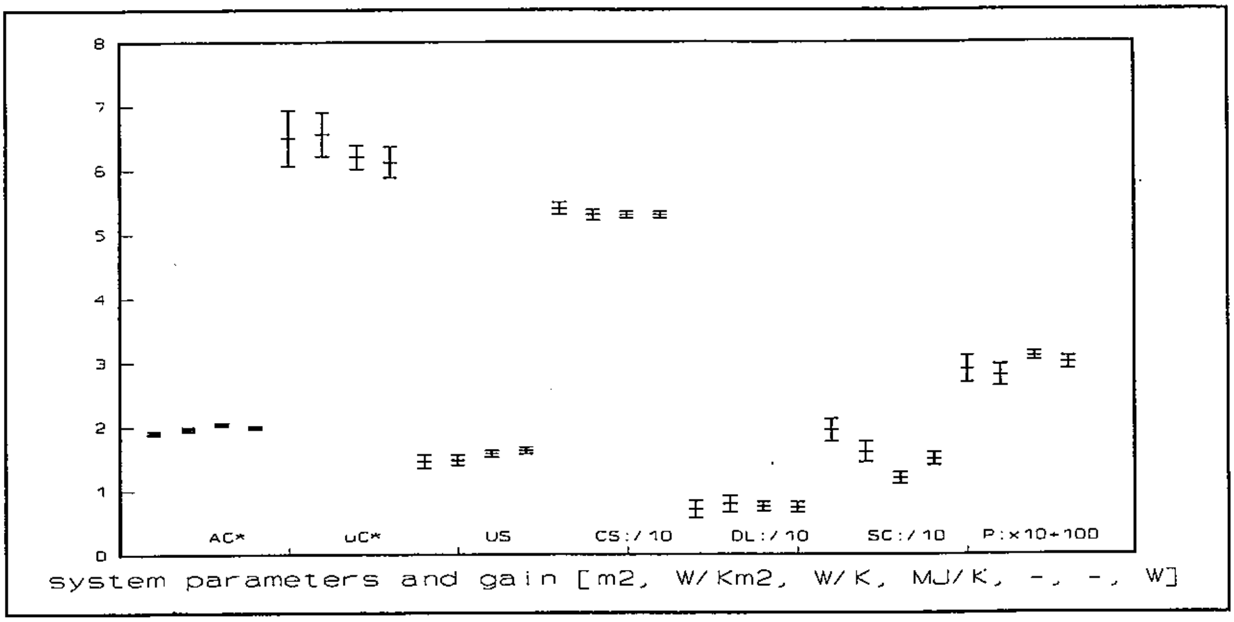

Figure 2: Results of DST parameter identification and predicted annual power delivered to a load of 110 litres per day, heated from 15°C to 65°C, and for weather according to TRY-De Bilt, Netherlands for solar pre-heat system I.

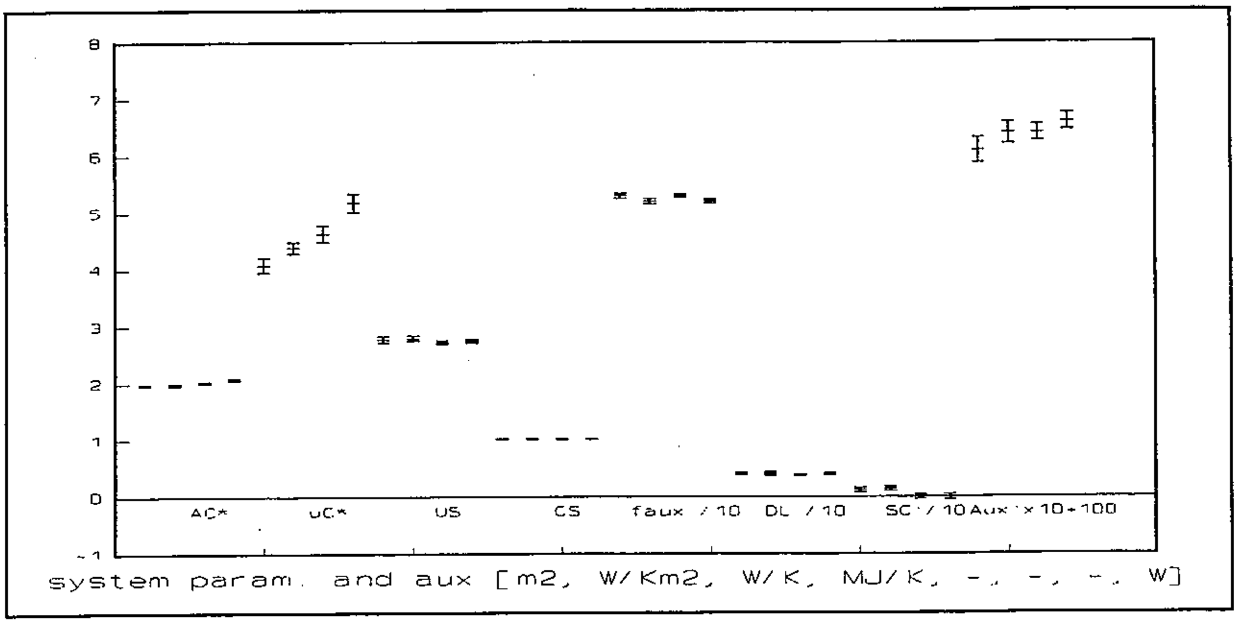

Figure 3: Results of DST parameter identification and predicted annual auxiliary power for a load of 110 litres per day, heated from 15°C to 65°C, and for weather according to TRY-De Bilt, Netherlands for solar plus supplementary system II.

