315
3-11-80

DR. 855

MSNW-78-3035(Vol.1)

ANALYSIS AND SIMULATION OF PERFORMANCE DATA FOR RESIDENTIAL SOLAR HEATING AND HEAT PUMP SYSTEM IN SEATTLE, WASHINGTON

Final Report, Volume I

By
Robert Taussig
James Lockett
Michael Storie
John Isakson
Benjamin Levy

June 15, 1978

Work Performed Under Contract No. EG-77-C-02-4229

Mathematical Sciences Northwest, Inc.
Bellevue, Washington

U.S. Department of Energy

Solar Energy

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy $7.00
Microfiche $3.50

MSNW-78-3035(Vol.1)
Distribution Category UC-59

ANALYSIS AND SIMULATION OF PERFORMANCE DATA FOR RESIDENTIAL SOLAR HEATING AND HEAT PUMP SYSTEM IN SEATTLE, WASHINGTON

VOLUME I

FINAL REPORT

Prepared by

Robert Taussig
James Lockett John Isakson
Michael Storie Benjamin Levy

MATHEMATICAL SCIENCES NORTHWEST, INC.
P.O. Box 1887
Bellevue, Washington 98009

For

Division of Solar Applications
Office For Conservation and Solar Applications
The U.S. Department of Energy
On Subcontract With the Solar Environmental Engineering Company
Fort Collins, Colorado

15 June 1978

ABSTRACT

The Pacific Cascades is a distinct climatological region for solar energy applications. In order to investigate the effect of the regional differences in solar energy availability on residential solar heating systems, a study was conducted to analyze the performance of a solar heated house in this region and to validate a solar heating and heat pump computer simulation program for this region. The house, called the Seattle City Light Project Weathervane house, uses solar energy from roof-top flat plate collectors to boost the performance of a water-to-air heat pump. If the temperature of the water storage tank drops too low, then auxiliary heating is provided by an off-peak immersion heater.

Performance data for the ten-month heating season was collected from Seattle City Light, and put into the form of a comprehensive baseline data document during this study. The University of Wisconsin TRNSYS solar heating computer simulation program was used to model the performance of the house. The computer results were compared to the actual performance data in order to help validate TRNSYS with regional solar heating data. The computer results were also used to help in understanding the behavior of the Seattle City Light Project Weathervane house heating system.

Actual solar heating system performance demonstrates that approximately 40 percent of the total house heating requirements were provided by the solar heating system. The impact on utility peak load requirements was reduced by the off-peak auxiliary heating requirements. Significant heating was supplied by hot water taken directly from the storage tank when the water storage tank temperature was high. The computer program modeled the heating system behavior qualitatively hour-by-hour, and over periods of a week or greater, the simulation also agreed quantitatively with the energy used by the actual heating system. Details of the analysis and results are presented in this report.

ACKNOWLEDGMENTS

The authors wish to extend their gratitude to Mr. Michael Maybaum, Division of Solar Applications, Office for Conservation and Solar Applications of the Department of Energy, for his support and encouragement to proceed with this research, and to Professor C. Byron Winn, president of the Solar Environmental Engineering Company (SEEC) for his assistance. We also wish to thank Mr. Alan Yamagiwa for his patience in teaching us about the Project Weathervane heating system and for supplying us unstintingly with his data and personal calculations. We commend Seattle City Light's Mr. Gordon Vickery and Mr. Robert Sheehan for their support in facilitating this project.

The work for this research was supported by ERDA (now Department of Energy) through a subcontract with the Solar Environmental Engineering Company of Fort Collins, Colorado.

TABLE OF CONTENTS

LIST OF TABLES

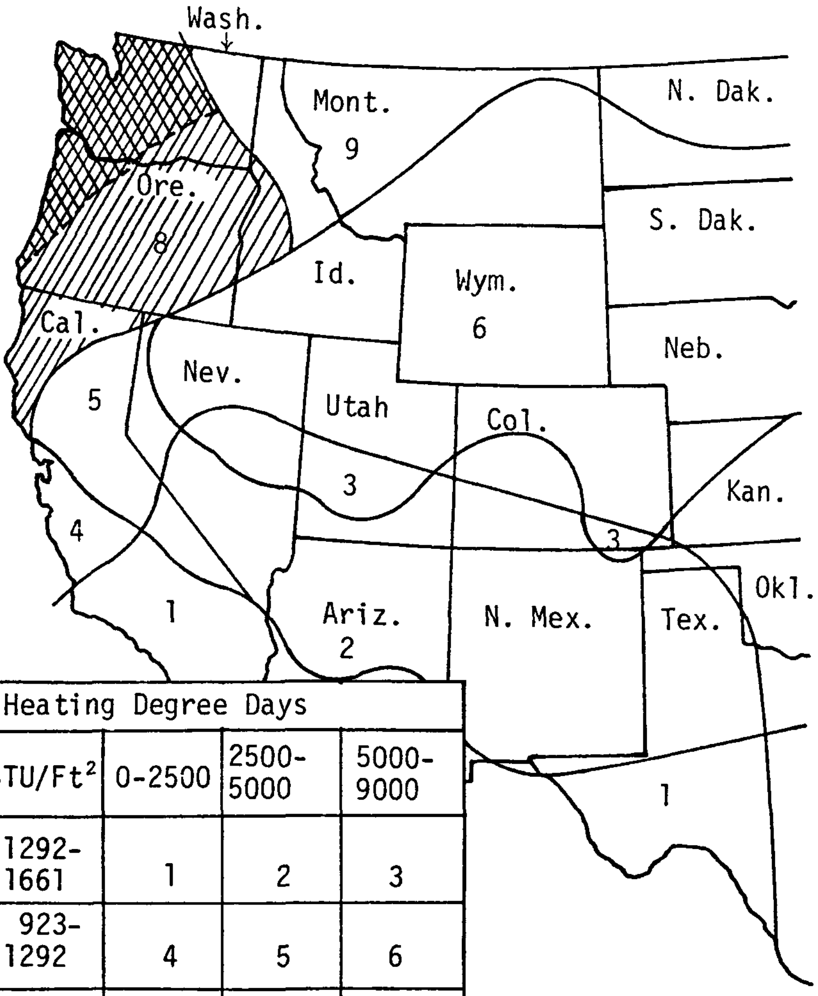
LIST OF FIGURES

I. INTRODUCTION

Computer simulation programs have become one of the quickest ways to analyze the performance of solar heating systems. Some of these programs are extremely accurate, but require extensive running time on the computer. Others such as F-Chart[1] or the newly generated short program called G-Chart,[2] produced by the Solar Energy Research Institute (SERI), try to circumvent detailed simulation of the house by substituting averaged performance data. The simulation programs have an advantage of allowing new designs to be evaluated without having to actually build the system in order to learn about it. To have confidence in the predictions of such programs one must first validate the modeling accuracy of these programs. This validation should encompass both the behavior of individual components of the heating systems and should also cover the response of such systems to varying weather and insolation conditions. The object of this research has been to validate one of the foremost computer simulation programs, TRNSYS,[3] for the Pacific Cascades climatological region.

The Pacific Cascades Region (see the cross-hatched area in Figure 1), has been identified as one of the major climatological regions for solar energy applications.[4] The region is characterized by mild winters, cool summers, and a heating season extending over ten months of the year. This latter fact accounts for the approximately 4,800 heating degree days, nearly the equivalent of places with more extreme winter conditions, such as Boston, Massachusetts.[5] Fairly extensive cloud cover exists during the winter months in this region. However, the very coldest days are clear and sunny, allowing good solar heating on the days when it is most needed.[6] In order for a simulation program to be applicable in this region it must accurately account for the performance of solar collectors which collect relatively small amounts of energy each day over a long heating season. The average energy collected each day is small because of the small collector-to-ambient temperature difference. Thus the seasonal performance is dependent on the sum of many small numbers: it would be natural to expect that large relative errors might occur under these circumstances. Hence, the Pacific Cascades presents a severe test of the accuracy of solar heating computer simulations.

Performance data for validating the computer program has been collected from a residential solar heating system called Project Weathervane, designed and installed in a house in Seattle, Washington, by the Department of Lighting of the City of Seattle (Seattle City Light). A picture of the house is shown in Figure 2. Flat plate collectors are mounted on the roof and the heated water-ethylene glycol mixture is piped to a storage tank where it exchanges heat with the water in the tank.



Mean Daily Solar Radiation*

		Heating Degree Days		
LY*	BTU/Ft^2	0-2500	2500-5000	5000-9000
350-450	1292-1661	1	2	3
250-350	923-1292	4	5	6
175-250	646-923	7	8	9

Figure 1. Regional Climatic Classification for the Heating Season (single-hatched) and Combined Heating and Cooling Season (double-hatched portion of Region 8) characteristic of the Pacific Cascade Region. *The BTU/Ft^2 per day Insolation Values equal 3.69 x Langleys (LY). (Adapted from Reference 4.)

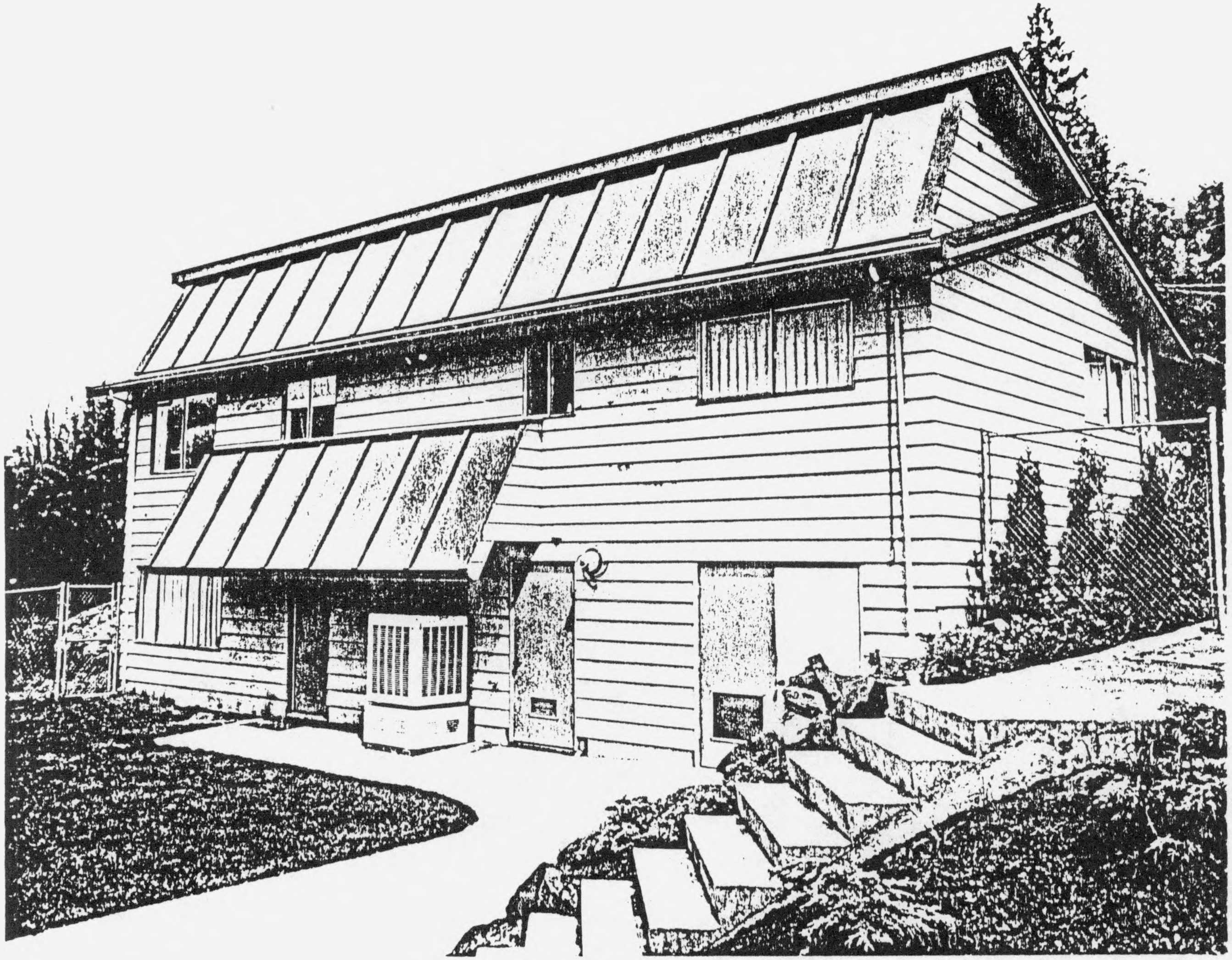


Figure 2. The Seattle City Light Project Weathervane House
Showing the Roof-Top Solar Collectors

The tank has an immersion heater in it to back up the solar heating system. The tank is used to pre-heat hot water for domestic use and to heat the house. Two modes of house-heating are possible: either the house is heated directly by hot water from the tank, or if the tank temperature is too low, a heat pump takes heat from the tank and delivers it at the appropriate temperature to the hot air heating duct.

The objectives of this study were to provide baseline solar heating data for the Pacific Cascade region and to verify the accuracy of the computer simulation model. The study tasks consisted of:

- Data acquisition, reduction and analysis
- Solar baseline data document assembly
- Validation of the computer simulation model
- Analysis of simulation results
- Assessment of the solar simulation computer code

In comparison to other broader studies, this is an in-depth case study. The advantages of such an analysis are that specific details of solar heating system performance can be analyzed and the computer simulations can be studied at the same level of detail, in order to assess the effectiveness of the code in modeling the solar heating system. The disadvantages lie in any restrictions in the data or system studied that tend to limit the conclusions of this analysis to the specific case studied. The results and limitations of this study are summarized in the final Section VI.

Considerable interest in the results of this research exists among the local utilities who view the advent of solar heating systems with some trepidation and skepticism. With inappropriately sized energy storage units or poorly conceived back-up heating systems, solar energy systems can impose an increase instead of a decrease of the peak generating capacity required for a particular service area. Specifically, if the back-up energy is electricity, then insufficient energy storage will require all of the back-up systems in a given contiguous weather region to turn on after several cloudy cold days. The heat pump and immersion heater combination used in Project Weathervane are a conscious design effort to buffer the solar energy system storage requirements so that peak load requirements can be reduced. In actual fact, such fears are largely misplaced in the Northwest where a tremendous peaking power capacity already exists in the hydroelectric facilities in this region.[7]

Some skepticism arises from the poor local information concerning the cost-effectiveness of solar heating in the Northwest, especially in the coastal regions where cloudy winter weather is in such evidence. To a certain extent, the recent report on solar energy in the Northwest issued by the Region X office of the Department of Energy and the Environmental Protection Agency helps to answer some of the elementary questions of economics for certain conventional types of solar heating and hot water systems.[5] However, the range of institutional arrangements for financing solar energy, particularly with the utilities as partners, has not yet been explored. Some of these questions are discussed in a preliminary way in the summary and conclusions of this report, as a result of the perspectives gained from the analysis of the Project Weathervane performance.

The Pacific Northwest also has its share of local manufacturers (e.g. Solergy, Inc., Boeing, Vertrex Industries, Oregon Equipment Manufacturing and Sigma Industries) who hope to develop markets for solar heating in this area. Regionally-adapted systems would be of distinct interest to this industry since they could afford to compete with more expensive, universal component manufacturers such as General Electric and Pittsburgh Plate Glass by offering a specific local product, possibly as an integral part of the building construction materials (e.g. walls and roofs). The result of this study may help to speed up market penetration of regionally-adapted residential solar heating and hot water systems.

This project is part of a more extensive computer validation study being carried out by the Solar Environmental Engineering Company (SEEC) of Fort Collins, Colorado. The SEEC study encompassed three computer programs, TRNSYS and F-Chart from the University of Wisconsin and SOLCOST from the Martin Marietta Company. It was decided early in the present study to restrict the validation procedure to just the TRNSYS program. A completely independent assessment of TRNSYS was carried out by Mathematical Sciences Northwest, Inc. (MSNW) using the performance data from the Project Weathervane house. This is perhaps the first validation of TRNSYS to include a heat pump in the solar heating system. All of the data reduction, data analysis, computer simulation and comparison of computer results with actual performance data was carried out by MSNW. MSNW also developed its own validation procedures, discussed in Section V.

