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Simulation Program Validation using domestic hot water system data

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List of reports previously published from
IEA Solar Heating and Cooling Programme,
Task 1
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THERMAL INSULATION LABORATORY
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INTERNATIONAL ENERGY AGENCY
solar heating and cooling programme

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investigation of the performance of solar heating and cooling systems

Simulation Program Validation

using domestic hot water system data

Ove Jørgensen

August 1982

report no. **125**

SIMULATION PROGRAM VALIDATION

using domestic hot water system data

Ove Jørgensen

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PREFACE

INTERNATIONAL ENERGY AGENCY

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Programme was formulated among a number of industrialized countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organization for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Programme, the participants undertake cooperative activities in energy research, development and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat, coordinates the energy research, development and demonstration programme.

SOLAR HEATING AND COOLING PROGRAMME

Solar Heating and Cooling was one of the technologies selected by the IEA for a collaborative effort. The objective was to undertake cooperative research, development, demonstration and exchanges of information in order to advance the activities of all participants in the field of solar heating and cooling systems. Several sub-projects or "tasks" were developed in key areas of solar heating and cooling. A formal Implementing Agreement for this Programme, covering the contributions, obligations and rights of the participants, as well as the scope of each task, was prepared and signed by 15 countries and the Commission of the European Communities. The overall programme is managed by an Executive Committee, while the management of the sub-projects is the responsibility of Operating Agents who act on behalf of the other Participants.

The tasks of the IEA Solar Heating and Cooling Programme and their respective Operating Agents are:

I. Investigation of the Performance of Solar Heating and Cooling Systems - Technical University of Denmark

II. Coordination of R & D on Solar Heating and Cooling Components - Agency of Industrial Science and Technology, Japan

III. Performance Testing of Solar Collectors - Kernforschungsanlage Jülich, Federal Republic of Germany

IV. Development of an Insolation Handbook and Instrumentation Package - United States Department of Energy

V. Use of Existing Meteorological Information for Solar Energy Application - Swedish Meteorological and Hydrological Institute

VI. Performance of Solar Heating, Cooling and Hot Water Systems using Evacuated Collectors - United States Department of Energy

VII. Central Solar Heating Plants with Seasonal Storage - Swedish Council for Building Research

VIII. Passive and Hybrid Solar Low Energy Buildings - United States Department of Energy

IX. Solar Radiation and Pyranometry Studies - Canadian Atmospheric Environment Service

Collaboration in additional areas is likely to be considered as projects are completed or fruitful topics for cooperation identified.

TASK I - INVESTIGATION OF THE PERFORMACE OF SOLAR HEATING AND COOLING SYSTEMS

In order to effectively assess the performance of solar heating and cooling systems and improve the cost-effectiveness of these systems, the Participants in Task I have undertaken to establish common procedures for predicting, measuring, and reporting the thermal performance of systems and methods for designing economical, optimized systems. The results will be an increased understanding of system design and performance as well as reports and/or recommended formats on each of the task activities.

The subtasks of this project are:

A. Assessment of modelling and simulation for predicting the performance of solar heating and cooling systems
B. Development of recommended procedures for measuring system thermal performance
C. Development of a format for reporting the performance of solar heating and cooling systems
D. Development of a procedure for designing economical optimized systems
E. Validation of simulation programs by comparison with measured data
F. Solar-assisted low-energy dwellings

The Participants in this Task are: Belgium, Denmark, Germany, Italy, Japan, the Netherlands, Spain, Sweden, Switzerland, United Kingdom, United States and the Commission of the European Communities.

This report documents work carried out under subtask E of this Task.

LIST OF CONTENTS

1. EXECUTIVE SUMMARY

1.1 Introduction

The present study is the third and final in a series of model evaluation studies undertaken as part of the activities within Task I of the IEA Solar Heating and Cooling Programme. The first of these activities consisted of model-to-model comparisons on two hypothetical systems (air and liquid) using a year of hourly data from three different locations. The second activity was a validation activity in which model predictions were compared to performance measurement data from the solar system at the Los Alamos National Laboratory Study Center in New Mexico. This was a large solar system with 716 m^2 of collector area and two storage tanks of 19 and 38 m^3. These two activities are documented in reference 1 and 2.

1.2 The Present Study

For the present study, system performance data for four domestic hot water systems, monitored by the United States National Bureau of Standards, were distributed to the participants. These data consisted of 10-minute values for August 1978. At a later date one additional week of data (from August 1981) was also distributed for one of the systems for a second round of validation. A parameter sensitivity analysis for one of the systems, to extend the validation spot-check of the models, was also repeated. In both cases the results improved drastically in the second round. In the case of the validation, the improvement is illustrated in table 1.1.

In the first round, the solar fraction of the single tank indirect system was over-predicted by up to 24%, whereas it was predicted within -2.4% and +1% in the second round.

A similar improvement was obtained in the parameter sensitivity analysis. In the first round, the predicted

Table 1.1 Measured and predicted solar fraction, round 1 and 2. Single tank indirect system.								
	Measured	Predicted						
		B & D	H	I	J	K	L.F.	T & K C & N
round 1	66	67	82	74	68	75	70	90
round 2	60.5	58.1	59.9	59.1	61.5	60.9	60.5	60.3

B & D: Boussemaere & Delire
H : Hedstrom
I : Inooka
J : Jørgensen
K : Kennish
L.F. : La Fontaine
T & K: Therre & Kuijk
C & N: Calatayud & Nilsson

solar fraction ranged from 61.8% to 83.5% in the base run while this range was reduced to 78.5% to 86% in the second round. Also, much closer agreement was obtained among the model predictions for the different parameter variations.

By the parameter sensitivity analysis it was established that not all the models were applicable for investigation of the impact of collector flow rate and control strategy variations.

1.3 General Conclusions

As mentioned above, the present study was the third and final in a series of model evaluations and validation activities. At this stage it therefore seems appropriate to sum up the findings of the entire effort. This is attempted in the following:

Accomplishments

- In general, these activities have been valuable exercises for locating and correcting model deficiencies and errors in many of the codes used.

- All the codes have, without a doubt, been further established as reliable research tools in the course of this work.
- By participating with their codes in this work and taking part in the many fruitful technical discussions, the participants have all extended their knowledge and understanding of modelling and simulation of active solar systems.
- The two validation exercises have filled important gaps since most countries had little or no data of a quality suitable for validation purposes available at the outset of this work.
- The combination of validation against measured data and model-to-model comparisons in a parameter sensitivity analysis proved to be useful for a broad evaluation of simulation models.
- The experience shows that meaningful results can be achieved in a two-round process. The first round of analysis provides a basis for discussion and identification of specific problems; the second round often results in more accurate predictions and increased comparability of data.

Recommendations

- The user's interpretation of the system specifications, also known as the user-effect, unfortunately plays a dominating role in the use of simulation models. Therefore, much more emphasis should be put into the generation of improved input schemes for the models rather than to the correct mathematical formulation of a certain phenomenom.
- Validation work is generally complicated by the fact that control decisions in the real systems are made by non-ideal devices whose switching points drift significantly with time in an unpredictable manner. A

temperature sensor drift of only a fraction of a degree may advance or delay the switching of a pump or valve by hours, causing large instantaneous differences between measured and predicted results throughout the system. Because of the negative feed-back mechanism of thermal solar systems, these differences might not cause significant disagreement when comparing model predictions and measurement of long term performance. Obviously it is important to take their effect into consideration when deciding on necessary time-periods for validation work.

- Further validation work should be more oriented towards the testing of component subroutines, algorithms and special assumptions. The results will be more generally applicable to different models and different systems.

Concluding remarks

- This task has been a valuable forum for comparing, testing, evaluating and improving the consistency of solar simulation codes used throughout the world.
- Methods of modelling, performance reporting and validation have been agreed upon in an international forum, and an international data base* of system performance data has been created.

* May be obtained by request to the author, Ove Jørgensen

2. INTRODUCTION

2.1 Modelling and Simulation

Mathematical modelling and computer simulation of solar systems has received a still growing interest in the solar energy research world during the past ten years. This is due to the advantages computer models offer over physical experimentation, such as: greater flexibility for system configuration design and modification; quick results allowing immediate evaluation and modification; freedom from instrumentation and performance problems which can result in major delays; ability to control input variables including system operation and climate conditions; ability to evaluate the performance of innovative concepts where little or no hardware exists; ability to identify optimal design parameters; ability to evaluate seasonal performance without a year or more of testing. Thus the models can be used to predict temperature profiles, collection efficiencies, solar energy savings, etc. of the systems modelled.

Mathematical modelling involves the system definition, the setting up of equations, the solution method, the handling of parameters, variables and data and the output requirements. As the exact modelling of a continuous system, such as a solar system, is impossible in practice, the mathematical model will always be an approximate representation of the real system. Besides the approximation which lies in the discretization of the system, many simplifying assumptions are made in general, such as considering some variables as constant parameters, neglecting minor interaction relationships or linearizing non-linear relationships. When the model is ready it has to be implemented on a computer (i.e. programmed and typed in) before it can be executed and the results analysed.

In the whole process of building computer models, there are many possibilites for errors, and there are so many different paths to follow that testing and evaluation of the models developed are necessities in order to obtain reliable results. When typing and programming errors have been debugged, the models have to be evaluated to test their limits of applicability. In many cases a given model will give reasonable results for a certain system, but the chosen level of discretization, the equation-solving technique and some of the assumptions made, may cause the model to react improperly on certain parameter variations.

2.2 Previous Task I Model Evaluation Work

When the work within Task I commenced in the beginning of 1977, one of the subtasks defined (subtask A, Modelling and Simulation) dealt with the evaluation of simulation models for active solar heating and cooling systems. Two hypothetical systems were defined, an air-based and a liquid-based system, both of them combined heating and domestic hot water systems. Participants set up their models to simulate these two systems on three different sets of yearly data, one from Madison, Wisconsin, United States, one from Santa Maria, California, United States and one from Hamburg, Germany. The model predictions were compared on an hourly, a monthly and a yearly basis. This work is documented in reference 1.

Model-to-model comparisons can be considered as the first step of the model evaluation procedure. The comparisons of temperature profiles and energy flows made it possible to detect some programming errors and test new ideas for the model development against more established models.

In Addition, some of the weaknesses of the models, (for example, the algorithms for calculating the incident solar radiation on sloping surfaces on the basis of global radiation) were identified.

The ultimate check of the models is, however, obtained by comparisons against data obtained from measurements of real systems. When the work within subtask A was finished in 1978, it was followed up by a new subtask, subtask E, Validation of Simulation Models. The background for the initiation of this new subtask as a cooperative project was that most countries, at that time, had little or no data available which were suitable for validation purposes. Consequently, experience with the comparison of model predictions to measured data was very limited. Therefore, the objectives of this subtask were to assess and provide high quality data useful for validation, to establish a forum for the discussion of results and to improve the state of the art through this collaborative intersection.

The solar system at the Study Center of Los Alamos Scientific Laboratory was the first system selected for the validation work. This is a rather large system with 716 m^2 of collector aperture area and a storage volume of 38 m^3 of water. This system can work both in heating and cooling modes, but only the heating mode was considered in this study. One of the subtask participants, Jim Hedstrom of Los Alamos National Laboratory, who was involved in collecting and reducing the system performance data, also selected and distributed the data to be used for the IEA study.

Although the system is used in practice for heating and cooling the Study Center, it is so extensively monitored and measured that it can be characterized as a research facility. For the other participants this meant that the parameters they received with the description of the system in most cases were measured to a relatively small uncertainty. This in many ways provided ideal conditions for the validation work, and the participants obtained close agreement between the model predictions and the measured results. The results of this first validation study have been extensively documented in reference 2.

2.3 The Present Study

For the second study undertaken within the validation subtask, four different domestic hot water systems located on the research grounds of the United States National Bureau of Standards, were selected. The National Bureau of Standards provided a magnetic tape containing ten-minute data for the four systems measured during August 1978. These data were distributed in October 1979 along with a validation format document drafted by William J. Kennish, a U.S. participant. The document (ref. 4) gave detailed specifications of the four systems and of the content of the data tape, which had been reformatted by Mr. Kennish in order to make it less cumbersome to read and treat by the participants. Furthermore, it included a sample of format sheets for the presentation of results in the form of tables and graphs.

To supplement the comparison of model predictions and measured data, it was agreed to include in the study a parameter sensitivity analysis for model-to-model comparisons of one of the systems. The reason for the inclusion of this analysis was that many models are used for this purpose; therefore it seemed appropriate to check whether or not the models used in this context gave comparable results.

The work was scheduled to end in the early part of 1981, but at a special working group meeting organized on request of the Executive Committee, the participants decided to conduct a second round of the two activities because they were not fully content with the results obtained. Hunter Fanney from the National Bureau of Standards provided a new data set consisting of one week of one-minute data from August 1981 for the single tank indirect system (still in operation), and the exercise was repeated by most of the participants. At the same time some of the reasons for the discrepancies among the model predictions in the parameter sensitivity analysis were resolved and the system specifications were further detailed.

During spring and early summer 1982 these final activities were completed and reported by the participants.

The nine participating groups representing seven countries have reported their work in 28 individual reports (ref. 6 - ref. 33). This report attempts to summarize the major findings and conclusions of this considerable amount of work comprising, in reality, five validation studies and two parameter sensitivity analyses.

3. SYSTEM AND DATA DESCRIPTION

3.1 The Systems

The four DHW systems that provided data for the validation work, were located at the research grounds of the United States National Bureau of Standards at a latitude of 39^{o}N and a longitude of 76.5^{o}W.

The four systems consist of two double tank systems (one direct and one indirect) and two single tank systems (also one direct and one indirect). The same collector, Lennox black chrome selective, was used on all four systems, two modules on the single tank direct system and three modules on each of the other three systems. The aperture area thus obtained was 2.88 m^2 and 4.32 m^2 respectively. The primary storage tanks contained 310 litres of water and the two auxiliary tanks, 159 litres each. Wrap-around heat exchangers were used on two indirect systems. Fig. 3.1 shows the schematics of the four systems which are described in details in Appendix 1.

The following abbreviations were accepted to be used for the four systems:

STD: Single tank direct

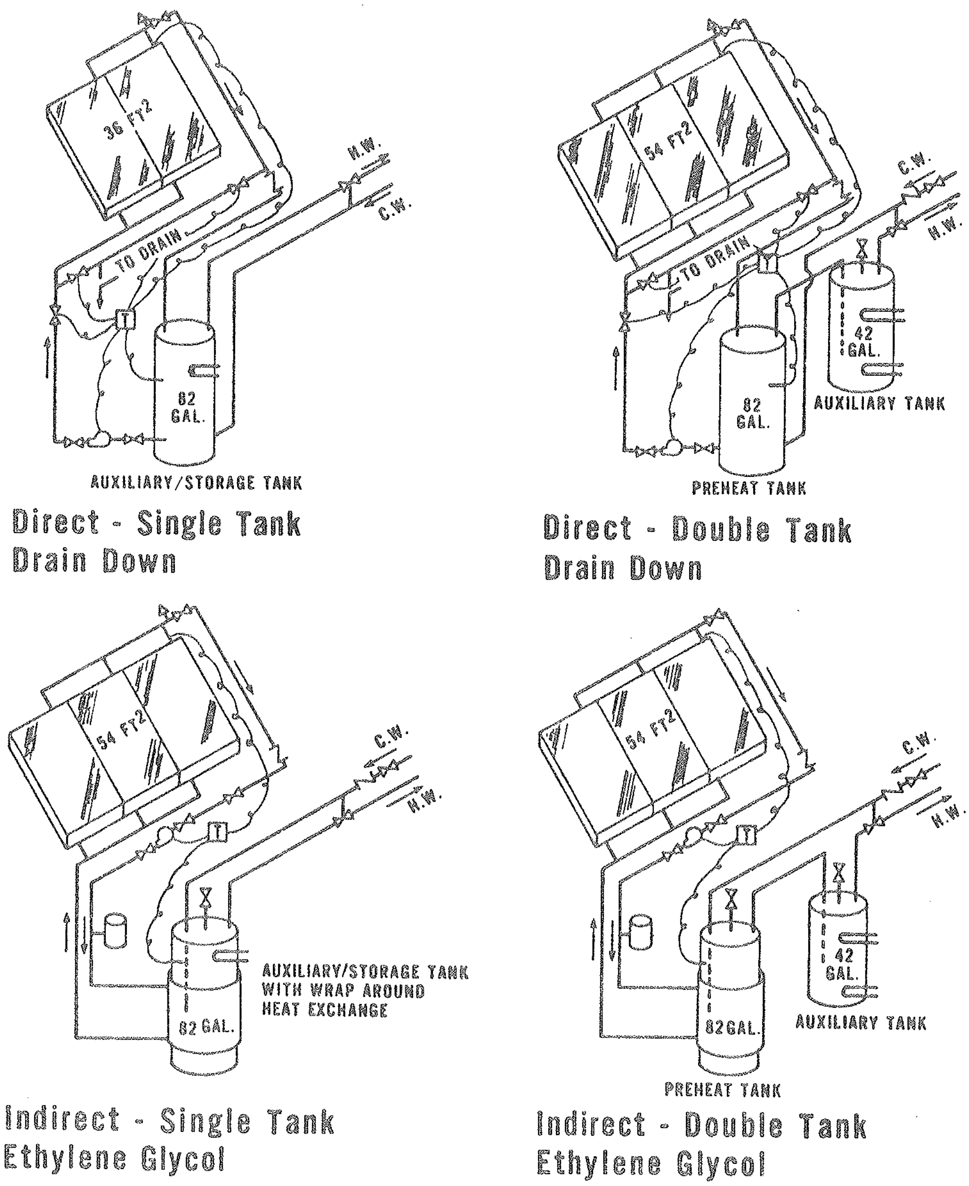
DTD: Double tank direct

STI: Single tank indirect

DTI: Double tank indirect

3.2 The Data

As explained in the introduction two sets of data were provided from the National Bureau of Standards. The first data set comprised one month of ten-minute data for all the four systems from August 1978. The second data set represented a period of six days of one-minute



$1\ ft^2 = 0.0929\ m^2$

$1\ gal = 3.785 \times 10^{-3} m^3$

Fig. 3.1 Schematic of the four systems

data taken in August 1981. The first data set consisted of a period with little sunshine and a period of clear days. The second data set was a series of clear days.

The data tape distributed for the first comparisons contained seven lines; the two last lines containing data for two systems which were not used in this exercise, namely an air system and a thermosyphon system, but made available for participants' individual use. The first line contained the exact time, total horizontal radiation, total tilted radiation, wind speed and direction, ambient and indoor temperatures. The following four lines contained the measured performance data as instantaneous values taken every ten minutes. Storage temperatures in three different layers, collector supply and return temperatures, draw supply and return temperatures, average tank temperatures and indicators for draw, pump and anti-freeze drain down operation. The data acquisition system is extensively described in Appendix 1.

The data set for the second period contained data from the single tank indirect system; this being the only system of the four still in operation in August 1981. This data set consisted of instantaneously taken one-minute values of weather data and system performance data for a full six-day period. For each minute 28 data items were given on the tape. Table 3.1 shows these items. As is seen, these data are somewhat more detailed than the August 1978 data set. The most important addition is that the flow rate has been measured every minute. Eight tank temperatures are given instead of three and the temperatures of the collector pump controllers are also given.

3.3 The Load

The same hot water load profile (see fig. 3.2) was used for all four systems. The hot water load was drawn during the first minutes of each hour at a rate of approximately one gallon/minute. The total hot water demand was integrated and read once a day for each system. Since the motorized valves used for the tapping of hot water did not operate totally alike, small variations were observed among the hot water loads on the systems.

In the upper part of the two single tank systems an electric coil heating element was placed to maintain a preset temperature of approximately 60°C. In the two auxiliary tanks of the two double systems, two heating elements were placed, one at the top and one at the bottom. The auxiliary energy consumed to maintain the preset temperature were read on the kWh-meters once a day.

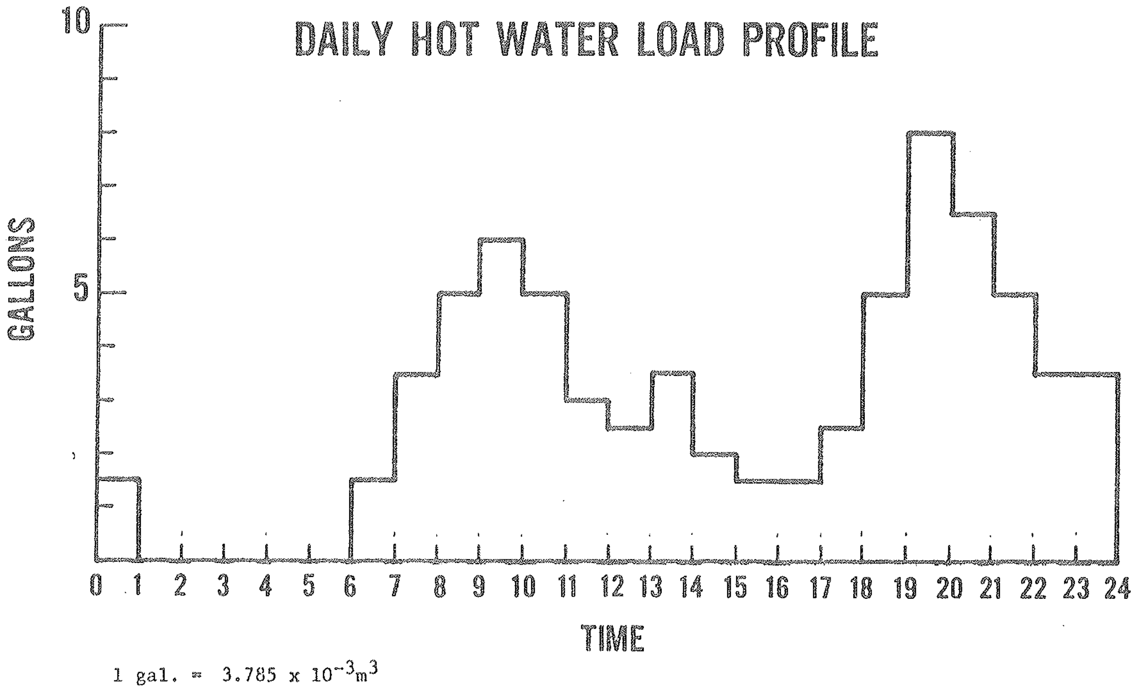


Fig. 3.2 Daily hot water load schedule

Table 3.1

List of data items on August 1981 data set

Item no.	Description
1.	Day of year
2.	Time of day expressed in number of minutes (HR*60 + MIN)
3.	Horizontal radiation, W/m^2
4.	Collector surface radiation, W/m^2
5.	Wind speed, m/s
6.	Wind direction, degrees (0°=North, 90°=East, 180°=South, 270°=West)
7.	Outdoor ambient temperature, °C
8.	Average trailer ambient temperature, °C
9.	Flag indicating if a draw is occurring (1=yes, 0=No)
10.	Flag indicating pump status (1=ON, 0=OFF)
11.	Flag indicating heating element status (1=ON, 0=OFF)
12.	Power Input to the auxiliary heating element, W
13.	Collector flow rate, l/s
14.	Temperature of storage tank controller sensor, °C
15.	Temperature of collector plate controller sensor, °C
16.	Tank Temperature 0.15 m elevation, °C
17.	Tank Temperature 0.30 m elevation, °C
18.	Tank Temperature 0.46 m elevation, °C
19.	Tank Temperature 0.61 m elevation, °C
20.	Tank Temperature 0.76 m elevation, °C
21.	Tank Temperature 0.91 m elevation, °C
22.	Tank Temperature 1.07 m elevation, °C
23.	Tank Temperature 1.22 m elevation, °C
24.	Average tank temperature, °C
25.	Cold water supply temperature to storage tank, °C
26.	Hot water supply temperature from storage tank, °C
27.	Collector supply temperature measured at solar array, °C
28.	Collector outlet temperature measured at solar array, °C

4. VALIDATION RESULTS ON AUGUST 1978 DATA

4.1 Introduction

This chapter presents an overview of the computer model predictions compared to the measured data for the four domestic hot water systems. Ten different persons or groups representing seven different countries participated in this work. Most of them presented results for all four systems, one showed predictions for three systems and two participants ran one system each.

The first impression of this exercise is likely to be that it should be very simple to set up the computer models to simulate a couple of domestic hot water systems. When the work commenced, however, several problems showed up, which had not been foreseen. These problems created great difficulties for the participants in obtaining meaningful comparisons to the measured data.

The first problem encountered by the participants had to do with the direct systems. At the beginning of each hour, when the collector pump was on at the same time as a hot water draw occurred, it was clear from the measured data that a great portion of the cold inlet water went directly to the collector inlet pipe instead of mixing with the storage tank bottom layer. The results are illustrated in fig. 4.1. The instantaneous reading for collector inlet temperature reflected the water main temperature. At that instant the collector outlet temperature reflected a temperature increase which originated in the bottom of the tank several minutes earlier, at much higher temperatures. Thus the instantaneous temperature differential across the collector was unrealistically high due to the time required for fluid to go from the inlet to the outlet temperature measurement points. When this instantaneous effect is applied to the entire ten-minute period, the problem is exacerbated. The negative spike is similarly explained because at that point in time the water, which originated at the tank when it was colder at the bottom (because of the draw), has reached the outlet sensor resulting in a fairly low outlet temperature reading. At the same instant the water at the bottom of the tank has remixed resulting in a higher inlet temperature.

This behaviour of the system was, of course, difficult to model closely. Some of the participants tried the assumption that a fixed portion, say 50%, of the cold inlet water went directly to the collectors when the collector pump was switched on, and this approach was somewhat successful.

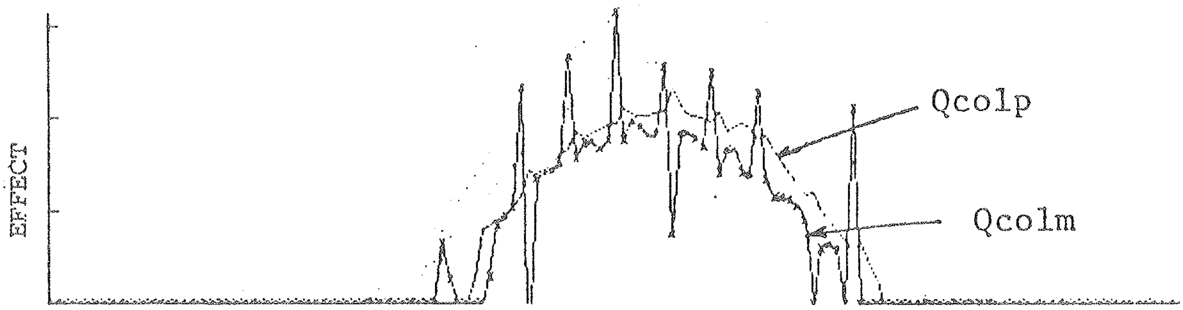
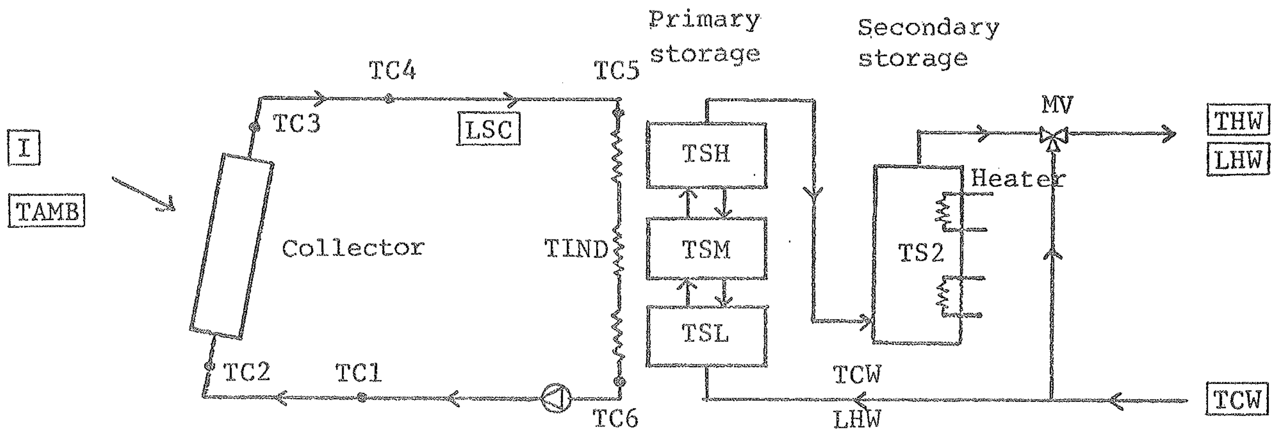


Fig. 4.1 Predicted and measured collector output for August 22, 1978. Ref. 13.