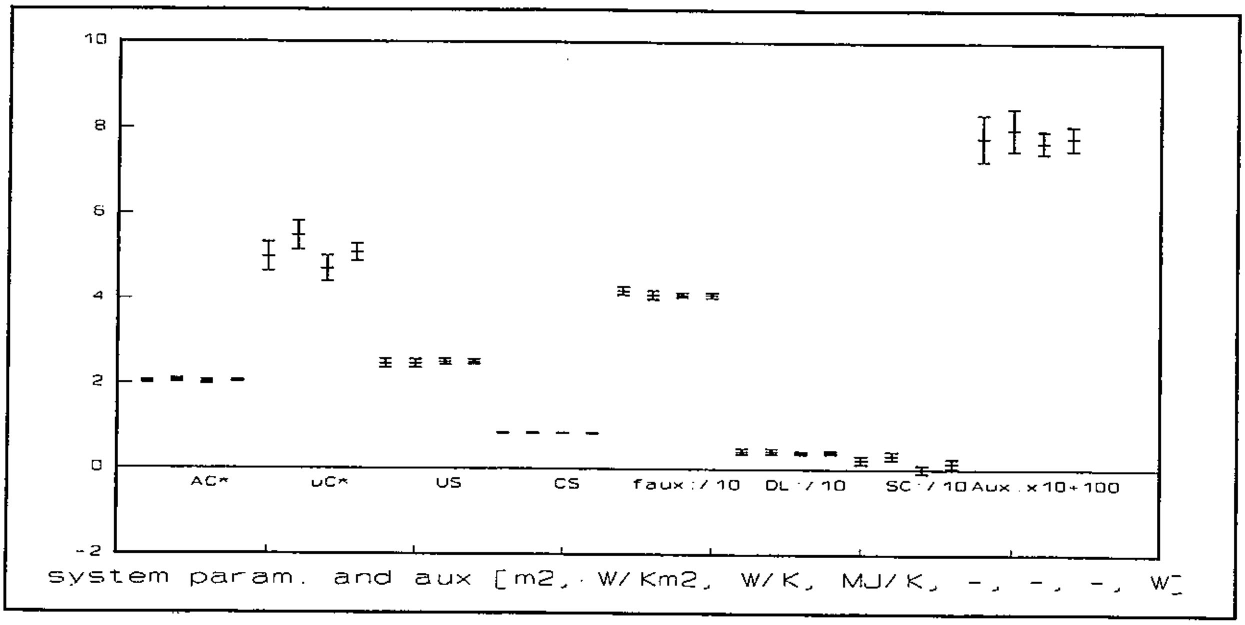

Figure 4: Results of DST parameter identification and predicted annual auxiliary power for a load of 110 litres per day, heated from 15°C to 65°C, and for weather according to TRY-De Bilt, Netherlands for solar plus supplementary system III.

Discussion of the results

1. The various sets of test sequences lead to very similar parameter values. The spread in parameter values is quite small; it is relatively largest for u_C^*. It is assumed that the scatter in u_C^* cannot be reduced by improvement of the test conditions as the reason for the spread is found to be the operation of collector pump control ([11]??).

2. The standard deviation appears to be a good indication for the spread in parameter values from the different sets of test sequences, i.e. if the scatter of parameters is relatively large, then, the standard deviation is relatively large.
   Moreover, most identified parameters coincide within their mutual rather small 2σ-bands. This indicates that the different parameters are identified quite accurately.

6.2 Results of annual performance predictions for different loads

Figures 2 - 4 also provide annual performance predictions for a load of 110 litres per day, heated from 15°C to 65°C, and for weather conditions following TRY-De Bilt, Netherlands. For solar pre-heat system, power delivered to the load P_L has been presented. Auxiliary power P_{aux} has been used for solar plus supplementary systems. Notice that the readings of P_L and P_{aux} should be multiplied by 10 and added to 100. The annual performance predictions have been provided with standard deviations based on the standard deviations in the identified parameters. The readings of these standard deviations should only be multiplied by 10.

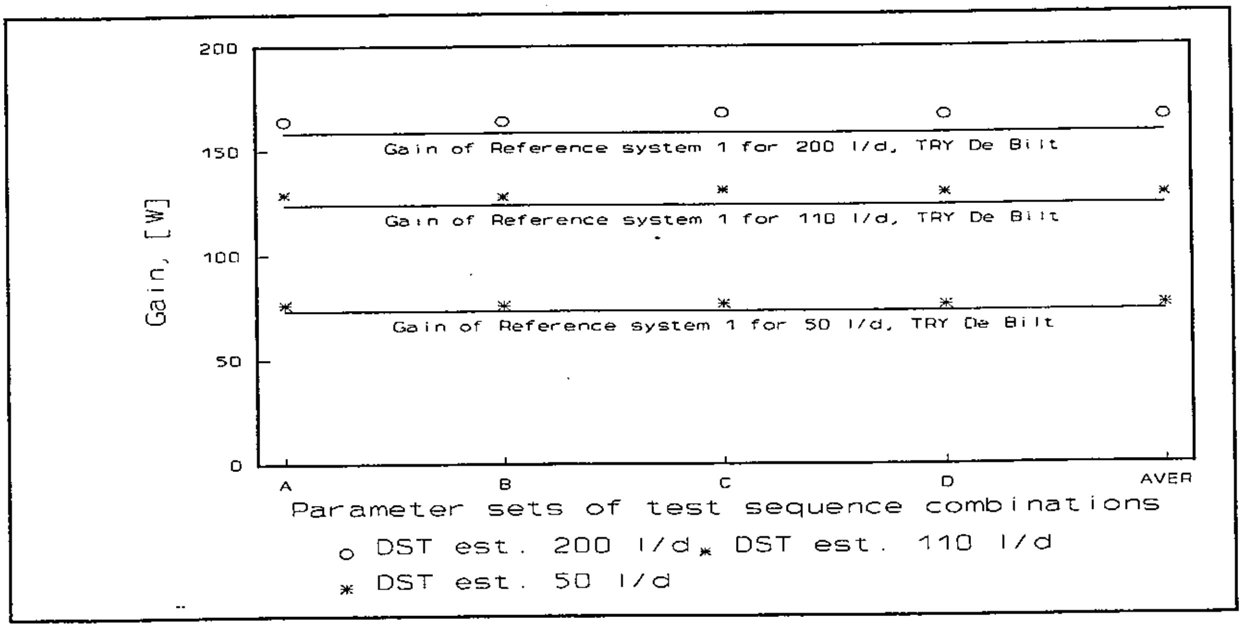

Figure 5: Predicted annual power delivered to various loads, heated from 15°C to 65°C, for weather according to TRY-De Bilt, Netherlands for solar pre-heat system I.

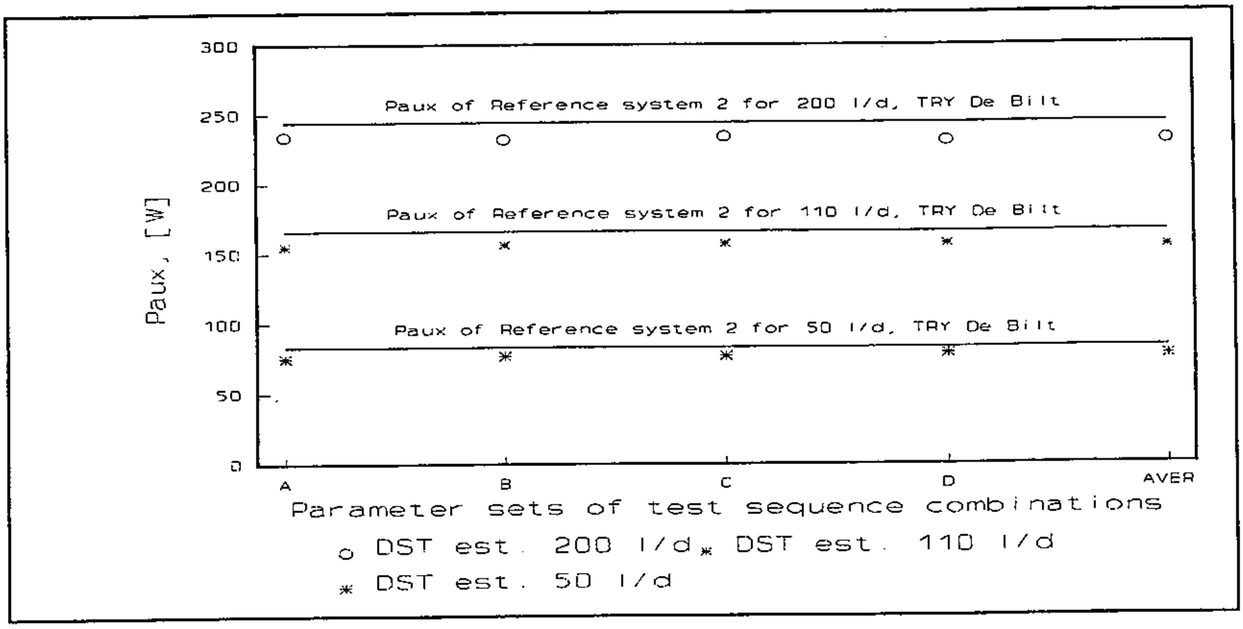

Figure 6: Predicted annual auxiliary power for various loads, heated from 15°C to 65°C, for weather according to TRY-De Bilt, Netherlands for solar plus supplementary system II.