Briefly, as a result of this study, a comprehensive solar data baseline document has been assembled and is included as Appendix B of this report, in separate volume. This document is constructed as a self-contained entity, complete with a brief description of the Project Weathervane house. Computer simulations, carried out for single days, weeks, and the entire heating season, were chosen to correspond to occasions when different parts of the solar heating system were operating by themselves, so that a component check on the TRNSYS program could be made. The results show that the computer program is capable of following the actual system performance. The qualitative variation of house room temperature, storage tank temperature and operating sequence of the various heating system components is mirrored very closely by the computer simulation.

Notwithstanding this qualitative validation of the computer program, it is still possible to have sizeable quantitative differences between the simulation program and actual heating system performance over the course of an entire heating system.

Using actual system performance as a guide it appears possible to refine the simulation parameters so as to eventually match the simulation results to every important aspect of the heating system. This approach allows one to optimize existing systems and it may also be possible to use the program for accurate design of new systems with the additional experience gained by comparing simulation parameters to actual system parameters. The lesson of this project has been that the calculated house and heating system parameters cannot be used without substantial numerical adjustment to achieve accurate results. The theoretical basis of these adjustments, arrived at empirically in this research, is discussed briefly to develop some rationale for imposing them on known data.

II. THE CITY OF SEATTLE PROJECT WEATHERVANE HOUSE

Project Weathervane is a house owned by the City of Seattle, retrofitted with a solar heating and hot water system and with a windmill to supply auxiliary power. The windmill power is accounted for in exactly the same way as power bought from the utility. Hence, the solar heating system can be studied by itself in conjunction with the house load and the ambient weather conditions.

The heating system consists of flat plate solar collectors mounted south-facing on the roof. Solar energy is stored in an insulated water tank in the basement. A heat pump can take energy from the tank and use it to supply heat to the hot air ducts in the house, or, if the tank temperature is high enough, the water from the tank can be used to heat the house air directly without using the heat pump. When the tank temperature drops too low, an immersion heater in the tank is used to boost the temperature back up. Hot water for the house is preheated through a separate circuit running through the energy storage tank. Figure 3 shows a schematic of the house heating system; double lines represent pipes connecting the collector, storage tanks, heat pump and other elements of the heating system.

A family occupying the house helped to take some of the instrument readings. The bulk of the data was recorded automatically on a ten-channel strip chart data logger and on separate weather station instruments located at the base of the windmill. A list of the separate pieces of data collected on a daily or hourly basis is given in Table 1. A more detailed description has been published in the recent paper by A. Yamagiwa of the Seattle City Light Department of Engineering.[8]

Flow tests were carried out by the City Light staff to determine the optimum flow rates for heat transfer between the various elements of the heating system. The trade-off yielding an optimum flow rate consisted of an increase in required pumping power accompanied by diminishing returns on the rate of energy transfer from the collector. It is worth noting that daily pyroheliometer readings were taken which gave the total solar radiation each day. Hourly readings were not taken, so that an hourly solar radiation intensity was constructed from cloud cover readings recorded at the Sea-Tac Airport weather station. More details of this conversion are discussed in Section III.

Figure 3. Schematic of Seattle City Light Project Weathervane House

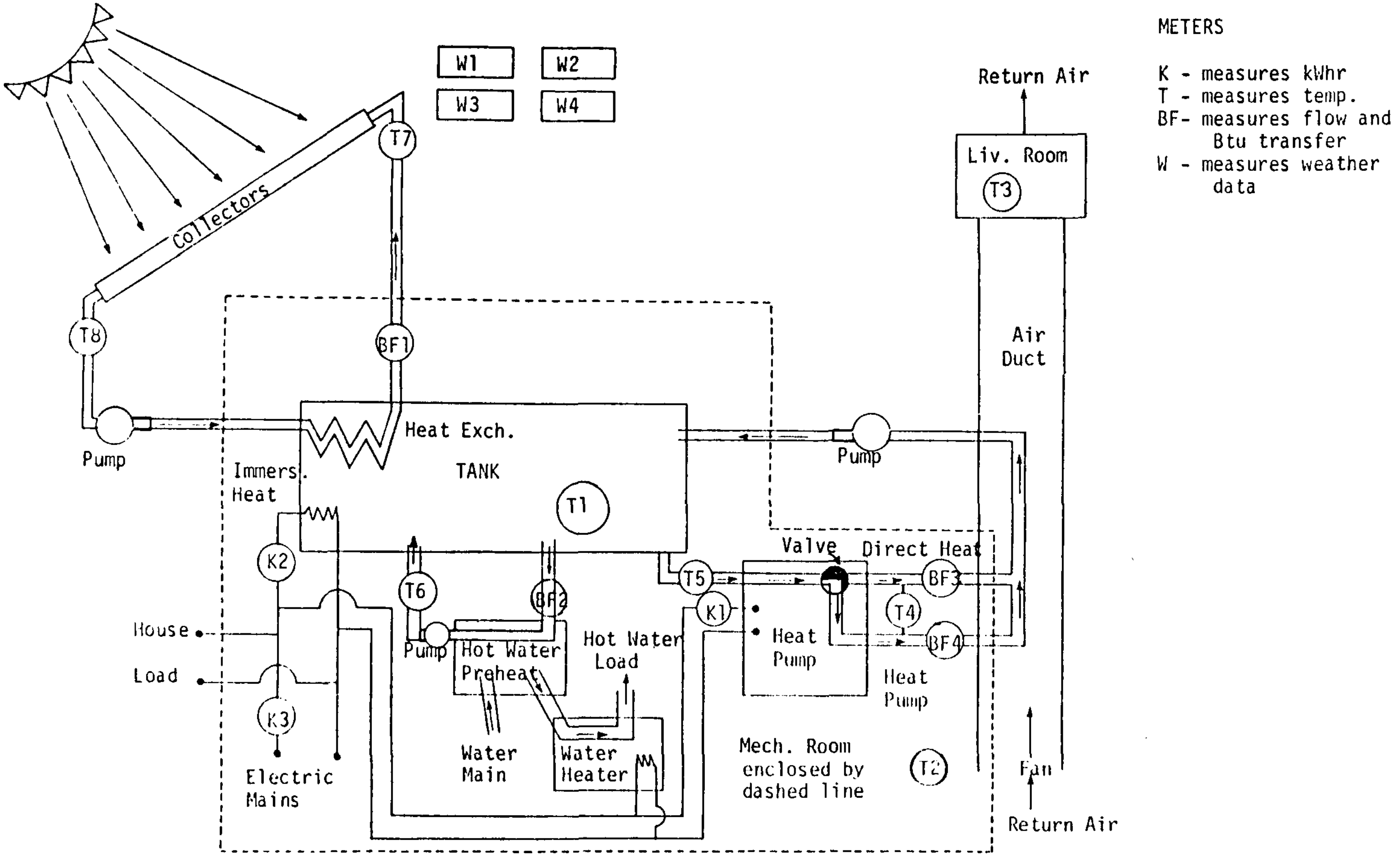


TABLE 1

LIST OF DATA COLLECTED

	Units	Daily Data Meter No. (See Figure 1)	Duplication of Daily and Hourly Data
Solar Insolation	Watts/m^2	W1	
Collector	Gal.	BF1	
	Btu	BF1	
Water Heater	Gal.	BF2	
	Btu	BF2	
Direct Heat	Gal.	BF3	
	Btu	BF3	
Heat Pump	Gal.	BF4	
	Btu	BF4	
Wind	KWHR	---	
Heat Pump	KWHR	K1	
Tank Heater	KWHR	K2	
Total	KWHR	K3	
Tank Temp.	°C	T1	
		Hourly Data	
Wind Direction	Degrees from North	W2	
Wind Velocity	MPH	W3	
Temperature	°F	W4	
Solar Radiation	Btu/hr/ft^2	W1	
Mech. Room	°C	T2	
Living Room	°C	T3	
Storage Tank	°C	T1	
Heat Pump Exit	°C	T4	
Heat Pump Enter	°C	T5	
Hot Water Exit	°C	T6	
Solar Collector Enter	°C	T7	
Solar Collector Exit	°C	T8	
Total House	KWHR	K3	
Immer. Heater	KWHR	K2	
Heat Pump	KWHR	K1	

III. THE SOLAR BASELINE DATA DOCUMENT

A full heating season (September 1976 to June 1977) of performance data has been collected, corrected for instruement errors, obvious reading inaccuracies, and data gaps have been noted and the more frequent measurements summed to obtain hourly data. In addition, daily averages and totals have also been computed where appropriate. The resulting data was stored on a magnetic tape to facilitate retrieval. Listings were also obtained in order to identify missing data and data errors, and to help to determine the appropriate units for each item. Range checks were made in order to pick out obvious errors in the corrected data set, and the number of hours per day and days per month were also checked. As a result of this data reduction exercise, a relatively error-free solar baseline data set was obtained.

A file of the original raw data has also been retained along with the original computer printout, in order to facilitate answering any future questions concerning the procedures used to correct the data or the actual values of the raw data. Some data was obtained from computer printout of data which had already undergone previous reduction to computer-readable form (i.e., the wind speed, wind direction, and ambient temperature). About one month of data was missing from this climatological subset; missing data such as this could be replaced by the nearest available weather station data, but we have chosen to leave it blank, so that future users can exercise their own discretion about which data to substitute for it. In the case of hourly solar insolation values, data was constructed from Sea-Tac three-hourly cloud cover data[9] and daily totals of insolation recorded on the Project Weathervane site, according to the scheme shown in Figure 4. This technique involves a theoretical calculation of the cloudy day insolation on a horizontal surface using an algorithm developed in the NECAP building simulation program, and subsequently modified for use in the CAL-ERDA simulation program.[10] The theoretical hourly values are then corrected by a multiplicative factor which makes the sum of the hourly values for a particular day the same as the observed daily total value. The three-hourly values of cloud cover data were interpolated with a cubic curve-fitting routine to obtain hourly values.

The corrected and augmented solar data set has been printed, hour by hour, for each day in the heating season. The printing format is largely self-explanatory. This Solar Baseline Data document is listed as Appendix B to this report but supplied as a separate volume. The baseline document has an abbreviated description of the Project Weathervane solar heating system and a short discussion of the data reduction techniques. The purpose of this document is to present a self-contained record of solar heating system performance for the Pacific Cascade region with as little interpretation as is necessary to make it comprehensible. Other analysts of solar system operation can therefore make their own comparisons

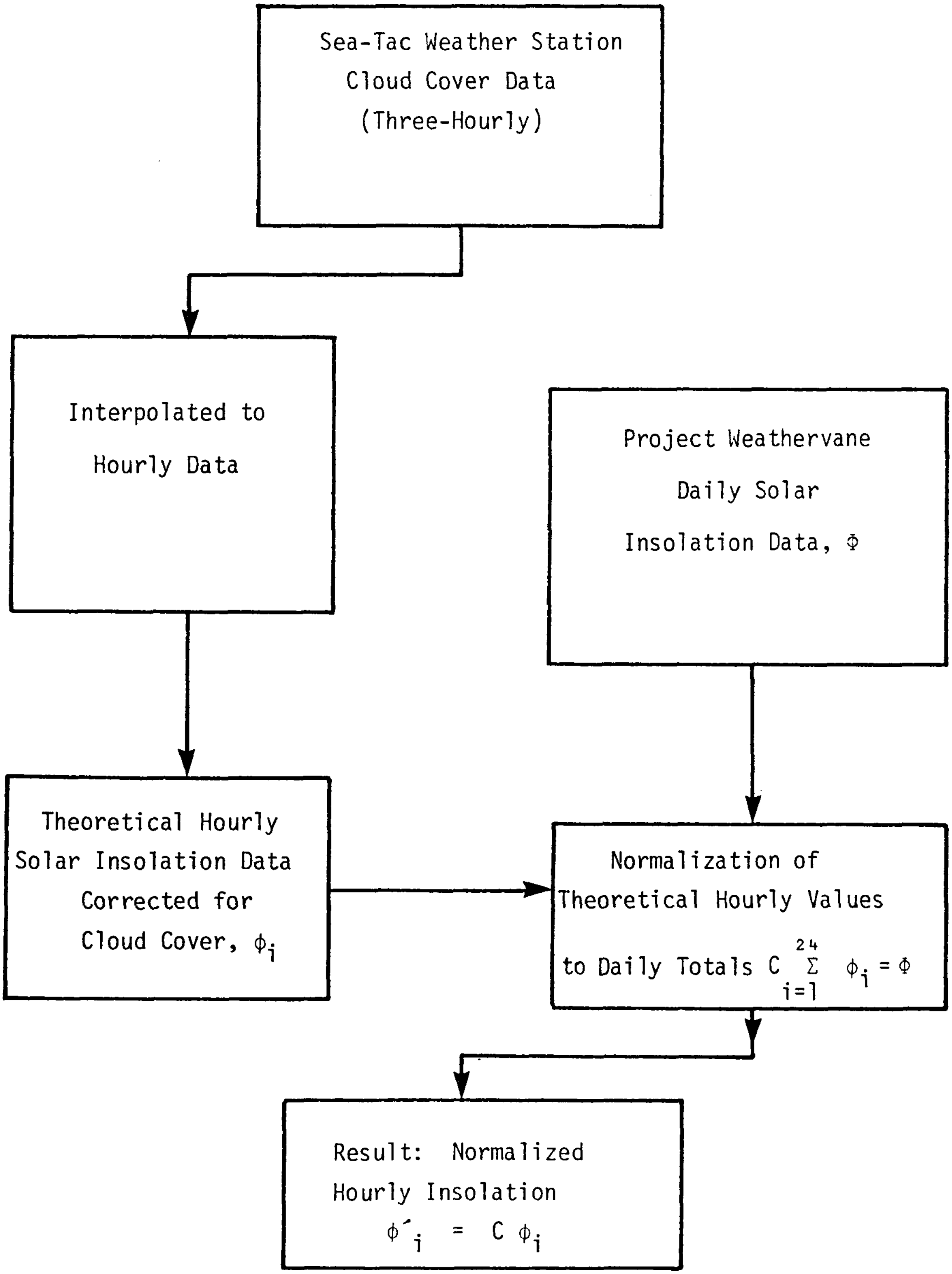


Figure 4. Computation of Normalized Hourly Insolation Values

using this data. We have used it in the following sections of this report as a standard by which to help validate the TRNSYS solar computer simulation program and to assess the relative merits of the particular heating system embodied by the Project Weathervane house.

It is worth noting that the heating season chosen for study (1976-1977) was an exceptionally dry, mild, year for Seattle. The whole Northwest suffered a drought so that the weather and operating conditions for the solar collector were somewhat abnormal. However, the correlation between the weather and the heating system performance is still strong and measurable and can therefore be used to validate the computer simulation program.

Statistics of the daily and hourly data are also incorporated in a final section of the solar baseline data document showing weather and operating condition extremes and means. Total energy supplied from the sun and the solar heating system efficiencies are explained and evaluated. Sample days of operation taken from this document are represented graphically in Figures 5 to 7. These cases illustrate days when direct solar heating occurred with no heat pump operation (Figure 5), with heat pump only (Figure 6), and where the auxiliary immersion heater was employed (Figure 7). In carrying out the computer simulation, the data document was used to guide the choice of relevant periods over which to conduct the simulation.

Similarly, several sample weeks were chosen in order to test the ability of the program to track the house heating system performance accurately over a period of time exceeding the buffering capacity period of the energy storage tank. This would allow initial value errors in the parameters to dissipate and thus permit a closer inspection of the control system operation during the simulation. The weeks chosen for the study were 10 October 1977 to 23 October 1977 (a cool but sunny period when both heat pump and direct heat were in use) and 21 December 1977 to 27 December 1977 (a cold, cloudy winter period when heat pump and auxiliary immersion heater were in use).

