LA-9028-MS

IEA

SOLAR R&D

INTERNATIONAL ENERGY AGENCY

programme
to develop and test
solar heating and
cooling systems

task 1

investigation of the performance of solar heating and cooling systems

validation of simulation models using measured performance data from the los alamos study center

SEPTEMBER 1981

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Los Alamos
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Los Alamos, New Mexico 87545

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 to administer that agreement. Twenty 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, assisted by a small Secretariat, coordinates the energy research, development, and demonstration program.

SOLAR HEATING AND COOLING PROGRAM

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, demonstrations, and exchanges of information in order to advance the activities of all participants in the field of solar heating and cooling systems. Several tasks were developed in key areas of solar heating and cooling. A formal Implementing Agreement for this program, 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 program is managed by an Executive Committee, while the management of the tasks 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 Julich, 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.

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

TASK I--INVESTIGATION OF THE PERFORMANCE 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 result 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 modeling 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. The cooperative work and resulting report are described in the following chapters.

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VALIDATION OF SIMULATION MODELS USING MEASURED PERFORMANCE DATA FROM THE LOS ALAMOS STUDY CENTER

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This report is part of the work within the IEA Solar Heating and Cooling Program, Task I: Investigation of the Performance of Solar Heating and Cooling Systems, Subtask E: Validation of Simulation Programs by Comparison with Measured Data.

PREFACE

In Subtask A of IEA Task I (Investigation of the Performance of Solar Heating and Cooling Systems), a common understanding and basis for the modeling and simulation of solar heating and cooling systems was established. This was done by comparing the performance predictions of models developed in the participating countries for a set of well-defined, representative, hypothetical systems. The results of that work are documented in Ref. 1. Subtask E (Validation of Simulation Programmes) was initiated as a natural continuation of the work of Subtask A to further evaluate the simulation codes by performing comparisons to measured data for real installed systems.

The subtask was planned in such a way that the participants jointly select new systems to provide data for comparisons when work on one system is completed. This is done in recognition of the fact that no simulation code can be claimed to be validated by comparisons to data from just one system.

At the commencement of this subtask, only a few systems existed with a sufficient period of high-quality data for detailed validation of computer simulation codes. As a consequence, rather limited experience had been gained with different system configurations, climate types, etc. The Task I group has, therefore, considered the work as a learning process. As the work has progressed, lessons have been learned that, through personal contacts, have been passed on to be used in corresponding national work.

Ove Jorgensen
Operating Agent, Task I

CONTENTS

VALIDATION OF SIMULATION MODELS USING MEASURED PERFORMANCE DATA FROM THE LOS ALAMOS STUDY CENTER

by

David Curtis, Tom Freeman, James C. Hedstrom, Tatsuo Inooka, Ove Jorgensen, M. Osumi, K. Hinotani, and Philippe Lermusieau

ABSTRACT

This report discusses the results and conclusions of an International Energy Agency (IEA) solar heating and cooling program to validate computer simulation codes using measured performance data from the Los Alamos Study Center. The Study Center is a 6000-m^2 solar heated and cooled building located in Los Alamos, New Mexico. The building includes a 716-m^2 flat plate selective surface solar collector. The computer modeling of this system was done by seven groups participating in the IEA Validation Subtask. Hourly weather and performance data were provided for a two-week period. After simulations were performed and comparisons made, a second two-week period of data was provided, this time without performance data. The report shows the comparison between the measured and the predicted energy terms and storage temperatures on an hourly, daily, and two-week basis.

EXECUTIVE SUMMARY

Introduction

As part of the IEA Solar Heating and Cooling Implementing Agreement, a group of experts was formed to perform a variety of studies involving solar system analysis and performance. These studies have been carried out within six subtasks.

Subtask A.	Modeling and Simulation,
Subtask B.	Thermal Performance Measurement Procedures,
Subtask C.	Reporting Format,
Subtask D.	Optimization,
Subtask E.	Validation, and
Subtask F.	Solar Assisted Low Energy Dwellings (SALED).

The study described in this report is the first of the validation studies performed under Subtask E. The purpose of the study was to identify differences between simulated and measured solar system performance and to improve the participants' capabilities to predict solar system performance.

The system chosen for the study is the National Security and Resources Study Center at the Los Alamos National Laboratory near Santa Fe, New Mexico, USA. The Study Center has approximately 6000 m^2 of air-conditioned space and a solar system that is an integral portion of the building design. The solar system provides energy for domestic hot water and space heating or space cooling, as needed. The system is comprised of 715.8 m^2 (aperture) of flat plate selective surface collectors and two insulated storage tanks (19 and 38 m^3).

A comprehensive and accurate instrumentation package is a part of the system and provides measured values of temperatures, flow rates, electrical consumption, and weather data to the data acquisition system. The data acquisition system scans every 15 seconds and provides instantaneous heat flows, integrated energies, weather data, and system temperatures and flow rates every half-hour from 6:00 a.m. to 6:00 p.m. The same data are provided every hour during other times of the day.

Approach

A detailed description of the solar system and its components was prepared. Hourly weather and performance data for a two-week period (February 1-14, 1978) were provided to each participant requesting the data (six). Simulations were performed and comparisons made. Some parameter modifications were necessary to obtain reasonable agreement.

A second set of input data was then provided to each participant (December 18-31, 1978), but only weather data (not performance data) were made available. Again, simulations were performed and comparisons made.

Results

For the first-period simulations, a good deal of parameter adjustment was necessary to obtain acceptable results. Heat loss from the storage tank was changed significantly, based on measured performance. After several iterations, the participants agreed within +6.1% of the measured solar fraction.

The second-period data did not include system performance data and was meant to be a check on the first-period results. Again, several iterations were required by some participants in order to obtain acceptable results. The final results show agreement with the measured solar fraction to within +7.7% and -3.9%. Table 0.1 shows the measured and predicted solar fractions for both rounds of the comparison.

TABLE 0.1

Data	First Round February 1-14, 1978 % Solar	First Round February 1-14, 1978 % Deviation	Second Round December 18-31, 1978 % Solar	Second Round December 18-31, 1978 % Deviation
Data	69.4		56.2	
USA (TRNSYS)*	70.0	0.9	55.5	-1.2
Denmark (SVS)*	70.2	1.2	60.5	7.7
USA (Los Alamos)	70.4	1.1	56.7	0.9
GB (FABER)	70.4	1.1	55.9	-0.5
Japan (NIKKEN)	71.3	2.7	54.0	-3.9
Japan (SANYO)	73.6	6.1		
Belgium			54.4	-3.2
Mean	71.0	2.3	56.2	0.1

*Computer code names.

The hourly comparisons of the simulations with measured data indicate large errors, primarily due to the high sensitivity to small shifts in time. If a simulated controller did not turn on at the correct time, large errors in collector temperature would occur, although relatively small errors in collected energy would result. Figure 0.1 is a typical hourly plot for a six-day period during the second analysis exercise. This illustrates the basic ability of the programs to track the system dynamically, although some constant biases may exist.

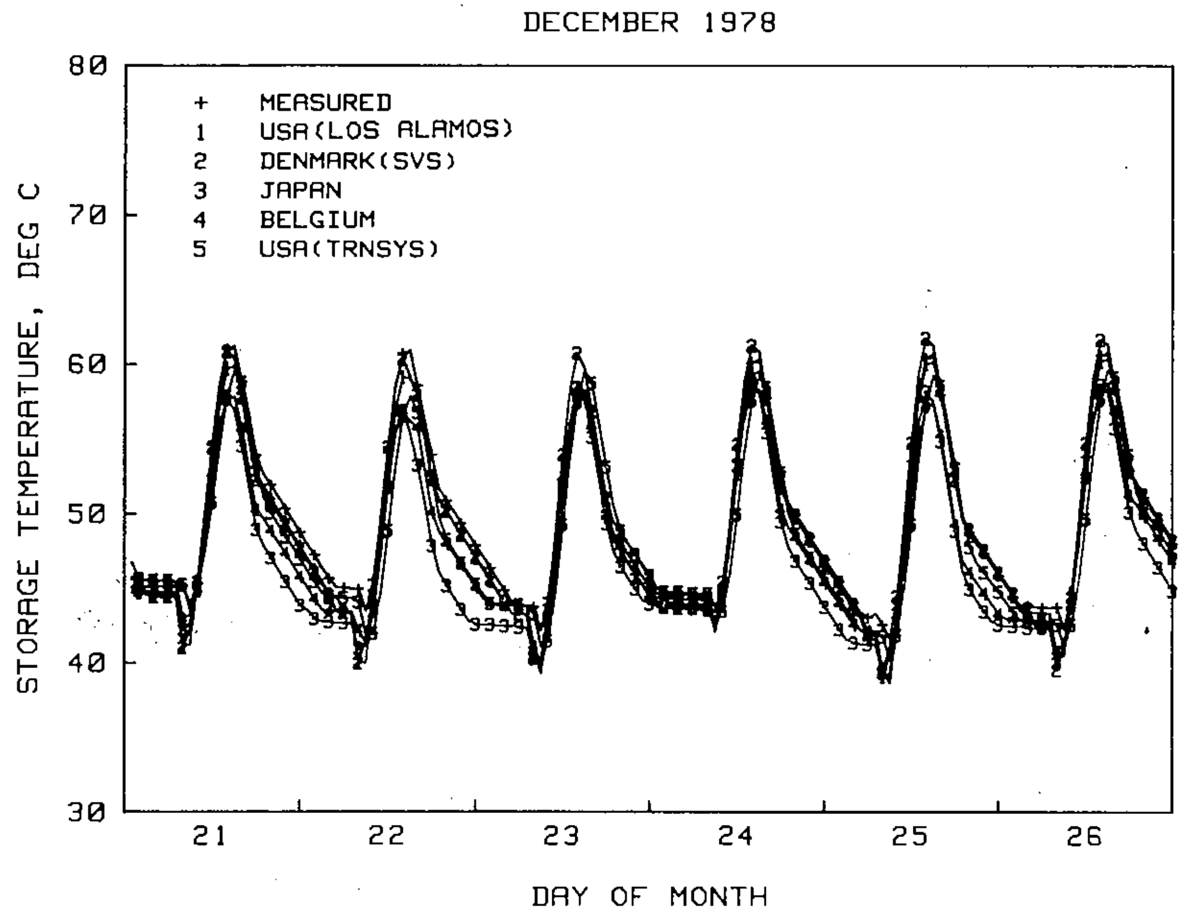

Fig. 0.1. Hourly measured and calculated storage temperature for the period December 21-26, 1978.

Conclusions

The benefit from this exercise to each participant varied because of disparity in the level of activity and in experience with previous validation efforts. Most participants were able to upgrade their computer programs based on the results. It was clear, however, that the "user effect" (errors introduced by the user due to misinterpretation of design data) was very significant and that it generally caused more uncertainty in an analysis than system modeling inaccuracies.

The hourly results seem to indicate that the switching of real controllers can be substantially different from that of ideal controllers and thus yield substantial hourly errors. These errors, however, usually tend to have relatively small effects on integrated energies over long periods of time.

A major conclusion that can be drawn from the results of this study is that validation at the systems level may be impractical due to the interrelationship of component performance. It is often difficult to determine the true source of inaccuracies because of these interrelationships. For future validation studies, it is recommended that more emphasis be put on the validation of component models that are part of the programs.

