THERMAL INSULATION LABORATORY
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COMMON SOLAR SIMULATION AND VALIDATION IN EUROPE

"A report presenting work of the CEC modelling group for SHS and DHW"

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Preface

The Commission of the European Communities is, as part of its Solar Energy Programme, conducting a Research and Development programme on Solar Energy Applications for Dwellings. The cooperative work within the European Modelling Group for Solar Heating Systems and Domestic Hot Water is one of the activities undertaken within this programme.

During the first one and a half years of operation of the current CEC 4-year programme this group has undertaken work in the following areas:

- analysis of data from the Solar Pilot Test Facilities
- validation of simulation models
- parameter sensitivity analyses
- investigation of simplifications and assumptions in simulation models
- simplified design methods

These activities have not only been co-ordinated within the group but also performed in close cooperation with two other concerted actions within the CEC programme for Solar Energy Applications for Dwellings: The Solar Pilot Test Facilities Group and the Performance Monitoring Group.

This report constitutes a detailed summary of the work done in the CEC Modelling Group during the 18-month period from January 1980 to July 1981. The intentions have been to present illustrative examples of the extensive amount of results presented in the individual reports, to give a picture of the nature of the work and, at the same time, draw some general conclusions on the basis of the results. Most of the work has been presented by the individual participants in their summary reports, ref. 5-14, and has been presented in a less complete form in the progress reports produced during the work.

February 28, 1982
Ove Jørgensen

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CHAPTER 1

INTRODUCTION

1. INTRODUCTION

Investigation of the performance of solar heating systems was both nationally and internationally recognised as a matter of great importance in 1979 when the current CEC 4-year programme was initiated. It was realised that the net energy output of a solar system was not only a question of component performance but also of system performance. For the CEC programme the result of this meant the initiation of three concerted actions: The Solar Pilot Test Facility Group (SPTFG), the Performance Monitoring Group (PMG) and the Modelling Group for Solar Heating Systems and Domestic Hot Water Systems (MG).

The work of the Modelling Group was officially initiated at its first meeting which took place in Brussels, January 16-17, 1980. Invited to this meeting were the participants of the already existing Modelling Group which had been in operation since 1977, see ref. 1 and 2. Before the meeting the participants had provided the coordinator with their proposals for the next 4-year programme. The following seven points of interest were stated:

1. Validation of simulation models
2. Development of models
3. Sensitivity analysis
4. Modelling of alternative systems
5. Development of simplified methods
6. The economics of solar systems in the CEC countries
7. Validation of simplified methods

It is very clearly seen that these activities can be divided into two areas, one for simulation models and one for simplified methods. This division and the existence of the Solar Pilot Test Facility Group and the Performance Monitoring Group structured the programme as sketched on fig. 1.1.

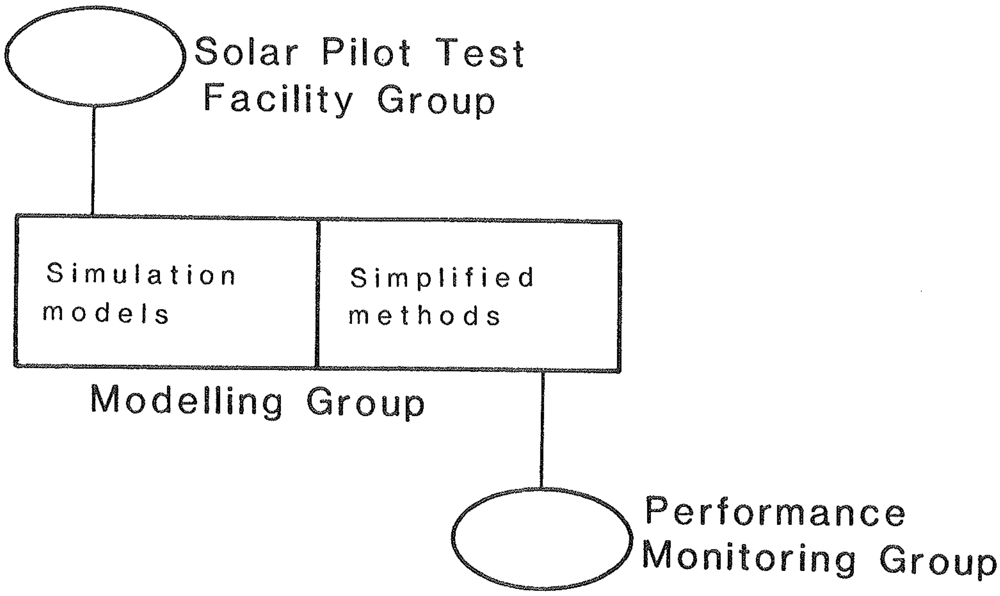

Fig. 1.1 Modelling Group working structure.

The MG - SPTFG Cooperation

To provide a background for the understanding of this co-operation a short introduction to the SPTF programme is given here:

Eight countries are participating in the Solar Pilot Test Facility Group and in each country a Solar Pilot Test Facility, consisting of two systems, system one and system two, was erected. All the systems are laboratory experimental type systems. Each system is controlled by a micro computer which calculates the buildings' space heating load on the basis of the actual weather data and subtracts this load from the storage tank.

All the systems designated number one were constructed to the same design which represents a solar energy system for a single family house with a collector area of 47 m^2 and a water storage tank of 3 m^3. Fig. 1.2 shows a diagram of system 1 of a Solar Pilot Test Facility.

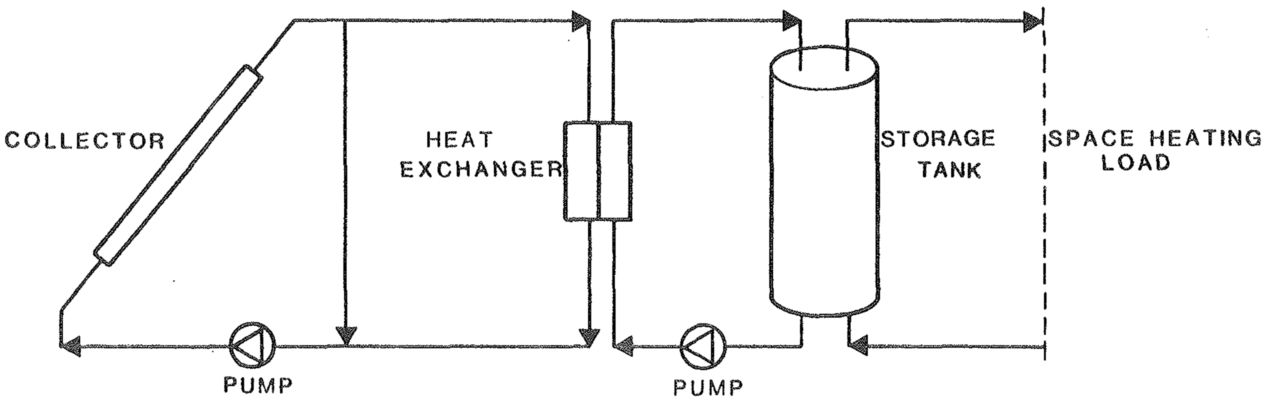

Fig. 1.2 The CEC Solar Pilot Test Facility, System 1.

As seen from the diagram the solar system incorporates two collecting loops separated by a heat exchanger. At the beginning of the program the two pumps were always running and the 3-way valve at the collector outlet was used to control the system. When there is energy available for collection, the valve diverts the fluid flow through the heat exchanger and otherwise by-passes it.

The independence of primary and secondary loops enables continuous running of the secondary loop pump, thus minimizing the stratification in the solar storage.

The systems are very extensively monitored and data can be taken and stored on magnetic tape cassettes at any time-interval from 5 minutes to one hour. For more information on the different systems in the countries (SS2) see ref. 23.

The primary aim of the work in the Modelling Group was to validate the simulation models in the group, using data from the 8 SPTF system 1 (SS1) in the different countries. To make effective use of the data available from the SPTF Group it was necessary to develop some formal way of information exchange about the data. Two formats were identified:

- a log sheet and
- an installation descriptor

The log sheets (see example in Appendix 2) were developed to pass information on the data on a given cassette (i.e. time periods, weather, problems, etc.), and the installation descriptor (see Appendix 1) was made to present the system parameters in a uniform way for eash system variant. Thus, for each cassette of data a log sheet and an installation descriptor would be included to make the data useful to the modeller for validation purposes.

This formality was necessary as it should be possible to distribute data obtained from any of the SSl's to any of the modellers without the risk of misunderstandings, for example: Which collector area was used when these data were taken? During the working period such problems did not occur, which proves the value of these documents.

The MG - PMG Cooperation

The Performance Monitoring Group had developed a format for the presentation of the performance of solar systems, and a number of systems has already been and were continuously being reported in this format. The objective of the cooperation between the Modelling Group and the PMG was to investigate the viability of using the information in the formats to validate simplified design methods.

The MG Working Plan

At the initiating meeting mentioned above, the group agreed on some short term and some long term goals. On the basis of these goals the detailed working programme was sketched out. As this programme dealt with two levels of cooperation it had to be very flexible and adjustable, as the work progressed. A total number of five meetings were held during the working period in order to coordinate the programme and to discuss technical problems. To keep the information level high a Newsletter was created and issued approximately every third month. Below is shown an overall schedule of the activities in this working period from January 1, 1980 to June 30, 1981.

Activity	1980	1981
Sensitivity Analysis I	o——o	
Validation on Danish PTF data	o————o	
Sensitivity Analysis II	o——o o——o	o——o
Sensitivity Analysis III	o——o o——o	o——o
National Validation	o——————	——o
Special Tasks		o——o
Validation of simplified methods	o——o	o——o
Validation on Belgian PTF	o——o	o——o
Paper on model eq. and method of solution	o——o	o——o
Meetings	1 2 3	4 5
Newsletters	1 2 3 4	5 6

Participation

Within the Modelling Group two levels of participation were identified. The 8 participants directly linked with a national Solar Pilot Test Facility, having the responsibility for continuously performing validation work on the data from these installations, were designated M2 participants. The other group of 5 participants, with no direct link to the SPTF Group, were designated M3 participants. The coordinator was designated the M1 participant.

As the validation of simulation models, using data from the SPTF's, was the main objective of the total programme for the Modelling Group, there was a significant difference between the size of the budget for these two groups. The M3-participants had a very small budget, but were, on the other hand, free to selectively take part in any of the activities of the group.

Appendix 3 contains a list of the participants in the Modelling Group.

CHAPTER 2

DESCRIPTION OF SIMULATION MODELS

2. DESCRIPTION OF SIMULATION MODELS

The simulation of solar heating systems always implies stepwise solving of a number of differential equations, one for each significant capacity of the system.

Thus the physical basis of the models is always the same: a differential equation. What makes the model differ are the assumptions and decisions taken by the modeller. First: What are the significant capacities? The tank? The collector and the tank? The pipes? The heat exchanger? The next assumption made has to do with the component interactions and the system interaction with the environment. Again, only the assumed significant contributions are accounted for to avoid too complex a model. At this step the modeller also has to decide on whether to linearize these interactions or to keep them non-linear and closer to the physical reality, e.g. temperature dependency of loss coefficients, flows and conduction terms.

Finally, the modeller must choose a differential equation solution technique. The set of linear or non-linear equations can either be solved sequentially or simultaneously. The actual integration of the differential equations over a time step can either be done analytically or by assuming linearity by applying a differential quotient, developed one way or the other for the whole time step. In most cases only the latter approach proves practical.

Thus a number of assumptions and decisions are taken by the modeller when developing a particular model. An important objective of this work was to cast light upon the impact on the results of the assumptions and options.

The fact that a number of the different possible paths in the model development were covered by the models of the participants in the Modelling Group made it feasible to approach this objective by using the models on the same problems and analyse the results.

To accomplish this objective using the models of the participants in the Modelling Group, the first necessity is to establish an overview and classification of these models with respect to the above mentioned assumptions and decisions upon which the models are built. A total number of nine simulation models were used by as many different participants. When referring to the models the national automobile code is used, i.e. B, D, DK, etc.

Below is a list of the models giving the model reference code, the name or the assigned name of the model (initials of the institution where it is developed) and the name of the modelling group participant using the model:

Model reference code	Name of model	Name of MG participant
B	KUL	Willy Dutré
D	SOLH	Jürgen Reichert
DK	SVS	Ole Balslev-Olesen
GB1	UKSSP1	Robin La Fontaine
GB2	PCL	Stephan Grove
GB3	SOWAHEMO	Joe Lee
F	HABSOL	Bernard Verdier
IRL	SUNSIM	Elaine Kelledy
N	TPD	Ed van Galen

A number of these models were used in the previous work of this group and are well documented in the summary report of that, ref. 1 and 2. However, in order to model the SPTF's accurately these models have been drastically changed, and it can be questioned whether they are still the same models. These remarks go for KUL, SOLH, SVS, PCL and TPD.

In the individual reports of the participants, ref. 5-14, the models are described according to a commonly agreed format which provides enough information to enable a good understanding of how the models work. In this report only a short presentation of each of the models is given to serve as a quick overview of the modelling assumptions and decisions inherent in the different models. Of course, such a presentation can by no means attempt to be complete. The intention is to present the models with their significant characteristics.

B

KUL was developed at the Katholieke Universiteit Leuven. It handles up to 5 solar collectors in series, each of them modelled with capacity and with a top loss coefficient found by Klein's formula. The solving of differential equations is done in a mixed approach where the equations for the primary loop are solved simultaneously by an iteration, while the storage temperature (nonstratified) is kept unchanged. When the iteration converges to the set criteria on the collector inlet temperature the energy output of the heat exchanger is calculated and the storage temperature updated.

D

SOLH was developed at Fraunhofer Gesellschaft. Like KUL the model deals with 1-5 collector nodes. The differential equations are solved simultaneously by an iteration on the collector outlet temperature. The iteration includes the storage temperature which is used for checking convergence when the pump in the primary circuit is not running.

DK

The SVS program developed at the Thermal Insulation Laboratory at the Technical University of Denmark originates from the system studies made when the Zero-Energy-House was built.

The program has a modular structure that allows for the implementation of any differential equation construction and solving technique. In this context the program operates with the system differential equations on a residual form. The equations are solved simultaneously by applying an iterative Newton-Raphson technique.

GB1

The program UKSSP1 was developed at Faber Computer Operations Limited. Based on a thermal network approach where the implicit thermal similarities between the different components in the system are exploited in creating a very modular type of model. The only model that assumes a certain heat capacity of the heat exchanger. The differential equations are solved simultaneously in an implicit form using successive substitutions. The model has a very well organised data input structure. It also allows for for the use of longer time steps at times when the situation is almost stable (at night).

GB2

PCL was originally developed at the Polytechnic of Central London to simulate the first solar house at Milton Keynes. A modular approach in the sense that subroutines easily can be added, which makes modification simple. The collector and pipe capacities are not accounted for. The differential equations for the different layers in the storage tank are integrated sequentially, but explicitly and analytically.

GB3

SOWAHEMO which is a completely new model for micro-computers, has been developed by Joe Lee. The only model using a programming language other than Fortran, namely Pascal. Like UKSSP1 a network approach exploiting similarities between components.

Iterates on the primary loop (as KUL). Takes less than 64 Kbytes RAM on the micro-computer. The simulation of the set through one year at hourly time steps takes two hours of computation on the micro-computer.

F

The program HABSOL was developed at the Commissariat á l'Energie Atomique. It is a general modular approach which has been used for many different systems. Very user-oriented as it is written in an interactive form, allowing the user to change and replace components in a conversation with the program. As in the models B and GB3 the iteration is performed only on the primary loop.

IRL

In Ireland a completely new model had to be developed from scratch, partly because of computer changes. The SUNSIM model was purposely developed as a simple model with one differential equation (for the non-stratified storage tank) solved explicitly for each time step using the Eulor method. The model does not account for pipe losses.

N

The TPD model was developed at Technisch Physische Dienst TNO-TH. The model is constructed on the principle of lumped circuits, e.g. in the primary circuit the capacity and heat losses of the pipes are included with these values for the collector to form only one equation (when the pump is running and no heat is transferred by the heat exchanger). The integration of the storage differential equations are done by the Euler method. When more than one layer of the storage tank is modelled the simulation proceeds at time steps given by the expression:

$$\Delta t = \frac{V\rho}{n \cdot \dot{m}g}$$

where

V = total volume of heat storage system (m^3)

ρ = density of water (kg/m^3)

n = number of sections in the storage

$\dot{m}g$ = mass flow rate in the secondary collecting circuit (kg/s)

The idea of this is that only one section of the storage will be refreshed during each time step.

To provide an overview of the models the table on the following page has been created. It needs to be emphasized that many of the models are very general in nature and therefore the table does not account for all the characteristics of the models, but shows only those used in this context.

Table 2.1

Model code	B	D	DK	GB1	GB2	GB3	F	IRL	N
Number of significant capacities:	6-10*	6-10*	4-10*	8*	1-5*	1-5*	6*	1*	6-10*
Interaction with environment:									
Solar collector: Constant U_L-value = c, linearly changing U_L-value = l, U_L calculated by Klein's formula = K, U_L calculated in more detail = d	K	K	l	K	l	c	d	c	l
Constant $\tau\alpha$-product = c, $\tau\alpha$-product calculated for each time step = ca	c	ca	c	c	ca	c	ca	c	c**
Component interaction:									
Heat exchanger: constant NTU or ε	NTU	ε	ε	ε	ε	opt	opt	ε	ε
Differential equations:									
Sequential = seq, simultaneous = sim	seq	sim	sim	sim	seq	seq	seq	seq	seq
Lumped circuit = lc								lc	lc
Successive substitution = s.s.		s.s.		s.s.					
Newton-Raphson = NR			NR						
Integration method:									
Explicit, exponential = E,e					E,e		E,e		
Explicit, linear = E,l (forwards Euler)	E,l					E,l		E,l	E,l
Implicit, linear = I (backwards Euler)		I	I	I					
Timestep, sec	5'-1 h	½'-1 h	5'-1 h	5'-1 h	15'-1 h	any	1 h	1 h	5'-1 h

* In principle any number of nodes in the storage tank
** Precalculated average value.

```
* DATA FILE FOR DANISH RIG
*  SET UP FOR DATA D.WTHR-1
PROGRAM CONTROL
2,9,1
2,14,24
3600,3600,0
NODE CAPACITANCES
3,523000.,6.0
4,452000.,6.0
5,10000.,6.0
6,442000.,6.0
7,10000.,36.9
8,30000.,36.9
9,12686000.,36.9
10,30000.,36.9
*
BRANCHES (FROM NODE,TO NODE,CONDUCTION TERM,CIRC. NO., % FLOW)
3,4,0.,1,100,3,100
4,5,0.,1,100
5,6,0.,1,100
6,3,0.,1,100,3,100
* BYPASS BRANCH
4,6,0.,3,100
* PIPE LOSSES TO AMBIENT
4,1,25.
4,2,1.4
6,1,25.65
6,2,1.35
* CIRCUIT NO 2
7,8,0.,2,100
8,9,0.,2,100
9,10,0.,2,100
10,7,0.,2,100
*PIPE LOSSES TO AMBIENT
8,2,1.5
9,2,15.0
10,2,1.5
*
HEAT EXCHANGERS
5,7,0.44
*
COLLECTOR
3
AREA=46.47 (M**2),FDASH=0.95,COVER=1
EMIT=0.7,LOSS=0.903,TILT=56.0, TAU-ALPHA=0.85
*
CIRCUIT FLOW RATES
1,3328,6,455
2,2900,10,230
3,3328,6,455,OFF AT THE START
*
CONDITIONS
1,3,9,2.,0.
2,9,9,-1.,-1.
3,9,3,0.,-2.
CONTROLS
1,1
2,2
3,3
*
TANK (NODE NUMBERS)
9
*
PIPE (NODE NUMBERS)
4,6,8,10
*
SHS (SPACE HEATING LOAD)
9,0,9
*
OUTPUT INFORMATION - FORMAT FIRST
(1X,I4,I4,F10.2,F9.2,4F10.2,7X,F7.1,3X,F7.1,6X,F8.1)
('0Totals',F10.2,F11.2,4F10.2,7X,F7.1,3X,F7.1,6X,F8.1//)
```

Fig. 2.1 Input data file for the Danish PTF, GB1 programme, ref. 10

CHAPTER 3

PARAMETER SENSITIVITY

ANALYSES

3. PARAMETER SENSITIVITY ANALYSES

3.1 Parameter Sensitivity Analysis I

A parameter sensitivity analysis was defined as the first cooperative activity of the Modelling Group. The modellers were to set up their models according to the specifications of their national SPTF solar system 1 and use a common set of weather data with a precalculated load for the simulations (see ref. 1). The objectives were:

- to establish a common starting position for all the modellers
- to identify, assess and analyse differences between the models as an aid to the validation work
- to provide a comparison data base for the validation of simplified methods.

The results of the models in Parameter Sensitivity Analysis I differed widely. A closer investigation revealed that this was primarily due to the differences in the 8 SPTF installations. Although they were all built to the same design specifications, the local situation of each of the SPTF's was different causing differences in pipe length, pump sizes, collector back loss, etc. The important conclusion drawn on this first analysis was that the SPTF rigs differed more than expected.

3.2 Parameter Sensitivity Analysis II

As the objectives of the work were not met by Analysis I, another parameter sensitivity analysis was defined (II). The same weather and load data were used and the same parameter variations made as in the first analysis, but instead of modelling each of the 8 SPTF's the Danish SPTF installation was taken as the base run case for all the models. The parameter variations in question were collector area, storage volume and pump starting and stopping differential set points.

The results of the models were in much closer agreement this time, the percent solar ranging from 55% to 61% in the base run (from 44% to 60% in Sensitivity Analysis I). Fig. 3.1 to 3.6 present a more detailed comparison of the results. The first of these figures shows the predicted, monthly performance of the system for the base run: the collector output, the storage loss and the percent solar. From the figures it is clear that the agreement among the models is not completely satisfactory on a monthly basis. Large variations are observed, especially on the storage losses.

Fig. 3.5 shows the predicted percent solar for the system as a function of the collector area variations. It is seen that some of the curves are more "flat" than others, even though the same trend can be observed for all the codes. The sensitivity to storage volume is shown on fig. 3.6, an almost complete set of parallel curves. The reason why the curve of model B is different is that a storage volume dependent heat loss coefficient for the storage has been used, whereas the prescribed value was constant. The main reason for the results of the F code differing quite a lot from those of the others is that the energy consumed by the pumps in the collector circuit was not included in the thermal balance of the system. In the case of the Danish SPTF, these pumps are somewhat oversized, which means that the energy consumed by these pumps is considerable, compared to other energy flows in the system.

With respect to the change in starting and stopping temperature differentials almost no sensitivity was observed. This is probably due to the special configuration of the system, where the primary collecting circuit pump is running all the time.

3.3 Parameter sensitivity analysis III

This analysis was designed for a final adjustment of the models, and to provide some information to the SPTF Group as to the impact on the system performance of certain system changes. The analysis consists of 17 runs with the main emphasis on stratification of the tank temperature. The runs are numbered from 0 - 16, run 0 being the base run.

The monthly predictions of the models on the base run have been computer plotted for comparison on fig. 3.7 to 3.10. The "net" collector output energies compared on fig. 3.7 show a reasonably good agreement among the models, except D, which predicts a somewhat lower collector output. The agreement between the four models, having the heat exchanger transfer energy as an option (shown on fig. 3.8), is very good. The largest differences range from 10-15%. As in the base run of Sensitivity Analysis II the storage losses exhibit the greatest variations, though the disagreement this time is much smaller. The B code predicts a higher storage loss than the others for the whole year. This is probably due to a higher storage temperature, which can be deduced from fig. 3.10 showing the monthly predictions of percent solar. The B and IRL codes are, in almost all months, predicting the highest percent solar.

Pump energy

In run 1 the pump energy input to the collector circuits was set to zero in order to check whether the energy consumption of the pump's transfer to the working fluids was incorporated correctly in the models. The bar chart shown on fig. 3.11 shows the decrease in percent solar from the base run results predicted by the models. It is seen that all the models, except the IRL, agree on a decrease from 7-9%. Thus the pump energy is treated similarly in all models but the IRL.

Distribution temperature

The well known fact that solar heating systems work best at the lowest possible temperatures was the background for run 2 and run 3. The requested distribution temperature is found by a straight line assumption:

RDT = RDTO + RDT1 * AT

where AT is the actual ambient temperature. In run 2 and run 3 the constants RDTO and RDT1 were changed to simulate a lower distribution temperature. The following table shows those two constants as in the base run and in run 2 and 3.

Table 3.1 REQUESTED DISTRIBUTION TEMPERATURES

^oC	Base run	Run 2	Run 3
RDTO	52	38.7	31.3
RDT1	-1.6	-0.94	-0.31

Table 3.2 shows the increase in yearly percent solar as calculated by the models in the two runs respectively.

Table 3.2 INCREASE IN PERCENT SOLAR AS A FUNCTION OF LOWER DISTRIBUTION TEMPERATURES

Δ%	B	D	DK	GB1	GB2	GB3	IRL	NL
Run 2	12.4	12.0	10.5	12.7	10.2	10.5	9.1	10.9
Run 3	16.0	16.0	13.9	16.9	13.5	13.8	11.8	14.5

From table 3.2. it appears that all the models agree that the lowering of requested distribution temperature, as expected, has a very positive impact on the percent solar. It needs to be said that these significant increases must be added to a fraction of solar of from 55-60% as predicted for the base run. As a consequence of these results several of the actual SPTF installations were changed to supply the load at a lower temperature.

As explained in the introduction at the outset of the experiment, the pumps in SPTF SS1 installations were constantly running, and the collection was controlled via a three-way valve. This strategy was chosen because it was considered the best way to obtain a very well "controlled" experiment in the sense that transients were slower and no stratification could occur in the storage tank. This objective was dictated by the wish to produce good data for validation purposes. On the other hand, it is very energy-consuming to have the pumps running all the time and besides, the efficiency of the system is expected to increase if temperature stratification in the storage tank is allowed for. Therefore, when the first validation work was completed, a change in the control strategy was considered. It was decided to model a case where the pumps were only running from 600 to 1800 hours, and at the same time change the direction of the flow of the fluid in the secondary circuit to have the tank outlet at the bottom and the inlet at the top to improve the stratification. This latter change was combined with a lowering of the flow rate in the secondary circuit to further improve the stratification. All these changes were implemented as run 4, and the net result was a slight decrease in the yearly fraction of solar predicted by the programs (about 1%). Thus the much smaller pump energy transferred to the working fluids was counterbalanced by the impact of stratification.

Heat exchanger effectiveness

Several of the participants questioned the stated value of the heat exhanger effectiveness during their validation work (see chapter 4 and 5). The stated value was .44 and the participants claimed that the correct value was more likely .34. This was the background for the choice of run 5 to run 10, which constitutes two series of three runs each to investigate the impact on system performance of heat exchanger effectiveness for two different flow rates in the secondary collecting circuit. The three heat exchanger effectivenesses modelled were: 0.4, 0.6 and 0.8.

The results obtained by the three models: DK, GB2 and NL, on these two series of runs are compared on fig. 3.12 and 3.13. It is seen that the heat exchanger effectiveness has the greatest impact when the flow is smallest (fig.3.13) and the greatest differences between the models show up in this case also. Note the scale which, especially on fig. 3.13, makes the disagreement among the models look worse than it really is.

Number of thermal layers in the storage tank

How many nodes are necessary in a model of a stratified storage tank to model it correctly? is a question often discussed, and also, what is the impact of stratification on system performance? These two questions were the reason for asking the participants with a model of a stratified storage to perform a small series of runs to find out the impact on model predictions of modelling the storage with different numbers of thermal layers. The storage tank was modelled with 1, 2, 3, 5, 7 and 10 layers. The results are shown in fig. 3.14 as increase in percent solar compared to the single node model. It is seen that the three models, DK, GB2 and NL seem to agree very well on the impact of number of layers. The step from 1 to 5 layers covers most of the increase in percent solar and the change observed in going from 5 to 10 layers is almost insignificant.

The relatively small change in percent solar, less than 3%, as a result of obtaining stratification in the storage tank, must be carefully interpreted. The control of the system is still not optimized with respect to stratification, which means that better stratification could be achieved, resulting in a more significant increase in percent solar.

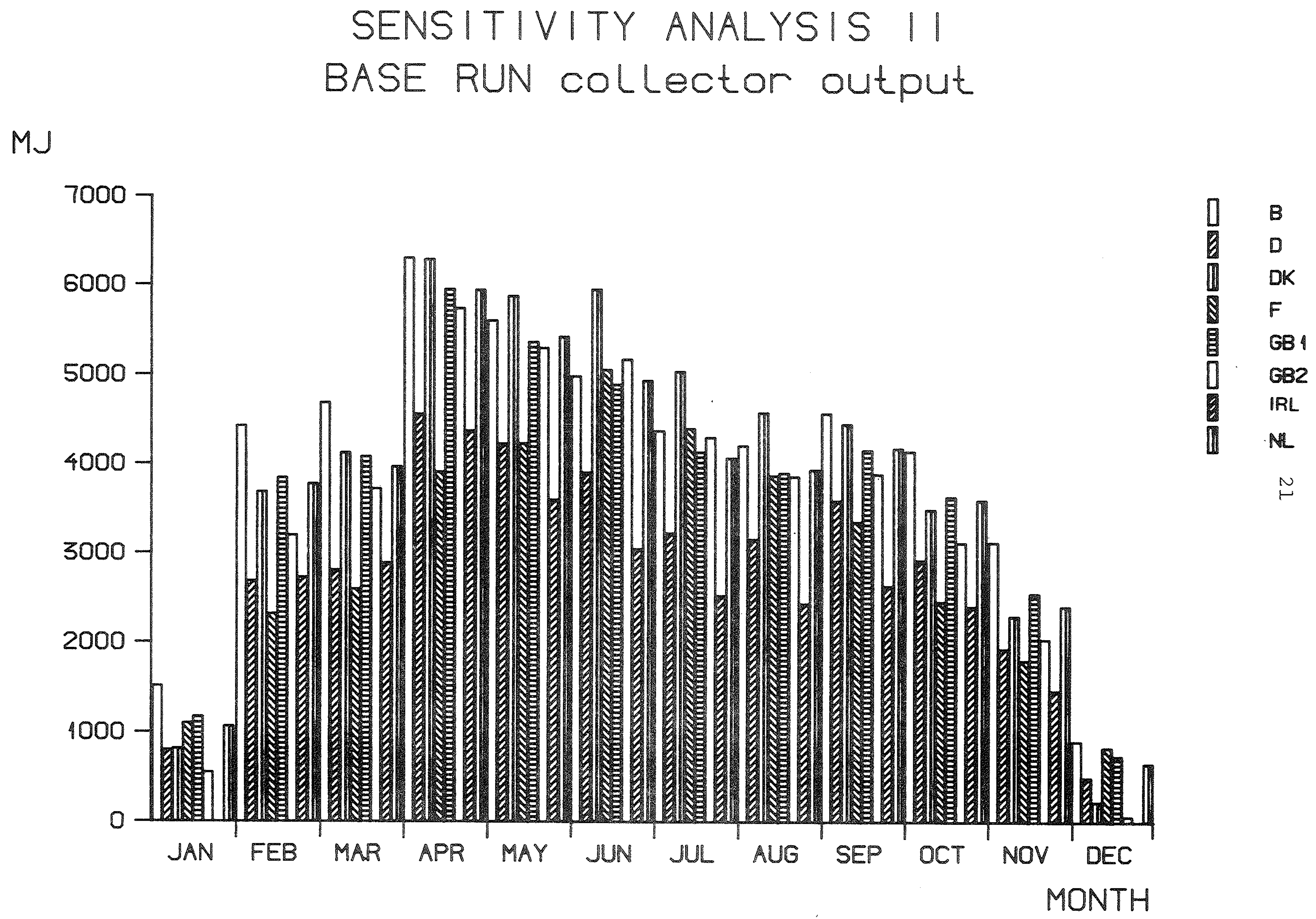

Fig. 3.1 Sensitivity analysis II.

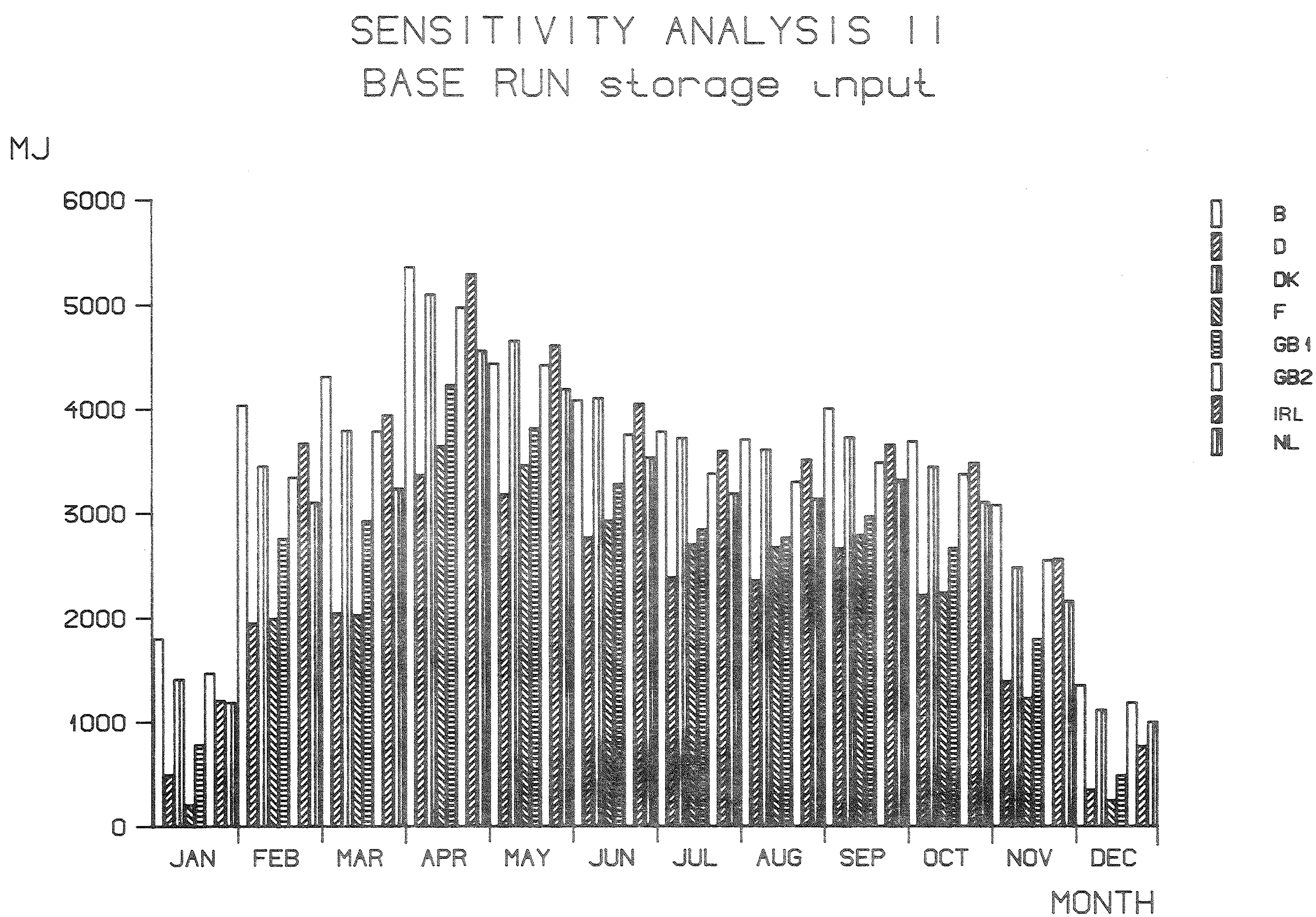

Fig. 3.2 Sensitivity analysis II.