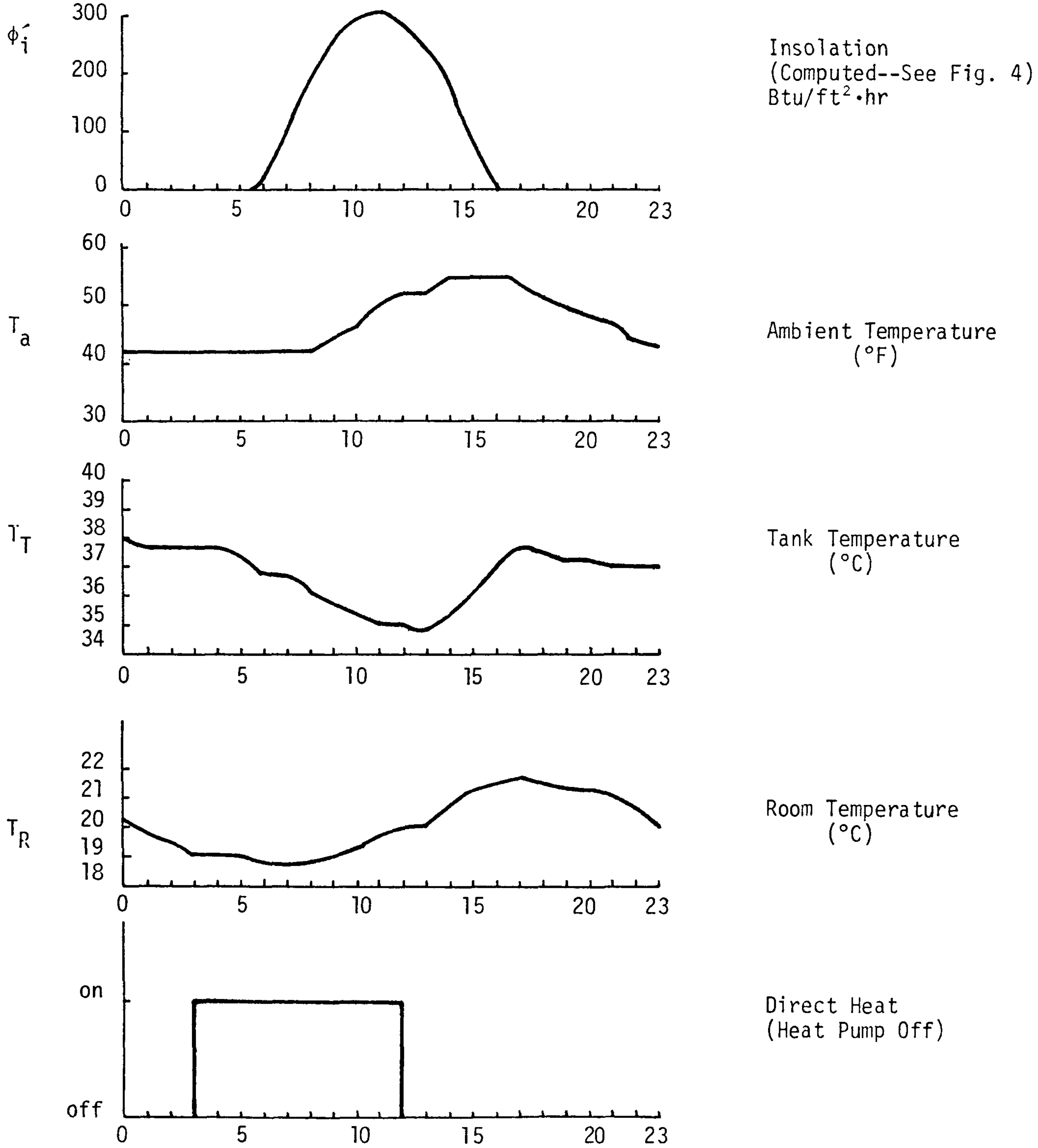


Figure 5. Actual Performance Data for
October 17, 1976
Direct Heat Only

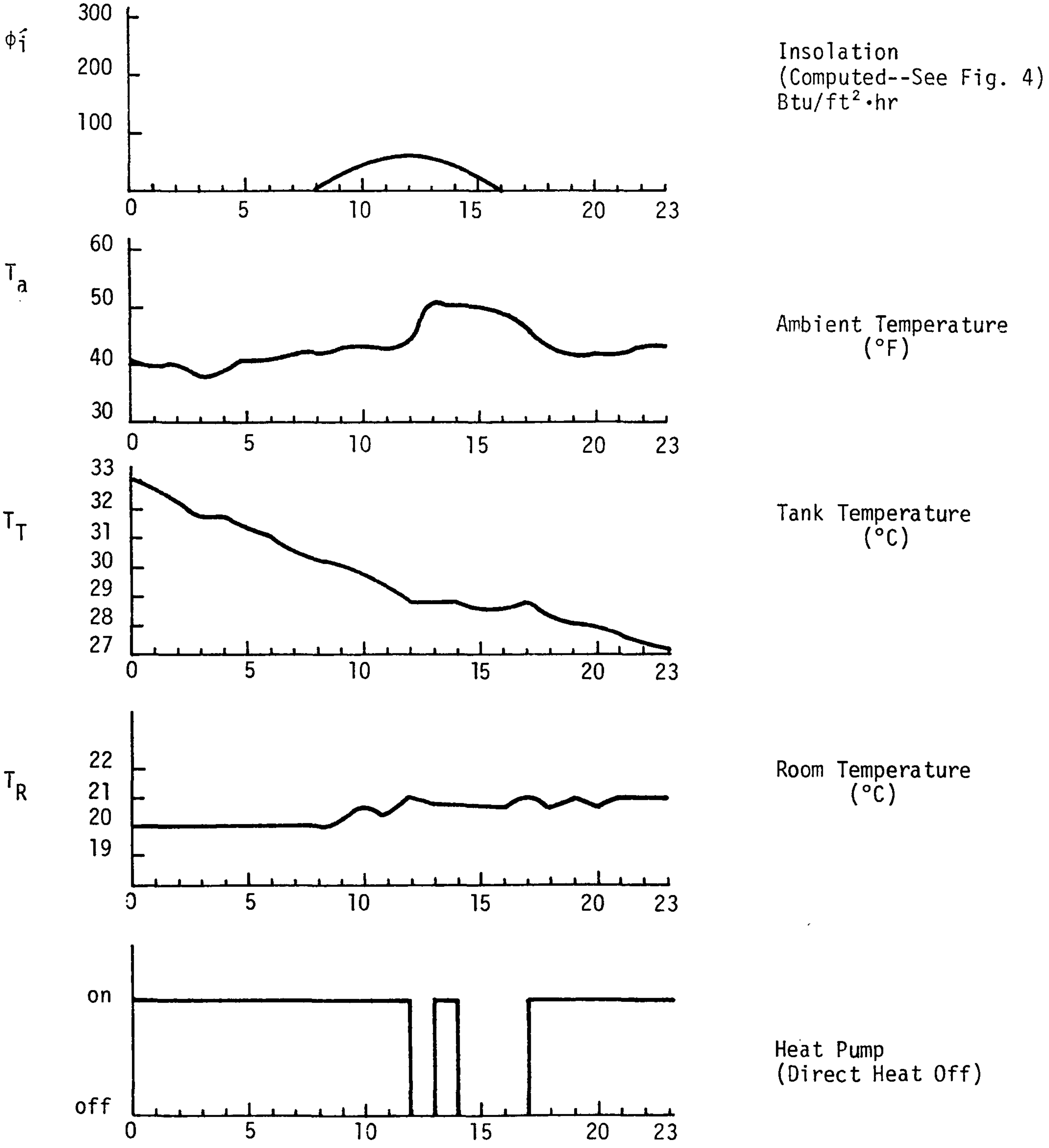


Figure 6. Actual Performance Data for October·22, 1976
Heat Pump Only

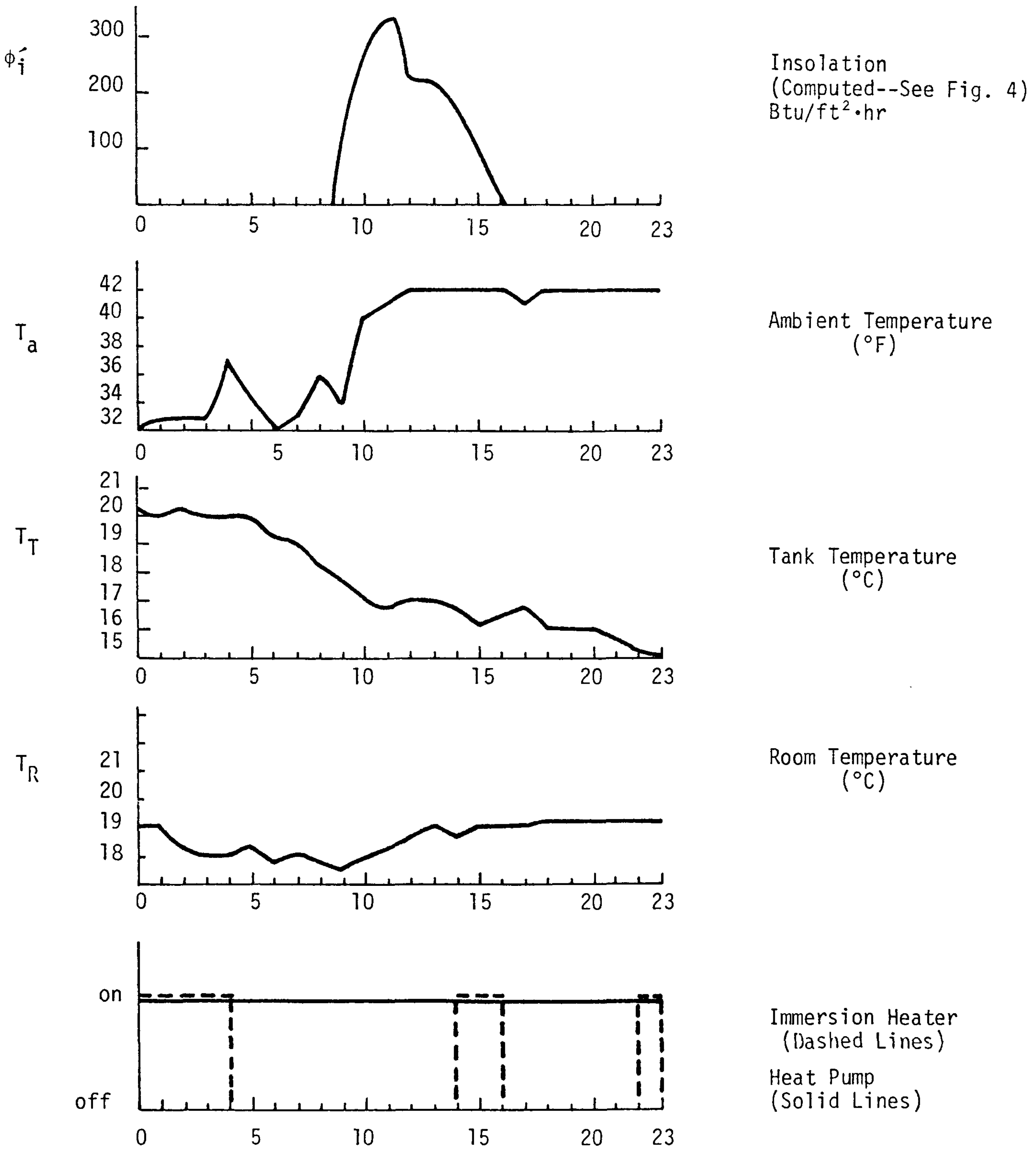


Figure 7. Actual Performance Data for December 22, 1976
Heat Pump and Immersion Heater

IV. SIMULATION OF PERFORMANCE DATA

The main objectives of simulating the performance data from Project Weathervane are to validate the accuracy of the computer code and to gain an understanding of the operation of the solar heating system. By carrying out this analysis carefully it is also possible to characterize the advantages and disadvantages (i.e., the limitations) of using the computer code as a design aid or predictive tool in various applications. In the future it may also be possible to explore ways that the solar heating system might be improved by carrying out simulations of modified versions of the present system.

The computer code chosen for this task is TRNSYS, developed by the University of Wisconsin. The research by the Solar Environmental Engineering Company indicates that TRNSYS is the best general purpose hour-by-hour simulation code presently available which has reached a degree of national acceptance. It has been partly incorporated into the CAL-ERDA building simulation program, an effort sponsored by the Energy Research and Development Administration with the University of California at Berkeley as the project managers. TRNSYS offers a modular approach to solar heating system simulation, whereby each individual component in the system is represented by a computer program subroutine that can be combined with all of the other components to constitute a whole system. The programmer is given considerable freedom in prescribing the attributes of each component, as well as the order in which the components are connected and controlled during the simulation. The program is driven by solar insolation and weather data (e.g. the ambient temperature) provided by the user. The user may also prescribe the time interval between calculations so as to have some control over the accuracy and running time of the simulation. New components can be introduced fairly easily into the TRNSYS vocabulary because of its modularity, and modifications are simplified by the use of a standard Fortran programming language. The various versions of TRNSYS software are maintained and updated by an active group at the University of Wisconsin.

The use of TRNSYS to model Project Weathervane was carried out in several successively more complete steps in order to verify at each stage that the program was operating properly and that the results were realistic. This process was carried out first with the use of dummy data given for test cases in the TRNSYS documentation. The results allowed an immediate comparison between the Weathervane system and a worked example. Then actual data was used for the house and equipment parameters, keeping the sample case weather data the same. Finally, actual weather data was used in order to obtain the closest match available between simulated and actual performance data. Some fine tuning of the parameters was made at this stage to improve the match.

Several difficulties presented themselves immediately in trying to represent the Project Weathervane system with TRNSYS. The first difficulty involved the existence of only one set of inlet and exit pipes from the water energy storage tank to the load. Thus, in order to connect both the domestic hot water preheat circuit and the heat pump circuit to the storage tank, a "Tee" piece and a divertor piece had to be included in the inlet and exit pipes, where none exist in the Weathervane house. Second, the heat exchanger transfering heat from the collector to the storage tank utilizes natural convection to circulate the storage tank water past the coils. No natural convection heat exchanger exists in the current vocabulary of TRNSYS. This heat exchanger had to be modeled by the approximations used by DeWinter[11] in his article on heat exchanger effectiveness for solar heating systems by assuming an effectiveness of 0.45 for the solar collector. Third, the actual hourly hot water consumption load for the house was unknown; only the average total daily consumption was known. Hence, the typical load pattern suggested by the TRNSYS authors was used. Each of these approximations and assumptions may affect the accuracy of the computer simulation and each will be analyzed to the extent possible by selecting appropriate intervals of actual performance data for comparison.

There are several possible sources of inaccuracy which can affect the simulation results. These can be classified as ambiguities in the instructions for the use of TRNSYS, as approximations in the component models of TRNSYS, as limitations in the ways in which the components can be connected, as the choice of time step, error tolerances and other controls used in the running of TRNSYS, as input data and parameters and generally user-dependent errors in interpreting the results of the simulation. We have emphasized those areas which are user-independent.

The specific choice of parameters for each of the components used in the TRNSYS model for Project Weathervane are summarized in Table 2. Details for the calculations leading to these parameter values are given in Appendix A. It should be mentioned here that the thermal capacity, CAP, representing the house was computed for each of the floors, walls, ceilings, using ASHRAE values for the building material heat capacities and multiplying by the amount of each type of material in each part of the building envelope. The air in the rooms as well as that part of the exterior walls beyond the inner wall board was ignored in this calculation on the assumption that the former would contribute little, and that the latter was at some mean temperature lower than the room temperature and would not vary much. This is a very simplistic assumption compared to the heat conduction transfer functions used in more sophisticated building energy simulation programs such as CAL-ERDA, and it may be a reasonable source of inaccuracy in the simulation. Calculations in which this variable was increased or decreased were also carried out and will be discussed to note the sensitivity of the results.