As the work progressed other problems became apparent and dominating. These problems which were inherent with the systems and the data taken, are as follows:

- the 10-minutes data were instantaneous data and not integrated
- the collector flow rate was not continiously measured
- there were missing data for two whole days of the period
- the heat exchanger was not well defined
- the temperature set points for the auxiliary heating coil were floating
- the load was not very well defined.

Some of these problems are very severe and imply an amount of guessing which can change the model predictions significantly. For example, if you start questioning the collector flow rate and the heat exchanger efficiency and modify these parameters, not to mention the temperature set points of the auxiliary heating coil, the model predictions will vary drastically. The participants in this exercise were divided roughly into two groups; one group preferred to use only specified parameters, and the other group tried some model modifications and some parameter variations to obtain better agreement. In all cases the storage loss value were modified to obtain agreement on storage losses.



T: Temperature
L: Flow rate
I: Solar radiation
[ ]: Input data

Fig. 4.2 Example of simulation model configuration, double tank indirect system. Ref. 17.

Finally, as an illustration of the complexity involved in the modelling of these systems, fig. 4.2 shows a schematic of the model for the double tank indirect system. In this case the collector is modelled as one node, the collector pipes as four nodes, the heat exchanger as three nodes, the storage tank as three nodes and the auxiliary tank as one node. What complicates the model is the strong stratification of the storage tank (increased in the single tank systems by the heating coil in the top layer of the tank). As a result, it is necessary to split the heat exchanger into three or more nodes.

What at the beginning looked like a small exercise turned out to be an involved, difficult task.

4.2 Results

The results of this activity were presented by the participants in the form of tables and plots, both following a standard format specified in reference 4. The results presented in the summary tables below have been taken directly from the tables produced by the participants. Following the tables several plots are presented to illustrate the level of agreement obtained by the participants.

A number of abbreviations are used in the summary tables. They have the following meanings:

QCOL : Energy collected by the solar collector

QLPIP : Energy lost by the pipes connecting the collector to storage/heat exchanger

QSTO : Energy transferred to the solar storage tank

QLSTO : Energy lost by the storage tank(s)

QTO : Energy output of storage tank (load)

QAUX : Auxiliary energy supplied by the heating element(s) to the system

F% : Fraction of load supplied by solar energy

NC% : Collecting efficiency $= \frac{QCOL}{QSUN}$ %, where

QSUN : Total energy input to the collectors

SE% : System efficiency $= \frac{QCOL - QLSTO - QLPIP}{QCOL}$ %

The comparison between the participants is complicated by the fact that some of the participants included the results of the two substituted days (18,28) in the energy flow totals (La Fontaine and Wensiersky), and the others did not (as recommended).

From table 4.1, it is observed that seven of the participants modelled and simulated the single tank direct system. Large differences can be observed for almost any number. For example, the collector output varies from 535 MJ to 903 MJ. Two participants neglect pipe losses and one calculates them to be as high as 70 MJ. The predicted solar fraction varies around the measured value of 57%, from 46% to 70%, close to ±20%.

The variations look similar in the following tables. In table 4.2 the predicted solar fraction varies around the measured value of 48%, from 44% to 64%, and predicted system efficiencies vary between 34% and 66%. In this case there seems to be a tendency to over-predict the performance of the system. The tendency is also apparent for the double tank indirect system (see table 4.4) where the predicted solar fraction ranges from 45% to 68%, whereas the measured value is 50%.

Table 4.3 presents the results obtained for the single tank indirect system. These results are of extra interest since this is the system that also provided the data for the second validation round. As in the case for the two double tank systems, the system performance is generally over-predicted by the simulation models. The predicted solar fraction varies from 67% to 90% compared to the measured 66%. In general, the reason for this seems to be an over-prediction of the collector output.

The variations in predicted system efficiency are less drastic than for some of the other systems: 71% to 84%.

The predicted storage losses vary from 107 MJ to 181 MJ. This difference is to some extent caused by the use of different loss values for the storage tank. This illustrates the impact of user interpretation of the given data. What was given was the size and shape of the storage tank, the type and thickness of the insulation material. These parameters could be used to calculate one loss value for the storage tank. To account for unavoidable thermal bridges and losses by natural convection to the pipes, some users would prefer to add a certain percentage to arrive at a more realistic loss. A more rigorous approach as suggested by Jim Hedstrom, is to deduct the correct storage loss coefficient from the measured data by dividing total measured energy loss by mean tank temperature and total length of period. Another example of this kind of parameter fitting was made by Boussemaere who adjusted the collector flow rates in the four systems individually to obtain close agreement on the collected energy. Fig. 4.5 shows how well this was accomplished. The agreement is very close.

The conclusion on this matter with regard to validation studies must be that a system providing data for validation purposes has to be measured and monitored to such a degree that (in the ideal situation) there is no doubt at all as to what the system parameters are.

From the tables it might look as if the programs do not come at all close to the measured system performance. This is generally not the case. The programs predict the dynamic behaviour of the systems very well. This is illustrated by figures 4.3 to 4.6 which have been extracted from the reports of different participants. At the same time this illustrates the point that computer plot comparisons alone cannot be trusted as an expression of how well the model predictions compare to the measurements in absolute terms. For example, the relatively small underprediction of collector inlet temperatures shown on fig. 4.4 results in an overprediction of collector output of more than 13%.

Fig. 4.3 and fig. 4.4 also constitute an example of a participant obtaining excellent agreement on one system and less agreement on another system.

Fig. 4.6 shows a comparison of measured and predicted average tank temperatures. It is obvious that the agreement is not perfect. On the other hand it can be seen that the predictions "track" the measurements very well; there is no significant time-shift, and except for the 28th (which is one of the substituted days) there is also good agreement with respect to the amplitudes of the curves.

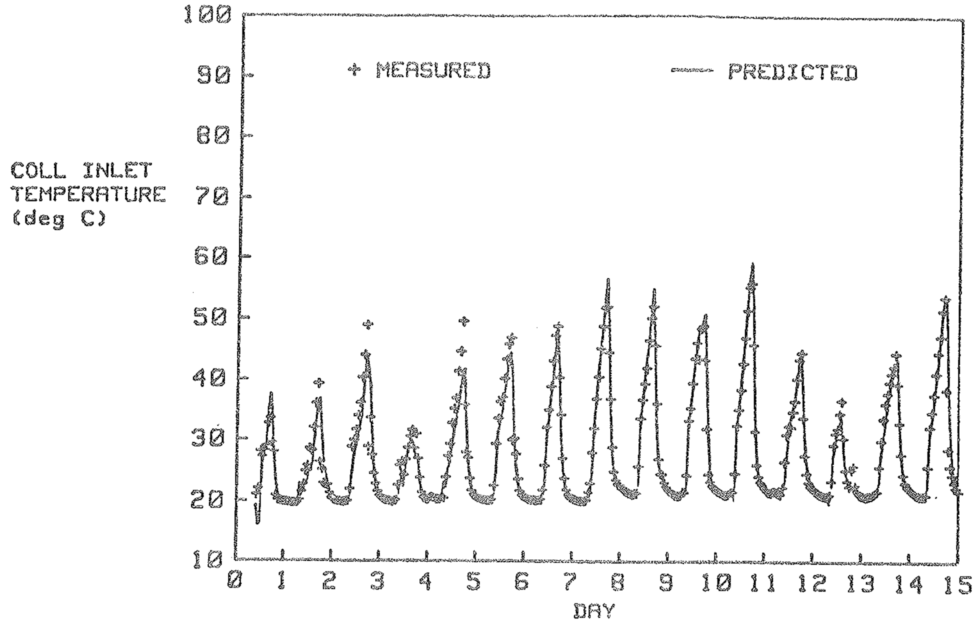


Fig. 4.3 Collector inlet temperature vs. day of the month. Single tank direct system, ref. 14.

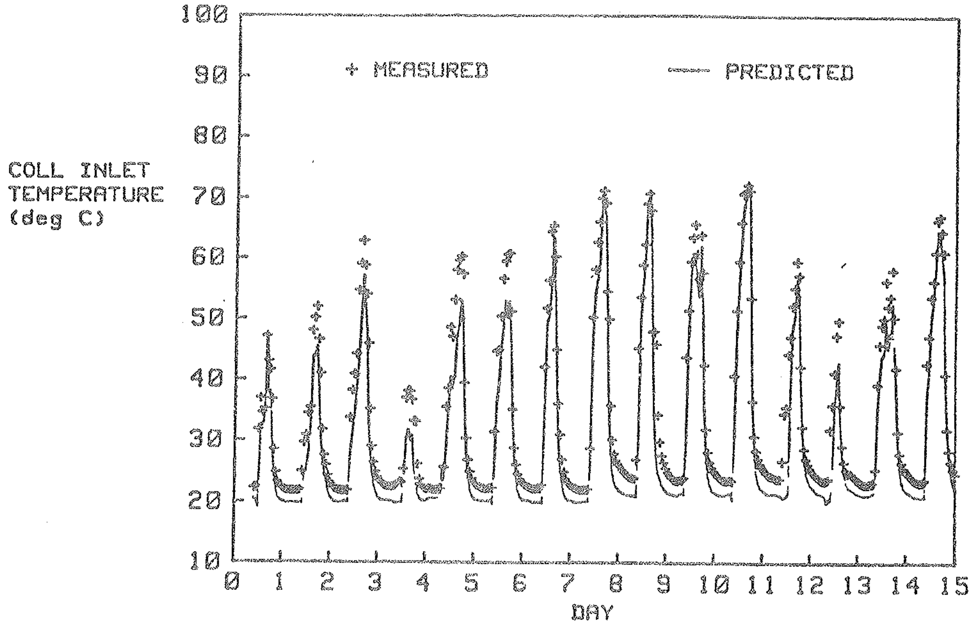


Fig. 4.4 Collector inlet temperature vs. day of the month. Single tank indirect system, ref. 14.

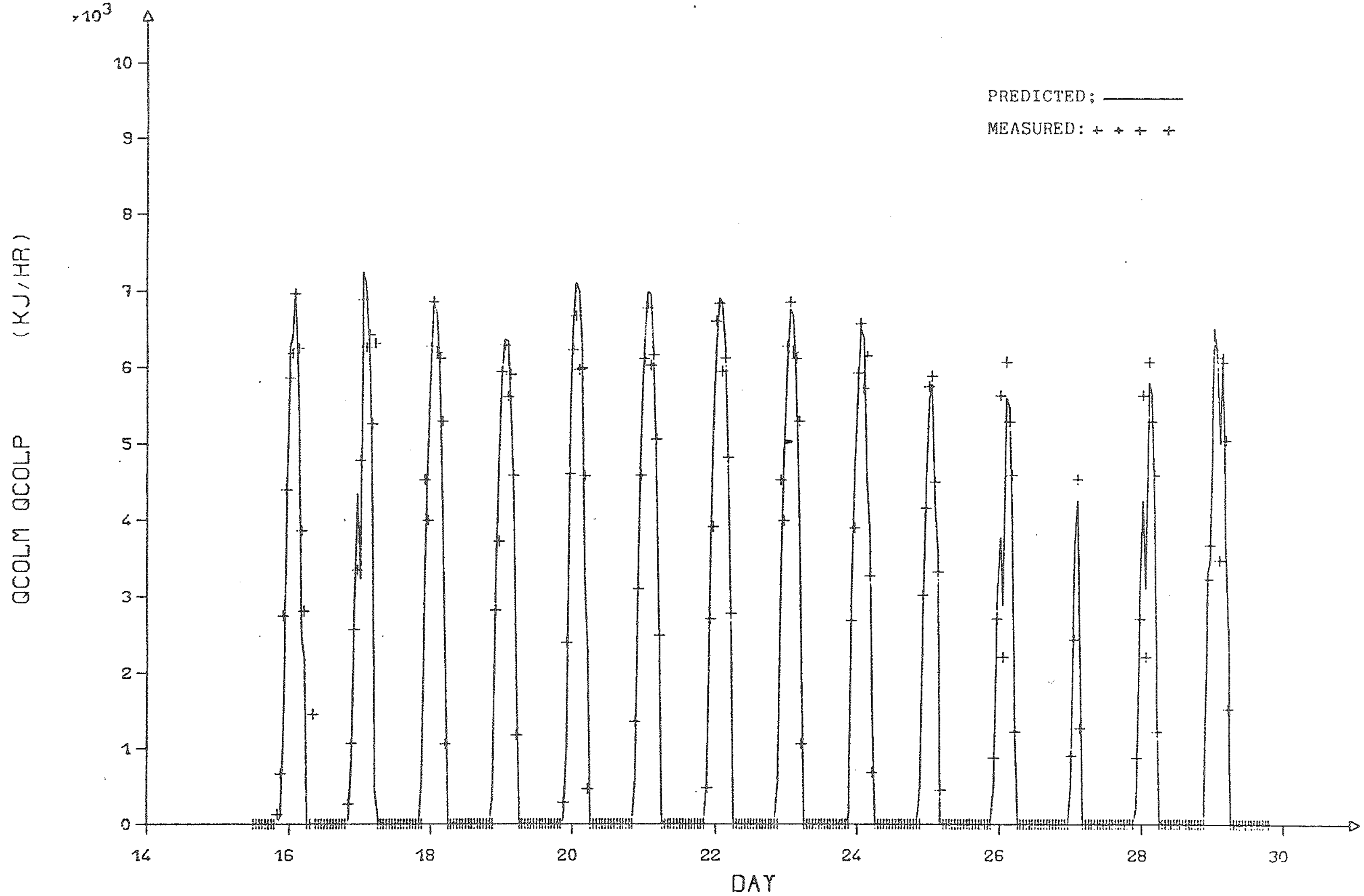


Fig. 4.5 Predicted and measured collector output vs. day of the month. Single tank direct system, ref. 6.

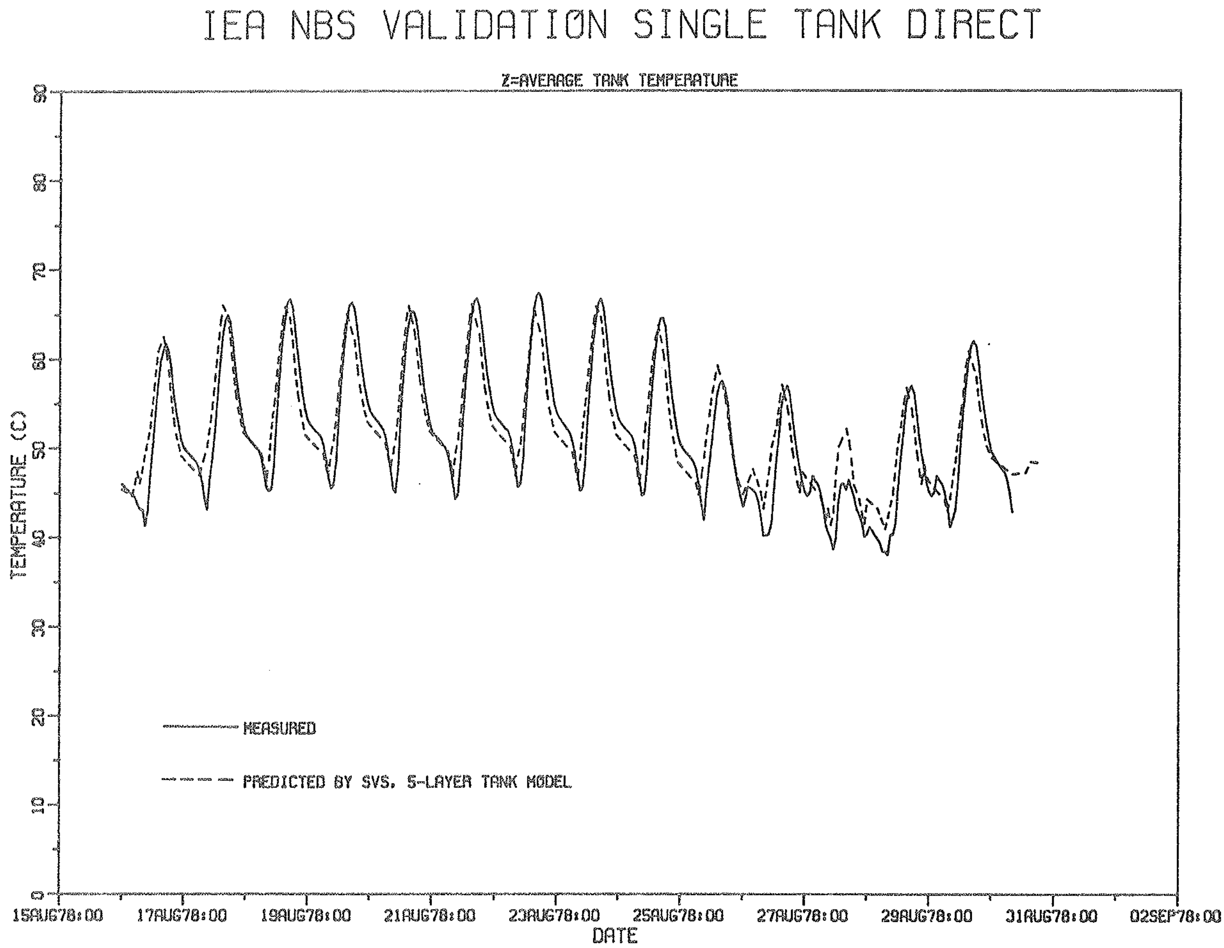


Fig. 4.6 Measured and predicted tank temperatures vs. day of the month, ref. 19

Table 4.1 Summary of measured and predicted energy flows and performance factors for the single tank direct system

MJ	Measured	Predicted									
		B	C & N	F	H	I	J	K	L.F	M & P	W
QCOL	759	739	862		772	635	641	535		903	
QLPIP	29	35	1		27	70	35	17		0	
QSTO	730	704	767		745	566	606	525		903	
QLSTO	259	255	242		239	198	147	130		241	
QTO	823	836	821		823	797	811	805		873	
QAUX	351	376	301		308	432	354	412		258	
F%	57	55	63		63	46	56	50		70	
NC%	55	51	63		57	46	47	40		66	
SE%	62	61	72		66	58	72	73		73	

B : Boussemaere
C & N : Calatuyud & Nilsson
F : Freeman
H : Hedstrom
I : Inooka
J : Jørgensen
K : Kennish
L.F : La Fontaine
M & P : More & Perrin
W : Wensiersky

Table 4.2 Summary of measured and predicted energy flows and performance factors for the double tank direct system

MJ	Measured	Predicted									
		B	C & N	F	H	I	J	K	L.F	M & P	W
QCOL	909	922	1137		1024	915	916	844	986		
QLPIP	45	46	1		35	73	38	51	47		
QSTO	864	876	932		989	844	877	794	926		
QLSTO	522	562	491		528	469	530	357	287		
QTO	710	720	680		711	679	701	695	618		
QAUX	370	406	270		253	303	348	320	392		
F%	48	44	60		64	55	50	54	49		
NC%	44	41	55		50	44	44	42	41		
SE%	38	34	57		45	41	38	52	66		

B : Boussemaere
C & N : Calatuyud & Nilsson
F : Freeman
H : Hedstrom
I : Inooka
J : Jørgensen
K : Kennish
L.F : La Fontaine
M & P : More & Perrin
W : Wensiersky

Table 4.3 Summary of measured and predicted energy flows and performance factors for the single tank indirect system

MJ	Measured	Predicted									
		B	C & N	F	H	I	J	K	L.F	M & P	W
QCOL	753	763	900	838	854	795	766	825	848		848
QLPIP	44	40	1	75	39	90	94	79	27		39
QSTO	709	-	769	757	815	625	648	706	754		751
QLSTO	160	181	139	112	161	136	128	101	143		109
QTO	812	811	806	814	807	769	800	788	875		954
QAUX	273	270	183	176	146	198	256	200	264		334
F%	66	67	90	78	82	74	68	75	70		67
NC%	37	307	43	41	42	39	37	40	35		39
SE%	73	71	84	78	77	72	71	78	80		83

B : Boussemaere
C & N : Calatuyud & Nilsson
F : Freeman
H : Hedstrom
I : Inooka
J : Jørgensen
K : Kennish
L.F : La Fontaine
M & P : More & Perrin
W : Wensiersky

Table 4.4 Summary of measured and predicted energy flows and performance factors for the double tank indirect system

MJ	Measured	Predicted									
		B	C & N	F	H	I	J	K	L.F	M & P	W
QCOL	796		919		942	862	811	874	909		
QLPIP	55		1		37	82	78	85	24		
QSTO	740		-		904	711	694	789	809		
QLSTO	337		315		365	309	330	237	105		
QTO	786		747		786	766	775	782	711		
QAUX	391		412		251	313	371	428	394		
F%	50		45		68	59	52	54	53		
NC%	39		45		46	42	39	42	38		
SE%	51		66		57	55	50	63	86		

B : Boussemaere
C & N : Calatuyud & Nilsson
F : Freeman
H : Hedstrom
I : Inooka
J : Jørgensen
K : Kennish
L.F : La Fontaine
M & P : More & Perrin
W : Wensiersky

5. VALIDATION RESULTS ON AUGUST 1981 DATA

5.1 Introduction

When the participants visited the National Bureau of Standards Laboratories in conjunction with the working group meeting in Annapolis, it became apparent that the single tank indirect system was still working. Hunter Fanney, the NBS Project Leader, stated that he would be able to provide the group with a new set of data on request. During the meeting the group decided to pursue this possibility and to request one week of new data. In order to be as effective as possible it was also decided that Jim Hedstrom would pre-analyse the data as soon as they were delivered by NBS. At the same time, the Operating Agent distributed the data tapes to the remaining participants making it possible for them to start working immediately when they received the "green light" from Jim Hedstrom.

By November 10, 1981, Jim Hedstrom had finished the pre-analysis of the data, assisted by Bill Kennish and Hunter Fanney. He then distributed a letter with his findings to the participants along with a list of recommended parameters for the system and the initial starting temperatures.

As explained in chapter 3, the data tape contained 28 variables for each minute of the period. The information that could be derived on the system performance was therefore far more detailed than in the case of the old data.

Not all the participants participating in the first validation round took part in this second round activity. Seven participants succeeded, however, in running their models using this new data set. The following paragraph presents a summary of their findings.

5.2 Results

The agreement obtained using the second round data was clearly excellent. The total measured and predicted energy flows and performance factors are presented in table 5.1, and figs. 5.1 - 5.7 graphically illustrate the quality of these comparisons.

The predicted solar fractions lie in a narrow band from 58.1% to 61.5% around the measured value of 60.5%. Six of the participants predicted a solar fraction within ±1% of the measured value.

When comparing the collected energy, it can be seen that most participants predict somewhat lower values of QCOL and QTSO than the measured values. A partial explanation for this might be found in the energy unbalance observed for the measured data. In general it must be concluded that all predictions are sufficiently close to the measurements and that this is as far as one can go with an experiment of this kind.

It should be noted that this agreement in all cases was obtained using the parameters recommended by Jim Hedstrom. This means that parameter fitting was not used to fine-tune the results. This indeed adds confidence to the use of all the models utilized in this exercise.

The exceptionally fine agreement between predictions and measurements obtained by all the participants justifies the selection methods used for the seven computer comparison plots, figs. 5.1 - 5.7. One plot has been selected from each of the participants' reports, all showing a comparison of a different aspect than the others, - collector inlet temperatures, collector outlet temperatures, collected energy, etc. As a whole they constitute a full system comparison. The idea is that these seven plots, as an illustration of the agreement obtained, represent the results obtained by any of the seven participants.

Table 5.1 Summary of measured and predicted energy flows and performance factors. August 1981 data.

MJ	Measured	D	H	I	J	K	L.F.	T & K
QSUN	457	457	456	456	456	457	469	457
QCOL	259	229	233	240	245	254	253	243
QLPIP	17	12	16	16	18	16	19	11
QSTO	242	220	217	222	232	231	232	231
QLSTO	33	34	34	37	36	37	37	35
QTO	298	297	298	295	299	297	299	300
QAUX	118	125	119	120	115	116	118	119
ΔE *	8	10	4	13	12	15	14	8
Unbalance**	21.1	3,7	.0	.0	4.4	-1.8	.0	
F%	60.5	58.1	59.9	59.1	61.5	60.9	60.5	60.3
NC %	56.7	50.1	51.1	52.6	53.7	55.6	53.9	53.2
SE %	80.7	79.9	77.3	77.9	78.0	79.1	77.9	81.1

* ΔE = change in energy stored in the tank

** Unbalance = QSTO + QAUX − ΔE − QTO − QLSTO

D: Delire
H: Hedstrom
I: Inooka
J: Jørgensen
K : Kennish
L.F. : La Fontaine
T & K: Therre & Kuijk

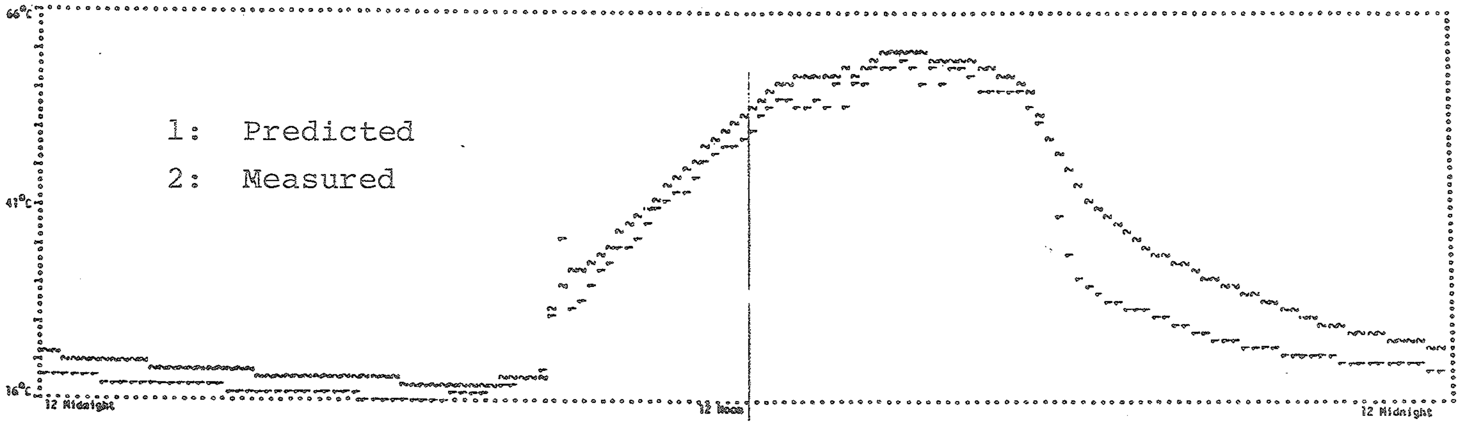


Fig. 5.1 Measured and predicted collector inlet temperatures, day 225, ref. 24.