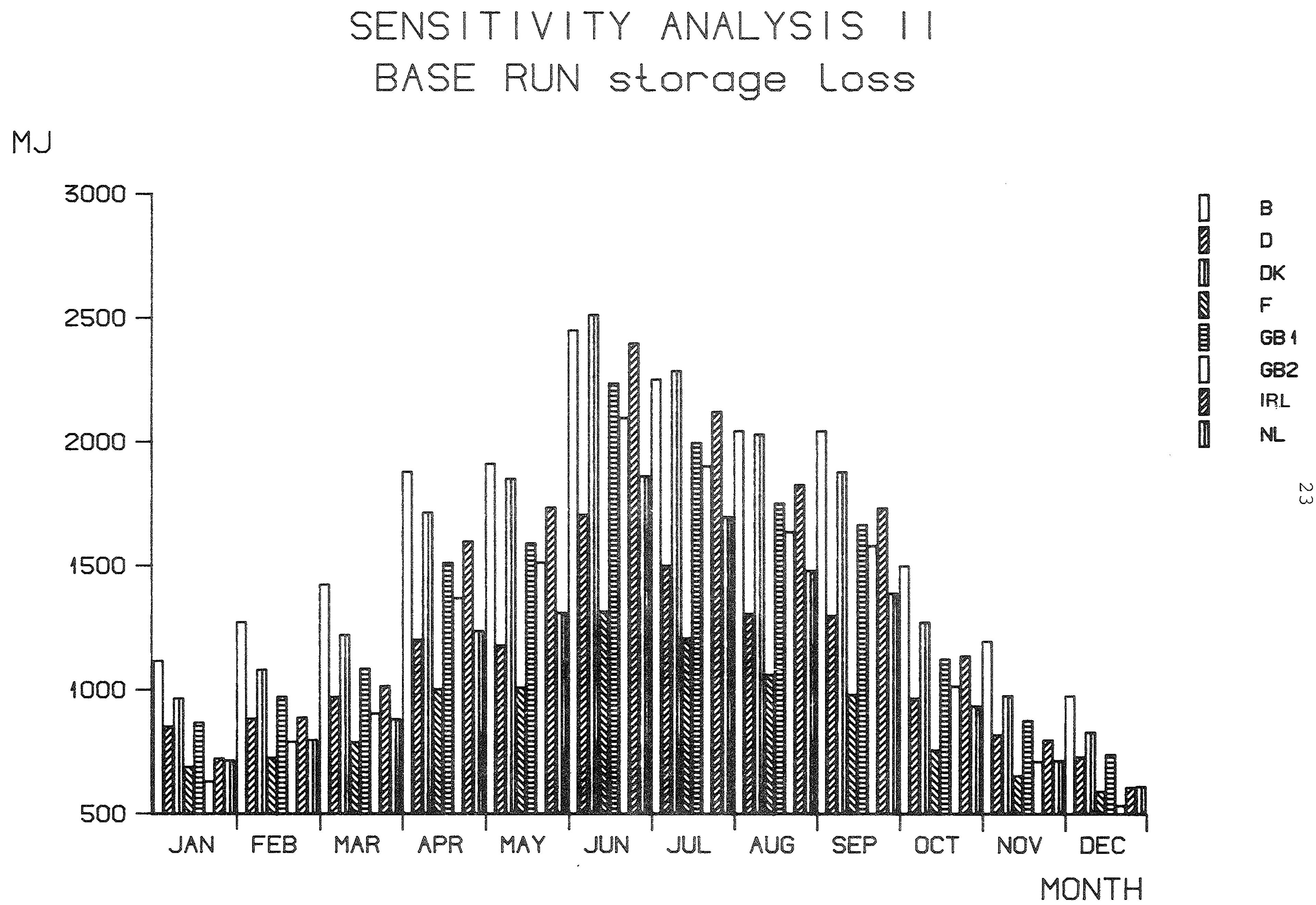

Fig. 3.3 Sensitivity analysis II.

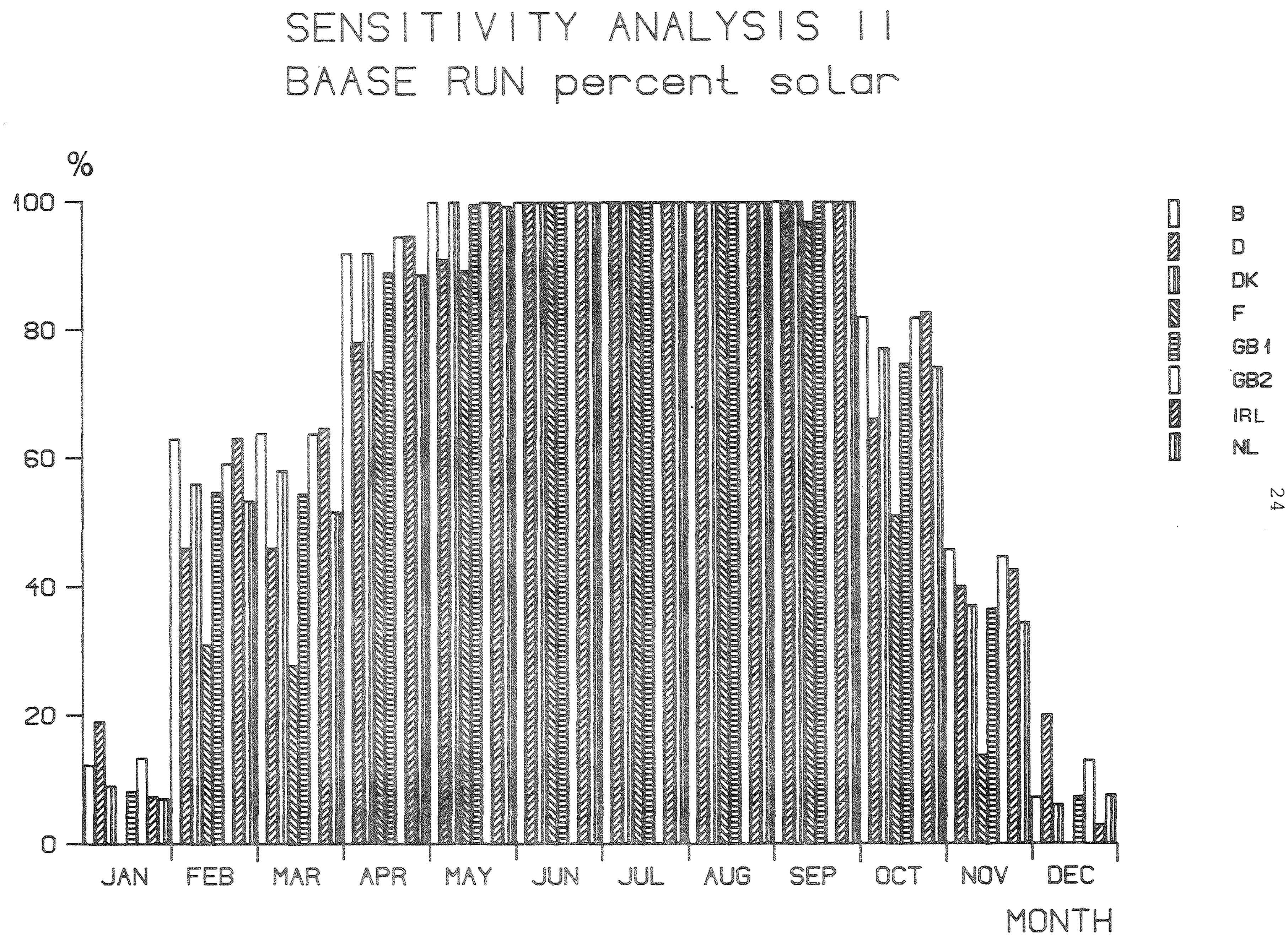

Fig. 3.4 Sensitivity analysis II.

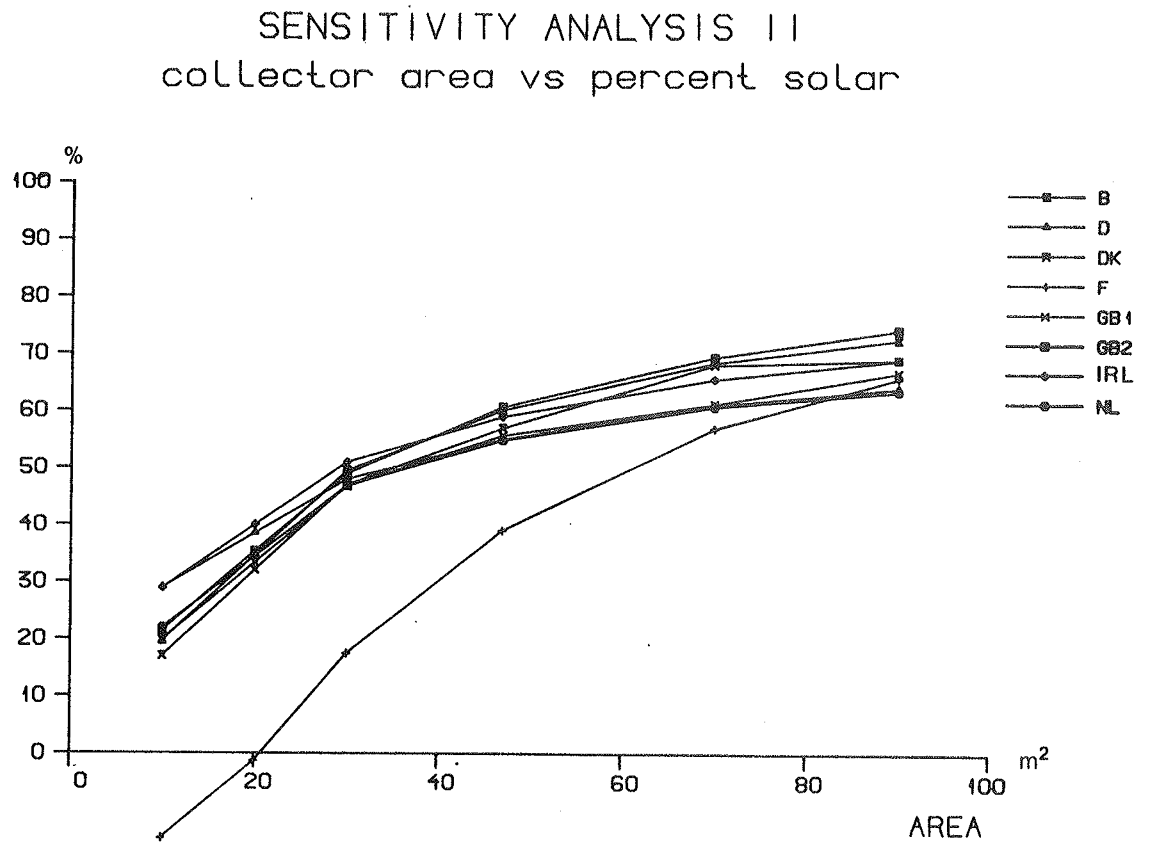

Fig. 3.5 Sensitivity analysis II.

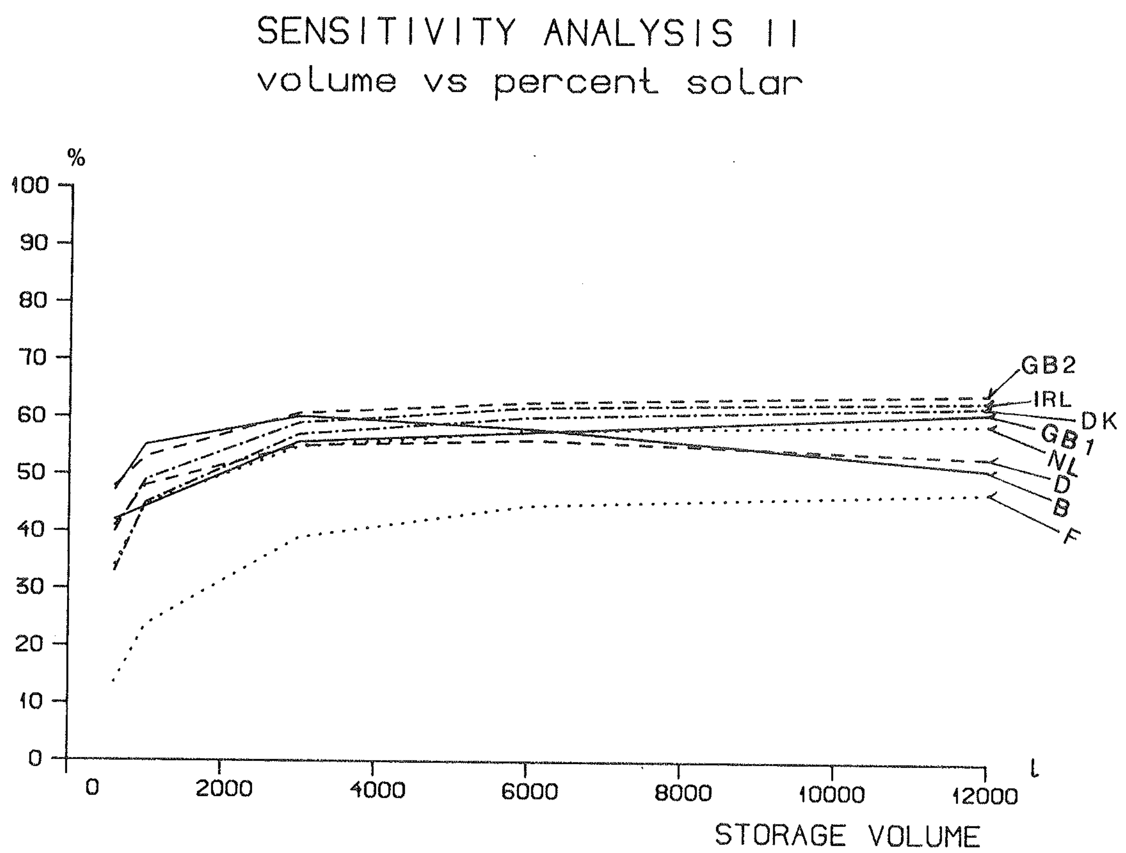

Fig. 3.6 Sensitivity analysis II.

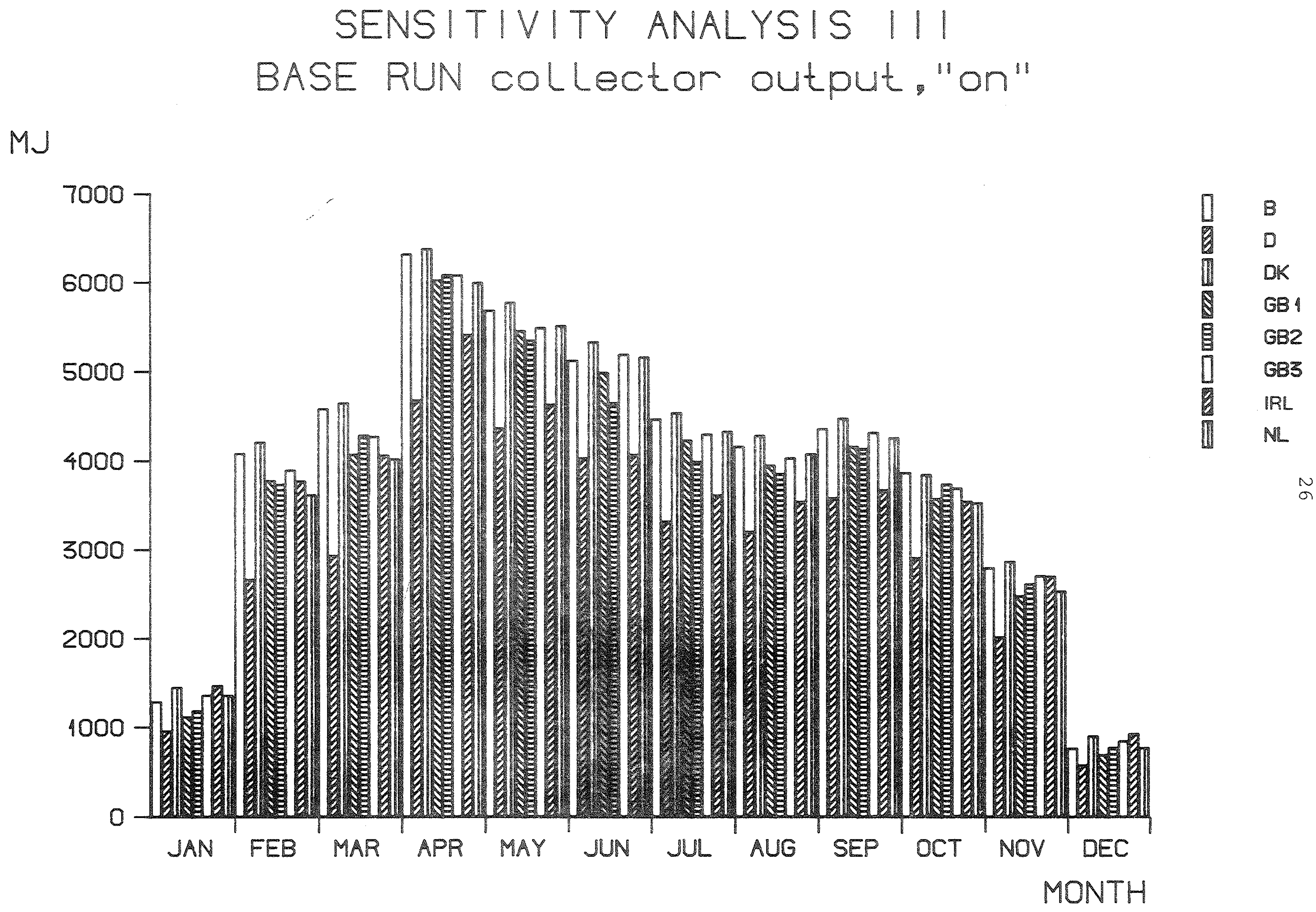

Fig. 3.7 Sensitivity analysis III.

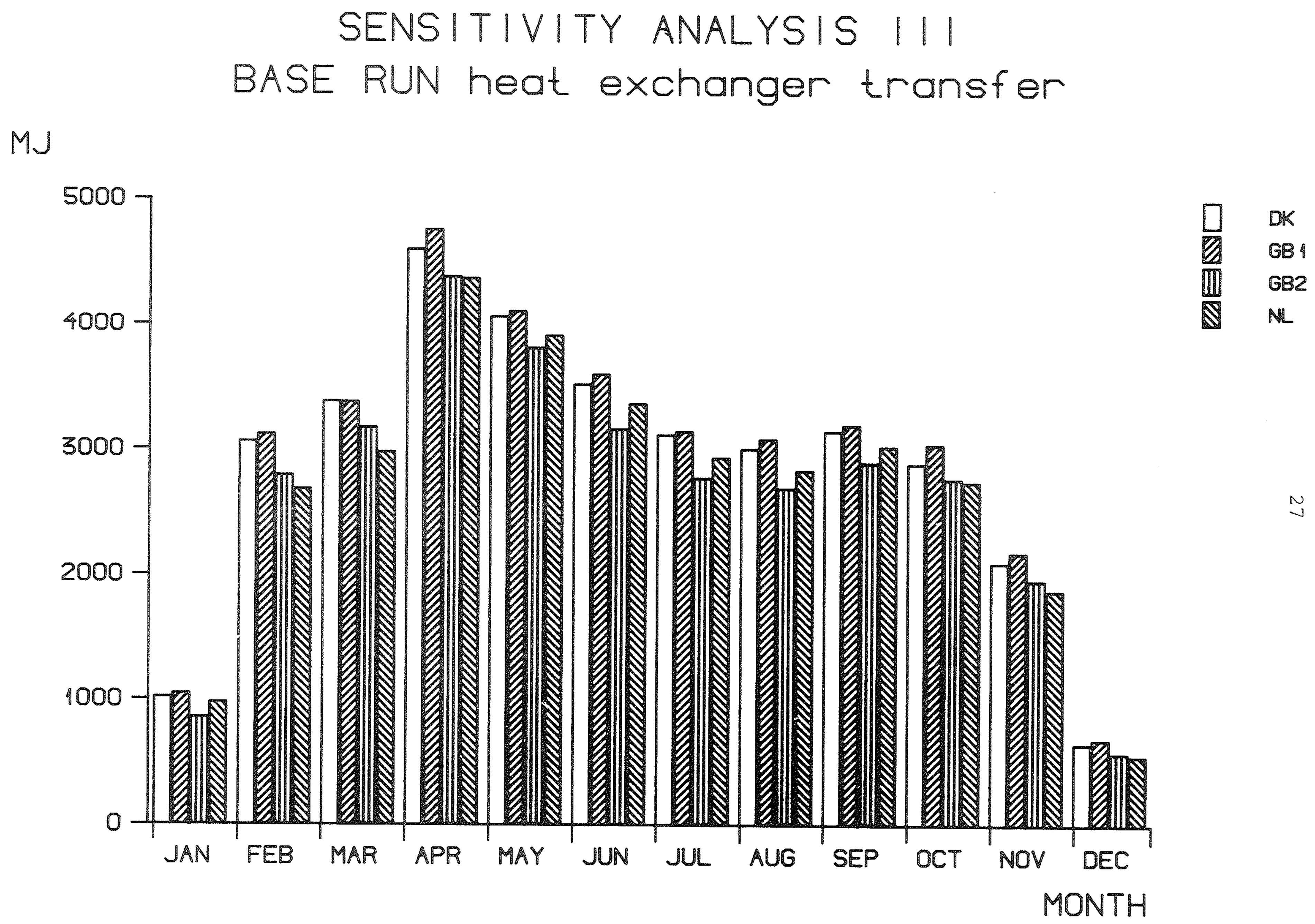

Fig. 3.8 Sensitivity analysis III.

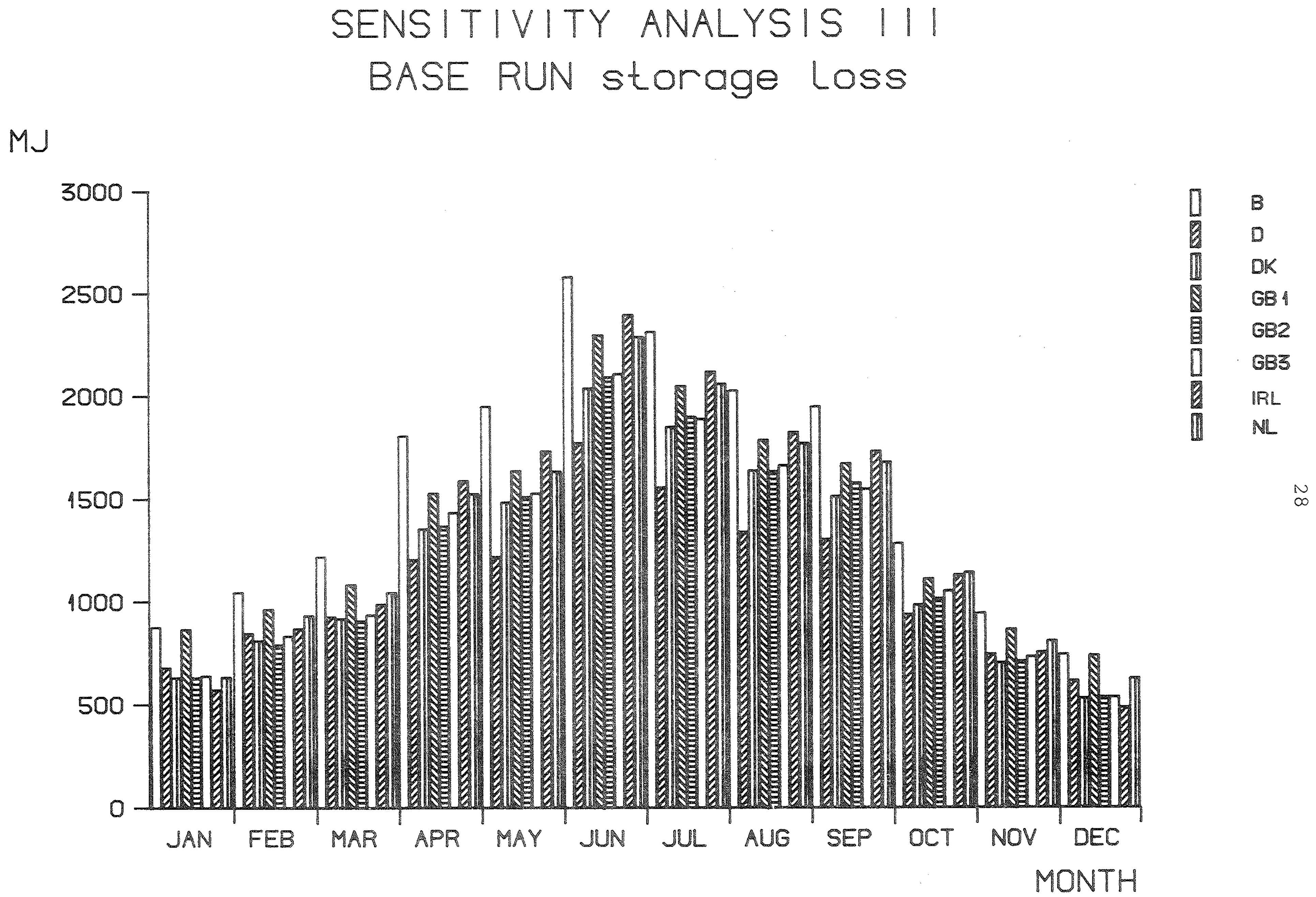

Fig. 3.9 Sensitivity analysis III.

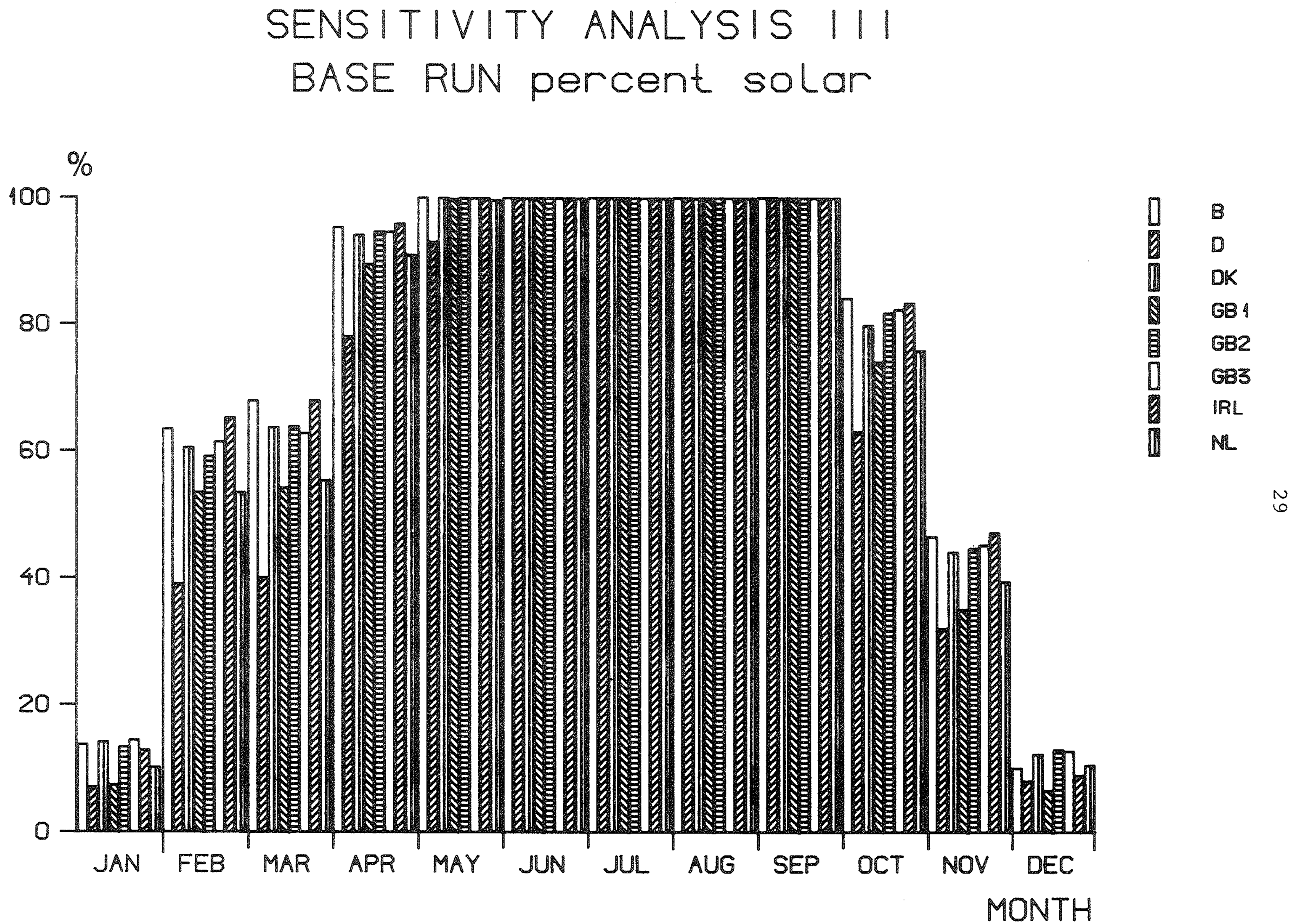

FIG. 3.10 Sensitivity analysis III.

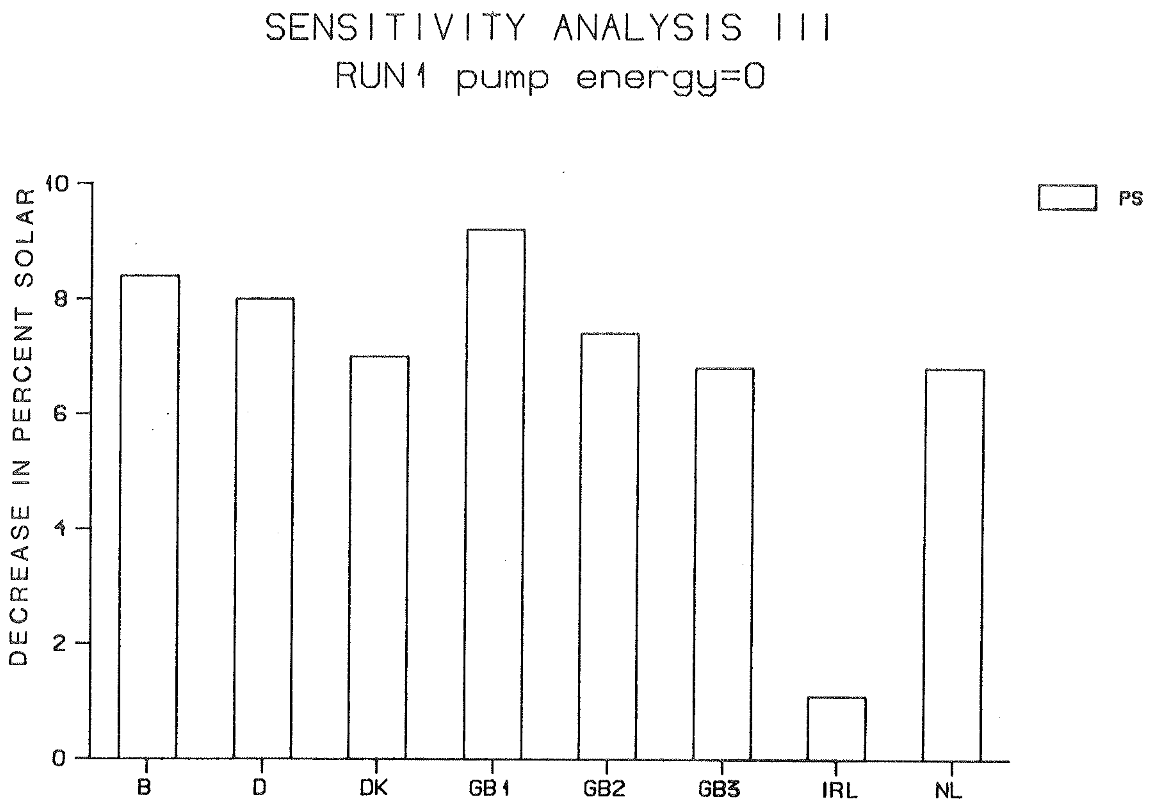

Fig. 3.11 Sensitivity analysis III.

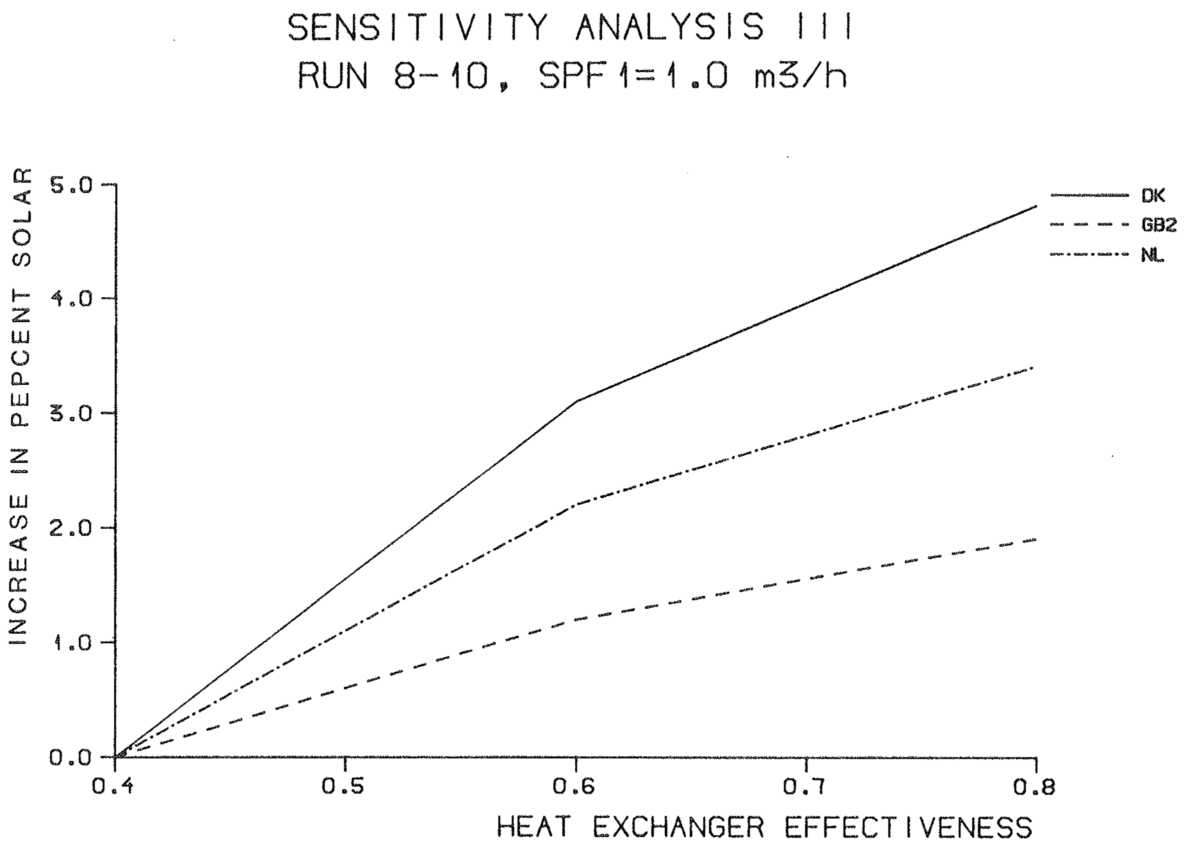

Fig. 3.12 Sensitivity analysis III.