CHAPTER 1

INTRODUCTION

Much has been written about solar heating and cooling (SHAC) system simulation validation in recent years. It is a complex and confusing subject for many reasons. There is no common agreement on a definition of validation. It can range from the consensus of a few experts to a very comprehensive statistical analysis of variance between modeled and measured results. Researchers have attempted to validate codes for very different purposes and with very different methods. Discussions of these various purposes and methods can be found in Refs. 1-6.

It was clear from the previous work in Subtask A[7] that a comprehensive and rigorously valid statistical validation of the participating computer codes was impractical for the purposes of the present study. The single most significant and pervasive problem in a rigorous validation exercise can be termed the "user effect." This is most evident in the form of user error that is almost unavoidable in practice, given the large amount of data that must be interpreted, converted, and input to a detailed hourly simulation program. Another aspect of the user effect that is more difficult to eliminate or control is the many small approximations and compromises made intentionally and inadvertently by the user in translating architectural and engineering data into computer input. Virtually no simulation code directly accepts raw component or system configuration data, like materials properties or fabrication geometry. Codes require varying levels of preprocessed data. Collectors, for example, may be modeled with tube-to-fluid heat transfer coefficients, collector heat removal factors (F_R), or measured subsystem performance characteristics (like slope and intercept of the collector efficiency curve). A great deal of judgment and chance go into preprocessing this data, whether by the individual who supplies the system description, or by the computer program user, or both.

There are many other factors that complicate a validation exercise. Often a program cannot model the system as described or built, and some facsimile must be modeled instead. Many programs in use today are constantly being improved and expanded, making any effort to validate them once and for all very unrealistic.

In spite of these problems, it is still possible and desirable to establish confidence in given programs by spot-checking them with experimental results. This form of verification is necessary to insure that component algorithms and modeling approaches have been incorporated properly and that the numerical methods correctly solve for the performance of the entire system. Just as important is the determination that the program is applicable to a broad range of real systems and is reasonably easy and flexible to use. Finally, programming bugs of all kinds must be assumed to exist in programs this large until proven otherwise.

For these reasons, the IEA Task I group decided to proceed with this, the first of several spot checks of measured-to-simulated solar system performance. The criteria for selection of the first system were that it be a relatively simple, straightforward, and very well instrumented solar heating system. It was very desirable that the data collection and reduction be the work of one of the subtask participants to insure complete understanding of and access to the system and the data. The solar system at the Los Alamos National Security and Resources Study Center in the United States was selected as the first system because it met all these criteria.

Participants from five different countries modeled this system using seven different simulation models. Six of these models are already described in the Subtask A report.[1]

Two rounds of comparison were undertaken in this exercise, using two separate two-week periods of wintertime-measured hourly meteorological and loads data. In the first round, hourly measured performance data were included with the meteorological and load forcing functions supplied to the participants. A detailed description of the system was provided. In the second round a two-week set of forcing function data from another month was distributed without any of the measured performance data. The system description data were also changed slightly.

A description of the Los Alamos Study Center solar, HVAC, and data acquisition systems is provided in Chapter 2. A more detailed discussion of the data provided to the participants is given in Chapter 3.

Results from both rounds of the comparison were collected and analyzed. Comparison tables and graphs were compiled and are presented in Chapter 4. A summary of the lessons learned in this work is presented in Chapter 5.

More detail can be obtained from the reports authored by the individual participants.[8-11]

CHAPTER 2

DESCRIPTION OF THE STUDY CENTER

The National Security and Resources Study Center at the Los Alamos National Laboratory was conceived as a solar heated and cooled demonstration building that would be fully instrumented for research into its thermal performance and energy effectiveness.[12] The building was designed with energy conservation as the primary objective. Many energy conserving features were combined with the solar energy system. Architecturally, the single collector array is used to enhance the appearance of the building and not give the impression of an add-on solar energy system.

An exterior view of the Study Center from the southwest is seen in Fig. 2.1. The gross area of the building is 6760 m^2 with 5978 m^2 of air-conditioned space. A cross section of the building is shown in Fig. 2.2. The lower floor contains the report library, and the ground floor contains the main technical library for Los Alamos. The upper floor houses two meeting rooms, offices, and several smaller conference areas. The enclosed bridge, seen in Fig. 2.1, connects the Study Center with the main Administration Building of Los Alamos. The bridge partially shades the collector array in the winter.

The collector array is inclined 35^{o} from the horizontal, and the building and array face 13^{o} east of south. The prefabricated collectors are supported by purlin beams over support trusses, forming the roof of the mechanical equipment room, visitors' gallery, and solar data room. The upper mechanical equipment room houses the cooling tower, which discharges through louvers to the north.

Heat losses from the solar energy system occur directly to the mechanical equipment room. Heat from the back of the collector array is vented through louvers at the top of the array. Heat losses from storage are useful in heating the equipment room during the winter.

2.1. Description of the Solar and HVAC Systems

A mechanical schematic of the chilled and hot water supply system is shown in Fig. 2.3. The collector heat transfer fluid is oil. The oil from the collectors heats water for the system through a shell-and-tube heat

Fig. 2.1. The National Security and Resources Study Center.

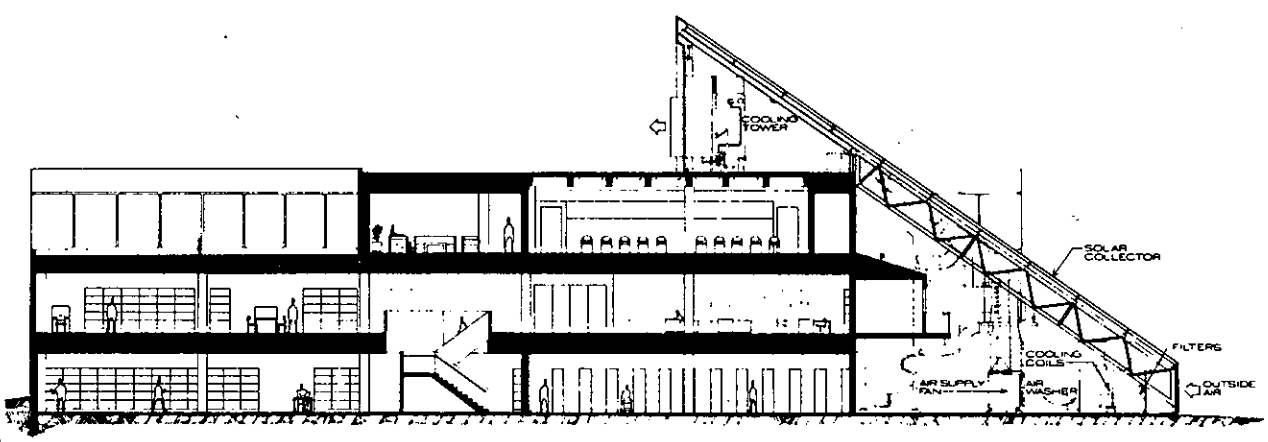

Fig. 2.2. Cross section of the Study Center.

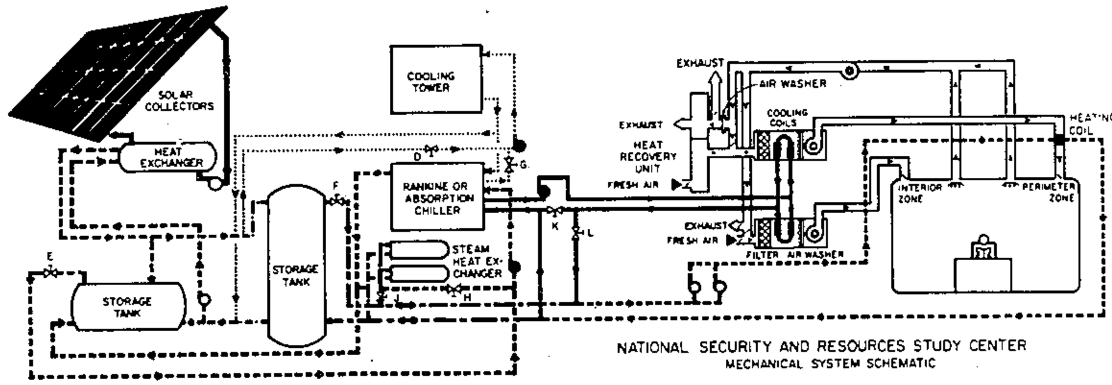

Fig. 2.3. Mechanical system.

exchanger. In the winter, hot water is stored in the larger of the two tanks for use in heating the building. During the summer, the solar hot water is stored in the smaller, pressurized tank. This hot water is used as an energy source for either the lithium-bromide absorption chiller or the Rankine cycle chiller. The chiller cold water supply is drawn out of the larger tank in the summer and passes through the chiller evaporator, whether or not the chiller is running. Cold water from the chiller goes through the main cooling coils in the air handling system and is returned to the larger tank.

A schematic of the HVAC system is shown in Fig. 2.4. Separate air handling systems are used for the perimeter and interior zones of the building. Air is distributed to the building by means of variable air volume terminal boxes. Heating coils are used only in the perimeter zone. Return air is used to cool the light fixtures, which reduces the cooling load in the summer, and provides warm air for recirculation in the winter. A freon heat pipe heat recovery unit is used in the perimeter zone to preheat outside air using the exhaust return air. The exhaust air can also be evaporatively cooled in the summer and then used to precool the outside air by means of the heat recovery unit.

2.1.1. Solar Collector Array

The solar collectors used in the Study Center were designed by the Solar Energy Group at Los Alamos. The array is made up of 407 individual collectors connected in parallel. The Study Center collectors were fabricated by the Turbo-Refrigeration Corporation.

Each 0.61-m by 3.05-m collector combines the functions of roof and solar collector by providing weather exclusion, structural support, thermal

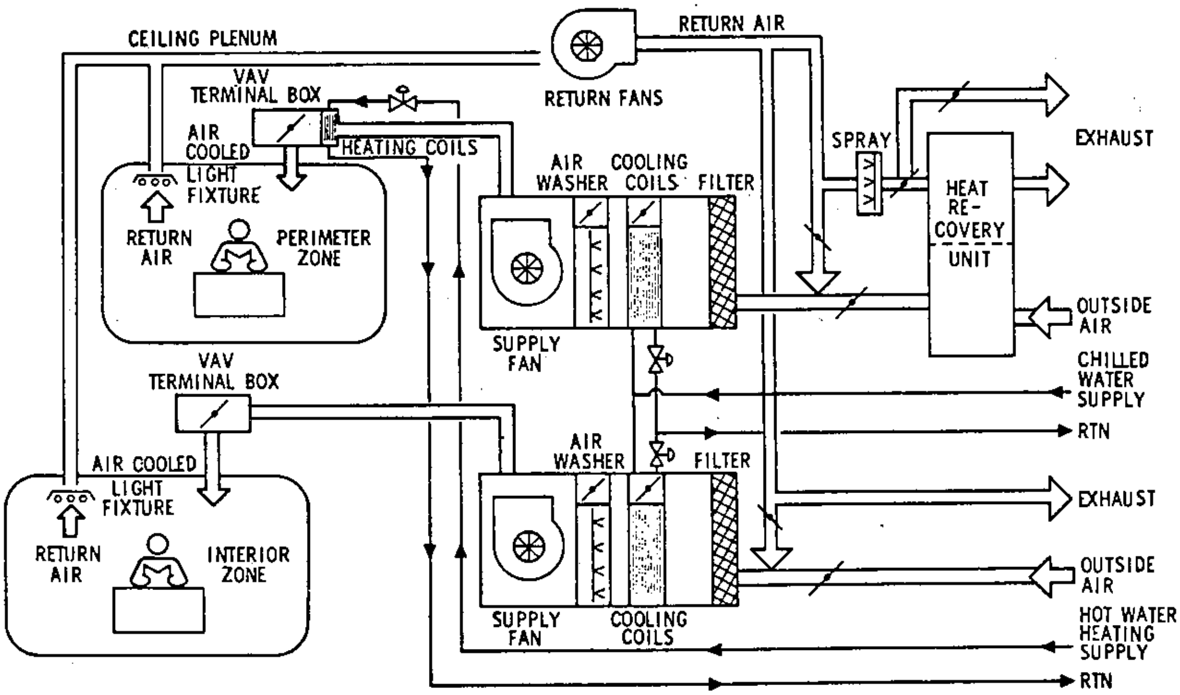

Fig. 2.4. HVAC system.

insulation, and energy collection. The collectors achieve good thermal performance through the use of single-pane, high-transmission, 0.318 cm-thick tempered plate glass glazing and an absorber surface that has been electroplated with highly selective black chrome to minimize heat loss by radiation. The absorber plate and all structural elements of the collector are fabricated from mild steel for strength and economy. The coolant passages are formed by seam-welding the edges of two steel plates together, intermittently spot-welding the surface, and expanding the assembly under pressure to give a quilted surface appearance.