TABLE 2

DESCRIPTION OF PHYSICAL CHARACTERISTICS OF PROJECT WEATHERVANE USED BY TRNSYS PROGRAM

Collector

Area: 36.2 m^2 (396 ft^2)
Efficiency Factor: 0.40 (includes storage tank heat exchanger)
Fluid Capacitance: 3.85 kj/kg °C (glycol-water mixture)
Collector Plate Absorptance: 0.95
Collector Loss Coefficient: 0.95
Transmittance of the Cover: 0.82
Orientation: South-facing, Slope 60° from horizontal

Pump

Flow Rate: 3 gallons/minute (738 kg/hr)
Operation: The pump is controlled by a Heliotrope differential temperature thermostat that turns the pump on when the temperature in the collectors is 27 °C or above and turns the pump off if a minimum temperature differential of 5 °C through the collectors is not reached within four minutes. If the maximum differential is not reached, the pump is restarted after four minutes and this cycle is repeated until the minimum temperature differential is reached. Once the temperature differential reaches 5 °C, the differential switch is reset to 1.7° to avoid short-cycling and the system continues to run.

House Load

Heat Loss: $U \cdot A = 450$ kj/C°· hr
Capacitance: $\Sigma M_i C_{pi} = 50{,}000$ kj/C° (summed over walls, ceilings, floors)

Thermostat

Direct Heating: $T_{Tank} > 35$ °C, $T_{room} < 20$ °C, $T_{AMB} < 21$ °C

Heat Pump: $T_{Tank} < 35$ °C, $T_{room} < 20$ °C, $T_{AMB} < 21$ °C

Auxiliary Tank Heating: $T_{Tank} < 13$ °C

Capacity: 18,514 kh/hr

See Notes A, B and C.

TABLE 2 (Continued)

Heat Pump

Type: Frederick "Climatronic" 27,000 Btu/hr capacity
Water to air heat pump (Model Number 27)

Flow Rate: 2 gal/min (1,780 kg/hr)

C_{Air} (m^*C_p product): 118,800 kj/C°

Storage Tank

Volume: 1,500 gallons (5.68 m^3)
Height: 4 ft. (1.22 m)
Fluid: Water
Loss Coefficient: 1.125 kj/hr·m^2 °C

Hot Water Heater

Daily Hot Water Demand: 276.3 kg
Volume of Preheat Tank: 0.151 m^3
Loss Coefficient: 1.51 kj / hr · m^2 ·°C
Tank Height-to-Diameter Ratio: 2.0
Delivery Temperature: 65.6 °C
Mass Flowrate Between Tank and Preheat Tank: 454.2 kg/hr
Effectiveness of heat exchanger: 0.9
Pump Operation: When T_{Tank} exceeds $T_{PREHEAT}$ by 5 °C or more

NOTES ON CONTROLS FOR TABLE 2

A. Immersion Heater

In the Seattle City Light House, the operation of the immersion heater is restricted to 11:00 P.M. to 6:00 A.M. except on very cold days. This restriction was not included in the simulation because weekly totals are obviously unaffected by this restriction. The only obvious effect is that the tank temperature is constant at 13 °C during cold days, whereas actual records show the temperature going down during the day and up at night. The actual thermostat was very variable, with immersion heating often being allowed when the tank temperature was as high as 15 °C. (See also Note C.)

B. Room Temperature

Page 3 of Mr. Yamagiwa's paper (see Reference 8) states that the daytime thermostat setting was 68° to 70°F (20.0° to 21.1 °C) with a night setback to 66 °F (18.9 °C). Specific hours for setback are not specified, however, and an examination of the record of actual room temperatures shows considerable variation, with some days when the room temperature hit 22°-23 °C. As a result the simulation assumed a constant thermostat at 20 °C (68 °F) which, it is hoped, is about equal to the average actual temperature inside throughout the heating season.

C. Immersion Heater Capacity

Page 7 of Mr. Yamagiwa's paper states "During periods of cold windy weather, when the solar system is unable to keep the water temperature in the storage tank above 55 °F (13 °C), heat is added to the tank by the electric immersion heater. Normally between 21 and 28 kilowatt hours (24 to 36 kwhr on very cold days) of heat is added to the tank per day on a timed cycle so that the electric immersion heater is only permitted to operate during nighttime off peak hours (11:00 P.M. through 6:00 A.M.)." Initially we took this to mean that the electrical demand of the heater when it is on is (36 kwhr/day/7 hours/day) = 36/7 kw = 5.14 kw = 18514 kj/hr. It later became apparent that the actual demand was 3 kw (= 10,800 kj/hr); this fact was realized too late to include it in the simulation. Since in the actual data the capacity of the auxiliary heater is never exceeded for as much as a day, however, the effect of this error should be small.

The heat loss rate for the house was computed from the actual house performance data by taking an average of the ratio of the total monthly heating load to the degree days for each month. This ratio varied considerably for each of the five months used to obtain the average, indicating that the occupants may have changed their living habits from month to month (e.g. see Appendix A, Type 12). Since no obvious changes in the internal heat load would have occurred during that period, we have assumed that infiltration losses and thermostat adjustments accounted for the variability. Certainly, the average value is less satisfactory than knowing the thermostat for each day and the amount of infiltration. However, measurements at that level of detail were not available.

Figure 8 shows the network of component connections forming the entire heating system model for TRNSYS simulations. Increasing detail can be added to this model by including relief values, hot and cold pipelines and additional controls. However, it was felt that the level of modeling used in Figure 8 was appropriate considering the fact that several approximating assumptions had already been made in rather important model areas, as noted in the paragraphs above.

Data for the heat pump was obtained from manufacturer's specifications, using flow rate measured and estimated by the Seattle City Light staff. Table 3 includes heating capacity phrased in the form of the data input file required for the heat pump module TRNSYS. The heat pump used was a water-to-air heat pump model number 27, Frederick's "Climatronic," a standard residential heat pump unit for such applications.[12]

The solar insolation on a horizontal surface and ambient temperature for the entire heating season has been extracted from the solar baseline data document. (Appendix B, Volume II). This data has obvious periods where data is missing. Hence the simulation periods were chosen to skirt those periods. The results of those calculations are shown in the following two sections.

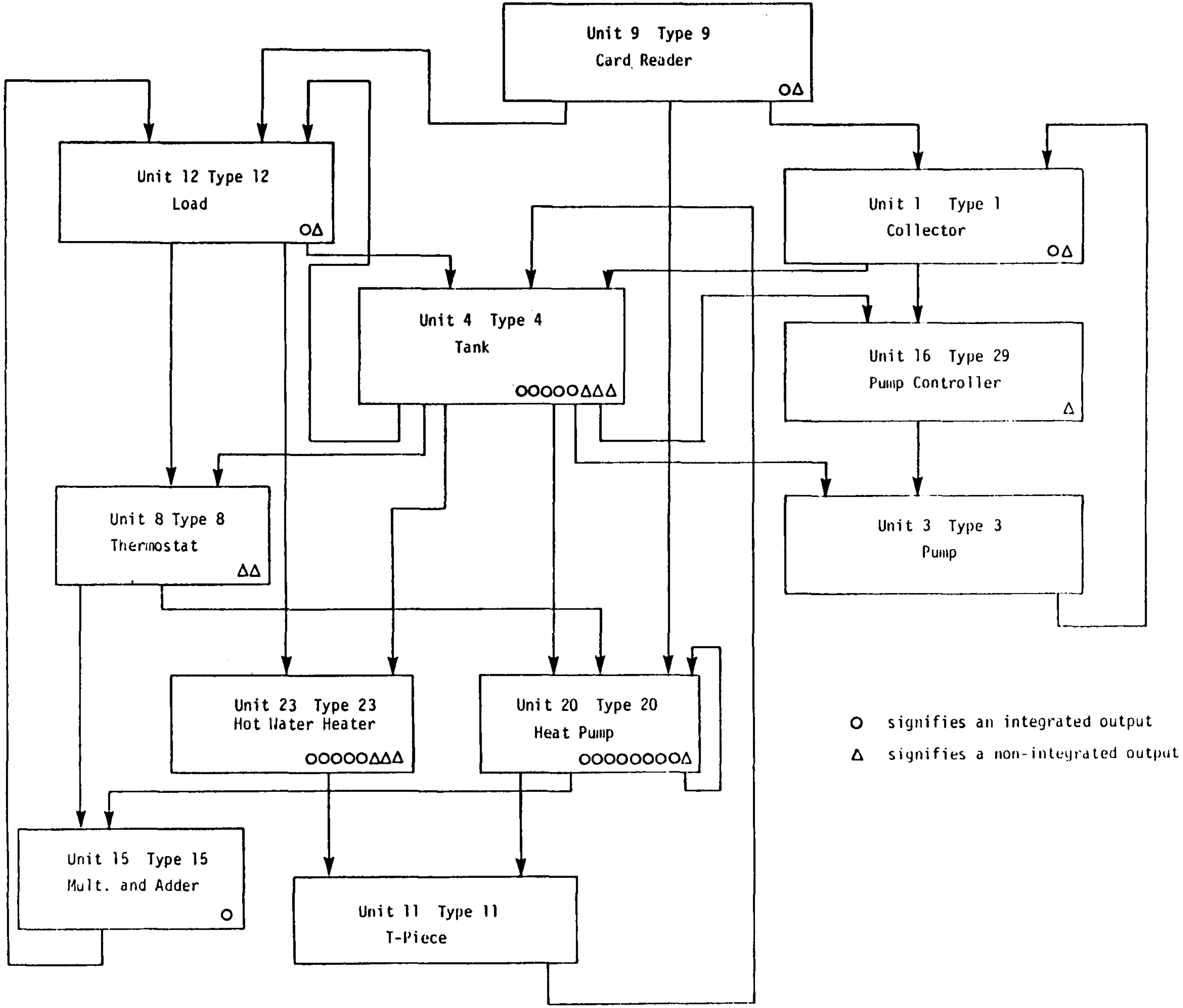


Figure 8. TRNSYS Network Modeling the Project Weathervane House

TABLE 3

PERFORMANCE DATA FOR TRNSYS HEAT PUMP (TYPE 20)

$T_{evap.\ in}$	Q_A	Q_R	W
15.56 (°C)	16,450 kJ/hr	27,944 kJ/hr	11,160 kJ/hr
18.33	17,926	29,631	11,484
21.11	19,824	32,373	12,060
23.89	21,511	34,692	12,672
26.67	23,199	37,118	13,320
29.44	24,780	39,543	13,968
32.22	26,362	41,968	14,652

$T_{evap.\ in}$: Temperature of the Storage Tank Water

Q_A : Rate of Heat Transfer from the Storage Tank

Q_R : Rate of Heat Transfer to the Air Duct

W : Heat Pump Compressor Power Input

Based on water-to-air heat pump Frederick's Climatronic Type 27 (27,000 Btu/hr)

Condensor Inlet Temperature = 20 °C

Condensor Air Duct Flow Rate = 850 cfm

Evaporator Water Flow Rate = 4 gal/min.

V. VALIDATION OF COMPUTER CODE

As indicated in the previous section, our analysis of the computer code validity rests primarily on the facility with which a given heating system can be modeled by TRNSYS, and the accuracy of the simulations. The ease of representing a given solar heating system depends on the variety and details of the components modeled within the computer program and on the clarity of the documentation describing how to use the program. The accuracy of the simulation will depend on the model chosen to represent the actual system and on the inherent numerical properties of the computational algorithms. We have selected several quantitative and qualitative measures by which to validate the TRNSYS program. These measures encompass the program and documentation dependencies just outlined and include specifically:

- A comparison of actual and modeled components which identifies specific areas of incongruity between the two and discusses possible consequences of these differences to simulated performance.
- A description of ambiguous documentation relating to the use of modeled components and controls.
- A qualitative and a quantitative comparison for short time periods of key simulation and actual performance variables such as the storage tank temperature and the amount of energy being supplied by the sun and by auxiliary power sources.
- A quantitative account of the energy inputs and outputs for each of the major components over the entire heating season.
- A qualitative comparison of the simulated and actual control systems to determine when various components are being turned on and off.

Areas of incongruity between actual and modeled components have been alluded to in Section IV. A more complete identification of modeled components is given in Table 4. The major incongruities consist of differences between the actual pump control for the collector described in Table 2 and the usual Type 2 TRNSYS control; the storage heat exchanger used and the lack of any corresponding element in TRNSYS; the lack of

TABLE 4

COMPARISON OF TRNSYS MODEL TO WEATHERVANE COMPONENTS

Components		Remarks on TRNSYS Model
Weathervane	TRNSYS (Type No.)	
Collector	1, Mode 1	Loss coefficients and transmittance estimated
Pump	3	
Pump Controls	29	MSNW model (replaces Type 2 TRNSYS model plus logic)
Heat Exchanger	--	No natural convection heat exchanger model (included in Type 1; see text)
Storage Tank	4	
Immersion Heater	--	Included in storage tank model (Type 4)
Heater Controls	15	Actual thermostat quite erratic--not feasible to model precisely
Storage Tank Connections	11	T-piece connection to storage tank (Type 15 controls)
Hot Water Heater	23	
Pump and Controls	--	Included in Type 23
Hot Water Load	--	Included in Type 23
Heat Pump	20	
Direct Heat	--	Included in heat pump model
Pump	--	Included in heat pump model
Two-Way Valve	--	Included in heat pump model
Valve Controls	--	Included in heat pump model
House Heating Load	12	
House Thermostat	8, 15	

multiple storage tank connections in TRNSYS (T-piece and divertor models had to be used); lack of data on hot water load (used the TRNSYS model load for Type 23).

These differences have potential for introducing error in the simulation. For example, the collector pump is modulated on a longer time scale (15-minute intervals) in the simulation than actually occurred. This would induce an on-off step which would not follow the temperature difference between the collector and storage tank very closely, leading to energy losses to the storage tank via the collector when the storage tank temperature exceeds the collector temperature during one iteration. Similarly, energy available to the collector in practice, might not be transferred to the storage tank during the simulation within a time interval where the collector pump was initially off. The net impact of these errors is to decrease the simulated amount of energy stored in the tank relative to actual performance. As we shall see, other errors may outweigh this effect.

The second error source concerns the lack of a suitable natural convection heat exchanger model in TRNSYS. By substituting a lower value of F', the solar energy collected under given weather conditions is reduced, so that the energy transferred to the storage tank is also decreased. However, there appears to be no physical basis for choosing an appropriate value for F'; natural convection should increase as the collector fluid temperature increases, thus making the heat transfer efficiency F' vary with temperature. A more detailed modeling effort would be required to obtain the correct averaged value of F' or to supplement TRNSYS with a better heat exchanger model.

The lack of multiple storage tank connections in TRNSYS, by contrast, appears to have no substantial impact on the physical behavior of the modeled system. It does add to the program length and possibly in a small amount to the running time to have to represent these connections with a divertor (or equivalent logic) and T-pieces

The deficit of data on hourly hot water usage was not considered critical over longer simulation intervals; that is, the actual energy consumed for hot water heating should average out to the values used as a fixed daily level of consumption for the simulation. However, in the short run (e.g. several hours,to a day in duration) variations in actual hot water usage could make a considerable difference in the storage tank temperature and thereby affect the operation of the house heating system as well. Daily values of hot water consumption were available but were not used in preference to the programming ease of using a fixed average daily value.

A series of documentation and program problems related to the Weathervane house application were encountered during the operation of TRNSYS. For example, in modeling the hot water components, the flow of water to the load was originally set as shown in Figure 9, where γ for the divertor was set at output 23.2/(output 23.2 + output 20.2 + 0.005) in order to send the hot water to the water heater if γ was 1. The parameter ICNTL on the water heater was set to 1. It seemed logical that this should work in an iterating type of program.

The first half of the problem was with the divertor. The initial flow was zero, so the initial output temperature was never set to the tank temperature, quoting the note on Page 4.11-2 of the TRNSYS manual "to avoid unnecessary calls to downstream components." The result was that the hot water heater never turned on, because the incoming water temperature appeared to be less than the preheat tank temperature. The heat pump also was prevented from turning on by a minimum source temperature of 12 °C (parameter T_{MIN1}).