Figure 5 - 7 show for SDHW system I, II and III respectively, annual performance predictions for more loads, i.e. 50, 110 and 200 litres per day, again for the identified parameters from the four sets of test sequences listed in Table 4. The values indicated with 'AVER' involve P_L and P_{aux} for the set

of averaged parameters from the four separate combinations of test sequences. Straight lines in the figures represent the 'real' annual performance calculated by the detailed SDHW system model ZBOIL4.

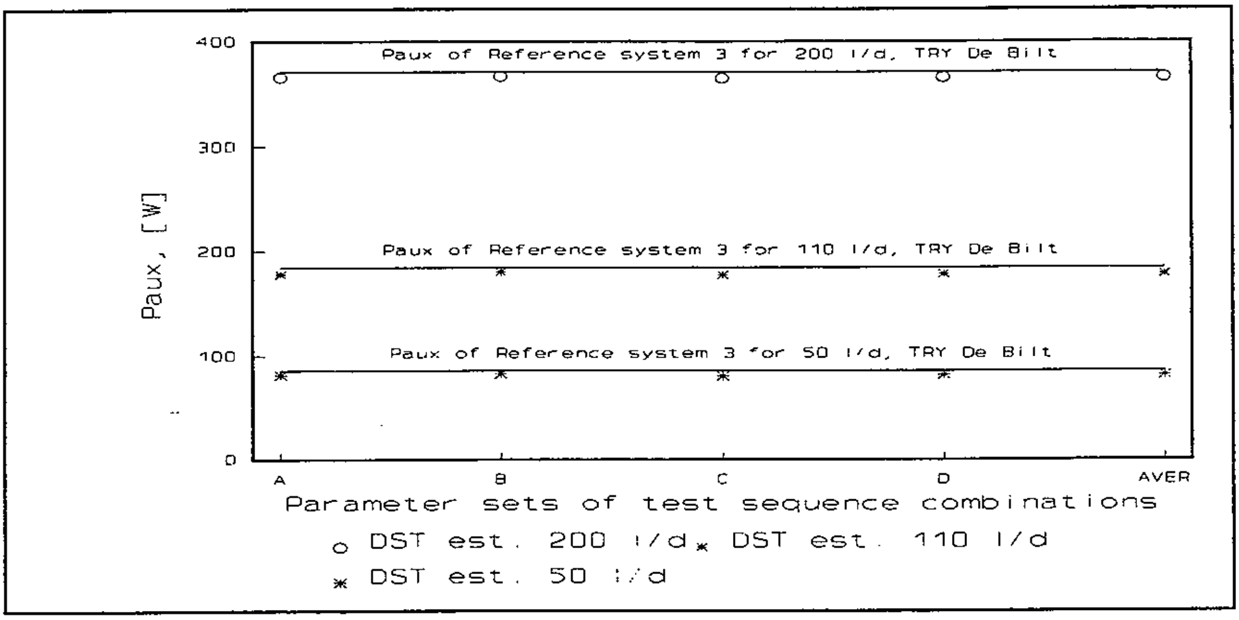

Figure 7: Predicted annual auxiliary power for various loads, heated from 15°C to 65°C, for weather according to TRY-De Bilt, Netherlands for solar plus supplementary system III.

Discussion of the results

3. The various sets of test sequences not only yield similar parameter values but also very comparable annual performances. The spread in annual gain and auxiliary power is minor for all loads. Predictions agree within their mutual 2σ-bands indicating that annual performance is predicted quite accurately as well.

6.3 Results of annual performance predictions for various locations

Annual performance predictions for two different locations, i.e. De Bilt, Netherlands and Trapani, Italy, have been presented in Figures 8 - 10 for the identified parameters from the four sets of test sequences in Table 4. For the Dutch location, predictions have been made for a load of 110 litres per day, heated from 15°C to 65°C, and for the Italian site, the load was 121 litres per day, heated from 20°C to 65°C. Moreover, values of P_L and P_{aux} corresponding to the averaged values of the parameters have been given as well. Straight lines in the figures represent again the 'real' annual performance calculated by the detailed SDHW system model ZBOIL4. The upper line displays the annual demand P_D.

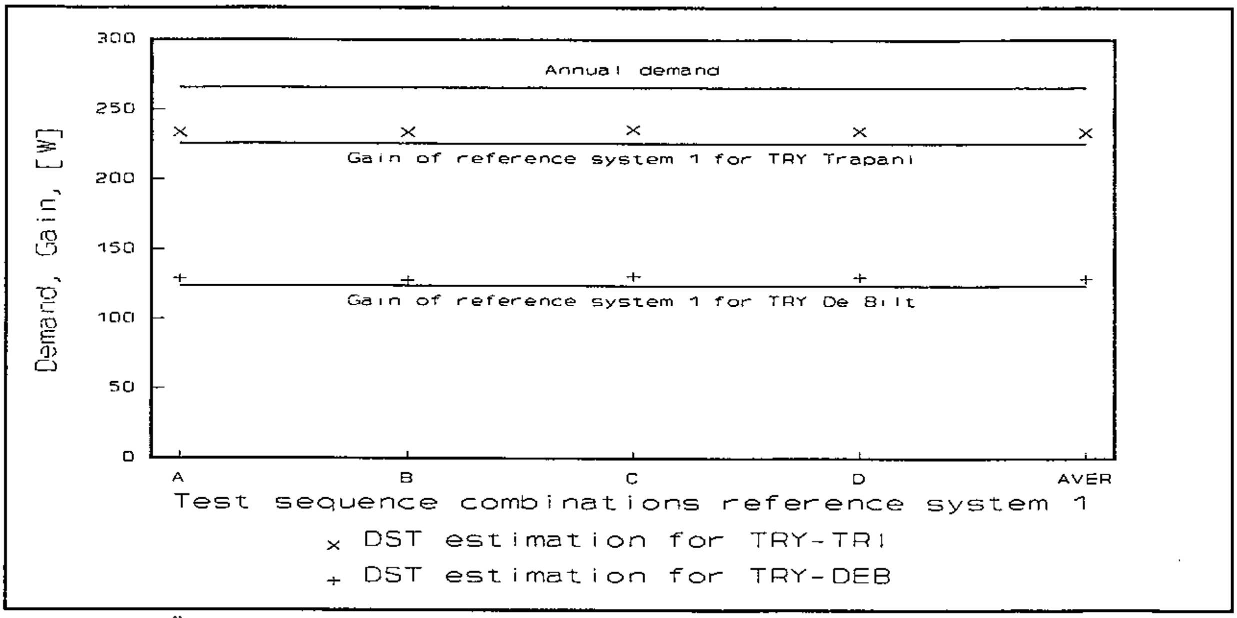

Figure 8: Predicted annual power delivered to a load of 110 litres per day, heated from 15°C to 65°C, for weather according to TRY-De Bilt, Netherlands and a load of 121 litres per day, heated from 20°C to 65°C, for TRY-Trapani, Italy for solar pre-heat system I.

