SIMULATION OF THE DYNAMIC PERFORMANCE OF AIR-SOURCE, EARTH-SOURCE, AND SOLAR ASSISTED EARTH-SOURCE HEAT PUMP SYSTEMS

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NOMENCLATURE

a_o, a_1,...., a_6	- constants used in Equation (1)
A_c	- solar collector area, ft^2
A_n	- surface area of nth well increment, ft^2
b_o, b_1,...., b_4	- constants used in Equation (2)
b	- length of bond between collector and tubing, ft
c_o, c_1,..., c_7	- constants used in Equation (3)
C_b	- solar collector plate-tubing bond conductance, Btu/hr-ft-°F
CFC, CFHC	- blower CFM correction factors for heating capacity, Equations (1,6)
CFCHR, CFHE	- blower CFM correction factors for the heat rejection and extraction rates, Equations (8,6)
CFKW, CKW	- blower CFM correction factors for compressor power input, Equations (7,2)
CFM	- air volume flow rate, ft^3/min
C_p	- specific heat of ethylene-glycol solution, Btu/lb-°F
D_i	- inside diameter of solar collector tubing, ft
D_o	- outside diameter of solar collector tubing, ft
e_o, e_1,..., e_7	- constants used in Equation (5)
EWT	- temperature of water entering well-heat pump heat exchanger, °F
f_o, f_1,..., f_7	- constants used in Equation (6)
F	- configuration factor between solar collector and sky
F	- fin efficiency, Equation (22)

F'	- solar collector efficiency factor
F_R	- solar collector heat removal factor
G	- mass flow rate per unit of solar collector area, lb/hr-ft^2
GPM	- water volume flow rate through the well, gal/min
G_r	- grashof number
$h_o, h_1, \ldots, h_7$	- constants used in Equation (8)
h_c	- natural convection heat transfer coefficient, Btu/hr-ft^2-°F
$h_{f,i}$	- film coefficient inside solar collector tubing, Btu/hr-ft^2-°F
$h_{r_{p-s}}$	- radiation heat transfer coefficient between solar collector plate and sky, Btu/hr-ft^2-°R
$h_{r_{p-w}}$	- radiation heat transfer coefficient between solar collector plate and adjacent wall, Btu/hr-ft^2-°R
h_w	- forced convection heat transfer coefficient, Btu/hr-ft^2
I_t	- total solar radiation incident on the solar collector surface, Btu/hr-ft^2
$j_o, j_1, \ldots, j_7$	- constants used in Equation (9)
k	- thermal conductivity of air, Btu/hr-ft-°F
k_p	- thermal conductivity of solar collector plate, Btu/hr-ft-°F
L	- length of the solar collector, ft
L_t	- total length of solar collector tubing, ft
$\dot{m}$	- ethylene-glycol solution mass flow rate, lb/hr
M	- mass of water in the nth well depth increment, lb
n	- number of tubes in solar collector
PCS	- power input to compressor (cooling), Kw
PHS	- power input to compressor (heating), Kw

P_r - Prandtl number

Q_{cond} - conduction heat transfer through the soil, Btu/hr-ft^2-°F

Q_{conv} - convection heat transfer to the well surface, Btu/hr -ft^2-°F

QCS - heat pump steady state cooling capacity, Btu/hr

Q_{cy} - heat pump cyclic capacity, Btu/hr

Q_{enth} - heat flow due to enthalpy change in the fluid passing through the nth well depth increment, Btu/hr

QHES - heat pump heat extraction rate, Btu/hr

QHRS - heat pump heat rejection rate, Btu/hr

QHS - heat pump steady state heating capacity, Btu/hr

Q_{sol} - heat transfer rate between the solar loop and the well, Btu/hr

Q_{st} - heat storage rate in the nth well depth increment, Btu/hr

Q_u - useful heat gain in the solar collector, Btu/hr

R_{p-f} - heat transfer resistance between the collector plate and fluid, hr-ft^2-°F/Btu

t - time, hour

t_c - heat pump cycle time, hr

t_o - heat pump operating time, hr

T_{avg_n} - fluid mean average temperature in the nth well depth n increment, °F

T_{and} - ambient temperature , °F

$T_{f,i}$ - solar collector inlet temperature, °F

$T_{f,m}$ - mean average temperature of fluid in collector tubing, °F

T_{f_n} - inlet temperature to the nth fluid increment in the well, °F

$T_{f_{n+1}}$ - outlet temperature of the nth fluid increment in the well, °F

$T_{f,o}$ - solar collector outlet temperature, °F

T_g - soil far-field temperature, °F

$T_{p,m}$ - mean temperature of solar collector plate, °F

T_w - temperature of the wall adjacent to solar collector, °F

T_{w_n} - surface temperature for the nth well depth increment, °F

TDB - dry bulb temperature of the air entering indoor coil, °F

TFC - temperature correction factor for heating capacity, Equation (1)

TF_{hp} - water temperature exiting the heat pump heat exchanger, °F

TO - outdoor dry bulb temperature, °F

TWB - indoor wet bulb temperature, °F

U_b - back heat loss coefficient for the solar collector, Btu/hr-ft^2-°F

U_o - overall heat loss coefficient for the solar collector, Btu/hr-ft^2-°F

U_t - top heat loss coefficient for the solar collector, Btu/hr-ft^2-°F

WV - wind velocity, mile/hr

GREEK LETTER SYMBOLS

α - solar absorptance of collector plate

$\Delta\theta$ - timp step, hour

ΔZ - well depth increment

γ - average thickness of collector-tube bond, ft

ε_p - heat exchanger effectiveness

ε_w - solar collector plate emittance

ε - emittance of wall adjacent to solar collector

σ - Stefan-Boltzman constant = 0.1712×10^{-8} Btu/hr-ft^2-°R^4

τ - heat pump time constant, hour

CHAPTER I

INTRODUCTION

More than one-fourth of the energy consumed in the United Sates is used for residential and commercial space heating, cooling, and water heating (1)*. About 83% of the energy used for these services is supplied by oil and natural gas. Because of the foreseeable increases in energy demands, and because of the widely publicized energy shortage, more efficient heating/cooling equipment and alternative energy sources are needed as means for energy conservation.

The heat pump presents an energy-conscious concept in the HVAC field. This is due to, first, its ability to deliver more energy (in the form of heat) than it takes to operate it and, second, to its attractive feature of performing the dual functions of heating and cooling with the same equipment. Awareness of such advantages led many people to install the heat pump in their homes. A 1977 survey indicated that over one and a half million unitary heat pumps were in operation in the United States (2). Some researchers project over one quarter million units to be sold annually (3).

The most widely used heat pump today is the air-source heat pump. This is mainly because most of the experience on the heat pump design

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*Numbers in parantheses refer to cited references except for equation numbers.

and testing has been with this type, and because air is universally available as a heat source/sink. However, because the efficiency of this heat pump type is dependent on the ambient temperatures, some type of backup heat (usually electric resistance) is usually required to assist or carry the heating load during periods of low ambient temperatures. The heat pump coefficient of performance decreases as the outdoor ambient temperautres increases. The use of electric heat backup and inefficient heat pump operations present winter and/or summer load peaking problems for the utility companies. As a result, the utility companies are interested in more efficient heat pump systems that will help in "shaving" off the peak load demands (see for example reference 4).

Water is a very satisfactory heat source/sink for the heat pump provided there is a sufficient quantity available. When water is the heat source/sink it usually comes from wells, city mains, or nearby bodies of water (lakes or rivers). Water temperatures from such sources are usually within the temperature range for efficient year-round heat pump operation. However, obtaining water from these sources (when possible) is always associated with some concerns besides those of high cost. When using well water, some measures must often be provided to prevent scaling or corrosion in the heat exchanger. Also, some means of returning the water to the ground (usually by means of a return well adjacent to the supply well) may be needed to prevent the depletion of this source. If water from city mains is the source/sink, then some means must be provided to return the cooled or heated water to the mains. This is becuase water is becoming an increasingly expensive commodity in most societies; therefore, its once-through use will surely be objected to by many localities. The possibility of any trace of contamination to the returned water is another concern. Such difficulties with water sources tend to impair the energy conservation potential of the water source heat pump. However, many studies (5, 6, and 7) indicate that such a potential can be better realized through the concept of Heat Pump Centered Integrated Community Energy Systems (HP-ICES). This concept calls for interconnecting buildings within a HP-ICES community by a common hydronic loop that would exchange heat with the individual heat pump units in each building. A central plant maintains the water temperature in the loop within the desired range. Waste heat (when available) from any nearby industrial plant can be utilized in the loop. An interesting feature of the HP-ICES is that when simultaneous heating and cooling demands exist within the community, wasted heat from buildings requiring cooling can be transferred to those requiring heating via the hydronic loop.

One heat source/sink that has not been given adequate attention in the past is the earth itself. At a sufficient depth, the ground retains a relatively uniform temperature throughout the year. Collins (8) stated that at depths from 30 to 60 feet the seasonal variation in ground temperature is not more than 1°F; and, for the major part of the continental United States the ground temperature, at these depths, will be in excess of 60°F. These figures were later supported by data compiled and analyzed by Kusuda et al. (9). The uniform temperature and the ease of accessibility make the ground an ideal heat source/sink for the heat pump and shows promise in reducing, if not eliminating, the electric resistance heat backup associated with the use of air-source heat pumps. This would, in turn, help in alleviating the load-peaking problems the utilities are experiencing and/or anticipating.

There are many methods that can be used for the heat exchange between the heat pump and the ground. Kemler (10) presented schematics of several earth heat recovery systems for the heat pump and pointed out the advantages and disadvantages of each. The configuration that Kemler recommended as best, and recently gave successful experimental results reported by Bose et al. (11) is essentially identical to that shown in Figure 1. This configuration is coupled with two of the heat pump systems considered in this study.

Solar energy can be used effectively to further upgrade the performance of ground source heat pumps (11, 12). First, the system can be improved by adding back to the ground heat that was absorbed. Second, solar collectors coupled with ground source systems would operate at higher efficiencies because of reduced operating temperatures. And, third, the heat pump will operate more efficiently because of relatively high temperatures through the earth heat exchanger.

The above review of different heat pump types indicates that there still exists room for doubt as to which heat pump type would be superior from technical and economical points of view. Therefore, some work is needed to compare the economics of different heat pump systems and establish the impact of their performances on utility systems. This is the objective of a project supported by both the Oklahoma Gas and Electric Company (OG&E) and the Electric Power Research Institute (EPRI), of which this study is a part. The project involves comparing the performance of three different heat pump systems presently installed in three nearly identical houses in Perkins, Oklahoma. The three heat pump systems are a conventional air-source, a ground-source/sink, and a

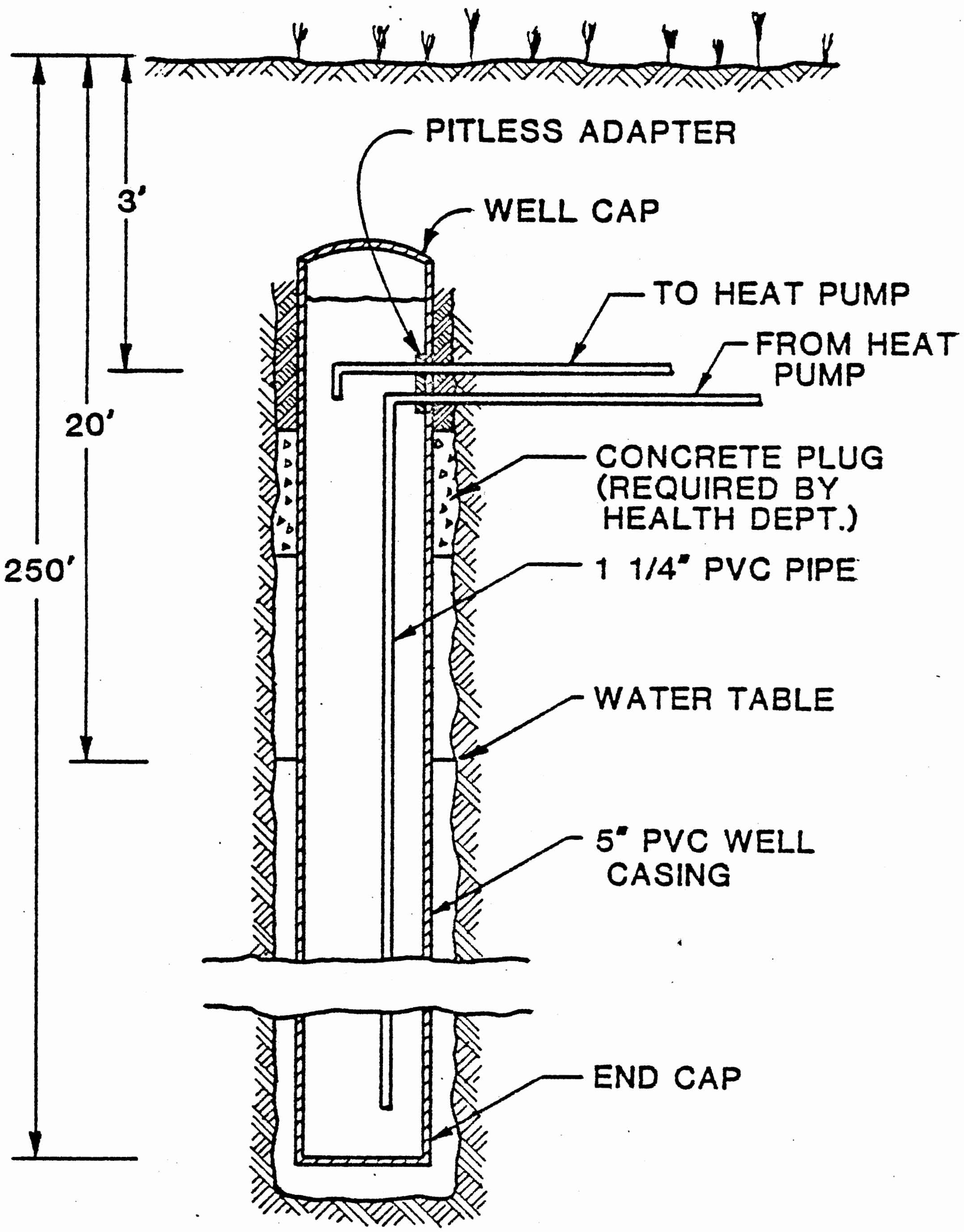


Figure 1. Schematic of the Vertical Water-Earth Heat Exchanger System (VEWEX)

solar assisted ground-source/sink. The performance of the three systems is to be measured in terms of:

1. Overall life-cycle cost,
2. Peak demand on the electric system,
3. Reliability and maintenance, and
4. Kilowatt-hour consumption by customer.

The main objective of this study was the construction and application of a computer program to simulate the dynamic performance of air-source/sink, ground-source/sink, and solar assisted-ground source/sink heat pump systems.

The simulation procedures and performances analyses are explained in detail in later chapters. It should be noted that the performance analyses in this study were based on energy perspectives only. No attempt was made to include economic analyses of the systems.

CHAPTER II

OBJECTIVE

The objective of this study was to construct and apply a computer program to simulate the dynamic performance of three different heat pump systems, and to perform comparative analyses of the performance of these systems in terms of electrical power consumption and system efficiency.

The heat pump systems are currently installed in three nearly identical houses located on adjacent lots in Perkins, Oklahoma. The three houses are facing north. The west house has been occupied by the owner since July, 1980, and the other two have been occupied since November, 1980. The east house is equipped with the air-to-air heat pump, the middle with the solar assisted ground-source/sink heat pump, and the west with the ground-source/sink heat pump. All the houses have been instrumented for direct measurement of heat pump performance data (see Chapter V for details) and a weather station has been located in one of the back yards. Table I shows the design data and loads for these houses. Table II shows number of occupants and appliances within each house.

System Simulation

A dynamic simulation model of the three heat pump systems was constructed and is described in detail in Chapter IV. The simulation model

TABLE I

DESIGN DATA AND LOADS FOR THE PERKINS HOUSES

Location	Perkins, Oklahoma
Latitude	36° 1' N
Longitude	97° 5' W
House Area (ft^2)	1200
Volume (ft^3)	9600
Ratio, window area to total area (%)	5
Number of Occupants (East)	4
Number of Occupants (Middle)	4
Number of Occupants (West)	2
Total number of degree days	3725
Design temperatures:	
Heating (°F)	0 Outdoors 76 Indoors
Cooling (°F)	100 Outdoors 74 Indoors
Heat Loss (Btu/hr)	18,860
Heat Gain (Btu/hr)	14,870
Insulation:	
Walls	R-19
Roof	R-34

TABLE II

SUMMARY OF RESIDENTS CONSUMPTION HABITS

	East	Middle	West
Number of Occupants			
During the Day	1	2	1
In the Evening	4	4	2
On the Weekend	4	4	2
Thermostat Setting*			
Day	72	72	68
Night	68	70	68
Appliances	washing machine dryer dishwater refrigerator TV (2) oven range freezer stereo	washing machine dryer dishwater refrigerator TV (2) oven range stereo small heater	washing machine dryer dishwater refrigerator TV (2) oven range freezer stereo
Loads of Laundry/Week	15	4	4
Water Temperature	warm	warm	warm, hot
Windows	double paned curtains	double paned curtains	double paned curtains
Lights Commonly Used	(1) 250W (2) 200W	(1) 250W (10) 60W	(3) 100W (1) Fluorescent

TABLE II (continued)

	East	Middle	West
Lights Commonly Used	(8) 60W (1) fluorescent		

*Heating season settings

was intended to predict the dynamic performance of each of the three systems as a function of the occupied space load and weather (air-to-air heat pump), the ground contribution (ground-source/sink heat pump), or the solar-ground contribution (solar assisted ground source/sink pump).