The solution is fairly simple: Either a two-line change of the source program, or adjusting the data deck so that the HEAT PUMP and the WATER HEATER take input temperatures from the TANK instead of the DIVERTOR. It is our feeling, however, that this constitutes an error in the program rather than an error in its use. This error also exists in the other modes of the TYPE 11 component. A documentation addendum of February 20, 1978 explained that input modulation was unnecessary. Hence, the DIVERTOR was eliminated, with the HOT WATER HEATER input fixed at a constant equal to the value of the 9th parameter ($\dot{m}_C$), and the HEAT PUMP input flowrate set equal to its output flowrate. Simulating the effects of the intricate pump controller also required us to improvise a new approach. We eventually used a custom TYPE 29 controller, but only after several attempts at duplicating the effect of this controller with TYPE 15 units. During these attempts we discovered that the TRACE routine does not work for units that use their own last outputs as inputs. The second is that the statement on Page 4.15-4 "After all parameters have been processed, the value on the top of the stack becomes the last output," does not work if a -3 or -4 parameter has been included in the TYPE 15 routine. Clearly, these are not specific to the Weathervane case, but did constitute obstacles in the use of TRNSYS. The program version of the final TYPE 29 controller is shown in Figure 10.

Our overall opinion of the program is fairly high despite the problem just described. Far more serious problems were caused by the unpredictability of the actual equipment (the tank temperature thermostat varied erratically from 13°-15°, representing its accuracy!). These problems were much more of a hindrance to obtaining simulation data that matched the actual data than the programming problems just described.

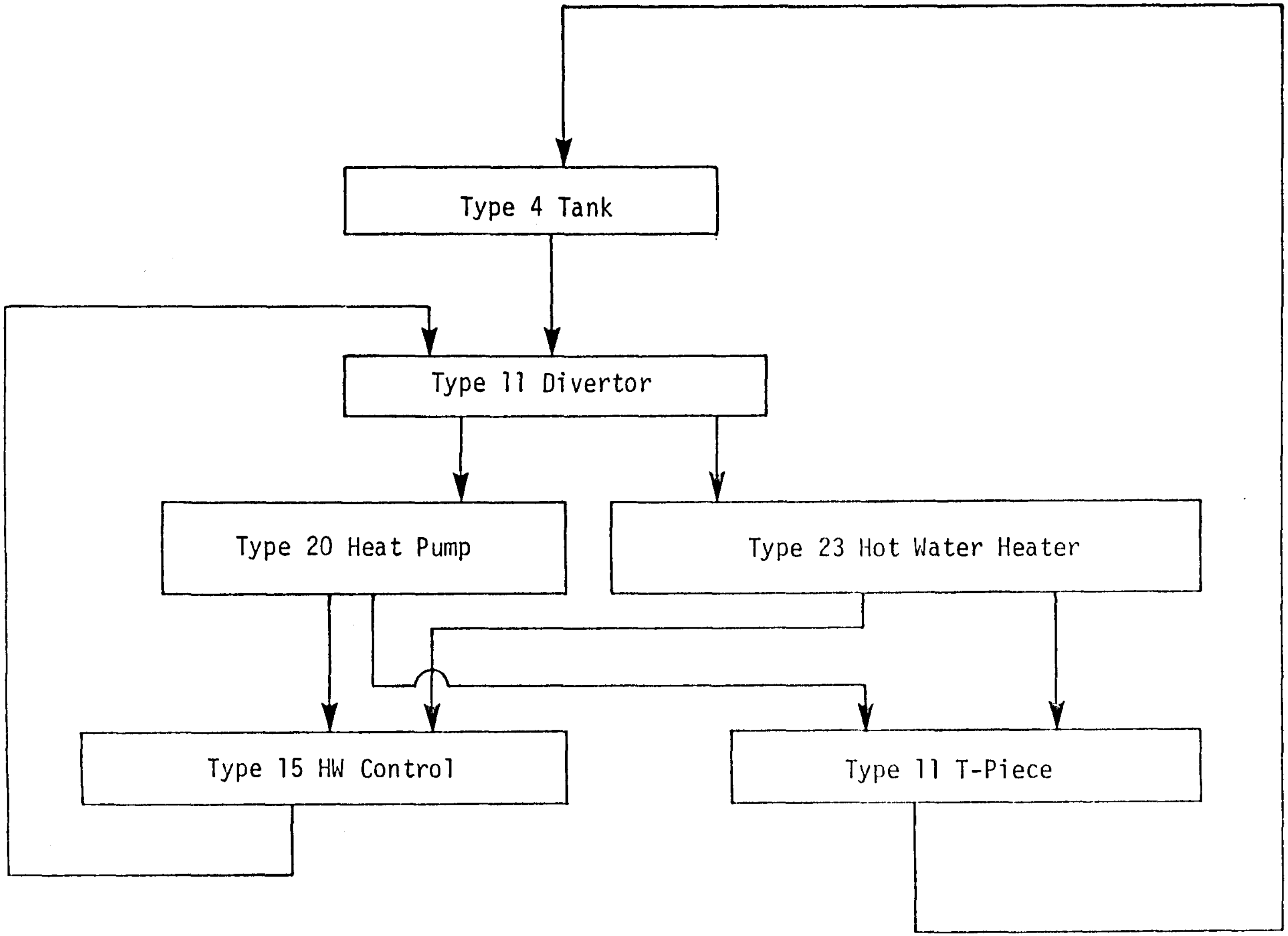


Figure 9. Divertor and T-Piece Flow Network

```
      SUBROUTINE TYPE29(TIME,XIN,OUT,T,DTDT,PAR,INFO)
C        SPECIAL PURPOSE CONTROLLER OUTPUT IS 0 OR 1
      DIMENSION XIN(3),PAR(5),OUT(1),INFO(9)
C
      IF (INFO(7).GE.0) GO TO 100
C        FIRST CALL OF SIMULATION
      INFO(6)=1
      INFO(9)=1
      LOCODE=1
      RTIME=TIME
      IF(PAR(2).LT.PAR(3)) CALL TYPECK(4,INFO,0,0,0)
      CALL TYPECK(1,INFO,3,5,0)
C        CHECK IF NEW COMPUTATION CALLED FOR
100   IF (INFO(7).GE.1) RETURN
      IF (TIME .LT. RTIME) RETURN
      T1=XIN(1)
      T2=XIN(2)
      DELTAT=T1-T2
      TCOL=XIN(3)
      TON=PAR(1)
      DTUP=PAR(2)
      DTLOW=PAR(3)
      DTIME1=PAR(4)
      DTIME2=PAR(5)
      IF (LOCODE.EQ.1) RTIME=TIME+DTIME1
      IF (LOCODE.EQ.2) RTIME=TIME+DTIME2
      NRMOUT=0
      IF(LOCODE.EQ.2) GO TO 300
C        THIS SEQUENCE FOR LOCODE EQUALS 1
      IF (TCOL.LT.TON) GO TO 500
      IF (DELTAT.LT.DTUP) GO TO 500
      NRMOUT=1
      LOCODE=2
      GO TO 500
300   LOCODE=1
C        THIS SEQUENCE FOR LOCODE EQUALS 2
      IF (DELTAT.GE.DTLOW) NRMOUT=1
      IF (DELTAT.GE.DTLOW) LOCODE=2
500   OUT(1)=FLOAT(NRMOUT)
      RETURN
      END
```

Figure 10. Specialized Pump Control
TYPE 29

In comparing simulation data to actual data, a strategy of successive approximation was employed. Calculated house parameters based on simple ASHRAE models of house heat capacity and wall/window U-values were used first, assuming that a designer who wished to evaluate a house would approach the use of TRNSYS in the same way. In the second step, the basic parameters were varied to achieve a better match in the agreement between real and simulated storage tank temperatures. These parameters were the collector efficiency F', the house heat capacity CAP, the room temperature thermostat setting, $T_{R,set}$, and the auxiliary immersion heater thermostat setting, $T_{A,set}$.

The impact of changing F' is shown in Figures 11 and 12 where the values of $F' = 0.6$ and 0.4 were used respectively. The lower value was chosen by noting that the simulated amount of energy transferred to the storage tank over the periods shown in Figure 11 exceeded the actual amount of energy recorded by nearly a factor of 1.5. An even closer fit was finally obtained when the custom TYPE 29 pump controller was used in the simulation. Similarly, we chose 20 °C as $T_{R,set}$ and 13 °C as $T_{A,set}$ to represent average values for the heating season despite rather random variations which occurred occasionally in the actual set point temperatures. The latter temperature adjustment allowed a reasonably good match between actual and simulated energy inputs due to the immersion heater. Despite the qualitative match for tank temperature and for the immersion heater contribution, the energy delivered to the tank by the solar collector and energy delivered to the house load from the tank still exceeded the actual energy throughput. By varying several other parameters, it became clear that a detailed energy balance matching the actual performance could be achieved within a reasonable number of trial and error guesses for the parameter values.

The equations governing energy balance are:

Heat Pump:

$$Q_R = Q_A + W_H \tag{1}$$

Useable Energy From Storage Tank:

$$Q_T = Q_A + Q_{DH} + Q_{HW} \tag{2}$$

House Heat Load:

$$Q_L = Q_R + Q_{DH} \tag{3}$$

Storage Tank Energy Balance:

$$\bar{Q} \leq Q_T + Q_E + \Delta E - Q_{IH} \tag{4}$$

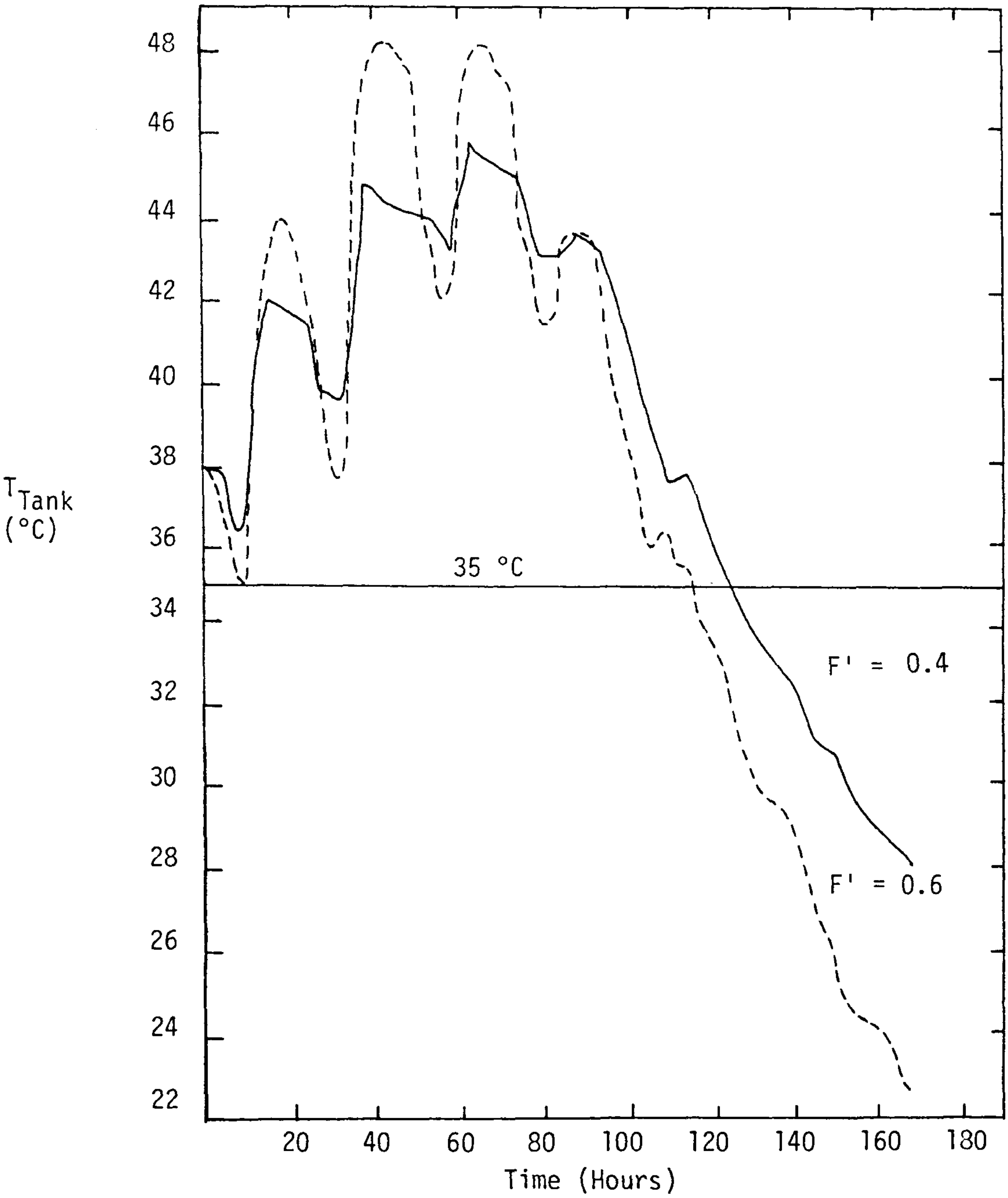


Figure 11. Comparison of Predicted Data for two Values of the Collector Efficiency Factor, F' (October 17-October 24, 1976).

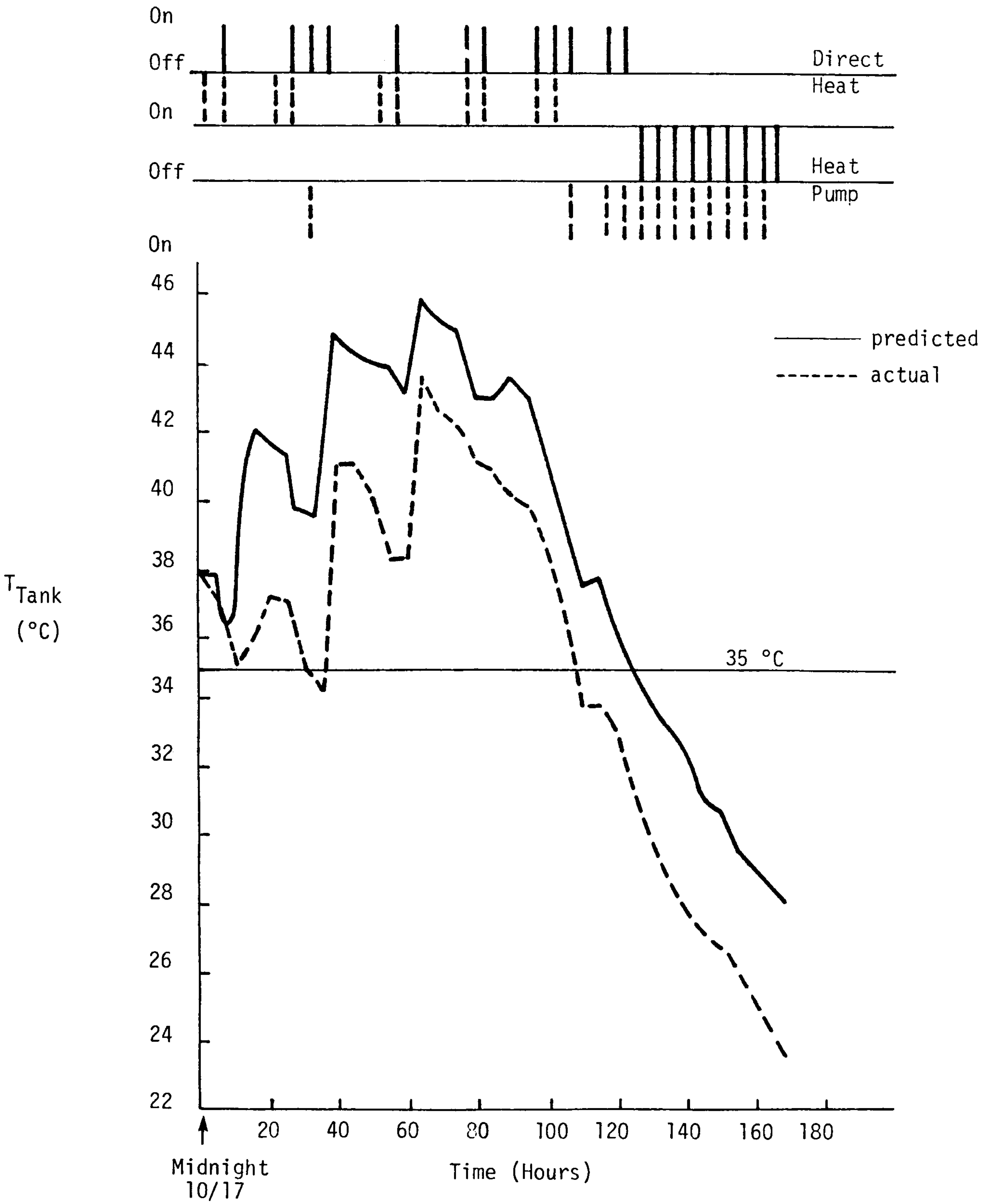


Figure 12. Comparison of Actual and Predicted Data for October 17-October 24, 1976