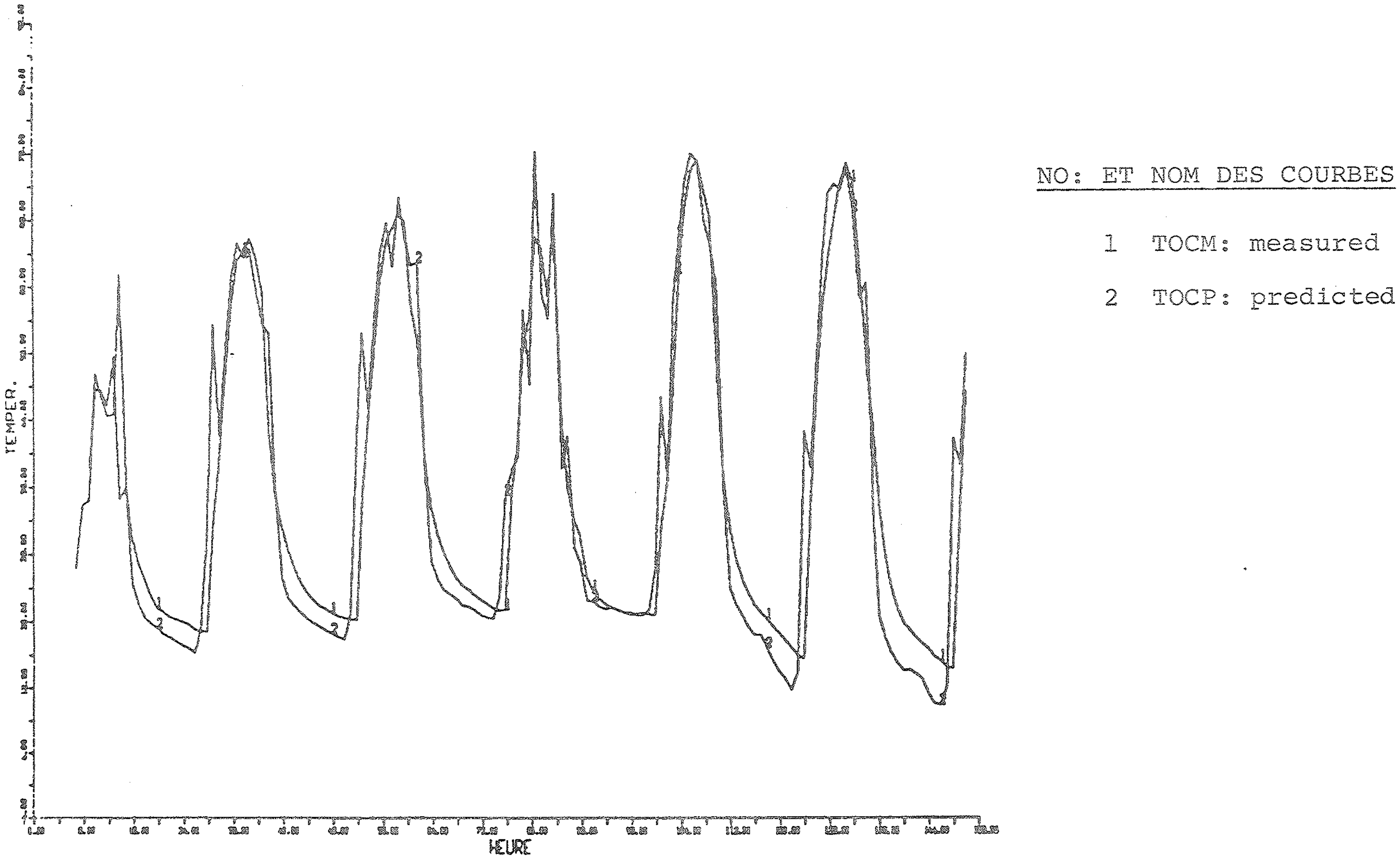


Fig. 5.2 Measured and predicted collector outlet temperatures, ref. 12

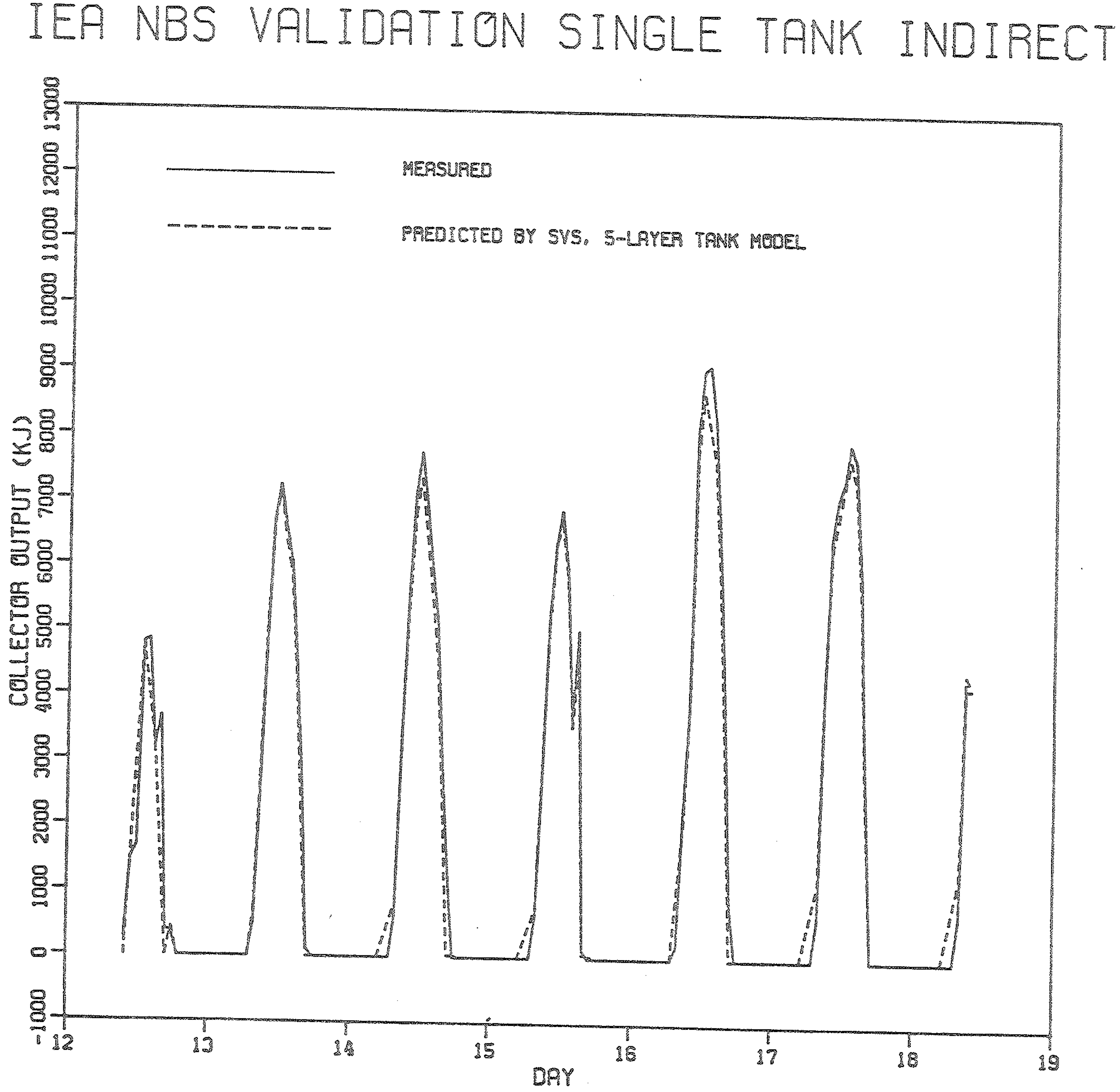


Fig. 5.3 Measured and predicted collected energy, ref. 20.

Faber

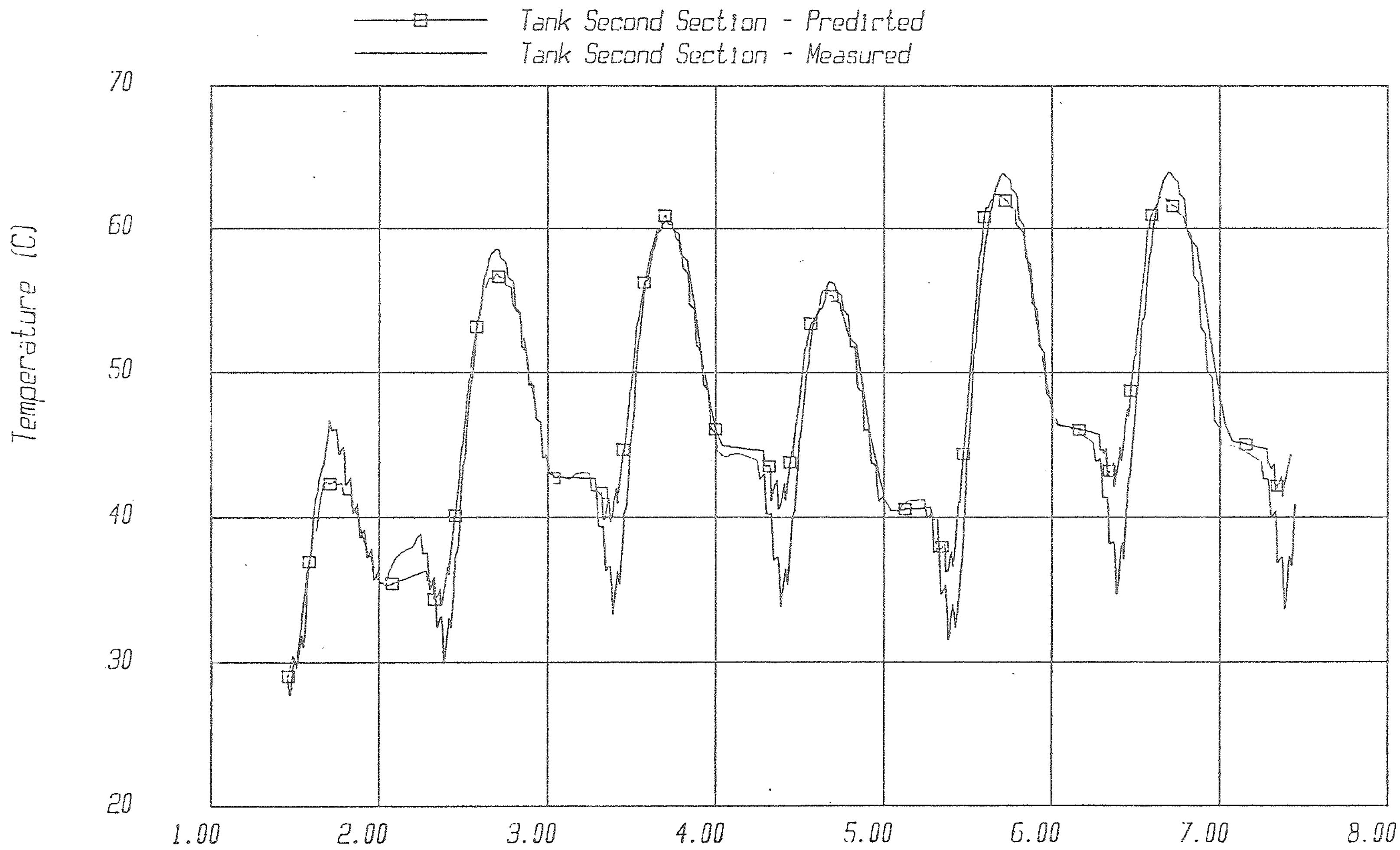


Fig. 5.4 Measured and predicted tank temperatures, second section, ref. 29.

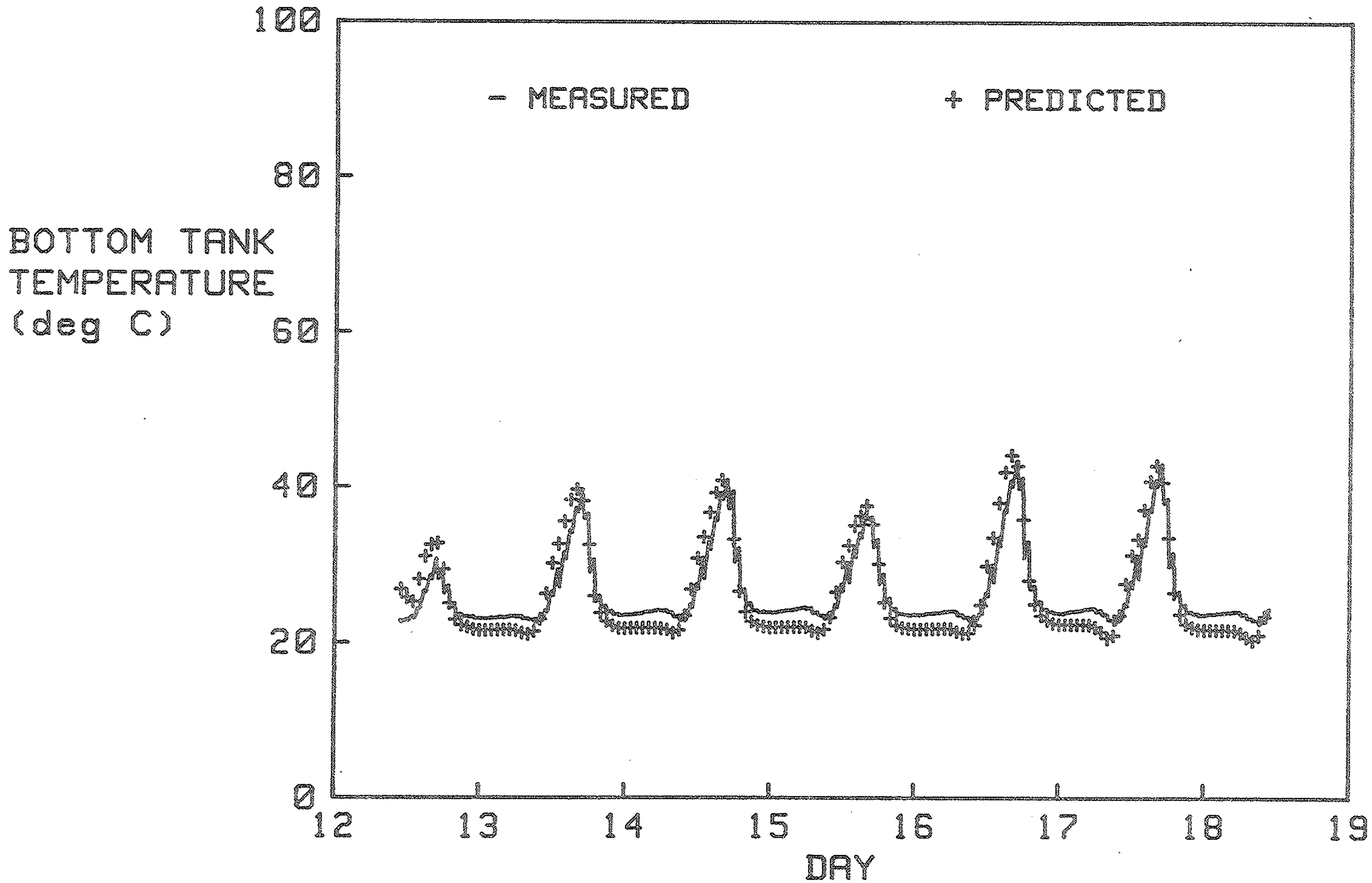


Fig. 5.5 Measured and predicted bottom tank temperatures, ref. 15

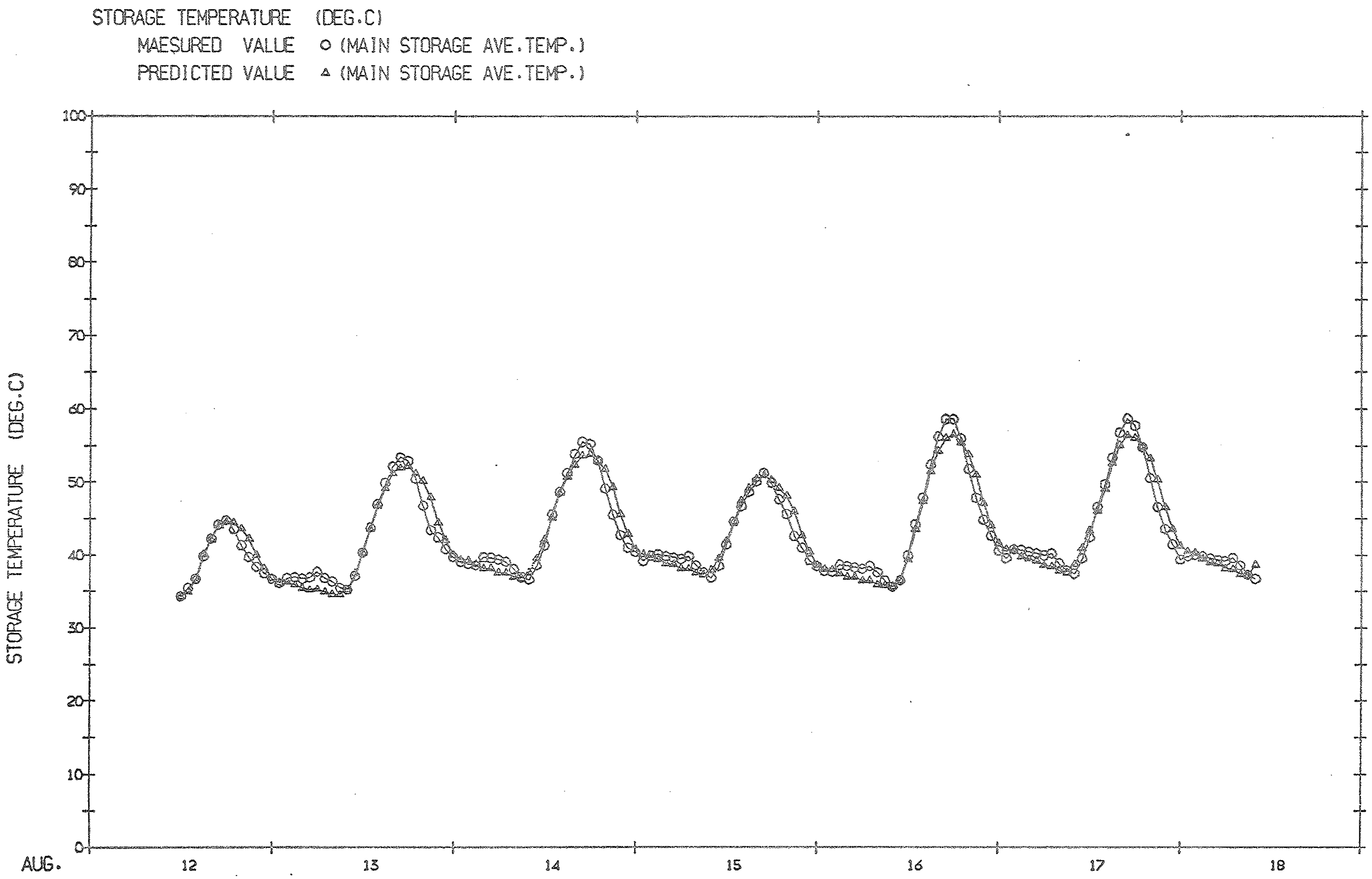


Fig. 5.6 Measured and predicted storage temperatures, ref. 18.

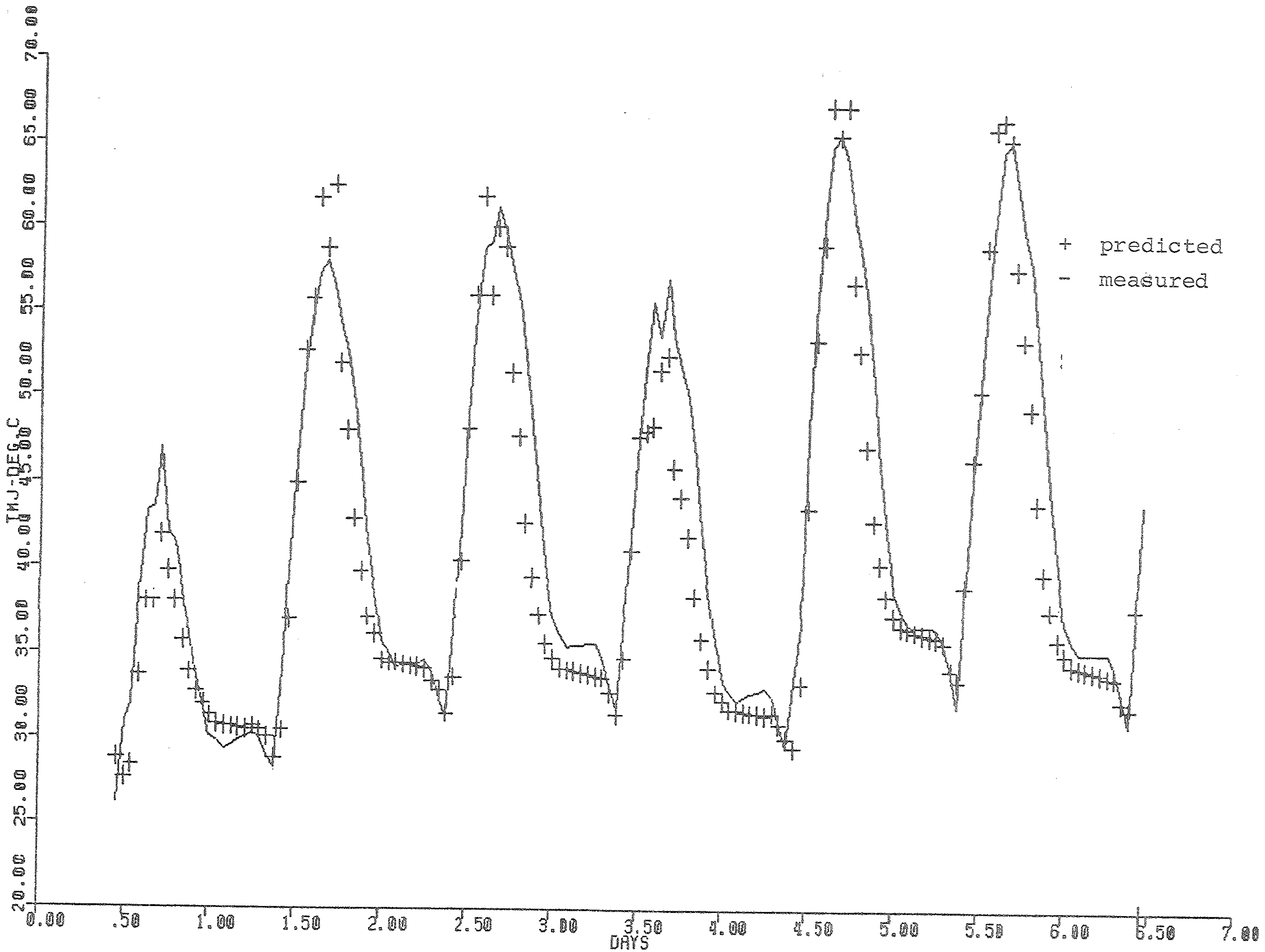


Fig. 5.7 Measured and predicted tank surface temperatures, ref. 7.

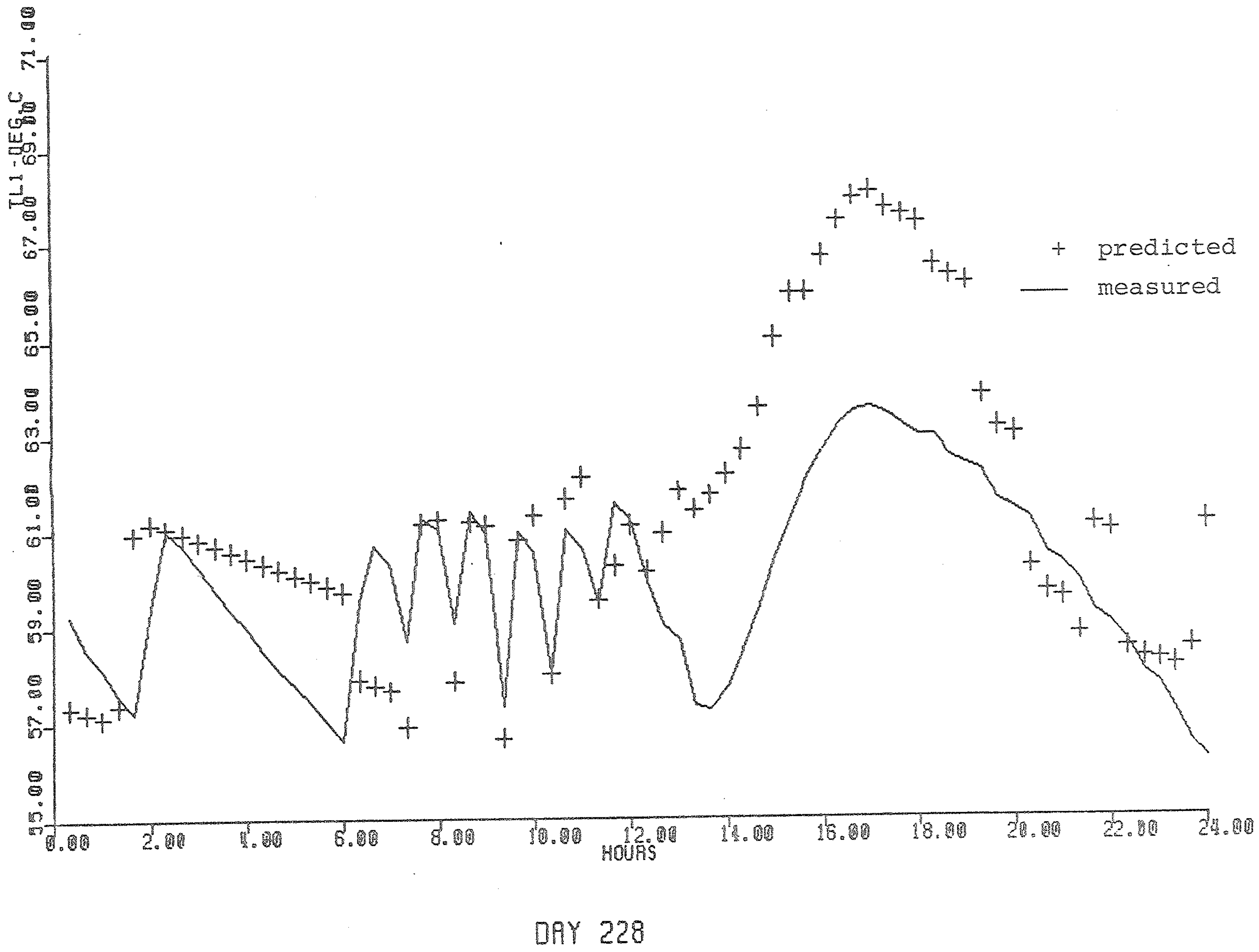


Fig. 5.8 Measured and predicted tank top layer temperatures, ref. 7

6. PARAMETER SENSITIVITY ANALYSES

6.1 Description of the Activity

Validation of computer codes as described in the previous sections of this report can be considered a spot-check on the validity of the codes. In most cases it is not practical to perform experiments for a variety of parameter changes to cover a broader range of the parameter space in which the models are likely to be used. A parameter sensitivity study for the models used in the validation activity was planned in light of this. By having all the models calculate the impact of the same parameter variations, a model-to-model comparison could give some indication as to the applicability of each model to these parameter changes. It should be noted that the model evaluation was the primary aim of this exercise, not the exact findings or whether or not some extra insulation on the pipes meant a significant improvement to the output of the system. If a standard parameter sensitivity analysis had been the aim, a series of runs would have been necessary, using much smaller steps in the parameter variations than chosen for this exercise.

The single tank indirect system used for the validation work was selected for the base case. Naturally, all parameters had to be fixed at certain values to make sure that everybody used the same starting point. The parameter variations adopted for the different runs are given below:

Run 1: Storage volume reduced by 33%, and
" area " correspondingly

Run 2: Storage loss value reduced by 24%

Run 3: " " " " by 62%

Run 4: Collector flow rate increased by 46%

Run 5: " " " reduced by 28%

Run 6: Pipe losses reduced by 47%

Run 7: The combination of run 1 to 6 that gives the highest solar output.