The panels are backed with foam insulation and a metal fire barrier. A cutaway drawing of an individual collector panel is shown in Fig. 2.5.

The use of a light paraffinic oil as the heat transfer fluid affords protection from freezing, boiling, and corrosion.

2.1.2. Heat Storage

Heat storage consists of two insulated steel tanks filled with water. A large tank is used in the winter for heating, and a smaller, pressurized tank is used in the summer for the hot water energy source for the chillers. The larger tank has a volume of 38 m^3. It is 2.44 m in diameter and 8.1 m high

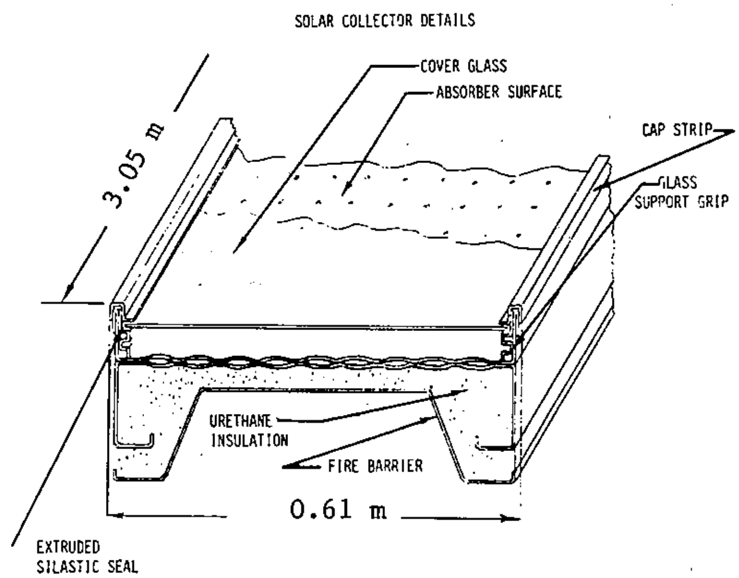

Fig. 2.5. Cross section of solar collector.

to promote stratification. The smaller tank has a volume of 19 m^3. Both tanks are insulated with fiberglass having a heat loss coefficient of 0.71 W/m^2 K.

2.1.3. Energy Distribution Systems

The air supply system for the building is a two-zone (perimeter and interior) variable air volume system, as shown in the HVAC system schematic in Fig. 2.4. The perimeter zone requires both heating and cooling and is provided with variable volume terminal boxes with hot water heating coils. The interior zone is isolated from the outside walls of the building and does not require hot water heating. The hot water for the terminal box heating coils is drawn from the top and returned to the bottom of the 38-m^3 tank or provided directly by the auxiliary hot water system.

The air handling system permits recirculation of the return inside air from the building with a provision for the delivery of a minimum outside air volume in full recirculation. Return air is drawn through the light fixtures. Each of the air handling units has supply and return fans, an air washer that also provides evaporative cooling of the supply air, and cooling coils. The air washers and the cooling coils are equipped with face and bypass dampers for control. The heat recovery unit is used in the perimeter zone only and may be used for outside air heating, outside air cooling, or may be bypassed.

2.1.4. Auxiliary Hot Water System

The auxiliary hot water for the heating or cooling system is generated by two steam-to-hot-water heat exchangers. Steam is supplied from an off-site central plant at 0.095 kg/sec and 103 kPa, reduced from 862 kPa. The auxiliary hot water is delivered at the temperature and flow required by the heating or cooling system.

2.2. Description of the Monitoring System

A computer-based data acquisition system was provided for the Study Center evaluation program. The system enables the researcher to add or modify engineering calculations, to display results in real time, and to save the results in a comprehensive summary format. This approach reduces the amount of data that must be stored and eliminates the need for extensive postprocessing of system data.

2.2.1. Solar Energy System Instrumentation

With the exception of the solar collector manifold temperatures, all temperature measurements are made with 100-ohm platinum resistance probes (RTDs) in Los Alamos-designed bridge completion networks. Temperatures are read with a resolution of 0.025°C to an accuracy of 0.12°C. The collector manifold temperatures are measured with copper-constantan (Type T) thermocouple probes referenced to 65.5°C. Resolution and accuracy are 0.1 and 0.25°C.

Flow measurements are made by turbine flowmeters (TFMs) and equal-area pressure-drop Annubar (Ellison Instrument Co., Boulder, Colorado) probes. The TFMs are used on 1/2-, 1 1/4-, and 3-in.-diam pipes, while the Annubar probes are used on the 4- and 6-in.-diam. lines. The TFMs and the Annubar probes are typically 1 per cent devices. Each TFM is provided with a pulse-rate-to-dc converter that transmits a 4- to 20-mA signal to the data acquisition system. The Annubar differential pressure signals are translated by means of individual differential pressure transducers, which send 4- to 20-mA signals to the data acquisition system.

The electrical power consumed by the major pumps in the solar energy system is measured by three-phase watt transducers whose 4- to 20-mA outputs are sent to the data acquisition system. The watt transducers are 480-volt delta-connected, and each reads the current in two legs of the three-phase line. Accuracy is better than ±1 per cent.

Weather data in the form of ambient temperature, wind speed, and wind direction are gathered from a small weather station located on the roof. In addition, the solar flux is measured in the horizontal plane by an Eppley Model 848 pyranometer and in the collector plane by an Eppley PSP.

2.2.2. Data Acquisition System

The data acquisition computer system consists of a PDP-11/34 (Digital Equipment Corporation, Maynard, Massachusetts) central processor with 48 k words of parity core memory, a 5-M-byte fixed disk, a 2.5-M-byte removable disk pack, a system console, a CRT terminal with limited graphics capability, and a process I/O subsystem. A communications interface is also available to permit access to the computer from remote terminals.

The local process I/O is presently configured with two A/D converters connected to 160 analog channels and a single 16-channel digital interrupt module.

Each A/D converter is capable of sampling analog channels at the rate of 200/s. By using the two converters in parallel, an effective sampling rate of 400/s is achieved. The full-scale range of each analog channel is programmable between $\pm$ 10 mV and $\pm$ 10 V in a 1-2-5 sequence with 12-bit resolution.

The system software, RSX-11M (Digital Equipment Corporation, Maynard, Massachusetts), is a real-time, multiuser, multitask operating system. All program development is done in FORTRAN IV. The system permits task scheduling as a function of time and specific events, permitting the system to operate around the clock with a minimum of operator intervention. The system provides for data acquisition, data conversion, energy calculations, interrupt processing, energy summaries, data storage, and data display.

The data acquisition task runs every 15 seconds. All of the channels are sampled at this interval and converted to engineering units. The converted values are stored in a permanently core-resident common data area, which provides the link for communication between the various tasks.

At the conclusion of a complete data scan, a task that performs the energy calculations is activated by the data acquisition task. This task uses the converted data to perform the energy flow calculations on the solar heating and cooling system components. Primarily, these calculations consist of multiplying mass flow rate times specific heat times temperature differentials, and calculating mass flow rates from pressure differentials, fluid density and temperature, and specific heats from temperatures. The instantaneous energy flows, as well as average values over the sampling interval, are stored in the common data area. The task also integrates these values to provide a total energy figure for each subsystem.

The total electrical power is tallied in the common data block, using interrupts from the main watt-hour meter. System operating mode changes are stored for examination by other tasks to determine which components should be analyzed.

A summary of all of the instantaneous heat flows, and integrated energies, weather data, and system temperatures and flow rates, is written on the fixed disk automatically every half-hour from 6:00 a.m. to 6:00 p.m., and every hour otherwise. Additional summaries are written in response to any operating mode change.

At the end of the day (midnight), all of these data are copied to the removable disk for permanent storage. One month's data typically use about 2/3 of a disk pack capacity. An additional file is then created that contains integrated energy values for the entire day, as well as other pertinent information, such as maximum and minimum storage and ambient temperatures. The condensed daily summary is also printed during the night. The daily summaries are saved for subsequent examination and display.

CHAPTER 3

MODEL INFORMATION AND DATA DESCRIPTION

This validation exercise involved the solar heating system only. A schematic of this system is shown in Fig. 3.1. This system is composed of three basic liquid flow loops. The first loop involves the collectors in which paraffinic oil circulates and transfers heat into a tube-and-shell heat exchanger. In the second loop, water circulates from the bottom of the tank, through the tube side of the heat exchanger, and back to the top of the tank. The third loop circulates water to the building heating and domestic hot water (DHW) systems from the storage tank. When the tank temperature is inadequate, the water is circulated through an auxiliary steam heat exchanger.

The participants were provided hourly weather data and building and DHW load data for both periods. As previously mentioned, measured results were provided for the first period, but not for the second period.

A complete description of the parameters supplied to the participants to model the system are given in Appendix A. The model modifications for the second period are given in Appendix B. The following paragraphs briefly describe what parameters were provided.

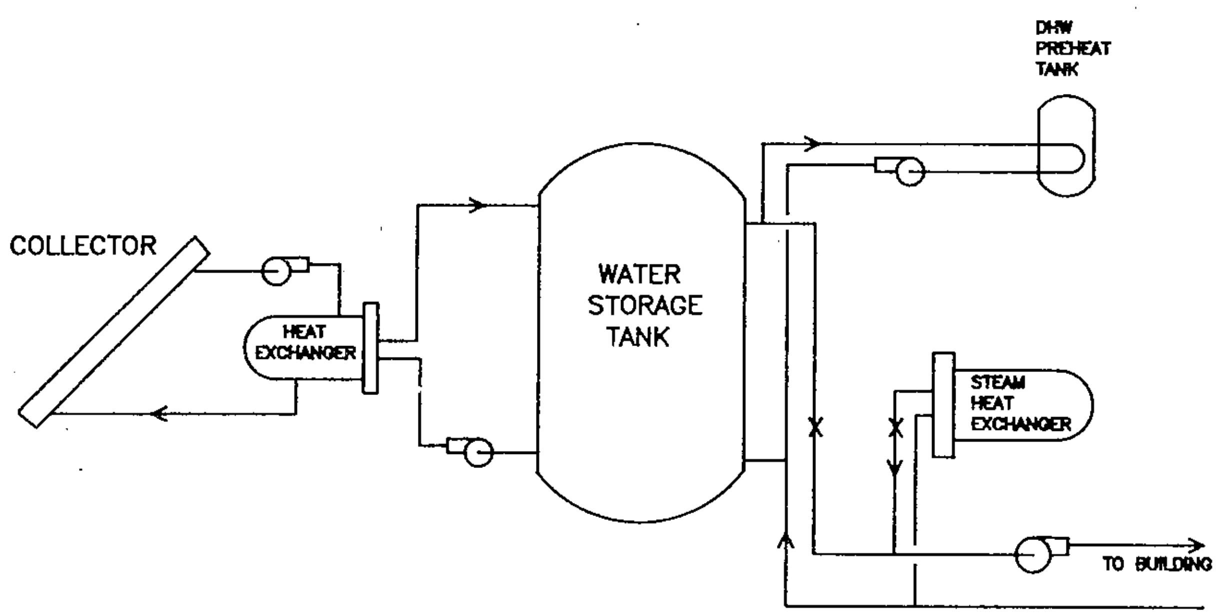

Fig. 3.1. Study Center solar heating system.