Where:

Q_R = Heat pump output to house load

Q_A = Heat input to heat pump

W_H = Work input to heat pump

Q_{HW} = Heat delivered to hot water load

$\overline{Q}$ = Total solar energy delivered to storage tank

Q_E = Heat lost to environment from storage tank

Q_T = Useable storage tank heat output

Q_{DH} = Direct heat delivered to house load

Q_L = Total heat delivered to house load

ΔE = Change in energy content of storage tank

Q_{IH} = Immersion heater input to storage tank

These quantities are accumulated over a period of time; ΔE measures the difference in energy from the beginning to the end of that period. The last relation is expressed as an inequality because the solar collector can also lose as well as gain heat for the storage tank. Generally, these losses are expected to be small due to the low value of F' chosen and to the mild ambient temperature conditions. No attempt was made to make an independent calculation of those losses. Note also that equation (3) ignores the change in heat stored in the air in the rooms as a small quantity. Quantitative comparison was developed for each of the major quantities in equations (1) to (4) for the entire heating season, excluding the period of 2/7/77 to 3/14/77 when no on-site weather data was available. Basic data for the fall and spring heating season, along with similar computations for selected weekly periods are shown in Table 5. Each individual variable in Table 5 has been compared to the actual value to obtain the percentage deviation shown in the third column of each entry. In many respects the closest quantitative match was achieved in the fall. That is, TOTQU (= $\overline{Q}$), QA1 (= Q_A), QR1 (=Q_R), QTANK (=Q_T) and QL (=Q_L) are relatively close to the actual values with the notable exception of QDH (= Q_{DH}) which was predicted to be more than twice the actual value. The absolute value of the error in QDH was only about ten percent of the total house heating load during the fall and therefore still tolerable in the context of the level of errors generally occurring during that period.

The evaluation of equations (1) through (4) is summarized in Table 6 for the two main seasonal periods shown in Table 5. Each of the first three energy balance equations is met within ± 2 percent for the simulation and even better accuracy is achieved for actual performance data. The fourth inequality is observed for simulation data, but not for the estimated actual data; the latter errors may be introduced by the use of predicted values for Q_E since no measured values were available. Furthermore, the agreement in absolute magnitude between corresponding terms in the actual

TABLE 5

CORRELATIONS

	Fall			Spring			10/17 - 10/23 Warm			11/26-12/2 Sunny-Cold			12/21-12/27 Cloudy-Cold		
Variable	Actual	Predicted	Percent	Actual	Predicted	Percent	Actual	Predicted	Percent	Actual	Predicted	Percent	Actual	Predicted	Percent
MFRL	$3.652.10^{5}$	$5.653.10^{5}$	+ 54.8	$3.979.10^{5}$	$7.077.10^{5}$	+ 77.9	$1.980.10^{4}$	$3.358.10^{4}$	+ 69.6	$1.946.10^{4}$	$2.989.10^{4}$	+ 53.6	$1.306.10^{3}$	$1.033.10^{4}$	+ 69.1
TOTQU	$9.804.10^{6}$	$1.044.10^{7}$	+ 6.5	$1.051.10^{7}$	$1.180.10^{7}$	+ 12.3	$5.185.10^{5}$	$6.803.10^{5}$	+ 31.2	$6.351.10^{5}$	$3.697.10^{4}$	+ 10.2	$5.646.10^{4}$	$5.646.10^{4}$	+ 52.7
HWQIN	$1.183.10^{6}$	$1.995.10^{6}$	+ 68.7	$9.962.10^{5}$	$2.695.10^{6}$	+170.5	$7.014.10^{4}$	$1.577.10^{5}$	+124.8	$4.265.10^{4}$	$1.940.10^{4}$	- 54.5	$3.223.10^{4}$	0	-
QDH	$8.918.10^{5}$	$2.865.10^{6}$	+221.3	$2.238.10^{6}$	$5.416.10^{6}$	+142.0	$2.947.10^{5}$	$5.972.10^{5}$	+102.6	0	0	0	0	0	0
MFRHP	$5.716.10^{5}$	$1.129.10^{6}$	+ 97.5	$1.725.10^{5}$	$2.948.10^{5}$	+ 70.9	$2.794.10^{4}$	$1.713.10^{4}$	- 63.1	$4.151.10^{4}$	$8.255.10^{4}$	+ 98.8	$4.702.10^{4}$	$8.010.10^{4}$	+ 70.3
QAI	$1.113.10^{7}$	$1.069.10^{7}$	- 4.0	$1.691.10^{6}$	$2.699.10^{6}$	+ 59.6	$2.054.10^{5}$	$1.439.10^{5}$	- 30.1	$9.535.10^{5}$	$8.949.10^{5}$	- 6.1	$9.475.10^{5}$	$7.402.10^{5}$	- 21.9
WAH	$9.418.10^{7}$	$7.046.10^{6}$	- 25.2	$1.584.10^{6}$	$1.654.10^{6}$	+ 4.4	$1.728.10^{5}$	$8.054.10^{4}$	- 53.4	$7.200.10^{5}$	$5.535.10^{5}$	- 23.1	$8.352.10^{5}$	$5.022.10^{5}$	- 39.9
TQAUX	$7.963.10^{6}$	$4.145.10^{6}$	- 48.0	$3.630.10^{5}$	$3.707.10^{5}$	+ 2.0	0	0	0	$6.372.10^{5}$	0	0	$9.576.10^{5}$	$5.952.10^{5}$	-37.8
TANKT	30.2	24.34		57.7	55.48		23.0	28.2		15.2	14.16		14.0	12.89	
QRI	$2.055.10^{7}$	$1.795.10^{7}$	- 12.6	$3.275.10^{6}$	$4.423.10^{6}$	+ 35.1	$3.787.10^{5}$	$2.294.10^{5}$	- 39.4	$1.674.10^{6}$	$1.467.10^{6}$	- 12.4	$1.783.10^{6}$	$1.257.10^{6}$	-29.5
QTANK	$1.320.10^{7}$	$1.555.10^{7}$	+ 17.8	$4.925.10^{6}$	$1.081.10^{7}$	+119.5	$5.707.10^{5}$	$8.996.10^{5}$	+ 57.6	$9.962.10^{5}$	$9.074.10^{5}$	- 8.7	$9.845.10^{5}$	$7.420.10^{6}$	-24.6
QL	$2.144.10^{7}$	$2.091.10^{7}$	- 2.5	$5.513.10^{6}$	$9.669.10^{6}$	+ 75.4	$6.734.10^{5}$	$8.378.10^{5}$	+ 24.4	$1.674.10^{6}$	$1.435.10^{6}$	- 14.3	$1.783.10^{6}$	$1.216.10^{6}$	-31.8
ΔE	$-5.902.10^{5}$	$-7.296.10^{5}$	+ 23.6	$1.047.10^{6}$	$9.944.10^{5}$	- 5.0	$-3.450.10^{5}$	$2.376.10^{5}$	- 31.2	$-1.261.10^{5}$	$-1.509.10^{5}$	+ 19.6	$-2.380.10^{4}$	$-5.021.10^{4}$	+111.0
QENV		$5.554.10^{5}$			$1.034.10^{6}$			$6.584.10^{4}$			$2.062.10^{3}$			$-2.453.10^{4}$	

and predicted values in Table 6 is quite good for the fall season, but systematically high for predicted values in the spring season. There is a direct explanation possible for the systematic errors: that is, the actual room thermostat may have been lower than 20 °C for most of the spring season--this would reduce Q_L and Q_T relative to the predicted values. Further, if the thermostat setback was carried out on days when direct heating predominated over heat pump use (i.e., the sunnier, warmer days) then Q_R actual would not be much less than Q_R predicted. Finally, in order to make $\overline{Q}$ nearly the same for actual and predicted cases, considerable difference in the hot water usage must exist between the two cases. This hypothesis is clearly borne out by the data in Table 5, as well as the room temperature data for the spring season (see Appendix B, Volume II for January 1, 1977 to June 30, 1977).

Also, as part of analyzing the performance of the Project Weathervane House, we developed an expression for the solar heating efficiency which extracts just that part of the solar energy used for heating the house from the data available. The expression for the solar heating efficiency is

$$\eta_{SH} = \frac{(Q_{DH} + Q_A)\ (Q_T + Q_E - Q_{IH})}{(Q_T + Q_E)\ Q_L} \qquad (5)$$

(its derivation is discussed in Section VI). The same expression was evaluated for both predicted and actual performance as yet another measure by which the computer program can be validated. The virtue of this particular comparison centers on the usefulness of the solar heating efficiency for predicting heating performance for a heating system design; it should be accurate in absolute terms in order for TRNSYS to be trusted in applications similar to the Project Weathervane. Values for expression (5) are also shown in the last line of Table 6. The difference between actual and predicted values of η_{SH} are large even for the fall season where most of the key variables are individually reasonably close to each other. Hence, η_{SH} acts as a sensitive and important indicator for comparing actual and predicted heating systems performance. The reason for the large divergence in the values shown in Table 6 can be traced principally to the differences between actual and predicted values of both Q_T and Q_{IH}. The Q_{IH} differences are especially large and may be traced in part to the tendency for the actual thermostat to turn on the heater when the T_{TANK} dropped below 15 °C (e.g. see Figure 13) instead of 13 °C. This would account for the substantially larger values of Q_{IH} for the actual data. Also, when the immersion heater was operated as an off-peak energy supply, apparently the thermostat could be superseded entirely, allowing the heater to be on even when tank temperatures exceeded the 13 °C to 15 °C thermostat cutoffs (for example, see 11/30/76 in Appendix B for this type of operation).

TABLE 6

EVALUATION OF ENERGY BALANCE EQUATIONS AND SOLAR HEATING EFFICIENCY

		Fall		Spring	
Equation Number	Variables	Actual	Predicted	Actual	Predicted
(1)	Q_R =	$2.06\text{x}10^7$	$1.80\text{x}10^7$	$3.28\text{x}10^6$	$4.42\text{x}10^6$
	$Q_A + W_H$ =	$2.05\text{x}10^7$	$1.77\text{x}10^7$	$3.27\text{x}10^6$	$4.35\text{x}10^6$
(2)	Q_T =	$1.32\text{x}10^7$	$1.56\text{x}10^7$	$4.93\text{x}10^6$	$1.08\text{x}10^7$
	$Q_A + Q_{DH} + Q_{HW}$	$1.32\text{x}10^7$	$1.56\text{x}10^7$	$4.93\text{x}10^6$	$1.08\text{x}10^7$
(3)	Q_L =	$2.14\text{x}10^7$	$2.09\text{x}10^7$	$5.51\text{x}10^6$	$9.67\text{x}10^6$
	$Q_R + Q_{DH}$	$2.14\text{x}10^7$	$2.08\text{x}10^7$	$5.51\text{x}10^6$	$9.84\text{x}10^6$
(4)	$\overline{Q}$ =	$9.80\text{x}10^6$	$1.04\text{x}10^7$	$1.05\text{x}10^7$	$1.18\text{x}10^7$
	$Q_T + Q_E + \Delta E - Q_{IH}$ =	$*5.20\text{x}10^6$	$1.12\text{x}10^7$	$*6.64\text{x}10^6$	$1.25\text{x}10^7$
(5)	η_{SH} =	23.6%	48.1%	66.9%	81.3%

*In calculating this value, Q_E predicted was used since no direct measure of storage tank energy losses to the environment was available. This estimate may contribute to the errors in evaluating Equation (4).

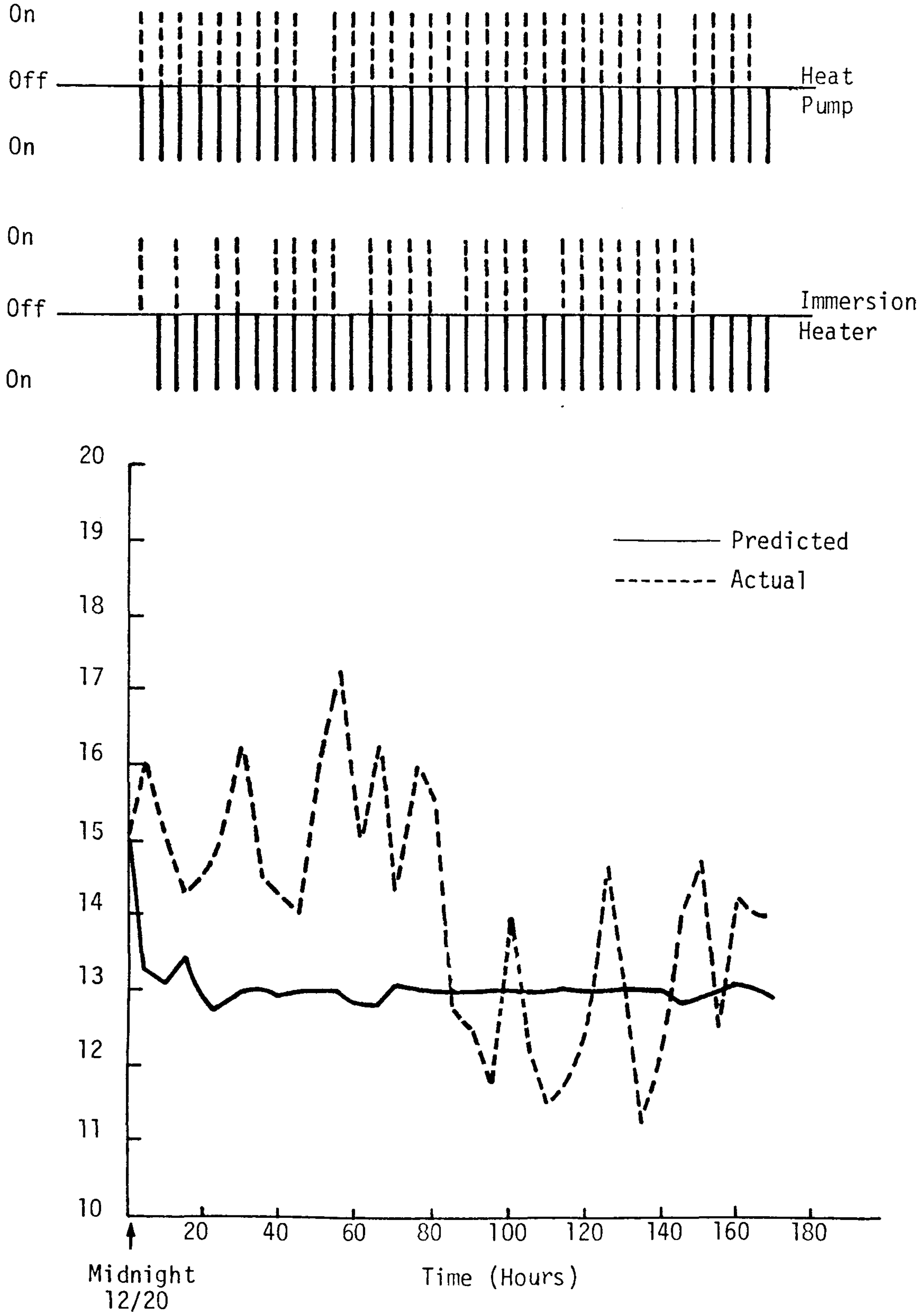


Figure 13. Comparison of Actual and Predicted Data for December 20-27, 1976

So far in this discussion we have attempted to find the course of error in the variations of actual performance, instead of seeking possible errors in TRNSYS. However, the analysis of η_{SH} for the spring season allows us to focus more on TRNSYS since here the error appears to lie in the difference between actual and predicted values of Q_{DH}, Q_A and W_H. More particularly, one would expect Q_A and W_H to be related in the same way for actual and predicted data, but that is not the case. In the actual data Q_A/W_H has the value of 1.07, whereas the value is 1.63 for the predicted data. Either TRNSYS is over-predicting the COP of the heat pump operation, or actual versus predicted heat pump operation occurs in entirely different temperature ranges. In the latter case, the actual operation would have had to occur at low tank temperatures compared to predicted operation. There is no simple way to distinguish these two possibilities without a lengthy hour-by-hour search for tank temperature versus heat pump operation. Within the constraints of the present research this was not possible, but could be pursued in a more detailed investigation. This leaves open the question of whether or not TRNSYS is operating properly. In the next few paragraphs where details of the component operation relative to the control system modeled for Project Weathervane are analyzed, we shall answer that question affirmatively.