SENSITIVITY ANALYSIS III
RUN 5-7 , SPF1=0.5 m3/h

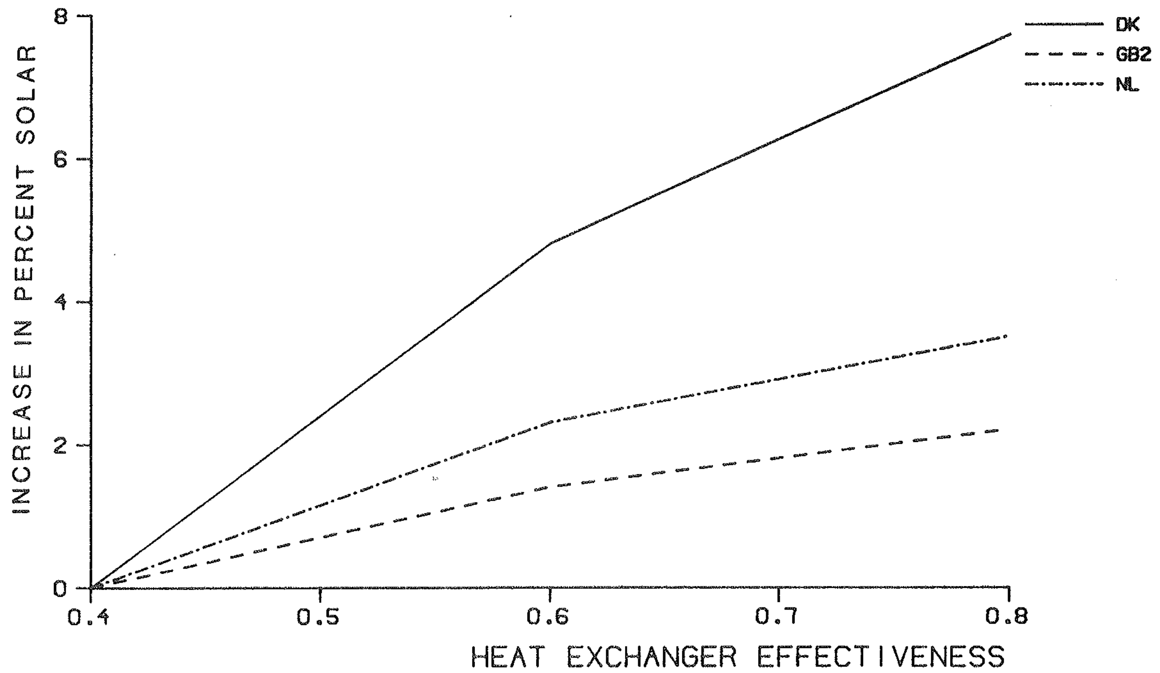

Fig. 3.13 Sensitivity analysis III.

SENSITIVITY ANALYSIS III
RUN 11-16 stratification

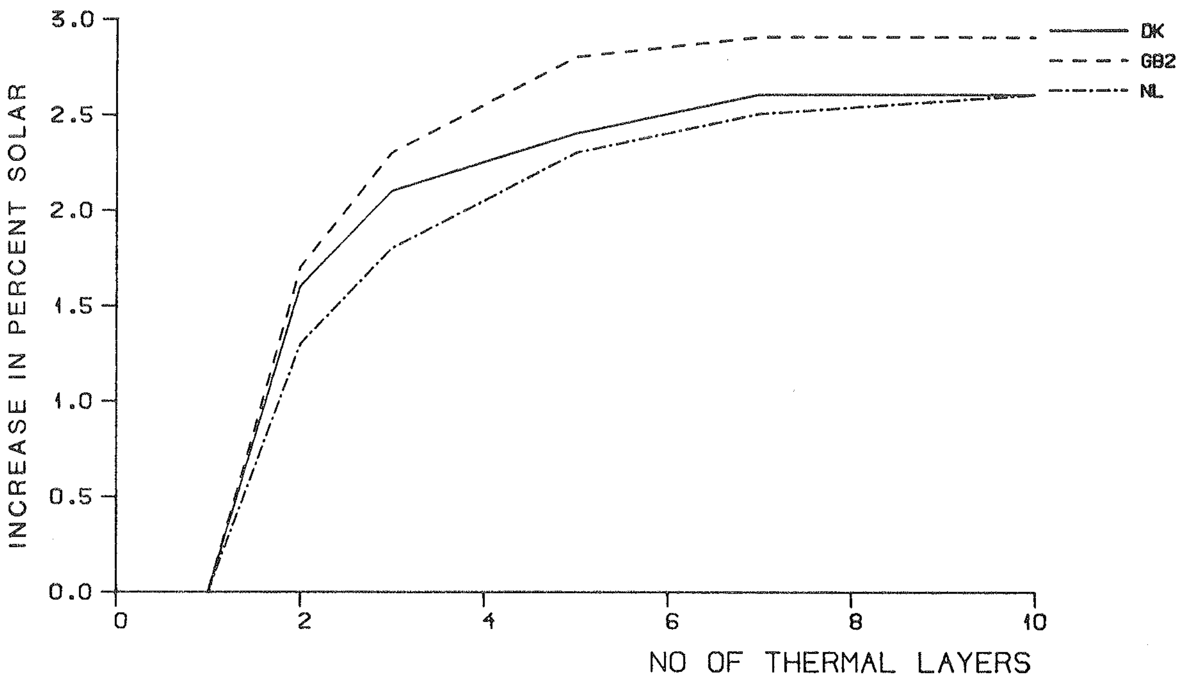

Fig. 3.14 Sensitivity analysis III.

CHAPTER 4

COMMON VALIDATION

4. COMMON VALIDATION

4.1 Description of the activity

The phrase "Common Validation" was chosen to describe this activity of the group which takes advantage of the high degree of similarity between the Solar Pilot Test Facilities in the participating countries. This similarity makes it very easy to simulate, in principle, all the other Solar Pilot Test Facilities as it is almost only a case of changing parameters, when the system model has once been made. Naturally, this also means that it is relatively easy to use all the models to simulate one of the Solar Pilot Test Facilities and compare the predictions of the models to measured data from this facility. This is exactly what was done under this activity.

Two sets of continuous data from two different Solar Pilot Test Facilities were distributed to be used by all the participants for the validation of their models. Compared to the national validation work this approach had certain advantages:

- Some participants could begin their validation work even before their national Solar Pilot Test Facility produced useful data.
- The data had to some extent been checked by one participant before the other participants began working with them.
- Each model was validated against data from at least two different systems.
- The distributed data were in this way double checked.

A disadvantage of using data from another country for validation purposes is, of course, not having the possibility of direct interaction with the system if a problem occurs. Another problem could have been the transfer of data from one system to another, but neither of these problems seemed to create severe difficulties.

The data distributed were 14 days of hourly data from the Danish Solar Pilot Test Facility from February/March 1980 and one month of 5-minutes data from the Belgian Solar Pilot Test Facility from March 1980. The results presented here are a summary of the results produced by the participants The selection is done with the main emphasis on showing an overall picture of the different approaches and the results obtained by the different participants. Therefore, it is not a country-by-country presentation and the selection of figures and tables should not be taken as a reflection on the quantity and quality of the work of the different participants.

4.2 Common validation on data from the Danish SPTF installation

A magnetic tape with hourly weather data measured at the Solar Pilot Test Facility and the predicted hourly load data on the basis of the weather data mentioned above was prepared and distributed by the coordinator. Along with the magnetic tape was sent an installation descriptor for the Danish system 1.

Six of the M2 participants have presented their results on these data. The models used by these participants were B, D, DK, GB1, IRL, N. The validation effort by these participants encompasses component validation, system validation and system parameter "fitting" and the combination of these. The results are presented both as graphical plots which show how well the predicted dynamic behaviour of the system corresponds to the measured, and tables which show how well the predicted and measured energy flows compare.

Component validation

The advantage of component validation in relation to overall system validation is that errors in the model for the modelling of other components have no influence on the investigated components, because measured data for the actual time step are used as input data for the component in question. Thus the computed values for the component give only information about the instantaneous behaviour of the component and not on accumulated errors. Since a component is treated in isolation this approach can be used for the estimation of correct parameters.

Three of the participants have presented results on component validation: B, D, and IRL.

The three component subroutines in question for component validation on the Solar Pilot Test Facility system 1 are the routines for the solar collector, the pipes and heat exchanger and the storage. Fig. 4.1 shows a comparison of calculated and measured temperature difference across the collector. A similar plot can be found in ref. 13. In both cases the agreement between measured and calculated values can be characterized as very good. The German participant performed isolated runs with the pipes and heat exchanger subroutine and concluded from these calculations that the stated efficiency of the heat exchanger was too high, which in the calculations resulted in too much energy being withdrawn from the primary circuit compared to the measured results. In a total system calculation this resulted in the prediction of too high storage temperatures. The Belgian and German participants also performed calculations with a storage routine and found that the calculated storage losses were too small, which could be caused either by an underestimated heat loss coefficient or by an overestimated constant temperature of the surroundings. The latter temperature was not given on the data tape and a constant value of 20^{o}C were assumed by the participants. In fact, for the period in question, the temperature varied between 16 and 17^{o}C, which shows that this approach can lead to sensible conclusions. More results on component validation are presented in the next paragraph and in chapter 5.

System Validation

When performing complete system validation the two dominant issues of interest are:

1. How well is the dynamic behaviour of the system simulated?
2. What is the impact of accumulated errors?

The dynamic behaviour of the system is expressed by the evolution of the state variables, the temperatures, and is therefore best presented in graphical plots. Fig. 4.2 - fig. 4.8 constitute a small but representative sample of the total amount of plots produced by the participants for the comparison of the predictions of their models to the measured data from the Danish PTF. Fig. 4.2 - fig. 4.5 show typical temperature plots for the storage and the collector. As is seen from these plots the prediction of the dynamic behaviour of the system is very good. The separation of the temperatures on the last day of fig. 4.2 is caused by a malfunction of the system. This is an illustration of an important aspect of validation work, which is too often overlooked; it can provide a very effective check on the functioning of a system.

Two of the figures illustrate an attempt of parameter estimation by validation. In this case some uncertainty existed on the temperature of the surrounding of the storage, ILT. Fig. 4.4 shows a comparison of predicted and measured storage temperatures, assuming ILT = $20^{\circ}C$. The difference between predicted and measured storage temperature increases during the first 7 days which most obviously could be caused by the prediction of low storage losses, which again can be caused by either too small a loss coefficient for the storage or too high a value of ILT. The latter has been lowered $5^{\circ}C$ to $15^{\circ}C$ on fig. 4.5, which seems to be a much better estimate for this temperature. The actual temperatures for this period were between $16^{\circ}C$ and $17^{\circ}C$.

The impact of accumulated errors shows up in the comparisons of energy flows. Fig. 4.6 - 4.8 are typical plots of measured and predicted energy flows, collector output and storage input. Again a very good agreement on the dynamic response of the system is observed and at first sight the agreement between absolute values of these flows day by day also seems satisfactory. The resolution, however, on these plots is not really high enough to judge this. Tables 4.1 - 4.2 have therefore been compiled from the tables presented in the individual reports of the participants in order to provide a basis for a more detailed evaluation.

Table 4.1 Common Validation, Danish SPTF
COLLECTED ENERGY, MJ

Date	Meas.	D	DK	GB1	N
March 1	351	369	346	356	356
March 2	188	210	166	198	185
March 3	230	267	205	256	206
March 4	379	418	342	410	342
Total	1148	1264	1059	1220	1089

Table 4.2 Common Validation, Danish SPTF
STORED ENERGY, MJ

Date	Meas.	D	DK	GB1	N
March 1	289	270	295	267	290
March 2	147	142	140	134	150
March 3	166	166	158	168	165
March 4	295	293	277	294	268
Total	897	871	870	863	873

The values of integrated collector output presented in table 4.1 do not contain the negative values of collector gain during nighttime, mainly because most of the collector subroutines do not handle this situation very well. The results of the Danish model, however, have only been presented as net energy gain, and to compare to the others approx. 10 MJ per day should be added to exclude the nighttime losses. The predicted total energy output of the collectors for this 4-day period ranges between 5.1% below to 10.1% above the measured value. It should be noted that the measured value includes the losses of the sections of pipes between the collectors and the sensors which are quite substantial in this system. The predicted energies do not account for these pipe losses and have therefore a small positive bias (5-10 MJ/day) in relation to the measured value.

From table 4.2 is seen that the total amount of stored energy predicted by the four programs for the period in question varies between 2.9% and 3.8% below the measured value. This seems like a reasonably good agreement, but on a closer look much larger differences are observed on a daily basis. In both tables differences in the order of ±10% can be found for the daily values.

The fine agreement in the net results (total stored energy) indicates that a simple accumulation of errors does not take place. This can, however, also be the effect of the errors balancing each other because of the interaction of components in the system. This is a consequence of the negative feedback mechanism in the solar system which, to some extent, prevents accumulation of errors.

4.3 Common validation on data from the Belgian SPTF installation

For this second part of the common validation work a selected period of data from the Belgian SPTF were used. The data constituting one month of 5-minutes data, were distributed on magnetic tape along with the installation descriptor for the system (see Appendix 1). The models validated on these data were: B, D, DK, F, GB1 and N.

The fact that these data were given at 5-minutes intervals was exploited by two of the participants to investigate the impact of the choice of simulation time step. The approach was taken for the models D and GB1. Two of the participants, B and D, have performed component validation and three have tried to obtain better agreement by parameter adjustment, B, D and F.

As the Belgian participant presents his work on these data in the context of his national validation work, his results on these data are discussed in the following chapter.

Component validation

The German participant chose to divide the system into three components: The collector, the pipes and heat exchanger, and the storage.

From the first comparisons of the collector output it appeared that the collector model was dynamically too slow resulting in a calculated net* collector gain 17% less than the measured. This difference was reduced to 1% by making the following parameter changes:

- Absorptance of cover = 0.04 instead of 0.084
- Emittance of absorber = 0.18 - " - 0.30
- Collector efficiency = 0.98 - " - 0.95

Although the use of these parameters made the calculated net collector output agree very well with the measured value, the agreement on gross collector outputs was still not satisfactory. The difference for the period was changed from 30% to 21%.

* valve in the primary circuit in the heat exchanger position

The comparisons on the pipes and heat exchanger show that the predicted collector inlet temperature is too small and the predicted storage temperature too high, when the collector supplies energy to the storage. This indicates that the heat exchanger effectiveness is overestimated. When no energy is delivered from the collectors to the storage the comparisons show that the measured integrated energy flow to the storage is higher than that calculated; this was taken as an indication of too small an estimate of pump power delivered to the fluid. Consequently the following changes were made and gave better agreement:

- efficiency of heat exchanger = 0.32 instead of 0.44
- pump power delivered to the fluid= 70 % - " - 50%

The calculations with the storage model alone gave satisfactory results and no parameter adjustments were needed.

System validation

Five of the participants have presented their results in both tabular and graphical forms (table 4.5 and fig. 4.9 are typical examples). On the basis of the tables the results obtained by these participants on this same data set can be compared. In table 4.3 the predicted storage input for 4 selected days and for the whole 30 day period are shown as a percentage of the measured storage input.

Table 4.3 Common Validation on Belgian Data
STORED ENERGY, PRED./MEAS., PERCENTAGE

Date	B ***	D **	DK	GB1	N
March 22	-	125/107	101	121	78
March 23	-	135/104	101	105	86
March 24	-	135/103	104	105	92
March 25	-	134/109	116	106	111
Mean *	101.3	119.6/100.2	101.8	113.2	92.5

* for all 30 days
** initial parameters/changed parameters
*** changed parameters

It should be noted that the results obtained with DK, GB1 and N have been calculated on the basis of the distributed installation descriptor, whereas the results obtained with B is calculated using the set of parameters found by component validation. For D both sets of results are presented. It is almost impossible to conclude anything on the basis of these numbers except that they show that the variations day by day are rather large and also that the variations among the models are very large. It is striking that the four codes using exactly the same input parameters predict 92.5, 101.8, 113.2 and 119.6 % of the measured storage input, a variation of 25%! This table illustrates the necessity of comparing predictions and measurements of integrated energy. If this is not done a graphical comparison of temperatures as shown on fig. 4.9 (which is a typical plot produced by the participants) may lead to the conclusion that the agreement is excellent in a case where the integrated energy flows are 13% off.

Parameter adjustments

As mentioned above three of the participants have sought to obtain better agreement by changing some of the input parameters to the model. This, however, is a very delicate matter because many of the parameters are inter-related.

To obtain a better collector performance, for example, the gain can be improved or the losses decreased and there are several ways to do both; and then the collector capacity can be changed. This does not mean that it should not be tried but rather that it should be done with care. In the case of the Belgian SPTF it is interesting to see which parameters the participants found to improve the agreement of the comparisons. In table 4.4 the "improved" parameters are presented along with the original values.

TABLE 4.4 "IMPROVED" PARAMETER VALUES				
Parameter	Original value from ID 1	Value obtained by B 1)	D 1)	F 2)
Storage loss coefficient W/K	15	15	15	5
Heat exchanger effectiveness	.44	-	.32	.35
Specific heat of fluid in primary circuit J/kgK	3873	3622 3)	-	-
Back and side collector loss coefficient W/K	37.55	60.41	-	-
Absorptance of the cover	0.84	-	.04	-
Emittance of the absorber plate	.3	-	.18	-
Collector efficiency factor	.95	-	.98	-
Power from pump to fluid %	50	-	70	-

1) component validation 2) system validation 3) measured

It appears from the table that the French and German participants seek to raise the system output by respectively lowering the storage losses and raising the collector efficiency. Both of them have found that the quoted heat exchanger effectiveness was too high. On the other hand the Belgian participant has found that the original value of the heat exchanger effectiveness is all right and that the collector efficiency has to be lowered by increasing the back and side losses.

This comparison, however, is not very meaningful because the Belgian participant had measured the specific heat of the fluid in the primary circuit to a somewhat lower value than given in the installation descriptor for the system. The measured collector output was then lowered accordingly.

5-minutes vs. 1-hour time step simulation

In the interest of saving computer time, the question of the length of time step to use in the simulation of solar systems is of great interest to modellers. Two of the modellers in the Modelling Group compared the predictions obtained with 5-minute time steps to those obtained with hourly time steps. Both concluded that, although a difference could be observed, it was of no significance for the simulation of this system. It has to be emphazised that the sensitivity to length of time step is very dependent on both system time-constant and on integration technique implemented in the model. In the case of the SPTF the time-constant is rather large which means that long time steps can be used in most models. This is very nicely supported by the results obtained by the German and English participants. This question is further treated in chapter 6.

The treatment of load in SPTF system validation work

The special configuration of the SPTF systems, with a simulated load and an artificial interface to withdraw the fraction of this load as a function of requested distribution temperature in the "heating system", invites a discussion among modellers on how to treat this load, when performing system validation. In the case of the Belgian data, the load was given as measured storage output and not as the required heating load of the simulated house. Therefore the latter could not be used as input for the models, but the storage inlet temperature and capacity flow rate from the interface were given on tape, and opened up a third (in between) possibility, which was chosen by the Danish participant. The impact of using these two variables is that the storage temperature becomes crucial for the amount of energy that can be withdrawn from the storage. In this way the load is treated in a manner similar to a true required heating load without modelling the control on the interface.

When using the measured storage output as a driving force in the model, this amount of energy is withdrawn from the storage whether or not the storage temperature is at a level where it can supply this amount of energy. The impact of this is illustrated on fig. 4.4 where the measured and predicted storage temperature are compared. During the period shown the difference increases slightly, which is an indication of a small underprediction of the system performance. The fact that the storage is forced to deliver more energy than it actually can, makes the predicted storage temperature lower and lower. Had the required heating load been used, implying that the program calculates how much of this can be supplied from the storage, the small underprediction would not have shown up as significantly on the storage temperature as on fig. 4.4, but instead resulted in a smaller fraction of solar.

The advantage of the former approach is that it very distinctly illustrates an accumulated error. The latter is a more realistic calculation and has the advantage that the comparisons are not that much affected by an accumulated error.

From table 4.3 it appears that the Danish participant predicts a storage input 1.8% higher than the measured. This corresponds very well with his prediction of the solar supply to the load which is 2.1% higher than the measured.

BELGIAN PILOT TEST FACILITY.

Validation Results - Daily Integrated Energies (MJ)

Day of year	Solar Radiation	Collected Meas	Collected Pred	Stored Meas	Stored Pred	Load
65	855.8	340.4	353.3	299.1	312.0	73.1
66	80.6	0.0	0.0	0.0	0.0	189.1
67	194.9	2.8	0.0	4.3	0.0	15.5
68	163.3	9.0	8.7	8.4	5.7	-9.9
69	186.1	9.1	15.1	7.0	13.1	9.0
70	229.3	18.6	26.2	16.7	24.6	9.4
71	372.8	128.1	137.5	116.0	125.3	74.1
72	79.8	0.0	0.0	0.0	0.0	39.3
73	166.0	28.9	35.1	25.4	29.0	12.0
74	235.3	17.6	28.0	16.1	26.1	0.1
75	40.9	0.0	0.0	0.0	0.0	-17.1
76	96.7	0.0	0.0	0.0	0.0	1.8
77	284.8	53.9	69.5	49.7	63.1	40.7
78	254.9	34.4	51.4	28.9	44.9	40.2
79	350.3	44.0	66.2	36.9	56.7	-34.6
80	267.4	12.8	24.6	11.2	20.7	-4.9
81	225.3	4.3	8.0	3.0	7.0	-9.3
82	345.8	58.9	73.1	49.5	59.9	38.4
83	566.7	184.7	197.8	163.9	172.5	79.3
84	618.0	204.7	217.1	183.2	191.7	124.7
85	376.4	79.1	90.0	72.3	76.4	118.5
86	525.8	171.9	178.0	154.2	156.6	109.9
87	210.1	37.2	47.9	34.0	40.5	149.9
88	279.9	65.0	90.6	60.0	76.4	51.5
89	76.2	0.0	0.0	0.0	0.0	-3.1
90	563.5	203.7	216.6	179.9	194.1	69.2
91	224.6	23.0	39.8	19.2	29.4	114.1
92	152.8	4.0	9.0	5.5	8.9	42.5
93	444.3	113.2	135.5	96.8	122.8	19.5
94	473.5	114.0	139.2	108.8	123.9	84.9
Totals	8941.	1963.	2258.	1750.	1981.	1428.

Table 4.5 Measured and predicted daily integrated energies(MJ), ref. 10

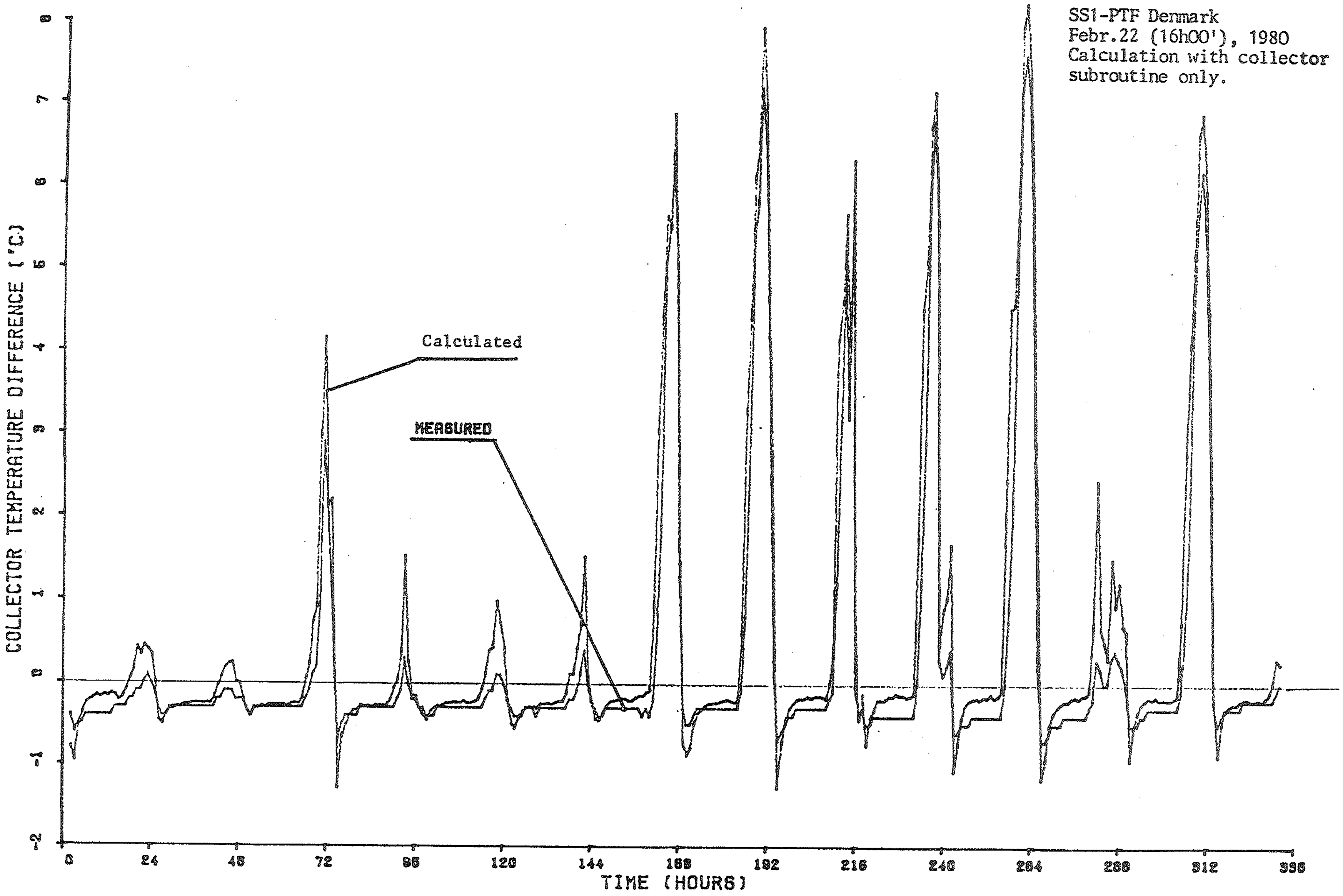

Fig. 4.1 Measured and predicted collector Δt, ref. 6

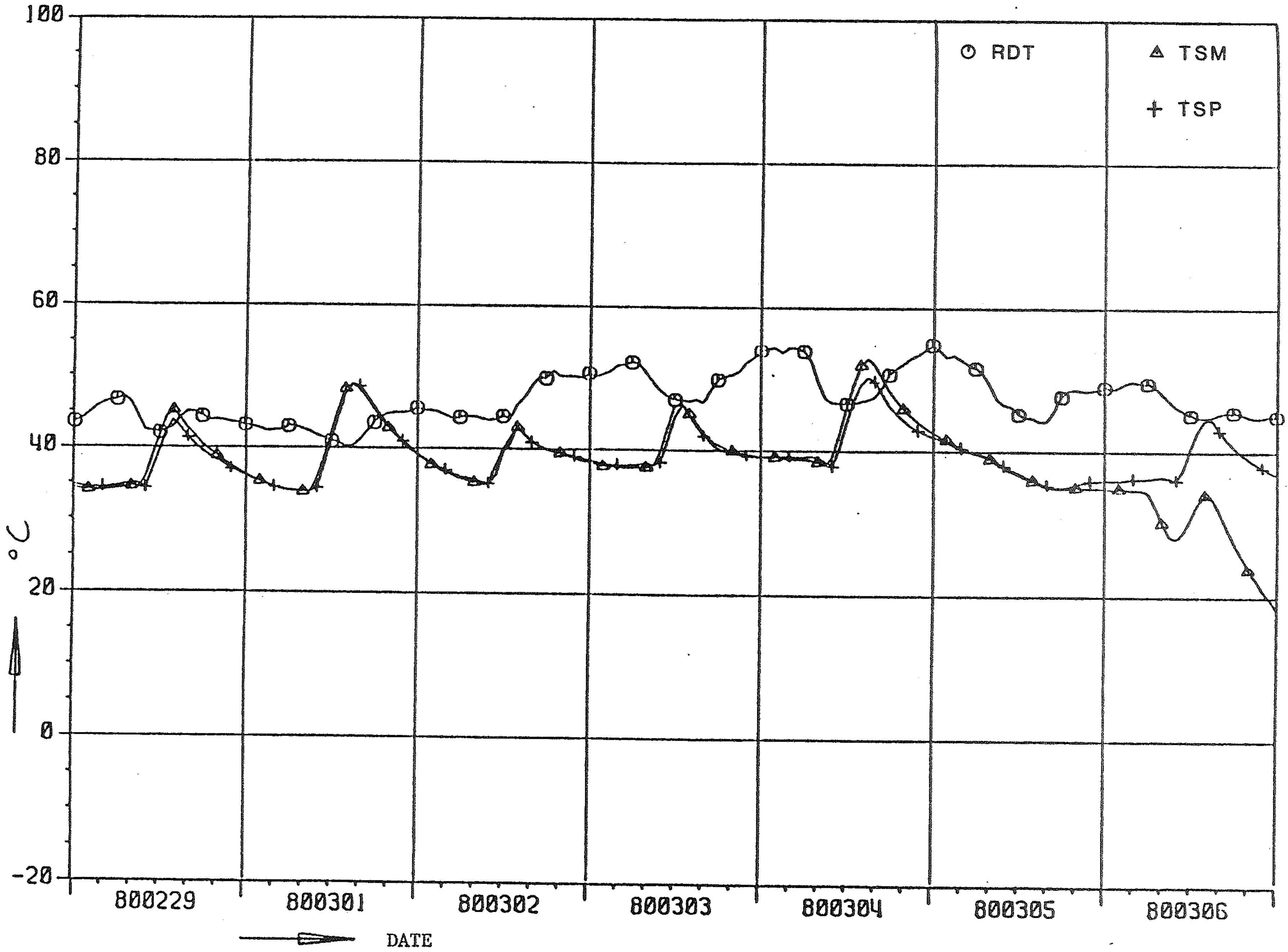

Fig. 4.2 Storage temperature measured versus predicted, Danish PTF , ref. 7

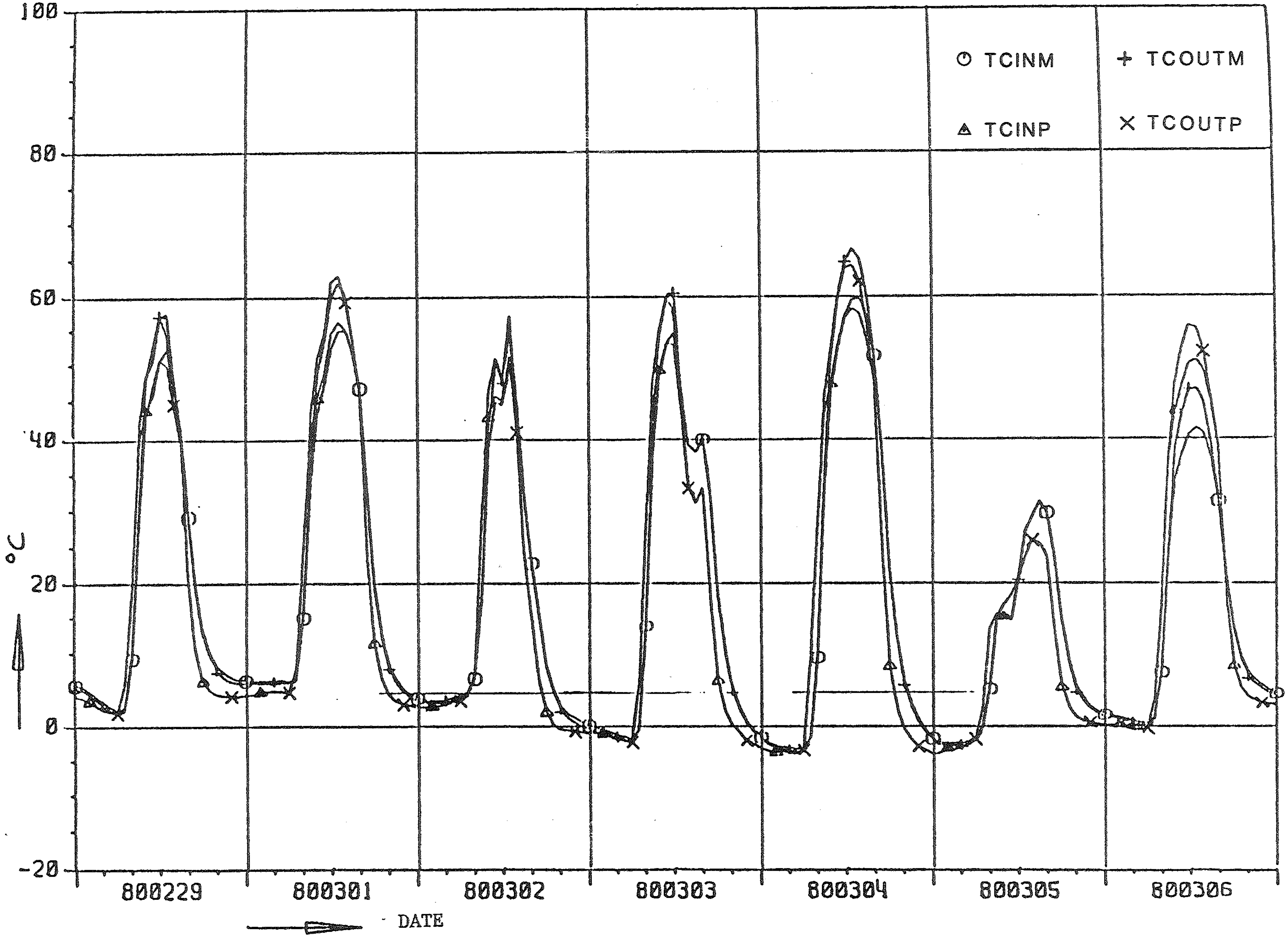

Fig. 4.3 Inlet and outlet collector temperatures, measured versus predicted, Danish PTF, ref. 7