The exact system specifications and parameter values appear from Appendix 2.

6.2 Results of First Round Analysis

As was the case with the validation work, two rounds of calculations were performed, one finished by spring 1981, the other by spring 1982. Between these two rounds some of the reasons for discrepancies were cleared up and some further system specifications given.

Table 6.1 presents a comparison of the base run predictions for the first round of analysis. The abbreviations have the same meaning as in the preceding paragraphs. All the energy flows in the system, the collection efficiency, the solar fraction and the amount of energy consumed for pump operation are compared. The latter expresses pump running time. Three of the participating groups used TRNSYS; these are marked with an asterisk in the tables because it is interesting to see how well they compare. Table 6.2 shows the results of the parameter changes as an absolute percentage difference from the fraction of solar calculated in the base run. These results are also visualized in fig. 6.1 on which the observed differences have been marked as a function of the percentage parameter change.

From table 6.1 it appears that not all the participants agree on the amount of incoming solar radiation, QSUN, and the load calculations exhibit an even greater disagreement. The latter might be because a cold water inlet temperature never was specified. It is assumed that the mean temperature for the month, 25.6^{O}C, should be used. For the whole period this should add up to a total load of 890 MJ, which was obtained only by Tom Freeman. It is difficult to say what impact these differences in the driving functions have on the results, but they certainly complicate the comparisons.

It can be seen that the calculated solar fraction F varies from 61.8% to 83.5%. The best agreement is obtained for the storage losses QLSTO, which lie within 100 and 126 MJ. However, the pipe losses vary between 1 and 104 MJ. The collector efficiency NC, varies as much as from 34.3% to 47.4%.

It is interesting to compare the results obtained by the three different TRNSYS users. Delfosse and Kennish agree exactly on the solar fraction and the storage losses, but differ on the collected energy and the pipe losses. Freeman gets a considerably smaller value for QCOL which shows up as a 3% lower solar fraction. From table 6.2 it is seen that the three TRNSYS versions do not react alike on the parameter variations.

Although TRNSYS was used by all three participants not all three models were constructed the same. Freeman and Delfosse developed special subroutines to represent the wrap-around heat exchanger whereas Kennish took the approach of using only normally available TRNSYS subroutines. This illustrates the sensitivity of results to user methodologies despite the use of the same basic simulation program. As for the other models the diminishing of the storage and the collector flow rate variations cause the solar fractions both to decrease and to increase. A quick glance at fig. 6.1 tells that the variations of collector flow rate cause the greatest disagreement among the models. The reason for this seems to lie mainly in the collector control strategy. As flow is increased, the temperature rise through the collectors is decreased and more energy would be collected at a temperature nearer to the storage temperature. The 1.7 K controller turn-off temperature differential therefore causes increasing amounts of collectable energy to be lost as the flow rate is increased. Also, the effect of flow rate on the effectiveness of the wrap-around heat exchanger was neglected. This point is illustrated in table 6.2 by the results of Jørgensen, who performed a second fourth run using a stop differential set point of .5 K. This changed the negative impact of increased flow rate of minus 1.8% to a positive impact of 2.4%. Some further comments on this subject can be found in chapter 7.

6.3 Results of Second Round Analysis

Before the second round analysis was performed, some of the problem areas of the first round were clarified. The load was specified and, since some of the participants, in the first round, had used an incidence angle modifier and other participants had not, it was recommended for the second round that nobody should use it.

The pump start and stopping differential set points were lowered to 5 K and .5 K respectively. Also, a questionnaire was distributed to the participants for them to fill in the characteristics on how they modelled the system. On the basis of the answers the Operating Agent recommended a few changes to individual participants in order to get a better basis for comparisons. Finally, some of the participants made minor modifications to their programs after it was pointed out at the Annapolis working group meeting that they showed relatively poor energy balances.

The results of the second round base run predictions are presented in table 6.3. Although he was unable to participate in the second round analysis, Tom Freeman's results for the first round analysis are shown for comparative reasons, since he was the only one in the first round using the load recommended for the second round. It can be observed immediately that the models now agree very closely on the driving functions, the incoming solar radiation, QSUN, and the load, QTO.

The highest amount of collected energy were predicted by Inooka and La Fontaine. This might be explained by the facts that Inooka is the only person having a model that splits the radiation into direct and diffuse sunlight, and that La Fontaine's model does not use the simple linear efficiency curve, but calculates the collector performance in detail. The relatively low predictions of collected energy by Delire is explained by the fact that she is still using the incidence angle modifier. There seems to be reasonable agreement on the storage losses, QLSTO. Those of La Fontaine are high because of higher storage temperatures due to the high QCOL. Inooka predicts very high pipe losses, QLPIP, which reduces the useful energy transferred to the storage, QSTO, considerably. The obtained agreement on solar fraction, F%, and collection efficiency, NC%, is now much closer than the case was in the first round, table 6.1.

Table 6.4 and fig. 6.2 present the results of the parameter variations. The agreement on the impact of all parameter variations is now much closer than in the previous round. Kennish produced his results before receiving the recommendation of using lower starting and stopping differential set points. This is why his predictions for run 5 show a small positive impact of reducing the collector flow rate, while all the other models predict a negative impact of this parameter variation, as would be expected. Runs 4 and 5, however, still present a problem, and it must be concluded that at least some of the models need some refinement before they can be used to optimize collector flow rate. The agreement on the impact of reducing heat losses of storage and pipes in runs 2, 3 and 6 is good and all the models can be used with confidence to investigate these parameters. The reduction of storage size by one third is predicted to lower the solar fraction by .4 to 2.2%. This difference might be due to the use of different integration methods in the models, but no conclusions can be made. This question has been further addressed by Tom Freeman and the results are presented in chapter 7.

From the above discussion, it appears that the undertaking of this exercise was a valuable part of the total evaluation of the models. The limits of applicability of the models were established within the range of the chosen parameters, and some of the inherent problems of this type of models were pointed out.

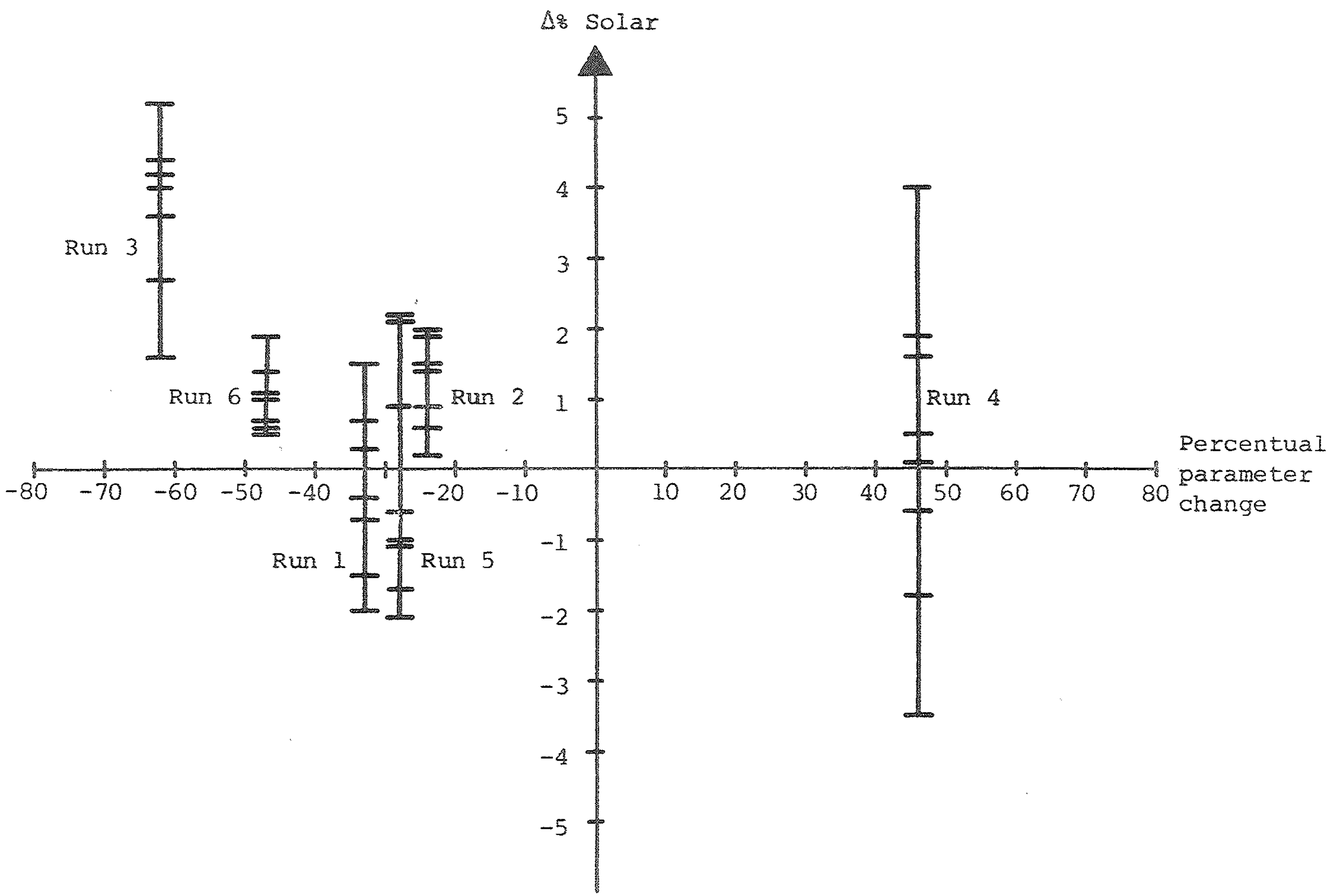


Fig. 6.1 The sensitivity of the models to parameter variations, first round analysis.

$$\Delta\% \text{ Solar} = \frac{\% \text{ Solar (Run x)} - \% \text{ Solar (Run Base)}}{\% \text{ Solar (Run Base)}}$$

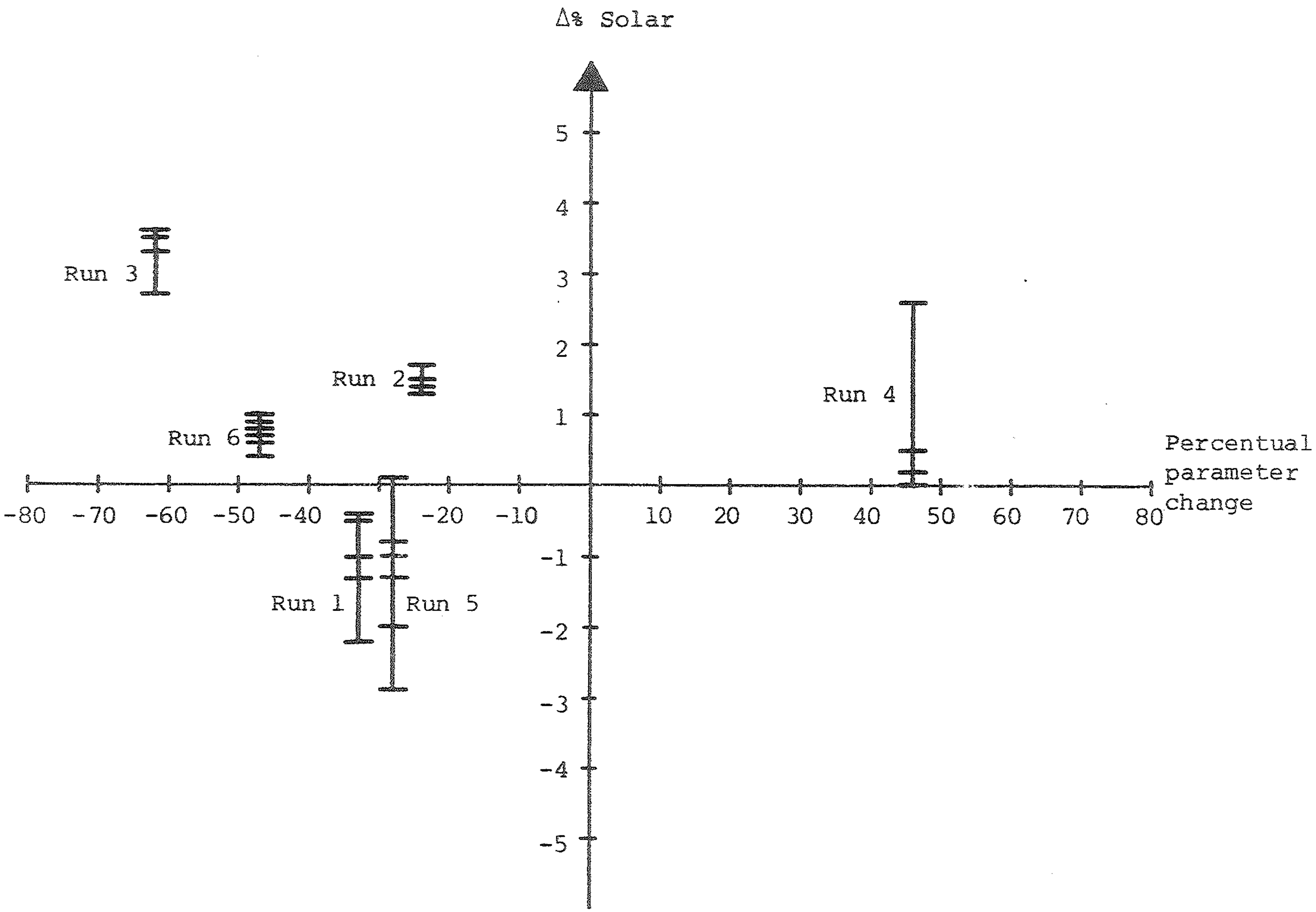


Fig. 6.2 The sensitivity of the models to parameter changes, second round analysis.

<u>Table 6.1</u> First round of the parameter sensitivity analysis. Base run results, MJ

Participant	QSUN	QCOL	QLPIP	QSTO	QLSTO	QTO	QAUX	QSOLAR	NC%	F%	QOP
*) Delfosse Therre Switzerland	2253	1068	1	900	116	936	181	755	47.4	80.9	61.9
*) Kennish Ahmed USA	2257	1016	68	900	117	933	177	756	45.0	81.0	75.0
*) Freeman USA	2248	925	79	838	126	890	196	694	41.1	78.0	60.8
Hedstrom USA	2139	922	56	866	110	908	149	759	43.1	83.5	50.4
La Fontaine UK	2245	853	24	786	100	926	235	691	38.0	74.7	69.1
Inooka Japan	2245	770	52	687	117	939	358	581	34.3	61.8	65.4
Jørgensen Denmark	2248	853	104	733	123	880	259	621	38.0	70.5	37.0
Wensiersky Germany	2174	848	39	750	109	954	334	620	39.0	66.5	36.3

*) TRNSYS

Table 6.2 First round of the parameter sensitivity analysis.
Results of parameter variations, % absolute deviation from base run.

Participant	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Delfosse **) Therre	+0.3	+1.4	+3.6	+0.1	-1.1	+0.6	+3.7
Kennish **) Ahmed	-2	+2	+4	+4	-1	+1	+8
**) Freeman	-0.4	+1.5	+4.2	-0.6	+2.1	+1.4	
Hedstrom	-1.5	+0.9	+2.7	+0.5	-0.6	+0.7	+3.4
La Fontaine	+0.7	+0.2	+5.2	+1.6	-1.7	+0.5	
Inooka	-0.4	+0.6	+1.6	+1.9	-2.1	+1.9	+3.2
Jørgensen	-0.7	+1.4	+4.0 +6.5 *)	-1.8 +2.4 *)	+0.8	+1.9	+8.9 *)
Wensiersky	+1.5	+2.0	+4.4	-3.5	+2.2	+1.1	

**) TRNSYS

*) Stop differential set point lowered to 0.5°C

Table 6.3 Second round of the parameter sensitivity analysis. Base run results, MJ

Participant	QSUN	QCOL	QLPIP	QSTO	QLSTO	QTO	QAUX	QSOLAR	NC%	F%	QOP
*) Kennish USA	2257	946	74	848	115	882	162	720	41.9	81.6	67
*) Freeman USA	2248	925	79	838	126	890	196	694	41.1	78.0	60
Hedstrom USA	2214	935	77	858	120	889	156	733	42.2	82.5	61
La Fontaine UK	2247	1028	61	918	134	877	123	744	45.7	86.0	63
Inooka Japan	2248	981	120	784	127	889	172	717	43.6	80.7	67
Jørgensen Denmark	2248	954	89	882	125	889	146	743	42.4	83.6	63
Delire Belgium	2248	881	59	838	126	888	191	697	39.0	78.5	50

*) TRNSYS

Table 6.4 Second round of the parameter sensitivity analysis.
Results of parameter variations, % absolute deviation from base run.

Participant	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Kennish	-.4	+1.4	+3.6	0.0	+0.1	+0.8	+4.6
Hedstrom	-1.3	+1.5	+3.5	+2.6	-2.9	+1.0	+6.2
La Fontaine	-2.2	+1.7	+2.7	+2.6	-2.0	+0.6	
Inooka	-1.0	+1.4	+3.6	+0.5	-1.3	+0.9	+4.8
Jørgensen	-0.5	+1.3	+3.6	0.0	-0.8	+0.4	+4.4
Delire	-1.0	+1.4	+3.3	+0.2	-1.0	+0.7	+4.2

7. INDIVIDUAL CONTRIBUTIONS

7.1 Introduction

When ten independent researchers and research groups undertake work of this nature, it is inevitable that they will approach the problems encountered differently and perform their own investigations of certain phenomena. Some of these individual investigations have been reported in the reports of the participants. Those of general interest are presented here.

7.2 New models

As mentioned previously the wrap-around heat exchanger on the indirect systems is not to be found in the standard TRNSYS model catalogue. The participants using TRNSYS therefore had to invent their own ways of handling this type of component. The information flow diagrams showing how the systems were modelled using TRNSYS, are presented in Appendix 3.

In all cases the participants did some further development of existing models and in two cases (La Fontaine and Jørgensen), a totally new model was developed. More details about these models can be found in the individual reports of the participants.

7.3 Solar radiation calculation methods

When the work commenced the Operating Agent recommended an incidence angle modifier to be used along with the given collector efficiency curve to account for the impact of the greater incidence angles on the solar gain:

$$K_{\alpha\tau} = 1. - 0.1\left(\frac{1}{\cos i} - 1\right)$$

One of the participants, Tatsuo Inooka, used another method for the same purpose and compared the two.

Tatsuo Inooka used the expression:

$$g_i = 1.08[2.3920 \cos i - 3.8636 \cos^3 i + 3.7568 \cos^5 i - 1.3952 \cos^7 i]$$

and published the following table:

Table 7.1 Comparison of incidence angle modifiers

I.a. modifier \ Incidence angle	0	15	30	45	60	75	80	85	90
$\tau \times K_{\alpha\tau}$	.96	.96	.95	.92	.86	.78	.5	-.05	-
g_i	.96	.96	.95	.93	.88	.73	.43	.22	0.0

The agreement between these two modifiers is so close that either of them can be used.

The data tape distributed contained not only the measured solar insolation on the collectors but also the global radiation. Tom Freeman took the opportunity of using the built-in Liu and Jordan correlation in TRNSYS to see how well the calculated radiation on the sloped surface applying this correlation, matched the measured values.

Tom Freeman's conclusion is quoted here (ref. 26):

> It is interesting to note in Table 1* how well the Liu-Jordan beam diffuse model and the TRNSYS tilted surface algorithms predict the daily total insolation on the collector surface. The modelled data seems to systematically over-predict the measured data slightly on cloudy days and to under-predict it slightly on sunny days. For the entire month the predicted total is within 1.25% of the measured total.

* Not in this report

7.4 Storage Volume Sensitivity

Inspired by the fact that the single tank indirect system in the parameter sensitivity analysis showed little or no sensitivity to the storage volume change, Tom Freeman performed a full sensitivity analysis of this parameter. Fig. 7.1 shows the results. It is seen that the solar fraction stays stable down to less than 150 litres of storage volume. This is quite a remarkable result, but Tom Freeman provides the following explanation for it (ref. 26):

> "Although these results seem to contradict accepted rules of thumb for sizing solar DHW storage, they are probably explained by two factors. First, the month being used in these simulations is uniformly sunny day-to-day. Second, the DHW load profile is identical day-to-day and has no really huge instantaneous or nighttime draws that would completely deplete small storage tanks. Finally, the fact that the heater set point is much higher than the required delivery temperature extends the effective size of storage."

7.5 Modelling Collector Pump Control

Also inspired by the parameter sensitivity analysis, but this time by the peculiar results obtained in varying collector flow rate, Ove Jørgensen investigated the impact on system performance of modelling the control of the collector pump in combination with size of time step. His findings are illustrated in figs. 7.2-7.4. Fig. 7.2 shows the collector input and the predicted collector output using 10-minute time steps for one of these days in the August 1978 data set. Fig. 7.3 shows the same, but this time the time step is one hour. It is noted that the collection stops at 1600 hours. This is because of the relatively high stopping differential set point used with these systems. For the predicted collector output on the next plot hourly time steps are also used, but this time a more advanced modelling of the control was incorporated in the model which allowed the collector pump to be on for part of the time step and off for the rest of the time. In the previous runs the pump is either on or off for the entire time step.

Once again, it becomes apparent that one cannot assume that any model can be applied for the investigation of any parameter. In this case the model which produced the results on fig. 7.3 could not be used to investigate flow rates and collector control differential temperature set points.

7.6 System Comparison

One of the objectives of having four different systems located at the same spot and exposed to almost identical loads is obviously to compare the performance of the systems and find which one is the best. This comparison, however, was slightly complicated to perform on the basis of the measurements alone, because the loads were not totally identical, the control set points were floating and thus not always identical, and one of the systems had a smaller solar collector. Jim Hedstrom therefore made the comparison by using his computer models of the four systems, equipping them with identical collectors and other system parameters and exposing them to the same driving functions, load and weather. The results of this are shown on fig. 7.5. Jim Hedstrom's own comments are (ref. 13):

> "The direct systems have the highest collector output because of the absence of the intermediate heat exchanger. However, the better insulation on the pre-heat tanks in the indirect systems results in better overall performance for these systems.

Double tank systems have higher collector output than single tank systems, but the large heat losses of the second tank results in lowest overall performance.

It is seen here that tank heat losses dominate the overall performance on each system. With better tank insulation, all systems could have comparable thermal performance"

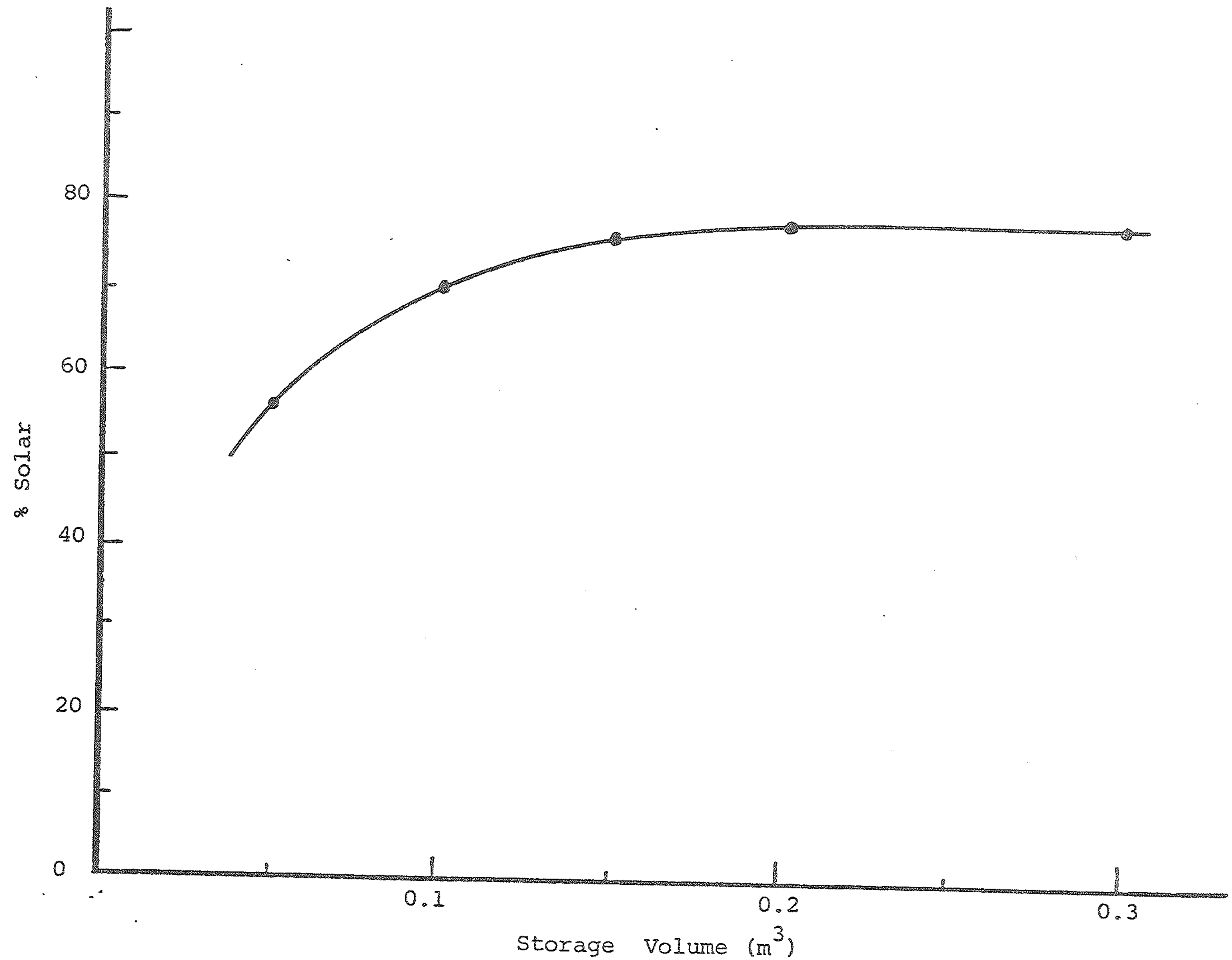


Fig. 7.1 Percent solar as a function of tank volume, ref. 26.