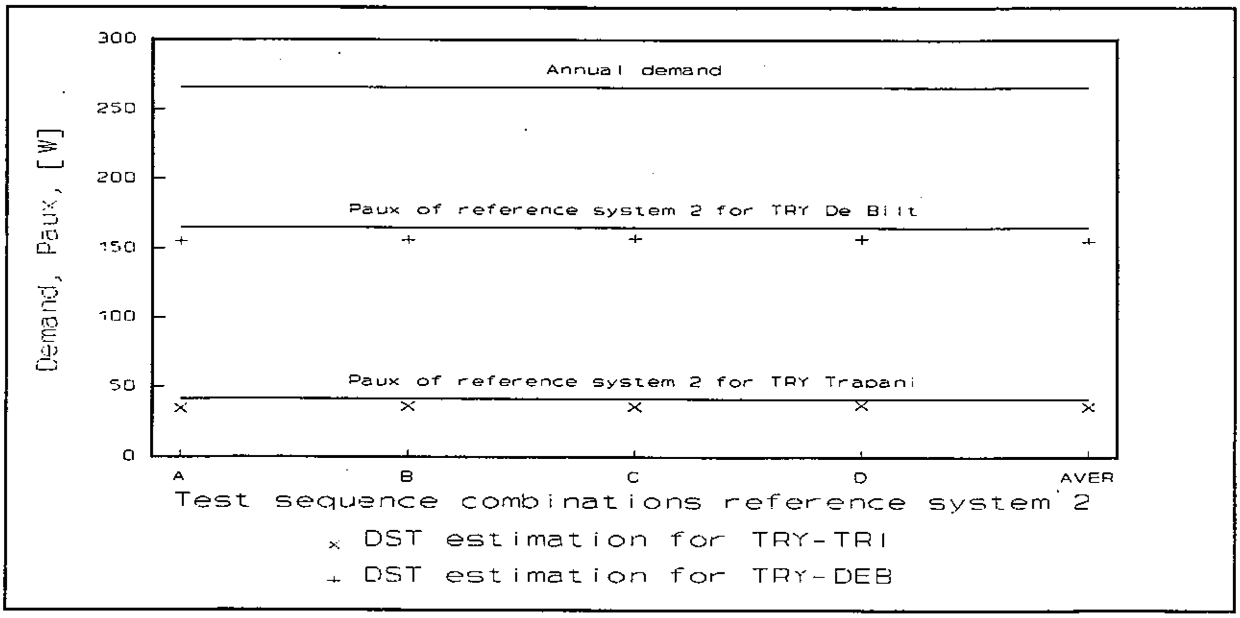

Figure 9: Predicted annual auxiliary power for a load of 110 litres per day, heated from 15°C to 65°C, for weather according to TRY-De Bilt, Netherlands and a load of 121 litres per day, heated from 20°C to 65°C, for TRY-Trapani, Italy for solar plus supplementary system II.

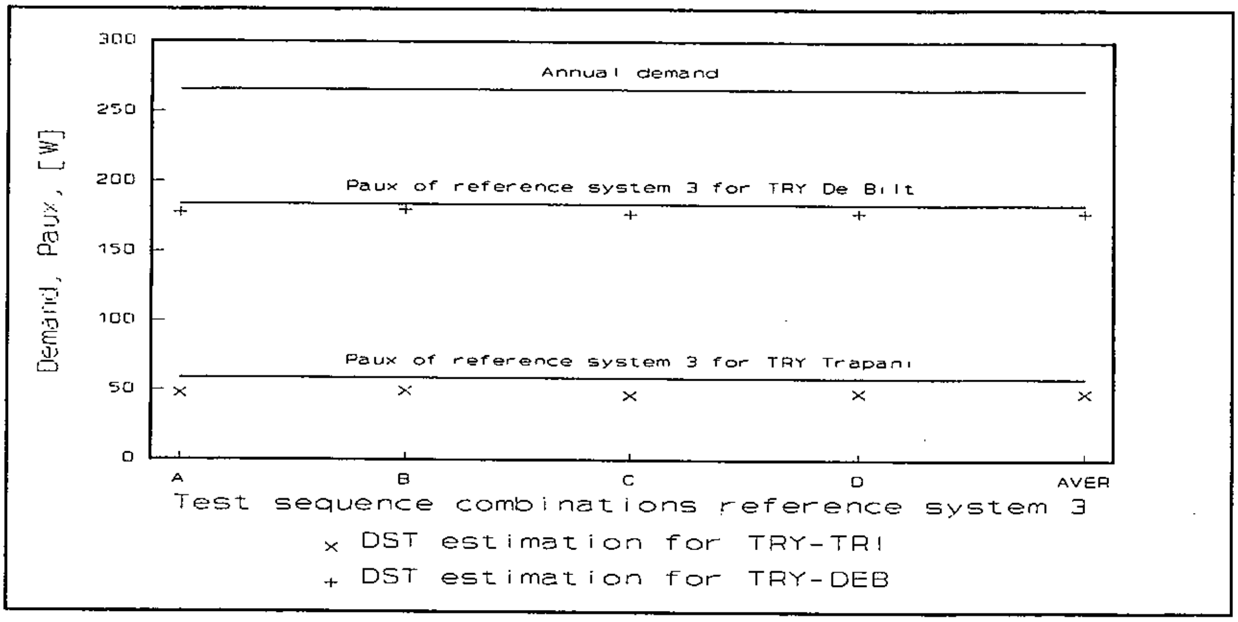

Figure 10: Predicted annual auxiliary power for a load of 110 litres per day, heated from 15°C to 65°C, for weather according to TRY-De Bilt, Netherlands and a load of 121 litres per day, heated from 20°C to 65°C, for TRY-Trapani, Italy for solar plus supplementary system III.

Discussion of the results

4. The identified parameters from the various sets of test sequences produce very similar annual performance predictions, also for locations with very different meteorological conditions. Prediction results correspond to results of performance prediction for different loads, i.e. the spread in annual gain and auxiliary power is very small.