3.1. Collector

The participants were provided with all the physical parameters that were known for the collector. These included collector area; absorber properties; glazing properties; fluid heat transfer coefficient; back, side, and end heat loss coefficients; collector mass; and shade factors from the adjacent structures. A measured efficiency curve obtained from the Los Alamos collector testing laboratory was also available. Collector manifold piping dimensions were specified, along with their mass and heat loss coefficients. Physical properties and flow rates of the paraffinic oil used in the collector loop were given.

3.2. Heat Exchanger

The heat exchanger model, tube number, tube diameter, surface area, and mass were made available. A correlation of the heat exchanger heat transfer coefficient, which was derived from measured data, was provided.

3.3. Storage Tank

The size, volume, and surface area of the tank were given. The heat loss coefficient of the tank insulation was given. Because the apparent tank heat loss was much larger than the tank coefficient would predict for the first data period, an increase by a factor of four was suggested. The losses were more in line with expectations for the second period so the use of the calculated coefficient was recommended.

A daily measured tank heat loss, determined by a heat balance on the tank (taking into account the change in energy stored in the tank), is shown in Fig. 3.2. The scatter in the data is large because of experimental errors, but the difference between the two periods is evident. The reason for this difference is unknown, but could be due to changes in instrumentation or thermocirculation in the piping. Also, the DHW system was not operating during the second period due to a failure of a flow meter.

Specifications of the tank inlet and outlet piping were given.

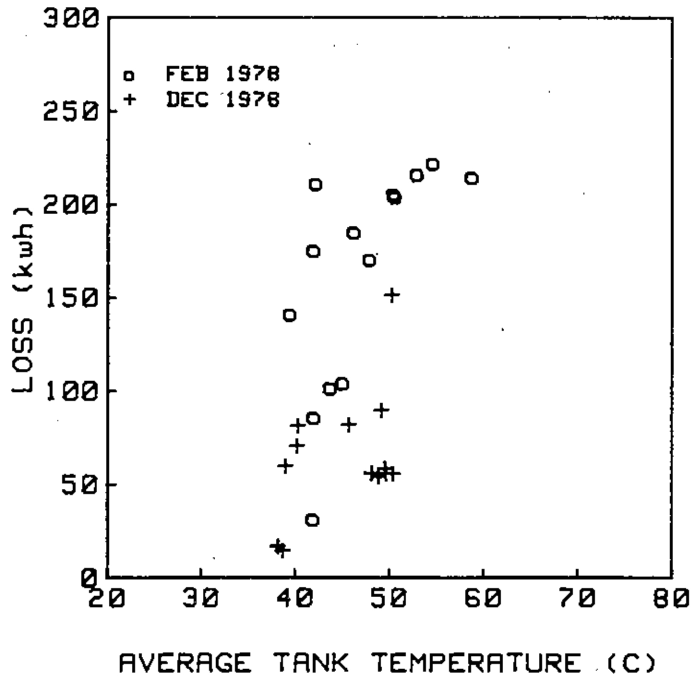

Fig. 3.2. Daily measured tank loss (by energy balance).

3.4. Auxiliary

The Study Center switches to auxiliary heat from steam heat exchangers whenever the storage tank drops below a setpoint, which is a function of outside temperature. The functional relationship was determined from the data and provided to the participants. The controller has hysteresis and is not perfectly repeatable, sometimes causing different auxiliary operation than the provided function would predict.

3.5. Collector Controller

The on-and-off differential settings between the collector absorber temperature and the storage temperature were given.

3.6. Building Load

The building load was defined to be the measured mass flow rate multiplied by the specific heat multiplied by the temperature difference of the water supplied to and returning from the building heating system. The DHW load was similarly defined with the water monitored at the heat exchanger on the DHW preheat tank. Both of these quantities were supplied on an hourly basis.

3.7. Data Information

The data were provided to the participants on punched cards, one card for each hour. Hourly values of all energy data were obtained by taking the differences between integrals recorded on the hour by the PDP-11. The ambient temperature and wind conditions were instantaneous values on the hour.

3.7.1. First Period

The first set of data provided was for the period from February 1-14, 1978. These data were supplied in August 1978, and the results of the simulation were reported at the IEA Task I meeting, held in Palermo in December 1978.

The data consisted of hourly values of horizontal insolation, solar radiation on the collector plane, ambient temperature, wind velocity and direction, building heating load, and DHW load.

The participants were also provided with measured results so that they could make their own comparisons. These data included the hourly total collector heat output, heat exchanger output, tank energy input, tank energy output, auxiliary heat, and the average tank temperature.

3.7.2. Second Period

For the second round of comparisons, a second two-week period of data was distributed <u>without</u> the measured results. The period selected was December 18-31, 1978. It included an initial cloudy two-day period, followed by eight sunny days, ending with four more cloudy days. It was cold during this period, and the building loads were high.

The weather data were provided to the participants in January 1979, the hourly results were due back at Los Alamos for detailed comparison in April 1979, and the comparisons were presented at the next IEA Task I meeting in Tokyo in May 1979.

CHAPTER 4

COMPARISON OF RESULTS

This chapter presents the comparisons between measured and calculated results for the two periods. Only overall results are presented for the first period. A more detailed comparison of the results from the second period is presented. Further details for each simulation are presented in the reports authored by the individual participants.[8-10]

4.1. First Period

The results from this first period were obtained and compiled by the participants at the Palermo meeting in December 1978. The Japanese group from Sanyo Electric Corporation submitted their results at a later date. In most cases, detailed hourly or daily results were not available for comparison. The overall results have been compiled, however, and are presented in Table 4.1. The parameters in the table are defined below.

QSUN	Incident solar,
QXHI	Heat exchanger input (collector output),
QXHO	Heat exchanger output,
QTI	Storage tank input,
QTL	Storage tank loss,
QTO	Storage tank output,
QAUX	Auxiliary energy, and
%SOL	Solar fraction.

The measured results are labeled DATA on the first line of the table. The calculated results submitted by the participants are listed from low to high per cent solar. The space heating load for this period was 17,274 kWh, and the DHW load was 333 kWh..

For this period, the predictions varied from 70.0% to 73.6% solar fraction when the measured solar fraction was 69.4%. This was a maximum deviation of 6.1%.

The collector efficiency for this period was 30.9%. The calculated values deviated as much as 2.1 percentage points from this value. Many of the

TABLE 4.1

NATIONAL SECURITY AND RESOURCES STUDY CENTER
Los Alamos, New Mexico
February 1-14, 1978

TWO-WEEK ENERGY COMPARISON

	QSUN	QHXI	QHXO	QTI	QTL	QTO	QAUX	%SOL
Data	46 509	14 370	14 557	12 404	561	11 843	5 382	69.4
USA (TRNSYS)	46 509	14 750	14 750	14 750	2 330	12 420	5 277	70.0
Denmark (SVS)	44 765	15 193	15 193	15 193	3 001	12 192	5 245	70.2
USA (Los Alamos)	46 509	14 548	14 548	14 446	1 547	12 360	5 208	70.4
GB (Faber)	46 509	13 430	13 432	12 951	810	12 141	5 208	70.4
Japan (Nikken)	46 509	13 719	13 719	13 511	443	12 509	5 047	71.3
Japan (Sanyo)	46 509	14 077	14 077	14 021	663	13 458	4 648	73.6

Units: kWh

simulators made compensating adjustments to the storage loss coefficient, as seen by the wide range in storage heat loss. This parameter, of course, was not well defined, as mentioned previously.

The per cent deviation from the measured data for the two-week period is shown in Table 4.2. The absolute deviation in collector output varies from -6.5% to +5.7%. Variations in tank output and auxiliary used were as high as 13.6% because of tank loss assumptions.

4.2. Second Period

The results for the second period from December 18 to December 31, 1978, are presented in this section. The participants provided Los Alamos with

TABLE 4.2

NATIONAL SECURITY AND RESOURCES STUDY CENTER
Los Alamos, New Mexico
February 1-14, 1978

TWO-WEEK ERROR

	QHXI	QHXO	QTO	QAUX
USA (Los Alamos)	1.24	-0.06	4.37	- 3.23
Japan (Sanyo)	-2.04	-3.30	13.64	-13.64
USA (TRNSYS)	2.64	1.33	4.87	- 1.95
Japan (Nikken)	-4.53	-5.76	5.62	- 6.22
Denmark (SVS)	5.73	4.37	2.95	- 2.55
GB (Faber)	-6.54	-7.73	2.52	- 3.23

Units: Per cent

hourly results for this period with the exception of the British group, which provided only daily results. Los Alamos was then able to make a direct comparison of the results on a common basis.

The two-week comparison for this period is given in Table 4.3. The parameter TSAV, the average daily storage temperature, was added to this table because it was available. The total heating load for this period was 24,717 kWh. The DHW load was zero because the flow meter in the circuit was malfunctioning and the pump was shut off. The per cent solar is seen to range from 54.0 to 60.5%, with the measured value being 56.2%. On an absolute basis, this is a deviation of -3.9 to +7.7%, which is larger than that for the first period. The original results submitted by Great Britain and Denmark were outside this range, but subsequent calculations showed better agreement with the measured data. Their latest results are reported in this chapter.

The measured collector efficiency for the second period was 33.9%. The calculated range on this parameter was from 31.9% to 34.3%, which was about the same deviation as in the first-period results.

Because the participants did not have measured results for comparison, Los Alamos suggested they use the given tank insulation loss coefficient of 0.71 W/m^2 K. All simulators predicted approximately the same tank heat loss

TABLE 4.3

NATIONAL SECURITY AND RESOURCES STUDY CENTER
Los Alamos, New Mexico
December 18-31, 1978

TWO-WEEK ENERGY COMPARISON

	QSUN	QXHI	QHXO	QTI	QTL	QTO	QAUX	TSAV	%SOL
Data	44 792	15 187	15 137	14 901	612	14 237	10 822	44.9	56.2
Japan (Nikken)	44 793	14 294	14 294	14 089	375	13 593	11 362	43.2	54.0
Belgium	44 793	15 927	14 364	14 061	380	13 306	11 262	43.5	54.4
USA (TRNSYS)	44 933	14 773	14 773	14 351	352	14 215	10 988	44.2	55.5
GB (Faber)	44 793	15 089	15 090	14 564	90	14 474	10 905	0.0	55.9
USA (Los Alamos)	43 798	14 786	14 786	14 696	396	14 283	10 707	44.3	56.7
Denmark (SVS)	42 863	15 383	15 383	15 383	394	14 954	9 764	44.5	60.5

Units: kWh

except the British group, whose prediction was low by about a factor of four. The storage tank increased in temperature 1.2°C over the 14-day period, which means about 54 kWh were stored in the tank. The apparent tank loss would then be 612 kWh. This value is about 61% greater than the average value obtained by 5 simulators. An effective tank heat loss coefficient of 1.15 W/m^2 K would have been needed to obtain the same apparent measured tank heat loss. However, this represents a difference of only 1.6% in the amount of energy delivered by the tank.