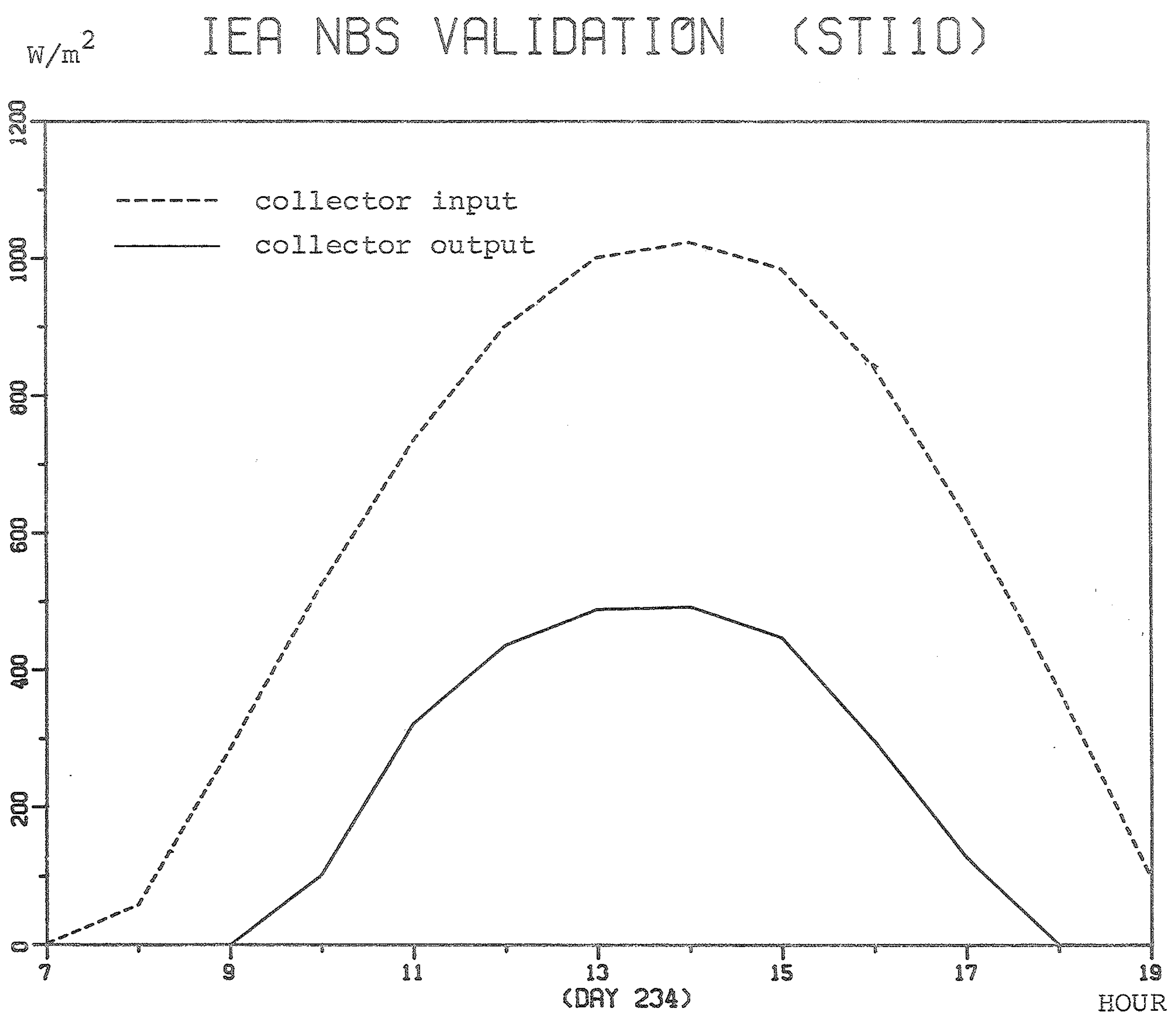


Fig. 7.2 Collector input and calculated collector output, 10-minutes time steps, ref. 19.

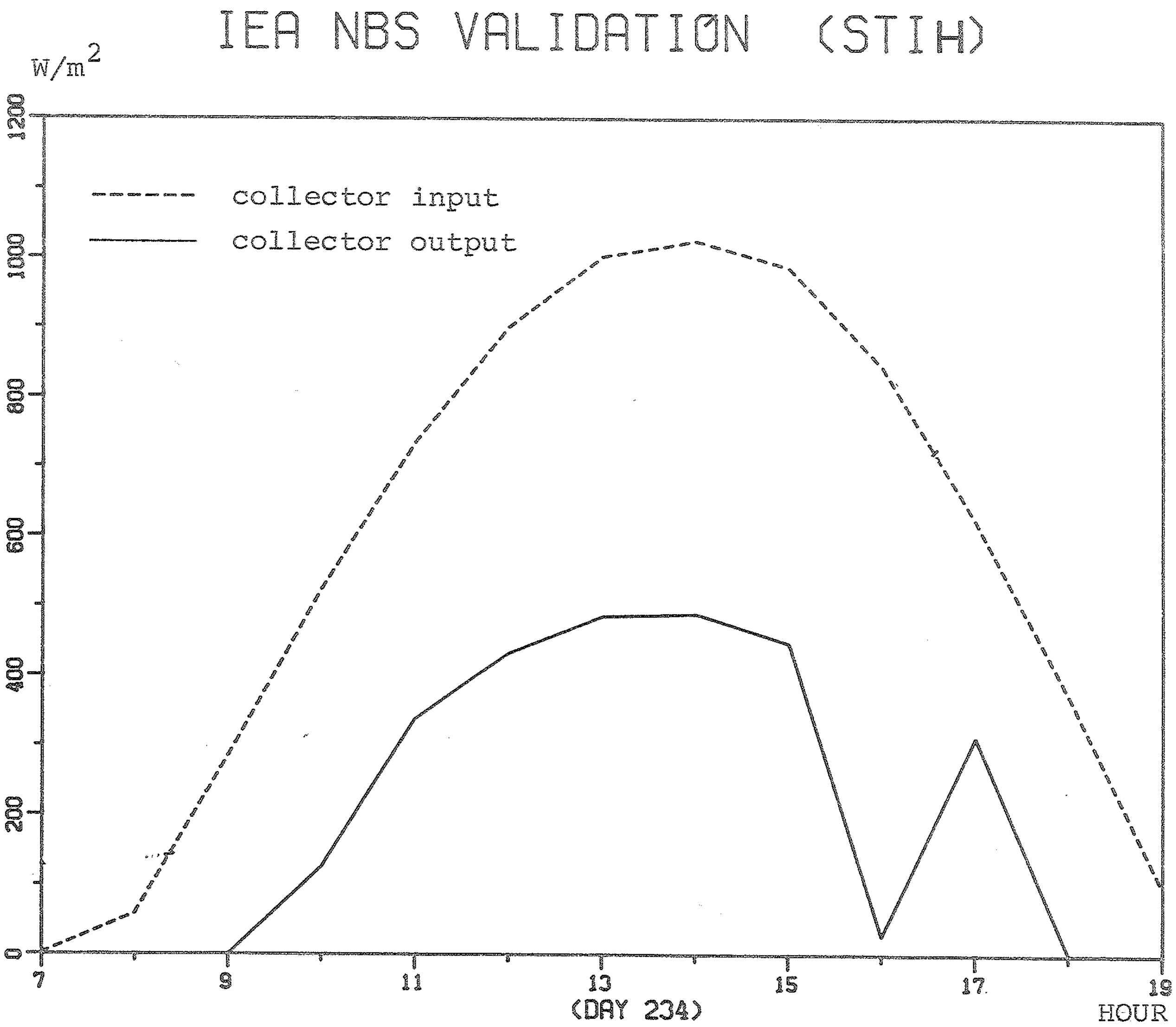


Fig. 7.3 Collector input and calculated collector output, hourly time steps, ref. 19.

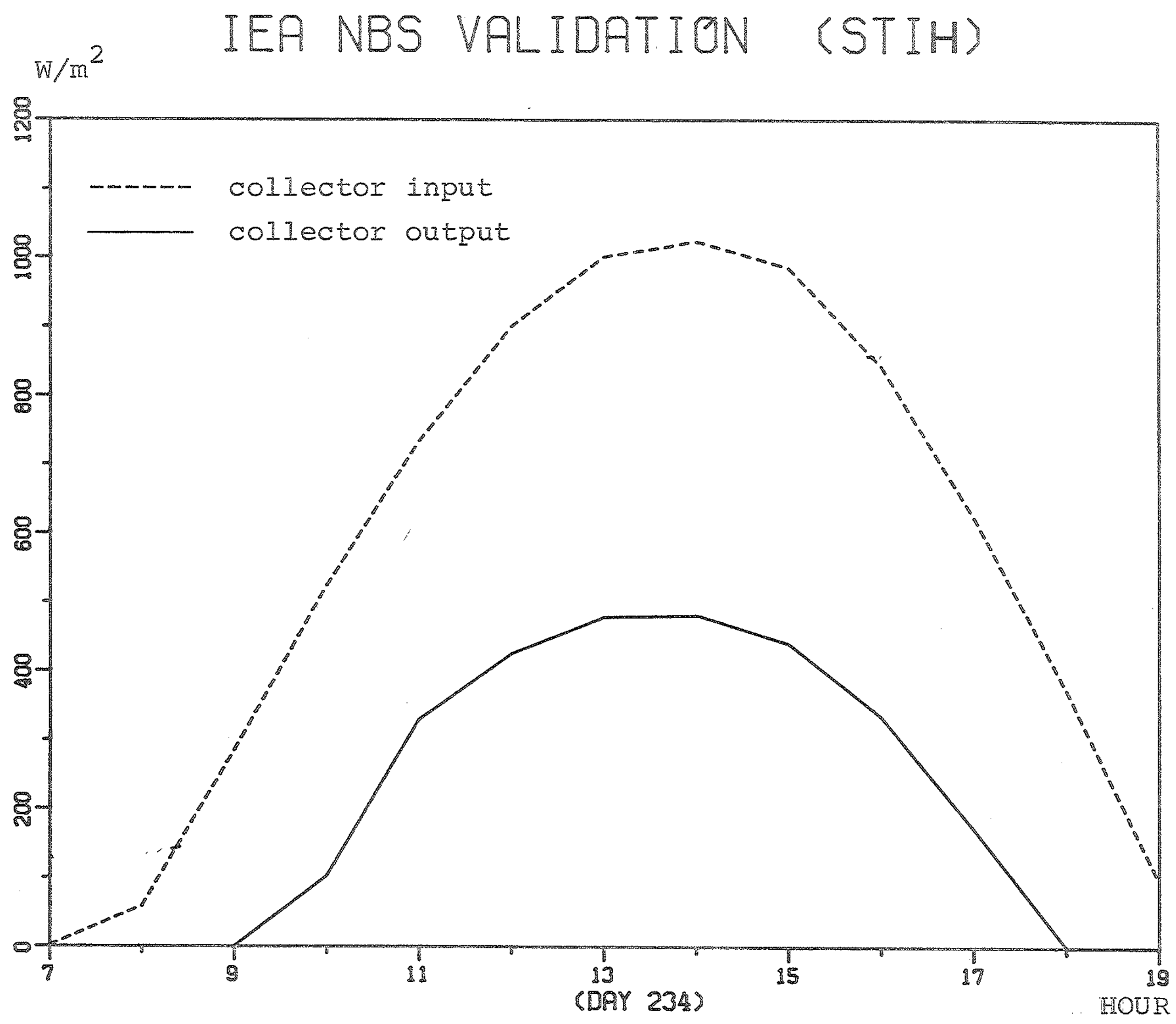


Fig. 7.4 Collector input and calculated collector output, hourly time steps using advanced control strategy, ref. 19.

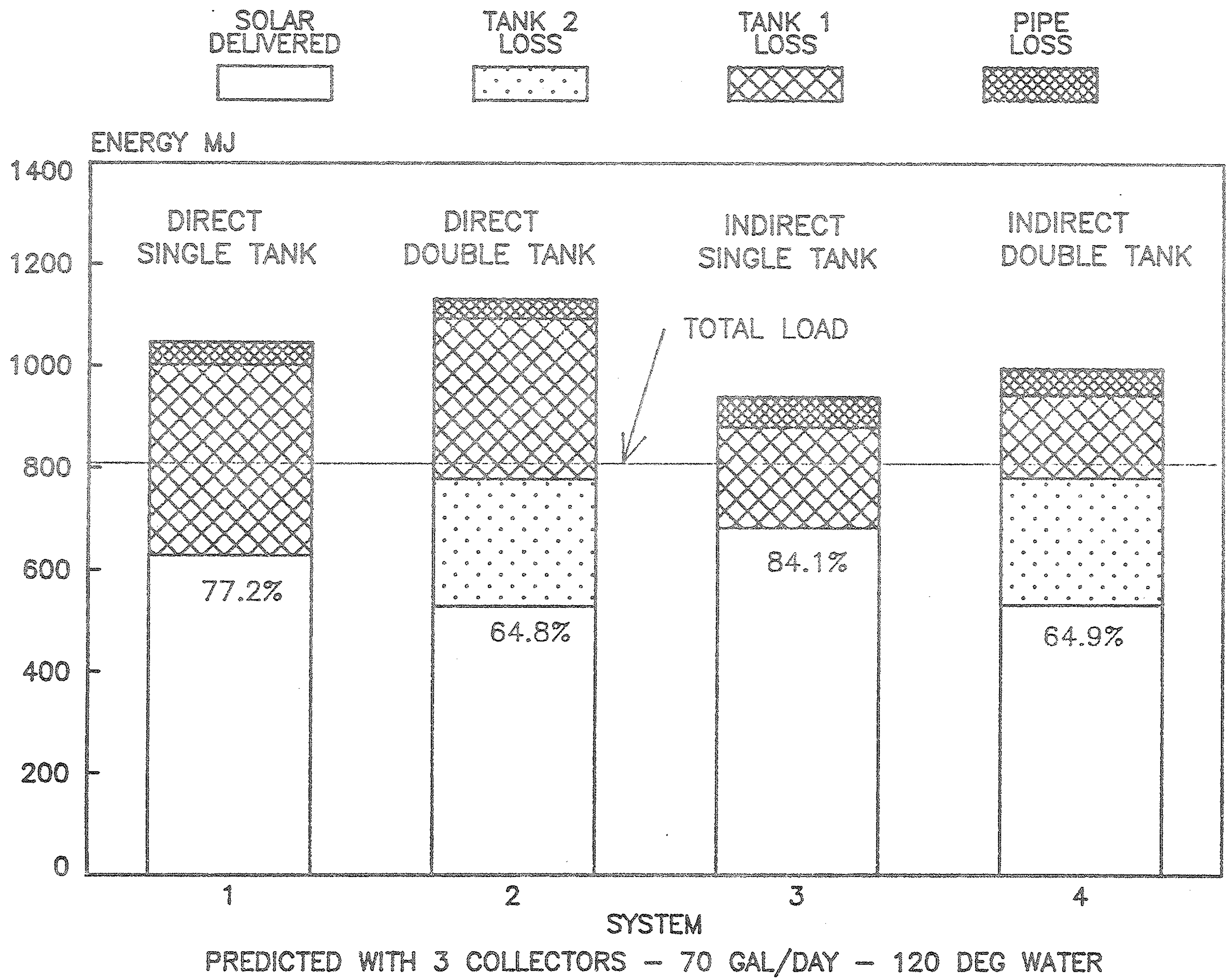


Fig. 7.5 Common prediction of the four systems, ref. 13.

8. CONCLUSIONS

Two rounds of computer simulation model evaluation work were undertaken. Both consisted of model-to-measurement validation and model-to-model comparisons in a parameter sensitivity analysis. The second round showed drastically improved results for both activities.

The main reason for this improvement lies in the fact that each modeller participating in this work interpreted the system description and the other specifications according to his/her own background. When the results were presented and discussed at experts meetings, the differences in interpretation became apparent and could be coordinated to achieve a more uniform approach of all the participants. This led to the more satisfactory results in the second round. This "user-effect" is inherent in the use of simulation models. It cannot be eliminated nor ignored; rather there must be attempts to diminish its impact. Future activities of this nature should be planned in the light of this.

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Appendix 1. Systems and instrumentation details.

1.1 Detailed description of the four DHW systems and the instrumentation.

The following pages have been extracted from ref. 34.

Single Tank Direct

The configuration of the single tank direct system is shown in Figure 1. This system consists of two solar collectors connected in parallel, one water storage tank, flow control valves, an on-off differential temperature controller with freeze protection circuitry, a Grundfos UPS-20-42 pump,* piping, and insulation.

The collectors used on all five liquid systems are Lennox Model LSC18-1S. This is a single-glass cover flat-plate liquid collector. The glass is tempered low iron with etched surface lines to reduce reflection. A steel absorber plate is formed around copper flow tubes and then coated with black chrome. Each collector has a gross area of 1.67 m^2 (18.0 ft^2) and a corresponding aperture area of 1.44 m^2 (15.5 ft^2). The collector enclosure is constructed of galvanized steel completely lined with 8.89 cm (3.50 in.) of glass fiber insulation. The collector efficiency curve is displayed in Figure 5.

The water storage tank is a 310 liter (82 gal.) State Industries conventional electric hot water tank. Within the tank are two 4500 watt heating elements of which only the top one is utilized in this experiment. Outside dimensions of this tank are 1.57 m (62.0 in.) in height by 0.19 m (24.0 in.) in diameter. The cold water inlet consists of a dip tube extending 0.41 m (53.0 in.) down from the upper surface of the tank. Glass fiber insulation, thickness 5.1 cm (2.0 in.), R-6.1, surrounds the actual storage tank which in turn is covered by a thin metal shell. The upper thermostat is set to maintain a temperature of 60°C (140°F). A hot water mixing valve tempers the 60°C water down to 49°C (120°F).

A Hawthorne Model 1504-A Fix Flo Controller is used to actuate the circulator pump when a temperature difference of 8.9°C (16°F) exists between the collector absorber plate and the storage tank temperature. A temperature difference of less than 1.7°C (3°F) causes circulation to cease. Collector flow rate is set at 3.3 ℓ/min (0.88 gal/min). The storage tank sensor is located on the exterior tank surface at an elevation of 15.3 cm (6.0 in.). The controller also actuates two solenoid valves to provide collector freeze protection. Freeze protection action is initiated if the absorber plate temperature reaches 2.8°C (37°F). One solenoid valve closes the supply to the collectors while the second one opens and allows drainage of the collectors. A fail-safe scheme is employed such that during a power failure the collector supply is closed and the collector drain is opened. An air vent and a vacuum relief valve attached to the highest point of the system allows venting of air during collector fill and eliminates a partial vacuum existing in the collectors during a drainage.

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* This report contains the names of manufacturers from which NBS purchased materials for use at the SDHW test facility. This is not an endorsement or recommendation of these products.

Hard copper tubing of 1.27 cm (0.50 in.) diameter is used throughout the installation except for 2.54 cm (1.00 in.) diameter headers interconnecting the two collectors. Armaflex insulation of 1.27 cm (0.50 in.), R-4, provides internal pipe insulation. Exterior insulation consists of 3.18 cm (1.25 in.) thick glass fiber insulation, R-5, covering the 1.27 cm piping while a 5.10 cm (2.0 in.) glass fiber insulation, R-8, encases the collector headers.

Double Tank Direct

The double tank direct system is shown in Figure 2. This system consists of three solar collectors connected in parallel, two water storage tanks, flow control valves, an on-off differential temperature controller with freeze protection circuitry, a Grundfos UPS-20-42 pump, and associated piping.

Lennox LSC18-1S solar collectors are utilized. The preheat storage tank is a 310 liter (82 gal.) State Industries conventional electric hot water tank. Both 4500 watt heating elements have been disconnected for this experiment. The auxiliary tank is a 159 liter (42 gal.) State Industries conventional electric hot water tank. Both 4500 watt heating elements are utilized to maintain the 140°F (60°C) set point temperature. A mixing valve reduces this to 49°C (120°F). Outside dimensions of the 159 liter tank are 1.22 m (48.0 in.) in height by 0.51 m (20.0 in.) in diameter. Water from the 310 liter tank enters through a dip tube extending 1.04 m (41.0 in.) down from the upper surface of the tank. Glass fiber insulation, thickness 5.1 cm (2.0 in.), R-6.1, surrounds the actual storage tank which in turn is covered by a thin metal shell.

A Hawthorne Model 1504-A Fix Flo controller regulates the circulator pump and freeze protection unit. All components and control temperature set points are identical to those utilized in the single tank direct system. Collector flow rate is set at 5.0 ℓ/min (1.32 gal/min). Piping and insulation are identical to the single tank direct system.

Single Tank Indirect

The single tank closed-loop indirect system, Figure 3, consists of three Lennox Model LSC18-1S collectors connected in parallel, a single water storage tank, an on-off differential temperature controller, a Grundfos UPS-20-42 pump, and associated piping and insulation.

The Solarstream 310 liter (82 gal.) water storage tank has an integral 4500 watt heating element located in the upper portion of the tank. Thus during periods of insuffcient solar energy, the heating element set at 60°C (140°F) satisfies the load requirements. The outside dimensions of this tank are 1.42 m (4.67 ft) in height by 0.71 m (2.33 ft) in diameter. A double-wall heat exchanger jacket surrounding the water tank allows the heat transfer fluid to heat the water within. Heat transfer fluid composition is a mixture of ethylene glycol (40% by weight) and distilled water. The heat exchanger jacket has an area of 1.58 m^2 (17.0 ft^2) which is attached to the surface of the tank by mechanical bonding. Insulation surrounding the heat exchanger and tank consists of 7.62 cm (3.0 in.), R-12, insulation. A 7.62 cm insulation slug also exists at the top and bottom of the tank. A mixing valve maintains the outlet water temperature at 49°C (120°F).

A Honeywell differential temperature controller actuates the pump when a temperature difference of 10°C (18°F) exists between the absorber plate and a tank surface temperature sensor. This sensor is located at a height of 0.74 m (29.0 in.). A 1.7°C (3°F) temperature difference causes the 5.0 ℓ/min (1.32 gal./min) circulation to terminate.

Piping and insulation are identical in nature as in the previously discussed systems.

Double Tank Indirect

The double tank indirect closed loop system, Figure 4, uses three Lennox Model LSC18-1S collectors connected in parallel, two water storage tanks, an on-off differential temperature controller, and a Grundfos UPS-20-40 two-speed circulator.

The Lennox Solarmate hot water preheat tank is identical to the Solarstream 310 liter tank except it lacks an integral heating element. Auxiliary energy, when needed, is supplied by a 159 liter (42 gal.) State Industries conventional hot water tank with both 4500 watt elements connected. The heating elements maintain the auxiliary tank temperature at 60°C (140°F). A mixing valve reduces this to 49°C (120°F). The Grundfos pump circulates the ethylene gylcol-water mixture (40%-60%) at 5.0 ℓ/min (1.32 gal/min). A Honeywell differential temperature controller, identical to the single tank indirect system controller, is employed.

Piping and insulation are identical to the previously discussed systems.

Inlet Water Temperature Control System

The inlet water temperature to all six SDHW systems is held constant over a given month as shown in Table 1. The temperature of the water is controlled by means of a 310 liter (82 gal.) storage tank with one 4500 watt integral heating element in combination with a 0.75 ton chiller. After a draw down has taken place, water from a well located at the test site replenishes the 310 liter tank. The water is circulated continously by the inlet of each system through the chiller and the 310 liter tank. A temperature controller interfaced with the electric heating element supplies the energy required to heat the water if necessary. A thermostat incorporated in the chiller actuates the chiller to remove heat, if so required.

The inlet water temperature control system maintains the set point temperature ± 2.5°C.

Automated Hot Water Draw System

The outlet of each hot water system interconnects with a main header. A normally-closed solenoid valve, located at the center of the header, releases the flow to a drain when actuated. An electronic timer combined with a stepping relay selects an interval timer corresponding to the desired hourly draw. The automatic reset interval timers range from 1.5 minutes to 10 minutes in duration. A throtting valve located at the exit of each system is set to maintain a flow rate of 3.79 ℓ/min (1.0 gal/min) when the solenoid valve is open. Thus when a given interval timer is energized for its set time interval, a corresponding amount of water is drawn from each of the six systems. A flow totalizer at the exist of the interconnecting header totalizes the draw down from all six systems. The load schedule, see fig. 3.2, was developed by J. Mutch of the Rand Corporation, is used in the TRNSYS User's Manual as a typical hot water use schedule, and was implemented for use in this experimental program.

Instrumentation

Each SDHW system is extensively instrumented. Located within each water storage tank are Type T copper-constantan thermocouples located in 15.24 cm (6.0 in.) increments. Thermocouples also monitor the collector inlet and outlet temperature for each system. The inlet and exit potable water temperatures are measured with thermocouples and a 3 junction thermopile measures the temperature difference durin draw down. The output of the thermopiles are feed to an electronic integrator during draw down periods.

A General Electric Type I-70-S kWh meter is used to measure the auxiliary energy consumed by the electric heating elements. A Duncan Electric Model EM 10 Wh meter measures the energy used by the circulators, controls, solenoid valves, etc. for each system. Additional, instrumentation for the air system includes thermocouples and thermopiles built across the inlet and exit of the collectors and heat exchanger.

Each systems' water consumption is measured by two Badger Meter Model 15 flow totaliziers. One measures the total amount of water which has been drawn off, while the second one measures the quantity of water which actually goes through the solar storage tanks. The quantity difference is the amount of cold water which enters the mixing valve.

A Brooks Instrument Company Rotometer measures the flowrate of the fluid circulating through the collectors of each liquid system. A three valve bypass arrangement is included on each liquid system such that a turbine flowmeter may be installed in the collector flow loop. This capability allows the flowrates to be continuously recorded if desired for any system.

An elapsed time meter connected to each system's controller measures the amount of time the circulators are in operation.

Recorded meteorological information includes horizontal surface radiation, tilted surface radiation, direct beam radiation, wind speed, wind direction, and ambient temperature. A listing of the instruments used to measure meteorological data is shown in Table 2. A complete list of all recorded measurements is shown in Table 3.

A Leads & Northrup Trendscan 1000 High Sensitivity Data Acquisition System scans all channels in ten minute intervals. The basic unit provides input processing and control for the system and can accommodate up to 20 inputs, although it can be expanded to scan up to 1000 points by addition of Trendscan Input Frames each of which accommodates 100 points. Each Input Frame can accommodate up to 10 input multiplexer cards, each card in turn is capable of switching up to 10 inputs. The basic unit has an integral high-speed, 21-column, alphanumeric, electronic discharge printer. An internal clock provides real time display and initiates periodic logs at specified time intervals. The shared digital displays enable readout of time or measurement data. The instrument is provided with three ranges, Type T thermocouple, 0 ± 400 mv, and 0 ± 10 V. Reference junction compensation for thermocouple measurements is located on the range cards in the basic unit. The SDHW test facility utilizes two input frames with a total of 15 input multiplexer cards, thus giving a total of 150 independent channels. The display resolution and system accuracy are given in Table 4.

The data acquisition system is interfaced with a Kennedy Model 1600/360 incremental write magnetic tape recorder. This 9 track incremental write only recorder writes at 800 BPI density at asynchronous rates of 0-500 characters/second. The magnetic tape is replaced every seven days and taken to NBS's computer center for data reduction.