The simulation model was intended to be general enough to accept a wide range of parameters and, of course, be able to predict heat pump performance in both the heating and cooling modes. An essential part of the objective was that the simulation model be able to predict the cyclic (on/off) behavior of the heat pump since it resembles that realistic heat pump performance under conditions of house heating or cooling loads below that of the heat pump capacity. Simplicity was a major concern in building the model. It was desirable that the program user not be burdened with a great deal of input. Rather, the particular house and the simulation period should suffice as input. On the other hand, it was borne in mind that generality should be reserved as a mark of the program. Therefore, all constants, in the model, are presented by variable names and made flexible for the user to change as desired.

System Performance Analysis

The second part of the objective involves the investigation and comparative analysis of the performance of the three heat pump systems in response to varying environmental parameters. The comparative analysis of the performance of these systems was to be based on the following:

1. Number of compressor cycles,
2. Compressor on time,

3. Electrical power consumption, and

4. Coefficient of performance of the heat pump system.

In particular, the analyses were to shed a light on the advantages of the ground-source/sink heat pump over the air-to-air heat pump. Furthermore, it was necessary to determine the merits (if any) of including the solar loop in the ground heat pump system.

CHAPTER III

LITERATURE SURVEY

Inspection of the available literature indicates that a great amount of research has been devoted to the simulation and analysis of the performance of the air-to-air heat pump. This is due to the fact that the air source heat pump has been manufactured in large quantities and has been the most popular type for several years. Relatively little work has been done on the water or ground source heat pumps, with most work in this area classified as being in the initiation stages.

Hiller et al. (13) and Ellison et al. (14) used similar techniques to simulate the air-to-air heat pump. Their approach consists of tracing the refrigerant path in the heat pump cycle and hunting for the state point temperatures at the various stages in the cycle. The compressor, expansion device, indoor and outdoor heat exchangers were accounted for by a sophisticated and a rather lengthy procedure. Their simulation programs can only predict the steady - state performance of the heat pump. However, it is well known that under circumstances when the space load is lower than the heat pump capacity, the heat pump will cycle to satisfy the low demand.

Kelly et al. (14) presented results of tests conducted on an air-to-air heat pump in an effort to evaluate its cyclic performance and to determine what effect this cycling would have on the seasonal performance factor of the heat pump. The test consisted of measurements of the length of time the heat pump was on during a cycle period. The measured data were then used to establish a pattern on the part-load performance of the heat pump. The findings were then used to compute the cyclic coefficient of performance (COP) and seasonal performance factor (SPF). The conclusion presented therein indicated that the cyclic, or part-load heat pump operation COP and SPF values were lower than those obtained with steady state operation. The magnitude of the difference was inversely proportional to the ratio of the cyclic to steady state heat pump capacity.

Groff et al. (15) described a computer program, developed at the Carrier Corporation Research Center, for predicting the dynamic performance of air-source heat pumps. The simulation procedure consists of modeling the structure load, the heat pump steady state capacity, thermostatic controls, and the actual capacity of the heat pump. The actual heat pump capacity was modeled by a first-order differential equation of the form:

$$\frac{dQ}{dt} = \frac{1}{\tau} (Q_{ss} - Q)$$

where:

Q = actual capacity,

Q_{ss} = steady state capacity,

t = time,

τ = heat pump time constant.

The Carrier Computer program is very complex and requires a great deal of detailed input including characteristics of the heat pump and controls. The model was validated by use of data from a heat pump installed within a controlled environment. The results indicated that the model can predict the air-source heat pump performance with a very reasonable accuracy.

Murphy et al. (16) and Goldschmidt et al (17) presented field-test results and performance analysis of a 3 ton air conditioner and an air-to-air heat pump, respectively. Their objective was to establish values of the degradation coefficient for the units. In simple terms, the degradation coefficient is a measure of the decrease in the steady state heat pump capacity due to the transient effects of cycling. The researchers performed detailed mathematical analysis on the experimental results with the purpose of establishing general correlations by which predictions of heat pump "on" time are made possible. The resultant correlations indicate that the heat pump "on" time is dependent on the structure thermal capacity, thermostat dead band, and the steady-state capacity of the heat pump.

The literature contains many other reports on experimental and analytical results of the cyclic behavior of air source heat pumps (see for example references 18 to 21). To some extent, the experimental and analytical procedures employed in these references for the determination of heat pump performance are similar to those described above. Common to all these works is the conclusion that cycling can cause a substantial reduction in the heat pump rated capacity and thus seasonal performance. The recommendation shared by some is that the rated capacity of heat pumps should be represented in terms of cyclic rather than steady state performance.

In the area of water source/sink heat pump systems, Lawrence (22) performed a parametric study on different techniques for reducing the operation costs of heat pumps in colder climates. The study included the use of solar energy and underground water. He used a very simplistic procedure to model a solar source heat pump with a closed loop that contained unglazed collectors, and thermal storage on the evaporator side. The heat pump model was obtained from a normalized empirical curve fit of an analytical model which assumes a constant condensing temperature. Lawrence concluded that solar energy can provide a heat pump source of marginal economic feasibility but does not compare favorably with deep well water (when available).

Freeman (23) prepared a generalized digital computer model for a residential size heat pump. His modeling strategy is to "design" or "size" the four major components of the vapor compression cycle to yield any desired condition performance. Once the system has been defined, the program computes an off-design "performance map" of heat added and heat rejected at all possible combinations of inlet flow-stream conditions. The model was then incorporated with the modular simulation program, TRNSYS (24) to simulate the performance of an "in-line" and a "parallel" solar-heat pump heating and cooling systems. Freeman compared the two systems and concluded that the "in-line" system performed with slightly better efficiency than the "parallel" one, while economically the latter was slightly less costly than the first system.

Search of the literature revealed that very little work has been devoted to the simulation of solar-assisted ground source/sink heat pumps. Andrews and Metz (12) have done a study on the utilization of ground as a heat source/storage. They prepared a computer simulation program of a groundcoupled heat pump connected, in series, to a solar load. Their work concentrated on the modeling of the earth coil. The space load, equipment and solar collectors were modeled through the use of TRNSYS (24).

Tank and pipe grid configurations were considered for the ground coil model. The computer model solves the heat flow finite difference equations over a system of "blocks" of earth. Each block can have a distinct shape, size and thermal properties specified by the user. Two types of blocks are used: "Rigged Blocks" that provide the necessary boundary conditions and "Free Blocks" for which the temperatures are solved.

In modeling the pipe grid, the pipe plane was assumed as a thin sheet of water flowing in the plane of the pipe field. The heat transfer area of the water sheet is that of the pipe array reduced by a factor that is dependent on the pipe and block dimensions and the distance between adjacent pipes.

Schlosser and Teisler (25) have written a computer simulation model to simulate the performance of solar-assisted heat pump systems using the ground for energy storage. The earth collector consisted of a buried pipe grid. The pipe grid was modeled in both the vertical and horizontal directions. Heat exchanger effectiveness was used to model the ground-heat pump heat exchanger, of which the effectiveness was assumed to vary according to the flow rate of the heat transporting fluid. The operation of the compressor was described with a polynomial regression at the two temperature levels. The solar collectors were modeled through the use of equations and empirical relations found in Duffie and Beckman (26). As for the earth collector, the transient temperature field in the soil was found by a finite element solution of one-dimensional heat equation. The spatial elements of integration are triangles with six nodes per element. In the simulation, 400 nodes were used and a time step of three days was found appropriate.

Bose et al. (11) studied the actual performance of a solar-assisted heat pump using geothermal source/storage. The findings describe the geothermal well as an excellent source/storage system for the heat pump. The inclusion of the solar energy system in the ground coupled heat pump showed some improvement in the heat pump performance.

Wise (34) addressed the problem of conduction heat transfer, caused by step function heat input from the heat pump, in the vertical earth-water heat exchanger system (VEWEX) shown in Figure 1. By using a Fourier series representation of step function heat input and adapting Bessel functions, Wise introduced an analytical solution to the temperature distribution and heat transfer in the soil surrounding a VEWEX system. However, his solution is only valid for ON-OFF step function heat input of heat pump cycle times greater than 10 hours. In real situations, however, the cycle times of heat pump operations are less than 30 minutes.

Kanchanalai (35) analyzed the same problem of Wise (34) using numerical solutions. Finite difference solutions were used to solve the one-dimensional heat conduction equation for the temperature distribution and heat transfer in the soil surrounding a ground well. Kanchanalai compared results from these solutions with those from the exact solutions of Carslaw and Jaeger (36) and obtained excellent agreement.

The numerical solutions used Kanchanalai (35) proved to be valid for long and short heat pump cycles. After some modifications (see Chapter VI for details) these solutions are used in this study to solve for the heat transfer rates and temperature profiles in the VEWEX heat exchanger of the ground source/sink and the solar assisted ground-source

/sink heat pump systems.

The determination of the transient heating and cooling demands of buildings is an essential part of predicting the behavior of heat pump systems. CHLSYM (30) is a computer simulation program developed in the school of Mechanical and Aerospace Engineering Department at Oklahoma State University to predict the transient heating and cooling demands of residential and commercial buildings. The program uses the transfer function method outlined in the 1972 ASHRAE Handbook of Fundamentals (31) to compute the transient heat transfer through the building exterior structure and the heating and cooling demands. Solar input and internal heat generation due to people, lights, and appliances are accounted for in the load calculations. The program is equipped with a routine for the computation of the indoor air temperature and heat extraction or addition rates as a function of equipment capacity and schedule of operation.

After slight modifications, to suit the requirements of the heat pump simulation program (see Chapter VI for details), CHLSYM has been used in this study to predict the heating and cooling loads and interior temperatures in the Perkins Houses.

CHAPTER IV

DESCRIPTION OF THE HEAT PUMP SYSTEMS

The systems described in this chapter are the air-to-air, the ground-source/sink, and the solar assisted ground-source/sink heat pump systems, briefly mentioned in Chapter II. Most of the information pertaining to the heat pump units were obtained from manufacturer's catalogs (27, 28).

The Air-to-Air Heat Pump System

The heat pump is a Carrier Model 38CQ015/40A018 of the split system type, with a rated cooling capacity of 15,500 Btu/hr and a heating capacity of 16,500 Btu/hr. The outdoor section contains the compressor, fan coil, and defrost mechanism. The defrost cycle is activated when the outdoor temperature is below 45°F and the coil saturated suction temperature indicates freezing. The maximum defrost time is 10 minutes within each 90-minute period. The indoor section contains a direct expansion fan coil unit supplied with a 3-kw electric heater for emergency heat (common to the three heat pumps). Physical data, dimensions, and performance data for the heat pump systems are presented in Appendix A.

The indoor thermostat (common to the three heat pump systems) is a Carrier model that uses mercury in glass for electrical switching (27). The thermostat provides two-stage heating and one-stage cooling controls.

The set point for energizing the second stage heat is set manually. Changeover of the heat pump mode of operation from heating to cooling, or vice versa, can be accomplished manually by setting a desired temperature differential. The thermostat is provided with two levers that can be parted to set this differential. The minimum value for the changeover temperature differential is 3°F. Information regarding the thermostat dead band temperature range and anticipator characteristics were not available.

The Ground Source/Sink Heat Pump System

This is a water-to-air heat pump model SWP-150 manufactured by Command-Aire Corporation. The unit is a single-package such that the compressor, coils, and blower are all housed in a single cabinet. The rated cooling capacity is 19,500 Btu/hr and the rated heating capacity is 28,000 Btu/hr. The water-refrigerant heat exchanger is connected to the VEWEX exchanger (as shown in Figure 2) for heat extraction or rejection.

Unprepared earth was drilled to contain the VEWEX system shown in Figure 1. A 5-inch Polyvinyl Chloride (PVC) casing was fitted in the 250-foot deep hole. The casing is capped, at both the top and bottom, and contains water as the heat transporting fluid. Two 1-1/4" PVC pipes are used to circulate the exchange fluid through the water-refrigerant heat exchanger. This type of earth heat exchange system has two major advantages over other types (10). First, it reduces to a minimum, if not eliminates, scale deposit in the heat exchanger. Scale deposit can be very detrimental to the heat exchanger from effectiveness and corrosion points of view. Second, pumping power required to circu-

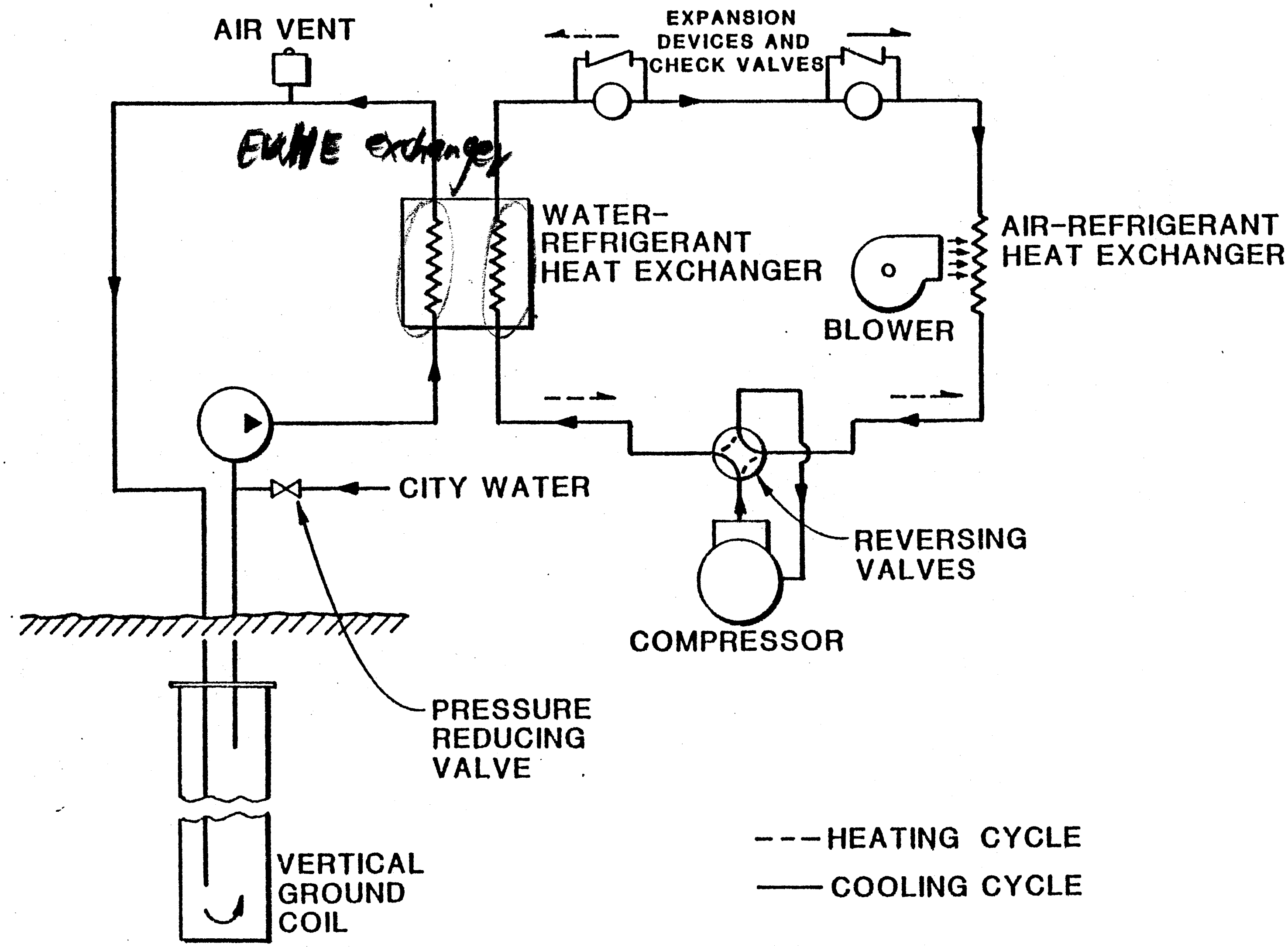


FIGURE 1-4 Schematic of the Ground-Source/Sink Heat Pump System.

late the water is reduced to that necessary only to overcome friction in the system.

The Solar-Assisted Ground Source/Sink Heat Pump System

Figure 3 shows a schematic of this heat pump system arrangement. The heat pump unit and earth-water heat exchanger are the same as those described for the previous system. The additional item in this system is the solar energy loop which is used to assist the heat pump during both the heating and cooling seasons.

The solar loop consists of the solar panels, the heat exchanger, the circulation pump, and the accumulator. The collection area consists of five bare steel plates (4' x 7') with 1/2" copper tubing spaced 4 inches center-to-center. The panels have nonselective black coating. The solar system is of the closed loop type and uses a 50% ethylene-glycol solution as the heat transfer fluid. Heat is exchanged with the VEWEX-heat pump system through the glycol-water heat exchanger. The exchanger is a TACO model B4414W 4-pass shell and tube with a total heat transfer area of 16.4 ft^2.