The per cent deviation in the second-period two-week results is given in Table 4.4. The participants are arranged in order of the absolute error in collector output. The deviation in collector output is from -5.9% to +4.87%. The deviation in auxiliary is from -9.8% to +5.0%. Generally, if the losses are calculated right, a high calculation in collector output results in a low calculation of auxiliary. The Belgian group predicted a large heat exchanger (or pipe) loss, which reversed that trend.

The root mean square (RMS) error between daily calculated quantities and daily measured quantities is given in Table 4.5. The RMS error is calculated in the following manner.

$$\text{RMS ERROR (\%)} = \sqrt{\left[\sum^{N} (Q_C - Q_M)^2/N\right]} \Big/ Q_M * 100 \quad .$$

The point counter (N) is not advanced when both Q_M and Q_C are zero. Most of the daily RMS error is within 10%, except for three predictions of

TABLE 4.4

NATIONAL SECURITY AND RESOURCES STUDY CENTER
Los Alamos, New Mexico
December 1-18, 1978

TWO-WEEK ERROR

	QHXI	QHXO	QTI	QTO	QAUX	TSAV
GB (Faber)	-0.65	-0.31	-2.26	1.66	0.76	0.00
Denmark (SVS)	1.29	1.62	3.23	5.03	-9.78	-1.00
USA (Los Alamos)	-2.64	-2.32	-1.38	0.32	-1.07	-1.24
USA (TRNSYS)	-2.73	-2.41	-3.69	-0.15	1.53	1.58
Belgium	4.87	-5.10	-5.64	-6.54	4.06	-3.12
Japan (Nikken)	-5.88	-5.57	-5.45	-4.53	4.99	-3.86

Units: Per cent

TABLE 4.5

NATIONAL SECURITY AND RESOURCES STUDY CENTER
Los Alamos, New Mexico
December 1-18, 1978

DAILY RMS ERROR

	QXHI	QHXO	QTI	QTO	QAUX	TSAV
GB (Faber)	3.40	3.43	3.78	6.19	15.31	100.58
Denmark (SVS)	4.92	4.90	5.66	9.14	13.91	2.75
USA (Los Alamos)	6.23	5.90	5.45	5.12	6.51	2.02
USA (TRNSYS)	7.18	6.90	7.41	4.67	8.31	2.45
Belgium	8.99	8.06	8.40	8.54	9.12	3.52
Japan (Nikken)	9.55	9.21	9.16	9.91	11.92	4.59

Units: Per cent

auxiliary usage, which were between 10 and 15.1%. This can be due, to some extent, to predicting the timing of auxiliary usage around midnight.

The hourly RMS error is shown in Table 4.6. This error is very sensitive to small timing (phase shift) errors; that is, if the collector is actually on and the prediction is off, a large hourly error will result. Errors in collector output ranged from 12 to 28%. Timing of auxiliary usage was particularly important in obtaining a low error on this quantity. No one came very close on this term, with the RMS error ranging from 36 to 58%. The error in average storage temperature is low because the base is $0^{\circ}C$. Perhaps a base of $35^{\circ}C$ should be used, which is about the minimum storage temperature allowed by the system.

The bar charts in Figs. 4.1 to 4.5 show the comparison between the various daily calculated and measured quantities. The latest results show a relatively good agreement between the measured quantity and the predicted quantities obtained by the various simulation codes.

Hourly plots of collector output and storage temperature are shown in Figs. 4.6 through 4.11. The plots in Figs. 4.6 and 4.7 are for the entire 14-day period. The switchover to auxiliary was specified at a storage temperature that was a function of ambient temperature. The actual controller in the Study Center had some hysteresis and drift in its switching points. Thus, the predicted storage temperatures drop below the measured storage temperature at the onset of several auxiliary periods. The results for six

TABLE 4.6

NATIONAL SECURITY AND RESOURCES STUDY CENTER
Los Alamos, New Mexico
December 1-18, 1978

HOURLY RMS ERROR

	QXHI	QHXO	QTI	QTO	QAUX	TSAV
GB (Faber)	25.65	26.06	27.42	44.55	54.70	7.34
Denmark (SVS)	17.25	18.23	19.05	49.91	57.61	3.90
USA (Los Alamos)	11.95	11.66	11.42	46.89	54.19	2.88
USA (TRNSYS)	16.87	16.90	18.31	28.02	36.43	3.76
Belgium	14.74	15.25	16.49	35.59	40.91	4.02
Japan (Nikken)	28.22	29.08	29.73	40.81	47.94	5.27

Units: Per cent

sunny days are shown in Figs. 4.8 and 4.9. Some of the details are evident in these plots. More details can be found in Figs. 4.10 and 4.11, which show the results for December 23 and 24. Phase shifts between the various simulations do not seem to be a problem.

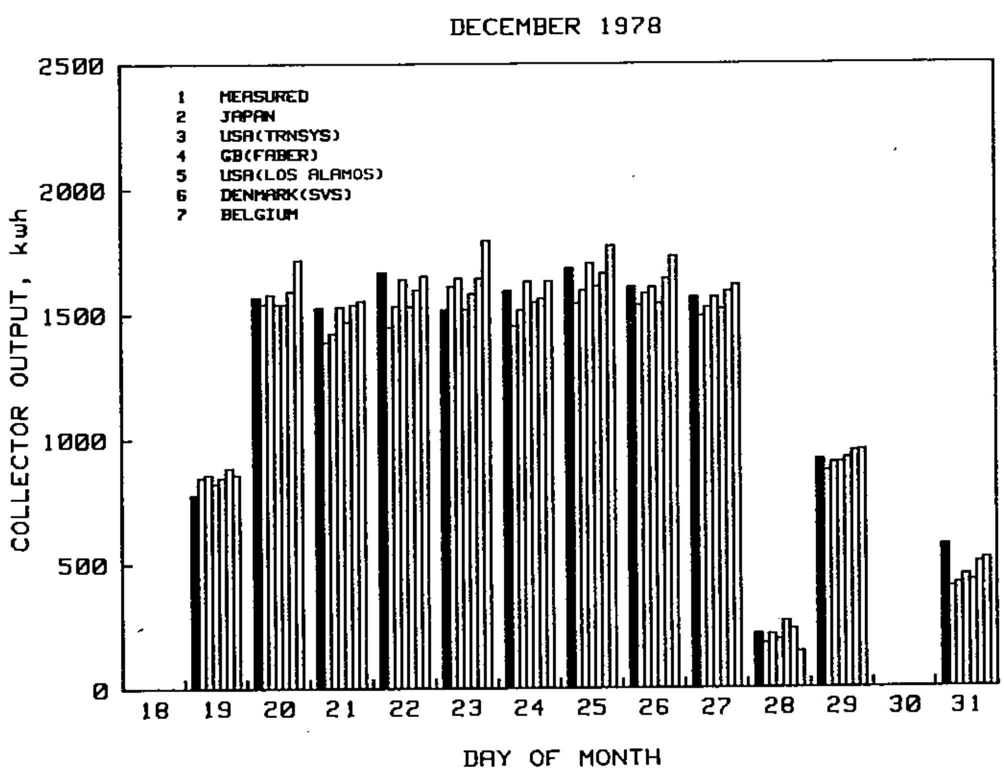

Fig. 4.1. Daily measured and calculated collector output.

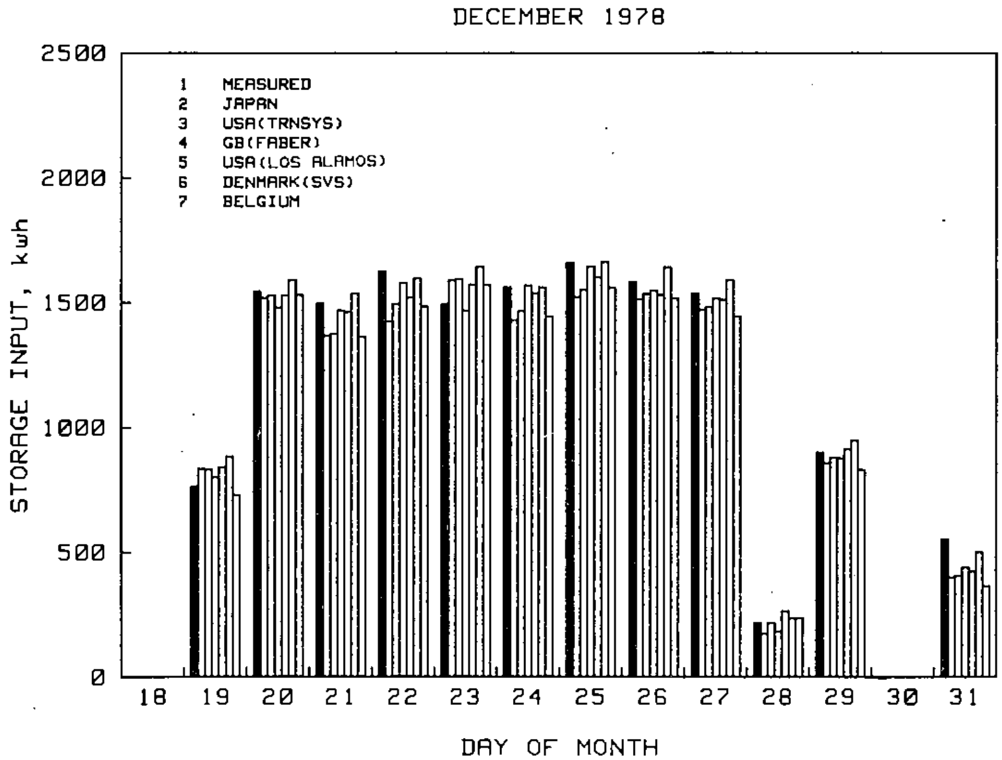

Fig. 4.2. Daily measured and calculated storage input.

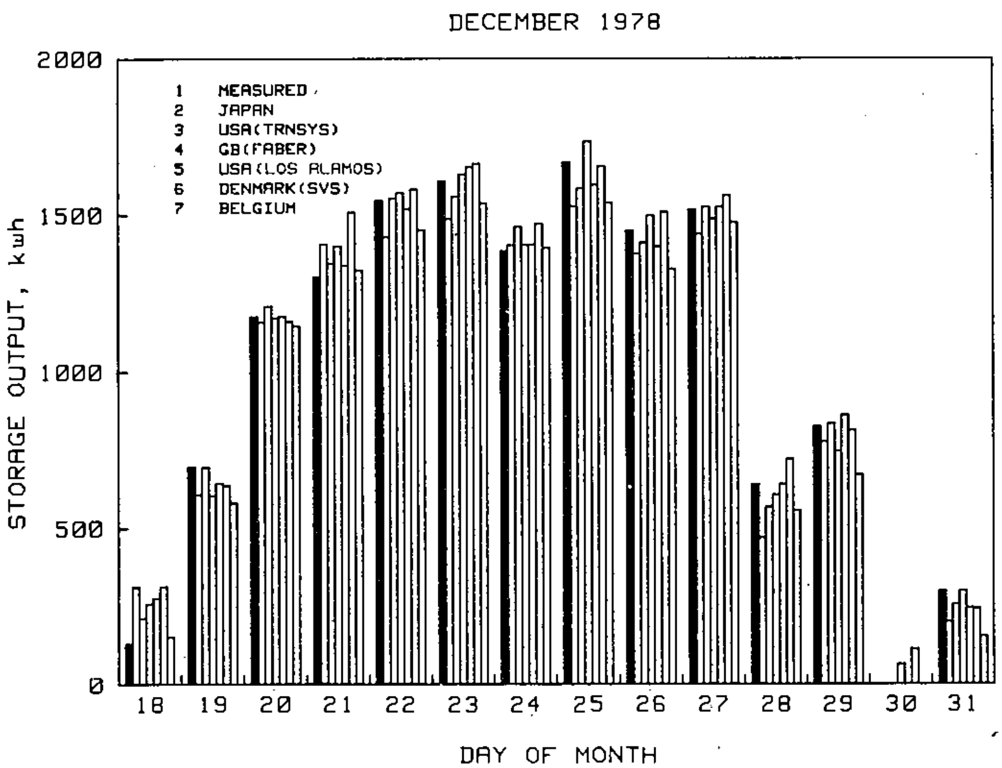

Fig. 4.3. Daily measured and calculated storage output.