6.4 Overview of results

Table 5 lists condensed results of the investigations in which identified parameter values and annual performance predictions for the four sets indicated in Table 4 have been averaged. Expected values of SDHW system parameters have been listed as well. For determination of these values, data from Tables 1 - 3 have been used. These are:

- A_C^* 2.7 m^2 * 0.80 = 2.16 m^2.
- u_C^* the temperature dependent heat loss coefficient complicates a simple calculation of u_C^*. Also, the collector pipe heat losses should be incorporated into u_C^*. The estimation is based on an average temperature difference of 30 K between collector and ambient. The overall heat loss reads : 2.7 (3.72 + 0.019*30) + 1 = 12.6 W/K. Based on A_C^*, u_C^* becomes : 5.83 W/m^{2}K.
- U_S for system I: 1.40 W/K, for system II: 2.50 W/K, and for system III: 2.14 W/K.
- C_S for system I: 0.50 MJ/K, for system II: 1.00 MJ/K, and for system III: 0.84 MJ/K.

- f_{aux} for system II: 0.50, and for system III: 0.40.

In Table 5 'ex' means expected value and 'id' means identified value.

Table 5: Compilation of all parameter identifications with DF_P and annual performance predictions with LTP_P.

parameter	load [l/d]/ TRY location	system, expected or identified					
		I, ex	I, id	II, ex	II, id	III, ex	III, id
A_C^* [m²]		2.16	1.97	2.16	2.01	2.16	2.04
u_C^* [W/m²K]		5.83	6.35	5.83	4.57	5.83	5.06
U_S [W/K]		1.40	1.53	2.50	2.75	2.14	2.49
C_S [MJ/K]		0.50	0.53	1.00	1.01	0.84	0.84
f_{aux} [-]		-	-	0.50	0.52	0.40	0.41
$D_L \cdot 10$ [-]		?	0.74	?	0.39	?	0.41
$S_C \cdot 10$ [-]		?	1.55	?	0.07	?	0.18
P_L [W] for system I or P_{aux} [W] for systems II and III	50/De Bilt	73	76	83	77	86	81
	110/De Bilt	124	129	165	155	184	178
	200/De Bilt	158	166	244	231	371	366
	110/Trapani	226	234	41	36	59	48

Discussion of the results

5. Identification of A_C^* is underestimated with respect to the expected value. Parameters u_C^* and U_S are slightly too high for the solar pre-heat system. For the solar plus supplementary systems, identification results in underestimation of u_C^* which is compensated by an overestimation of U_S.

However, when making a comparison between identified and expected values one should always have in mind that DST data processing includes a general SDHW system model. Second order system properties for which there are no separate parameters, are taken into account by identification of parameter values which deviate from the expected values to some extent. Hence, only the order of magnitude of the parameters should be compared. Based on this consideration, the conclusion of good agreement between identified and expected parameter values is very well justified.

6. Predicted annual power delivered to the load for solar pre-heat system I is within 3 % to 6 % of the expected values (calculated by ZBOIL4).
For solar plus supplementary systems II and III, the deviation between predicted and expected annual auxiliary power better be related to the annual demand, as P_{aux} is quite small for the 50 l/d demand and for the Trapani location. Errors related to P_{aux} would be pretty large and would not give essential information. Hence, related to the demand, predictions of the annual auxiliary power for the different and locations are within 1 % to 7 % of the expected values. For all systems, the major part of the deviation is systematic, and should mainly be attributed to model differences. For comparison: maximum systematic errors in annual performance prediction caused by realistic systematic measuring errors in the quantities needed for DST data processing are 2.5 % for solar pre-heat systems, and 5 % for solar plus supplementary systems ([12]).
Appendix I gives more information about the relative deviations.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Development of test conditions have provided a test procedure from which main parameters of both solar pre-heat and solar plus supplementary systems can be determined uncorrelatedly to a large extent. This is subscribed by the result reported in this paper that various sets of test sequences within the requirements of the procedure produces very similar parameter values. Standard deviation provided by DST data processing gives a good indication for the uncertainty of the various parameters.

Test and data processing procedure can be used for accurate annual performance predictions for very different loads and locations with very different meteorological conditions. Accuracy of annual performance prediction of tested SDHW systems is in the order of magnitude of 5 %. Major part of this small error is systematic, probably caused by the general character of the SDHW model in the data processing procedure.

Strictly spoken, conclusions above are valid for the investigated systems, i.e. systems with spectral selective collectors and remote heat stores, and with forced circulation conventional flow in the collector loop. On the other hand, investigations included a wide range of SDHW systems, i.e. solar pre-heat and solar plus supplementary systems with various control of the auxiliary heater.

7.2 Recommendations for further research

With respect to application range of the DST procedure

The boundaries of the application range of the DST procedure should be investigated more profoundly. Accuracy of the method should be evaluated for systems with non-spectral selective absorbers and absorbers without cover. Systems with different flow regime in the collector loop, such as low flow and thermosyphon flow, should be taken into account as well. Finally, the procedure should be evaluated for integral collector storage systems.

With respect to the test conditions

From adaptations of test conditions, only minor improvement of DST parameter identification and annual system performance prediction results can be expected, however, some adaptations might simplify the procedure. The following adaptations may be considered:

- The 12 MJ/m^2 demand for valid A- and B-days should perhaps be flexible and linked to the ratio of store volume and collector area. System temperatures during S_{sol} and S_{store} test sequences can reach higher values then, possibly reducing correlation between u_C^* and U_S, and (to a smaller extent) between A_C^* and u_C^*.
- Test sequence S_{aux} might be skipped for solar plus supplementary systems as S_{store} also reveals information for decoupling identification of u_C^* and U_S.
- The strict limit of 1/3 valid days for both $S_{sol,A}$ and $S_{sol,B}$ test sequences might be more flexible. Maybe this criterion can be dropped.
- The same might be valid for the criterion that the number of valid B-days in $S_{sol,B}$ should be equal or 1 or 2 larger than the number of valid A-days in $S_{sol,A}$.

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APPENDIX I: PARAMETER IDENTIFICATION AND ANNUAL PERFORMANCE PREDICTION RESULTS

This appendix contains investigation results from the individual combinations of test sequences indicated in Table 4. Tables I.1 - I.3 list results of parameter identification for SDHW systems I, II and III respectively, and Tables I.4 - I.6 give corresponding annual performance predictions. Parameter values for the four sets of test sequences have been averaged. These mean values were used for determination of the annual performance prediction indicated with "AVER" in Tables I.4 - I.6.

Table I.1: Identified parameters and annual power delivered to a load of 110 litres per day, heated from 15°C to 65°C, for weather according to TRY-De Bilt, Netherlands for solar pre-heat system I.

	A_C^* [m²]	u_C^* [W/m²K]	U_S [W/K]	C_S [MJ/K]	D_L·10 [-]	S_C·10 [-]	Obj. [W]	P_L [W]
A	1.90	6.50	1.45	0.54	0.70	1.94	1.96	129
B	1.96	6.56	1.47	0.53	0.78	1.60	1.51	128
C	2.04	6.20	1.57	0.53	0.74	1.19	1.76	131
D	1.98	6.12	1.62	0.53	0.73	1.49	1.58	130
AVER	1.97	6.35	1.53	0.53	0.74	1.55		129

Table I.2: Identified parameters and annual auxiliary power for a load of 110 litres per day, heated from 15°C to 65°C, for weather according to TRY-De Bilt, Netherlands for solar plus supplementary system II.