During the heating seasons, the collected solar heat will be transferred to VEWEX exchanger in order to assist in the energy supply to the heat pump. However, during the cooling season, the heat pump rejects heat to the VEWEX exchanger. Under suitable weather condition, the solar system will dissipate some of this heat to the ambient. This, in turn, will mean lower return fluid temperatures to the heat pump and thus more efficient heat pump operation.

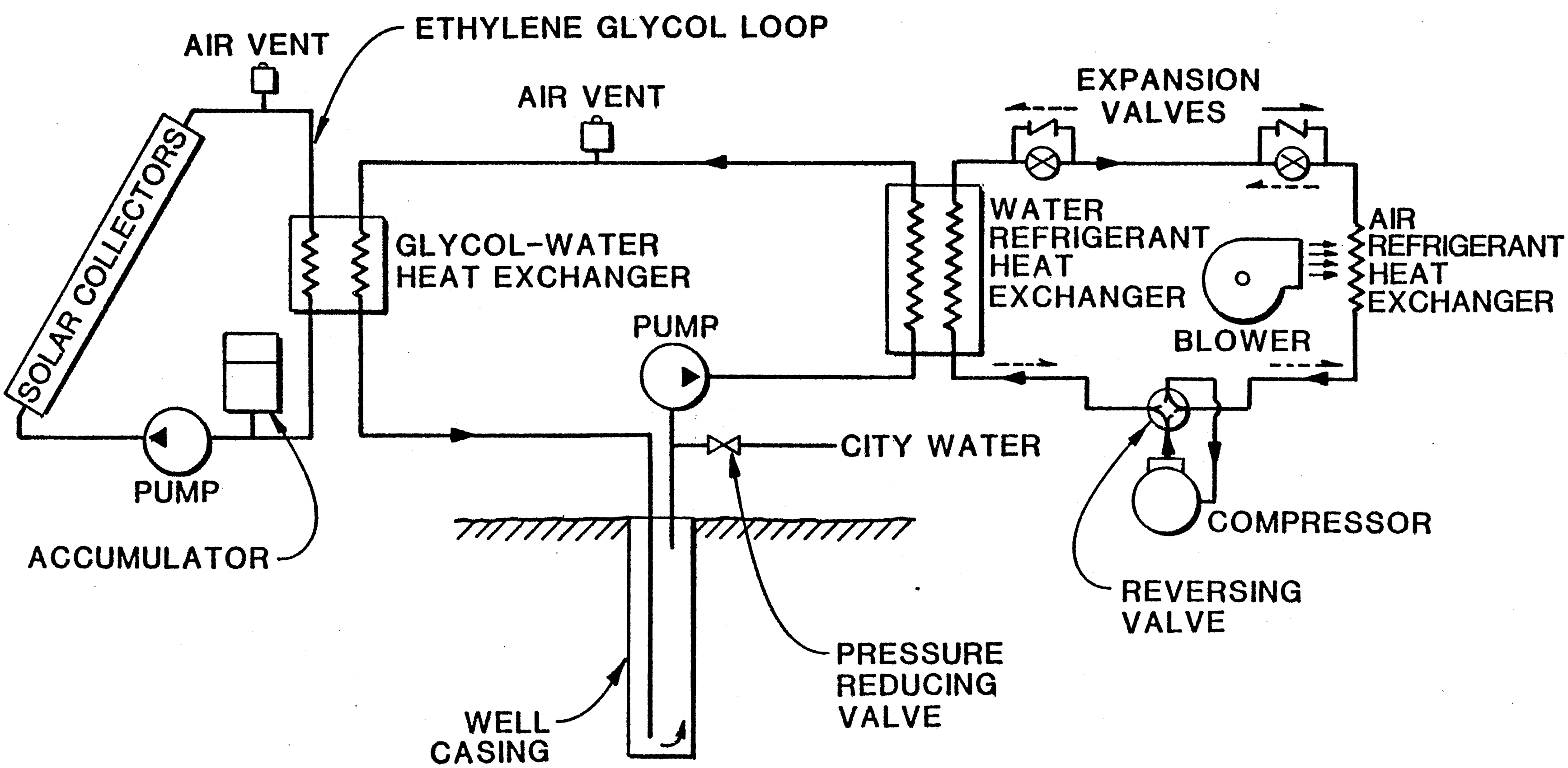


Figure 3. Schematic of the Solar Assisted Ground-Source/Sink Heat Pump System

Both convection and radiation heat transfer to the air are greatly enhanced through the use of bare collectors. Furthermore, to maximize the performance of the collectors, they are vertically located on the south wall of the house. This will enable the collection of winter energy (low sun rays) and better heat rejection during summer (since the collectors would be partly shaded because of high sun rays and the house overhang). The solar loop can make great use of the lower night temperatures for heat rejection.

For the above two heat pump systems, the VEWEX circulating pump operates whenever the heat pump is on. The present control strategy for turning the solar loop pump requires a temperature differential of 20°F or greater to exist between the solar panels and the water in the VEWEX exchanger. The pump ceases operation when this differential falls below 5°F.

CHAPTER V

DATA ACQUISITION

On-site data measurement is very necessary for more accurate comparisons of the performance of the heat pump systems. Also, the measured data can be usefully utilized in validating the computer simulation model. Presented in this chapter is a brief description of the data acquisition process. Most of the information on this topic was obtained from Frierson (29) which covers data acquisition and storage procedure in great detail.

The parameters needed to compare the three heat pump systems were determined from energy balances performed on various parts of the occupied space-heat pump systems. Figure 4 shows points in the system where power consumption, heat transfer, and environmental parameters were to be measured for the solar-assisted ground source/sink heat pump system. A list of all the measured parameters, for the three houses, is shown in Table III.

The data acquisition system is composed of three parts: the transducers, the data logger, and the data storage and transmission devices. Figure 5 shows the data collection system and identifies the devices involved. The "brain" of the collection system is a Campell Scientific CRS data logger which receives analog or pulse signals from various sensors, conditions the signals and outputs the data, in meaningful units, to recording devices. The pulse signals from the various sensors

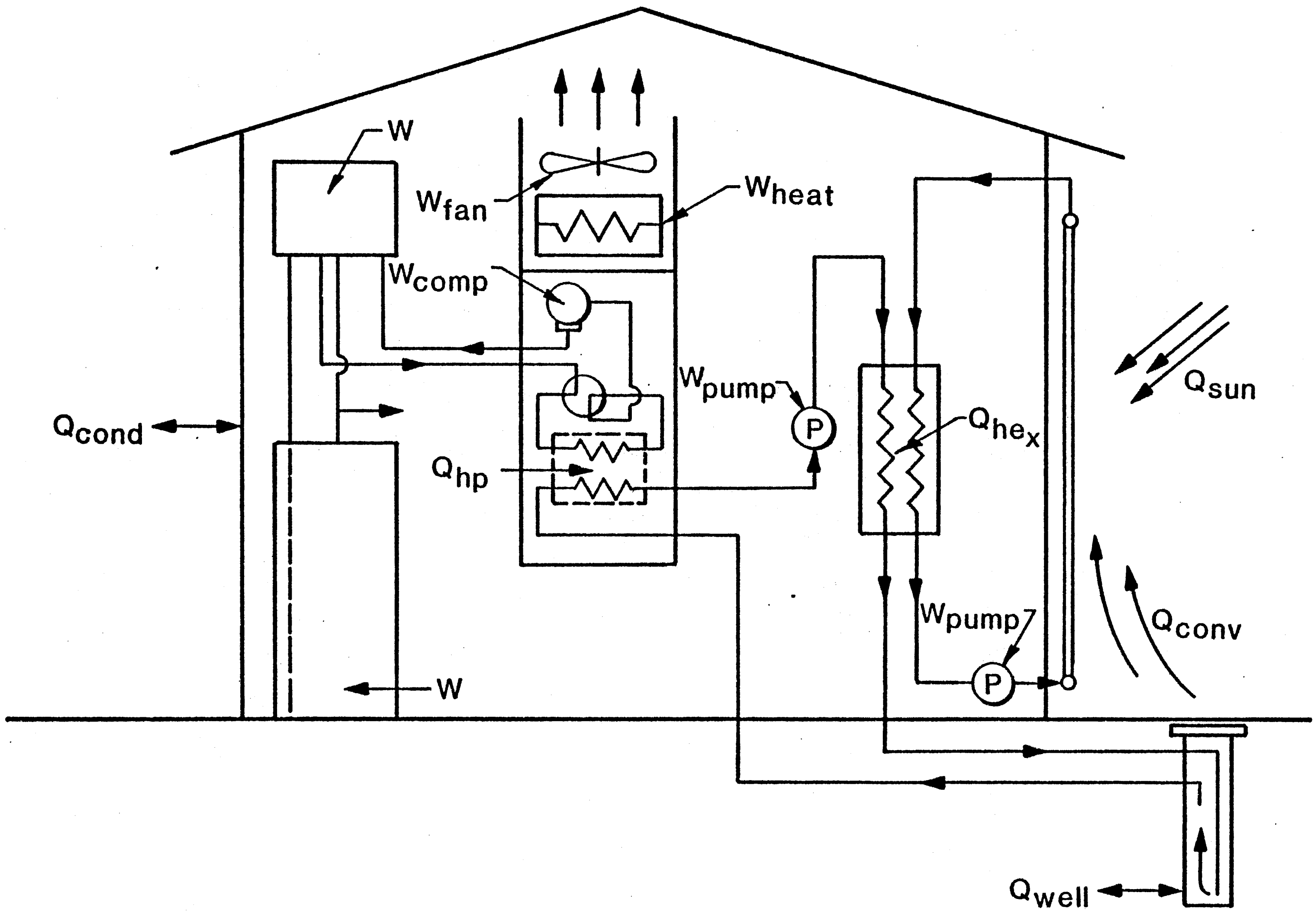


Figure 4. Energy Gains and Losses in the System

TABLE III

MEASURED PARAMETERS

	East House	Middle House	West House
Environmental Measurements	Dry Bulb Temperature Humidity	Dry Bulb Temperature Humidity Water Temp from Well Water Temp to Well EGS Temp from Collector	Dry Bulb Temperature Humidity Water Temp from Well Water Temp to Well
Heat Transfer Measurements	Hot Water Usage Hot Water Btu	Hot Water Usage Hot Water Btu Rate Well Water Flow Rate Well Water Btu Rate Solar Loop Flow Rate Solar Loop Btu Rate	Hot Water Usage Hot Water Btu Well Water Flow Rate Well Water Btu Rate
Power Consumption Measurements	Total Resistance Heat Hot Water Hot Shot Compressor and Crankcase Heater Inside Blower Outside Blower	Total Resistance Heat Hot Water Hot Shot Compressor Inside Blower Well Pump Solar Loop Pump	Total Resistance Heat Hot Water Hot Shot Compressor Inside Blower Well Pump

Weather data are: Solar Insolation
Dry Bulb Temperature
Humidity
Wind Speed and Direction

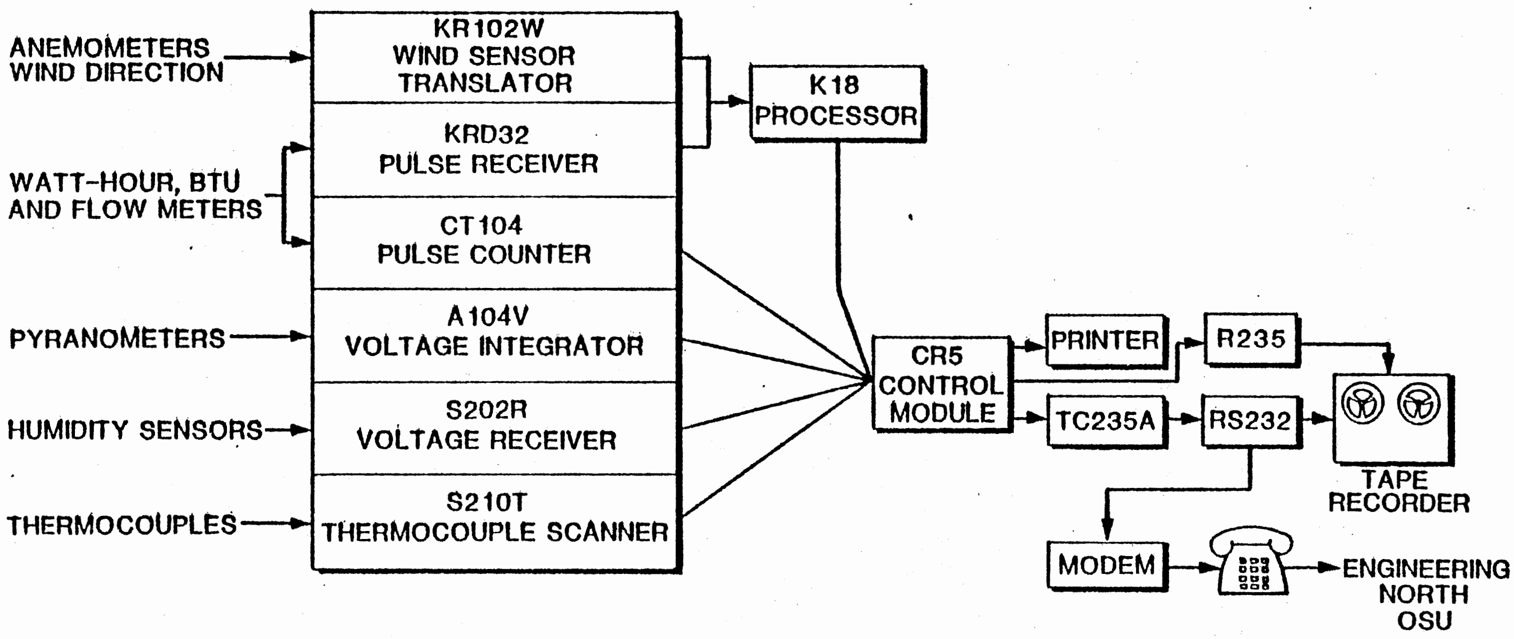


Figure 5. Basic Data Collection System

are input through 60 channels (five channels were recently added for measurement of additional data). Data from the channels are scanned every 15 minutes and output to a TEAC audio tape recorder. The recorder has the capability of storing 7 - 10 days worth of data unattended.

The process currently used to convert data from the audio tape recording to a useable form is charted in Figure 6. Data recorded on the audio tapes are transmitted to the Interdata mini-computer, in the School of Mechanical and Aerospace Engineering at Oklahoma State University (OSU), and are retained in disk storage. This data file is then copied onto a magnetic tape for backup and is transmitted by phone to the OSU IBM 370 computer. The data in the IBM 370 file are then edited for missing and inaccurate data, formated and copied on another magnetic tape for permanent storage. From the permanent storage tapes, TSO data set file can be created for any desired period of time for use by the computer simulation model (details are given in the next chapter). Figure 7 shows a sample of the data, from the 60 channels, after editing. Description of the content of each channel is presented in Table IV.