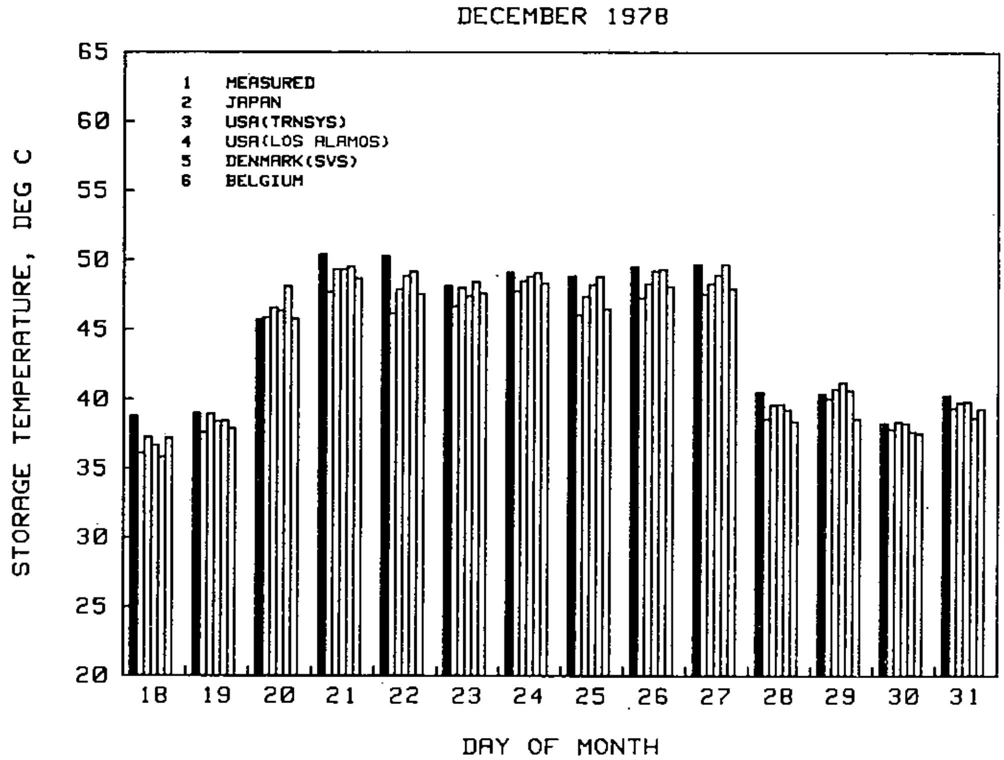

Fig. 4.4. Daily measured and calculated storage temperature.

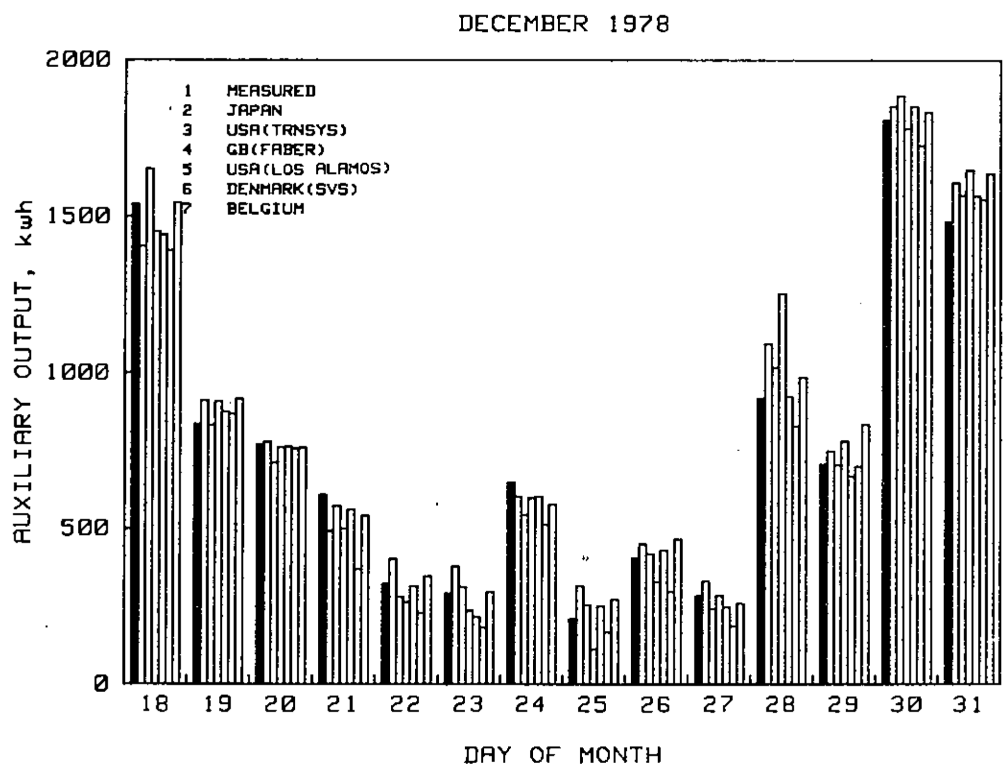

Fig. 4.5. Daily measured and calculated auxiliary output.

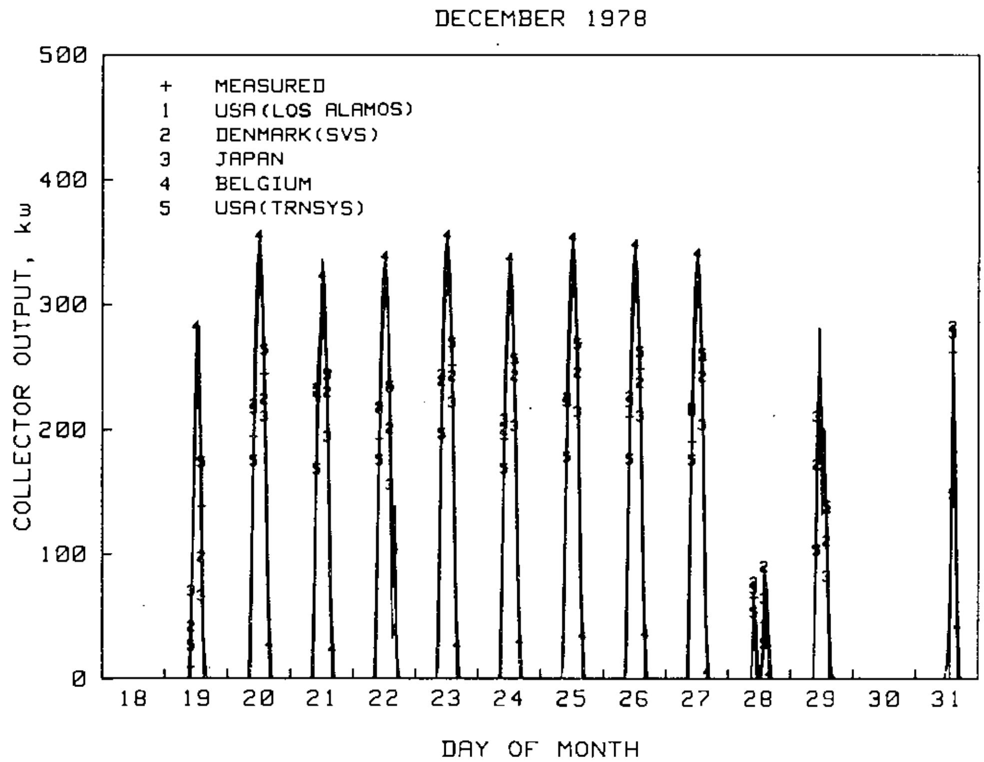

Fig. 4.6. Hourly measured and calculated collector output.

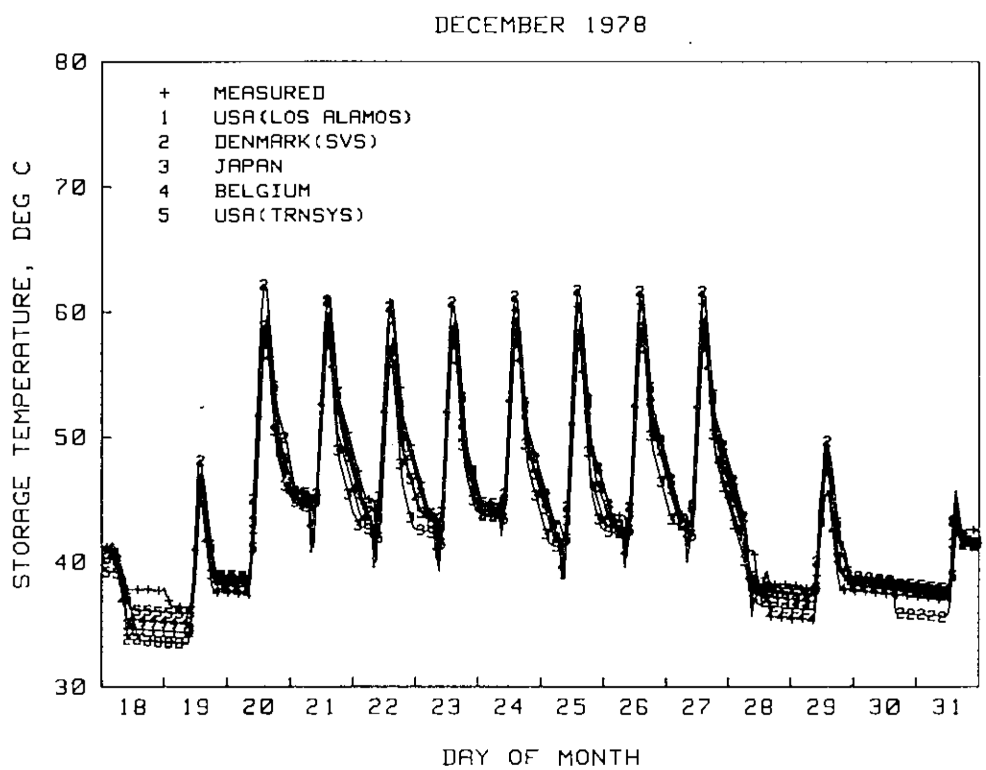

Fig. 4.7. Hourly measured and calculated storage temperature.