	A_C^* [m²]	u_C^* [W/m²K]	U_S [W/K]	C_S [MJ/K]	f_{aux} [-]	D_L·10 [-]	S_C·10 [-]	Obj. [W]	P_{aux} [W]
A	1.98	4.08	2.77	1.01	0.53	0.40	0.12	1.53	155
B	1.98	4.39	2.79	1.01	0.52	0.40	0.14	1.56	156
C	2.02	4.64	2.72	1.01	0.53	0.38	0.00	1.33	157
D	2.07	5.18	2.74	1.01	0.52	0.40	0.00	1.36	157
AVER	2.01	4.57	2.75	1.01	0.52	0.39	0.07		155

Table I.3: Identified parameters and annual auxiliary power for a load of 110 litres per day, heated from 15°C to 65°C, for weather according to TRY-De Bilt, Netherlands for solar plus supplementary system III.

	A_C^* [m²]	u_C^* [W/m²K]	U_S [W/K]	C_S [MJ/K]	f_{aux} [-]	D_L·10 [-]	S_C·10 [-]	Obj. [W]	P_{aux} [W]
A	2.03	4.98	2.47	0.84	0.42	0.42	0.22	3.25	178
B	2.06	5.48	2.47	0.84	0.41	0.42	0.32	2.99	180
C	2.02	4.70	2.51	0.84	0.41	0.39	0.01	2.75	177
D	2.05	5.08	2.51	0.84	0.41	0.40	0.15	2.69	178
AVER	2.04	5.06	2.49	0.84	0.41	0.41	0.18		178

Table I.4: Predicted and 'real' (i.e. calculated by ZBOIL4) annual power delivered to various loads, heated from 15°C to 65°C, and weather according to TRY-De Bilt, Netherlands and TRY-Trapani, Italy, for solar pre-heat system I. The error in the predicted value is related to the 'real' value.

load / P_D / TRY location	50 l/d / 121 W / De Bilt		110 l/d / 266 W / De Bilt		200 l/d / 484 W / De Bilt		110 l/d / 266 W Trapani	
	P_L [W]	ΔP_L [%]	P_L [W]	ΔP_L [%]	P_L [W]	ΔP_L [%]	P_L [W]	ΔP_L [%]
Real	73		124		158		226	
A	76	4.0	129	4.0	164	3.6	234	3.5
B	76	3.4	128	3.2	164	3.6	234	3.5
C	77	4.4	131	5.6	168	6.1	234	4.4
D	76	4.0	130	4.8	167	5.5	236	4.0
AVER	76	3.8	129	4.0	166	4.9	234	3.5

Table I.5: Predicted and 'real' annual auxiliary power for various loads, heated from 15°C to 65°C, and weather according to TRY-De Bilt, Netherlands and TRY-Trapani, Italy, for solar plus supplementary system II. The error in the predicted value is related to the annual demand.

load / P_D / TRY location	50 l/d / 121 W / De Bilt		110 l/d / 266 W / De Bilt		200 l/d / 484 W / De Bilt[1)]		110 l/d / 266 W Trapani	
	P_{aux} [W]	ΔP_{aux} [%]	P_{aux} [W]	ΔP_{aux} [%]	P_{aux} [W]	ΔP_{aux} [%]	P_{aux} [W]	ΔP_{aux} [%]
Real	83		165		244		41	
A	76	-6.4	155	-4.1	234	-2.1	35	-2.6
B	77	-5.1	156	-3.8	232	-2.5	36	-2.0
C	77	-5.2	157	-3.4	234	-2.1	36	-2.0
D	79	-3.6	157	-3.4	231	-2.7	37	-1.6
AVER	77	-5.1	155	-4.1	231	-2.7	36	-2.1

1) The heat demand for the load of 200 litres per day is not met by SDHW system II. The 'real' system delivers 398 W instead of the required 484 W. The average parameter set delivers 393 W.

Table I.6: Predicted and 'real' annual auxiliary power for various loads, heated from 15°C to 65°C, and weather according to TRY-De Bilt, Netherlands and TRY-Trapani, Italy, for solar plus supplementary system III. The error in the predicted value is related to the annual demand.

load / P_D / TRY location	50 l/d / 121 W / De Bilt		110 l/d / 266 W / De Bilt		200 l/d / 484 W / De Bilt		110 l/d / 266 W Trapani	
	P_{aux} [W]	ΔP_{aux} [%]	P_{aux} [W]	ΔP_{aux} [%]	P_{aux} [W]	ΔP_{aux} [%]	P_{aux} [W]	ΔP_{aux} [%]
Real	86		184		371		59	
A	81	-3.6	178	-2.3	366	-1.0	48	-4.2
B	83	-2.5	180	-1.5	367	-1.0	50	-3.5
C	80	-4.3	177	-2.6	365	-1.2	46	-4.7
D	82	-3.2	178	-2.3	366	-1.0	48	-4.1
AVER	81	-3.6	178	-2.3	366	-1.0	48	-4.1

Sources of the Inaccuracies of the DIS 9459/5 Test Results

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1. Abstract

The goal of this work is to analyse the accuracy of the test method for solar domestic hot water (SDHW) systems proposed in the February 1994 version of the Draft International Standard (DIS) 9459/5 [1]. Validation has been performed using synthetical data generated by the TRNSYS [2] program. Two representative synthetical tests were used for analysis. One test was created using summer weather data and other using winter/spring data. The test sequence as described in the DIS was used as a load forcing function for the SDHW systems under consideration. The identification procedure has been repeated for three solar collector types - with selective and non-selective absorber. The identified sets of parameters were used afterwards for prediction of yearly energy yield for two diverse climatic conditions. It is shown that the predicted energy yields by different test sequences differs up to 18 % and the difference in predicted energy yields by DST algorithm in comparison with the TRNSYS exceeds 20 %. The possible reason for the inaccuracy may be the DST simplifications used for component theoretical models.

2. Introduction

Economic assessment of solar domestic hot water (SDHW) systems requires reliable characterization of their performance. For that reason, a test method delivering accurate results is necessary. It would be desirable that the test method would be able to predict the yearly energy yield within ± 10 % accuracy. The prediction should not be dependent on climatic conditions of a test site; various sets of system parameters identified under various climatic conditions and/or during different seasons should give the same (± 10 % accuracy) prediction of the yearly energy yield. In that sense, test results would be transferable to various consumption and/or weather conditions.

The DST algorithm [3] - as basis of the DIS - uses a plug flow model for characterization of storage performance and the Hottel-Whillier-Bliss [4] equation as a universal model for collector loop performance.
The analysis on the possible sources of inaccuracy of the DIS has been recently published in the report available on request [5]. In this article we regard only influences of certain simplifications used in the collector model: neglecting of the incident angle dependency of collector optical efficiency and the temperature dependency of overall heat loss coefficient.
The aim of this work is to clearly quantify yearly energy yield inaccuracy introduced by these simplifications. Estimation of the inaccuracy is especially important for SDHW systems equipped with collectors where the importance of neglected effects is doubtless (e.g. collectors with non-selective absorbers, evacuated tube collectors and double glazed collectors). The wind dependence of the overall heat loss coefficient is not considered in this work. Furthermore, this work does not consider influences of measurement uncertainties.