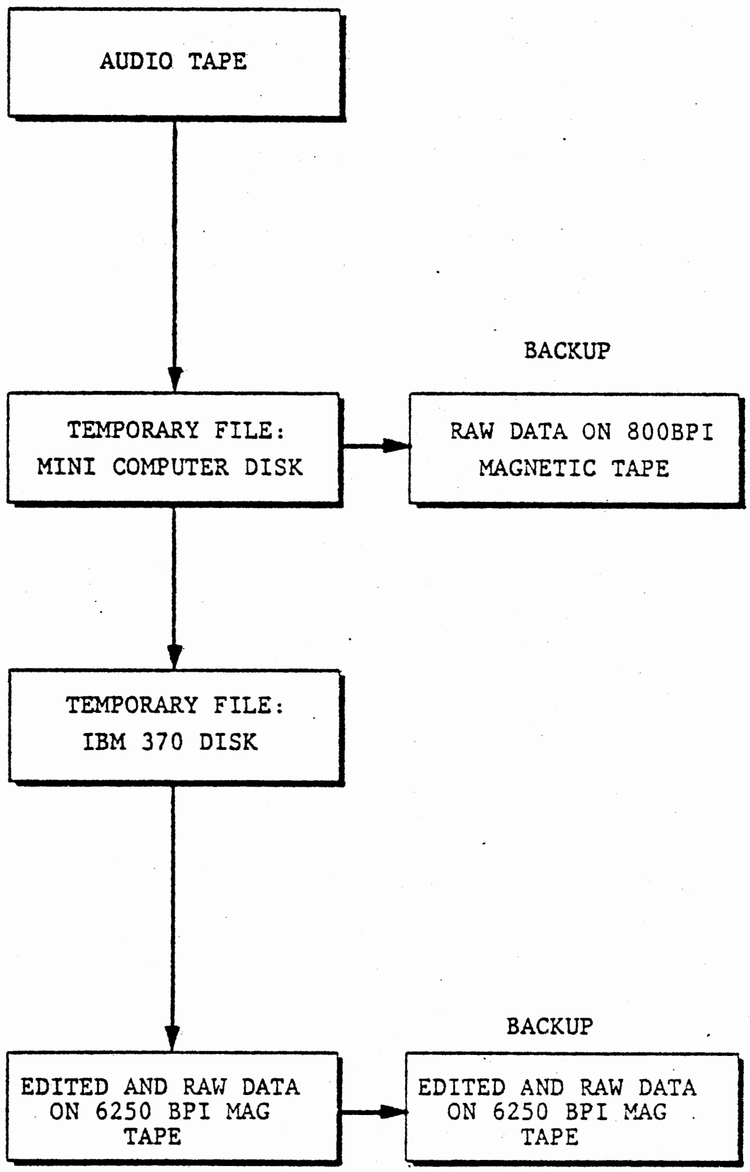


Figure 6. Data Conversion and Storage

00+1513	01+1510	02+1543	03+0117	04+0236	05+0204	06+0209	07+0135	08+0095	09+0214
10+0207	11+0208	12+0260	13+0518	14+0333	15+0250	16+0321	17+0421	18+0588	19+0001
20+0001	21+0016	22+0007	23+0034	24+0001	25+0087	26+0003	27+0003	28+0000	29+0000
30+0003	31+0000	32+0009	33+0000	34+0168	35+0111	36+0078	37+0000	38+0000	39+0012
40+0000	41+0000	42+0000	43+0007	44+0120	45+0048	46+0026	47+0000	48+0000	49+0082
50+0003	51+0177	52+0003	53+0000	54+0690	55+0000	56+0000	57+0000	58+0141	59+0217

Figure 7. Sample of Recorded Data From a Data Set File

TABLE IV

ORDER OF EDITED DATA ON TAPE

Permanent Storage Order	Original Channel Number	Description	Conversion factor	Units
1	0	Day		
2	1	Hour		
3	2	Minute		
4	3	Outdoor Temp.	0.1	°C
5	4	East Air Temp.	0.1	°C
6	6	Middle Air Temp.	0.1	°C
7	9	West Air Temp.	0.1	°C
8	13	Outdoor Humidity	0.1	%
9	14	East Humidity	0.1	%
10	16	Middle Humidity	0.1	%
11	15	West Humidity	0.1	%
12	25	Wind Direction	1	
13	26	Wind Speed	1	MPH
14	27	Mean Wind Run	1	
15	18	Horizontal Insolation	1/886	KW/M^2
16	17	Vertical Insolation	1/688	KW/M^2
17	11	Middle to Well Temp.	0.1	°C
18	10	Middle from Well Temp.	0.1	°C
19	12	Solar Collector Outlet Temp.	0.1	°C
20	Open			
21	49	Middle Well Flow	1/15	gal/15 min
22	50	Middle Well Btu	1000.	btu
23	Open			
24	51	Middle Solar Flow	1/15	gal/15 min
25	52	Middle Solar Btu	1000.	btu
26	Open			
27	Open			
28	Open			
29	8	West to Well Temp.	0.1	°C
30	7	West from Well Temp.	0.1	°C
31	39	West Well Flow	1/15	gal/15 min
32	40	West Well Btu	1000.	btu
33	Open			
34	21	East Total Wh Usage	24	Wh
35	29	East Hot Water Usage	1	gal/15 min
36	28	East Hot Water Btu	1000	btu
37	31	East Hot Water Wh	0.9	Wh
38	34	East Compressor and Crankage Heat Wh	0.72	Wh
39	30	East Resistance Heat and Controller Wh	0.72	Wh
40	32	East Hot Shot Wh	0.24	Wh
41	35	East Indoor Fan Wh	0.24	Wh

TABLE IV (continued)

Permanent Storage Order	Original Channel Number	Description	Conversion factor	Units
42	36	East Outdorr Fan Wh	0.24	Wh
43	22	West Total Wh Usage	24.	Wh
44	37	West Hot Water Usage		
45	38	West Hot Water Btu	1000.	btu
46	42	West Hot Water Wh	0.9	Wh
47	44	West Compressor Wh	0.72	Wh
48	41	West Resistance Heat Wh	0.72	Wh
49	43	West Hot Shot Wh	0.24	Wh
50	45	West Indoor Fan and Controller Wh	0.24	Wh
51	46	West Well Pump Wh	0.24	Wh
52	23	Middle Total Wh Usage	24.	Wh
53	48	Middle Hot Water Usage	1/15	gal/15 min
54	47	Middle Hot Water Btu	1000.	btu
55	54	Middle Hot Water Wh	0.9	Wh
56	56	Middle Compressor and Controller Wh	0.72	Wh
57	53	Middle Resistance Heat Wh	0.72	Wh
58	55	Middle Hot Shot Wh	0.24	Wh
59	57	Middle Indoor Fan Wh	0.24	Wh
60	58	Middle Well Pump Wh	0.24	Wh
61	59	Middle Solar Pump and Solar Loop Controller Wh	0.24	Wh
62	5	Shed Temp.	0.1	°C
63	Open			
64	Open			
65	Open			

CHAPTER VI

SIMULATION PROCEDURE

The total system consists of "sub-systems" that represent the heat pump units, the solar loop, and the VEWEX system. Each of these sub-systems is modeled by a separate subroutine. The space heating and cooling demands are simulated by a separate computer program. The procedure for interconnecting these subroutines to interact with each other is explained in the discussion on the total system. Program listings, flow charts, and input/output instructions are presented in Appendix B.

The Space Heating/Cooling Loads

In order to determine performance characteristics of the heat pump, it is necessary to establish the heating and cooling demands of the building. CHLSYM (30) the transient heating/cooling load simulation program (described in Chapter III) is used to predict the heating/cooling demands in the Perkins houses. The input to the program include hourly weather data, structure geometry, and internal load generation. Some modifications were applied to CHLSYM (not conflicting with the calculation procedure) in order to make it adaptable to the form of measured data. The modifications to CHLYSM are:

1. The program inputs 15-minute data, from the weather tapes, averages them for hourly data input. Appropriate conversion factors are applied to each of the input data

to agree with the units used in the program.

2. The outside surface film coefficient is made to vary with wind speed by using the following empirical correlation (32),

$$h = 2.2 + WV [\, 0.32 + 0.001\ (WV) \,]$$

3. Sensible internal loads from lights and appliances are made hourly inputs.

4. Outdoor and indoor relative humidities are made hourly inputs.

5. Equations used to calculate the declination and equation of time were replaced by more accurate correlations found in reference (33).

6. The procedure for calculating the air humidity ratio has been replaced by a subroutine (13) that computes the psychrometric properties of air for a wet bulb temperature range of $-32 \leq Twb \leq 100^{\circ}F$.

The modified version of CHLSYM is called LDSIM. The user's input to the program consists of an index identifying the house, the month of simulation, the first and last days of simulation, and the desired type of output.

The Heat Pump Units

The steady-state performance of the heat pump units is described by polynomials obtained from least-square curve-fit of the manufacturer's performance data. For the Carrier air-to-air heat pump unit, the polynomials are:

Heating capacity (Btu/hr)

$$QHS = CFC \cdot TFC(a_o + a_1 \cdot TO + a_2 \cdot TO^2 + a_3 \cdot TO^3 + a_4 \cdot TO^4 + a_5 \cdot TO^5 + a_6 \cdot TO^6) \quad (1)$$

Power input, heating, (KW)

$$PHS = CKW \cdot TKW(B_0 + b_1 \cdot TO + b_2 \cdot TO^2 + b_3 \cdot TO^3 + b_4 \cdot TO^4) \quad (2)$$

Cooling capacity (Btu/hr)

$$QCS = C_o + C_1 \cdot TO + C_2 \cdot TO^2 + C_3 \cdot TWB + C_4 \cdot TWB^2 + C_5 \cdot CFM + C_6 \cdot CFM^2 + C_7(TO \cdot TWB \cdot CFM) \quad (3)$$

Power input, cooling, (KW)

$$PCS = d_o + d_1 \cdot TO + d_2 \cdot TO^2 + d_3 \cdot TWB + d_4 \cdot TWB^2 + d_5 \cdot CFM + d_6 \cdot CFM^2 + d_7(TO \cdot TWB \cdot CFM) \quad (4)$$

?

where:

TO = outdoor dry-bulb temperature. (°F)

TWB = indoor air wet-bulb temperature. (°F)

CFM = air volume rate. (ft^3/min)

CFC,CKW = heating capacity and power input correction factors, respectively, when the air volume ≠ 575 CFM.

CFC = 0.82022 + 2.25E - 05(CFM)

CKW = 0.91011 + 1.12E - 04(CFM)

TFC,TKW = heating capacity and power input correction factors, respectively, when the inlet air dry-bulb temperature ≠ 80 °F.

TFC = 1.28 - 0.004 (TDB)

TKW = 0.86 + 0.002 (TDB)

TDB = entering air dry-bulb temperature. (°F) a's, b's, c's, d's = resultant curve-fit coefficients.

For the Command-Aire water-to-air heat pump unit, the polynomials are;

Heating capacity (Btu/hr)

$$QHS = CFHC(e_o + e_1 \cdot EWT + e_2 \cdot EWT^2 + e_3 \cdot TDB + e_4 \cdot TDB^2 + e_5 \cdot GPM + e_6 \cdot GPM^2 + e_7(EWT \cdot TDB \cdot GPM)) \quad (5)$$

Heat extraction rate (Btu/hr)

$$QHES = CFHE(f_o + f_1 \cdot EWT + f_2 \cdot EWT^2 + f_3 \cdot TDB + f_4 \cdot TDB^2 + f_5 \cdot GPM + f_6 \cdot GPM^2 + f_7(EWT \cdot TDB \cdot GPM)) \quad (6)$$

Power input, heating, (KW)

$$PHS = CFKW(g_o + g_1 \cdot EWT + g_2 \cdot EWT^2 + g_3 \cdot TDB + g_4 \cdot TDB^2 + g_5 \cdot GPM + g_6 \cdot GPM^2 + g_7(EWT \cdot TDB \cdot GPM)) \quad (7)$$

Cooling capacity (BTU/hr)

$$QCS = CFCHR(h_o + h_1 \cdot EWT + h_2 \cdot EWT^2 + h_3 \cdot TWB + h_4 \cdot TWB^2 + h_5 \cdot GPM + h_6 + GPM^2 + h_7(EWT \cdot TWB \cdot GPM)) \quad (8)$$

Heat rejection rate (Btu/hr)

$$QHRS = CFCHR(j_o + j_1 \cdot EWT + j_2 \cdot EWT^2 + j_3 \cdot TWB + j_4 \cdot TWB^2 + j_5 \cdot GPM + j_6 \cdot GPM^2 + j_7(EWT \cdot TWB \cdot GPM)) \quad (9)$$

Power input, cooling, (KW)

$$PCS = CFKW(k_o + k_1 \cdot EWT + k_2 \cdot EWT^2 + k_3 \cdot TWB + k_4 \cdot TWB^2 + k_5 \cdot GPM + k_6 \cdot GPM^2 + k_7(EWT \cdot TWB \cdot GPM)) \quad (10)$$

where:

EWT = entering water temperature. (°F)

GPM = water volume flow rate. (gal/min)

CFHC, CFHE, CFKW = correction factors for heating capacity, heat extraction rate, and power input, respectively, when the air volume $\neq$ 600 CFM.

CFCHR = correction factor for cooling capacity and heat rejection rate when the air volume $\neq$ 600 CFM. The correction factors for the Command-Aire unit are represented by fourth-order polynomials in the air volume rate.

During cyclic operations, the heat pump capacity rises slowly until it approaches its steady-state value. Figure 8a shows typical response curves for the heat pump capacity. This transient behavior is due to the refrigerant dynamics and in part to the thermal mass of the heat exchanger (17). Experimental studies (16, 19) showed that the transient performance of the heat pump can be satisfactorily represented by a first order response of the form:

$$\frac{\dot{Q}_{cy}}{\dot{Q}_{ss}} = 1 - e^{-t/\tau} \qquad (11)$$

where:

$\dot{Q}_{cy}$ = heat pump cycle capacity.

$\dot{Q}_{ss}$ = heat pump steady-state capacity.

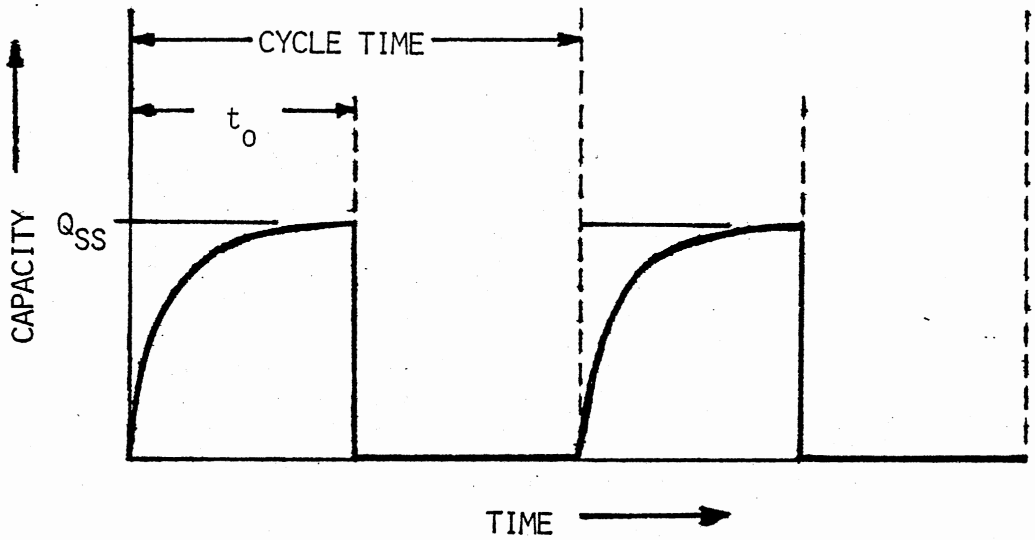
t = time

τ = heat pump time constant.

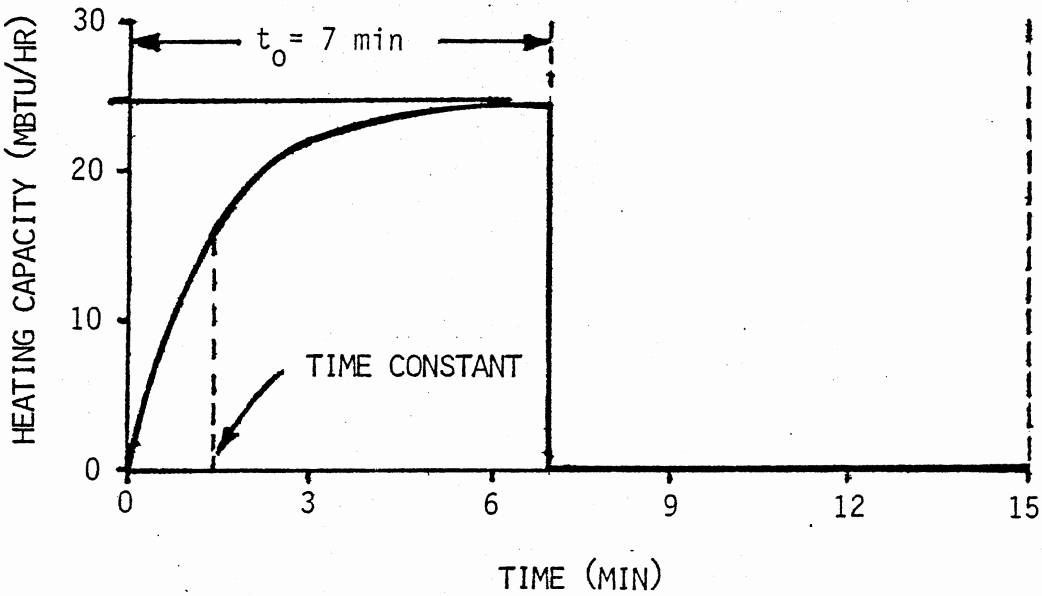
The cyclic heating/cooling output for a heat pump on-time period, t_o, can be determined by integrating Equation 11 over that time period. The integration yields.

$$Q_{cy} = \dot{Q}_{ss}[t_o - \tau(1 - e^{-t_o/\tau})] \qquad (12)$$

Equation 12 is used in this study to compute the heat pump cyclic output. Solving this equation, however, involves two unknown variables. The first is the heat pump on-time which is dependent on the type of thermostat



(a) CYCLIC CAPACITY FOR 50% ON-TIME HEAT PUMP OPERATION



(b) 15-MINUTE CYCLE OF THE EARTH SOURCE HEAT PUMP

Figure 8. Heat Pump Cyclic Heating/Cooling Capacity

used, thermal capacity of the structure, and the steady-state capacity of the heat pump. The second variable is the heat pump time constant, τ, which is usually experimentally determined.

The procedure used to solve Equation 12 begins with assigning a value for the heat pump cycle time. For this simulation model, a cycle time of 15 minutes has been assigned. The 15-minute value is somehow arbitrary, however, inspection of the measuared data, for several months, indicated that the cycle times for each of the heat pump units average to about this value. The next step is computing the cyclic output involves determining how long, during a cycle, would the heat pump be operating. According to Murphy et al. and Bullock et al. (16, 19) the heat pump on-time can be closely approximated by the ratio of the building heating or cooling demand to the steady-state heat pump capacity.

That is:

$$t_o = t_c\left(\frac{QLOAD}{Q_{ss}}\right) \tag{13}$$

where:

t_o = heat pump on-time in hours.

t_c = heat pump cycle time in hours.