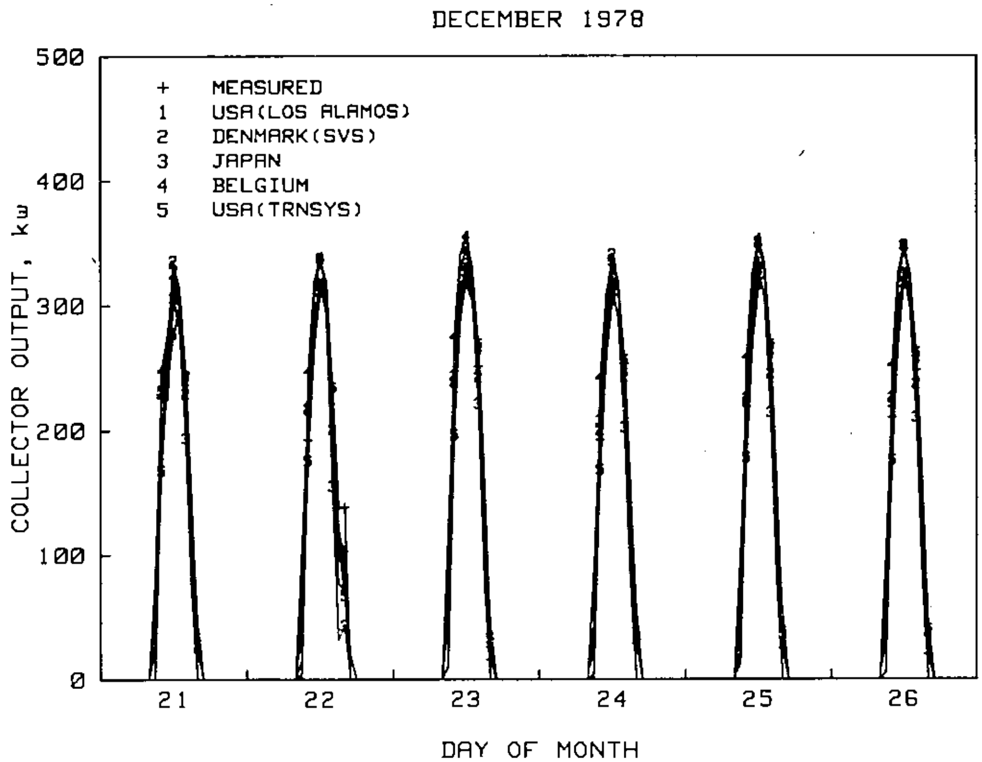

Fig. 4.8. Hourly measured and calculated collector output.

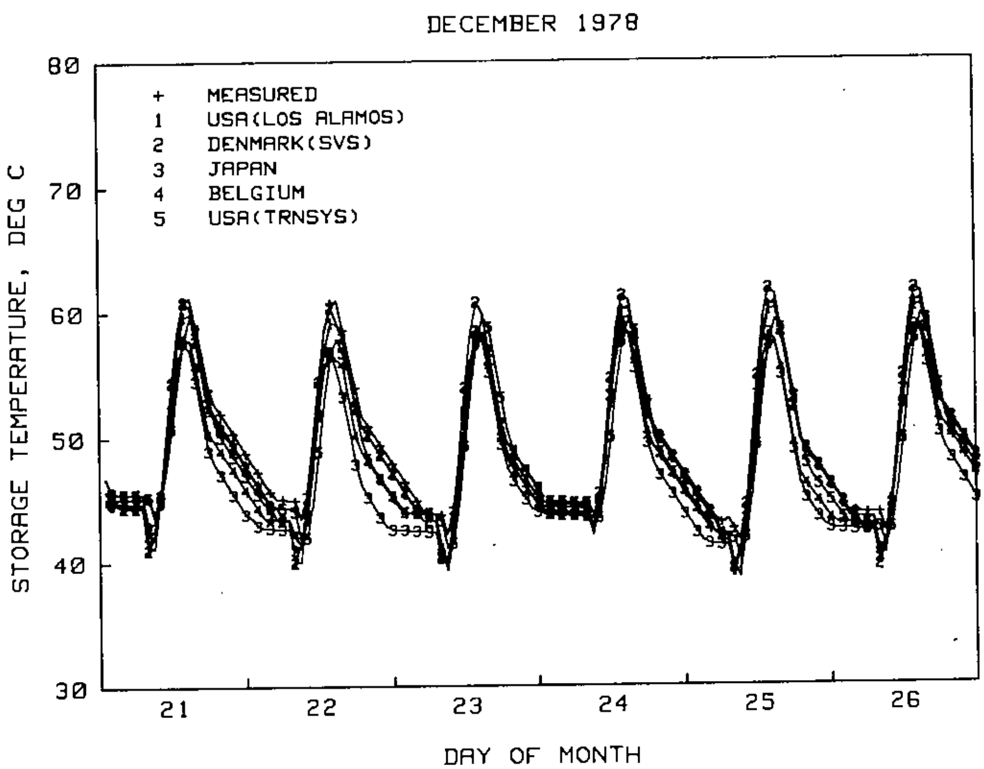

Fig. 4.9. Hourly measured and calculated storage temperature.

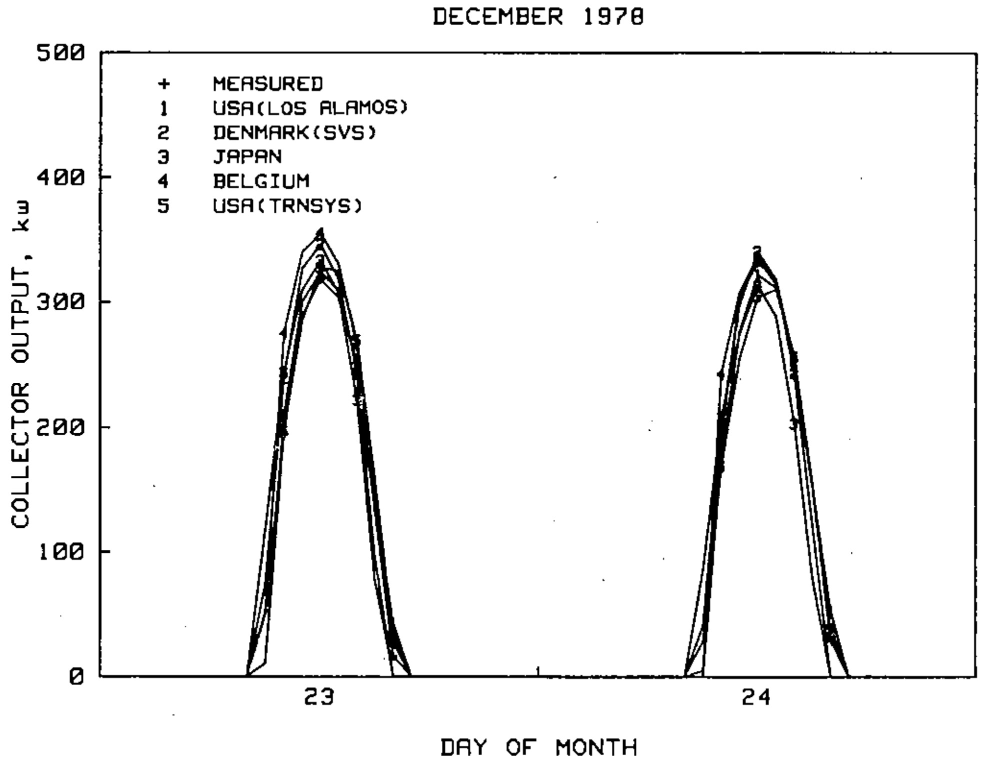

Fig. 4.10. Hourly measured and calculated collector output.

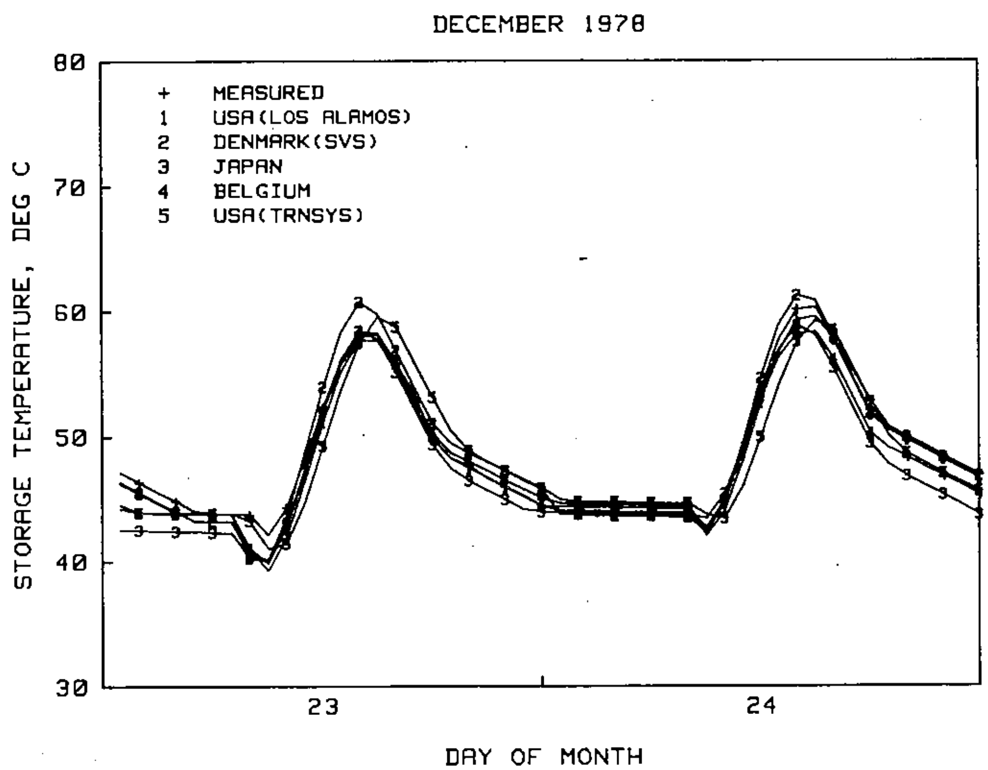

Fig 4.11. Hourly measured and calculated storage temperature.

CHAPTER 5

CONCLUSIONS

This validation study has generally been a valuable exercise for locating and correcting modeling deficiencies in each of the codes. The value to the individual participants varies due to the varied prior use and validation histories of each of the programs. Many of the participants took good advantage of the exercise to refine their codes in many ways. (See the reports authored by the individual participants.) Perhaps the most significant result has been the further consolidation of methods and understanding in the solar system simulation area. Methods of modeling, performance reporting, and validation have been agreed upon in an international forum, and steps have been taken in the formulation of an international data base of system performance data and analysis tools.

It has been shown that all the programs involved in this study are capable of closely predicting the measured performance of a real solar heating system. However, this is generally not likely to occur without prior knowledge of the results. The "user effect," that is, both user error and user interpretation of design data, adds a great deal of uncertainty to the results. In practice, the "user effect" contributes much more uncertainty than any remaining errors or differences in the modeling approaches or algorithms. No data are available on the extent of iterative input adjustment in the first round of this exercise, but it is estimated that two or three iterations were typically required before results were obtained that were within the error tolerance capability of the codes. A typical user is likely to make far more mistakes than the experts who ran each of the codes in this study. It should, hence, be concluded that efforts to simplify, standardize, and otherwise make foolproof the task of data entry into the programs is at least as important as refining the models in the codes if accurate predictions are to be expected without prior knowledge of results.