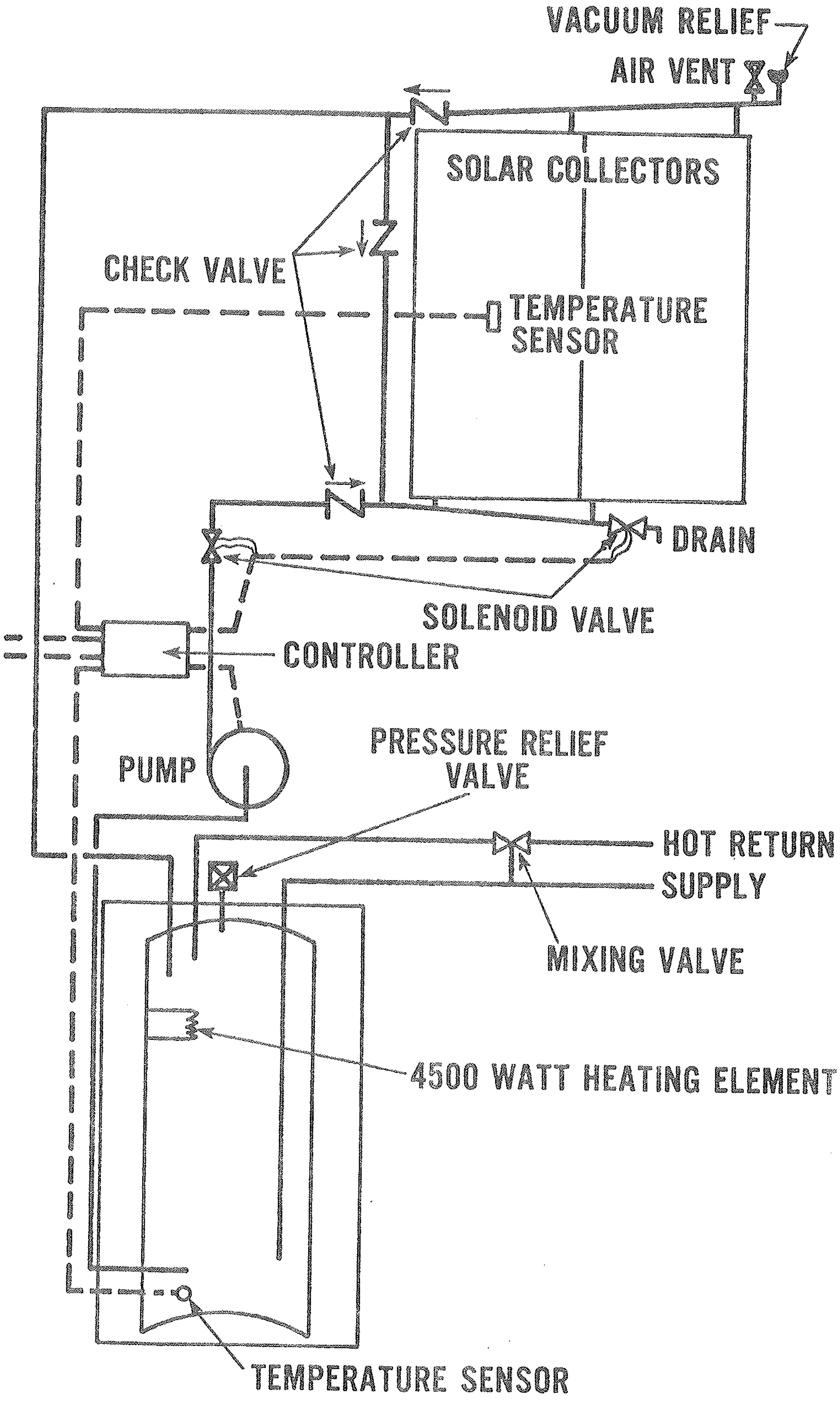


Figure 1. Single Tank Direct System

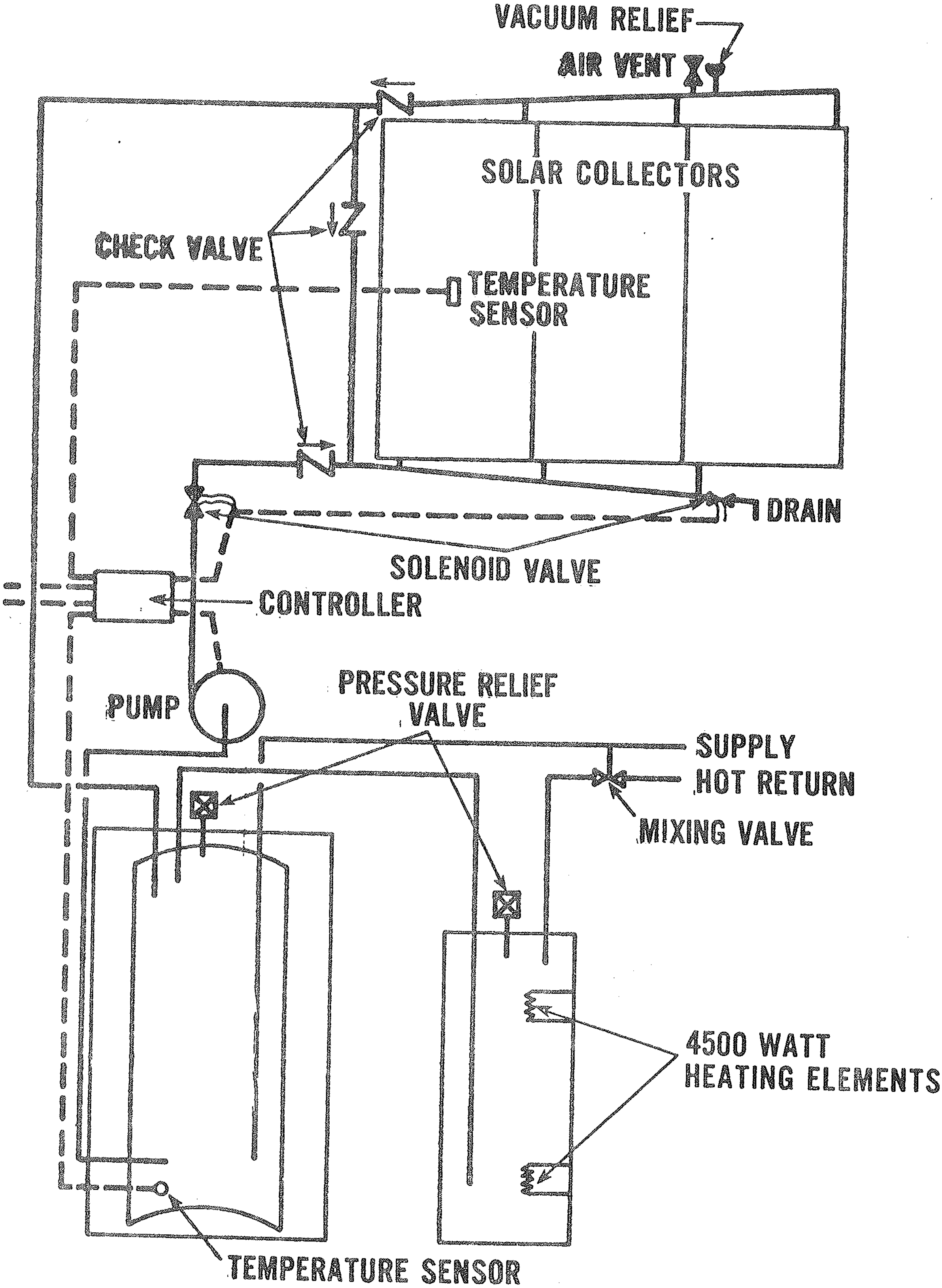


Figure 2. Double Tank Direct System

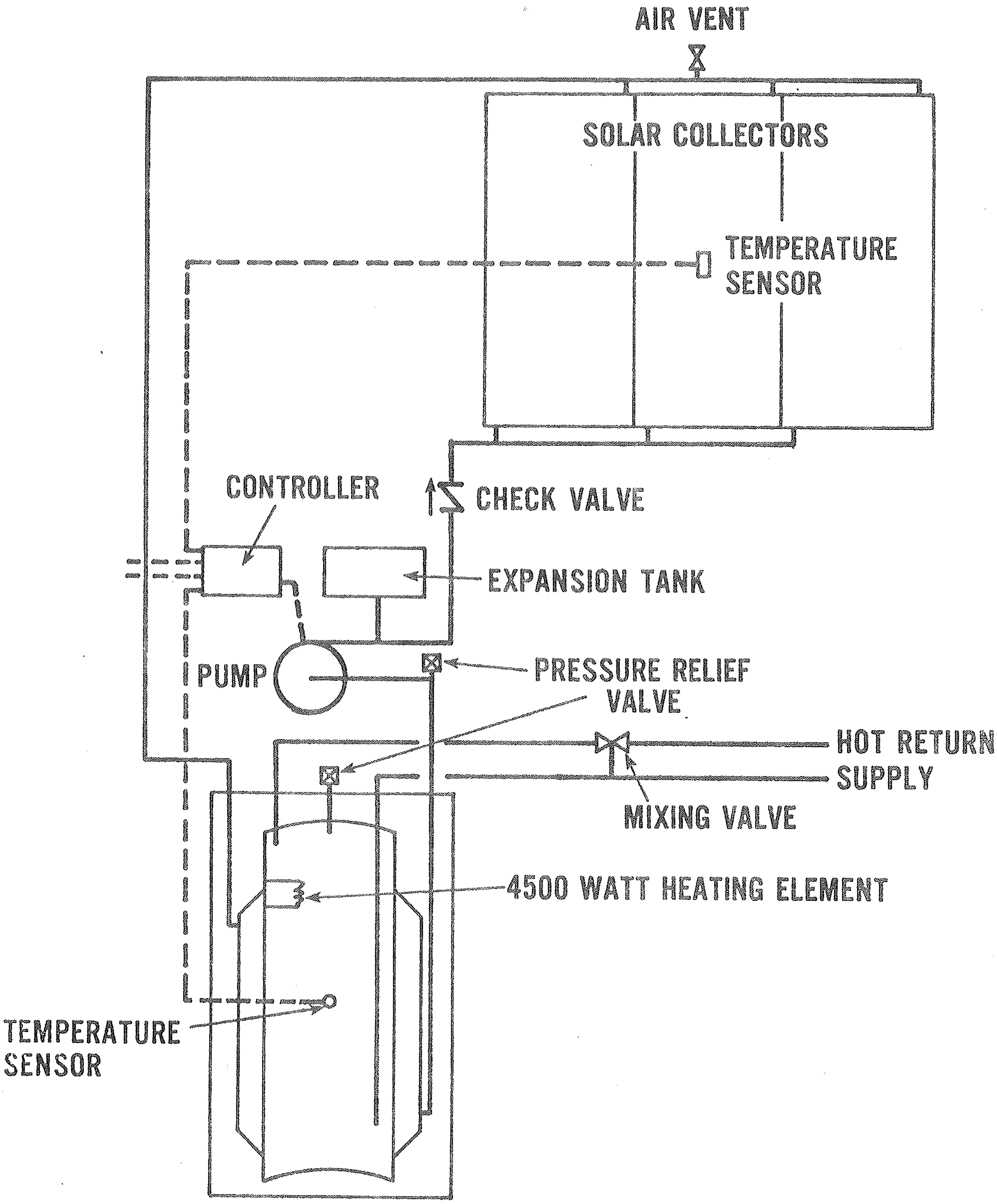


Figure 3. Single Tank Indirect System

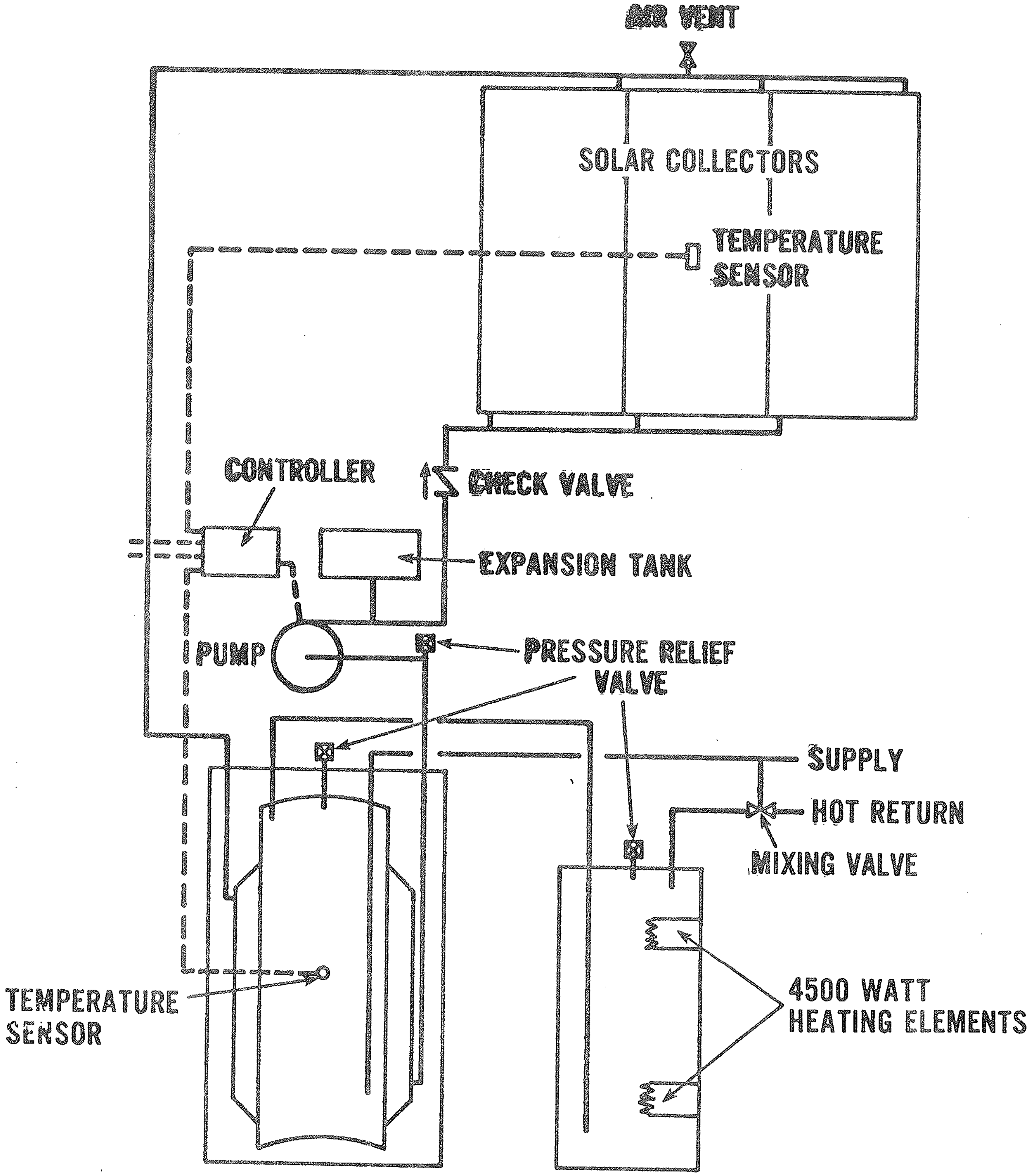


Figure 4. Double Tank Indirect System

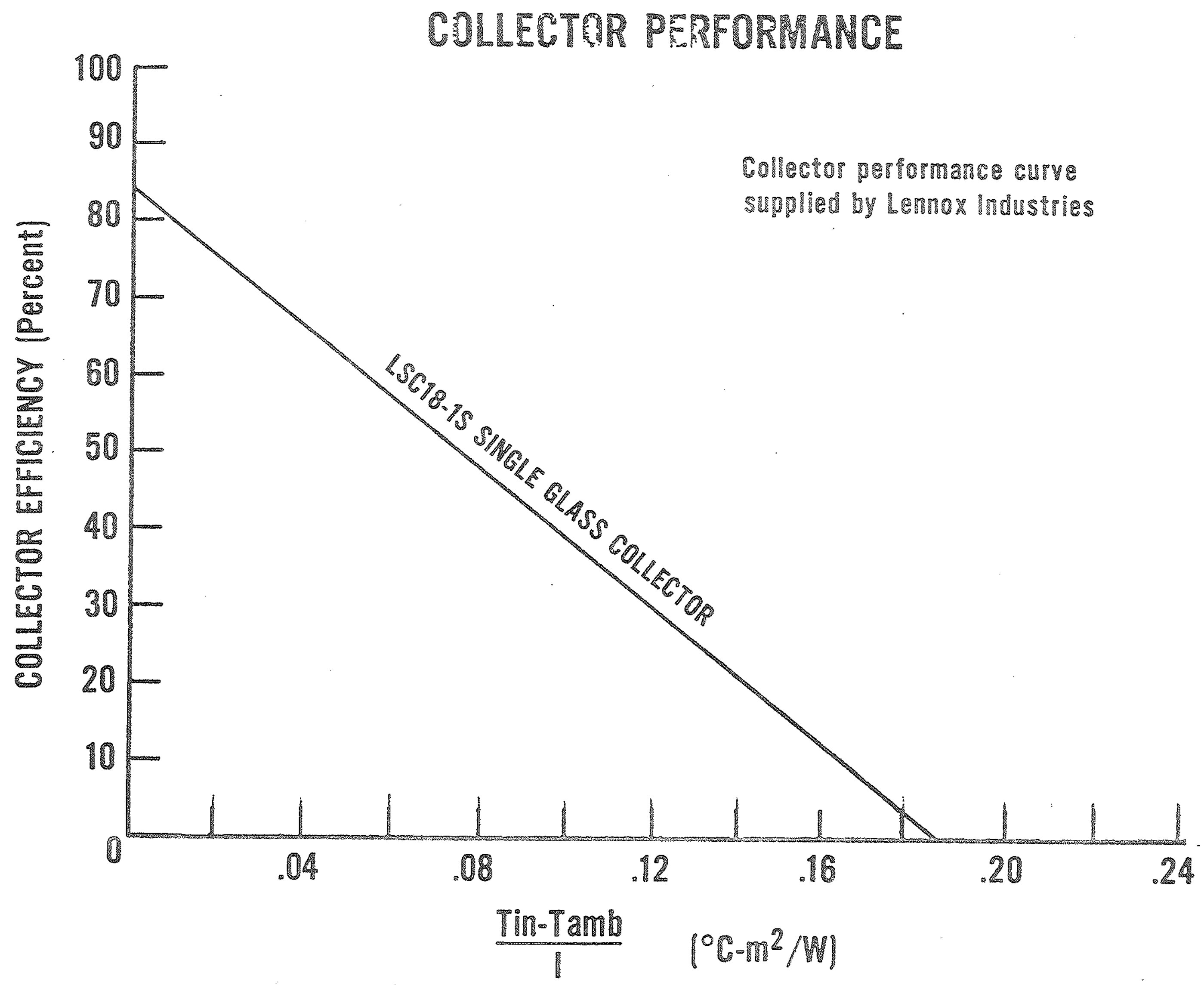


Figure 5. Collector Efficiency Curve

Table 1

Washington D.C. Monthly Source Water Temperature [9]

Month	Temperature °C	Temperature °F
Jan	5.6	42.0
Feb	5.6	42.0
Mar	11.1	52.0
April	13.3	56.0
May	17.2	63.0
June	19.4	67.0
July	19.4	67.0
August	25.6	78.0
Sept	26.1	79.0
Oct	20.0	68.0
Nov	12.8	55.0
Dec	7.8	46.0

Table 2

Meteorological Instrumentation

Measurement	Instrument
Total Horizontal Incident Radiation	Epply 8-48 Pyranometer
Total Tilt Surface Incident Radiation	Epply PSP Pyranometer
Direct Beam Radiation	Epply Normal Incidence Pyrheliometer
Wind Velocity	Weather Measure Corporation Wind Cup Anemometer W103-B
Wind Direction	Weather Measure Corporation Light Weight Vane W104
Ambient Temperature	Type T Thermocouples

Table 3

Solar Domestic Hot Water Test Site
Data Channel Assignment

Channel No.	Measurement			
1	Temperature	Single Tank Direct (82 gal)	6"	From Tank Bott
2	Temperature	Single Tank Direct (82 gal)	12"	From Tank Bott
3	Temperature	Single Tank Direct (82 gal)	18"	From Tank Bott
4	Temperature	Single Tank Direct (82 gal)	24"	From Tank Bott
5	Temperature	Single Tank Direct (82 gal)	30"	From Tank Bott
6	Temperature	Single Tank Direct (82 gal)	36"	From Tank Bott
7	Temperature	Single Tank Direct (82 gal)	42"	From Tank Bott
8	Temperature	Single Tank Direct (82 gal)	48"	From Tank Bott
9	Temperature	Single Tank Direct (82 gal)	54"	From Tank Bott
10	Temperature	Single Tank Direct (82 gal)	60"	From Tank Bott
11	Temperature	Double Tank Direct (82 gal)	6"	From Tank Bott
12	Temperature	Double Tank Direct (82 gal)	12"	From Tank Bott
13	Temperature	Double Tank Direct (82 gal)	18"	From Tank Bott
14	Temperature	Double Tank Direct (82 gal)	24"	From Tank Bott
15	Temperature	Double Tank Direct (82 gal)	30"	From Tank Bott
16	Temperature	Double Tank Direct (82 gal)	36"	From Tank Bott
17	Temperature	Double Tank Direct (82 gal)	42"	From Tank Bott
18	Temperature	Double Tank Direct (82 gal)	48"	From Tank Bott
19	Temperature	Double Tank Direct (82 gal)	54"	From Tank Bott
30	Temperature	Double Tank Direct (82 gal)	60"	From Tank Bott
31	Temperature	Double Tank Direct (42 gal)	6"	From Tank Bott
32	Temperature	Double Tank Direct (42 gal)	12"	From Tank Bott
33	Temperature	Double Tank Direct (42 gal)	18"	From Tank Bott
34	Temperature	Double Tank Direct (42 gal)	24"	From Tank Bott
35	Temperature	Double Tank Direct (42 gal)	30"	From Tank Bott
36	Temperature	Double Tank Direct (42 gal)	36"	From Tank Bott
37	Temperature	Double Tank Direct (42 gal)	42"	From Tank Bott
38	Temperature	Single Tank Indirect (82 gal)	6"	From Tank Bott
39	Temperature	Single Tank Indirect (82 gal)	12"	From Tank Bott
40	Temperature	Single Tank Indirect (82 gal)	18"	From Tank Bott
41	Temperature	Single Tank Indirect (82 gal)	24"	From Tank Bott
42	Temperature	Single Tank Indirect (82 gal)	30"	From Tank Bott
43	Temperature	Single Tank Indirect (82 gal)	36"	From Tank Bott
44	Temperature	Single Tank Indirect (82 gal)	42"	From Tank Bott
45	Temperature	Single Tank Indirect (82 gal)	48"	From Tank Bott
46	Temperature	Single Tank Indirect (82 gal)	54"	From Tank Bott

Channel No.	Measurement			
47	Temperature	Double Tank Indirect (82 gal)	6"	From Tank Bottom
48	Temperature	Double Tank Indirect (82 gal)	12"	From Tank Bottom
49	Temperature	Double Tank Indirect (82 gal)	18"	From Tank Bottom
50	Temperature	Double Tank Indirect (82 gal)	24"	From Tank Bottom
51	Temperature	Double Tank Indirect (82 gal)	30"	From Tank Bottom
52	Temperature	Double Tank Indirect (82 gal)	36"	From Tank Bottom
53	Temperature	Double Tank Indirect (82 gal)	42"	From Tank Bottom
54	Temperature	Double Tank Indirect (82 gal)	48"	From Tank Bottom
55	Temperature	Double Tank Indirect (82 gal)	54"	From Tank Bottom
56	Temperature	Double Tank Indirect (42 gal)	6"	From Tank Bottom
57	Temperature	Double Tank Indirect (42 gal)	12"	From Tank Bottom
58	Temperature	Double Tank Indirect (42 gal)	18"	From Tank Bottom
59	Temperature	Double Tank Indirect (42 gal)	24"	From Tank Bottom
70	Temperature	Double Tank Indirect (42 gal)	30"	From Tank Bottom
71	Temperature	Double Tank Indirect (42 gal)	36"	From Tank Bottom
72	Temperature	Double Tank Indirect (42 gal)	42"	From Tank Bottom
73	Temperature	Air System (82 gal)	6"	From Tank Bottom
74	Temperature	Air System (82 gal)	12"	From Tank Bottom
75	Temperature	Air System (82 gal)	18"	From Tank Bottom
76	Temperature	Air System (82 gal)	24"	From Tank Bottom
77	Temperature	Air System (82 gal)	30"	From Tank Bottom
78	Temperature	Air System (82 gal)	36"	From Tank Bottom
79	Temperature	Air System (82 gal)	42"	From Tank Bottom
90	Temperature	Air System (82 gal)	48"	From Tank Bottom
91	Temperature	Air System (82 gal)	54"	From Tank Bottom
92	Temperature	Air System (82 gal)	60"	From Tank Bottom
93	Temperature	Air System (42 gal)	6"	From Tank Bottom
94	Temperature	Air System (42 gal)	12"	From Tank Bottom
95	Temperature	Air System (42 gal)	18"	From Tank Bottom
96	Temperature	Air System (42 gal)	24"	From Tank Bottom
97	Temperature	Air System (42 gal)	30"	From Tank Bottom
98	Temperature	Air System (42 gal)	36"	From Tank Bottom
99	Temperature	Air System (42 gal)	42"	From Tank Bottom
100	Temperature	Single Tank Direct	Collector Supply	
101	Temperature	Single Tank Direct	Collector Return	
102	Temperature	Single Tank Direct	Collector Supply	
103	Temperature	Single Tank Direct	Collector Return	
104	Temperature	Single Tank Indirect	Collector Supply	
105	Temperature	Single Tank Indirect	Collector Return	
106	Temperature	Single Tank Indirect	Collector Supply	
107	Temperature	Single Tank Indirect	Collector Supply	

Channel No.	Measurement		
108	Temperature	Thermosyphon System	Collector Supply
109	Temperature	Thermosyphon System	Collector Return
110	Temperature	Single Tank Direct	Cold Water Supply
111	Pump Status	Single Tank Direct	Cold Water Supply
112	Temperature	Double Tank Direct	Cold Water Supply
113	Solenoid Status	Single Tank Direct	
114	Temperature	Single Tank Indirect	Cold Water Supply
115	Pump Status	Double Tank Direct	
116	Temperature	Double Tank Indirect	Cold Water Supply
117	Solenoid Status	Double Tank Direct	
118	Temperature	Air System	Cold Water Supply
119	Pump Status	Single Tank Indirect	
120	Pump/Blower Status	Air System	
121	Indoor Temperature	Location A	
122	Indoor Temperature	Location B	
123	Indoor Temperature	Location C	
124	Indoor Temperature	Location D	
125	Indoor Temperature	Location E	
126	Indoor Temperature	Location F	
127	Indoor Temperature	Location G	
128	Indoor Temperature	Location H	
129	Open		
130	Temperature	Thermosyphon System	Cold Water Supply
131	Pump Status	Double Tank Indirect	
132	Temperature	Thermosyphon System	6" From Tank Bottom
133	Temperature	Thermosyphon System	12" From Tank Bottom
134	Temperature	Thermosyphon System	18" From Tank Bottom
135	Temperature	Thermosyphon System	24" From Tank Bottom
136	Temperature	Thermosyphon System	30" From Tank Bottom
137	Temperature	Thermosyphon System	36" From Tank Bottom
138	Temperature	Thermosyphon System	42" From Tank Bottom
139	Temperature	Thermosyphon System	48" From Tank Bottom

Channel No.	Measurement
140	Temperature Single Tank Direct Hot Water Exit
141	Temperature Double Tank Direct Hot Water Exit
142	Temperature Single Tank Indirect Hot Water Exit
143	Temperature Double Tank Indirect Hot Water Exit
144	Temperature Air System Hot Water Exit
145	Temperature Thermosyphon System Hot Water Exit
146	Temperature Outdoor
147	Solar Radiation Tilt-Integrated
148	Solar Radiation Horizontal-Integrated
149	Temperature Air System Heat Exchange Water Supply
150	Temperature Air System Heat Exchanger Water Return
151	ΔT Thermopile Heat Exchanger
152	ΔT Thermopile Air Collectors
153	Temperature Air System Heat Exchanger Inlet Location A
154	Temperature Air System Heat Exchanger Inlet Location B
155	Temperature Air System Heat Exchanger Outlet Location A
156	Temperature Air System Heat Exchanger Outlet Location B
157	Temperature Air Collector Inlet Location A
158	Temperature Air Collector Inlet Location B
159	Temperature Air Collector Inlet Location C
170	Temperature Air Collector Inlet Location D
171	Temperature Air Collector Outlet Location A
172	Temperature Air Collector Outlet Location B
173	Temperature Air Collector Outlet Location C
174	Temperature Air Collector Outlet Location D
175	Wing Speed - Integrated
176	Wing Direction
177	Open

Channel No.	Measurement
178	Open
179	Flow Rate - Selected System
190	Radiation - Tilted Surface
191	Radiation - Horizontal Surface
192	Open
193	Wind Speed
194	ΔT Integrated Single Tank Direct
195	ΔT Integrated Double Tank Direct
196	ΔT Integrated Double Tank Indirect
197	ΔT Integrated Double Tank Indirect
198	ΔT Integrated Air System
199	ΔT Integrated Thermosyphon System

Table 4

Data Acquistion System Accuracy

Range Description	Total Range	Display Resolution	System Accuracy
Type T TC Copper-Constantan	-200°C to +400°C	0.1C	0.9°C
EMF	± 40 mV	1μV	± (0.02% +40μV)
EMF	± 10 V	1 mV	± (0.02% +4mV)

1.2 Details of wrap-around heat exchanger storage tank.

Details for the storage tank with the wrap-around heat exchanger were sent together with the data set from August 1981. The details are in the form of a drawing of the tank with the exact measures in inches. Figure 6 is a copy of this specification drawing on which the measures in inches have been replaced by the corresponding numbers in centimeters.