A detailed survey of the operation of the heatpump and immersion heater was made every five hours for actual and predicted operation during the seven-day period starting on 12/20/76. The results are shown in Figure 13 where the dashed lines represent actual operation and solid lines are predicted operation. Note that the predicted heat pump operation mimics the actual operation very closely, but that the tank temperature is not followed very closely during this period. Evidently, the actual immersion heater thermostat has two states of operation during this period; one at 15 °C and one at 13 °C. Also, rather large fluctuations occur in actual T_{TANK} whereas the predicted values are very smooth. The peaks in actual T_{TANK} are roughly 24 hours apart suggesting that a night setback in the house thermostat is operating, where none was modeled. However, the peaks are not totally regular implying considerable difficulty in modeling the actual performance. Also, the dead band on the actual immersion heater thermostat may be larger than was initially thought, which would explain the large dips in actual T_{TANK} below 15 °C or 13 °C, depending on the time inverval. These dips can also be correlated in some cases with periods when the actual immersion heater was off.

Similar studies were made of the heat pump and direct heat operation and controls for the week of October 17-24, 1976, as shown in Figure 12. Again, correlation between actual and predicted use of these two heating modes is quite good.

In conclusion, we can state that the TRNSYS is a remarkably flexible tool for modeling solar heating systems and that it appears to be capable of representing the details of systems which are regionally adapted to the Pacific Northwest climatic conditions. Deviations between real and predicted performance for the heat pump and hot water heating system could be explained by simplifications introduced in modeling the heating system for TRNSYS and by erratic behavior in the actual system. The TRNSYS program is therefore a valid computational procedure for simulating solar house performance for this region.

VI. USES OF THE SIMULATION PROGRAM

While only one aspect of TRNSYS was investigated, namely the validity of using it to predict the performance of a Northwest solar heat pump system, a variety of other uses also appear possible. These uses can be classed as concentrating on the optimization of future solar heating system designs or on the testing and improvement of the performance of existing systems. In the latter case, as in Project Weathervane, TRNSYS finds its most accurate application since the computer parameters can first be adjusted to match the real data before investigating variations in the simulation which attempt to improve system performance by changing the system itself. Optimization of future systems may include both designer and operating strategies which lead to more efficient and more economical systems than presently exist for the Northwest climate. Solar heating systems can be optimized according to a number of different measures of performance. Such measures include energy efficiency for space heating or for hot water and space heating, lowest first cost, lowest life cycle cost, peak load capabilities and so on. These measures will find their use in choosing the appropriate system for a given application, in estimating future Northwest markets for solar heating system, and in helping to calibrate simpler programs such as F-chart and G-chart to this region.

The unique nature of the present study has been to correlate actual solar heating system performance with the hour-by-hour operation of TRNSYS for the Pacific Northwest. The results should lend a high degree of confidence in the use of TRNSYS for this region. With a more detailed modeling effort many of the built-in features of TRNSYS such as the hot water load can be corrected for the Pacific Northwest by using actual data for this region. At present, the user must exercise care by substituting actual efficiencies and operating characteristics, where possible, in the components and loads modeled by TRNSYS. Having done this, our studies show that good correlation between actual and predicted performance can be achieved from this simulation code.

The energy efficiency used in Section V is just one possible definition of efficiency. One must appreciate that alternate definitions do exist and have been used by other authors to judge the potential for solar energy in the Northwest. The numerical value obtained for each of these definitions of efficiency may vary considerably. Hence it is important to know the basis for the definition in order to understand its true meaning. In our definition, the solar efficiency or load factor is:

$$\eta_{SH} = \frac{\text{Fraction of house heating load supplied by solar energy}}{\text{Total house heating load}}$$

or

$$\eta_{SH} = \frac{Q_{solar}}{Q_L} \tag{6}$$

Now, $Q_{solar} = Q_L$ -(electrical contributions)

$$= Q_L - W_H - \alpha Q_{IH} \tag{7}$$

where α = fraction of immersion heater energy supplied to heat the house ($1 - \alpha$ heats hot water and/or is lost to the environment or stored in the tank).

Assuming that the total house load is met,

$$Q_L = Q_{th} + W_H \tag{8}$$

where Q_{th} = thermal power supplied to heat the house load. Note also that

$$Q_T = Q_{th} + Q_{HW} \tag{9}$$

representing the total useable thermal flux leaving the storage tank.

At this point we assume that the fraction α of immersion heater energy supplied to meet space heating loads is the same as the fraction of total thermal energy from the storage tank used to meet space heating loads. That is,

$$\alpha = \frac{Q_{th}}{Q_T} \tag{10}$$

This leads to the final definition of efficiency,

$$\eta_{SH} = \left(Q_L - W_H - \left(\frac{Q_L - W_H}{Q_T + Q_E}\right) Q_{IH}\right) Q_L^{-1} \tag{11}$$

where equations (6), (7), (8), and (10) have been used. Some algebraic manipulation is required to put η_{SH} in the form used in Section V. One might also define a solar efficiency for heating and hot water. That would be defined as,

$$\bar{\eta} = \left[Q_{HW} + Q_L - W_H - 1 - \frac{Q_E}{Q_T + Q_E} Q_{IH} \right] Q_L^{-1} \tag{12}$$

and would yield values different from η_{SH} (i.e., 55 percent instead of 48 percent for the fall season).

Generally, the forecasts of solar heating potential in the Pacific Northwest have been unattractive, not because of the capacity of such systems to heat the homes but because of the present low cost of electricity in this region. Furthermore, these forecasts have used a standardized solar heating system to compare the economic attractiveness of solar heating in the Northwest to other parts of the country. In most cases these standardized systems were designed for cold winter climates and are not the best configurations for the Northwest. In particular, they may require too many cover plates for the mild climate of this region, and may suffer reduced heat transfer because of the use of isolating heat exchangers in the storage tank. As a result the performance is not optimized for the region studied which in turn penalizes the economic forecast. The use of a program such as TRNSYS would allow an analysis of the optimal configuration for a regionally adapted solar heating system to be made.

The Northwest has become active in coordinating the activities of solar energy interest groups. The American section of the International Solar Energy Society now has a Northwest Chapter reaching the States of Washington, Oregon and Idaho. The western states regional Solar Energy Research Institute Office, called Western SUN, has also recently opened its offices in Portland, Oregon. These organizations, along with state and other federal agencies, will have a strong influence on the growth of solar energy use in the Northwest. Their ability to make use of validated computer programs such as TRNSYS is therefore critical in terms of obtaining accurate forecasts of the solar market potential in this region.

A number of different solar homes supported by individuals, local utilities, and in some cases, by federal funds, now exist in the Northwest. A partial listing of these residences is given in Table 7. As more data accumulates on the performance of these homes, programs such as TRNSYS can assist in the interpretation of that data to determine if the solar heating systems are working in the most cost-effective mode. Results from that analysis will lend further credibility to solar market assessments for this region.

TABLE 7

SELECTED SOLAR HEATING PROJECTS IN THE PACIFIC CASCADES REGION

Location	Solar System	Organization
Seattle, Washington	Project Weathervane: House and Hot Water Heating; Wind Power Generator for Electricity and Heat (Electric Auxiliary Heat)	Seattle City Light
Bellevue, Washington	Hot Water Heating and Hot Air House Heating (Gas Auxiliary Heat)	Washington Natural Gas Company
Portland, Oregon	Solar Heating, Hot Water and Cooling: Three Houses (Electric Auxiliary Heat)	Portland General Electric Company
Portland, Oregon	Solar Hot Water Heating: Five Houses (Electric Auxiliary Heat), TERA One; Solar House	Pacific Power & Light Company
Ashland, Oregon	Heating and Hot Water: One House	V. L. Oredson Company (Solar Demonstration Project, ERDA)

In summary, considerable interest in solar energy use exists in the Pacific Northwest. A marketing infrastructure is emerging which will help to coordinate public and private sector activities in the utilization of solar energy. Simulation programs such as TRNSYS will serve a vital need in assessing the economic potential of solar heating systems for this region and in the adaptation of such systems to the local climatic conditions.

VII. REFERENCES

1. W. A. Beckman, S. A. Klein, and J. A. Duffie, Solar Heating Design by the F-Chart Method (John Wiley and Sons, Inc.) 1977.

2. G. F. Lameiro, Solar Energy Research Institute, Golden, Colorado, private communication, 1978.

3. TRNSYS: A Transient Simulation Program, Report 38, prepared by the Solar Energy Laboratory, University of Wisconsin, Madison, Wisconsin, October 1977.

4. Solar Heating and Cooling of Buildings (Phase "0"), Volume II, Final Report, TRW Systems Group, California (Report No. NSF-RA-N-74-072B, May 1974, pp. 3.2-11 to -12).

5. Solar Energy for Pacific Northwest Residential Heating, An inter-agency report by the U.S. Department of Energy, Region X at Seattle and Richland, Washington, and the U.S. Environmental Protection Agency, Region X at Seattle, May 1978.

6. J. S. Reynolds, Solar Energy for Pacific Northwest Buildings, The Center for Environmental Research, University of Oregon, Eugene, Oregon 1974.

7. G. W. Hinman, "Use of Federally Owned Hydropower to Encourage Solar Energy Development" presented at The Energy Incentives Workshop, sponsored by Battelle Pacific Northwest Laboratories, 31 May-2 June 1978, Seattle, Washington.

8. A. Yamagiwa, "Experimental Evaluation of a Solar/Wind-Powered Space Heating and Hot Water Heating System in the Pacific Northwest," 12th Intersociety Energy Conversion Engineering Conference, 1977.

9. "Observations at 3-Hour Intervals" Monthly Summaries, Seattle-Tacoma Airport Weather Station, National Climatic Center, U.S. Department of Commerce, Federal Building, Asheville, North Carolina, 1976-1977.

10. CAL-ERDA Program Manual, Loads Subroutine CCM Page III.56 ff, Version 1.2, Argonne National Laboratory, Argonne, Illinois, October 1977.

11. F. DeWinter, "Heat Exchanger Penalties in Double-Loop Solar Water Heating Systems," Solar Energy 17, 335-337 (1975).

12. Vendor literature from Frederick's Corporation.

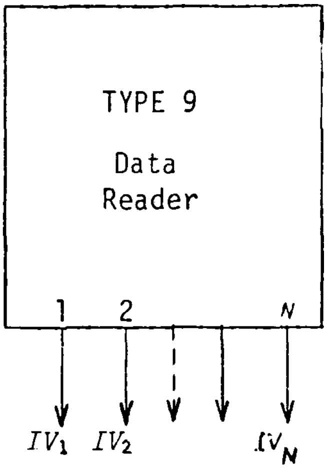
13. J. A. Duffie and W. A. Beckman, <u>Solar Energy Thermal Process</u>, (John Wiley and Sons, Inc.).

APPENDIX A: INPUT PARAMETERS FOR THE TRNSYS PROGRAM

Specific values are given below for each of the parameters for each of the TRNSYS subroutines used in simulating the Project Weathervane solar heating system. As explained in the text of the report, some of these parameters were varied arbitrarily from the values given below in order to obtain a better match between the house performance and the simulation results. The diagrams for each of the components have been reproduced directly from the TRNSYS manual to avoid any ambiguity in interpretation. The reader should refer to Figure 8 in the text of the report for the heating system configuration using the following components.

Card Reader Type 9

INPUTS - 0
OUTPUTS - up to 20
PARAMETERS - 2 or more
DERIVATIVES - 0

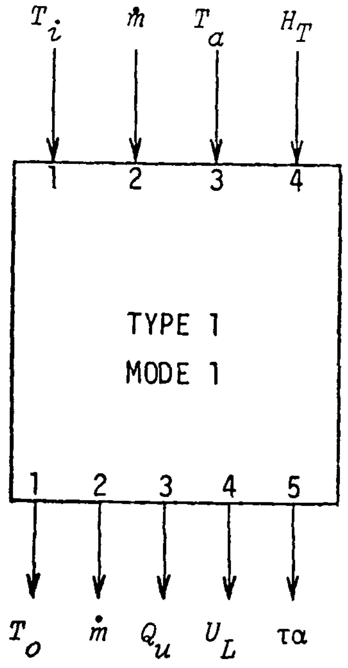


Eight Parameters

N = No. of input values = 6
Δt = Data intervals (hours) = 1
i = Output Number = 5 (Corresponds to Solar Radiation)
m_i = Multiplicative factor = 11.35
a_i = Additive factor = 0
i = Output Number = 6 (corresponds to Ambient Temperature)
m_i = Multiplicative factor = 0.5556
a_i = Additive factor = -17.78

Collector Type 1

INPUTS 4
OUTPUTS 5
PARAMETERS 7
DERIVATIVES 0

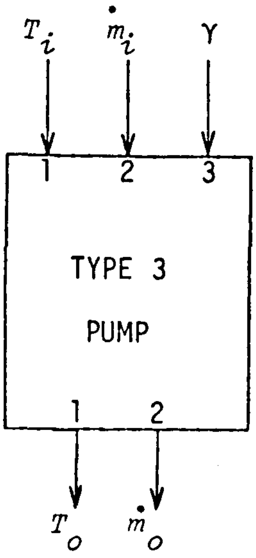


Seven Parameters

Mode No. = 1
A = Collector Area (396 ft^2) = 36.8 m^2
F' = Collector Efficiency Factor = 0.855
C_p = Fluid Heat Capacity (Water-Glycol Mix) = 3.85 kJ/kg°C
α = Collector Plate Absorptance (from Vendor Literature) = 0.95
U_L = Collector Loss Coefficient (from Duffie & Beckman, Ref. 13, pp. 133-136 assuming a mean ambient temperature of 4.4 °C, a mean plate temperature of 30 °C and a mean wind speed of 3.6 m/sec; See Figs.7.4.4a and b on p. 134 of Ref. 13). = 9.5 $kJ/hr \cdot m^2 \cdot °C$
τ = Cover Transmittance (Ref. 13 p. 112, Fig. 6.1.3, $\Theta_I \approx 50$ °C) = 0.82

Pump Type 3

INPUTS 3
OUTPUTS 2
PARAMETERS 1
DERIVATIVES 0



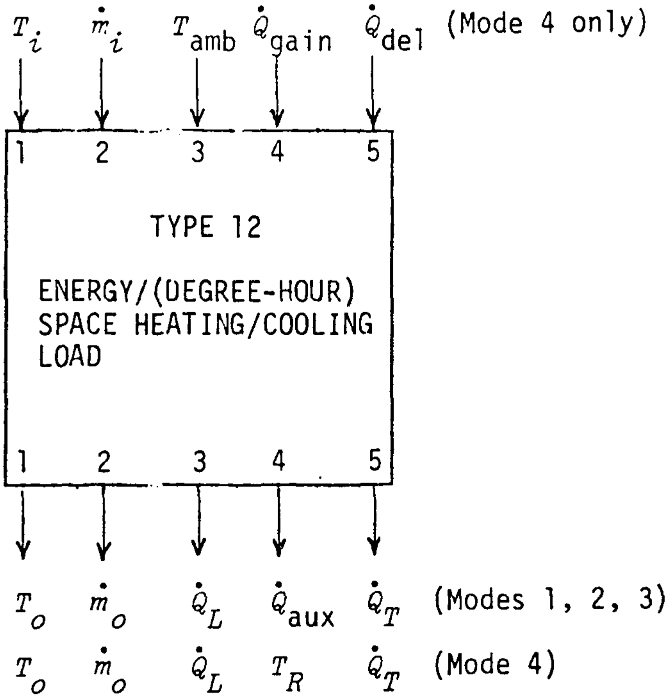
One Parameter

$\dot{m}_{max}$ = Maximum Flow Rate (3.25 gals/min) = 738 kg/hr.