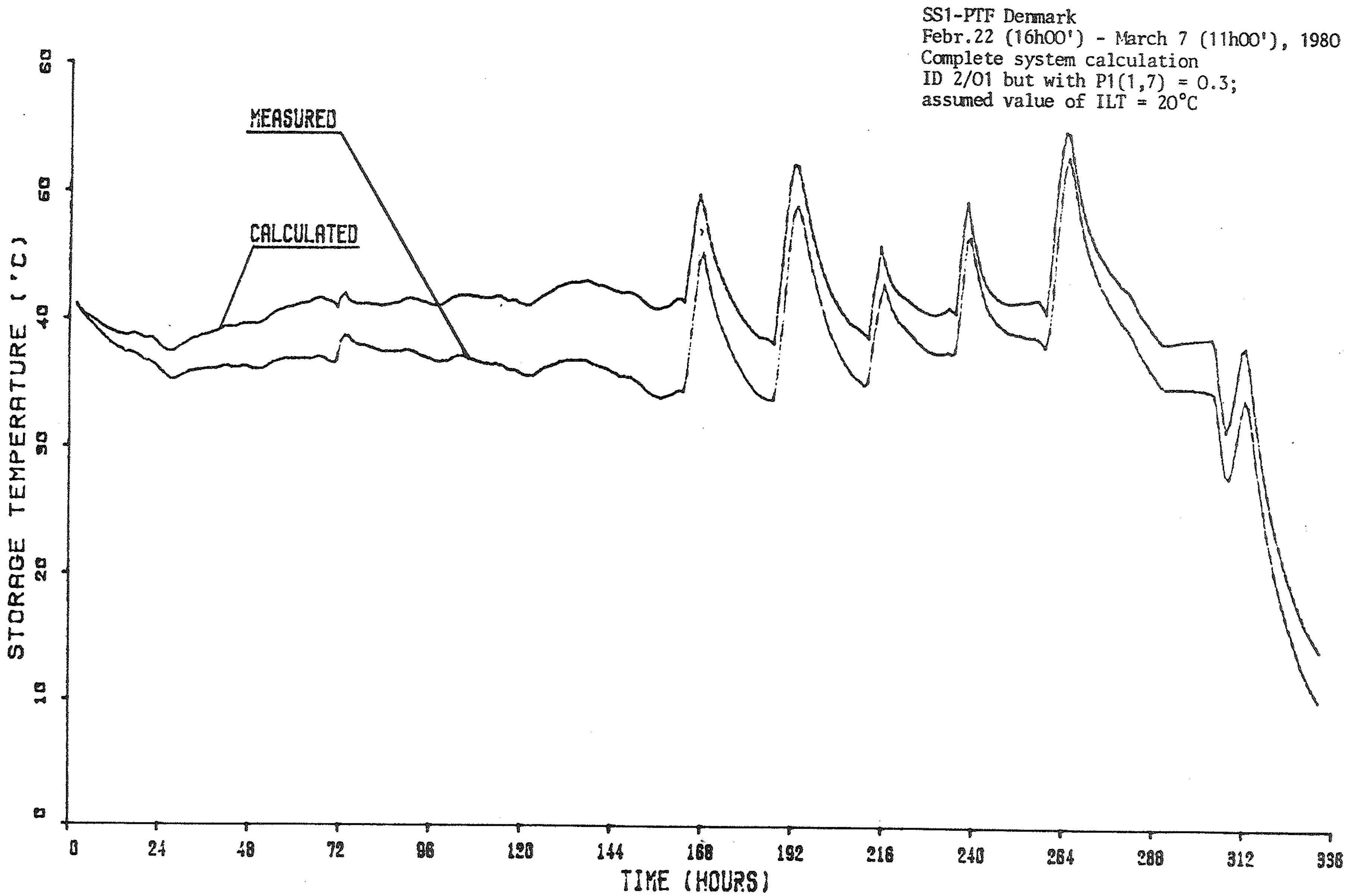

Fig. 4.4 Measured and predicted storage temperature, ref. 6

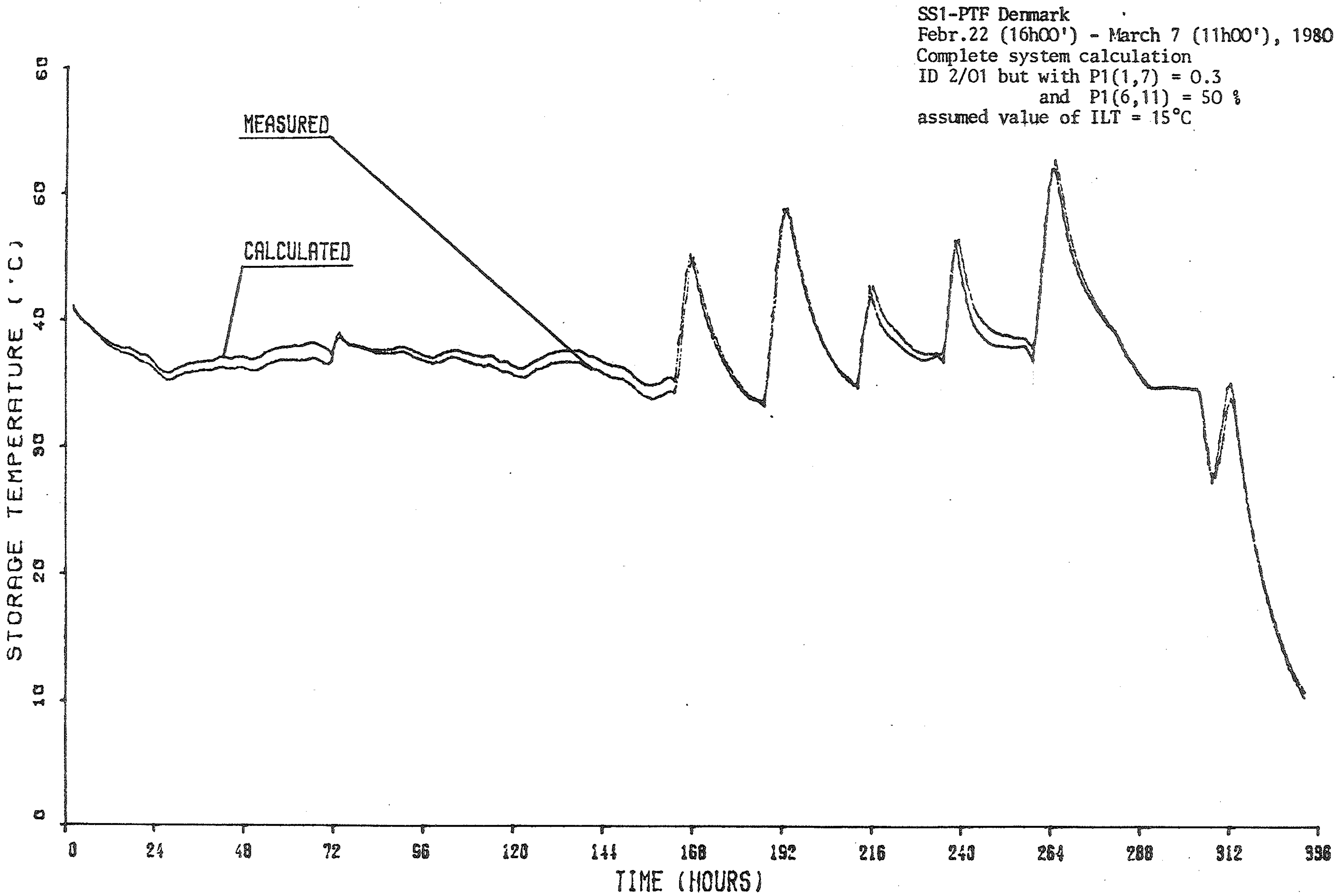

Fig. 4.5 Measured and predicted storage temperature, ref. 6

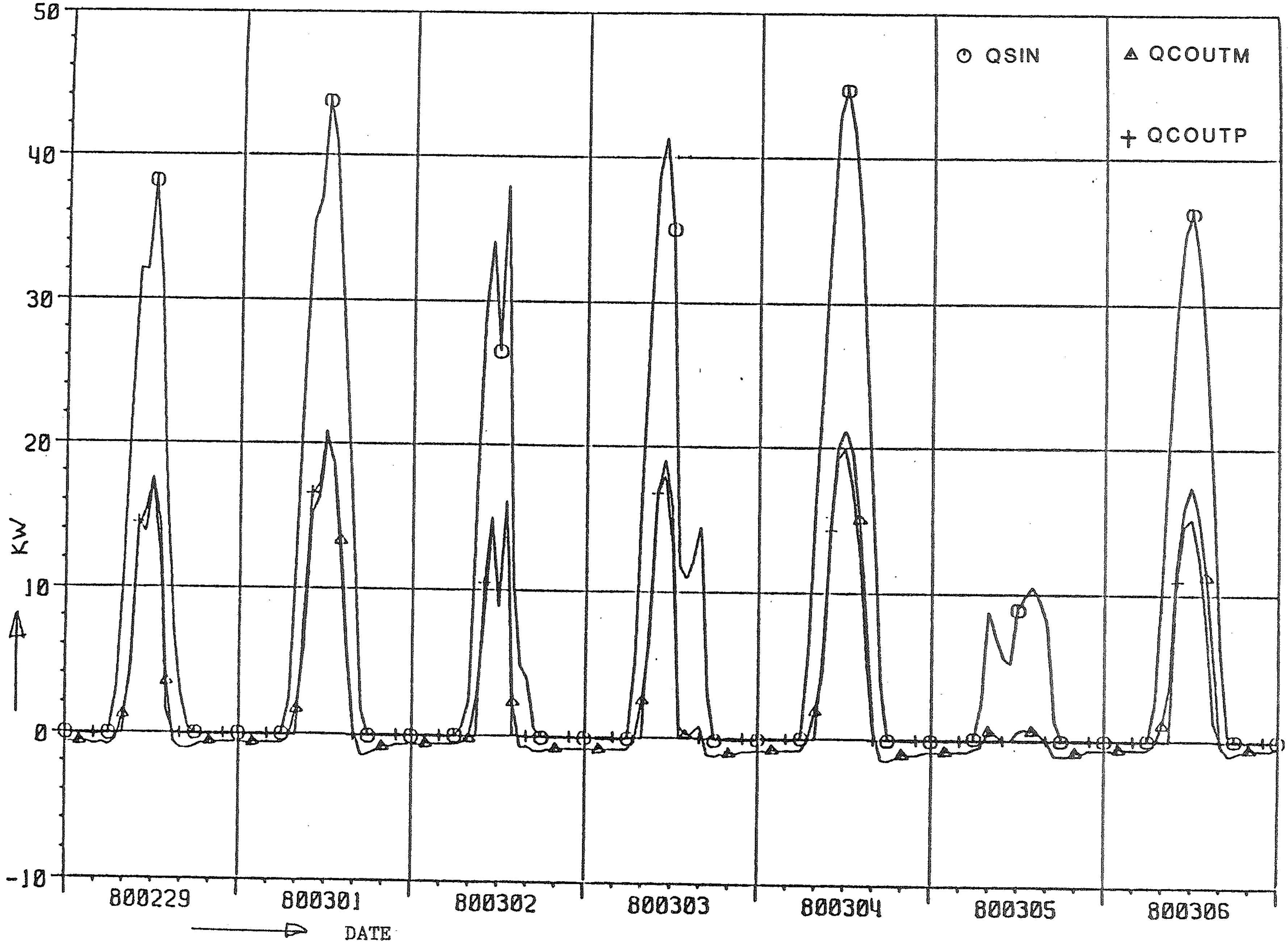

Fig 4.6 The collector output measured versus predicted, Danish PTF, ref. 7

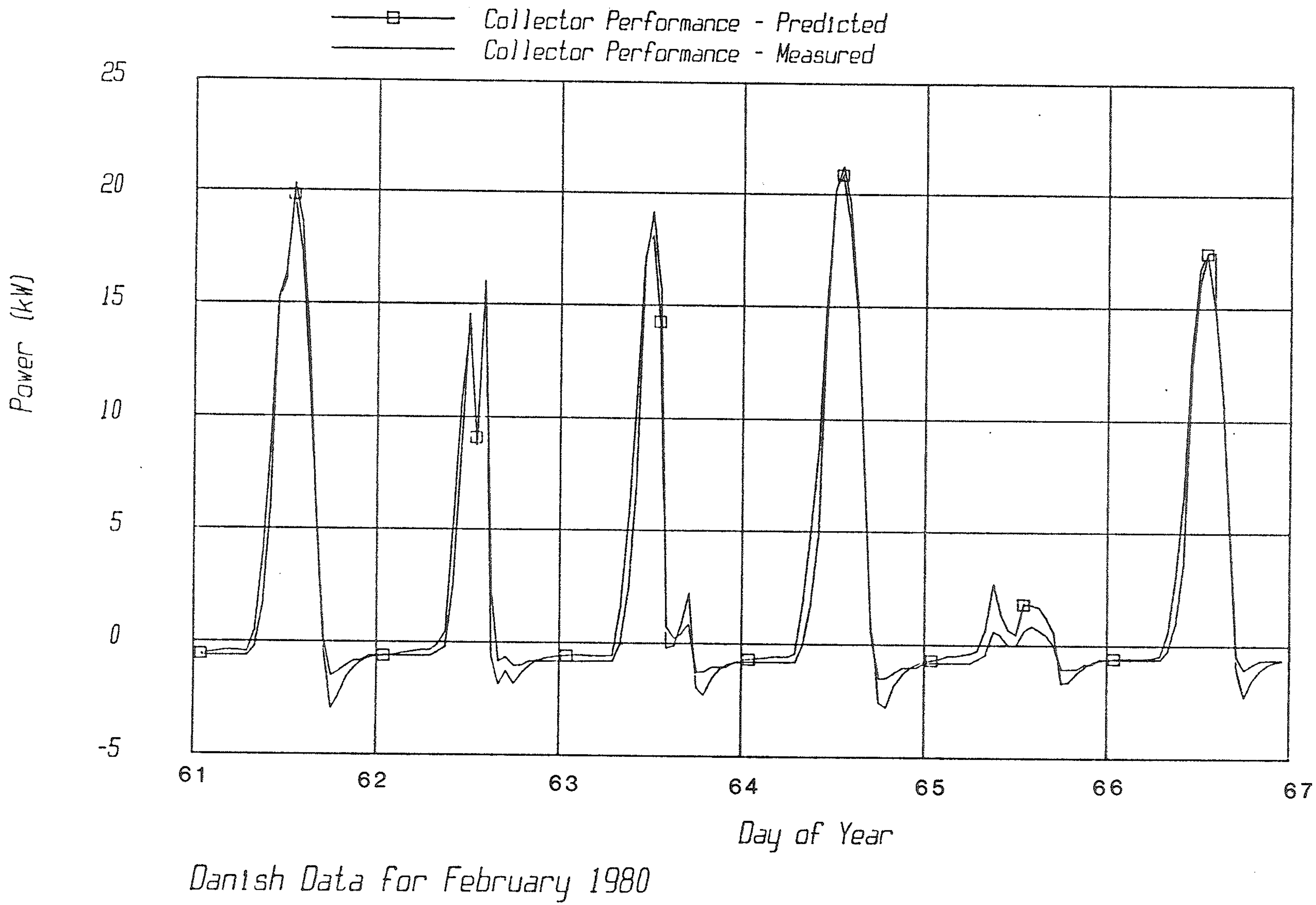

Fig. 4.7 Measured and predicted collector output, ref. 10

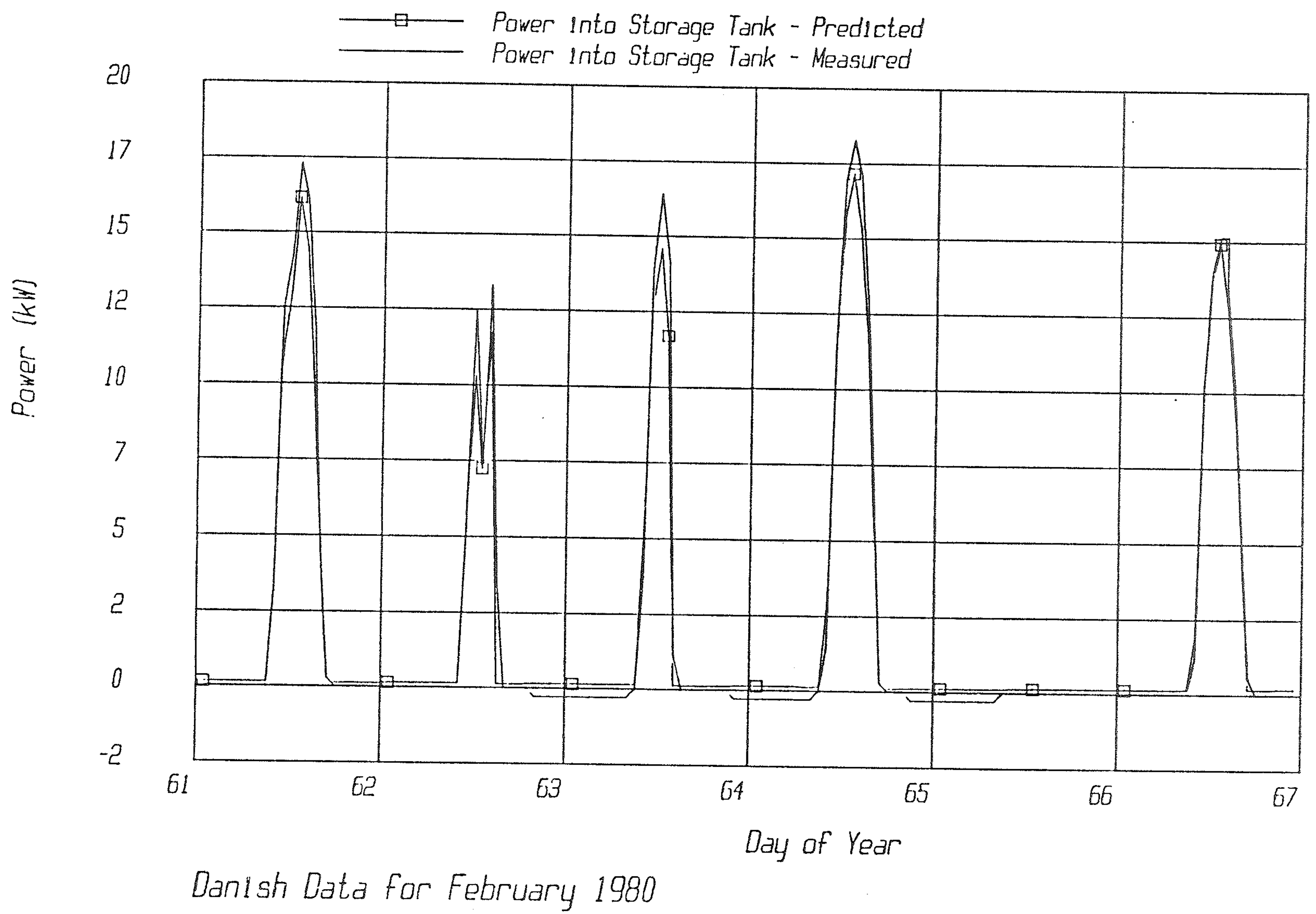

Fig. 4.8 Measured and predicted storage input, ref. 10

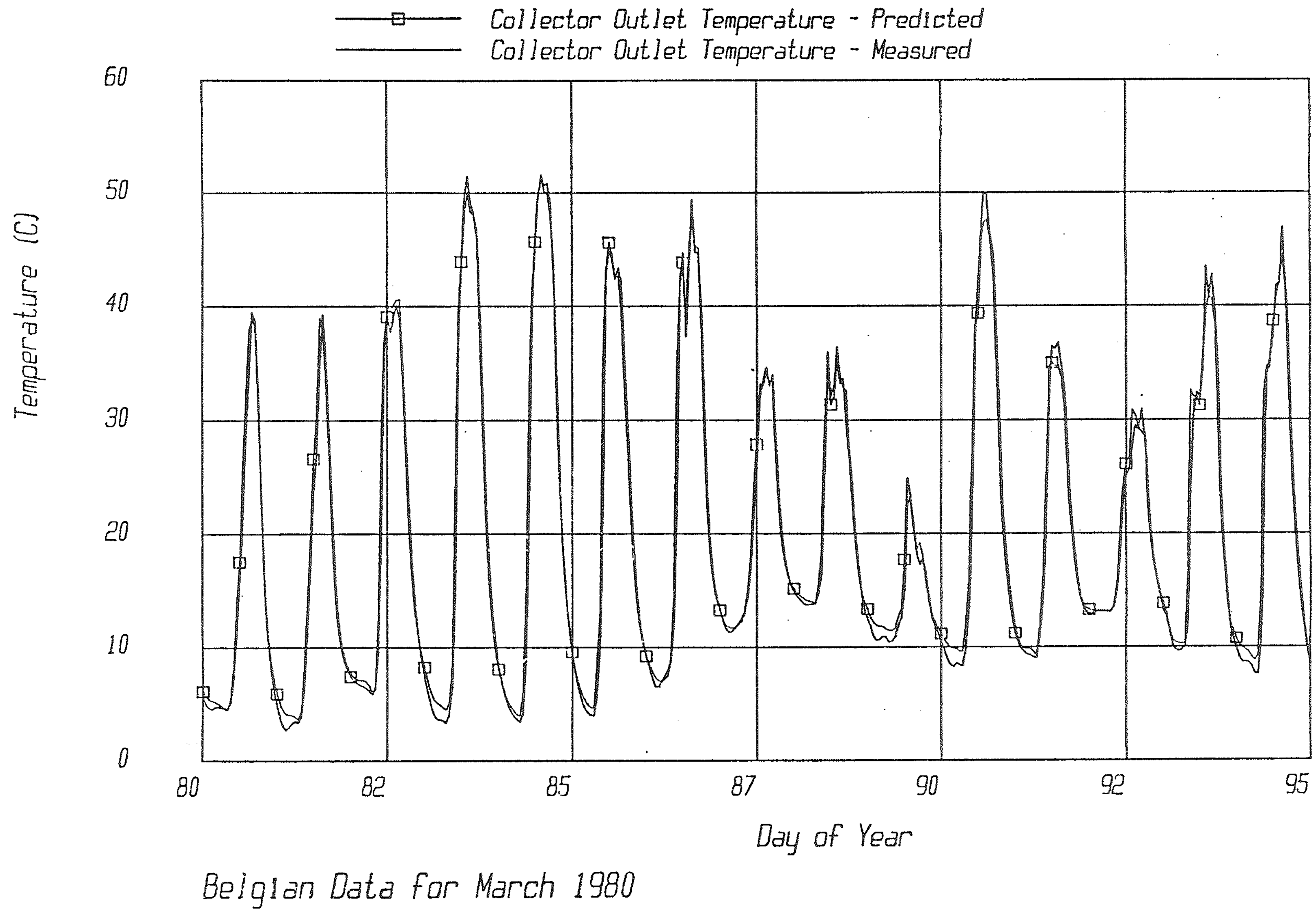

Fig. 4.9 Measured and predicted collector outlet temperature, ref. 10

CHAPTER 5

NATIONAL VALIDATION

5. NATIONAL VALIDATION

5.1 Country by country presentation

The national validation work constituted a considerable part of the work of the Modelling Group participants during the period in question. Each modeller performed data analysis and model validation work on all the data produced by the SPTF SS1 in his/her own country. Since not all the SPTF's were completed at the same time the amount of data produced for validation work differed a great deal from country to country. Six of the eight participants have presented results under this activity. Below a short presentation of the work of each of the six participants is given.

Belgium

The Belgian participant performed national validation work on five sets of data from 1980. The periods are between 13 and 30 days long. In ref. 6 both component and system validation works are documented. All the calculations are performed with a time step of 5 minutes. The primary aim of the component validation work has been to find the correct parameters for the description of the components. The calculations have been performed for all five periods to give a better estimation of the parameters in question. Fig. 5.1-5.3 show a set of curves in order to find the correct value for the tank heat loss coefficient, the collector back and side loss coefficient and the heat exchanger heat transfer coefficient respectively. The expectation was that the curves on each figure intersect the abscissa axis at the same point. This is not the case; on the contrary the spread is rather large. There can be several reasons for the observed discrepancy:

- measured errors and uncertainties
- wrong estimation of other parameters (such as capacities and pump energy dissipation)

The Belgian participant intends to repeat these calculations on new sets of data to obtain a better statistical basis for the estimation of the parameters.

Two pairs of curves from ref. 6 are shown here to illustrate how the choice of parameter values affects the simulation results. Fig. 5.4 and fig. 5.5 show a plot of measured and predicted storage temperatures using storage loss coefficients of 5 W/K and 13 W/K respectively. Likewise fig. 5.6 and fig. 5.7 show the measured and predicted differences between collector inlet and collector outlet temperatures for two values of the collector back and side loss coefficient, 101 W/K and 37.55 W/K respectively. In both cases the agreement between measured and predicted values are significantly improved by changing the parameter.

Germany

The German Modelling Group participant received only one set of data useful for validation work from the German SPTF, (April 3-9, 1980). More data were sent from the SPTF, but most of them represented very short periods of time. No data were produced during a period of more than half a year because of alterations of the system installation, and when data collection was resumed, problems with temperature and insolation measuring equipment meant that the data could not be used for validation purposes.

In April 1980 the SPTF was not quite completed, so the validation work on these data was mainly made to check the performance of the system and the measuring equipment. One of the results of this was that the measurements of the storage temperature difference was found to be erroneous.

Because of a shortage of national data the German participant concentrated his effort on the common validation work, see chapter 4.

Denmark

Validation on the Danish SPTF data has been performed continuously during the period. Results from three different periods containing 14-16 days of hourly data have been reported in ref. 5 using comparison plots of collector output, storage input, collector inlet temperature and storage tank temperature, and tables of daily energy flows. No attempt has been made to adjust some of the parameters for better agreement, and only total system validation calculations have been performed.

Fig. 5.8 - 5.11 show the set of comparison plots from one of the periods and table 5.1 is the daily energy flow comparison table for the same period. Results show a remarkably good agreement between measured and predicted values. The Danish participant mentions three reasons for the discrepancies:

- measurement errors
- wrong estimation of system parameters
- model shortcomings

Because of the inter-relationship between these factors it is very difficult to estimate the relative importance of each of them.

United Kingdom

Validation of the model GB1 using data from the UK SPTF has been carried out on four sets of data of 8-16 days. During the working period the model was modified and improved and a final series of simulations have been performed for all four sets of data. In ref. 10 the results of these simulations are compared to the measured results by computer plots and tables. For each set of data the following plots have been made: Storage Tank Temperature, collector outlet temperature, collector inlet temperature, collector output and storage tank input. The tables contain daily integrated values of collected and stored energy. Special consideration was given to the pipe losses as input parameter to the model. An assessment of the area of uninsulated parts of the pipes (rotameters, valves, pumps, etc.) was made and it was found that the heat losses from these parts accounted for a significant proportion of the total losses of the pipes. In the secondary circuit, the loss coefficient from the insulated parts was 0.5 W/K, and 3.8 W/K from the uninsulated parts.

The storage tank heat loss coefficient was initially calculated to be 4.56 W/K. From the validation work on the fourth set of data it became evident that this value was too small and a value of 15 W/K, as used by other participants of the Modelling Group in their national validation work, was adopted. In fact, it was later discovered that there had been an increase in the losses from the storage prior to the recording of the set of data. This was due to distortion of the bottom section of the tank as a result of overheating, caused by a pump failure in the cooling circuit. Reasonably good agreement has, however, been obtained with three of the four sets of data with a loss value of 15 W/K. Thus, some uncertainty remain as to what the correct loss value is.

Four plots have been selected from ref. 10 as a typical example of the results of the U.K. participant, fig. 5.12 - fig. 5.15. All four plots show a fine agreement between measured and predicted values.

Table 5.2 and 5.3 have been selected to show how well the daily integrated flows compare. It is seen that the predicted energy stored is higher than the measured. Taking into account the accuracies of the measurements of temperature differential, flow rate and the error in specific heat capacity of the fluid, the predicted energy lies well within the range of accuracy of the measured data.

The energy collected shows more deviation. One particular source of error here is the variation in specific heat capacity of the primary circuit fluid with temperature. This will be taken into account in future work.

In addition to the four sets of data mentioned above, one particular day (October 31, 1979) has been selected for more detailed analysis. Data for that day were supplied at five-minute intervals instead of hourly intervals. Fig.5.16 and 5.17 show the comparisons between measured and predicted collector outlet and storage input. Also on these plots the predicted collector output is somewhat higher than the measured, whereas the agreement on the storage input is quite satisfactory.

Ireland

The Irish Modelling Group participant has presented validation results using one week of data from the Irish SPTF. In ref. 9 the results are presented as two computer print-out tables showing energy collected, energy stored, collector inlet, collector outlet and storage temperatures. From the tables it can be seen that the model provides a comparatively poor fit to the observations of the real system. Collector inlet and outlet temperatures were under-predicted by about $6^{o}C$ on average, while the mean difference between measured and predicted store temperatures was $-12.5^{o}C$.

The observed discrepancies may largely be due to malfunctions and measurement errors in the SPTF installation over the period in question. Also the use of incorrect parameter values as input to the model is part of the reason for the poor agreement; e.g. the heat loss coefficient used was 3.19 W/K, which is considerably lower than the 15 W/K used by the other Modelling Group participants.

The Netherlands

The Dutch participant has presented his national validation work during the period on several sets of data. In ref.7 some of the results are presented in the form of comparison plots and tables. What is shown in fig. 5.18 - fig. 5.22 is taken from this reference.

Again it was concluded that an accuracy of 15% for the prediction of the daily storage input for clear days has been reached. The agreement on the collector output (fig. 5.18) is less good than in the case of the Danish data. The rather high calculated values are probably caused by the value of heat loss coefficient of the collector given in the Dutch Installation Descriptor ($U_L = 3.8 + 0.02\ \Delta T$), which is low in comparison with the Danish value ($U_L = 6.54$). The relatively high start differential of the Dutch installation is clearly shown.

Fig. 5.19 shows that the calculated storage input, in contrast with the high calculated collector output, are lower than the measured values, especially when the temperature in the collector circuit are high. The most likely reason for this is that the heat losses of the pipes are less than calculated. An inaccurate heat loss coefficient in the Installation Descriptor could be the reason for this. It was also found that the laboratory temperature was significantly affecting the heat losses of the pipes (most of the Dutch installation pipes are placed inside the laboratory). It was therefore necessary to measure the laboratory temperature more accurately at various points.

The storage temperature is well predicted (fig. 5.20). Inaccuracies in the prediction of the storage input are compensated by adjusted values for the storage output.

Fig. 5.21 shows that the interface of solar system 1, in general, operates well, but some irregularities can be seen on day 21 and day 22. An important result from validation work during other periods is that the cooling unit appears to have insufficient capacity to operate the interface during the summer.

Fig. 5.22 shows relatively high calculated collector temperatures during the mornings and relatively low temperatures during the nights. This was also the case in the validation work on Danish and Belgian data.

As a result of this validation work convection heat losses from the heat exchanger were identified. These losses occurred at night when the heat exchanger was bypassed.

ENERGY QUANTITIES, PREDICTED VS. MEASURED, DAY VALUES

OBS	TID	CGR47	HCC1	HCC1P	HOC1N	MEAN1	STD1	SSG1	SSG1P	MEAN2	STD2	HP1	IL1	DG
1	24MAY80	180	32	46	37	-0.55	0.85	22	25	-0.09	0.58	5	59	15
2	25MAY80	55	2	7	4	-0.22	0.38	0	0	0.00	0.00	1	60	2
3	26MAY80	64	4	11	6	-0.28	0.41	0	0	0.00	0.00	1	58	1
4	27MAY80	253	88	92	86	-0.18	0.73	74	72	0.11	0.44	25	47	55
5	28MAY80	182	49	59	52	-0.42	0.99	39	41	-0.05	0.69	32	29	76
6	29MAY80	41	2	5	3	-0.13	0.35	0	0	0.00	0.00	81	47	173
7	30MAY80	82	30	31	30	-0.04	0.63	31	27	0.14	0.68	30	36	78
8	31MAY80	228	96	100	96	-0.17	0.81	85	85	0.00	0.61	28	49	59
9	01JUN80	308	131	138	133	-0.29	0.72	116	119	-0.14	0.47	82	52	140
10	02JUN80	97	13	19	14	-0.26	0.49	8	7	0.03	0.17	45	45	103
11	03JUN80	210	89	91	86	-0.09	0.64	78	76	0.09	0.43	26	28	69
12	04JUN80	311	117	121	114	-0.13	0.80	77	96	-0.79	2.16	13	15	-81
13	05JUN80	306	86	91	83	-0.23	0.84	67	63	0.15	0.30	-0	6	2

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Table 5.1 Measured and predicted energy flows, ref. 5

UK SOLAR PILOT TEST FACILITY.

Validation Results - Daily Integrated Energies (MJ)

Day of year	Solar Radiation	Collected Meas	Collected Pred	Stored Meas	Stored Pred	Load
37	37.1	0.0	0.3	-0.6	8.6	-8.5
38	172.5	11.2	19.3	16.1	15.1	-8.8
39	36.1	0.0	2.6	-1.5	15.6	36.9
40	64.0	0.0	6.3	-8.1	15.2	-10.8
41	849.5	263.3	293.5	243.3	257.0	84.0
42	328.9	45.6	59.1	30.1	45.7	145.1
43	333.7	51.4	67.6	35.3	56.9	31.4
44	142.1	7.8	16.0	-8.8	15.0	17.9
45	99.1	1.0	7.7	-9.5	15.1	3.5
46	620.4	202.6	236.8	189.4	214.4	113.2
47	76.2	0.0	8.9	-7.8	13.6	71.3
48	312.0	53.4	78.3	50.8	65.5	51.2
49	657.6	202.0	238.2	193.8	212.4	118.4
50	333.4	32.6	70.6	40.0	58.0	85.6
51	319.0	36.5	61.1	28.2	46.6	54.7
52	0.7	0.0	0.0	-2.8	4.9	24.3
Totals	4382.	907.	1166.	788.	1060.	810.

Table 5.2 Measured and predicted daily integrated energies, ref. 10

UK SOLAR PILOT TEST FACILITY.

Validation Results - Daily Integrated Energies (MJ)

Day of year	Solar Radiation	Collected Meas	Collected Pred	Stored Meas	Stored Pred	Load
105	55.8	0.0	0.0	-4.4	1.3	0.6
106	235.2	2.3	25.7	-9.6	8.5	139.4
107	732.0	193.6	216.0	159.0	181.3	117.6
108	865.0	258.2	296.3	254.3	254.3	157.8
109	1078.2	302.7	326.7	280.5	272.7	142.8
110	347.1	14.8	30.3	2.3	8.4	296.0
111	889.9	238.2	287.6	247.0	246.2	63.7
112	30.6	0.0	4.8	-2.0	5.0	150.5
Totals	4234.	1010.	1187.	927.	978.	1068.