Since no information could be obtained from either of the heat pump manufacturers, some approximations were made to compute the heat pump time constant using Equation 11. It was assumed that at the end of a heat pump on-time period, the actual capacity ($\dot{Q}_{cy}$) will be 99.5% of the steady-state value. Therefore, the ratio $\dot{Q}_{cy}/\dot{Q}_{ss}$ in Equation 11 is fixed at 0.995 when the time is equal to t_o. Substituting this ratio into Equation 11 and solving for τ, the following expression was obtained for the time constant,

$$\tau = \frac{t_o}{\ln(0.005)} \tag{14}$$

Equation 14 was used to compute the time constant for the heat pump units. It was found that the time constant varied from 48 seconds for a heat pump on-time of 3 minutes to 2.8 minutes for a heat pump on-time of 15-minutes. Figure 8b shows a cycle for the earth source heat pump operating for 7 minutes when the outdoor temperature was 13°F. For this case, the cyclic output of this heat pump was about 20% less than the steady state capacity.

In summary, the steps for computing the heat pump actual capacity are:

1. Compute the space heating or cooling demand, QLOAD,
2. Use the curve-fit equations to compute the steady-state capacity of the heat pump, $\dot{Q}_{ss}$,
3. Use Equation (13) to determine t_o,
4. Use Equation (14) to determine τ,
5. Substitute the results from steps 2-4 into Equation (12) to obtain the cyclic capacity, Q_{cy}.

The power input to the heat pump unit (compressor and fan) is calculated using the curve-fit relations of the manufacturers' steady-state data. Experimental data (15, 19) indicate that during each on-time period, the power consumption is characterized by a sharp spike as the motors develop speed, followed by a flat curve. Since this start-up transient occurs very fast (generally within a few seconds), its effect on the total energy consumption is practically negligible. Therefore, steady-state values would be sufficiently accurate for heat pump power consumption.

The Solar Energy System

Figure 9 shows a schematic of the solar energy system. The solar panels were modeled using the correlations and procedure outlined by Duffie and Beckman (26). The following assumptions were incorporated in the simulation model:

1. Dust and dirt on the panels have negligible effects.
2. Properties of the working fluid in the solar loop are independent of temperature.
3. No heat loss in the piping connecting the solar panels to the heat exchanger, so that the outlet and inlet temperatures of the collectors are the same as the exchanger's inlet and outlet temperatures, respectively.

The equations describing the solar collection system involve the overall heat loss coefficient (U_o) and the useful energy gain (Q_u). The overall loss coefficient consists of the front or top losses (U_t) and the back losses (U_b). The top loss coefficient is composed of convection and radiation terms. The convection heat transfer coefficient is described by the following relation (33).

$$h_w = 0.8 + 0.23\ (WV) \tag{15}$$

where:

h_w = convection heat transfer coefficient (Btu/hr-ft^2- F)

WV = wind velocity (mile/hr)

Wind direction is accounted for by inserting a simple control logic in the simulation model. The control logic checks the direction of the prevailing wind and adjusts the value of measured wind velocity accordingly. If the wind is prevailing from east, north, west, or anywhere in between, the

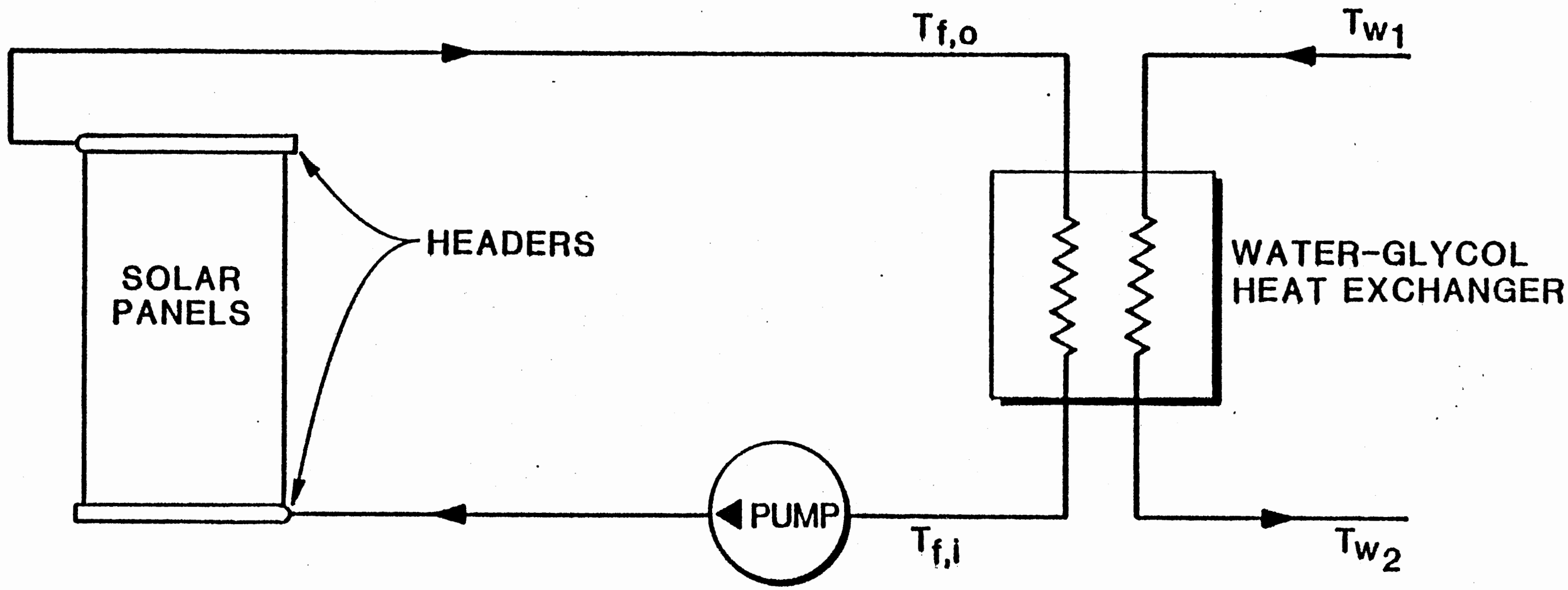


Figure 9. Schematic of the Solar Energy System

measured wind velocity is substituted in Eqn. (15). If, on the other hand, the wind is prevailing from any other direction and the measured velocity exceeds 5 mph, then a value of 5 mph is used in Eqn. (15). This strategy was adopted because if the wind is prevailing from the north, or due north, the solar panels will not experience the full extent of the wind velocity since they will be on the leeward side.

The radiation coefficients between the collector plate and the ambient and the collector plate and the ground are given by the following two expressions:

$$h_{r_{p-s}} = \sigma \varepsilon_p F(T_p^2 + T_s^2)(T_p - T_s) \tag{16}$$

$$h_{r_{p-g}} = \sigma \varepsilon_p (1-F)(T_p^2 + T_a^2)(T_p - T_a) \tag{16a}$$

where:

$h_{r_{p-s}}$ = radiation heat transfer coefficient (Btu/hr-ft^2-°R)

σ = Stefan-Boltzman constant

= 0.1712×10^{-8} Btu/hr-ft^2-°R^4

ε_p = collector plate emittance

F = configuration factor between panels and sky

T_p = collector plate temperature (°R)

T_a = ambient temperature (°R)

T_s = sky temperature = $1.8 * 0.0552 * (T_a + 273)^{1.5}$ (°R)

The top loss coefficient is then the sum of the convection and radiation terms,

$$U_t = h_w + h_{r_{p-s}} + h_{r_{p-g}} \tag{17}$$

The solar panels are mounted vertically on the south wall of the middle house with a 3-inch gap separating the panels from the wall. ~~The back~~

heat loss coefficient is composed of radiation and natural convection terms. The radiation coefficient is given by:

$$h_{r_{p-w}} = \sigma \frac{(T_p^2 + T_w)(T_p + T_w)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_w} - 1} \tag{18}$$

where:

$h_{r_{p-w}}$ = radiation heat transfer coefficient between the panels and wall (Btu/hr-ft^2- R)

T_w = wall surface temperature (R)

ε_w = emittance of the wall

The natural convection term is given by (37),

$$h_c = \frac{k}{L}(0.021)(PrGr)^{2/5} \tag{19}$$

where:

h_c = natural convection coefficient (Btu/hr-ft^2-°F)

k = air conductivity (Btu/hr-ft-°F)

L = vertical length of collector (ft)

Pr = Prandtl number for air

Gr = Grashof number

The back loss coefficient is then given by,

$$U_b = h_{r_{p-w}} + h_c \tag{20}$$

The overall heat transfer coefficient for the solar collector is the sum of Eqn's 19 and 20.

$$U_o = U_t + U_b$$

The total useful energy gain of the collector is represented by the following equation:

$$Q_u = A_c F_R [I_t \alpha - U_o (T_{f,i} - T_a)] \tag{21}$$

where:

A_c = collector area of the solar panels (ft^2)

I_t = total radiation incident or the collector surface ($Btu/hr\text{-}ft^2$)

α = absorptance of the collector plate

$T_{f,i}$ = collector inlet temperature (°F)

T_a = ambient temperature (°F)

The collector heat removal factor (F_R) is given by,

$$F_R = \frac{Gc_p}{U_o} [1 - \exp(\frac{U_o F'}{G\bar{c}_p})] \tag{22}$$

where G is the mass flow rate per unit of collector area ($lb/hr\text{-}ft^2$), and c_p is the specific heat of the working fluid (Btu/lb-°F). The collector efficiency factor (F') is given by,

$$F' = [U_o W(\frac{1}{U_o \; D+(W-D)F} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{f,i}})]^{-1} \tag{23}$$

where:

W = tube spacing (ft);

D = tube nominal diameter (ft);

C_b = bond conductance; $C_b = K_b b/8$ (Btu/hr-ft-°F);

K_b = bond thermal conductivity (Btu/hr-ft-°F);

b = bond length (ft);

γ = bond average thickness (ft);

D_i = tube inside diameter (ft);

$h_{f,i}$ = tube-fluid film coefficient ($Btu/hr\text{-}ft^2\text{-}°F$);

F = fin efficiency; $F = \tanh m(W-D)/2 \,/\, m(W-D)/2$;

$m = U_o/K_p\delta^{-\frac{1}{2}}$

K_p = plate thermal conductivity (Btu/hr-ft-°F); and

δ = plate thickness (ft).

The mean fluid temperature in the tubes of the collector is given by

$$T_{f,m} = T_{f,i} + \frac{Qu}{A_cU_oF_R}(1 - \frac{F_R}{F'}) \tag{24}$$

and the mean plate temperature is described by the relationship

$$T_{p,m} = T_{f,m} + Q_u(R_{p-f}) \tag{25}$$

where:

R_{p-f} = heat transfer resistance between the plate and fluid;

$= 1/(h_{f,i}\pi D_i n L_t)$

n = number of tubes; and

L_t = length of tubes (ft).

Once the useful heat gain has been computed, the collector exit temperature ($T_{f,o}$) can be determined from,

$$T_{f,o} = T_{f,i} + Q_u/\dot{m}cp \tag{26}$$

where $\dot{m}$ is the fluid mass flow rate in the collector (lb/hr).

The computation of the top loss coefficient, and consequently the overall loss coefficient, requires knowledge of the plate temperature. However, computation of the absorber plate temperature demands knowledge of the value of the overall loss coefficient. Therefore, an iterative solution ~~is~~ is employed in which an assumed value of the plate temperature is used to solve for U_o. This U_o value is then used to calculate approximate values of F', F_R, Q_u, $T_{f,m}$, and finally a new plate temperature. The newly calculated plate temperature is used to compute a new value of

U_o and the process is repeated until convergence is established between two successive U_o values.

The solar energy subroutine (SOLAR) is provided with an option so that either horizontal surface or tilted surface radiation can be input. If radiation incident on a horizontal surface is the input, then it will be converted to that incident on a tilted surface. Correlations found in reference 35 were utilized to perform the conversion process.

The Vertical Earth-Water Heat Exchanger

Numerical solutions proved to be responsive to short heat pump cycles (see Chapter III). Therefore, they were employed to compute the transient heat transfer and temperature distribution in the soil surrounding the vertical earth-water heat exchanger (VEWEX). In particular, the finite difference implicit method is used to avoid the time increment restriction imposed by the explicit method.

The VEWEX subroutine is based on a program provided in reference 35. Some modifications were made to generalize the program and have it take into effect the fluid temperature variation along the well depth. The following assumptions were used in the VEWEX model:

1. There is no heat transfer by radiation in the system.
2. There is no heat transfer by conduction in the vertical direction of the fluid stream or earth.
3. The mass flow rate of fluid in the well is constant.
4. No horizontal temperature gradient exists in the fluid stream.
5. Constant earth thermal diffusivity.
6. Perfect contact between the coil pipe and earth.

7. The well is sufficiently long so that end effects can be neglected.

8. At large radial distance from the wall (r>30 ft), each earth slice (see Figure 10) will remain at its far-field temperature.

9. Initially both the exchange fluid and earth are at the far-field temperatures.

To solve for the fluid temperature along the well depth, the well is divided into a finite number of increments (ΔZ)* as shown in Figure 10. Each increment is characterized with a constant far-field temperature (T_g) in the surrounding soil. For each increment, the heat exchange between the fluid and soil is computed and fluid temperature at the end of an increment is determined. This temperature acts as inlet temperature for the next increment. The process is continued until the fluid temperature at the well exit is established.

Solving for the fluid temperatures in dimensional steps, by incrementing the well depth, yields a more accurate picture of the vertical temperature profile. This was demonstrated by the line-source solutions used by Moss (38) to compute temperature profiles in water injection wells.

In solving for the fluid temperature at the end of each increment, the solutions, outlined by Shenck and Dusinberre (39, 40) for buried pipes, were applied in this study. Figure 10 shows fluid increments ΔZ long. Three heat transfer terms must be considered when solving for the fluid temperatures. These are the heat transfer by convection be-

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*See nomenclature section for designations.

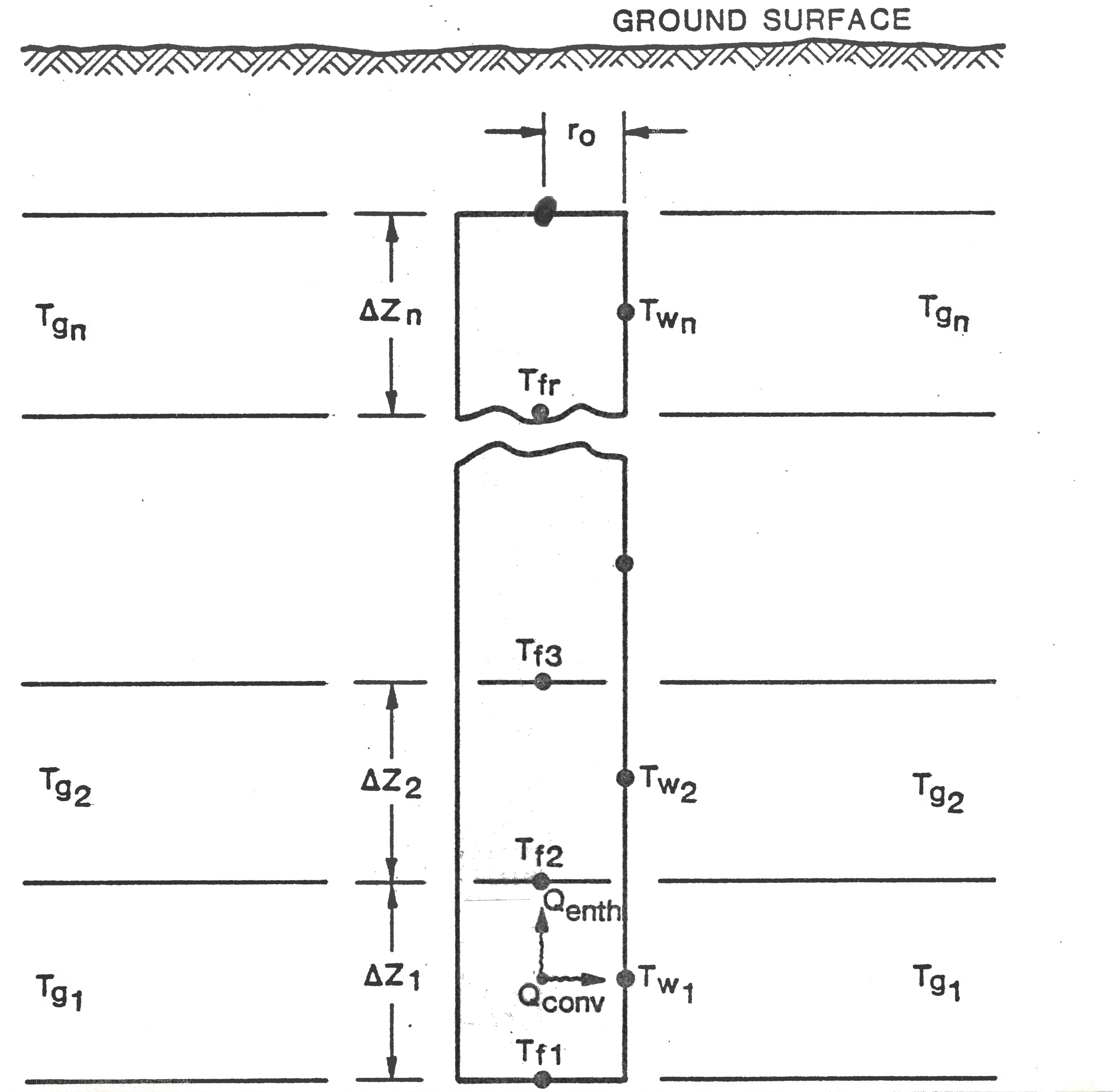

FIGURE 2-4 Schematic of VEWEX for Computational Purposes

tween the fluid and the well inner surface, the heat flow involving the enthalpy change in the fluid passing through the region and carried out of it, and the heat stored in the fluid increment due to the transient rise in the fluid temperature over a time step.