The accuracy of predicted energy yield is analysed referring to (1) repeatability of energy yield predicted by various sets of parameters identified from different synthetical test sequences and (2) accuracy of predicted energy yield regarding to the yield predicted by the TRNSYS program.

3. Collector and storage model used for generation of synthetical sequences

The multi-node collector model available as TRNSYS component and the standard TRNSYS storage component model have been used for generation of synthetical data.
We recall here briefly the main features of the multi-node collector model published in [6].
Each node of a flat-plate collector is characterized by:

$$C_n\, dT_n/dt = A_n\, F'[(\tau\alpha)_0\, G_{eq} - U_L(T_n - T_a)] - q_{u,n} \qquad (1)$$

where: G_{eq} is the equivalent normal irradiance taking into account irradiance components multiplied by respective incident angle modifiers :

$$G_{eq} = K_{\tau\alpha,beam}\, G_{beam} + K_{\tau\alpha,diff}\, G_{diff} + K_{\tau\alpha,alb}\, G_{alb} \qquad (2)$$

U_L is the overall heat loss coefficient :

$$U_L = U_0 + U_v\, v + U_T(T_n - T_a) \qquad (3)$$

$q_{u,n}$ is the rate of energy gain by the collector node:

$$q_{u,n} = m_c c_p(T_n - T_{n-1}) \qquad (4)$$

An incidence angle modifier for direct irradiance is defined by the Ambrosetti [7] equation:

$$K_{\tau\alpha,beam}(\theta) = 1 - \tan^{1/r}(\theta/2) \qquad (6)$$

The incident angle modifier for diffuse irradiance assuming isotropic distribution is used as derived in [6]. The incident angle modifiers for diffuse irradiance and for albedo we assume to be equal. They are both derived in [6] as a function of parameter r.

Taking into account the fact that identification of wind dependency of overall heat losses is still under consideration in the DIS, we have excluded this effect in our analysis, i.e. we have set Uv=0 for collectors taken in the analysis. Naturally it implies that results of the analysis are moderate regarding the case if wind dependency would be taken into account. That specially holds for non-selective collectors where this dependence could not be neglected.

The standard TRNSYS component model for storage has been used with various levels of stratification within storage. The storage was simulated as a well mixed, with a fixed and with a variable inlet position.

4. Generation of synthetical data

The TRNSYS program has been used to generate synthetical data according to the test sequence described in the DIS. The meteorological data - Test Reference Year (TRY) for Wuerzburg (Germany) - were used as a basis for synthetical data sequences. The sequences were created using summer weather data only and the other using autumn and winter/spring data - abbreviated S, A and W in the respective tables. Each synthetical sequence consists of storage heat loss test (two sunny days followed by 48 hours cooling period and conditioning) and the standard test consisting of 3 so-called type `A` days and 3 so-called type `B` days of which 2 `B` days had to be consecutive. Solar daily irradiation of each day used for the analysis exceeded 12 MJ/m²day. The other requirements requested by the DIS were completely fulfilled as well.

The synthetical sequences were generated for SDHW systems with forced circulation with - (1) collector equipped with selective or non-selective absorber and (2) well mixed and a stratified storage.

The parameters of three types of collector used for analysis follow:

Collector A: Manufacturer: Djurs Solvarme, Collector type: DS-3:

$$\hat{\eta} = 0.8 - [2.7 + 0.032\, G\, T^*]\, T^* \qquad r = 0.275$$

Collector B: Manufacturer: Solar Energy Products Inc., Collector type: CU 30-WW

$$\hat{\eta} = 0.683 - [4.321 + 0.054\ G\ T^*]T^* \qquad r = 0.295$$

Collector C: Same as collector B but reduced heat loss coefficient:

$$\hat{\eta} = 0.683 - [2.2 + 0.025\ G\ T^*]T^* \qquad r = 0.295$$

Other collector parameters are $A = 4\ m^2$ and $Cc = 8.42$ kJ/K

Storage parameters are $V = 250$ l, $UsAs = 1.5$ W/K

5. Results of the Analysis

Each synthetical sequence is analysed by searching for 15 local minima, starting from the expected values of the parameter to be identified.

Statistical analysis performed by the identification of system parameters have shown the following:
(i) objective function did not exceed 2 % of the respective system gain over the sequence and
(ii) standard deviation of the identified parameters for collector loop did not exceed 5 % of the corresponding parameter value.

This briefly indicates that enough data were used for identification of system parameters for the given theoretical model.

Reliability of the set of identified parameters was examined by predicting the yearly energy gain for Test Reference Year for Wuerzburg and for yearly weather data for Phoenix. The Phoenix weather data were generated using TRNSYS weather data generator.

Seq.	Consum. l/day	Coll. type	Store	Yield(DST) [W]	Repeat-ability [%]	Yield(TRN) [W]	**ERROR** [%]
S	150	B	s-f	287	-	285	0. 7
A	150	B	s-f	298	3. 8	285	4. 6
W	150	B	s-f	300	4. 6	285	5. 3
S	250	B	s-f	398	-	389	2. 3
A	250	B	s-f	430	8. 0	389	10. 5
W	250	B	s-f	448	12. 6	389	15. 2
S	350	B	s-f	461	-	447	3. 0
A	350	B	s-f	499	8. 2	447	11. 6
W	350	B	s-f	544	18	447	21. 2

Tab 1. Predicted yearly energy yield by the DIS and TRNSYS for Phoenix weather data.

Seq.	Consum. l/day	Coll. type	Store	Yield(DST) [W]	Repeatabi-lity [%]	Yield(TRN) [W]	**ERROR** [%]
S	250	B	s-f	195	-	195	0. 1
W	250	B	s-f	224	14. 9	195	14. 9
S	250	A	s-f	258	-	252	2. 4
W	250	A	s-f	288	11. 6	252	14. 3
S	350	B	s-v	305	-	296	3. 0
W	350	B	s-v	325	6. 1	296	9. 8
S	350	B	s-f	219	-	219	0
W	350	B	s-f	250	14. 1	219	14. 1
S	350	A	s-f	286	-	280	2. 0
W	350	A	s-f	327	14. 3	280	16. 6

Tab 2. Predicted yearly energy yield by the DIS and TRNSYS for Wuerzburg weather data.

seq.	Consum l/day	Coll. type	Store	Yield(DST) [W]	Repeat-ability [%]	Yield(TRN) [W]	**ERROR** %
S	350	A	s-v	593	-	588	1.0
W	350	A	s-v	630	6,2	588	7.1
S	350	C	w-m	468	-	461	1.5
W	350	C	w-m	495	5,8	461	7.4
S	350	A	s-f	558	-	542	2.4
W	350	A	s-f	636	14	542	17.3

Tab 3. Predicted yearly energy yield by the DIS and TRNSYS for Phoenix weather data.