(See text of report for explanation of pump controller.)

Load Type 12

INPUTS - 4 or 5
OUTPUTS - 5
PARAMETERS - 8
DERIVATIVES - 0 (Modes 1, 2 and 3)
1 (Mode 4)



Eight Parameters

Mode No. = 4
UA = Average Heating Load Characteristic = 778 $\left(\frac{\text{kJ}}{°\text{C}\cdot\text{hr}}\right)$
CAP = Load Capacitance = 50,000(kJ/°C)
$\dot{m}_C$ = Maximum Flow Through Load (= Code for Mode 4) = 0
C_p = Specific Heat of Flow Stream = 1.0 (kJ/kg•°C)
ε = Effectiveness of load heat exchanger (not operative Mode 4) = 1.0
C_{min}= Minimum Capacitance Rate of load heat exchanger (not operative in Mode 4) = 1.0
$\dot{Q}_{gen}$= Constant source of heat gain = 0

Computation of UA

$$UA = \text{average of } \frac{TSNL}{DD} = \frac{\text{Total Space Heating Load/month}}{\text{Degree Days/month}}$$

The average is taken from the months of March, April, November, December and January using data given in Reference 8, Figures 9 and 11. The individual values of UA for each of these months is 756, 612, 720, 936, 864, respectively (in kJ/°C•hr).

Computation of CAP

a. Areas

Exterior Wall Areas: frame $= 1{,}610 \text{ ft}^2 = 150 \text{ m}^2$
concrete $= 537 \text{ ft}^2 = 50 \text{ m}^2$

Interior Wall Areas: frame $= 896 \text{ ft}^2 = 83 \text{ m}^2$

Floors and Ceiling Area: frame $= 2{,}008 \text{ ft}^2 = 187 \text{ m}^2$
concrete $= 1{,}004 \text{ ft}^2 = 93 \text{ m}^2$

b. Unit Specific Heats

Exterior Walls: frame (1/2" gypsum wall, 4" airspace)
$C_{p1} = 12.2 \text{ kJ/m}^2 \text{ °K}$

concrete (4" concrete, 1/2" gypsum wall), $C_{p2} = 203 \text{ kJ/m}^2 \text{ °K}$

Interior Walls: $C_{p3} \approx 2\ C_{p1} \cong 24.5$

Floors: (1/8" linoleum, 5/8" plywood, 3/4" subfloor, 4" airspace)
$C_{p4} \cong 41.0 \text{ kJ/m}^2 \text{ °K}$

Ceiling: (same as floor; substitute 1/2" gypsum for linoleum) $C_{p5} \cong 48.2 \text{ kJ/m}^3 \text{ °K}$

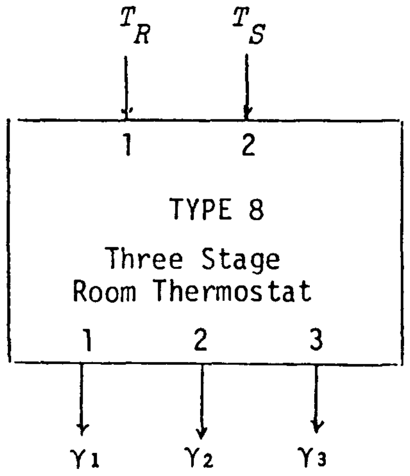
Floor Slab: (6" concrete), $C_{p6} = 286 \text{ kJ/m}^3 \text{ °K}$

Total Heat Capacity:

$$CAP = \sum_{i=1}^{6} M_i\, C_{pi} = 150 \times 12.2 + 50 \times 203 + 83 \times 24.5 + 187 \times 45 + 93 \times 286 = 49{,}027 \approx 50{,}000 \text{ kJ/°K}$$

Thermostat Type 8

INPUTS 2
OUTPUTS 3
PARAMETERS 6
DERIVATIVES 0

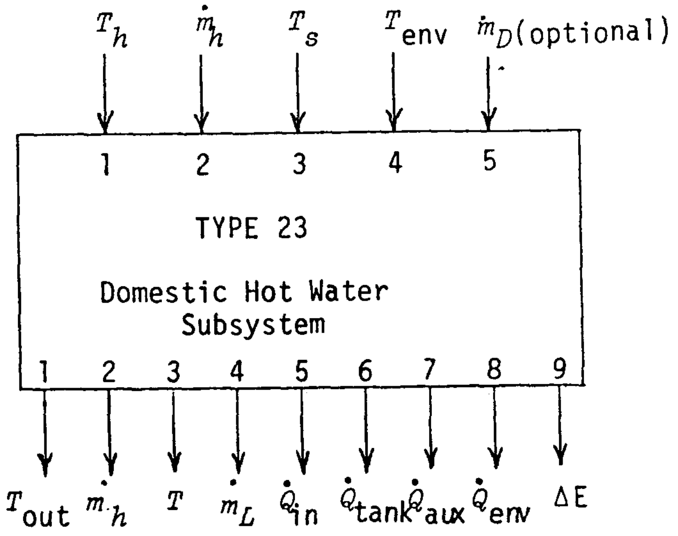


Six Parameters

ISTICK	=	Number of iterations per time step	=	3
ISTG	=	Code for combinations of heating	=	1
T_{min}	=	Minimum solar source temperature required in order to use solar heating	=	12 °C
T_c	=	Coded value to exclude cooling	=	1000 °C
T_{H1}	=	Set temperature below which first stage heating (e.g. heat pump or direct heating) occurs	=	20 °C
T_{H2}	=	Set temperature for second stage heating (not applicable)	=	18 °C

Hot Water Heater Type 23

INPUTS - 4 or 5
OUTPUTS - 9
PARAMETERS - 13
DERIVATIVES - 0

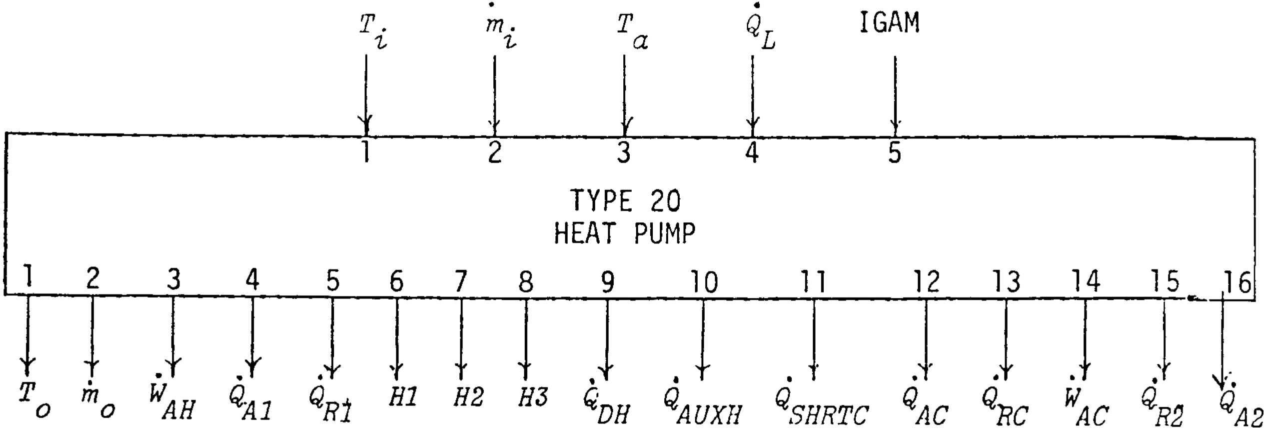


Thirteen Parameters

M_D = Total daily mass demand of hot water = 276.3 kg
V = Volume of preheat storage tank = .151 m^3
ρ = Density of water in preheat tank = 1 x 10^3 kg/m^3
C_{pc} = Specific heat of water in preheat tank = 4.19 kJ/kg °C
U = Loss coefficient of preheat tank to surroundings = 1.51 kJ/hr °C m^2
R = Preheat tank height-to-diameter ratio = 2.0
T_{req} = Minimum required hot water delivery temperature = 65.56 °C
C_{ph} = Specific heat of fluid from the heat source = 4.19 kJ/kg °C
$\dot{m}_c$ = Mass flow rate of water in cold side of heat exchanger = 454.2 kg/hr
ε = Effectiveness of optional heat exchanger = 0.9
ΔT = Minimum temperature difference by which heat source must exceed the preheat tank temperature in order to keep the pumps on = 5 °C
ICNTL = Specifies control of heat source flowstream = 1
T_0 = Initial temperature of the preheat tank = 38 °C

Heat Pump Type 20

INPUTS 5
OUTPUTS 16
PARAMETERS 18
DERIVATIVES 0



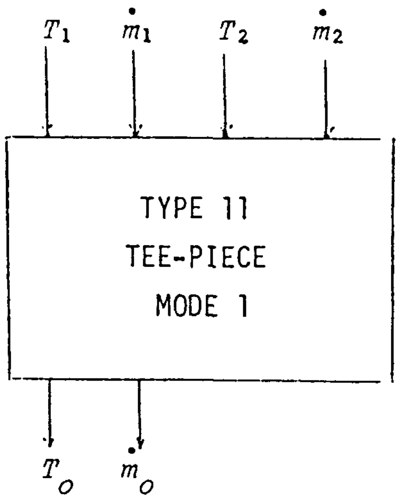
Eighteen Parameters

C_{p1} = Specific heat of heat source fluid = 4.19 kJ/kg °C
$\dot{m}_1$ = Mass flow rate of heat source fluid = 1,780 kg/hr
T_{roomH} = Constant room temperature for heating modes = 20 °C
T_{roomC} = Constant room temperature for cooling modes (not applicable) = 22 °C
T_{min1} = Minimum liquid source temperature for heating operation = 12 °C
T_{min2} = Minimum air source temperature for heating (not applicable) = 1000 °C
NDATAH1 = Number of heating data points for heat pump operation = 7
NDATAH2 = Number of equally spaced ambient source data points (not applicable) = 7
NDATAC = Number of equally spaced cooling data points = 5
LUH1 = Logical unit for solar heating data points = 7
LUH2 = Logical unit for ambient heating data points = 7
LUC = Logical unit for cooling data points = 7
T_{cool} = Minimum ambient temperature when cooling is allowed (not applicable) = 10 °C
C_{air} = $\dot{m} \cdot C_p$ product for room air flowing through heat exchangers = $1.118 \times 10^5 \frac{\text{kJ}}{\text{hr °C}}$
EFF = Heat exchanger effectiveness = 1

T_{set} = Minimum liquid source temperature for direct heating = 35 °C
I_{cool} = Cooling condensor selection (not applicable) = 0
T_{heat} = Maximum ambient air temperature when heating is allowed = 21 °C

T-Piece Type 11

INPUTS 4 (mode 1)
3 (mode 2)
5 (mode 3)
OUTPUTS 2 (modes 1&3)
4 (mode 2)
PARAMETERS 1
DERIVATIVES 0

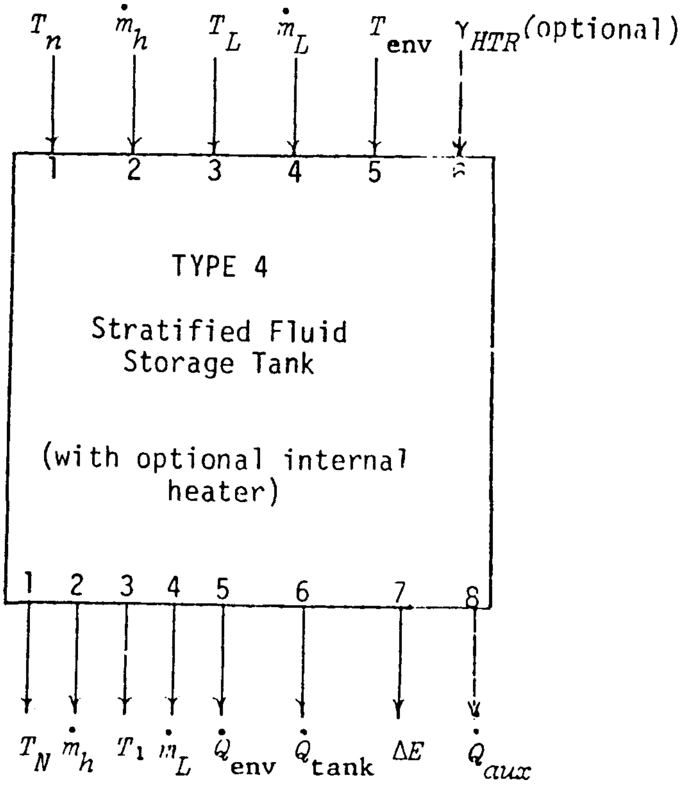


One Parameter

Mode Number = 1

Storage Tank Type 4

INPUTS 5 or 6
OUTPUTS 8
PARAMETERS 5 or 9
DERIVATIVES N



10/77

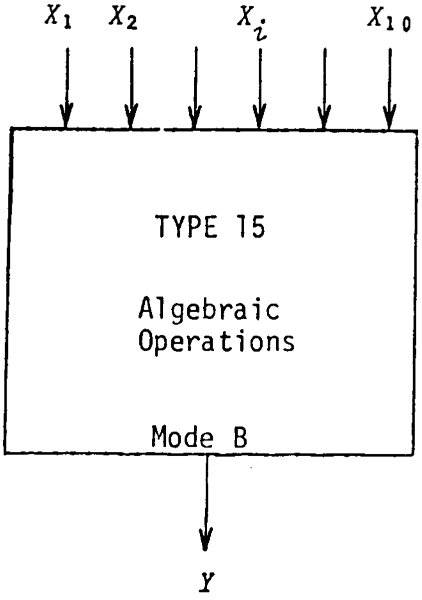
Nine Parameters

V = Tank volume = 5.68 m^3
H = Tank height = 1.22 m
C_{pf} = Specific heat of fluid = 4.19 kJ/kg °C
ρf = Fluid density = 1,000 kg/m^3
U = Loss coefficient between tank and environment (8" Vermiculite) = 1.125 kJ/hr °C m^2
$\dot{Q}_{HE}$ = Maximum immersion heater input = 18,514 $\frac{\text{kJ}}{\text{hr}}$
l = Number of tank segment containing the heater = 1
l_T = Number of tank segment containing the thermostat = 1
T_{set} = Set temperature of immersion heater thermostat = 13 °C

Adder Type 15

Mode B:

INPUTS - up to 10
OUTPUTS - up to 20
PARAMETERS - N_p
DERIVATIVES - 0



Five Parameters

(P_i determine sequence of input, adding and output operation)

$P_1 = 0$, $P_2 = 0$, $P_3 = 3$, $P_4 = 0$, $P_5 = 0$, $P_6 = 1$, $P_7 = -3$, $P_8 = 3$, $P_9 = -4$

producing $Y_1 = X_3 X_4$

$Y_2 = X_1 + X_2 + X_3 X_4$

S. GOVERNMENT PRINTING OFFICE: 1980-640-258-1964