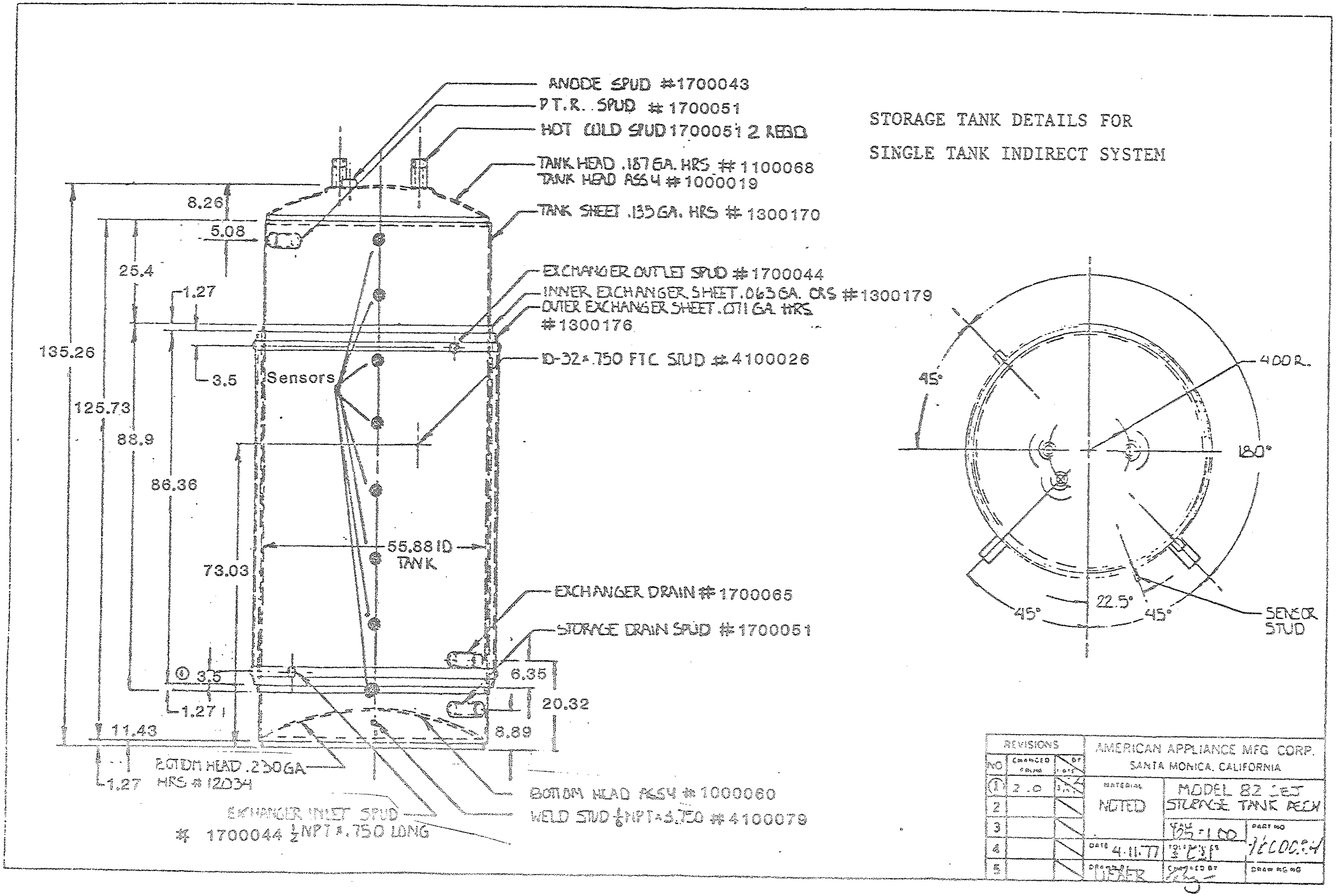


Figure 6. Details of wrap-around heat exchanger storage tank, cm.

Appendix 2. Parameter sensitivity analysis specifications.

As explained in chapter 6, a set of detailed system specifications were distributed for the parameter sensitivity analysis. The system configuration chosen for the analysis was the NBS single tank indirect system used in the validation part of this activity. The exact specifications of the system parameters to be used in the base run and in run 1 through 8, are given on the following page. At a later date, November 30, 1981, some further recommendations were given by the Operating Agent to assure better comparability among the predictions of the program. They are the following:

- Pump starting differential set point: 5 K
- Pump stopping differential set point: .5 K
- Collector heat capacity stated includes fluid content
- Do not use the previously recommended incidence angle modifier (many of the participants never used it).

IEA Task I, Subtask E, Validation

Parameter specification for sensitivity analysis on NBS - DHW Single Tank Indirect System.

Parameter	Base case, Run 0	Run no: Parameter value
Collector: MCp	16.55 kJ/m^2 ^{o}C	
$\dot{m}$Cp	343 W/^{o}C	Run 4: 500 W/^{o}C Run 5: 250 W/^{o}C
Piping: Uinside	.19 W/m^{o}C, l = 7.3 m	Run 6: 0.10 W/m^{o}C
Uoutside	.13 W/m^{o}C, l = 2.4 m	Run 6: 0.07 W/m^{o}C
MCp	.78 kJ/m^{o}C	
Tank: AT	2,70 m^2	Run 1: 2.10 m^2
MCp	1282 kJ/^{o}C	Run 1: 855 kJ/^{o}C
UL	.525 W/m^2 ^{o}C	Run 2: .4 W/m^2 ^{o}C Run 3: .2 W/m^2 ^{o}C
EFFHX	.25	
Headers: U	.15 W/^{o}C m	
l	6 m	
MCp	2.8 kJ/^{o}C m	
		Run 7: Best combination of Run 0 - Run 6

Daily draw (constant): 300 l

Draw temperature = 50^{o}C

Deadband for auxiliary: 57 - 63^{o}C

Include day and 18 and 28 in summaries

Present results according to table 2 in format and add performance factors NCP and FP.

Ove Jørgensen
Operating Agent
80-08-19

July 31, 1981 added:

Water main temperature = 25.6^{o}C

Load calculation: LFHx300.x(50.-25.6)x4186.J

where LFH is the hourly fraction of the daily load.

Appendix 3. TRNSYS INFORMATION FLOW CHARTS

Four different research groups have used TRNSYS for the simulations in the context of the present work. The groups used individual combinations of the individual TRNSYS sub-routines as no standard TRNSYS routines could handle the wrap-around heat exchanger used in the indirect systems. Since TRNSYS is a world-wide utilized program it was agreed to present the TRNSYS flow charts used by these participants as an illustration of the use of the program. The flow charts have been copied from the individual reports of the participants and put together in this appendix. On the next page is a complete listing of the TRNSYS input card deck. This card deck has been produced by Tom Freeman, who is the most experienced TRNSYS user of the group with a background at the University of Wisconsin Solar Energy Laboratory.

INPUT CARD DECK, Ref. 26

```
                TRNSYS - A TRANSIENT SIMULATION PROGRAM
      FROM THE SOLAR ENERGY LAB AT THE UNIVERSITY OF WISCONSIN
                         VERSION  10.1  6/1/79


*IEA/NBS SINGLE TANK INDIRECT SYSTEM

 WIDTH    72

 SIMULATION          8.833E+00    7.048E+02    1.667E-01

 TOLERANCES         -1.000E-01   -1.000E-01

 LIMITS   50   10

 UNIT  9      TYPE  9
      PARAMETERS 10
      1.500E+01    1.667E-01    1.000E+00    6.000E-01    0.
      2.000E+00    3.600E+00    0.           1.000E+01    1.000E+(
       (10X,2F9.2,13X,2F6.1/9F6.1,2F1.0)

 UNIT 16      TYPE 16
      PARAMETERS  5
      1.000E+00    2.130E+02    3.900E+01    4.871E+03   -1.500E+(
      INPUTS  6
       9, 1         9,19         9,20         0, 0         0, 0
       0, 0
      0.           0.           0.           2.000E-01    3.900E+(
      0.

 UNIT 36      TYPE 36      DHW LOAD
      PARAMETERS 30
      7.040E+01    8.670E+01    6.680E+01    6.983E+01    6.983E+(
      6.983E+01    7.280E+01    6.800E+01    6.850E+01    6.940E+(
      6.630E+01    6.630E+01    6.630E+01    6.640E+01    6.590E+(
      6.660E+01    6.750E+01    7.140E+01    5.780E+01    5.780E+(
      6.600E+01    6.920E+01    6.940E+01    7.140E+01    8.730E+(
      8.730E+01    8.730E+01    8.730E+01    7.680E+01    7.680E+(

 UNIT  2      TYPE  2
      PARAMETERS  3
      5.000E+00    1.000E+01    1.700E+00
      INPUTS  3
       1, 1         4, 1         2, 1
      0.           0.           0.

 UNIT  3      TYPE  3      COL PUMP
      PARAMETERS  2
      3.000E+02    3.060E+02
      INPUTS  3
      34, 1        34, 2        2, 1
      0.           0.           0.
```

INPUT CARD DECK, Ref. 26

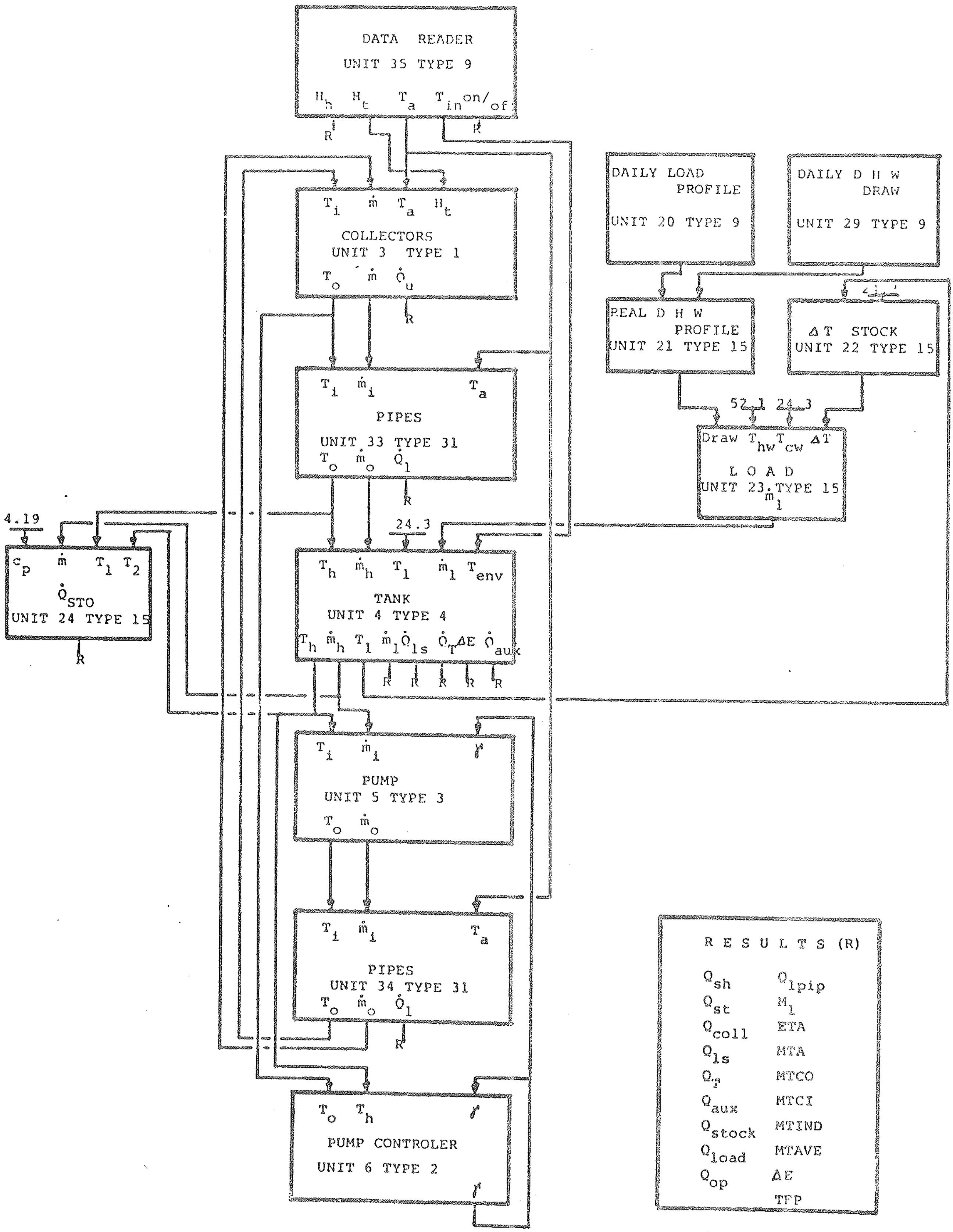
```
UNIT  1      TYPE  1
     PARAMETERS  5
     5.000E+00    4.320E+00    3.560E+00    7.000E+00    2.000E+00
     INPUTS  4
      3, 1         3, 2         9, 3         9, 2
     0.           0.           0.           0.

UNIT 31      TYPE 31
     PARAMETERS  4
     5.600E-01    9.400E-01    3.560E+00    2.000E+01
     INPUTS  3
      1, 1         1, 2         9, 3
     0.           0.           0.

UNIT 32      TYPE 31
     PARAMETERS  4
     2.500E+00    2.850E+00    3.560E+00    2.000E+01
     INPUTS  3
     31, 1        31, 2         9, 4
     0.           0.           0.

UNIT 33      TYPE 31
     PARAMETERS  4
     2.500E+00    2.850E+00    3.560E+00    2.000E+01
     INPUTS  3
      4, 1         4, 2         9, 4
     0.           0.           0.

UNIT 34      TYPE 31
     PARAMETERS  4
     5.600E-01    9.400E-01    3.560E+00    2.000E+01
     INPUTS  3
     33, 1        33, 2         9, 3
     0.           0.           0.

UNIT 11      TYPE 11
     PARAMETERS  2
     4.000E+00    5.000E+00
     INPUTS  4
      9, 9        36, 1         4, 3         9,10
     2.560E+01    0.           4.000E+01    4.900E+01

UNIT  4      TYPE  4
     PARAMETERS 12
     3.100E-01    1.268E+00    4.190E+00    1.000E+03    1.700E+00
     8.100E+03    1.000E+00    1.000E+00    6.000E+01    3.073E+02
     2.000E+00    3.560E+00
     INPUTS  5
     32, 1        32, 2        11, 1        11, 2         9, 4
     0.           0.           0.           0.           2.000E+01
     DERIVATIVES  3
     3.910E+01    3.910E+01    3.910E+01

UNIT 15      TYPE 15
     PARAMETERS 12
     0.           0.           0.           0.           3.000E+00
     3.000E+00    3.000E+00   -4.000E+00    0.           0.
     1.000E+00   -4.000E+00
     INPUTS  6
     31, 3        32, 3        33, 3        34, 3        36, 1
      9,11
     0.           0.           0.           0.           0.
     0.
```

INPUT CARD DECK, Ref. 26

```
*

UNIT 28      TYPE 28      TABLE 1 (LU11)
    PARAMETERS 16
     2.400E+01   -1.667E-01    7.200E+02    1.100E+01    0.
    -4.000E+00    0.          -4.000E+00    0.          -2.000E+00
     2.000E+00   -4.000E+00    0.          -2.000E+00    2.000E+00
    -4.000E+00
    INPUTS  4
      9, 2        16, 6         9, 3         9, 4
    LABELS  4
    QSUNM        QSUNP        TAMB         TINDRS

UNIT 29      TYPE 28      TABLE 2C (LU12)
    PARAMETERS 33
     2.400E+01   -1.667E-01    7.200E+02    1.200E+01    0.
    -4.000E+00    0.          -4.000E+00    0.          -4.000E+00
     0.          -4.000E+00   -1.000E+00    4.190E+00    0.
     1.000E+00   -4.000E+00    0.          -4.000E+00    0.
    -4.000E+00   -1.000E+00    4.190E+00   -1.500E+01    1.000E+00
    -1.600E+01    4.000E+00   -1.000E+00    4.190E+00   -1.500E+01
     1.000E+00    2.000E+00   -4.000E+00
    INPUTS  7
      1, 3         4, 7         4, 5        15, 1        15, 2
      4, 8         3, 3
    LABELS  8
    QCOL         QSTO         QLSTO        QLPIP        QTO
    QAUX         QOP          FP

UNIT 30      TYPE 28      TABLE 3C  (LU13)
    PARAMETERS 27
     2.400E+01   -1.667E-01    7.200E+02    1.300E+01    0.
    -2.000E+00    2.000E+00   -4.000E+00    0.          -2.000E+00
     2.000E+00   -4.000E+00   -1.600E+01   -1.300E+01    2.000E+00
    -1.000E+00    4.320E+00    2.000E+00   -4.000E+00   -1.600E+01
    -1.400E+01    4.000E+00   -1.500E+01    4.000E+00   -1.600E+01
     2.000E+00   -4.000E+00
    INPUTS  6
      4, 9         9, 8         9, 2         4, 5        15, 1
      1, 3
    LABELS  4
    TAVP         TAVM         CEFFP        SEFFP

UNIT 26      TYPE 26      PLOTTER
    PARAMETERS  4
    1.000E+00    1.680E+02    2.160E+02    1.000E+00
    INPUTS  2
      4, 9         9, 8
    TAVP         TAVM

END
```

S I N G L E   T A N K   D I R E C T   S Y S T E M

(TRNSYS information Flow Diagram) Ref. 9



DOUBLE TANK DIRECT SYSTEM

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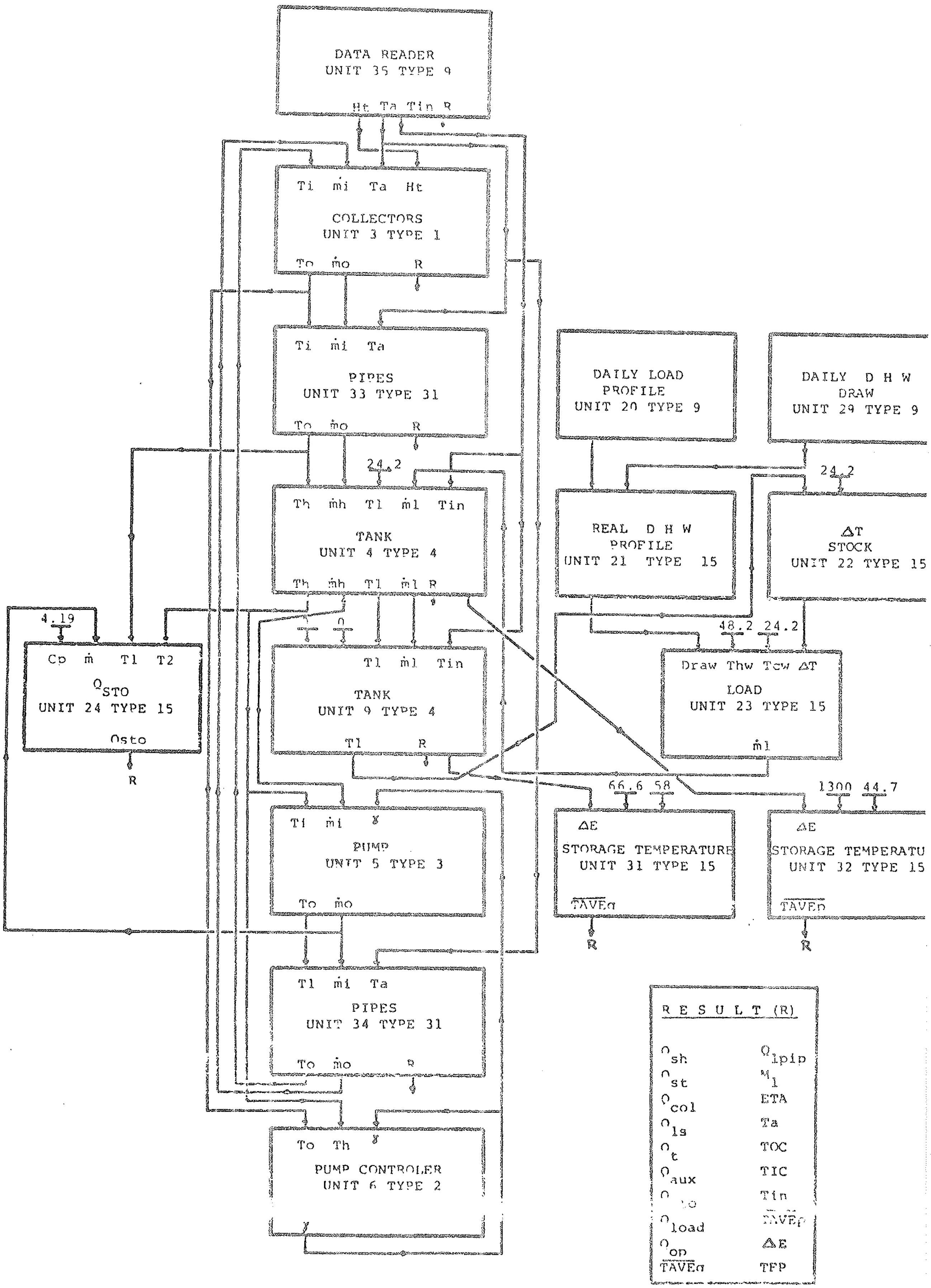

S I N G L E   T A N K   I N D I R E C T   S Y S T E M

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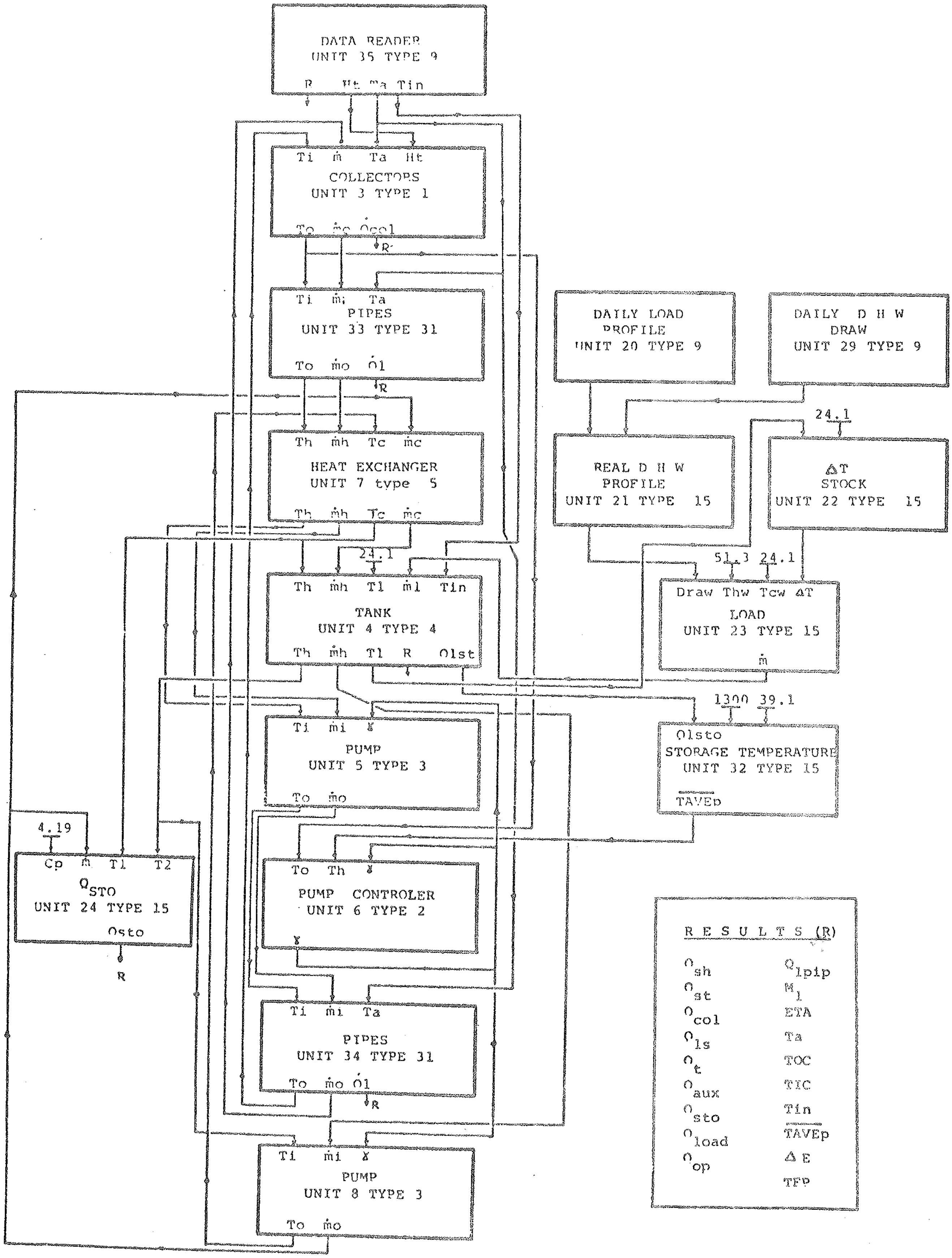