Following the notation in Figure 10, the heat flow by convection is given by,

$$Q_{conv} = hA_n(T'_{avg_n} - T_{w_n}) \tag{27}$$

where:

h = convection heat coefficient (Btu/hr-ft^2-°F)

A_n = surface area of a ΔZ_n increment (ft^2)

T_{w_n} = well surface temperature for the nth increment (°F)

T'_{avg_n} = mean average of inlet and outlet temperatures;

$= (T_{f_n} + T_{f_{n+1}})/2$ (°F)

The convection heat transfer coefficient, h, is computed using the Dittus-Boelter correlations (41).

The heat flow due to enthalpy change in the fluid passing through an increment, ΔZ, is given by,

$$Q_{enth} = \dot{m}c_p(T_{f_n} - T_{f_{n+1}}) \tag{28}$$

where:

$\dot{m}c_p$ = fluid capacity rate (Btu/hr-°F)

The storage term in the fluid increment over a time step is represented by,

$$Q_{st} = \frac{Mc_p(T'_{avg_n} - T_{avg_n})}{\Delta\theta} \tag{29}$$

where:

M = mass of the fluid increment (lb_m)

T'_{avg_n} = mean average temperature in the fluid increment a time step later (°F)

$\Delta\theta$ = time step (hr)

Energy balance on a fluid increment can then be written as,

$$Q_{st} = Q_{enth} - Q_{conv} \qquad (30)$$

Substituting the terms from Equations 27, 28 and 29 into equation 30 and rearranging, the temperature of the fluid at the end of an increment can be written as:

$$T_{f_{n+1}} = \frac{1}{XX}\left[2T_{avg_n} + YY \cdot T_{w_n} - ZZ \cdot T_{f_n}\right] \qquad (31)$$

where:

$$XX = 1 + \left(\frac{2\dot{m}}{M} + \frac{hA_n}{Mc_p}\right)\Delta\theta$$

$$YY = \frac{2hA_n}{Mc_p}\,\Delta\theta$$

$$ZZ = 1 - \left(\frac{2\dot{m}}{M} + \frac{hA_n}{Mc_p}\right)\Delta\theta$$

The temperature distribution in the soil is governed by the one-dimensional heat conduction equation:

$$\frac{\partial^2 T}{\partial r} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial \theta} \qquad (32)$$

with the initial condition:

$$T(r,\theta) = T_i \qquad \text{for all } r > r_o$$

and boundary conditions:

$$T(a, \theta) = T_i \qquad \text{for all } \theta > \theta_o$$

$$-\left.\frac{\partial T}{\partial r}\right|_{r=r_o} = \frac{Q}{\pi D \Delta Z k} \qquad \text{for all } \theta > \theta_o$$

Finite difference techniques are employed to solve for the radial temperatures in the ground. Specifically, the implicit method with nonuniform grids, as described in reference 42, is used to solve the problem of cyclic heat input at the well surface.

The computational strategy applied in the VEWEX model is summarized by the following steps:

1. Use the heat extracted or rejected by the heat pump (plus the solar loop contribution in the case of the solar-ground heat pump) as a first estimate of the heat conducted to, or from the ground (Q_{cond}).
2. Use this estimated heat conduction value to solve Equation 32 for the wall temperature, T_w, (the implicit method).
3. Compute the fluid temperature at the end of the nth increment, $T_{f_{n+1}}$, using Equation 31 and T_w computed in step 2.
4. Calculate Q_{conv} using Equation 27.
5. Compare Q_{conv} (step 4) with the estimated conduction heat transfer (step 1). If the difference ($Q_{conv} - Q_{cond}$) is within a specified tolerance limit, then begin computation for a new fluid increment. If not, then increment or decrement the Q_{cond} value and repeat steps 2 to 5 until convergence is established.
6. Use Q_{cond} from step 5 as a first estimate for the next fluid increment.
7. Steps 2 through 6 are repeated for each fluid increment. It should be noted that the larger the number of ΔZ

increments the better the accuracy of results. However, computer run cost increases with the number of increments. In this study, 50 - ft depth increments were found optimum.

The far-field temperatures for the soil increments, T_{g_n}, were assigned according to Collins' recommendation (8). For Oklahoma, the Collins map gives an annual average ground temperature of 62 F for depths from 30 to 60 ft. For greater depths, Collins recommended a 1°F increase for every 64 ft increase in depth.

Flow of Information in the Dynamic Simulation

This section explains the flow of information among the various subroutines and the control logic. Figure 11 shows a schematic of the flow of logic for the dynamic simulation procedure.

The procedure begins with running LDSIM program to compute the heating/cooling demands and indoor temperatures. User's input to the program consists of indices identifying the house, days and month of simulation, thermostat throttling range, thermostat settings and their times, and the equipment maximum and minimum capacities. Other inputs to the programs are stored in data sets for each house which are input automatically through the house index. LDSIM will output the loads and indoor temperatures into a data set file that is linked with the heat pump simulation program (HPSIM). HPSIM is then executed to simulate the performance of a particular heat pump system. User's input to HPSIM includes specifying the house and period of simulation. HPSIM reads the heating/cooling loads and indoor temperatures from the link file; then, linearly interpolates between the hourly points for

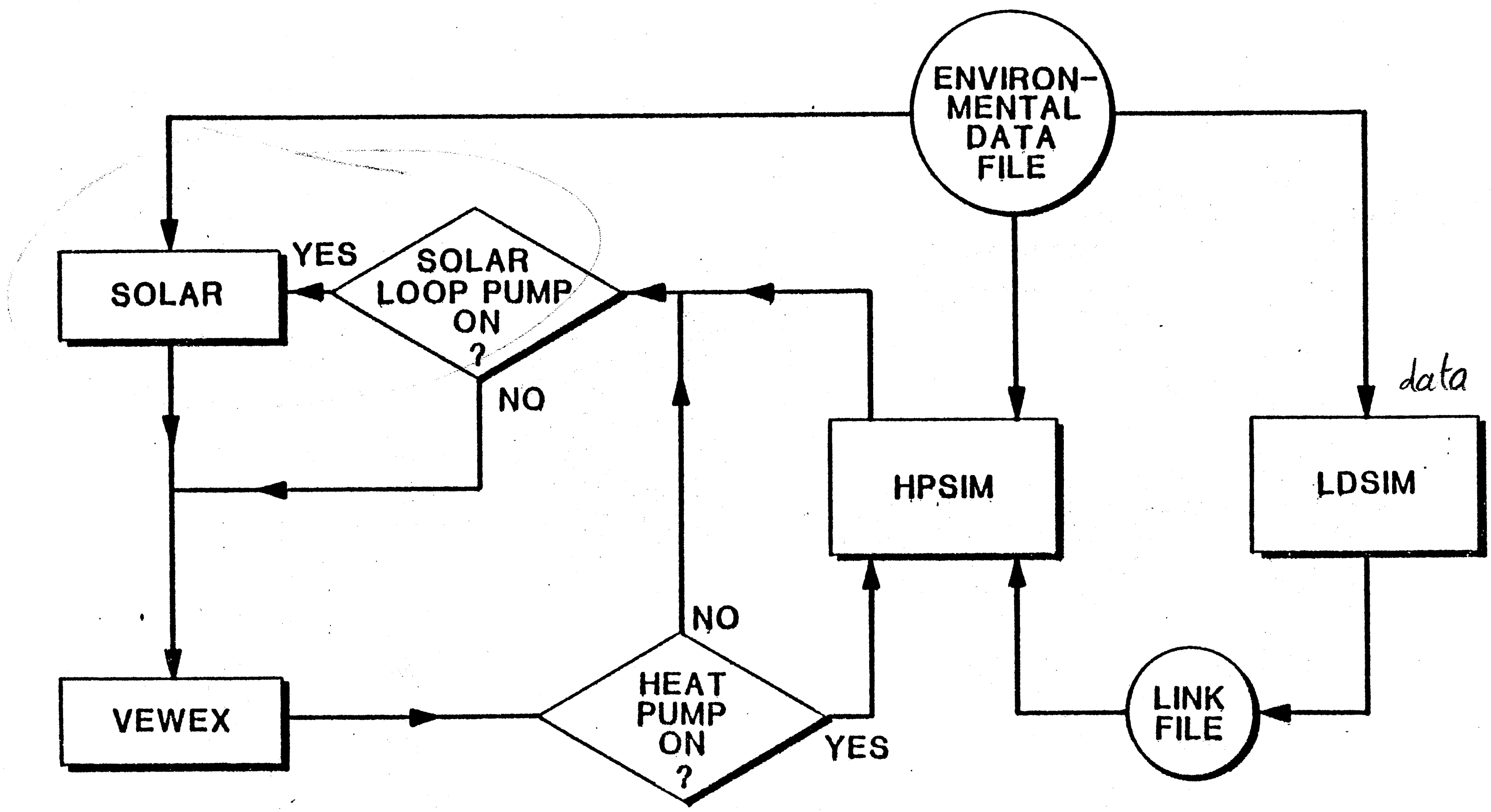

Figure 11. Flow of Information for the Dynamic Simulation

the 15-minute values. The mode of heat pump operation (heating or cooling) is determined by a check on the house load and the outdoor temperature. The heat pump will not be operating if the indoor temperature is within the thermostat throttling range.

The type of heat pump system to be simulated is decided by the house index specified by the user. If, for instance, the middle house were specified, then subroutine HPUMP or HPUMPC would be called depending on whether the mode of operation is heating or cooling. The heat pump actual capacity, heat extraction or rejection rate to the well water, operation time, power usage, and the heat pump coefficient of performance are computed in the respective subroutine. Temperature of the water exiting the water-refrigerant heat exchanger is then computed using the heat extraction or rejection rate and the water capacity rate. Next, a check is made to determine whether or not the solar loop pump is circulating fluid. If the pump is on then subroutine SOLAR is called to determine the collector exit temperature.

The control logic for turning on the solar loop pump requires a temperature differential of 20 F between the collector plate temperature and the water temperature at the middle of the well. The pump is turned off when this differential falls below 5 F. In this simulation program the temperature differential for the solar pump control is determined using the sol-air temperature. This is because the sensor for the collector plate temperature is located at the center of the solar panels and is exposed more to the outdoor environment than to the plate temperature, which is influenced by the outdoor environment and the water in the tubing. Simulation runs of some November days showed excellent agreement between predicted and measured times of the solar loop pump operation.

The heat transfer rate between the well circulating water to the solar loop (via the glycol-water heat exchanger, shown in Figure 3) is computed from:

$$Q_{sol} = \varepsilon(\dot{m}c_p)_w (TC_o - TF_{hp}) \tag{33}$$

where:

ε = heat exchanger effectiveness (considered constant at 63%);

$(\dot{m}c_p)_w$ = heat capacity rate of water (Btu/hr- F);

TC_o = collector outlet temperature (°F);

TF_{hp} = water exit temperature from the refrigerant-water heat exchanger (°F).

Q_{sol} is then used to compute the temperature of the water entering the well.

The last step in the simulation is calling subroutine VEWEX (Vertical Earth-Water Heat Exchanger) to calculate the water temperature exiting the well, which is influenced by the heat transfer between the water and the earth. The value of time step is set according to the heat pump operation time. VEWEX is called twice during a 15-minute cycle time. The first time step is set equal to the heat pump on-time during the 15-minute cycle, and the second time step is that of the cycle time minus the heat pump on-time. If the heat pump were operating or not operating the full 15 minutes, then the time step is set equal to one-half the cycle time. This strategy was adopted in order to account for the solar contribution when the heat pump is off, or the heat transfer occuring between the water and earth when the well circulating pump is off.

The same logic is used in simulating the ground-source heat pump (west house), except that subroutine SOLAR is bypassed. As for the air-to-air heat pump (east house), the cyclic performance is determined by subroutine APUMPH or APUMPC depending on whether the mode of operation is heating or cooling, respectively.

Model Validation

On-site measured data proved very helpful in the verification of the simulation model. Actual data a for few days in both the heating and cooling seasons were chosen for comparison with predictions of the simulation model. These comparisons were used to refine the values of some constants and factors related to the structures, the equipment and controls, the solar loop, and the vertical earth-water heat exchanger. Some of these factors included infiltration and internal heat generation rates, thermostat throttling range, effective solar absorptance and emittance for the solar panels, thermal diffusivity of the ground, etc.

Figures 12 and 13 show comparisons of actual and simulated results of hourly average indoor temperatures for the west and east house for selected days in the heating and cooling seasons for which complete data were available. Tables V through VII show comparisons of actual and simulated heat pump performance in the respective houses for the selected days. Reasonably good agreement exists between the predicted and actual data considering unpredictability of the habits of the people occupying the houses. For instance, observation of the available measured data for some December days for the east house indicated that the residents turn off the heat pump for a few hours after midnight and

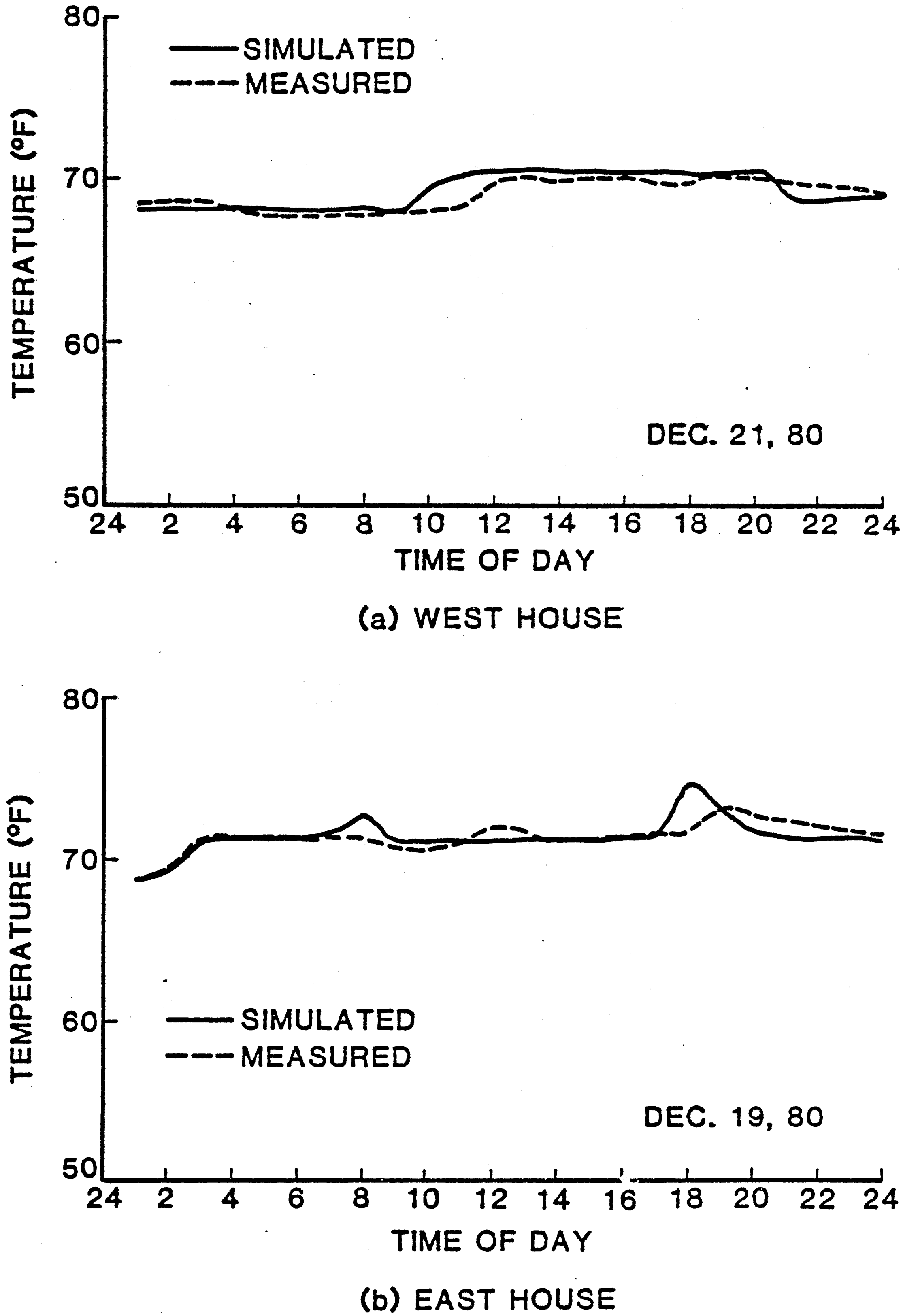

Figure 12. Simulated vs. Measured Indoor Temperatures

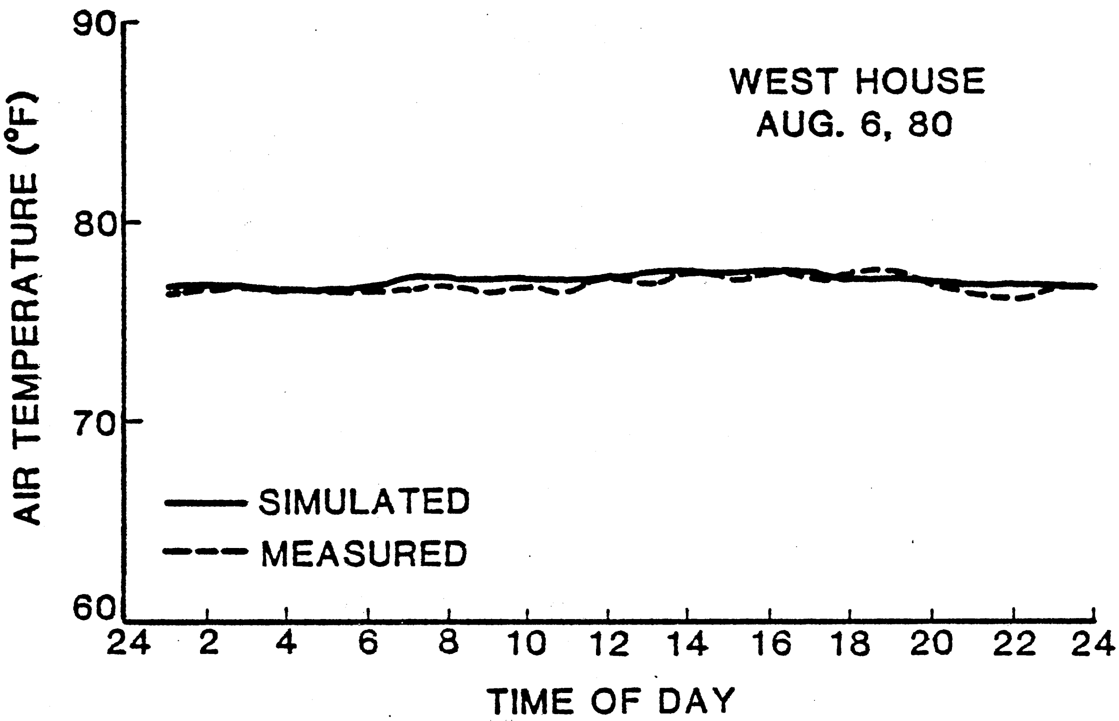

Figure 13. Simulated vs. Measured Indoor Temperatures

TABLE V

SIMULATED VS. MEASURED PERFORMANCE OF
THE GROUND-AIR HEAT PUMP SYSTEM
(WEST HOUSE - DEC. 21, 1980)