Prediction of yearly energy gain was carried out for the identical load time profile for each day in the year. Three equal withdraws at 7 a.m., 12 a.m. and 19 p.m. have been applied. Three daily consumption volumes were used: 150 l, 250 l and 350 l. Mains temperature was 10 deg. C and set temperature 60 deg. C.

The main criterion in analysing the accuracy of the test method was the repeatability accuracy of the predicted energy yield using identified parameters from various test sequences as well as the accuracy of prediction in comparison with the energy yield computed by the TRNSYS program.

Tab. 1 shows results of the analysis for Phoenix weather data and Tab. 2 for Wuerzburg weather data.
Abbreviations used in the Tables are: w-m -- well mixed storage, s-f -- stratified storage with fixed inlet position, s-v -- stratified storage with variable inlet position, ERROR is difference in yields predicted by the DIS and the TRNSYS in percentage.

Both yearly energy gains predicted by the DST algorithm and TRNSYS program are presented. It is noticeable systematic over-estimation of energy yield predicted by DST algorithm in comparison with reference, TRNSYS results. Over-estimation ranges up to 21 %.

In the Tab 4 we have listed system parameters of the same SDHW system identified from two different synthetical test sequences. It is noticeable that collector and store parameters (collector type B and s-f store) are ambiguously identified. This is reflected in the inaccuracy of predicted energy gain of 18 %.

seq	A*	UL*	AsUs	Cs	DL	SC
s	2.054±.03	11.28±.43	1.158±.11	1.04±.02	0.366±.04	0.174±.02
w	2.561±.04	13.15±.23	1.354±.07	1.08±.01	0.105±.01	0.161±.01

Tab 4. Identified system parameters for two different synthetical tests.

6. Draw-off Profile

The draw-off profile requirements are unnecessary complicated. They are reasonable only for ICS systems were collector loop is not distinguishable from storage loop. The goal of the draw-off profile - to cover a variety of system operating states - can be reached with a considerably simpler requirements as for example draw-off profile created within TC312 and reported in the CEN documents (see paragraph C.3.2.1). An extra sensor in collector loop measuring the collector outlet fluid temperature should be installed for this reason. The majority of laboratories continuously measure collector loop temperatures during the DST test. This information is valuable tool to carry out the draw-off profiles which will certainly enable better repeatability and accuracy of the test results.

Herewith the proposal for the optimized draw-off profiles for days A and B is presented:

Test A Day
The purpose of this test is to get information about collector array performance at high efficiencies. Thus, the collector inlet temperature is to be kept cool by means of subsequent discharging the store. The draw-off rates should be regulated in a way to keep the mean fluid temperature of collector array as close as possible to collector ambient air temperature. If the draw-off rates cannot be regulated automatically, the test engineer should continuously monitor the collector outlet fluid temperature and, if necessary, draw-off such quantity of water from the store that the collector mean temperature approximately reaches the ambient temperature. The discharged volume depends on the store dimensions and should be adjusted to the particular conditions.

NOTE: A simple method is to start discharging whenever the collector inlet fluid temperature exceeds the collector ambient temperature $T_{c,amb}$, by more than 10 K (20 K for low-flow collectors), and to stop it when the collector fluid mean temperature decreases as close as possible to the ambient temperature.

If the ambient air temperature of the collector T_a is lower than the mains water temperature, T_{cw}, then the collector inlet fluid temperature shall be kept as close as possible to the mains water temperature.
The draw-off rate shall be less than (10 ± 1) l/min. However, it is recommended to apply a flow rate of (1 ± 0.5) l/min during the first minute of each discharge in order to reduce any measurement error due to the thermal inertia of the sensors.
The mains water temperature shall be between 8 and 15 deg C; any deviation during a sequence shall not exceed ± 2 K.

Test B Day
The purpose of this test is to get information about store heat losses and collector array performance at low efficiencies. The draw-off rates shall be such that the collector array becomes as warm as possible for longest possible period. Any overheating of the store shall be avoided.
During the test, no discharging is applied until the temperature of the fluid entering the store from the collector loop exceeds 90 deg C, and discharging is stopped when this temperature reaches 85 deg C. The discharged volume depends on the store dimensions.
In regard of the draw-off rates, the same principles as for test A day apply.
The same considerations regarding discharging flow rate as for Test A day apply here.
The mains water temperature shall be between 8 and 15 deg C; any deviation during a sequence shall not exceed ± 2 K.

7. Conclusion

The analysis of the accuracy of energy yield predicted by the DST algorithm has shown that for certain synthetical test sequences the predicted energy yield is excellent - comparable with that predicted by the TRNSYS within the numerical accuracy of simulation. Unfortunately, for a number of synthetical sequences this difference exceeds ± 10 %.

The seasonal influence on the test results is very strong although the dependence of collector heat loss coefficient on ambient temperature is not taken into account in the TRNSYS collector model used for generation of synthetical sequences.

Yearly energy yield predicted by the DST algorithm differs up to 18 % in dependence which test sequence is taken for identification of system parameters. Furthermore, the difference between yearly energy yield predicted by DST algorithm and that predicted by TRNSYS is as remarkable as 21 %

These facts clearly suggest that more suitable - or more sophisticated - theoretical models of components have to be applied for identification of system parameters.

In order to improve the accuracy of the test results it is suggested to consider the proposal for draw-off profiles described in Section 6 of this work.

It should be pointed out that the reported uncertainties do not include measurements errors and other sources of uncertainties intentionally excluded in this analysis. This means that calculated errors are certainly conservative estimation of the real errors to be expected. The forthcomming SM&T Project should certainly address in more details the problems listed.

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NOMENCLATURE

A	-	*total collector (aperture) area of array,*
C	-	*collector array total thermal capacity,*
C_n	-	*the heat capacity of each collector node*
c_p	-	*specific heat coefficient of fluid in collector loop,*
F'	-	*collector array efficiency factor,*
G	-	*incident total radiation on a flat surface per unit area,*
G_{beam}, G_{diff}, G_{alb}	-	*incident direct, diffuse and ground reflected radiation,*
K_{beam}, K_{diff}, K_{alb}	-	*incidence angle modifiers, beam, diffuse and ground reflected radiation,*
m_c	-	*collector fluid mass flow rate,*
r	-	*parameter for incident angle modifier,*
N	-	*number of nodes,*
$q_{u,n}$	-	*rate of energy gain by collector node,*
T_a	-	*ambient air temperature in vicinity of collector array,*
T_m	-	*collector mean fluid temperature,*
T_n	-	*collector node temperature,*
T^*	-	*reduced temperature*
U_L	-	*overall heat loss coefficient,*
U_o	-	*overall heat loss coefficient when $T=T_a$, and $v=0$,*

U_v	-	*coefficient characterising wind dependence of the heat loss coefficient,*
U_T	-	*coefficient characterising temperature dependence of heat loss coefficient,*
v	-	*wind speed in collector plane,*
dt	-	*time step,*
dT	-	*increment in node temperature over the time step,*
$(\tau\alpha)_0$	-	*product of cover(s) transmittance and absorber absorptance for normal incident angle,*
θ	-	*incident angle of radiation*

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