Table 5.3 Measured and predicted daily integrated energies, ref. 10

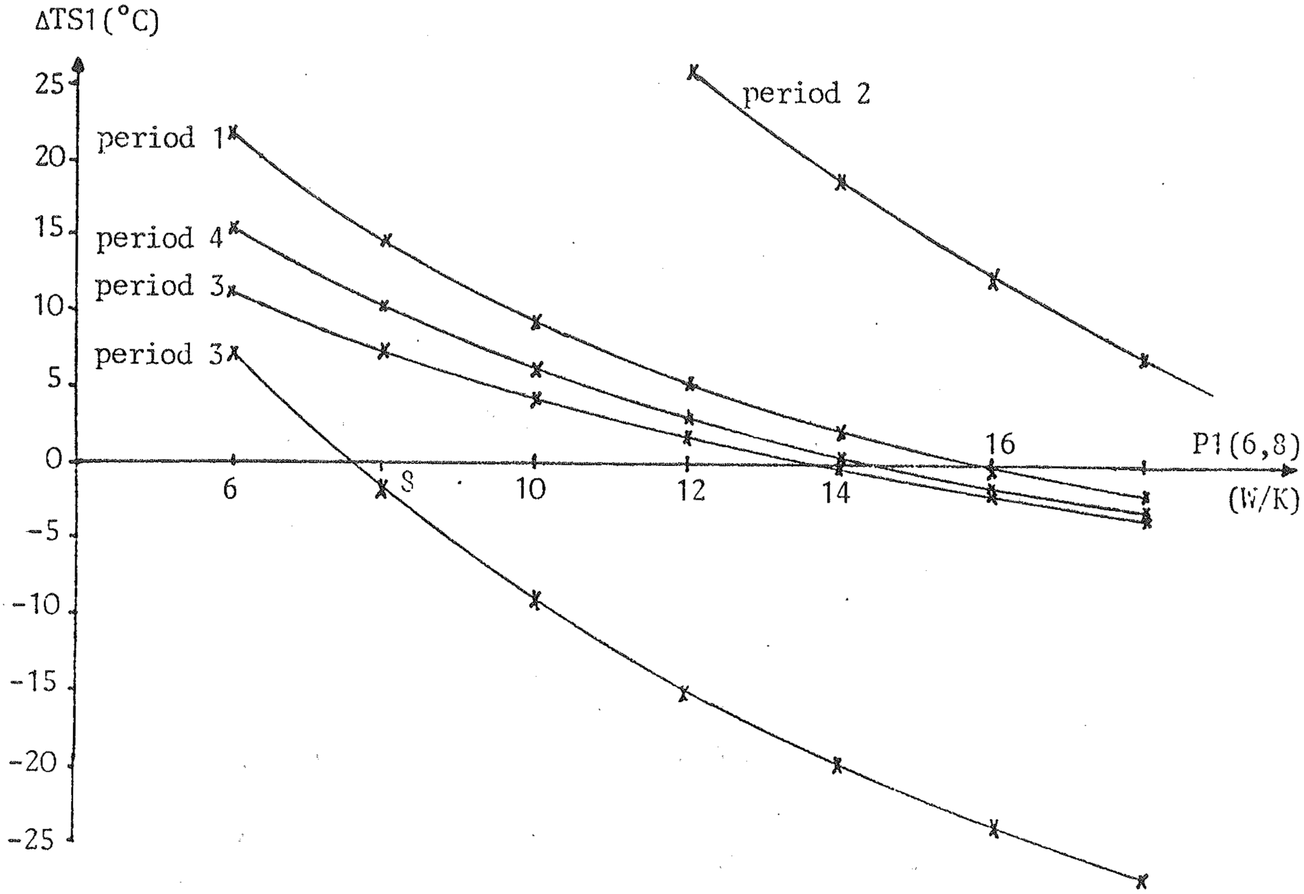


Fig 5.1 Predicted temperature difference to measured at the end of the period as a function of storage loss coefficient, ref. 6

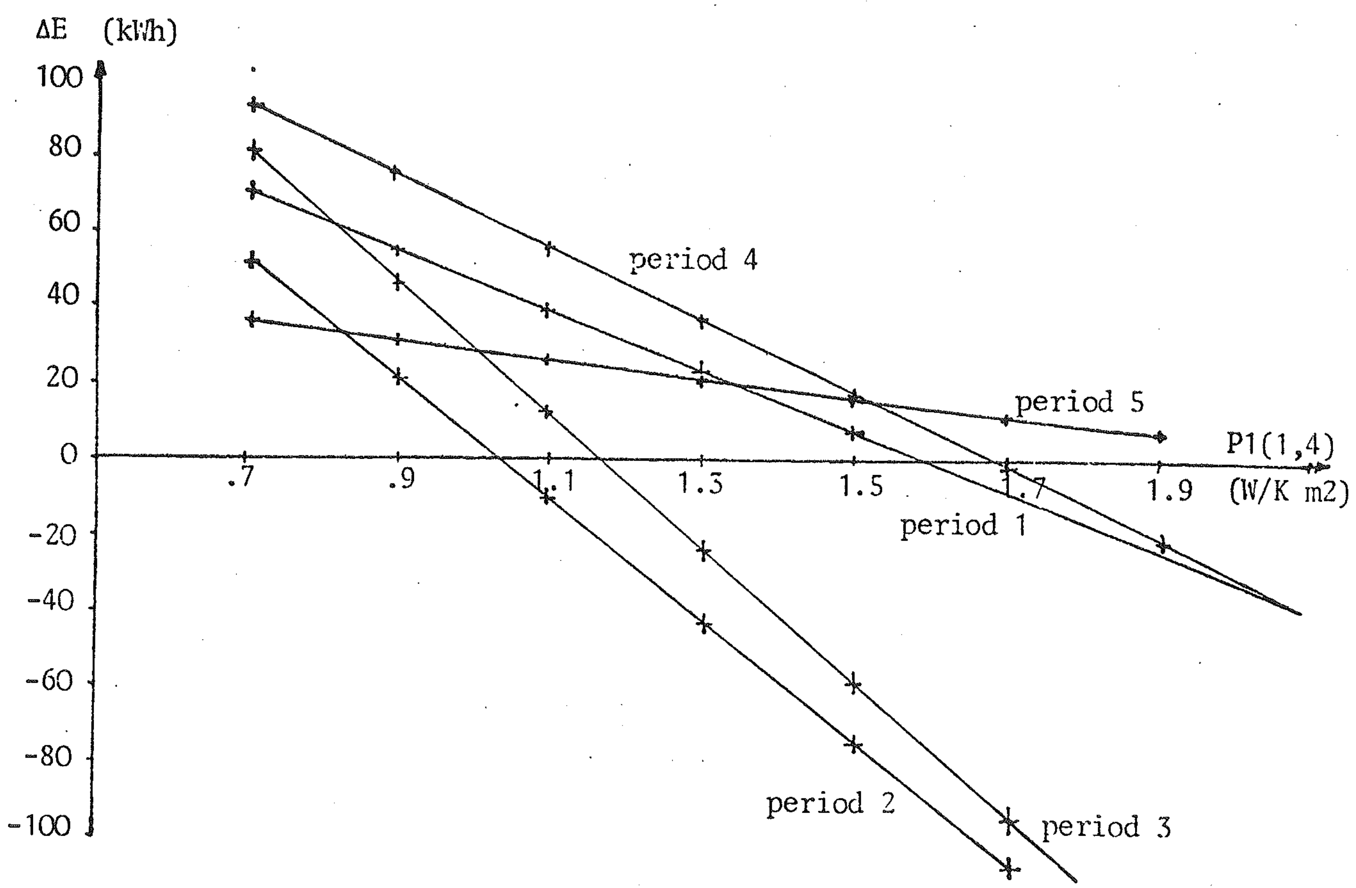


Fig. 5.2 Difference between predicted and measured amount of collected energy as a function of collector back and side losses, ref. 6

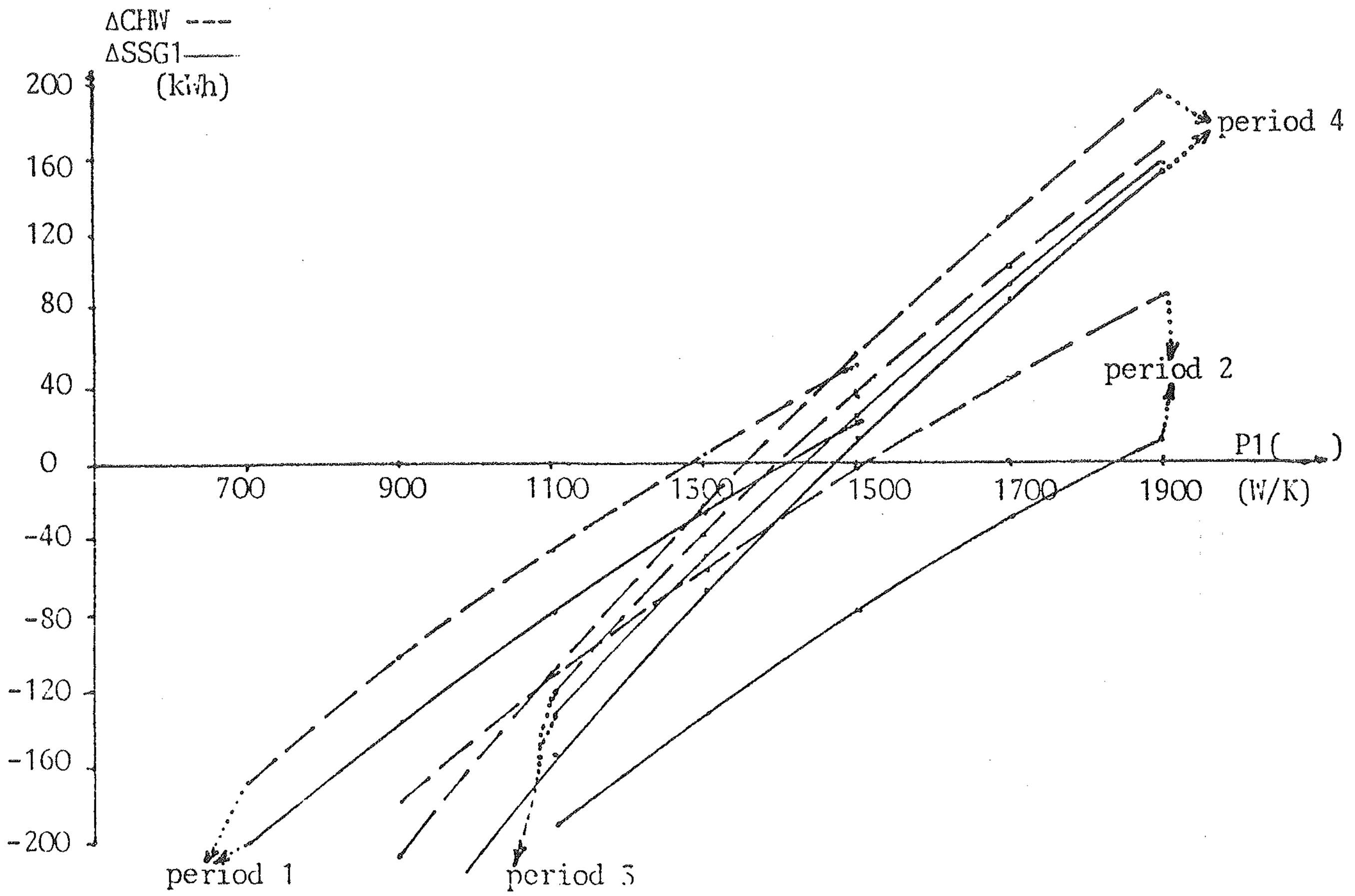


Fig. 5.3 Differences between measured and predicted collector output (ΔCHW) and storage input (ΔSSG1) as a function of heat exchanger transfer coefficient, ref. 6

SS1-PTF Belgium
1980, day 65 - day 94
Storage subroutine only

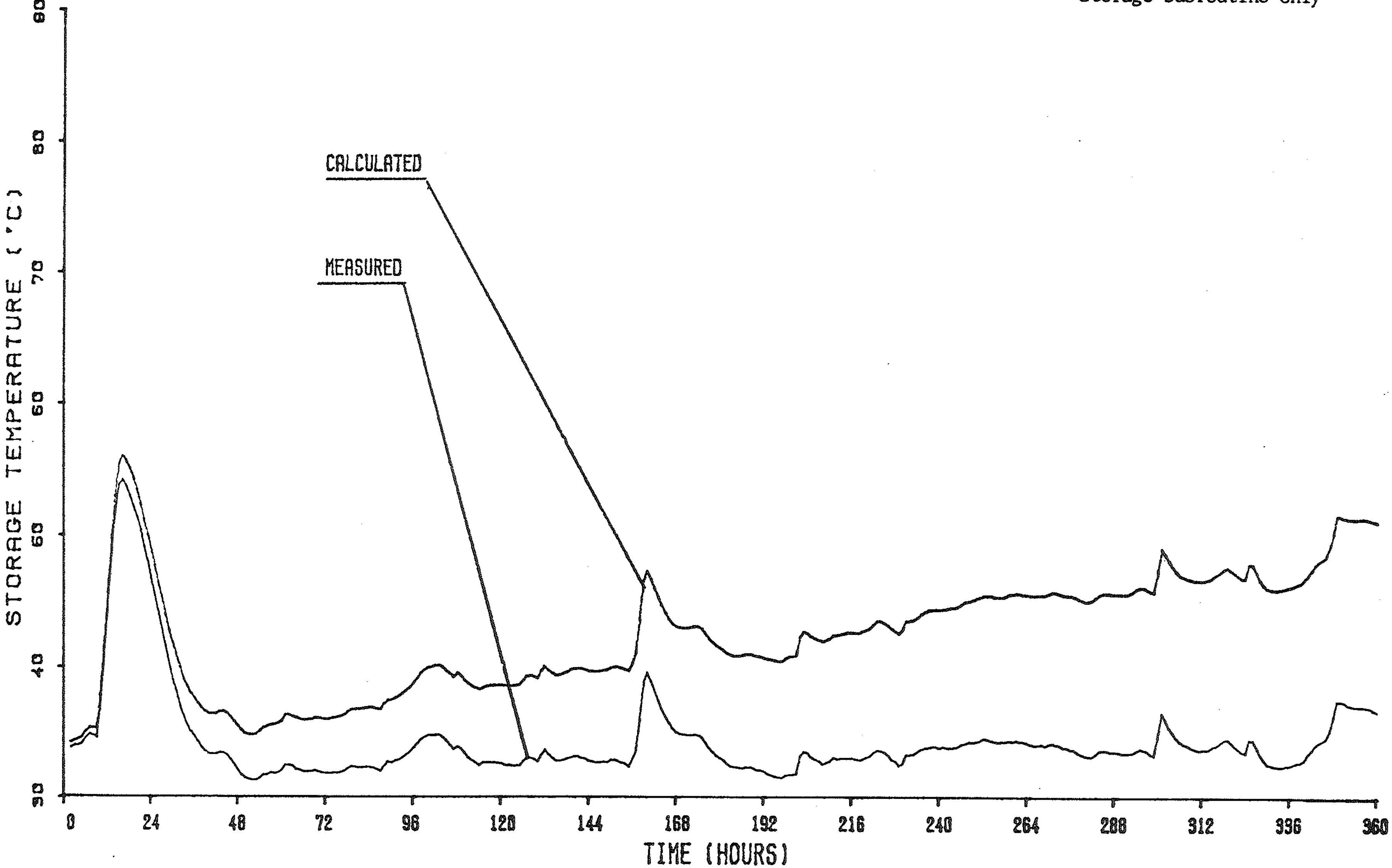


Fig. 5.4 Measured and predicted storage temperature, ref. 6

SS1-PTF Belgium
1980, day 65 - day 94
Storage subroutine only
P1(6,8) = 15 W/K (instead of 5 W/K)

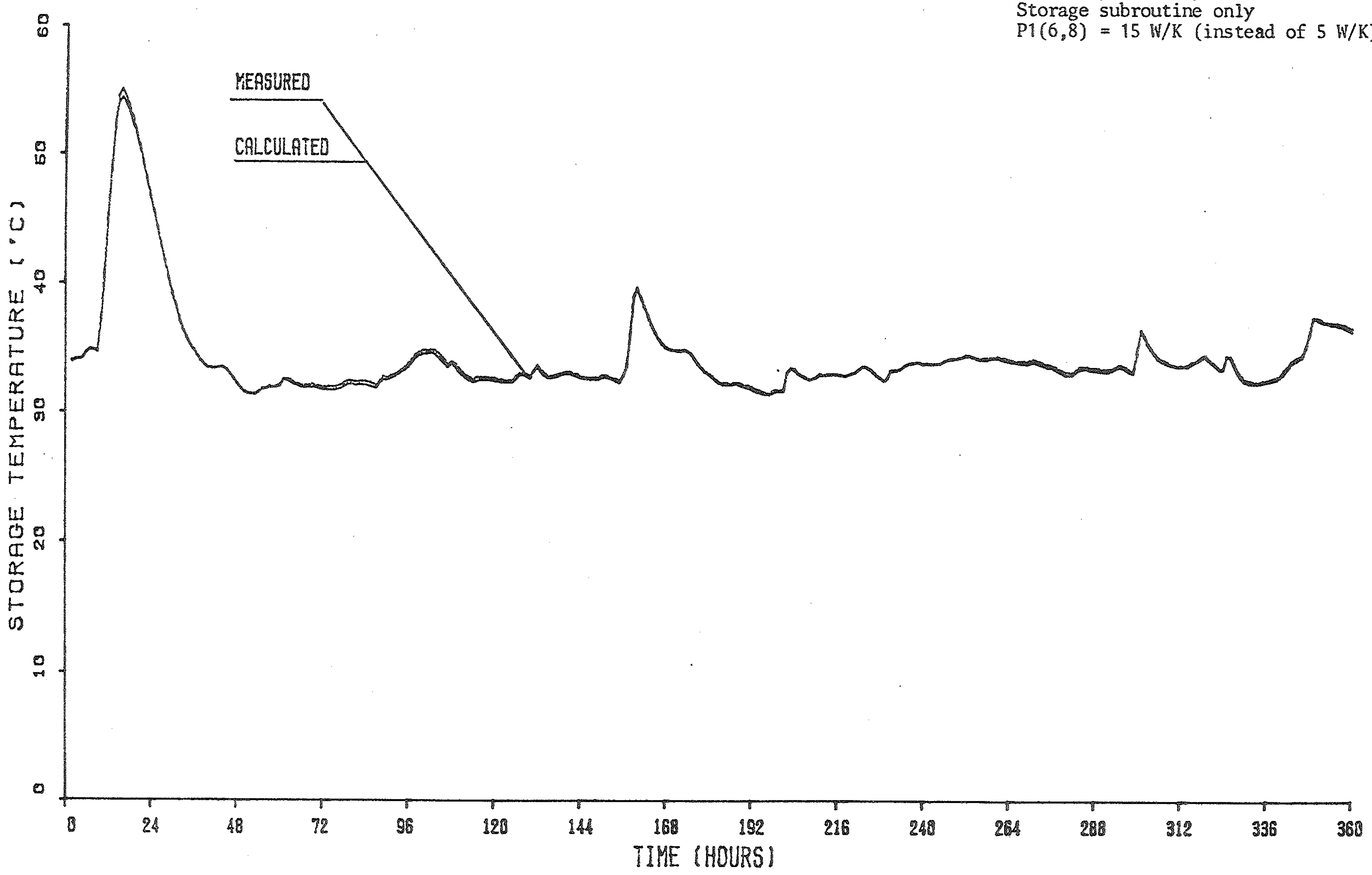


Fig. 5.5 Measured and predicted storage temperature, ref. 6

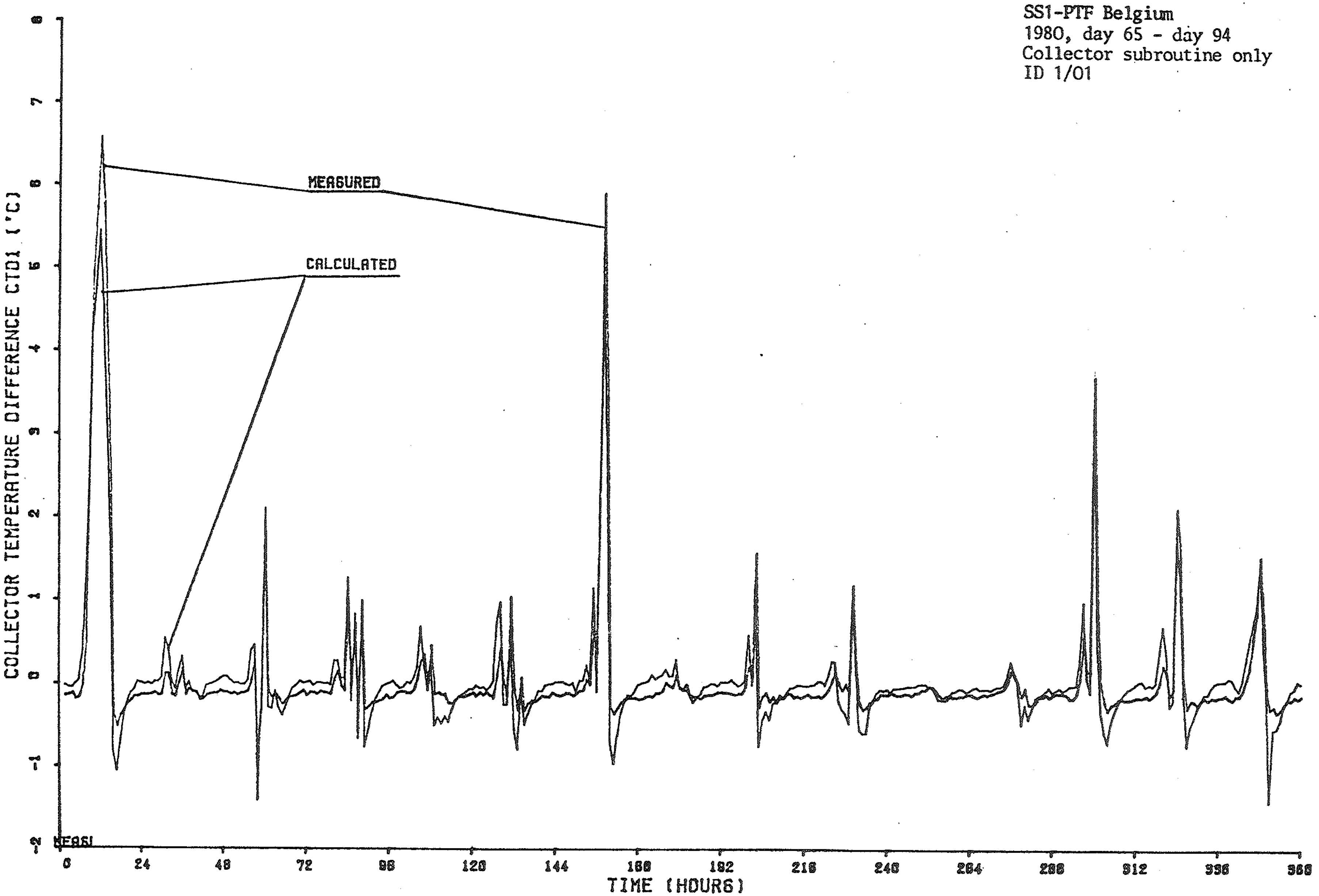


Fig. 5.6 Measured and predicted collector Δt, ref. 6

SS1-PTF Belgium
1980, day 65 - day 94
Collector subroutine only
P1(1,9) = 37.55 W/K (instead
of 101 W/K)