DOUBLE TANK INDIRECT SYSTEM

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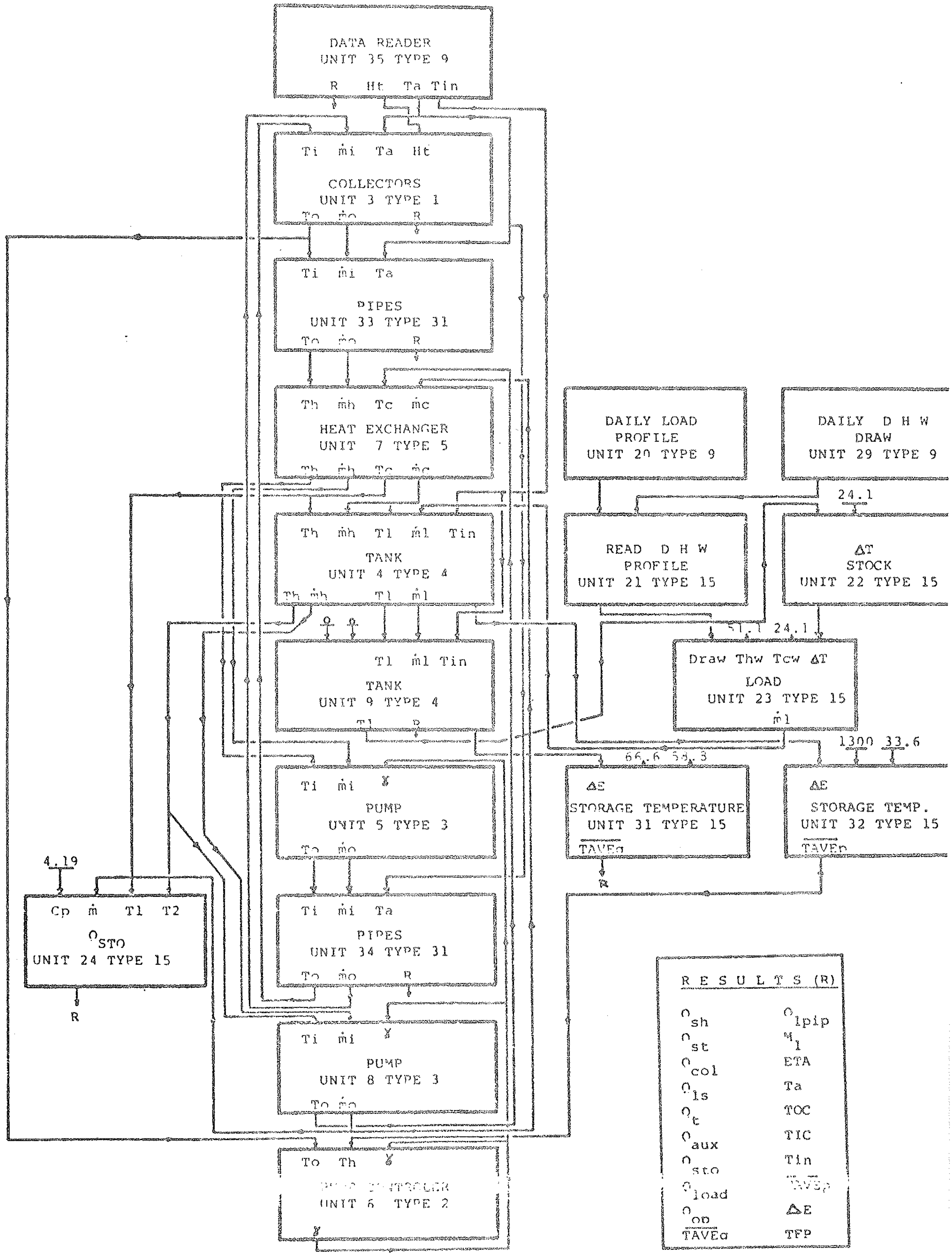
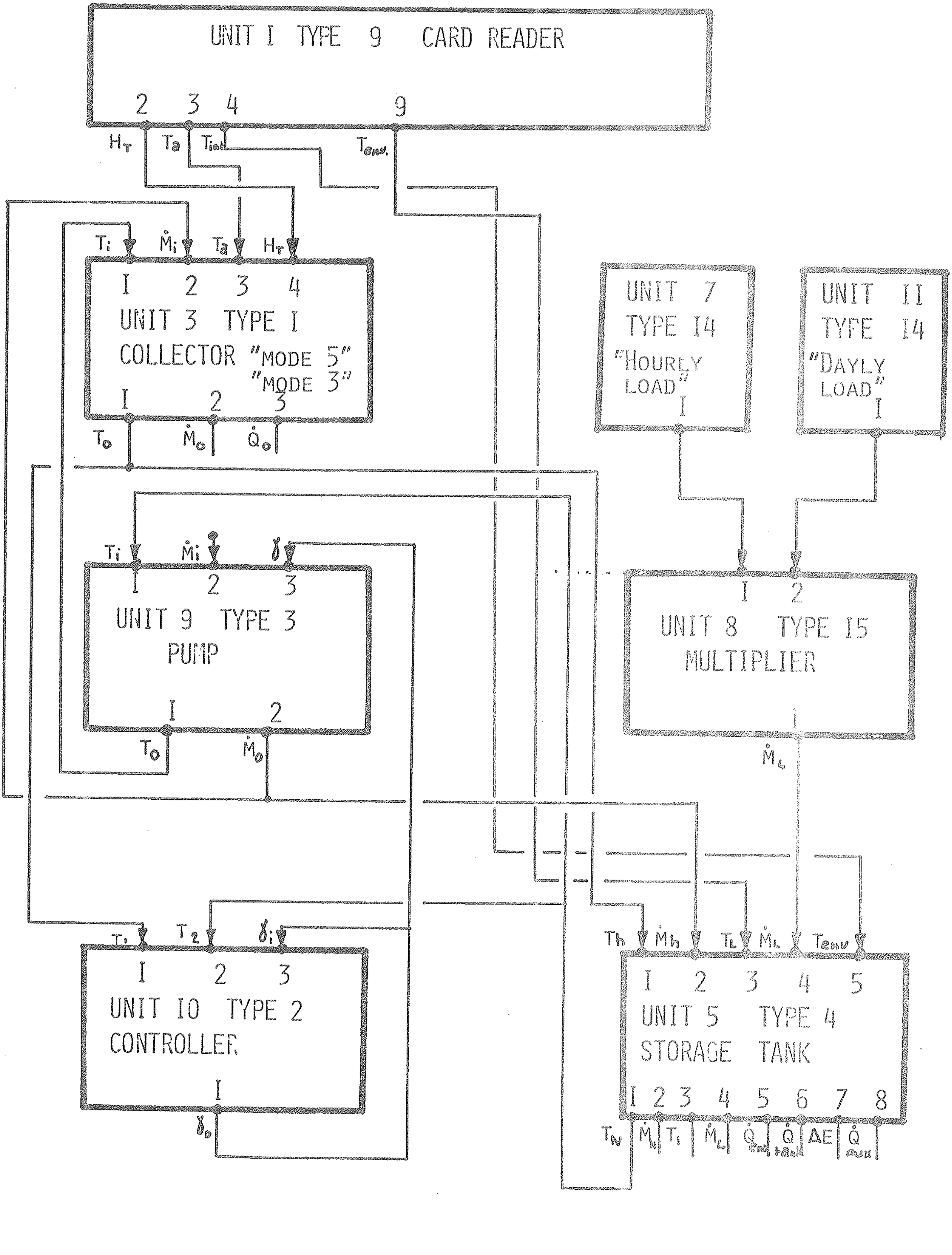
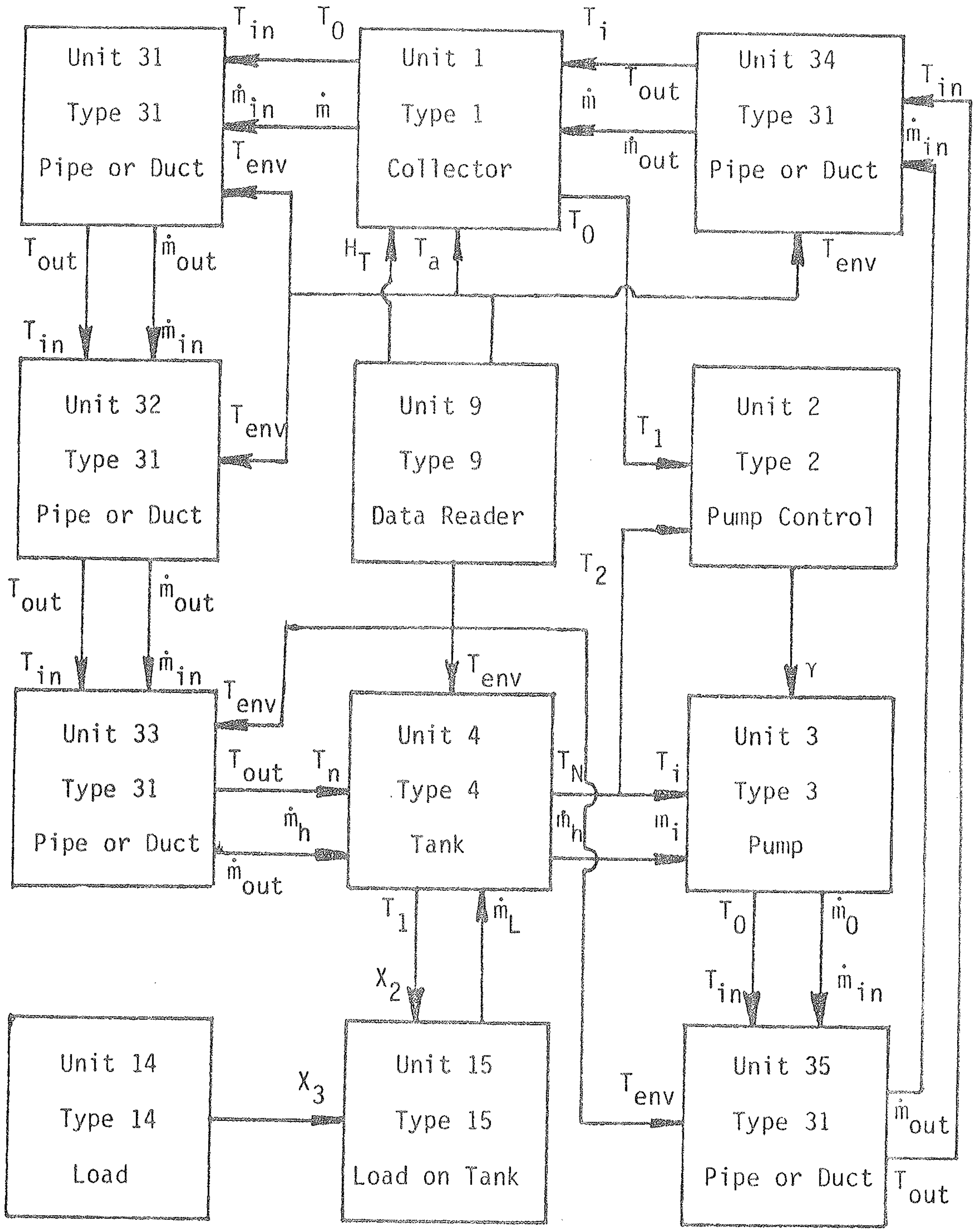


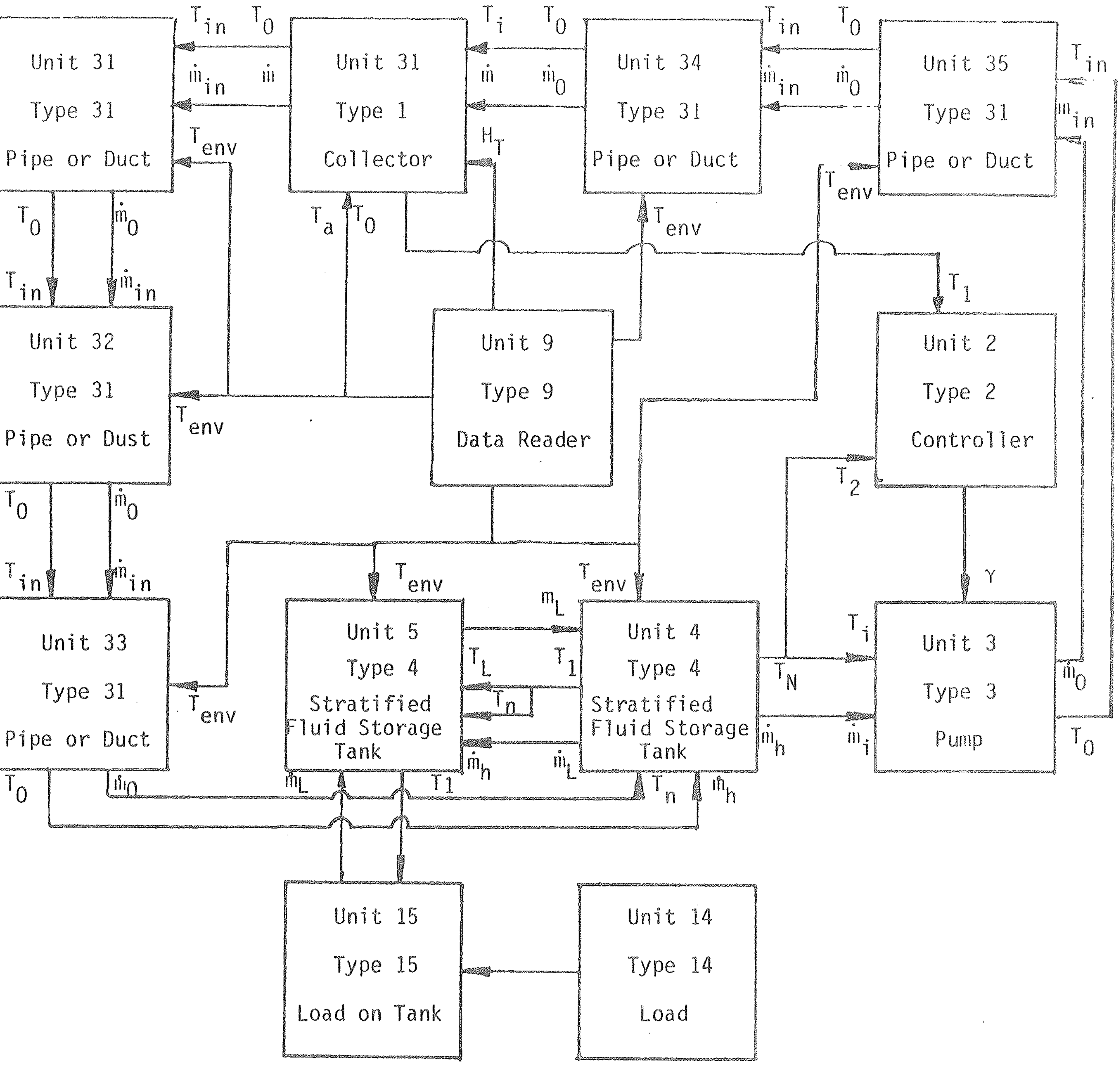
DOMESTIC HOT-WATER SYSTEM Nº I "FLOW-CHART" Ref. 10



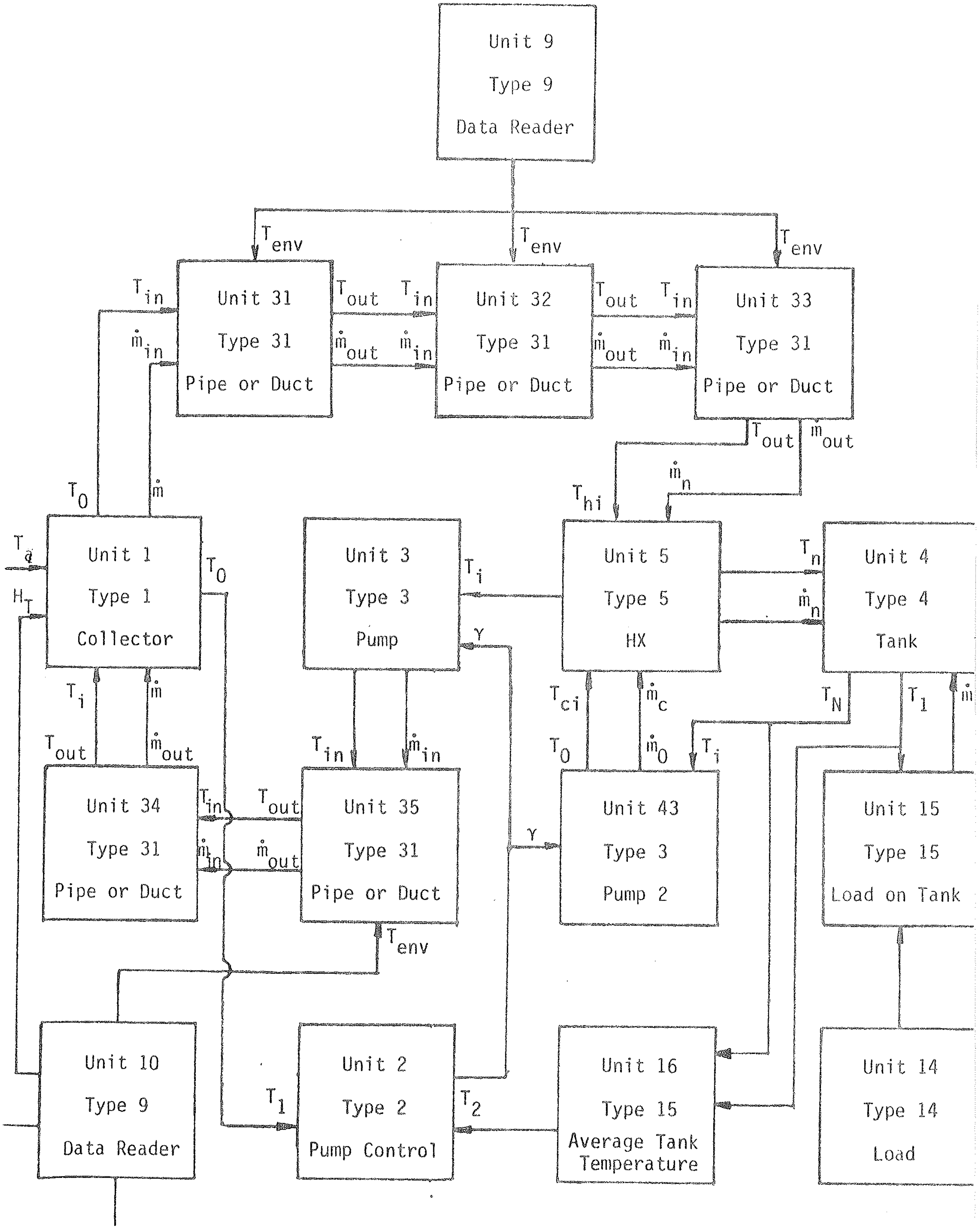
System 1 - Single Tank Direct **Ref. 22**



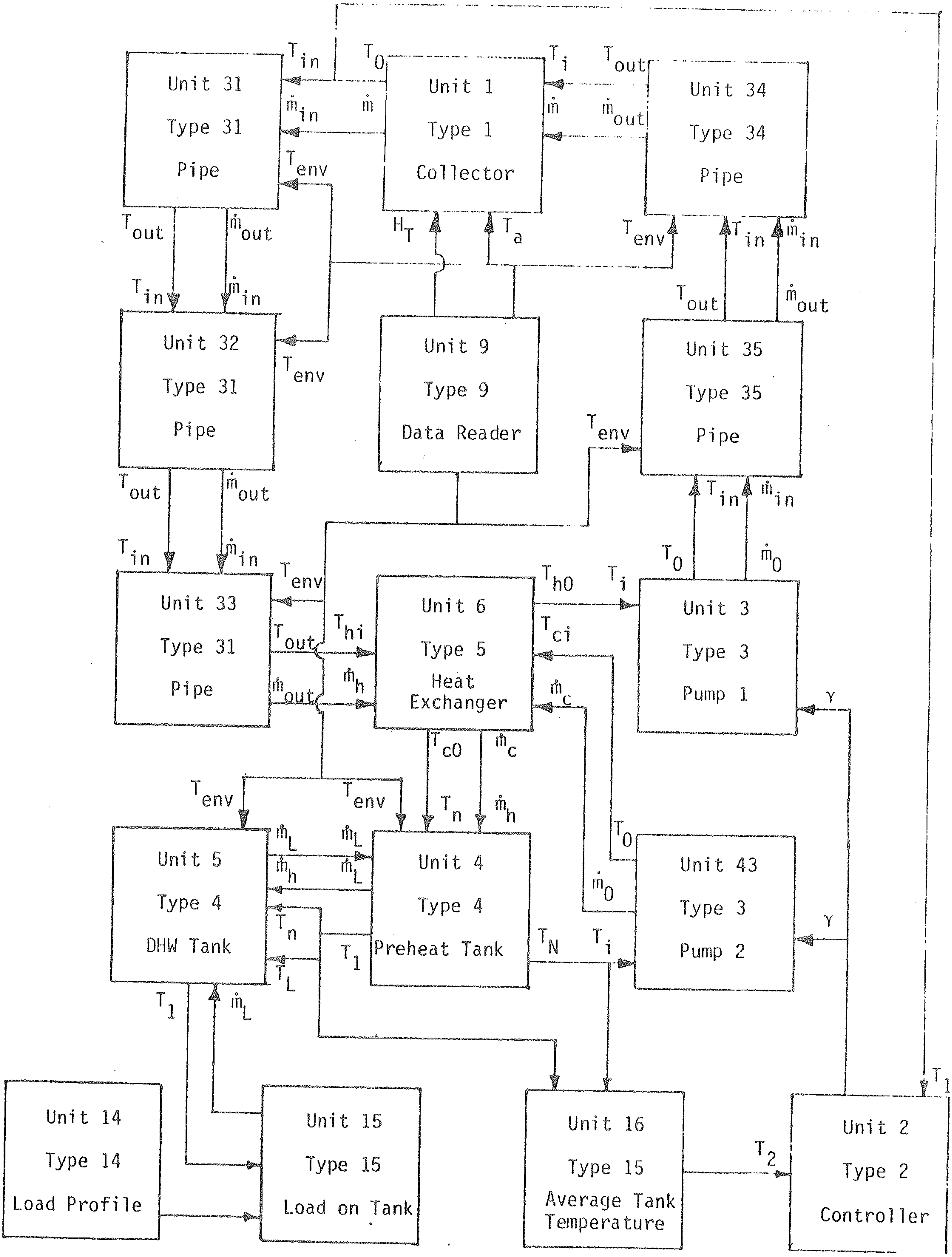
System 2 - Double Tank Direct Ref. 22



System 3 - Single Tank Indirect **Ref. 22**



System 4 - Double Tank Indirect **Ref. 22**



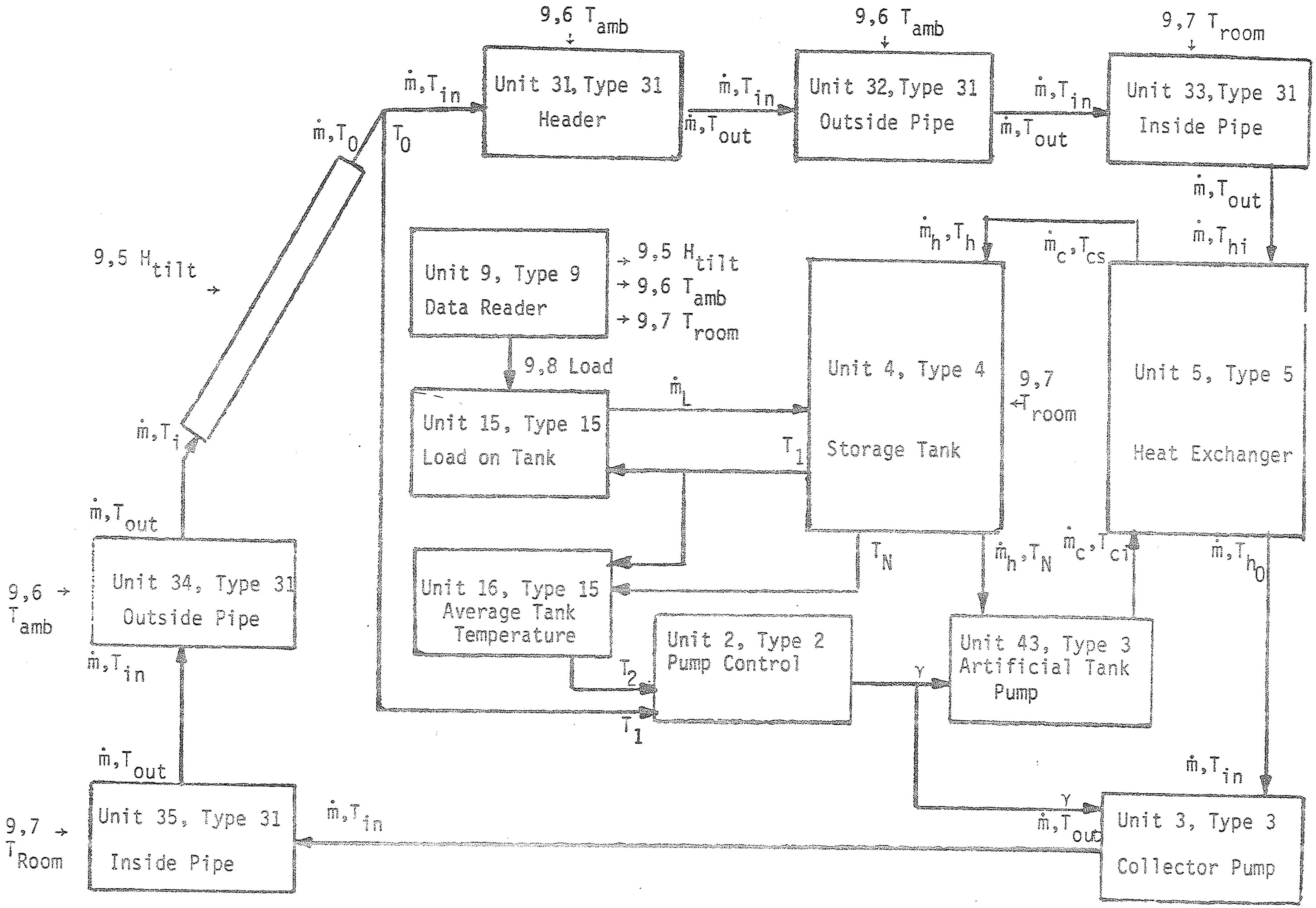


Figure 2. TRNSYS Flow Diagram for NBS Single Tank Indirect System Ref. 24

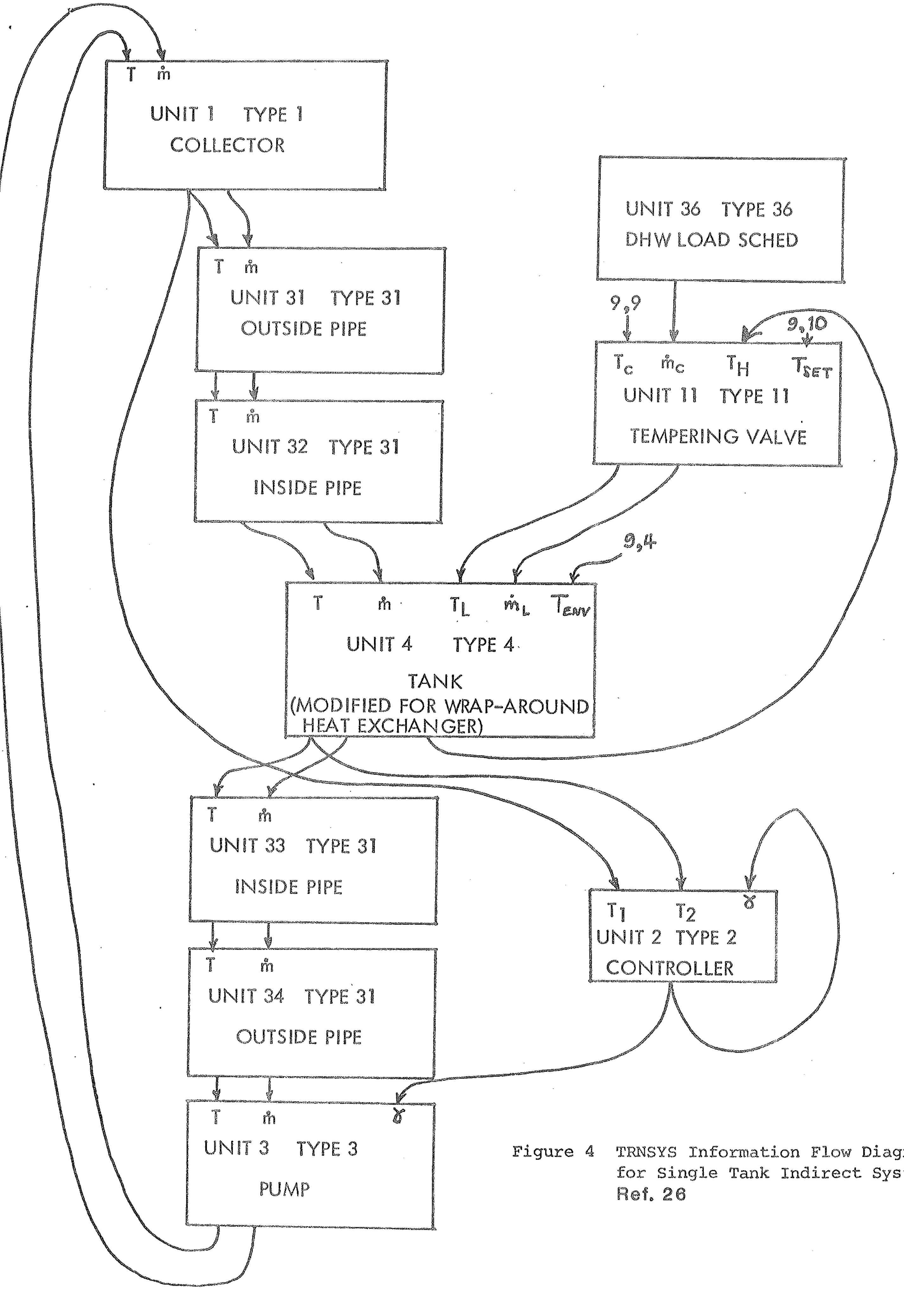


Figure 4 TRNSYS Information Flow Diagram for Single Tank Indirect System Ref. 26

Appendix 4. Address Lists

June 1982

IEA SOLAR HEATING AND COOLING PROGRAM

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