	Measured	Simulated
Total heat pump operating time (hr)	6.0	6.4
Compressor and fan total energy usage (KWH)	16.3	17.1
Total electric resistance heat (KWh)	0.0	0.0

TABLE VI

SIMULATED VS. MEASURED PERFORMANCE
OF THE AIR-AIR HEAT PUMP SYSTEM
(EAST HOUSE - DEC. 19, 1980)

	Measured	Simulated
Total heat pump operating time (hr)	---	16.9
Compressor and fans total energy usage (KWH)	26.4	28.9
Total electric resistance heat (KWh)	1.4	1.5

TABLE VII

SIMULATED VS. MEASURED PERFORMANCE OF
THE GROUND-AIR HEAT PUMP SYSTEM
(WEST HOUSE - AUG. 6, 1980)

	Measured	Simulated
Total heat pump operating time (hr)	9.7	10.6
Compressor and fan total energy usage (KWh)	25.9	24.8

change their thermostat setting twice during the day. The observation also indicated high intermittent internal heat generation throughout the day which was probably caused by frequent cooking or operation of home appliances. This high internal heat generation caused higher indoor temperature fluctuations than otherwise would be attained by the thermostatic control.

Comparison between measured and simulated data on the performance of the solar-earth heat pump system in the middle house was not possible. This is because this heat pump system has been malfunctioning since its installation. The malfunction was detected very recently and has been attended to. In regard to the solar loop-earth heat exchanger performance, however, some comparisons with the actual data were possible. Visual inspection of the measured data for the month of November indicated that there were two days during which the heat pump was turned off for the entire day, while the solar loop was adding heat to the well water. Forcing the heat pump to be off during those November days, the simulation model was used to predict the rise in both the solar collector and well outlet temperatures as a result of solar heat addition. Figures 14 and 15 show the simulated and measured collector and well outlet temperatures respectively. Good agreement exists between the measured and simulated data during the solar collection period (when the solar and well pumps are activated). The difference can be attributed to the assumed constant physical properties of soil and solar loop fluid. During the period of no solar heat collection, the collector outlet temperature (measured) is approximately that of the house attic since that is where the temperature sensor is located. The well temperature is virtually that of the house since the sensor is located in the utility closet in the living room.

It was desired that simulation results be compared with measured data for more days in both the heating and cooling seasons. However, very few data (in useable format) were available for the simulation tests. All the compiled measured data are "raw data". They are stored in a form such that they cannot be used directly in a computer program. The storage tapes contain missing data for hours and sometimes days. This has been caused by the frequent breakdown of the data recording equipment. Presently, however, the measured data are being checked and corrected for missing scans and unrecognized characters. Data for several months will be stored on a single tape. This will improve both the method and the speed of inputing the data into the simulation program and will allow for long simulation period.

Finally, due to the difference in the daily habits of the residents of the Perkins houses, the difference in their preference for indoor temperature setting, and the malfunction of the middle house heat pump,

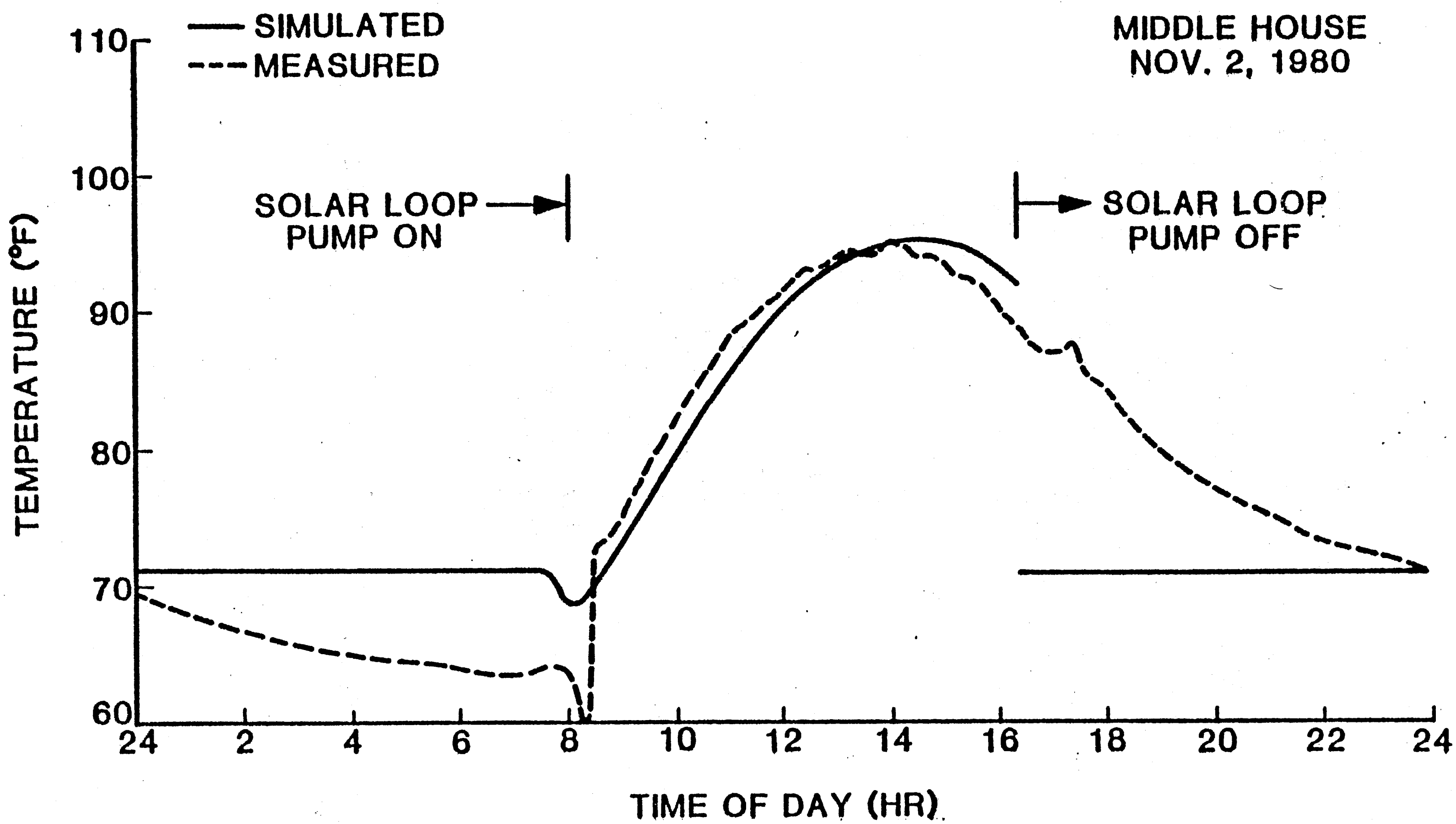

Figure 14. Simulated vs. Measured Collector Outlet Temperatures (Heat Pump Off - Well Pump On)

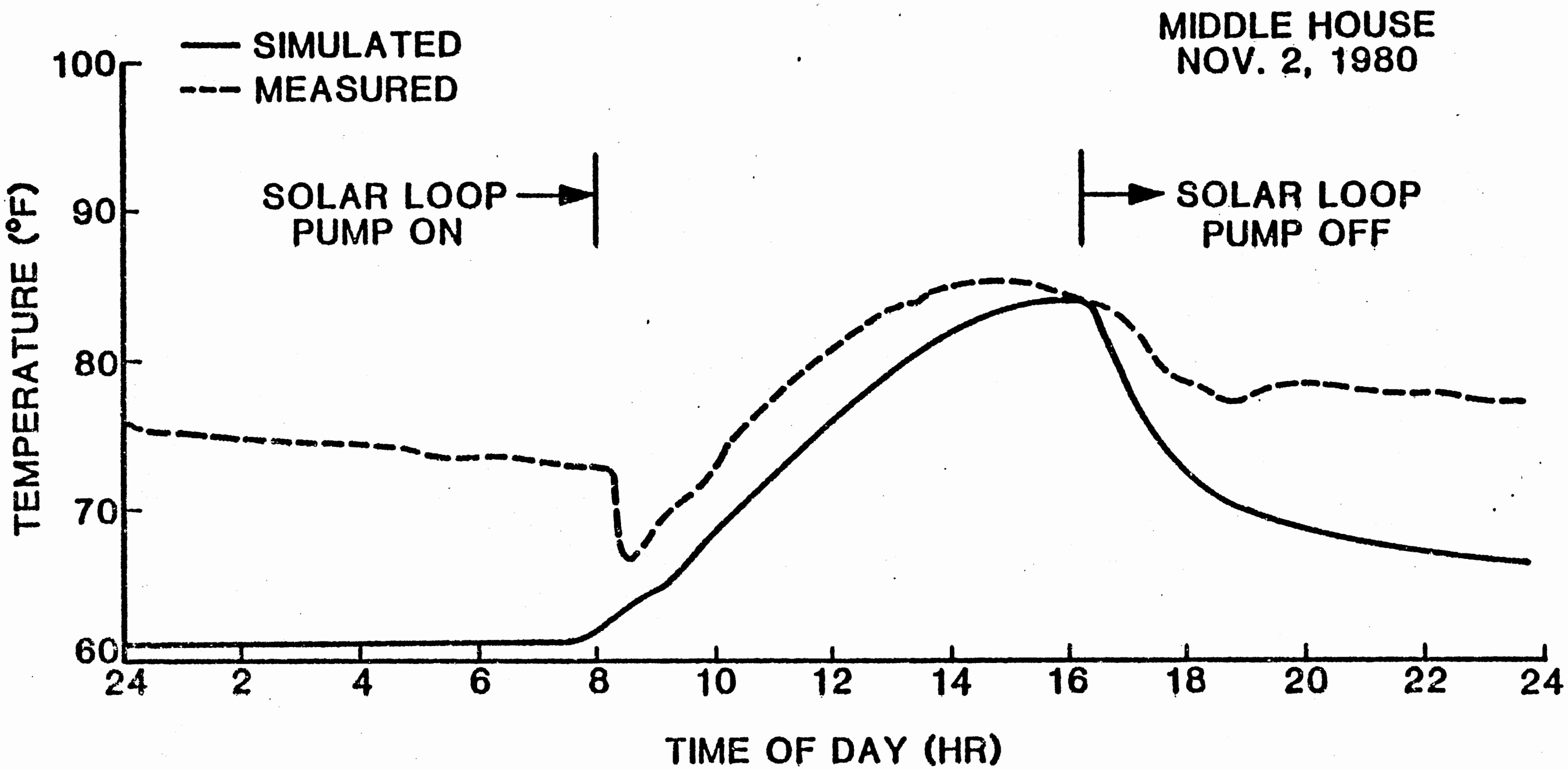

Figure 15. Simulated vs. Measured Well Outlet Temperatures (Solar Heat Addition - Heat Pump off)

it is very difficult to make a decision (using measured indoor data) regarding the merits of one heat pump system over the others. Therefore, it was decided to assume unified values for the internal heat generation and temperature settings for the three houses, and use these values with the measured weather data to simulate the performances of the three heat pump systems. The results of these simulations are discussed in the next chapter.

CHAPTER VII

DISCUSSION OF SIMULATION RESULTS

In order to compare the performances of the three heat pump systems, simulation runs were made for three winter and three summer days for each of the houses (results are presented in Tables IX and X). In these simulation runs, internal loads, infiltration and ventilation rates, and thermostat settings were assumed to be the same for each of the three houses. These assumed values are tabulated in Table VIII.

Inspection of the winter simulation results (Table IX) clearly indicates the superior performance of the earth and solar-earth heat pumps over that of the air-to-air heat pump. During the simulation period, the electrical energy consumption by the air-to-air heat was approximately 43% higher than that used by either of the other two heat pump system. Its heating coefficient of performance, COP*, was about 47% lower than that of the other two. The reason for the less efficient performance of the air source heat pump is the cold temperature it experienced during those December days. The averages of measured outdoor temperatures for those days were 28°, 18°, and 24°F. In contrast, the earth and solar-earth heat pumps operated at

*For the air-to-air heat pump, COP is based on energy usage by indoor-outdoor fans and resistance heat; for the other two heat pumps it is based on resistance heat, indoor fan and the well pump energy usage.

TABLE VIII

ASSUMED VALUES FOR INETERNAL GENERATION, INFILTRATION RATES AND TEMPERATURE SETTING FOR THE AUG. AND DEC. SIMULATION RUNS

	Daytime (8.0-17 hrs)	Nightime (0-8.0 and 18-24 hrs)
Number of people in house	1	4
Infiltration rate (air changes / hr)	1/2	3/4
Thermostat setting (F)	76 (summer) 70 (winter)	76 (summer) 70 (winter)
Lighting (KW)	0.5	1.0
Sensible heat loads from appliances, etc. (Btu/hr)	300	500
Latent heat loads from appliances, etc.	100	300
Relative humidity	50%	50%

TABLE IX

WINTER SIMULATION RESULTS FOR THE THREE HEAT PUMP SYSTEMS (DECEMBER 19-21, 1980)

Day		Air Heat Pump	Earth Heat Pump	Solar-Earth Heat Pump
19	Heat pump operating time (hr)	16.38	7.12	7.12
19	Energy consumed by compressor and fan(s) (KWh)	27.8	19.28	19.28
19	Resistance heat (KWh)	1.73	0.00	0.00
19	Avearage COP*	1.54	2.15	2.15
20	Heat pump operating time (hr)	20.87	9.72	9.72
20	Energy consumed by compressor and fan(s) (KWh)	34.59	25.95	25.95
20	Resistance heat (KWh)	16.76	0.00	0.00
20	Average COP	1.36	2.14	2.14
21	Heat pump operating time (hr)	16.87	7.71	7.67
21	Energy consumed by compressor and fan(s) (KWh)	28.48	20.60	20.57
21	Resistance heat (KWh)	5.51	0.00	0.00
21	Average COP	1.52	2.14	2.14
	Totals and Averages			
	Total heat pump operating time (hr)	54.12	24.54	24.51
	Total energy consumed by compressor and fan(s) (KWh)	40.86	65.83	65.80
	Total resistance heat (KWh)	24.00	0.00	0.00
	Average COP	1.46	2.14	2.14

higher efficiency because of the higher heat source temperatures (water from the earth heat exchanger) that averaged 60, 58, and 58 F for the respective simulation days. The coefficient of performance of the heat pumps versus the outdoor and well exit temperatures are plotted in Figure 16.

A somehow unexpected result is that of the performance of the solar-earth heat pump. The simulation results indicate that the solar panels were unable to collect enough heat to transfer it to the well water, which in turn would result in increase in the heat pump efficiency. This is despite the fact that both December 19 and 21 were sunny days (the 20th day of December was a very cloudy day with very low levels of insolation recorded). The solar loop pump operated intermittently about midday of December 21st for a collector time of 1.5 hours. However, the contributed solar heat hardly affected the performance of the heat pump. The middle house recorded data for the 19th and 21st days of December show that the solar loop pump was in operation for approximately 4 and 5 hours, respectively. However, the recorded well temperatures were in the high 40's-low 50's range when the solar loop pump began operation. This is a good indication that during cold sunny days, the solar loop will assist in maintaining the well water temperature at a convenient level for efficient heat pump operation (50-90°F).