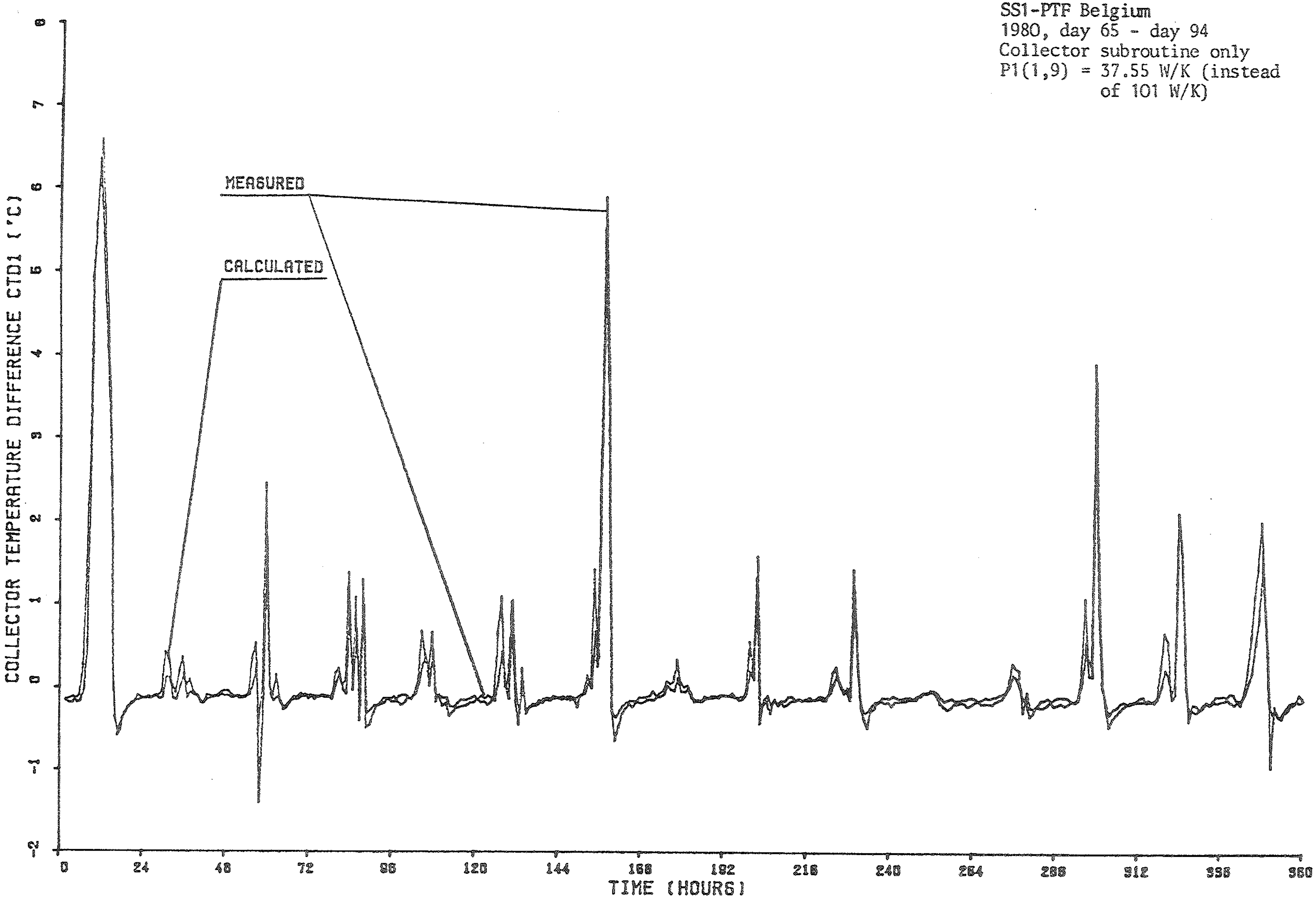


Fig. 5.7 Measured and predicted collector Δt, ref. 6

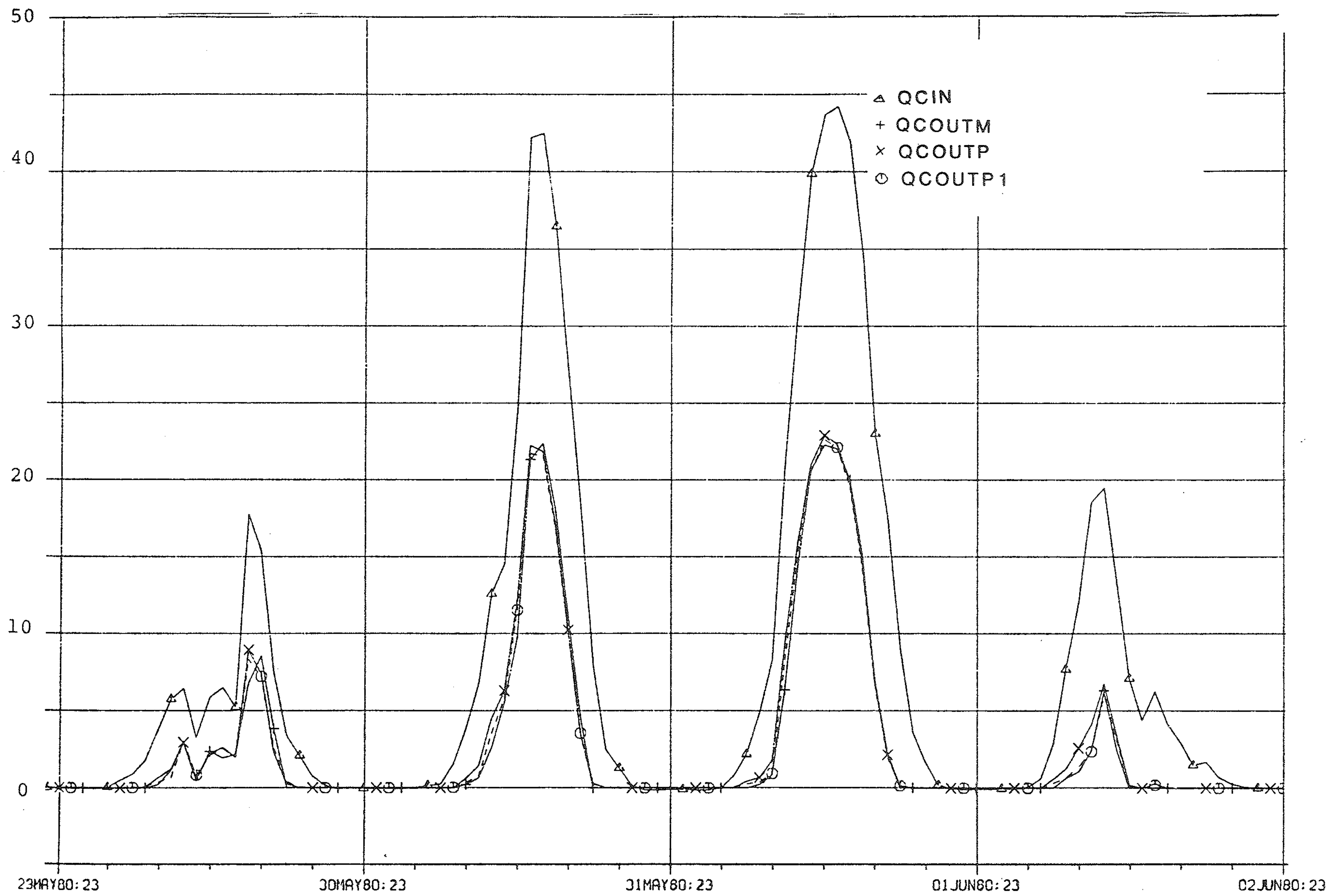


Fig. 5.8 Collector output, ref. 5

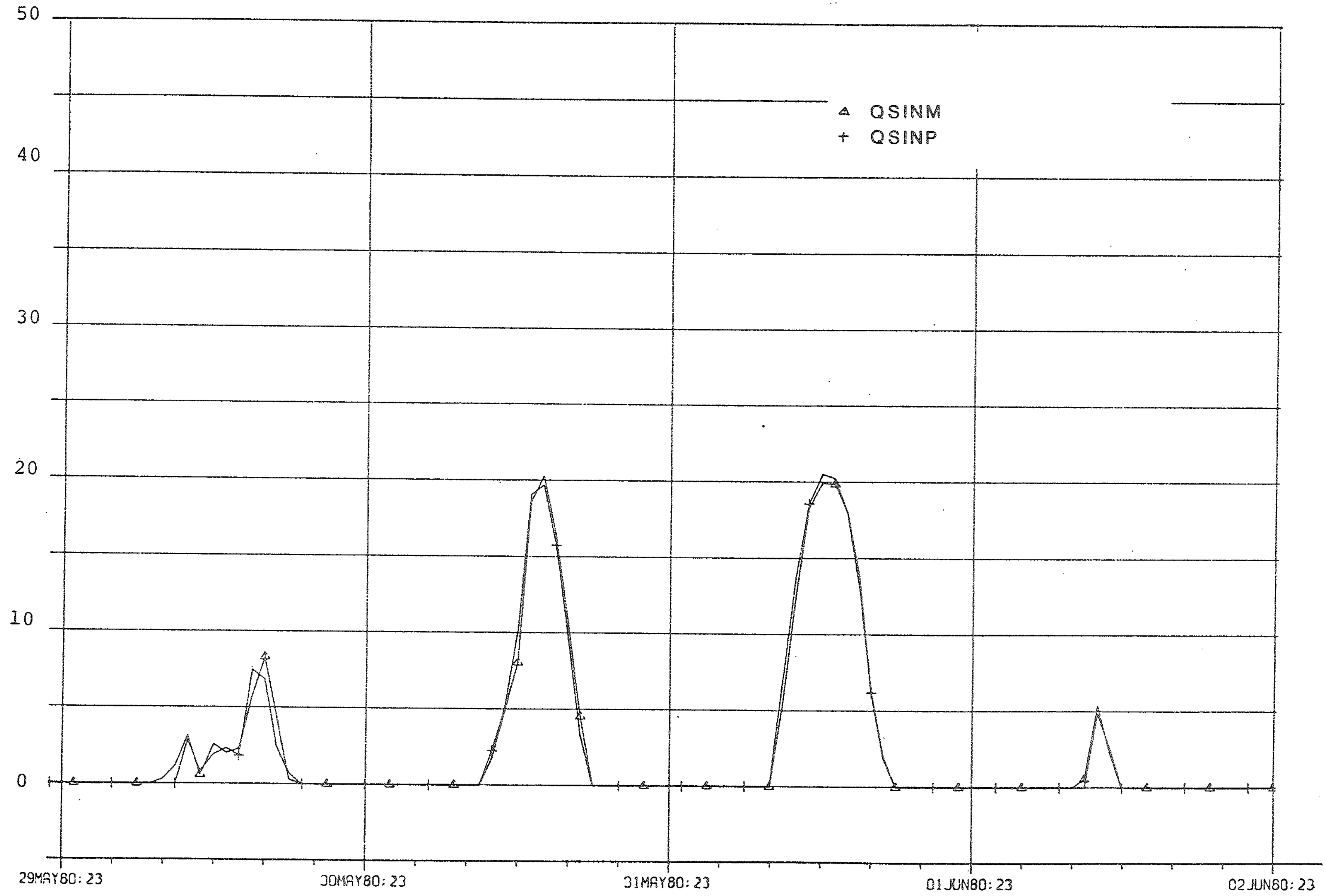


Fig. 5.9 Storage input, ref. 5

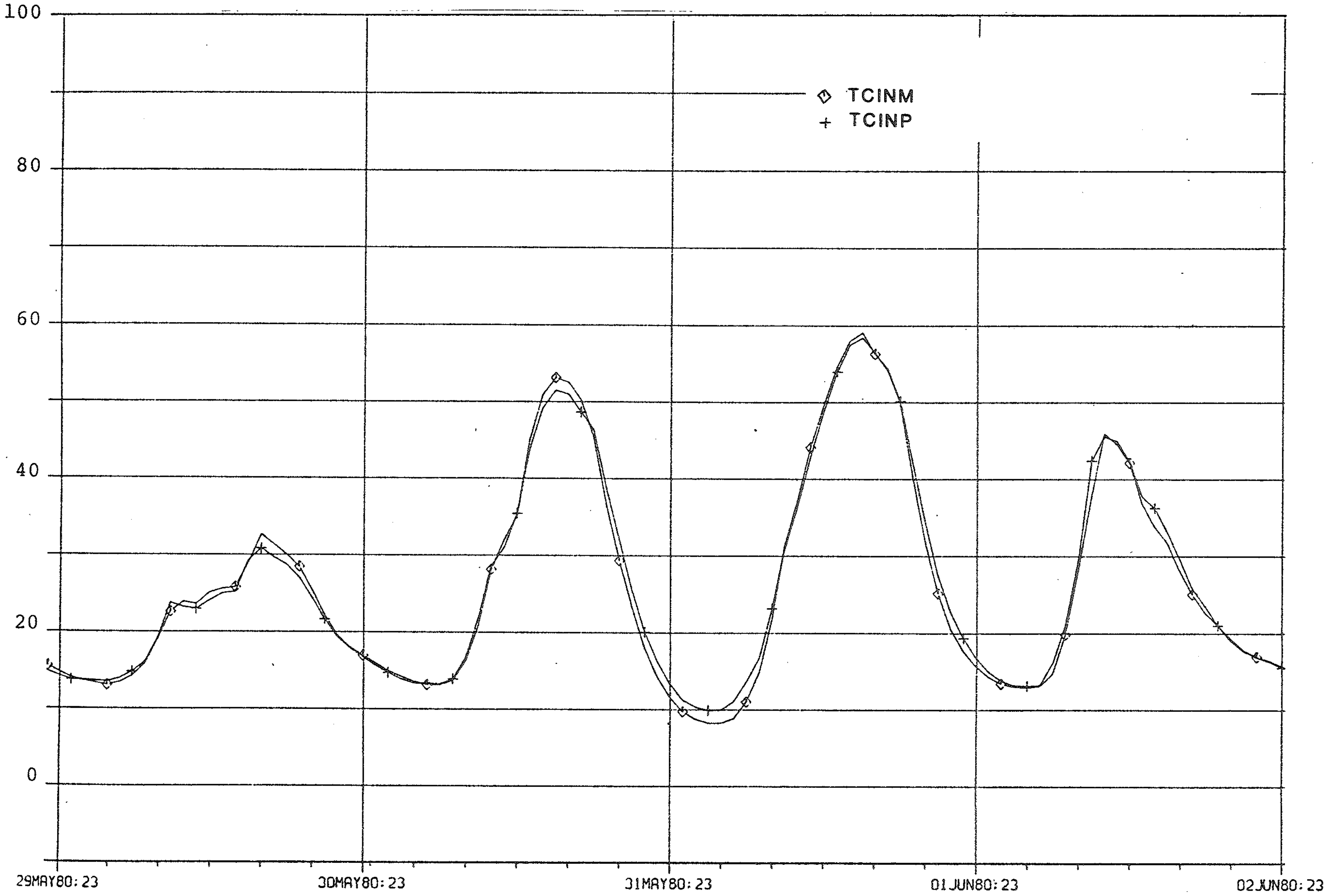


Fig. 5.10 Inlet collector temperature, ref. 5

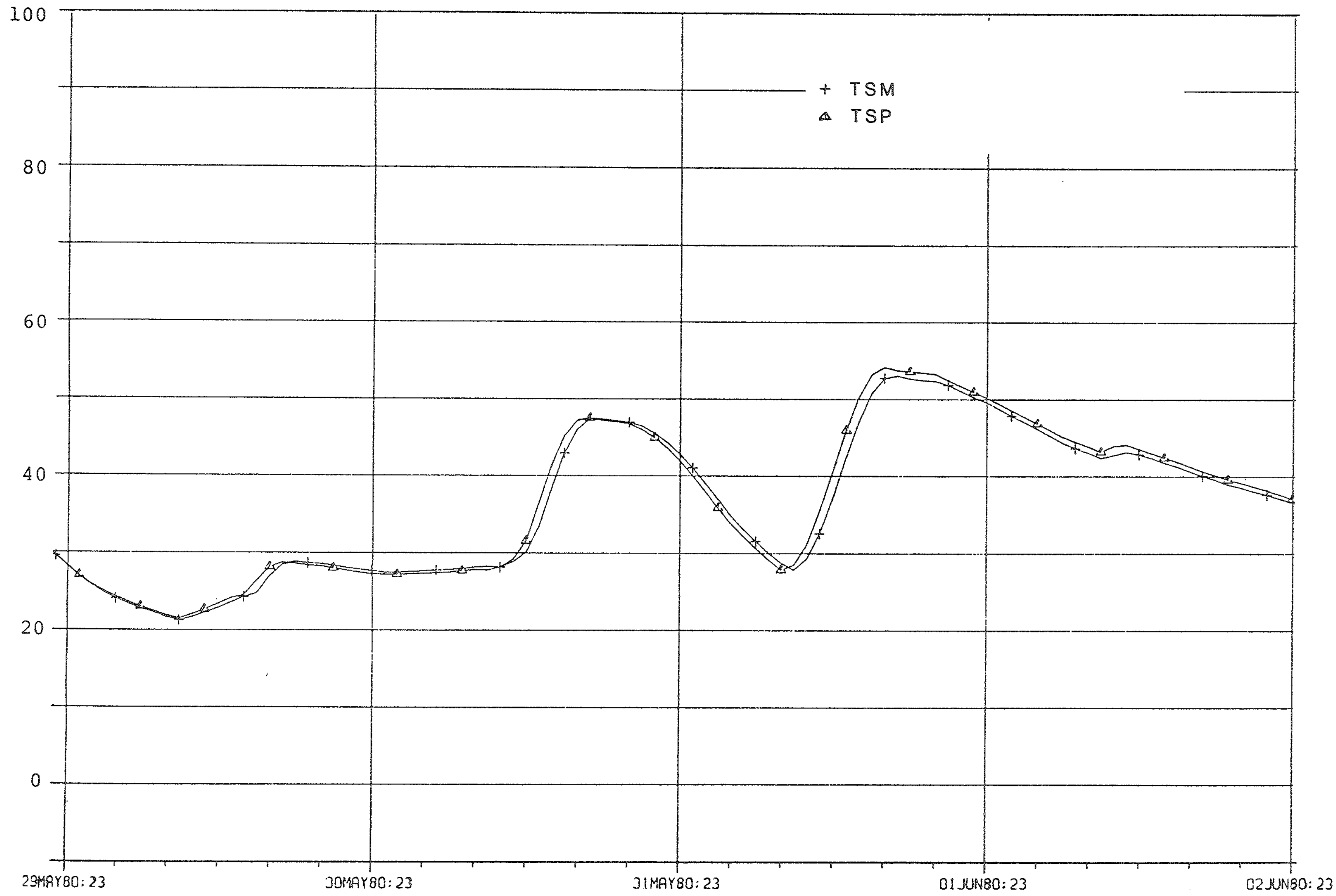


Fig. 5.11 Storage tank temperature, ref. 5

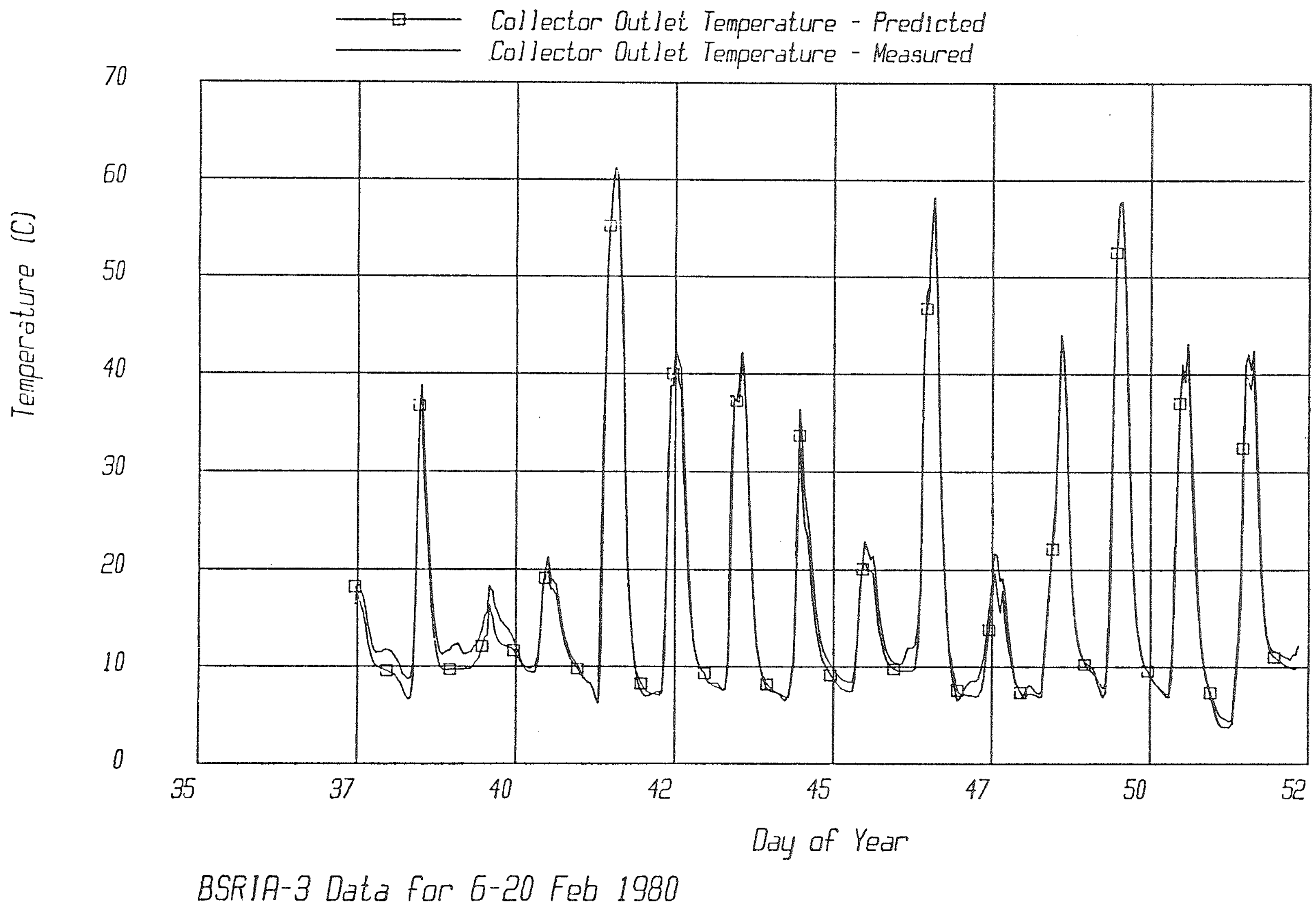
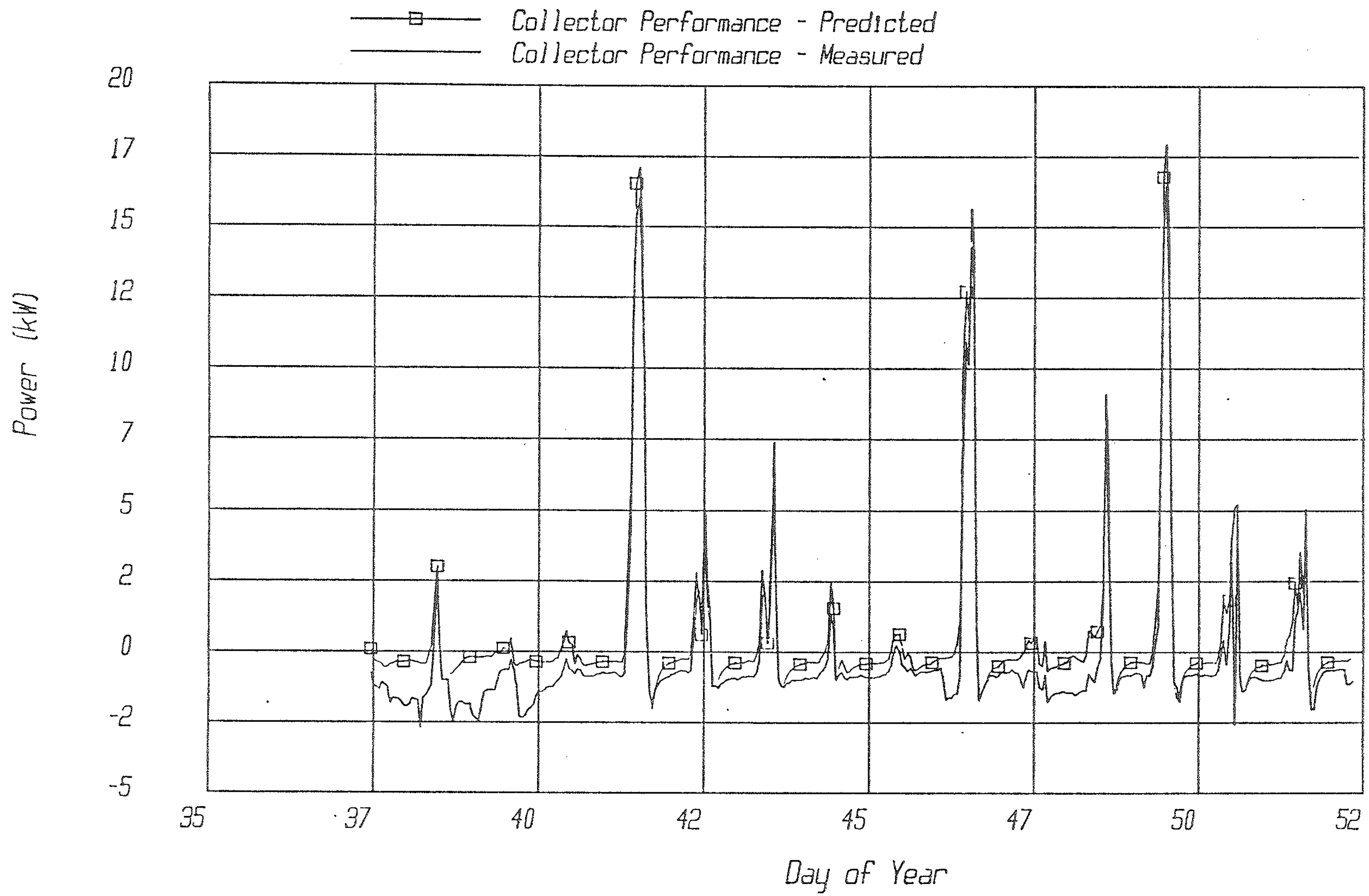


Fig. 5.12 Measured and predicted collector outlet temperatures, ref. 10



BSRIA-3 Data for 6-20 Feb 1980

Fig. 5.13 Measured and predicted collector output, ref. 10

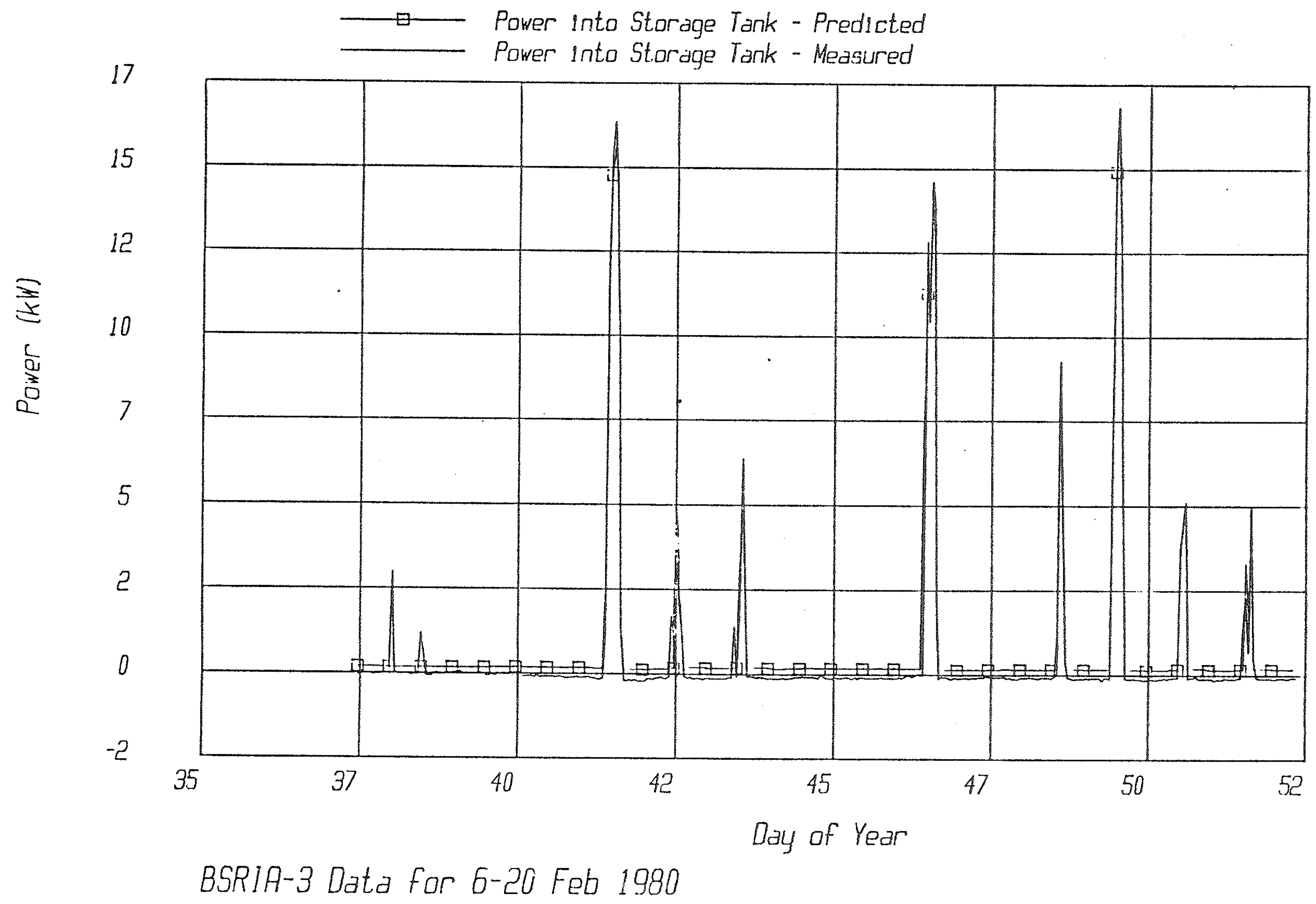


Fig. 5.14 Measured and predicted storage input, ref. 10

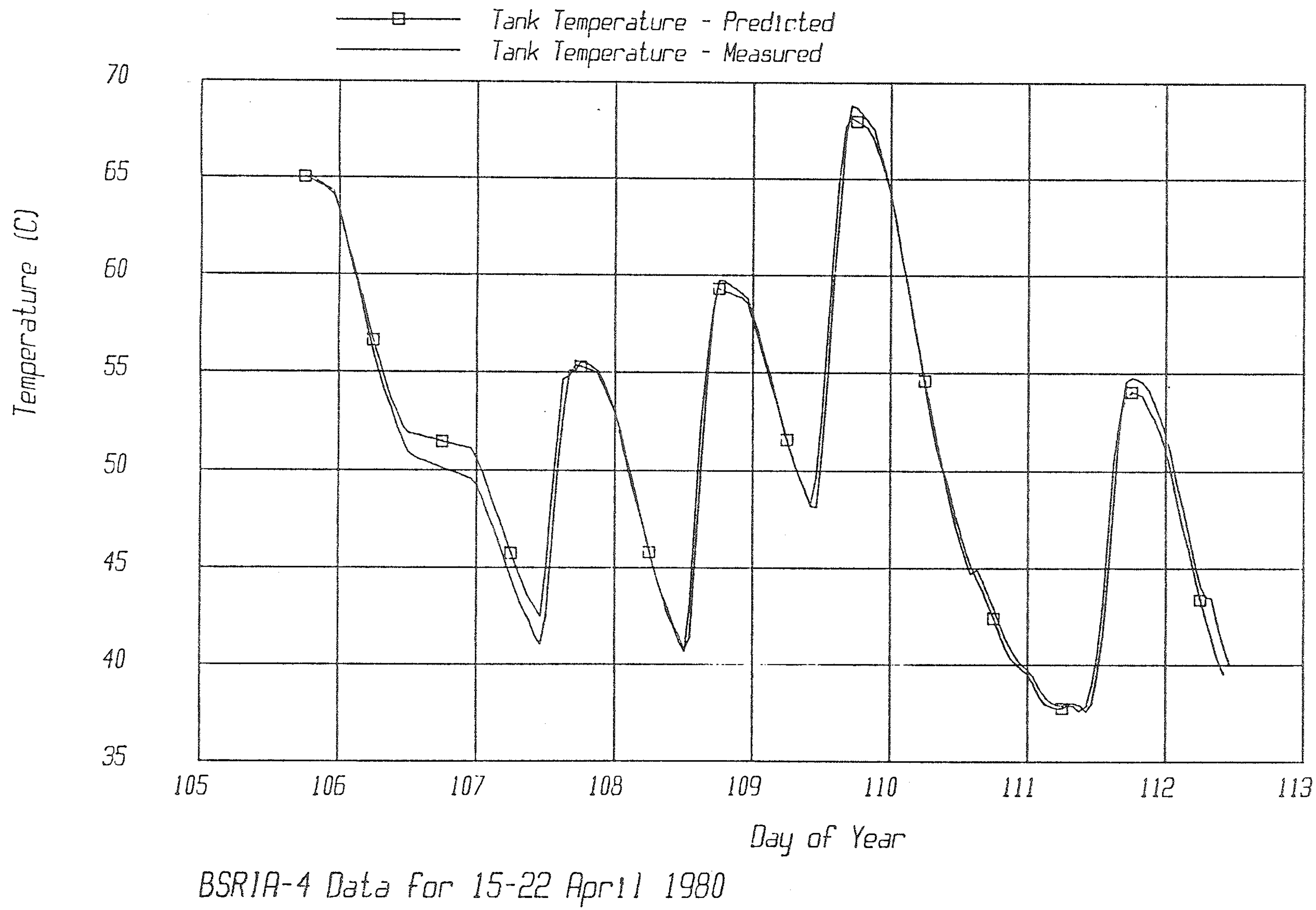
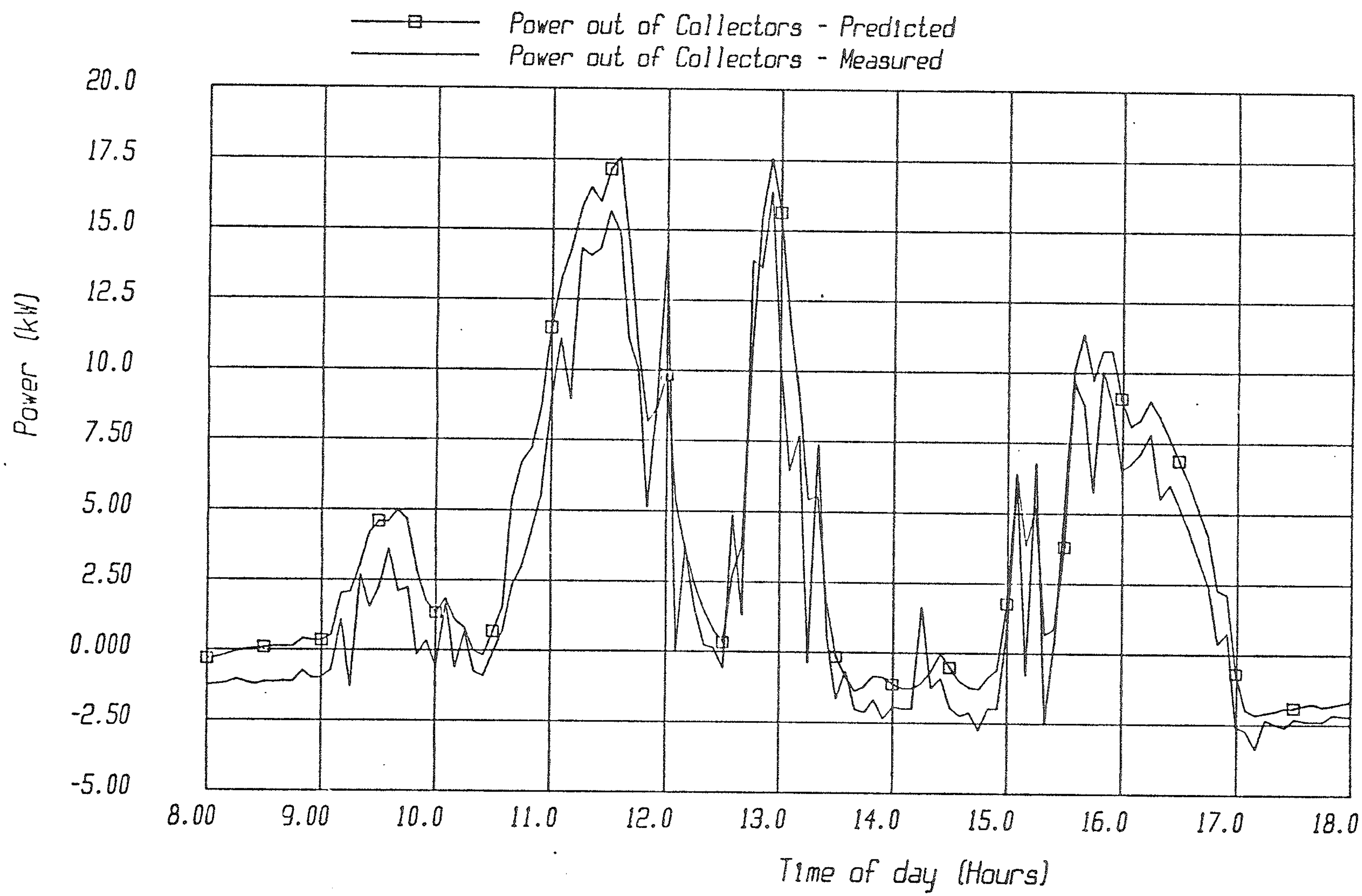
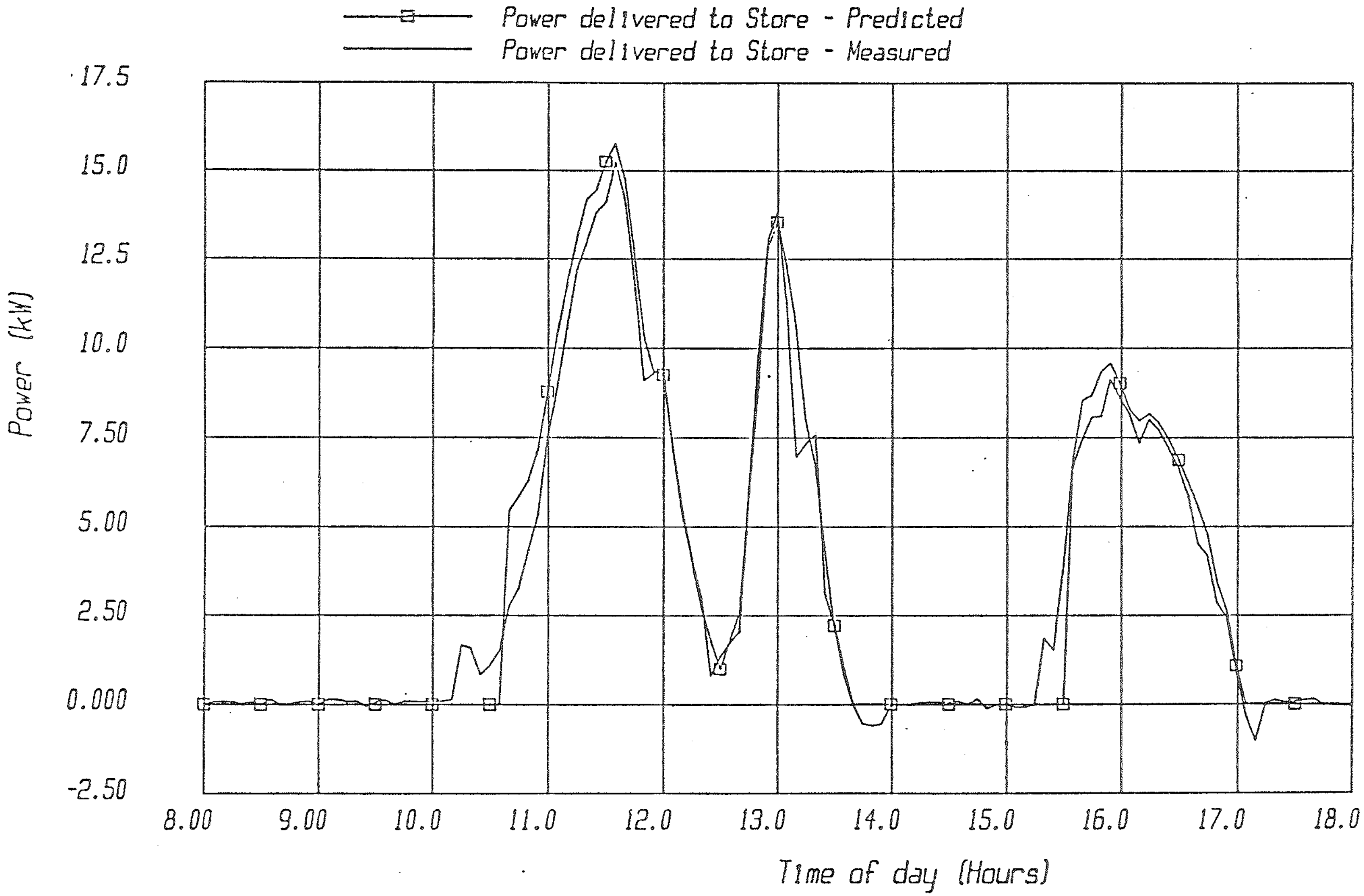


Fig. 5.15 Measured and predicted storage temperature, ref. 10



Detailed analysis at 5 minute intervals.

Fig. 5.16 Measured and predicted collector output, ref. 10



Detailed analysis at 5 minute intervals.