The statistical analysis of results of the participants has produced an abundance of data to support at least one important conclusion. It is generally not possible to precisely track measured hourly results for the simple reason that control decisions in real systems are made by nonideal 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, which, of course, will cause significant instantaneous differences between measured and predicted results throughout the system. Fortunately, in the long run, these differences are largely self-correcting, particularly if the set points drift back in the opposite direction, because of the stable equilibrium of most solar thermal systems. As a result, it is possible to predict quite accurately the long-term performance of systems (where "long term" means a time much longer than the time constant of the parameter drift rates).

Both advantages and disadvantages can be discerned in the training period/checking period validation methodology inherent in this two-round study. The advantage is that the "user effect" can be greatly reduced in the training period. Appropriate values of parameters may be inferred by trial and error so that the accuracy of the data as provided in the system description or as derived by the users for input to the codes does not limit the inherent accuracy of the simulation program. The disadvantage is that the data derived in this empirical way may mask one or more important effects not properly accounted for in the model. The inference of the tank loss coefficient in this exercise is an example of this problem. The apparent losses from the measured data were much higher than expected, possibly due to thermosiphoning or some other phenomenon not modeled. The range of tank losses predicted by the codes in the first round shows that most participants used the tank loss coefficient parameter to adjust their results. Thus, not only was the actual cause of the unexpectedly high losses falsely described, but other modeling inaccuracies or user errors were compensated by adjustments in the tank loss coefficient. Presumably, a more rigorous approach to this methodology, like that discussed in Ref. 5, would solve this problem.

A final problem relates to the lack of sufficient code output data to identify completely all the sources of differences. In a system simulation, the performance of all components is interrelated such that an error in one component creates disagreement between measured and predicted results in all components. Either stand-alone component tests are required, or more short-term data must be measured in the experiment and output by the codes for comparison. As an example, hourly measured and simulated collector input and output data could be plotted in the efficiency vs $\Delta T/I$ format to validate the collector component in this system test.

In summary, this validation exercise,* and others like it, are valuable for locating and correcting significant modeling errors and lack of modeling capability. They are not appropriate, however, for defining the error bounds or confidence intervals of the codes. A much more comprehensive and rigorous statistical approach is needed before that can be accomplished. In light of the almost insurmountable practical problems associated with such an undertaking, it would seem that a more realistic task for future validation efforts in the IEA would be to validate (i.e., determine the accuracy and limits of applicability of) specific algorithms and modeling assumptions. Individual codes incorporating these validated features can then be verified with spot checks with other software or experiments such as in the present study.

The IEA has provided a valuable forum for comparing and improving the consistency of solar simulation codes used throughout the world. The Los Alamos Study Center has been established as an appropriate system for performing code comparisons, and the consistency and quality of the performance data have been established for future validation efforts.

*Data sets for this exercise may be obtained from J. C. Hedstrom or the operating agent, Ove Jorgensen.

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APPENDIX A

SYSTEM DESCRIPTION

A. Collectors

1. Gross Area — 8060 ft^2 (748.8 m^2)
2. Aperture Area — 7705 ft^2 (715.8 m^2)
3. Tilt — 35^o
4. Direction — 13^o east of south
5. Glazing — 1 sheet ASG white glass
   - Transmission — 0.91
   - Thickness — 0.125 in. (0.3175 cm)
   - Ext. Coeff. — 0.06 $in.^{-1}$ (0.024 cm^{-1})
6. Absorber Surface - Black Chrome
   - α — 0.93
   - ϵ — 0.09
7. Absorber — Seam-Welded Expanded Steel
   - Steel Thickness — 0.03 in. (0.76 mm)
   - Flow Path — 0.07 in. (1.78 mm)
   - Heat Transfer Coeff. — 10 Btu/h ft^2 ^oF (57 W/m^2)
8. Back Insulation - Urethane Foam
   - Thickness — 2 in. (5.08 cm)
   - Conductivity — 0.2 Btu/h ft^2 ^oF/in. (0.014 W/m K)
   - U Value — 0.1 Btu/h ft^2 ^oF (0.567 W/m^2 K)
   - Heat Loss to Room — 70^oF (21.1^oC)
9. Side Heat Loss (from Heat Transfer Model)

$$U_L = -0.10 + 1.18 * 10^{-3} * \Delta T \quad \text{Btu/h ft}^2\ ^oF$$
$$\Delta T = T_{coll} - T_A (^oF)$$
$$U_L = -567 + 0.0121 * \Delta T \quad W/m2\ K$$
$$\Delta T = T_{coll} - T_A (^oC)$$

(T_A = ambient temperature)

10. End Heat Loss (from Heat Transfer Model)

$$U_L = -0.015 + 1.71 * 10^{-4} * \Delta T \quad \text{Btu/h ft}^2\ ^oF$$
$$\Delta T = T_{coll} - T_A (^oF)$$
$$U_L = -0.085 + 1.75 * 10^{-3} * \Delta T \quad W/m^2\ K$$
$$\Delta T = T_{coll} - T_A (^oC)$$

11. Collector Mass

Total Weight 120 lb/20 ft^2 (264 kg/1.9 m^2)

Estimated Heat Capacity 1.0 Btu/^{o}F ft^2 (20.4 kJ/m^2 K)

12. Shade Factors (calculated for February)

Time	7	8	9	10	11	12	13	14	15	16	17
SF	0.907	0.949	0.964	0.974	0.978	1.0	1.0	0.969	0.899	0.781	0.763

Shading from adjacent structures - apply to direct beam only

Qder = SF * Qder

13. Measured Collector Performance (at Los Alamos Collector Test Station)

$\tau\alpha$ 0.810

U_L 0.875 Btu/h ft^2 ^{o}F(4.962 W/m^2 K)

where $\eta = \tau\alpha - U_L\ (T_{IN} - T_A)/I$.

B. Collector Loop

1. Fluid Paraffinic Oil (Shell Thermia 33)

Specific Heat

$$Cp = 0.41 + 5 * 10^{-4} * T(^{o}F) \quad Btu/lb^{o}F$$

$$= 1782 + 3.766 * T(^{o}C) \; J/kg\ K$$

Density

$$\rho = 0.9 - 3.5 * 10^{-4} * T(^{o}F) \quad gm/cc$$

$$\rho = 889 - 0.63 * T(^{o}C) \quad kg/m^3$$

Viscosity

100 ^{o}F (38^{o}C) 50 cp (0.05 Pa-s)

210 ^{o}F (99^{o}C) 6.4 cp (0.0064 Pa-s)

Conductivity

100^{o}F (38^{o}C) 0.076 Btu/h ft^{o}F (0.132 W/m K)

300^{o}F (149^{o}C) 0.071 Btu/h ft^{o}F (0.123 W/m K)

2. Pump Taco Model No. 5010

Flow Rate (derived from February data)

$$\dot{m} = 166600 + 5008 * T - 15.66 * T^2 \; (lb/h)$$

T = collector inlet temp (T2) ^{o}F

$$\dot{m} = -2.82 + 0.908 * T - 0.0064\ T^2 \; (kg/s)$$

T = collector inlet temp (T2) ^{o}C

Pressure Rise	65 ft	(20 m)
Power		
Rating	10 bhp	(7.40 kW)
Measured	9.5 kW	

(assume 50% into fluid)

3. Collector Inlet Piping

DIA (in.)	L (ft)	A_s (ft^2)	V (ft^3)	M_{oil} (lb)	U_L (Btu/h ^oF)
6	176	305.2	36.0	1943	51.0
4	20	23.6	1.8	95	5.9
3	10	9.2	0.5	28	2.3
2-1/2	9	6.8	0.3	16	16.9
2	835	519.1	19.5	1051	129.8
1/2	1745	285.0	2.4	128	71.3
Total		1148.9	60.4	3261	277
		106.7 m^2	1.71 m^3	1479 kg	146 W/K

4. Collector Outlet Piping

DIA (in.)	L (ft)	A_s (ft^2)	V (ft^3)	M_{oil} (lb)	U_L (Btu/h ^oF)
6	178	308.7	36.2	1966	51.6
4	20	23.6	1.8	95	5.9
3	11	10.1	0.6	30	2.5
2-1/2	10	7.5	0.3	18	1.9
2	828	514.7	19.3	1043	128.7
1/2	1745	285.0	2.4	128	71.3
18	3.5	20.0	6.2	334	1.3
Total		1170	67.0	3614	263
		108.7 m^2	1.90 m^3	1639 kg	139 W/K

5. Pipe Insulation Fiberglass

6 in. Pipe - 1.5 in.

1/2 to 4 in. - 1.0 in.

Loss coefficients in above tables.

Heat loss to 70^{o}F (21.1 ^{o}C).

C. Heat Exchanger

1. Tube in Shell

Model	B&G 2010-46
Tube Surface Area	647 ft^2 (197 m^2)
Number of Tubes	320
Tube O. D.	0.75 in. (1.90 cm)

2. Measured Heat Transfer Coefficient

$$U_H = 14254 + 298*T_{cin}\ (^oF)\quad Btu/h^oF$$
$$= 12521 + 282*T_{cin}\ (^oC)\quad W/K$$

T_{cin}= Collector Inlet Temperature
= T2 (Fig. 1)

D. Heat Exchanger Loop (water)

1. Flow Rate 315 Gpm (19.85 kg/s)

2. Pump

Measured Input 1.15 kW
(assume 50% to fluid)

3. Piping

	DIA (in.)	L (ft)	A_s (ft^2)	V (ft^3)	M_{H_2O} (lb)	U_L (Btu/h^oF)
Inlet	4	60	70.7	5.3	341	17.6
Outlet	4	60	70.7	5.3	341	17.6
Total			141.4	10.6	682	35.2
			13.1 m^2	0.3 m^3	309 kg	18.6 W/K

E. Storage Tank

1. Fluid	Water
2. Size	8 ft (2.44 m) dia * 26 ft (7.92 m) high
3. Volume	10,000 gal (71.6 m^3)

3. Auxiliary Control Temperature

(steam valves modulate auxiliary water temperature according to ambient temperature)

$T_c = 135 - 0.5\, T_A$

T_c = Control Temperature ^{o}F

T_A = Ambient Temperature ^{o}F

$T_c = 48.33 - 0.5\, T_A$

T_c = Control Temperature (^{o}C)

T_A = Ambient Temperature (^{o}C)

I. Collector Controller

1. Differential temperature controller works between absorber surface temperature and tank temperature
2. ON $\Delta T \geq 10^{o}F$ ($5.6\ ^{o}C$)
3. OFF $\Delta T \leq 0^{o}F$ ($0^{o}C$).

APPENDIX B

REVISED INFORMATION FOR DECEMBER 18-31 STUDY CENTER DATA

A.12 SHADE FACTORS (CALCULATED FOR DECEMBER)

Time	7	8	9	10	11	12	13	14
SF	1.0	0.948	0.964	0.972	0.979	1.0	0.997	0.944

Time	15	16	17
SF	0.841	0.749	1.0

H.2 SWITCHOVER TEMPERATURE

Mode 1 → 2 $T_s \leq 125.0 - 0.7T_A$

Mode 2 → 1 $T_s \geq 127.1 - 0.7T_A$

(temperatures in $^\circ$F)

Mode 1 → 2 $T_s \leq 39.2 - 0.7T_A$

Mode 2 → 1 $T_s \geq 40.4 - 0.7T_A$

(temperatures in $^\circ$C)

H.3 AUXILIARY CONTROL TEMPERATURES

$T_c = 158.9 - 0.69T_A$

(temperature in $^\circ$F)

$T_c = 57.7 - 0.69T_A$

(temperature in $^\circ$C)