Fig. 5.17 Measured and predicted storage input, ref. 10

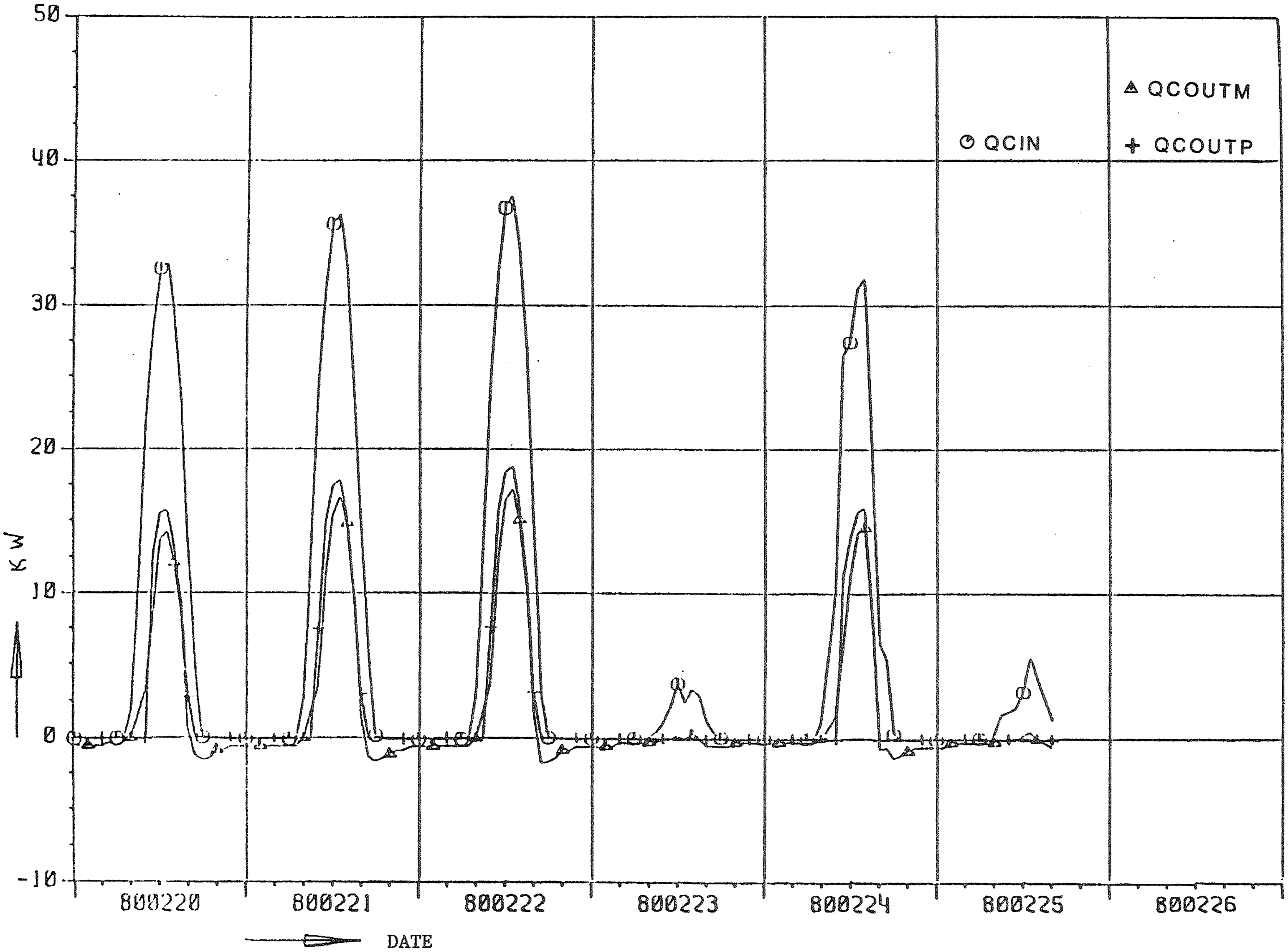


Fig. 5.18 Collector output measured versus predicted, ref. 7

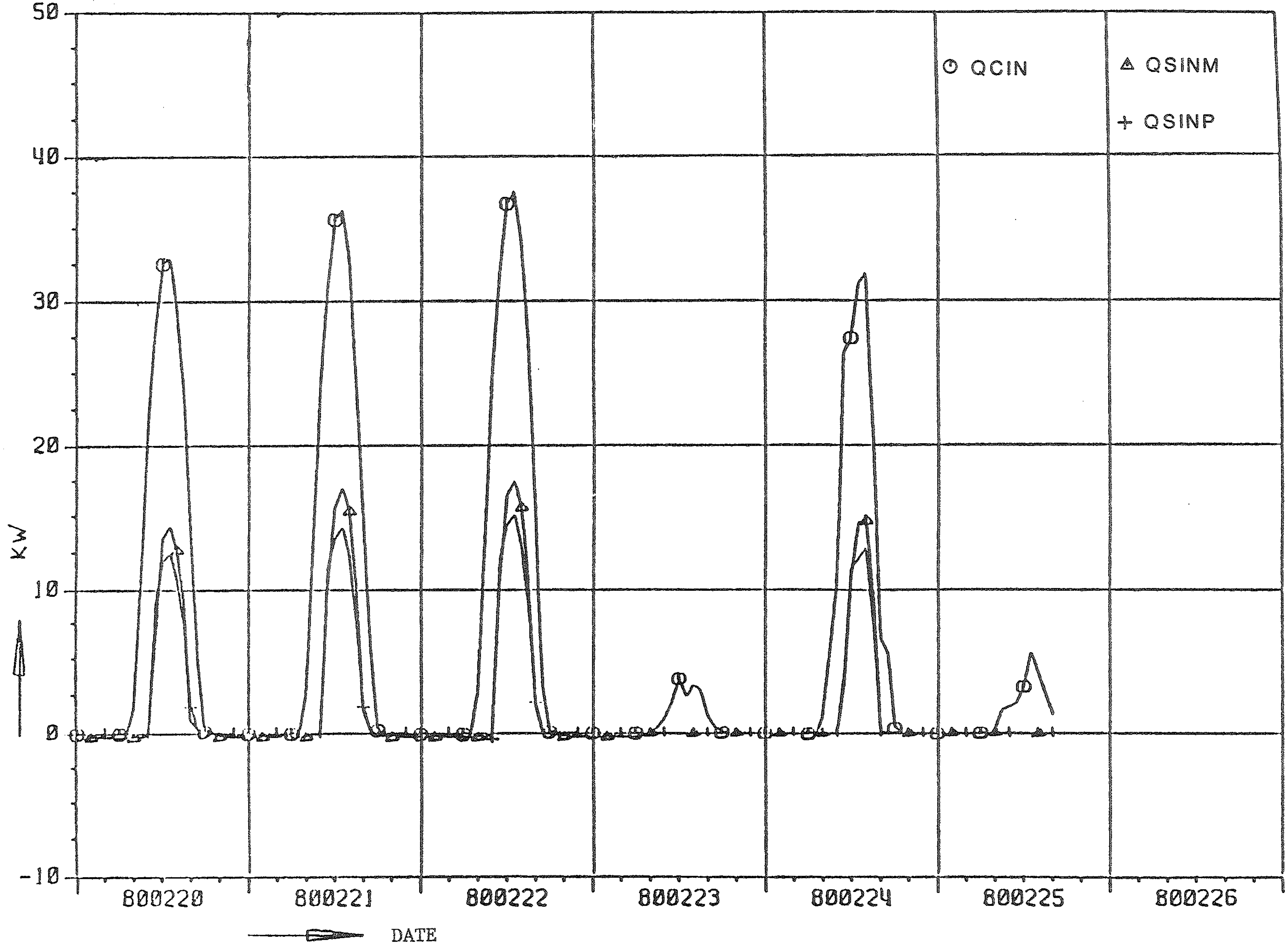


Fig. 5.19 Storage input measured versus predicted, ref. 7

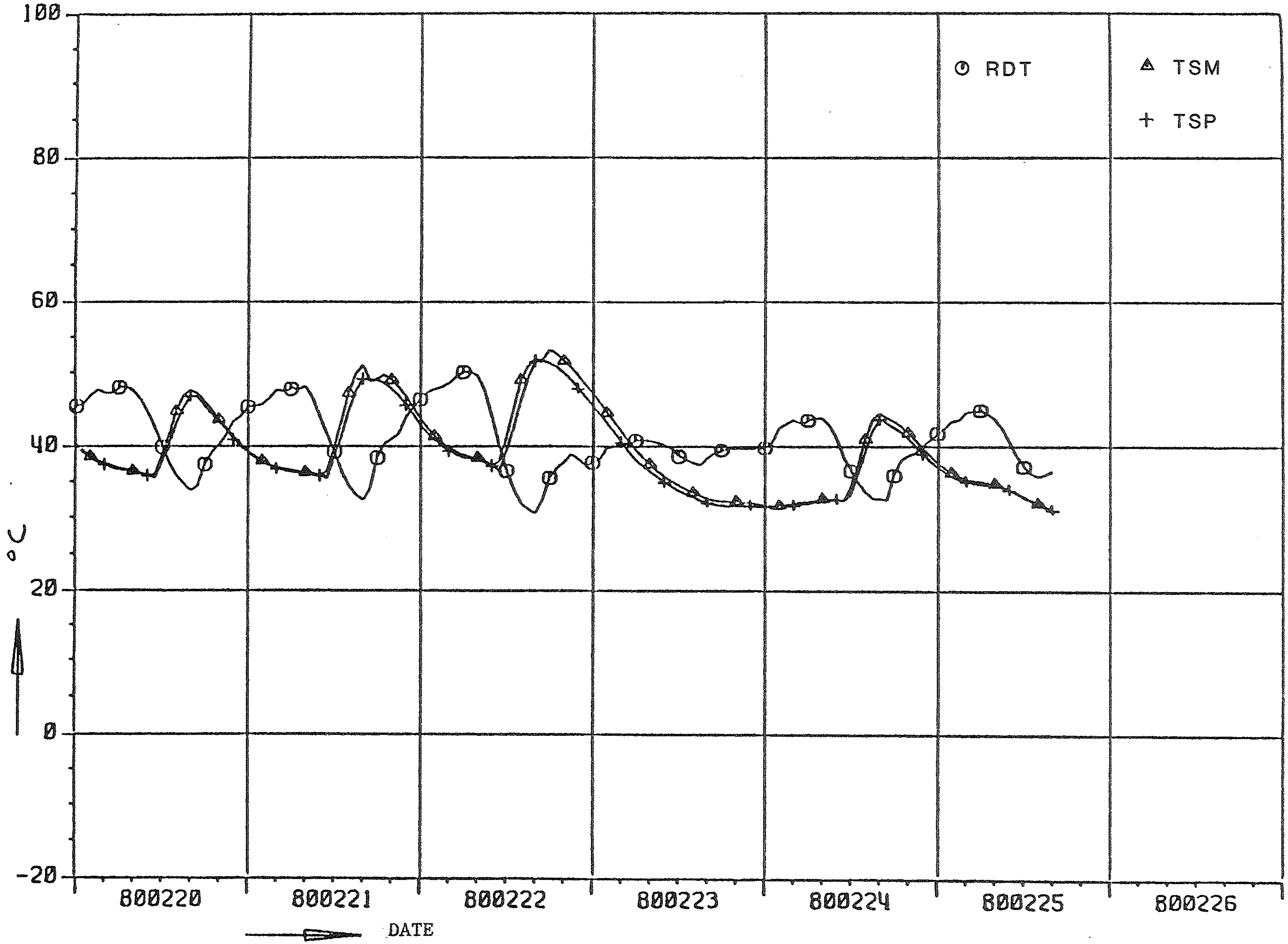


Fig. 5.20 Storage temperature measured versus predicted, ref. 7

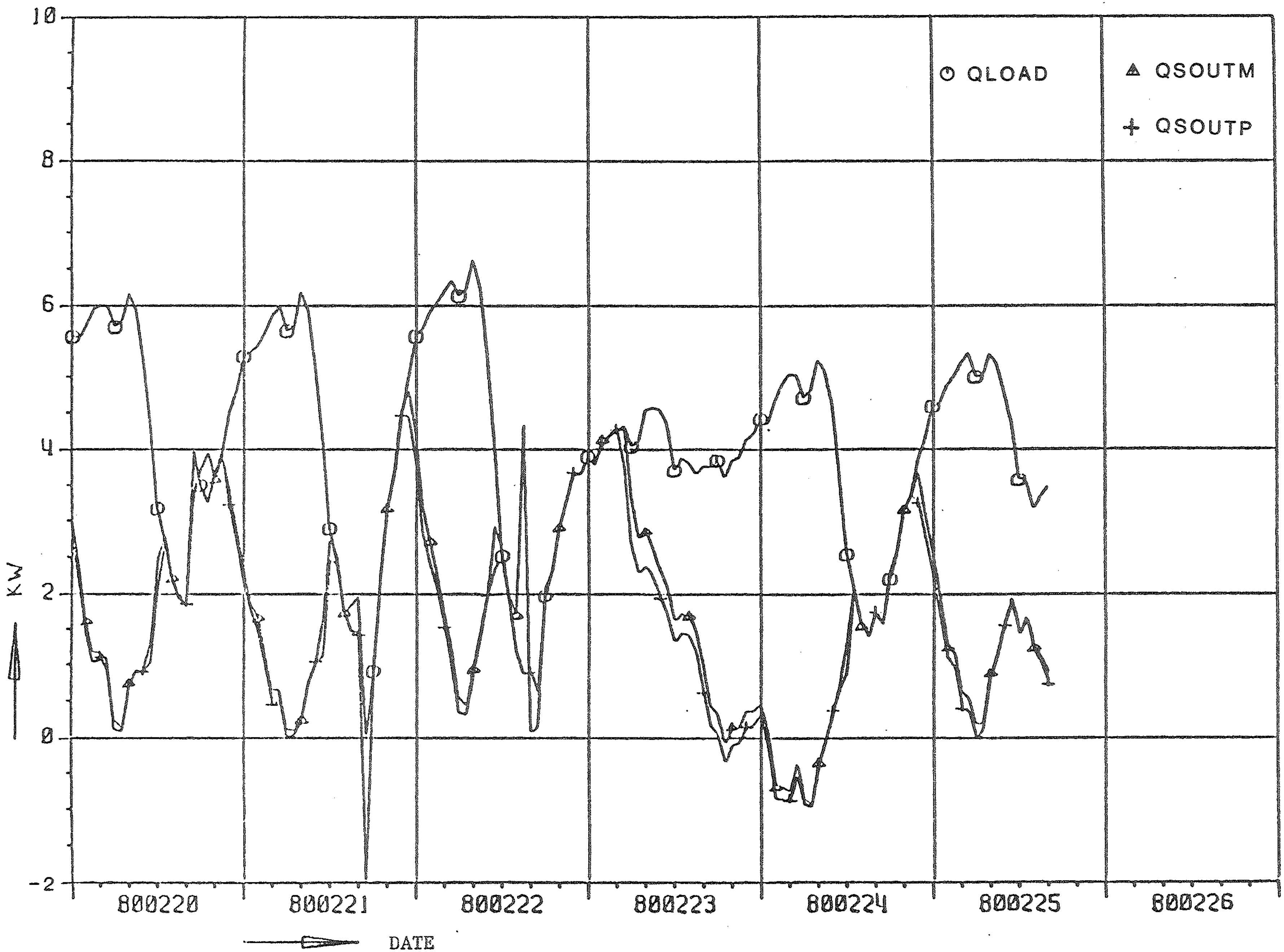


Fig. 5.21 Storage output measured versus predicted, ref. 7

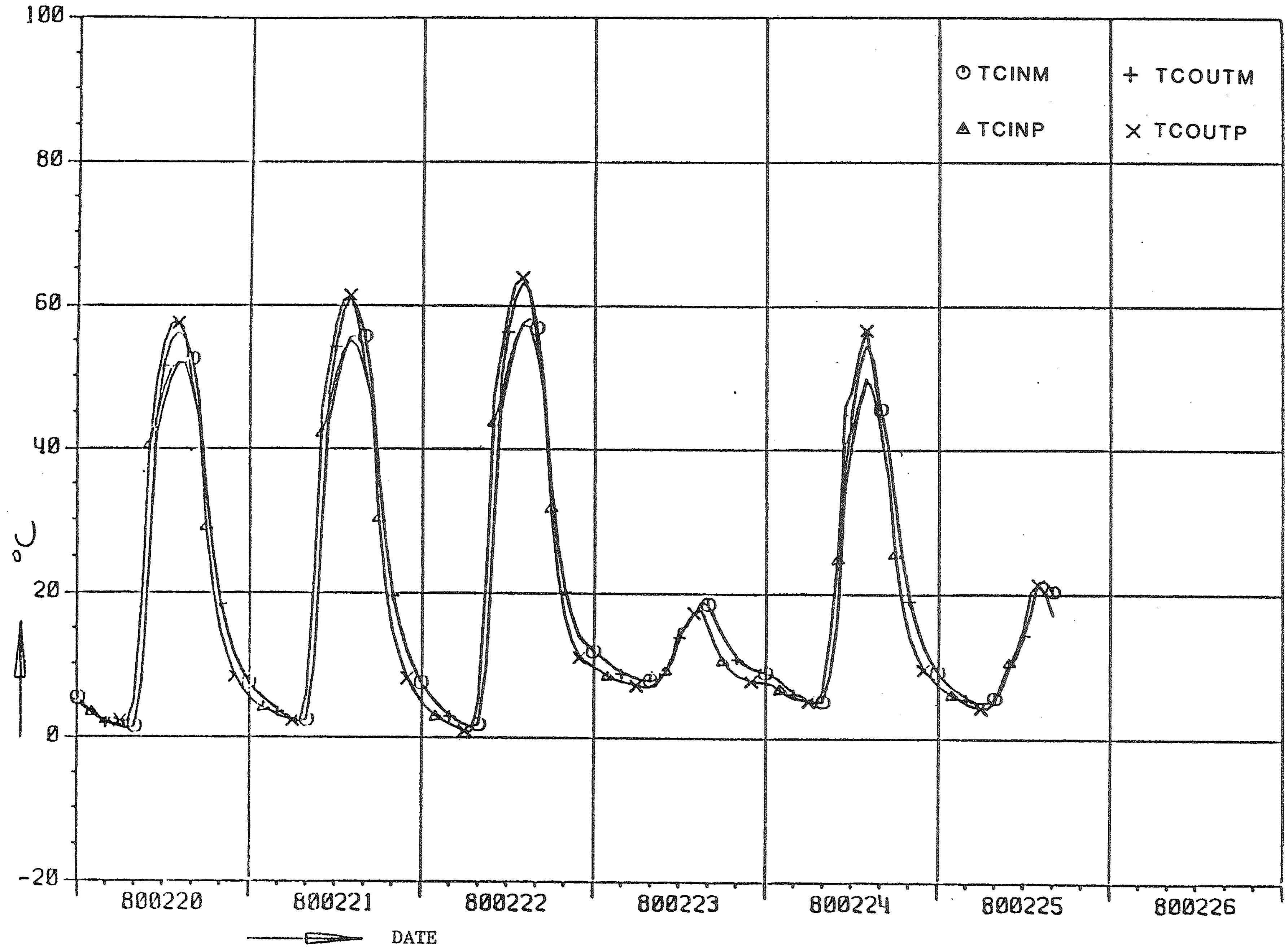


Fig. 5.22 Inlet and outlet collector temperatures measured versus predicted, ref. 7

CHAPTER 6

VALIDATION OF SIMPLIFIED METHODS

6. VALIDATION OF SIMPLIFIED METHODS

6.1 Introduction

Simplified methods can be validated either by comparison to more sophisticated simulation models, or by a direct comparison to the results of experiments. The latter approach was chosen for this initial phase of the work on simplified methods in the Modelling Group.

Within the Performance Monitoring Group a format for reporting the thermal performance of solar heating systems has been developed. The group provided a filled out format for the Milton Keynes Solar House in the United Kingdom. The format specifies the system and gives information on the monthly performance. Two methods were compared to these data: The F-chart method (20) developed at the University of Wisconsin, Madison, USA, and the CFC-2 method (17,18,19) developed at Ecole de Mines, Paris, France.

The two main objectives for this exercise were to have a first trial check on this validation procedure and to provide important feedback to the Performance Monitoring Group with respect to the usefulness of the format developed for this purpose.

6.2 Description of the CFC-2 method

Collected power

Basically: $P = AF_R \left[(\tau\alpha) I - U_c (T_i - T_a) \right]^+$

$$P = AF_R (\tau\alpha) \left[I - I_c \right]^+$$

Where I_c is the threshold radiation:

$$I_c = \frac{U_c}{(\tau\alpha)} (T_i - T_a)$$

and + means "null if negative"

Available energy

The integration gives: $Q_o = AF_R(\tau\alpha) \cdot \bar{H}\cdot_{\varphi}$ kWh/day

φ : "Utilisability" factor

$\bar{H}\cdot_{\varphi}$ is a function of the threshold radiation and is computed using the Cumulative Frequency Curve of solar irradiance on collector plane.

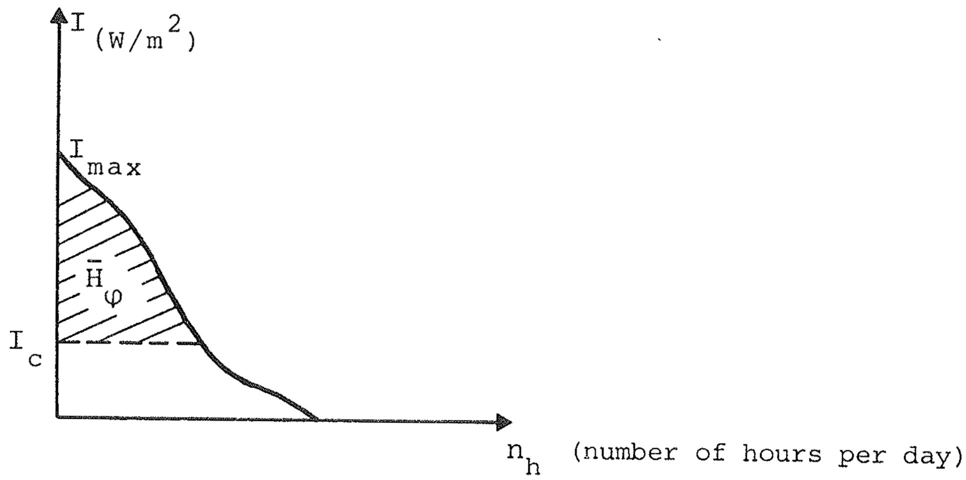


Fig. 6.1 Cumulative frequency curve of solar irradiance

The threshold radiation I_c is computed month by month with a base-temperature T_i equal to the mean outlet temperature of heat emitters.

Useful energy of the system

Only a fraction of available energy Q_o is used by the system to give useful energy Q: the solar useful fraction is given by:

$$Q/L = f = 1 - \exp\left[-0.8\cdot Q_o/L\right]$$

where L is the space heating and DHW load (kWh/day)

These corrective terms to give useful energy from available energy are defined by sample of simulation results.

6.3 Results

Results for the CFC-2 method

The monthly computations give the following results:

$\tau\alpha = 0.85$ $U_c = 6.5\ W\ m^{-2}K^{-1}$ $T_{Base} = 21^o$

Month	φ	Solar fraction (computed)	Solar fraction (measured)
1	0.27	0.13	0.15
2	0.35	0.21	0.23
3	0.54	0.55	0.61
4	0.62	0.81	0.84
5	0.77	1	0.91
6	0.78	1	0.97
7	0.80	1	0.94
8	0.79	1	0.99
9	0.79	1	0.99
10	0.68	1	0.86
11	0.53	0.74	0.64
12	0.25	0.13	0.19

Yearly solar fraction: 0.475 (Measured: 0.483)

Only the data given by the PMG have been used (with exception of the collector parameters not included in the PMG format).

The agreement between predicted and measured values is very good at a monthly level, both for winter months (space heating) and for summer months (domestic hot water heating). On a yearly basis the prediction agrees perfectly with the measurements.

Results for the F-chart method

The monthly computations are the following:

Month	Load (kWh/day)	$\bar{H}$ (kWh/m /day)	Solar fraction (computed)	Solar fraction (measured)
1	53.9	1.16	0.077	0.15
2	56.9	1.63	0.231	0.23
3	39.9	2.55	0.631	0.61
4	30.4	3.39	0.885	0.84
5	16.1	4.77	1.000	0.91
6	6.7	4.56	1.000	0.97
7	6.7	4.28	1.000	0.94
8	5.5	4.86	1.000	0.99
9	6.7	3.89	1.000	0.99
10	11.6	2.32	1.000	0.86
11	21.9	1.56	0.618	0.64
12	37.6	0.85	0.087	0.19

Yearly load: 8870 kWh

Yearly solar fraction: 0.466 (measured 0.483)

On a yearly basis the result is very close to the result predicted by the CFC-2 method, and to the experimental one.

On a monthly basis, larger discrepancies occur due to an under-evaluation of the solar gain in December and January and an over-evaluation in May and October, both phenomena being related to the meteorological basis of the method (direct use of average values of solar radiation and not prediction of the distribution as in CFC-2).

6.4 Conclusions

Naturally, no general conclusions can be drawn from only one case of validation, but both methods predict results in very fine agreement with the measured data. This adds confidence to the use of these methods and provides a background for continuing this work.

With respect to the other objective of this work, important feedback was given to the Performance Monitoring Group and suggestions were very quickly implemented as changes in the format to include more system and component specifications. For example, the collector efficiency equation and the overall loss coefficient of the thermal storage were added.

CHAPTER 7

SPECIFIC TASKS

7. SPECIFIC TASKS

7.1 Introduction

After about one year of operation, the Modelling Group participants recognised that the results obtained so far were not enough to judge some of the model assumptions, the reason being the complexity of the interaction pattern in solar systems modelling. Therefore, it was decided that the participants should form smaller groups to investigate specific aspects of the modelling of solar heating systems.

7.2 Differential equations solution methods

As seen in chapter 2, a very destinct grouping exists between models using an explicit (forwards) Euler and an implicit (backwards) Euler integration method for the system differential equations. The assumption was that the difference between these two methods will show up, when the system time-constant is lowered stepwise by decreasing the storage volume.

Four models were used in this exercise: B, N, GB1 and DK. The two former are both of the explicit Euler type and the two latter use an implicit Euler solution. The Danish participant decided to perform another series of calculations this time using a Trapez method (like in TRNSYS). The results are shown in table 7.1.

As seen in the table, all the models agree very well on the decrease in percent solar for decreasing storage volumes. This is in contradiction to the assumption. The reason for this is that the modellers, using the models with an explicit integration of the system equations, either throughout used a time step of 5 minutes (B), or lowered the time step as the storage volume was decreased (N). This means

Table 7.1 PERCENT SOLAR FOR DECREASING STORAGE VOLUMES

VOL [ℓ]	B 1)	N 2)	GB1 3)	DK 4)	DK 5)
3000	62.5	57.0	62.5	60.4	61.8
2000	61.8	53.2		59.3	
1000	57.4	49.2	51.5	54.5	55.8
500	49.3	42.1	40.5	46.7	
250	38.6	30.4	29.8	36.6	37.8
125	29.7	20.3		27.4	
50	19.7	17.3		21.5	21.5

1) 5-minute timestep
2) varying time step
3) 1 month simulation only
4) hourly time step, Implicit Euler
5) hourly time step, Trapez

that the original intention of finding out at which system time constant the results of the models began to differ, could not be done. On the other hand, some other conclusions can be drawn, namely:

1. Explicit methods can be used for very small time constants as long as the simulation time step is chosen correspondingly.

2. With a simulation time step of one hour, the implicit methods give results in agreement with explicit methods using a time step of 5 minutes, even on very small system time constants.

7.3 Accuracy of collector top loss modelling

From the description of the models it was observed that the collector top loss coefficient was either assumed to be constant, changing linearly with temperature difference between collector plate and ambient, or calculated in more detail, for instance using Klein's formula.

It was assumed that the calculation of the collector loss coefficient has an impact especially on the control of the system. Therefore, a series of four runs was defined to investigate this effect. The starting differential control set point was varied in four steps: 2, 4, 7, 10 °C; and the difference in percent solar was noted. The results are given in table 7.2.

Table 7.2 DIFFERENCE IN PERCENT SOLAR AS A FUNCTION OF DIFFERENTIAL CONTROL SET POINT

	B	GB1	IRL	N
2 °C	(62.9)	(66.1)	(60.5)	(66.1)
4 °C	-0.4	-0.1	-	+0.4
7 °C	-1.1	-0.1	-	+0.4
10 °C	-2.4	-0.2	-	+0.4

The two models using the Klein formula for the top loss coefficient predict a small decrease in percent solar for increasing control set points, whereas the IRL code using a constant U_L value exhibits no difference at all, and the Dutch code predicts a slight increase in percent solar. Although the significance of these results is debatable, they at least provide some background for recommending the use of Klein's formula.

7.4 Collector efficiency curve

Two activities were formulated to test the impact of using detailed collector efficiency calculations, straight line or curved line assumptions. Three of the participants volunteered to investigate this question: Jürgen Reichert (D), Elaine Kelledy (IRL) and Stephen Grove (GB2).

Jürgen Reichert from Germany investigated four cases compared to a base case, see table 7.3.

Table 7.3 CASES STUDIED BY GERMAN PARTICIPANT					
Case	0 (base)	1	2	3	4
$\tau\alpha$-product	c.t. 1)	.85	.77	.77	c.t.
U_L-value, $W/m^2/K$	c.t.	6.54	5.35	c.t.	5.35
1) c.t. = calculated at each time step					

Normally the German model calculates both the $\tau\alpha$-product and the U_L-value at each time step, and on request it prints out the monthly and yearly mean of these values (when the collector delivers energy to the system). These values were used in case 2 and compared to case 1 in which the values from the installation descriptor were used. The two sets of constants gave almost the same results. Compared to the base case there was considerable overprediction in summer and a small underprediction in winter.

In cases 3 and 4 either a constant $\tau\alpha$-product or a constant U_L- value was used. The results are compared to the base case in fig. 7.1 It is very clearly seen that the use of a constant U_L-value and a varying $\tau\alpha$-product provides the best fit with the base run. The conclusion, therefore, is that it is important to calculate the $\tau\alpha$-product at each time step rather than the U_L-value. The opposite choice is often made by solar system modellers (see chapter 2).

Elaine Kelledy from Ireland investigated the same four cases but did not come up with any conclusion with respect to using either a constant $\tau\alpha$ or U_L-value. Her calculations indicated that the true value of the average $\tau\alpha$-product should be 0.75, which is in good agreement with what Jürgen Reichert found.

Stephen Grove from the United Kingdom concentrated his effort on finding an average collector loss coefficient. The approach was to find which constant number for U_L gave the best fit to the results obtained by using the linearly varying U_L-value proposed by the Dutch participant: $3.8 + 0.02\Delta T$ W/K/m^2. The U_L-value found was approximately 4.6 W/K/m^2, which compares reasonably well with the value found by Jürgen Reichert.

As a general conclusion from this exercise it can be stated that straight line approximations to the collector efficiency curve can be used in the simulation models, and reasonable results can be obtained, presuming the straight line parameters (slope and intersect) have been established by a detailed analysis. If only one of these values can be calculated at each time step it should be the $\tau\alpha$-product. (This is a great advantage because it allows for time saving pre-processing of the weather data).

7.5 System Dynamics

A special task was devoted to an investigation of how well the simulation model predicts the dynamic behaviour of the system. In this case it was decided to compare the measured and predicted duration of periods of collecting and not collecting solar energy.

Fig. 7.2 shows a comparison of the measured and calculated collecting periods derived from the Belgian 5-minute data. The figures to the right represent the difference between calculated and measured 5-minute time steps, the positive values indicating the number of time steps in which the calculated system is "on" and the measured one is "off"; the negative values indicating the number of time steps in which the measured system is "on" and the calculated one is "off". In general, the results are reasonable taking into account the rapidly changing weather conditions during some periods. However, the calculated system has more "on" time steps and almost always switches to the "on" position a few steps before the measured system. This may be caused by the values of the start and stop differential, which are not known exactly. The Belgian PTF participants confirmed that there were indications of a possible variations in these values.

7.6 Time Step

The sensitivity to the size of simulation time step differs among programs using different equation solution techniques. To test this sensitivity a short series of calculations were performed with the time step changed in steps from one hour to 5 minutes. The results are presented in table 7.4.

Table 7.4 SENSITIVITY TO TIME STEP, PREDICTED PERCENT SOLAR

Time step	DK	GB2
3600	56.7	37.0
1800	59.9	46.6
900	61.1	53.2
300	61.7	57.8

It appears from the table that the GB2 model is highly sensitive to the choice of time step. The English participant, Stephen Grove, has not experienced a sensitivity of this order of magnitude of the model on other systems and believes it is because of the special control strategy of the PTF system, where both pumps are running all the time, and collection is initiated by allowing the fluid in the primary circuit to pass through the heat exchanger. The GB2 model solves the system equations sequentially which, in the case of a SPTF type, might be more critical than in other systems. Even the DK model, which solves the equations simultaneously by an implicit method, shows a great deal of sensitivity to the choice of time step. The percent solar increases relatively almost 10%.

The Danish participant investigated this problem a little further and found that the differences found for different time steps were due to two separate effects:

1. Control shift during a time step.
2. Integration error accumulation.

He therefore changed the program in such a way that, when a control shift was happening, the program automatically used 5-minute time steps during the hour in question. The results obtained this way are compared to the results of the original version of the program for various time steps on fig. 7.3. From this figure it appears that the prediction of the accurate time of control shift during a time step is the reason for the biggest part of the observed difference. Almost 4% of the 5% difference stems from that. From fig. 7.3 it can also be concluded that a time step of 10-15 minutes seems to be appropriate to obtain very accurate results with this type of model. Alternatively, a model that automatically switches to smaller time steps, when a change in the system operating mode occurs, give fairly good results.

7.7 Statistical analysis of PTF-validation calculations

The Belgian participant, Willy Dutré, volunteered to study the effect of uncertainty of model predictions and system measurements on the validation results and to develop a procedure to systematically treat these problems in the validation work. This work was completed and reported in March 1981, ref. 15, and the method developed has been implemented in the programme of the Modelling Group.

7.8 Detailed studies of components

The French participant had a special simulation code available, ORIENT, which takes into account many more details of the systems than the code HABSOL used elsewhere in this context. Using this model a series of calculations on one day's data were performed to find the parameter values resulting in best agreement with the measurements. Fig. 7.4 shows such a series of runs to obtain a correct estimate of the absorber plate emittance.

7.9 Measured collector performance

The Danish participant volunteered to investigate the agreement between the collector efficiency curve obtained by a single collector efficiency test, and the curve obtained by analyzing the data from a real system installation (the Danish SPTF).

The type of collector used on the SPTF's has been tested by the European Communities Collector Testing Group in a Round Robin testing programme (ref. 23). The dashed curve on fig. 7.5 is the efficiency curve obtained by this group. By analyzing selected data points (solar radiation above 700 W/m^2, small incidence angle) from a four month period, Ole Balslev-Olesen has obtained the two other curves on fig. 7.5. Curve no. 3 is obtained by taking into account the transient effects (e.g. collector heat capacity), and curve no. 2 by ignoring these. It was not possible to obtain the y-axis intercept (η_o) from the SPTF data. Therefore the value obtained by the Collector Testing Group was used.

The agreement seems satisfactory, but what does the difference mean over a year's simulation of a complete system? Ole Balslev-Olesen compared two simulations of the SPTF system using curve 1 and curve 3 on the Danish Test Reference Year and found a relative difference of 8% on the percent solar. This result shows that the use of collector efficiency curves obtained by collector testing must be done very carefully and with an analysis of the effect of integrating collectors in a system. In this case heat losses especially, because of wind speed, were drastically reduced in the system integration of the collectors compared to the individual collector testing.

7.10 Statistical validation methods

In the search for criteria for how well model predictions agree with experimental results, the Danish participant, Ole Balslev-Olesen, identified four statistical methods and made some trial calculations with them (5). The methods identified were MEAN, STANDARD DEVIATION, RANGE and NUMBER OF ACCEPTABLE DATA POINTS. Such methods can be used for the comparison of the results of different models to the same set of data and can be used in addition to simple comparisons of state and flow variables. For validation methods see also ref. 16.

7.11 Extrapolation of results

One of the basic objectives of working with simulation models is to be able to predict the performance of solar systems in different climates and under different working conditions. When a simulation model has been validated, using data obtained from a certain system configuration, the model can be used to simulate this system by using another set of weather data, another load profile and, perhaps, another collector area, and thus extrapolating the results of the experiment to a number of cases. One of the questions this procedure raises is, how long a period of continous measurements is needed for each sequence of data to get some stability of the validation results. This question was addressed by the Danish participants by plotting the accumulated difference between model predictions and experimental results for energy flows and efficiencies. Fig. 7.6 and 7.7 in ref. 5 show these differences for the collector efficiency and the system efficiency respectively, for six different sets of data. The conclusion is that reasonable stability is reached after a period of 12-14 days. The appropriate length of data sequences for validation purposes is therefore 12-14 days.

7.12 Temperature stratification in storage tank

At the end of the working period the Danish SPTF-SS1 installation was changed allowing for thermal stratification, and at the same time the Danish code was modified to model this. Some validation comparisons and the method used are presented in ref. 5. Fig. 7.8 shows how well the predicted top and bottom tank temperatures agree with the measured. The agreement is fairly satisfactory. In this case a model with five layers in the storage tank was used. These results therefore add confidence to the assumption that five layers in a storage tank model will be adequate for most purposes.

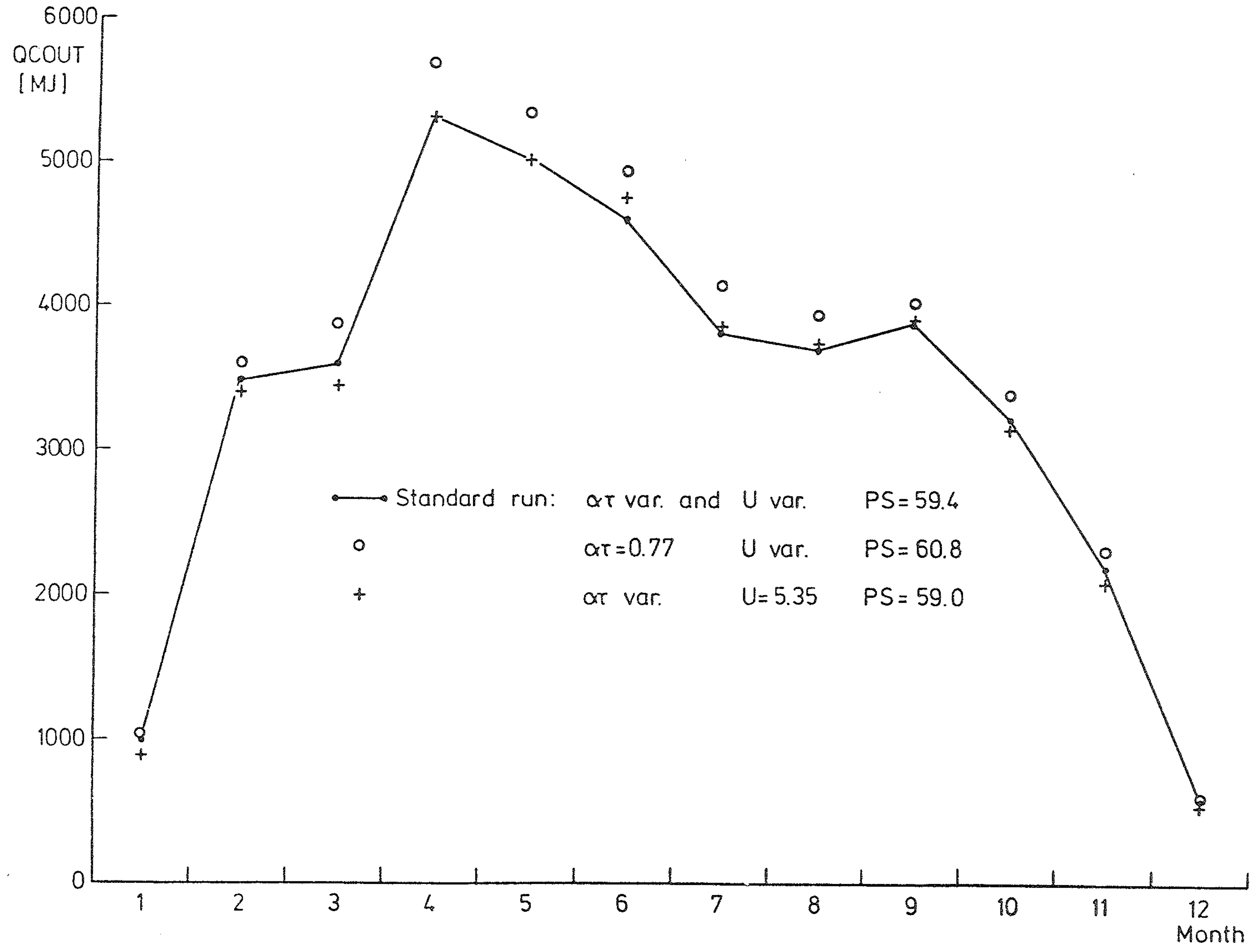


Fig. 7.1 Monthly collector output for variable vs. constant values of $\alpha\tau$ and U , ref. 13

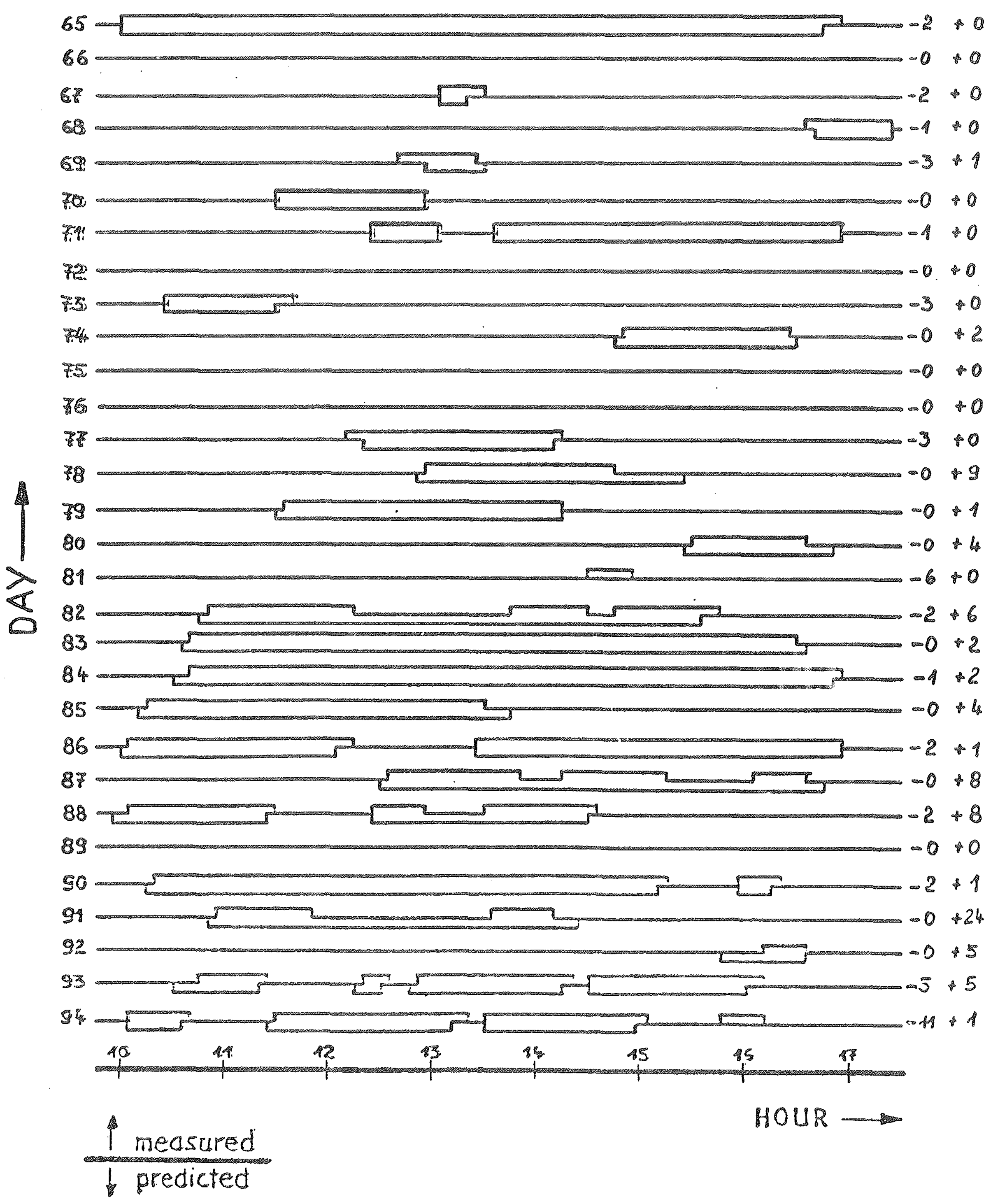


Fig. 7.2 Comparison of measured and predicted status of collecting/non collecting, ref. 13

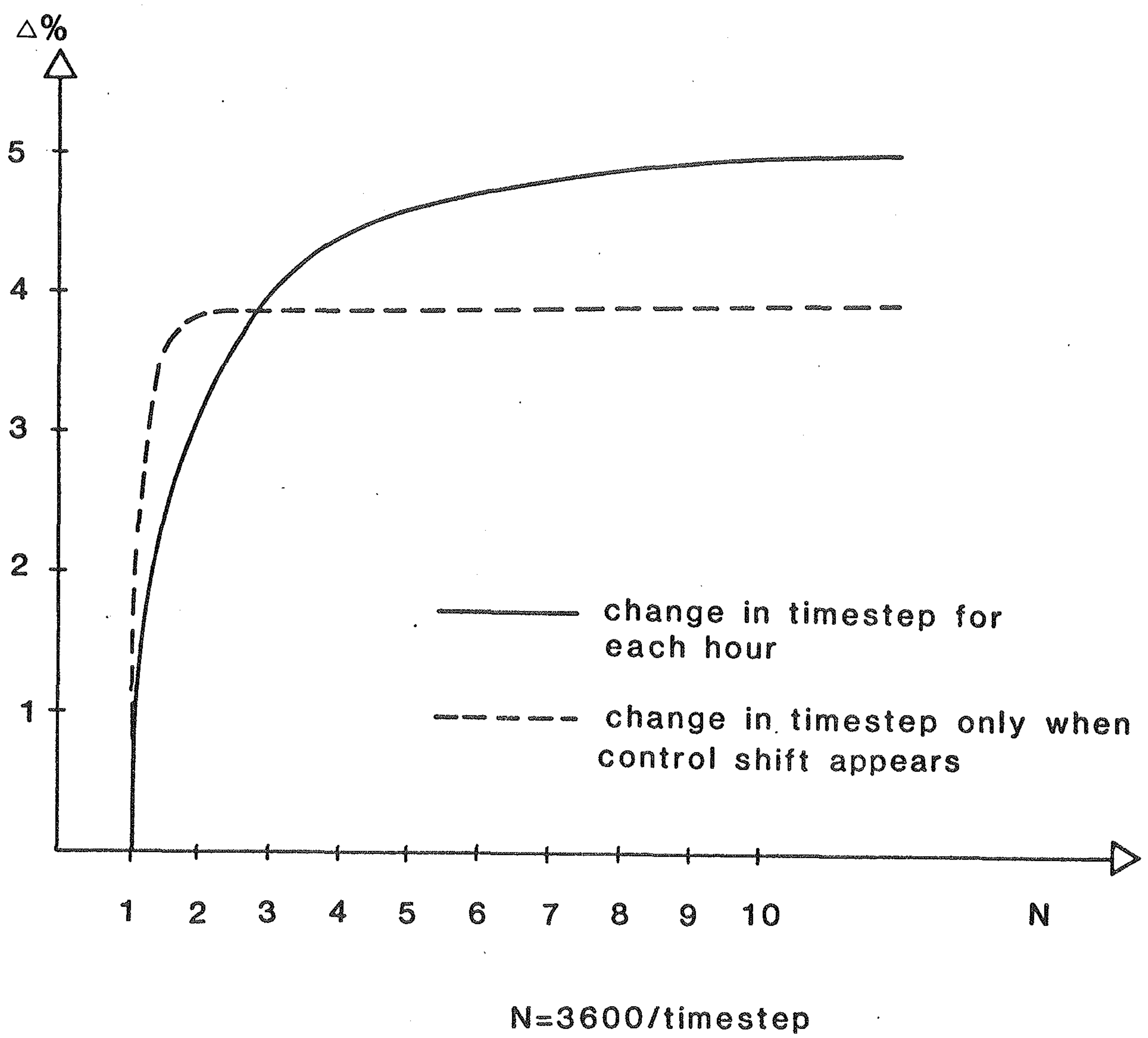


Fig. 7.3 Change in predicted percent solar by Danish code as function of time step.

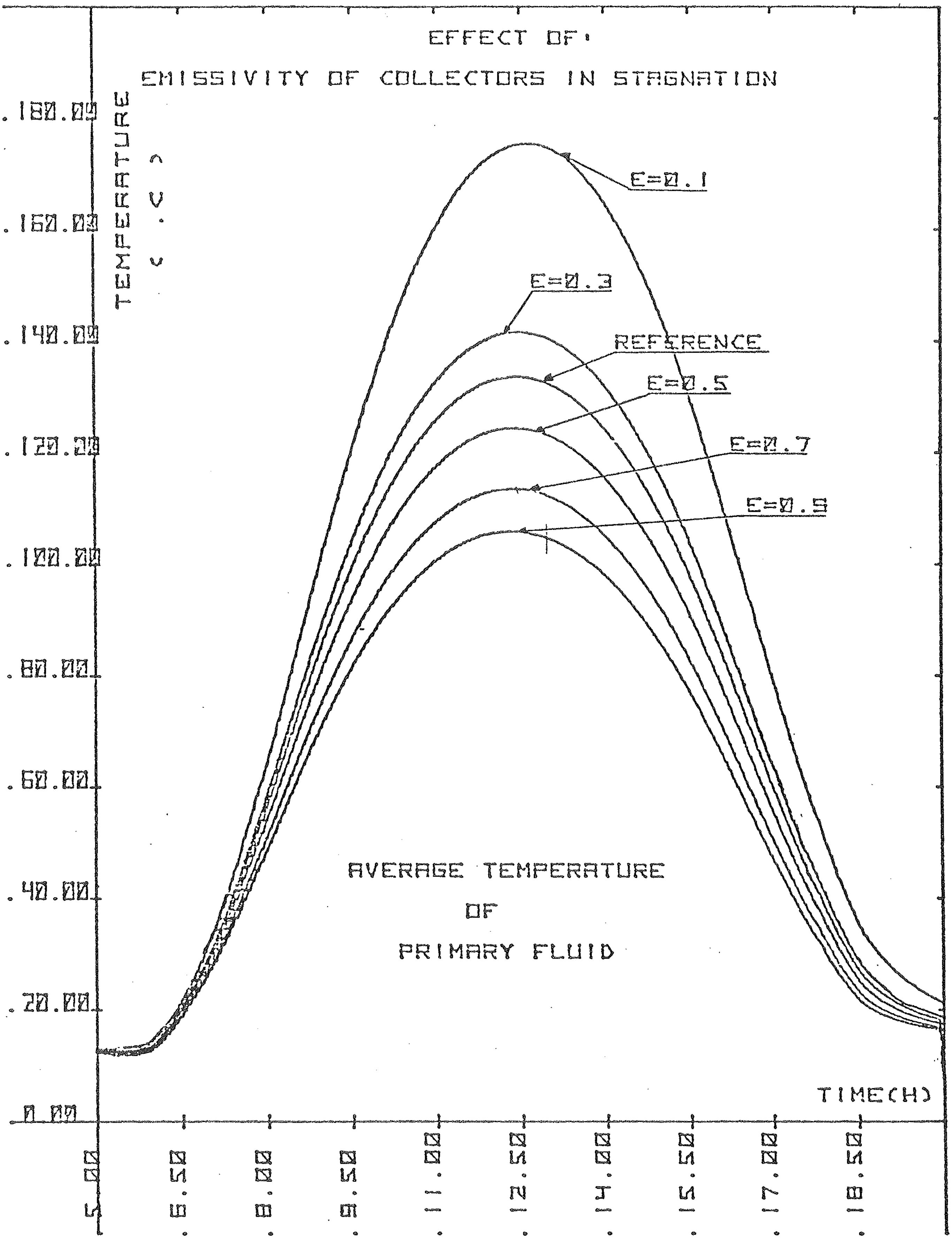


FIG. 7.4 Search for correct absorber plate emissivity, ref. 14

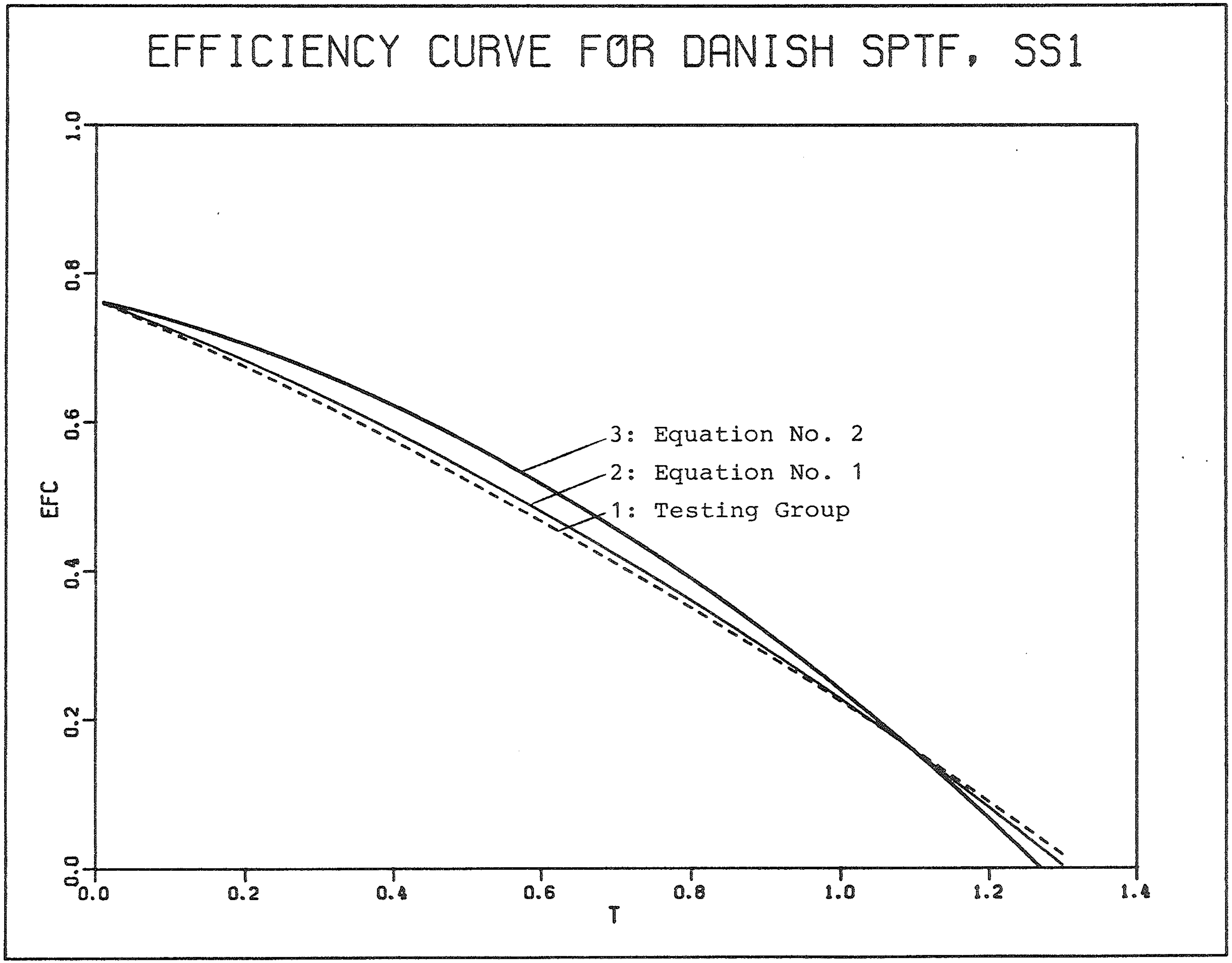


Fig. 7.5 Comparison of efficiency curves, ref. 5

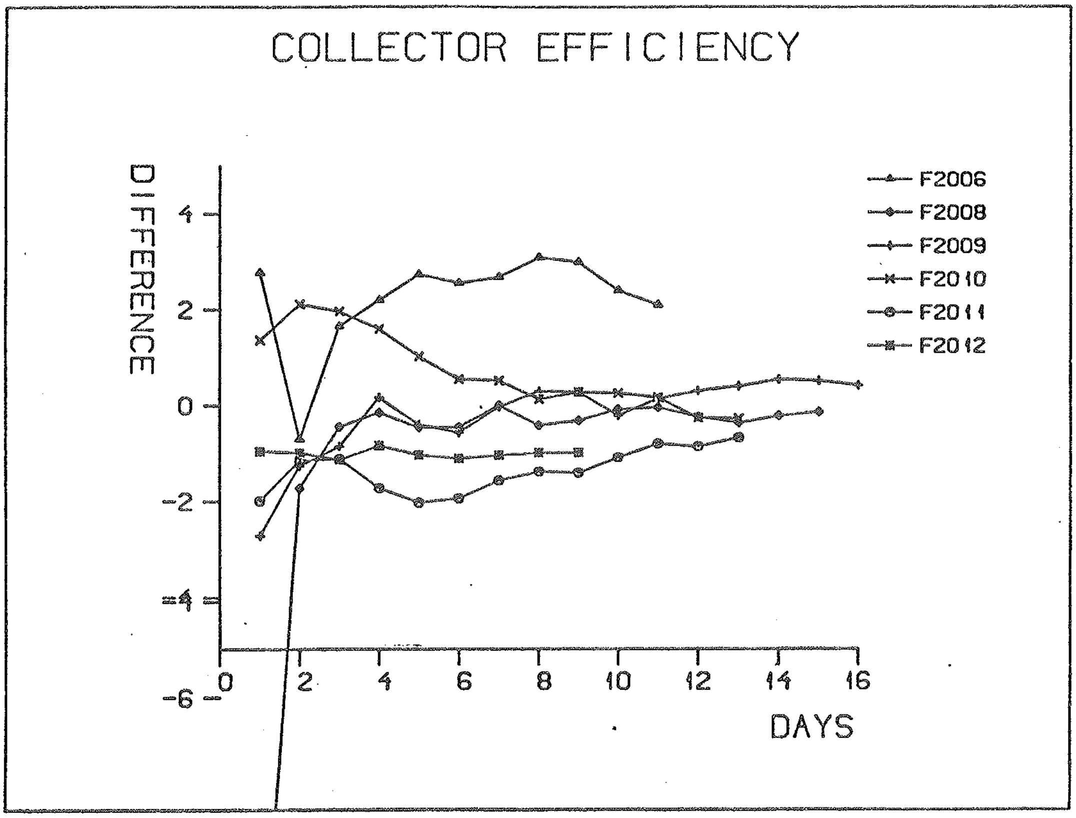


Fig. 7.6 Plot of the differences (in percent) between measured and predicted collector efficiency.

$$D_n = \sum_{i=1}^{n} \left(\frac{E1^P}{EO} \right)_i - \sum_{i=1}^{n} \left(\frac{E1^M}{EO} \right)_i \qquad M = 1,2,\ldots\ldots.16 \text{ days}$$

EO: Integrated collector global radiation

$$\left.\begin{array}{l} 2006 \\ 2008 \\ 2009 \\ 2010 \\ 2011 \\ 2012 \end{array}\right\} \text{number on the cassettes used}$$

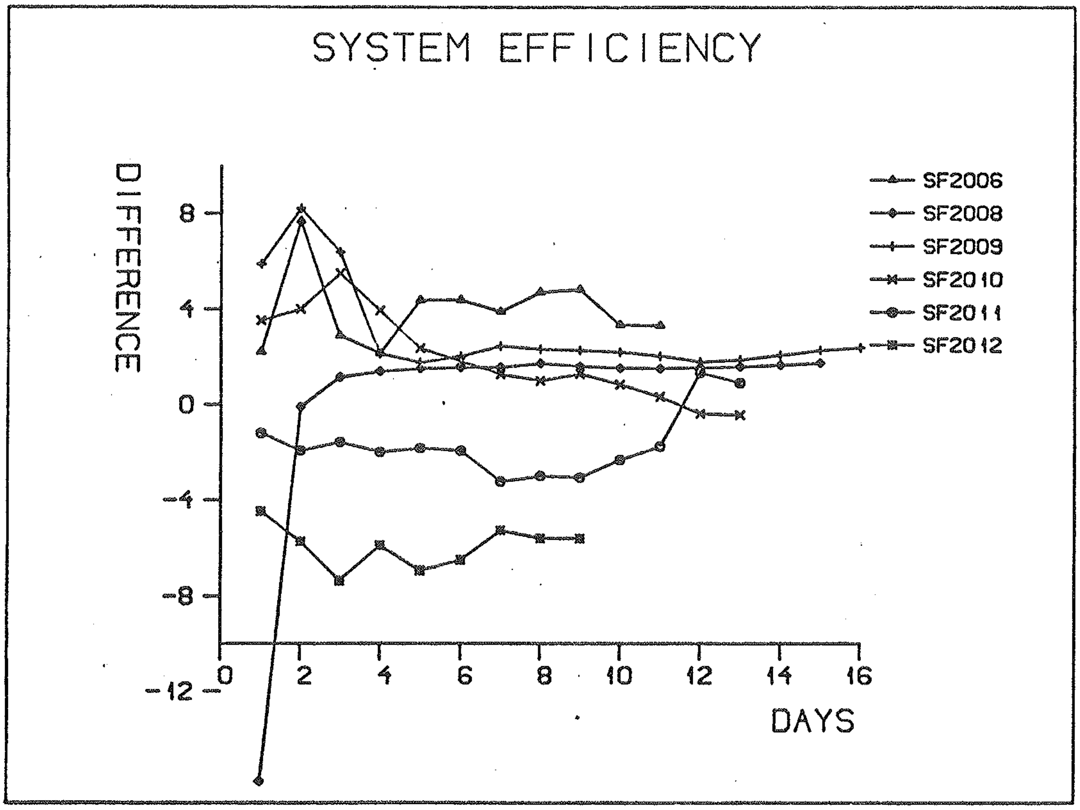


Fig. 7.7 Plot of the differences (in percent) between measured and predicted system efficiency.

$$D_n = \sum_{i=1}^{n} \left(\frac{E3^P + E4^P}{E1^P} \right)_i - \sum_{i=1}^{n} \left(\frac{E3^M + E4^M}{E1^M} \right)_i \qquad i=1,2,\ldots .16 \text{ days}$$

$E3^P$: integrated interface loss, predicted.

$E3^M$: integrated interface loss, measured.

$E4^P$: integrated heat gain for domestic hot water (predicted)

$E4^M$: integrated heat gain for domestic hot water (measured)

2006
2008
2009
2010
2011
2012

} number on the cassettes used

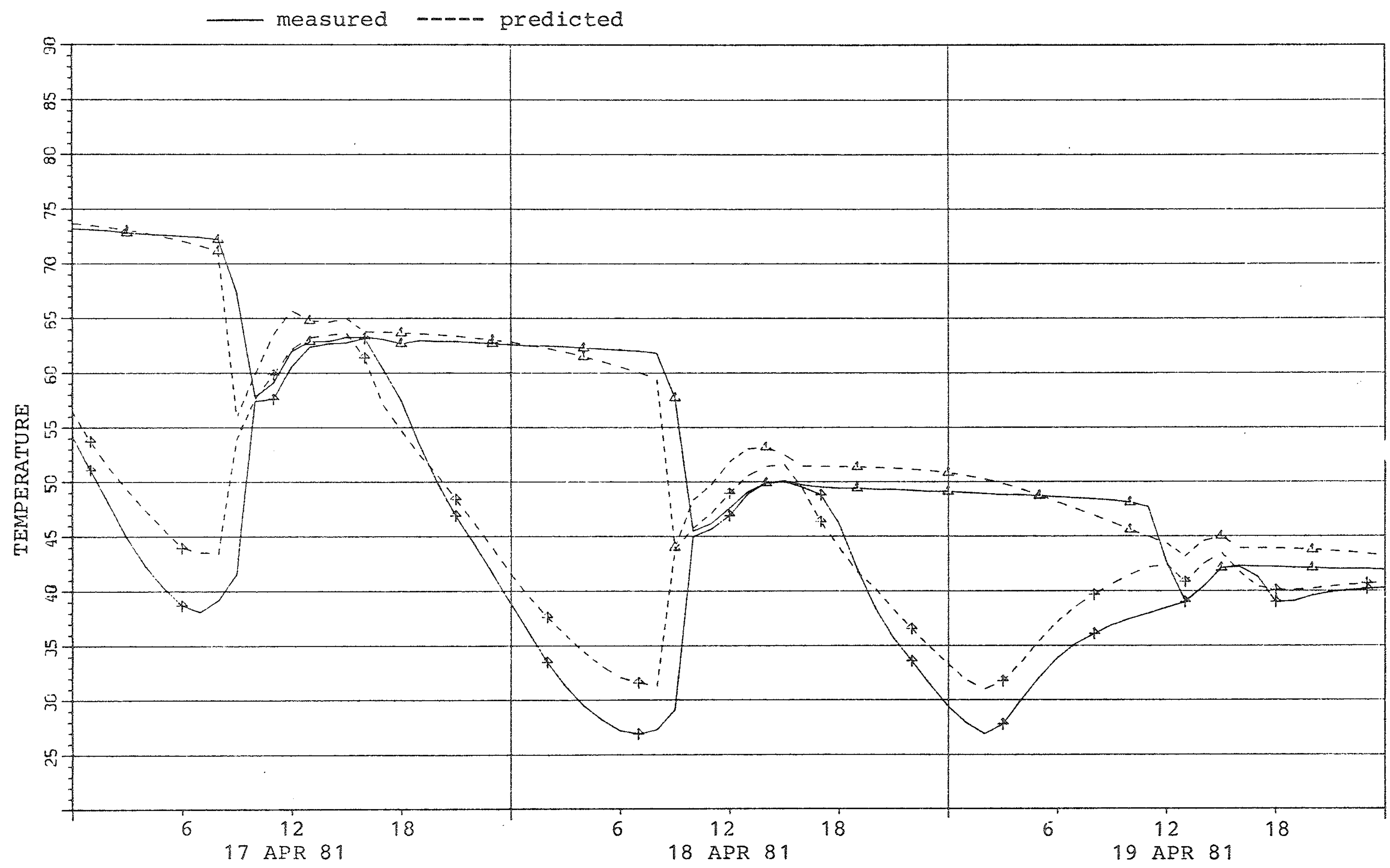


Fig 7.8 Measured and predicted temperature at top and bottom of the storage tank.

CHAPTER 8

CONCLUSIONS

8. CONCLUSIONS

8.1 Objectives

At the outset of this cooperative programme a number of goals or objectives for this first one and a half year working period were identified:

- Model - model comparisons and sensitivity analyses on SPTF-type of system.
- Component model validation on SPTF-data
- Overall system validation on SPTF-data (from at least two different installations).
- Extrapolation of results in time and location.
- Small time increment validation.
- Recommendations for mathematical descriptions of solar heating system modelling.
- Simplified design method validation using PMG format.

At the end of the working period it could be established that these objectives had been met in a satisfactory way. This is thoroughly documented in details in the preceding chapters and in the reports of the participants, see ref. 5-14. The results of these activities are briefly summarized in the paragraphs below, and some general conclusions are drawn.

8.2 Parameter sensitivity analyses

All the participants had their models set up to model the SPTF-SS1 system, and a total number of three parameter sensitivity analyses were performed. An improvement in the modelling of this system was achieved resulting in an improved agreement among the models in the final analysis.

In the third parameter sensitivity analysis the models were used to extrapolate from a given configuration of the system to another, thus enabling clear directions to be given to the SPTF Group with respect to system changes.

8.3 Validation of simulation models

This activity was undertaken both as a local activity (national validation) and by exchange of data from a SPTF in one country to modellers in other countries (common validation). Both activities were considered very useful, but with a slightly different scope. The national validation activity allows for direct interaction between the modeller and the person responsible for the system hardware (who in some cases is the same person). This interaction enabled progress to be made on both fronts. The model showed up deficiencies in the systems and changes in their performance, and the measurements highlighted areas where the models required improvement. Only the latter achievement was practical for the common validation activity. However, a very significant advantage of this activity was that two of the participants, who had received no or very little data useful for validation work during the working period, by this activity obtained valuable data from other systems. This gave them an opportunity to gain important experiences from validation of their models.

The results of the national and common validation work were very similar. By comparing measured and predicted states of the system and dynamic behaviour on comparison plots, the agreement seemed satisfactory. A detailed comparison of integrated energy flows revealed, however, in some cases unacceptable differences in the order of 10-15%. The reasons for these differences are difficult to identify. Some of the reasons are:

- wrong input data
- inaccurate operation of the building load interface of the SPTF-system
- malfunctioning of components
- model shortcomings

8.4 Recommendations for validation

From some of the detailed component validation work it can be concluded that one of the most important factors for good validation work is to have accurate input data.

The model input data describing the system should be based on the system as built or, even better, as measured to provide meaningful comparisons between model predictions and thermal performance measurements. Experience with the SPTFs and other solar systems has shown that the systems are very rarely built to the design specifications.

One of the questions often raised with respect to the validation of simulation models of solar heating systems deals with the necessary amount of data for this purpose. The answer found during this work is that the appropriate length of data sequences is 12-14 days. It is recommended that the data sequences used are taken under different weather conditions, e.g. during spring, summer, autumn and winter.

8.5 Recommendations for modelling

It appears from chapter 2 that the models used within this programme covered a wide variety of model assumptions and philosophies. One of the objectives of this work was to clarify the impact of these different model strategies on the simulation results.

Besides the activities scheduled in the programme from the outset (parameter sensitivity analysis and validations), a number of special tasks were identified during the work, most of them designed especially for one model or group of models, to better accomplish this objective. This work is described in detail in chapter 7. Below the results are generalized and summed up.

Collector loss coefficient

Many of the models make use of Klein's formula (20) for the top loss coefficient, and all the results obtained with this expression in this context support the continued use of it. Another approach attempted was a linear dependency of plate and ambient temperature difference. This also seemed to be a reasonable assumption. Even the use of a constant loss coefficient can be justified from the results obtained under this work, provided that a detailed analysis goes into finding the right parameter to use.

Collector transmission-absorption-($\tau\alpha$) product

One of the special tasks performed gave the conclusion that it is more important to calculate the $\tau\alpha$- product than the collector loss coefficient at each time step.

Time step and integration methods

Two of the special tasks performed clearly showed that using a time step of one hour does not always lead to correct results. These factors influence the size of time step necessary:

- type of model, explicit or implicit
- system time constant
- system control strategy

As a general rule implicit methods are much less sensitive to the choice of time step than explicit methods. It is shown, however, that even for normal system time constants (storage volume/collector area = 100 litre/m^2) a time step of one hour, used in an implicit method, yields results that are 5% off in absolute value from predictions obtained with a time step of 10-15 minutes. This difference is mainly due to changes of system mode operation occurring during a time step.

8.6 Validation of simplified methods

Two simplified design methods, the French CFC-2 and the American F-Chart method, were compared to a year's measurement of the first solar house at Milton Keynes, reported in the reporting format developed by the Performance Monitoring Group.

The two methods showed exceptionally good agreement to the measured results, both on a monthly and a yearly comparison basis. The exercise resulted in important feedback to the Performance Monitoring Group with respect to the usefulness of the format for validation purposes. This feedback was quickly implemented as changes to the format.

8.7 Future work

At the outset of the programme the development of the two European Solar Heating System Yearly Forecast Programmes (one simulation model and one simplified method) were identified as long term goals. To achieve these goals it was decided to focus the work of the group on one simulation model in the current programme. This model has been distributed to all the participants and is being reviewed and validated against data from the SPTF installations.

The work on simplified methods has been greatly extended, and at the moment several of these methods (approx. 8) are being evaluated, both with respect to ease of use and to accuracy. The latter is being assessed using the results of the detailed simulation model mentioned above.

8.8 Concluding remarks

Many of the participants of the Modelling Group have expressed their satisfaction with the work in the group. A couple of citations from the final reports of the participants are presented here to illustrate their viewpoints:

> "Generally, the work done by this group was very encouraging. Cooperating with the SPTF Group was a stimulation to develop models more practically." (ref.13)

"During the period of this work considerable progress has been made with both model development and understanding of the nature and behaviour of active solar energy systems ......" (ref. 10)

"Discussion with other members of the group, and comparison of models, has meant that more progress has been made than would have been, had the work been done in isolation." (ref. 10).

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Address inquiries to: Mr. T.C. Steemers.

Appendix 1 INSTALLATION DESCRIPTOR ID1	ID1 describes a configuration of SS1 in the country concerned. (See schematic overleaf)	(1) 2 | (2) 0 1 version

PARAMETER	VALUE	UNIT
P1 (1,1) : ABSORBER AREA FOR ALL COLLECTORS	46.47	[m^2]
P1 (1,2) : TILT	56	[°]
P1 (1,3) : AZIMUTH	SOUTH	
P1 (1,4) : COVER ABSORPTANCE	~~0.84~~ 0,084	
P1 (1,5) : COVER REFRACTIVE INDEX	1.52	
P1 (1,6) : ABSORBER ABSORPTANCE	0.93	
P1 (1,7) : ABSORBER EMITTANCE	~~0.70~~ 0,3	
P1 (1,8) : SPACE BETWEEN COVER AND ABSORBER	0.035	[m]
P1 (1,9) : BACK AND SIDE LOSSES (FOR ALL COLLECTORS)	42	[WK^{-1}]
P1 (1,10) : HEAT CAPACITY for all collectors and their connections incl. fluid	523	[kJK^{-1}]
P1 (1,11) : FLUID CONTENT (FOR ALL COLLECTORS)	0.0564	[m^3]
P1 (1,12) : SPECIFIC HEAT OF FLUID (20 [°C])	3.914	[$kJK^{-1}kg^{-1}$]
P1 (1,13) : DENSITY OF FLUID (20 [°C])	1063	[$kg\ m^{-3}$]
P1 (1,14) : OPTICAL FACTOR OF COLLECTOR ($\alpha\tau$)	0.85	
P1 (1,15) : THERMAL FACTOR OF COLLECTOR (U_L)	6.54	[$Wm^{-2}K^{-1}$]

(1) Country : 1 = Belgium, 2 = Denmark, 3 = France, 4 = Germany, 5 = Ireland, 6 = Italy, 7 = The Netherlands, 8 = United Kingdom

(2) : Version number

INSTALLATION DESCRIPTOR ID1	ID1 describes a configuration of SS1 in the country concerned. (See schematic overleaf)	(1) 2 (2) 0 1 version

PARAMETER	VALUE	UNIT
P1 (2,1) : TOTAL LENGTH OF COLD SIDE PIPING	54.0	[m]
P1 (2,2) : OUTSIDE LENGTH	51.25	[m]
P1 (2,3) : TOTAL VOLUME	0.086	$[m^3]$
P1 (2,4) : HEAT CAPACITY (INSIDE PIPING) steel only	~~1.742~~ 8.0	$[kJK^{-1}m^{-1}]$
P1 (2,5) : HEAT CAPACITY (OUTSIDE PIPING) steel only	1.83	$[kJK^{-1}m^{-1}]$
P1 (2,6) : HEAT LOSS COEFFICIENT (INSIDE PIPING)	0.5	$[WK^{-1}m^{-1}]$
P1 (2,7) : HEAT LOSS COEFFICIENT (OUTSIDE PIPING)		$[WK^{-1}m^{-1}]$
P1 (2,8) : ELECTRICAL POWER OF THE PUMP	910	[W]
P1 (2,9) : POWER DELIVERED TO THE FLUID	50 ~~[illegible]~~	[%] of P1 (2,8)
P1 (2,10) : VOLUME OF THE BYPASS		

(1) Country : 1 = Belgium, 2 = Denmark, 3 = France, 4 = Germany, 5 = Ireland, 6 = Italy, 7 = The Netherlands, 8 = United Kingdom

(2) : Version number

INSTALLATION DESCRIPTOR ID1	ID1 describes a configuration of SS1 in the country concerned. (See schematic overleaf)	(1) 2 / (2) 0 1 version

PARAMETER	VALUE	UNIT
P1 (3,1) : TOTAL LENGTH OF HOTSIDE PIPING	52.8	[m]
P1 (3,2) : OUTSIDE LENGTH	50.05	[m]
P1 (3,3) : TOTAL VOLUME	0.084	[m^3]
P1 (3,4) : HEAT CAPACITY (INSIDE PIPING) steel only	~~1.74~~ 8.0	[$kJK^{-1}m^{-1}$]
P1 (3,5) : HEAT CAPACITY (OUTSIDE PIPING) steel only	~~1.74~~ 1.83	[$kJK^{-1}m^{-1}$]
.1 (3,6) : HEAT LOSS COEFFICIENT (INSIDE PIPING)	0.5	[$WK^{-1}m^{-1}$]
P1 (3,7) : HEAT LOSS COEFFICIENT (OUTSIDE PIPING)		[$WK^{-1}m^{-1}$]

(1) Country : 1 = Belgium, 2 = Denmark, 3 = France, 4 = Germany, 5 = Ireland, 6 = Italy, 7 = The Netherlands, 8 = United Kingdom

(2) : Version number

INSTALLATION DESCRIPTOR ID1	ID1 describes a configuration of SS1 in the country concerned. (See schematic overleaf)	(1) 2 (2) 0,1 version

PARAMETER	VALUE	UNIT
P1 (4,1) : Δ T on	2	[K]
P1 (4,2) : Δ T off	0	[K]

(1) Country : 1 = Belgium, 2 = Denmark, 3 = France, 4 = Germany, 5 = Ireland, 6 = Italy, 7 = The Netherlands, 8 = United Kingdom

(2) : Version number

INSTALLATION DESCRIPTOR ID1	ID1 describes a configuration of SS1 in the country concerned. (See schematic overleaf)	(1) 2 (2) 0,1 version

PARAMETER	VALUE	UNIT
P1 (5,1) : HEAT TRANSFER COEFFICIENT	1000	$[WK^{-1}m^{-2}]$
P1 (5,2) : HEAT TRANSFER AREA	1.47	$[m^2]$
P1 (5,3) : EFFICIENCY	0.44	
P1 (5,4) : HEAT LOSS COEFFICIENT		$[W K^{-1}]$

(1) Country : 1 = Belgium, 2 = Denmark, 3 = France, 4 = Germany, 5 = Ireland, 6 = Italy, 7 = The Netherlands, 8 = United Kingdom

(2) : Version number

INSTALLATION DESCRIPTOR ID1	ID1 describes a configuration of SS1 in the country concerned. (See schematic overleaf)	(1) 2 (2) 0 1 version

PARAMETER	VALUE	UNIT
P1 (6,1) : VOLUME OF TANK	3	[m^3]
P1 (6,2) : VOLUME OF SECONDARY CIRCUIT	0.010	[m^3]
P1 (6,3) : LENGTH OF SECONDARY LOOP	6	[m]
P1 (6,4) : SPECIFIC HEAT OF THE FLUID (20 [°C])	4.185	[$kJkg^{-1}K^{-1}$]
P1 (6,5) : DENSITY OF THE FLUID (20 [°C])	1 atm 998	[$kg.m^{-3}$]
P1 (6,6) : HEAT CAPACITY OF TANK (INCL. FLUID)	12686	[kJK^{-1}]
P1 (6,7) : HEAT CAPACITY OF PIPING (INCL. FLUID)	60	[kJK^{-1}]
P1 (6,8) : HEAT LOSS COEFFICIENT OF TANK	15	[WK^{-1}]
P1 (6,9) : HEAT LOSS COEFFICIENT OF PIPING	0.5	[$WK^{-1}m^{-1}$]
P1 (6,10) : ELECTRICAL POWER OF THE PUMP	460 ~~[illegible]~~2	[W]
P1 (6,11) : POWER DELIVERED TO THE FLUID	~~250~~ 50	[%] of P1 (6,10)

(1) Country : 1 = Belgium, 2 = Denmark, 3 = France, 4 = Germany, 5 = Ireland, 6 = Italy, 7 = The Netherlands, 8 = United Kingdom

(2) : Version number

Appendix 2

PTF LOG SHEET

LS

(1)	(2)	(3)	(4)	(5)
1 0	0 1			
cassette number		date sent		

DESCRIPTION OF SEQUENCES

S (6)	START (7)					DD (8)							ID (9)				END (7)				
						CASE	DD0		DD1		DD2		ID1		ID2						
	M	D	H	m	F (10)		C	V	C	V	C	V	C	V	C	V	M	D	H	m	(10) F
1	11 or 12	x	18		100	1	1	01	1	01			1	01			11 or 12	x+15	17		435
2																					
3																					
4																					
5																					
6																					
7																					
8																					
9																					
10																					
11																					
12																					
13																					
14																					
15																					

REMARKS

Daily global radiation [$Wh\ m^{-2}$] / ($\sum_{day}$ C.G.R.)

x+1 - 7 9	1 0 1	x+8 - 7 9	1 2 0
x+2 - 7 9	5 0	x+9 - 7 9	2 6 0
x+3 - 7 9	2 6 5	x+10 - 7 9	2 3 1
x+4 - 7 9	1 0 7 4	x+11 - 7 9	1 5 6 6
x+5 - 7 9	3 0 1	x+12 - 7 9	1 1 5 6
x+6 - 7 9	3 4 2	x+13 - 7 9	3 9 0
x+7 - 7 9	9 5	x+14 - 7 9	2 1 2

EXPLANATION

(1) : Sender : 1 = Belgium
2 = Denmark
3 = France
4 = Germany
5 = Ireland
6 = Italy
7 = The Netherlands
8 = United Kingdom

(2) : Cassette number given by the PTF participant

(3) : Day

(4) : Month

(5) : Year

(6) : Sequence

(7) : M : Month
D : Day
H : Hour
} date in Apparent Solar Time
m : minute - multiple of 5
F : File number

Case : 1 use of DD0 and DD1
2 use of DD0 and DD2
3 use of DD0, DD1 and DD2

(8) : Data Descriptor : V : Version number
C : Country (see (1))

(9) : Installation Descriptor : V : Version number
C : Country (see (1))

(10) : Each of the four tracks contains 100 files numbered 00 to 99 which gives the following numbering of the files from 100 to 499.

Appendix 3

EUROPEAN MODELLING GROUP FOR SHS AND DHW

List of Participants with direct links with S.P.T.F.

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EUROPEAN MODELLING GROUP FOR SHS AND DHW

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