The simulation results of the three summer days of August, shown in Table X, show a different trend for the performance of the three heat pumps than that of the winter days. The results indicate that the three heat pump systems operated with nearly the same efficiency. The cooling coefficient of performance of the air source heat pump

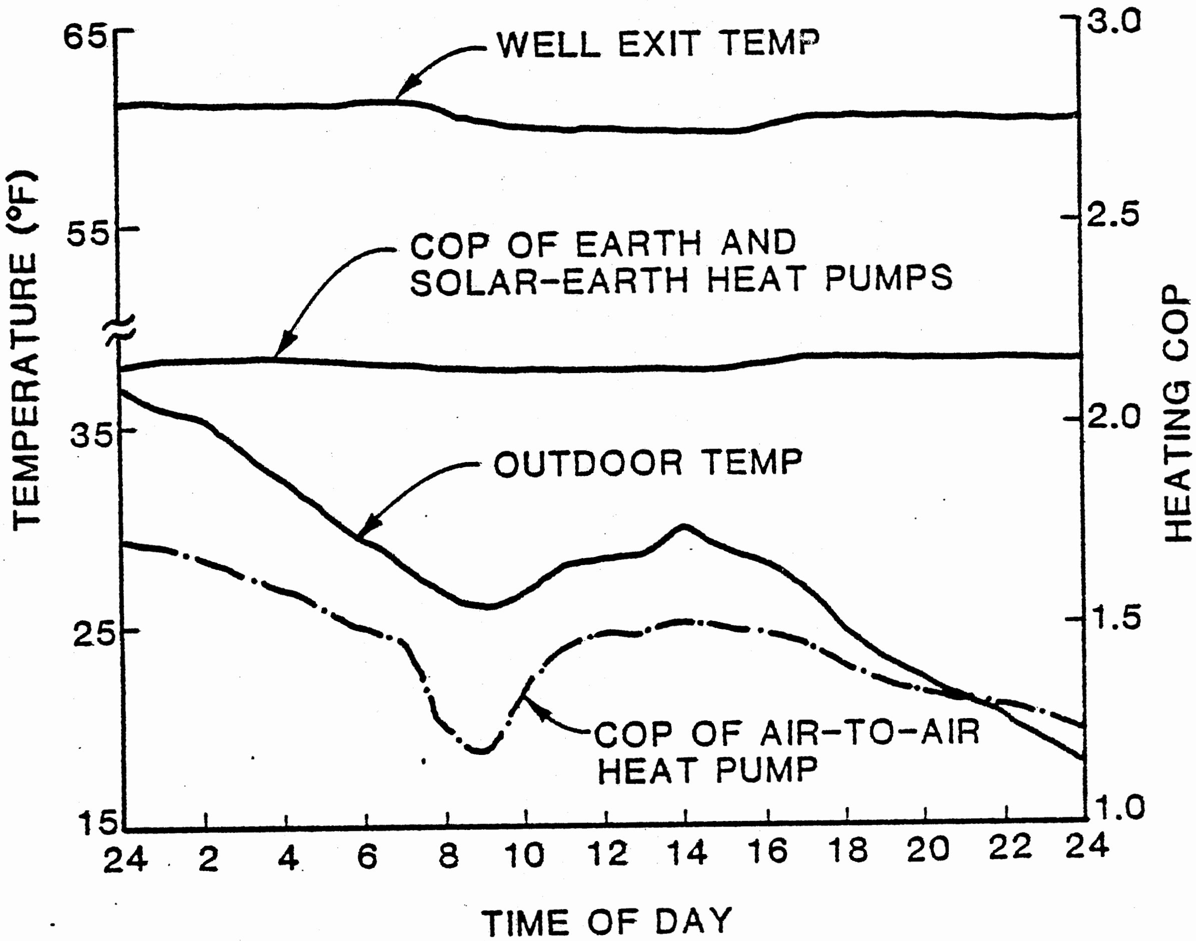

Figure 16. Simulated Effect of Temperature on the Heating Coefficient of Performance (December 19, 1980)

TABLE X

SUMMER SIMULATION RESULTS FOR THE THREE HEAT PUMP SYSTEMS (AUGUST 4-6, 1980)

Day		Air Heat Pump	Earth Heat Pump	Solar-Earth Heat Pump
4	Heat pump operating time (hr)	18.56	14.64	14.64
4	Energy consumed by compressor and fan(s) (KWh)	38.93	36.16	36.16
4	Average COP	1.70	1.80	1.80
5	Heat pump operating time (hr)	18.94	15.26	15.26
5	Energy consumed by compressor and fan(s) (KWh)	39.84	38.56	38.56
5	Average COP	1.70	1.72	1.72
6	Heat pump operating time (hr)	19.45	15.84	15.84
6	Energy consumed by compressor and fan(s) (KWh)	41.00	40.47	40.47
6	Average COP	1.71	1.70	1.70
	Totals and Averages			
Total heat pump operating time (hr)		56.95	45.74	45.74
Total energy consumed by compressor and fan(s) (KWh)		119.77	115.18	115.18
Average COP		1.70	1.74	1.74

lagged that of either of the other two heat pump systems by only 4%. The close proximity among the cooling efficiencies of the three heat pump systems can be explained by reviewing Figure 17. The air source heat pump makes use of the low night temperatures operating at higher efficiency which drops fast as the ambient temperatures climb up to the 100's. The earth and solar-earth heat pump systems, however, operated at a relatively constant efficiency droping off slightly late in the day as the well temperature keeps building up. A very probable reason for the high well temperatures is that the heat is rejected continuously to the well, due to non-cycling of the heat pump.

Theoretically, the solar loop in the solar-earth heat pump system should be able to assist in maintaining the well temperatures at a lower level during the evening and early morning hours by dissipating some of the heat in the well to the cooler surroundings. However, the 3-day August simulation results did not support this theory. Unfortunately, there are no recorded data of the actual performance of the solar-earth heat pump system during the cooling season of 1980 to validate the simulation results.

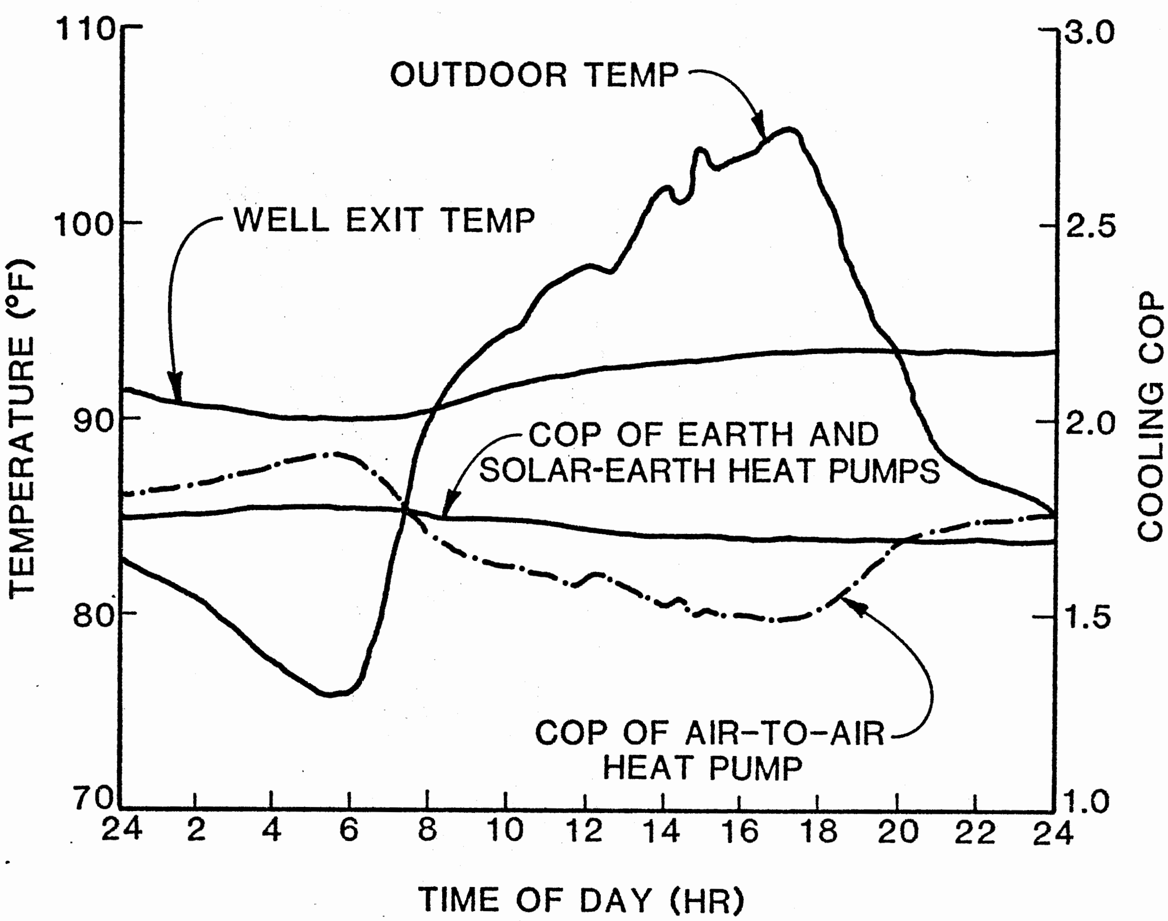

Figure 17. Simulated Effect of Temperature on the Cooling Coefficient of Performance (August 5, 1980)

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

A heat pump simulation model was constructed to simulate the performances of an air-to-air, an earth-source/sink, and a solar-assisted earth-source/sink heat pump systems. With the aid of the building cooling/heating load simulation program CHLSYM (30), the model is capable of predicting the heat pump cyclic performance as influenced by the building external and internal loads. The model was validated using the few days of available useable computer data and was found to be in reasonable agreement with the recorded data.

The model was used to compare the performances of the three heat pump systems during both summer and winter operations when subjected to similar external and internal loads. The outcome of these comparisons favors both the earth and solar-earth heat pump systems. The simulation results indicate that the earth-source/sink heat pumps operate at a relatively constant coefficient of performance and consume less electrical energy to perform the same duties required from an air-to-air heat pump. This is especially true for winter operations as demonstrated by the results of Table IX. It should be noticed that throughout the winter simulation period, neither of the earth coupled heat pump systems required resistance heat although the outdoor temperatures were in the low teens for long durations. Because of the relatively constant coefficient of performances, lower energy consumption, and the possibility of very low backup resistance heat requirement, it can be concluded that earth source heat pumps would prove to be very helpful in reducing the load peaking problems of the electric utility companies.

Neither the summer or the winter simulation results showed the anticipated advantages of the solar loop in the solar-earth heat pump system. However, the available recorded winter data for the middle house indicate that the solar loop can be of a great help in maintaining the well water temperatures at a level much above freezing during very cold sunny days. No definite conclusion can be made regarding the summer performance of the solar loop.

It should be noted that all the conclusions made regarding the efficiency and power consumption of the heat pump units do not take into consideration the difference in the rated capacities and designs of the heat pump equipments.

Some suggestions regarding further work on this project are listed in the following:

1. Currently, the well inlet and outlet temperatures are measured across the heat pump. This arrangement does not allow the effect of the solar loop heat exchange on the water entering the well to be seen. The suggestion is to measure the well inlet temperature downstream of the solar loop.
2. More study of the summer data of the middle house is needed in order to determine the extent of summer solar assist.
3. Multiple-well arrangement should be studied and compared to the solar loop in the earth coupled heat pump system.

4. Economic study should be performed in order to determine the economic feasibility of the inclusion of the solar loop in the earth coupled heat pump system.
5. If possible, the telephone link with data logger should be connected to the computer for short period (few days) data file creation. This might prove helpful in monitoring and presention of the measured data graphically.
6. It is strongly suggested that more frequent communications be made with the Perkins houses occupants regarding daily indoor activities. This will be very helpful in future simulations.

REFERENCES

1. Calm, J. M. "Heat Pump Systems for District Heating and Cooling". ASHRAE Journal, Vol. 21, No. 9 (Sept. 1979), pp. 54-58.

2. Pietsch, J. A. "The Unitary Heat Pump Industry - 25 years of Program". ASHRAE Journal, Vol. 19, pt. 2 (July 1977), pp. 15-18.

3. Duffy, G. and T. A. Mahoney. "Statistical Panorama". Air Conditioning, Heating and Refrigerating News (January 29, 1979), pp. 52-61.

4. Greiner, P. C. "Electric Utility Outlook for Heat Pumps". Heat Pump Technology Conference. Stillwater: Oklahoma State University, 1975.

5. Christian, J. E. Unitary Water-to-Air Heat Pumps. Oak Ridge, Tennessee: Oak Ridge National Laboratory, Lab. Report ANL/CES/TE-77-9, 1977.

6. Smith, Wade W. "Water Cooled Heat Pumps: Energy Savers?". Heating Piping, and Air Conditioning, Vol. 51, pt. 1 (March 1979), pp. 49-61.

7. Crane, R. E., H. G. Lorsch, and R. G. Werden. "Integrated Community Energy System Based on Existing Heat Pump Technology". Proceedings of the 5th Annual Heat Pump Technology Conference. Stillwater: Oklahoma State University, 1980.

8. Collins, W. D. "Temperature of Water Available for Industrial Use in the United States". U.S. Geological Survey Water Supply, Paper 520-F, 1925.

9. Kusuda, T. and P. R. Achenbach. "Earth Temperature and Thermal Diffusivity at Selected Stations in the United States". ASHRAE Trans., Vol. 71, pt. 1 (1965), pp. 61-75.

10. Kemler, E. N. "Methods of Earth Heat Recovery for the Heat Pump". Heating and Ventilating, Vol. 44 (Sept. 1947), pp. 69-72.

11. Bose, J. E., C. W. Ledbetter, and J. R. Partin. "Experimental Results of a Low Cost Solar-Assisted Heat Pump Using Earth Coil and Geothermal Well Storage". Proceedings of the Fourth Annual Heat Pump Technology Conference. Stillwater: Oklahoma State University, 1979.

12. Andrews, J. W. and P. D. Metz. "Computer Simulation of Ground Coupled Storage in a Series Solar Assisted Heat Systems". Unpublished report, Brookhaven National Laboratory, New York: Upton, 1978.

13. Hiller, C. C. and R. Glickman. Improving Heat Pump Performance Via Compressor Control-Analysis and Test. Cambridge, Massachusetts: Heat Transfer Laboratory, Massachusetts Institute of Technology, Report No. 24525-96, 1976.

14. Kelly, G. E. and J. Bean. "Dynamic Performance of a Residential Air-to-Air Heat Pump". Second Annual Heat Pump Technology Conference. Stillwater: Oklahoma State University, 1976.

15. Groff, G. C. and C. E. Bullock. "A Computer Simulation Model for Air-Source Heat Pump System Seasonal Performance Studies". Second Annual Heat Pump Technology Conference. Stillwater: Oklahoma State University, 1976.

16. Murphy, W. E. and V. W. Goldschmidt. "The Degradation Coefficient of a Field-Tested Self-Contained 3-Ton Air Conditioner". ASHRAE Trans., Vol. 85, pt. II (1979), pp. 396-405.

17. Goldschmidt, V. W., G. H. Hart, and R. C. Reiner. "A Note on the Transient Performance and Degradation Coefficient of a Field Tested Heat Pump - Cooling and Heating mode". ASHRAE Trans., Vol. 86, pt. II (1980), pp. 368-375.

18. Hart, G. H. and V. W. Goldschmidt. "Cycle Times of a Unitary Heat Pump Under a Revised Cycle for Defrosting: Some Measurements and Observations". Heat Pump Technology Conference. Stillwater: Oklahoma State University, 1978.

19. Bullock, C. E. and W. R. Reedy. "Heat Pump Cyclic Performance and it's Influence on Seasonal Operation". Heat Pump Technology Conference. Stillwater: Oklahoma State University, 1978.

20. Parkins, W. Jr., R. W. Beausoliel, and G. Kelly. "Factors Affecting the Performance of a Residential Air-to-Air Heat Pump". ASHRAE Trans., Vol. 83, pt. I (1977), pp. 839-849.

21. Bonne, U., A. Patini, R. D. Jacobson, and D. A. Mueller. "Electric Driven Heat Pump Systems: Simulation and Controls". ASHRAE Trans., Vol. 83, pt. I (1977), pp. 849-859.

22. Lawrence, R. A. "Performance of Heat Pumps Using Cold-Side Energy Storage and Unconventional Heat Sources". Presented at ASME Winter Annual Meeting, Paper 74-WA/HT-17, November 1974.

23. Freeman, T. L., W. A. Beckman, J. W. Mitchell, and J. A. Duffie. "Computer Modeling of Heat Pumps and the Simulation of Solar Energy-Heat Pump Systems". M.S. Thesis, University of Wisconson, Madison, Wisconson, June 1975.

24. Solar Energy Laboratory of University of Wisconson. "TRNSYS-A Transient Simulation Program". Engineering Experiment Station Report 38, December, 1976.

25. Schlosser, K. and B. Teislev. "Mathematical Simulation of a Solar Assisted Heat Pump System Using the Ground for Energy Storage". Energy and Buildings, Vol. 2, No. 1 (Jan. 1979), pp. 37-43.

26. Duffie, J. and W. Beckman. Solar Energy Thermal Process. New York: John Wiley & Sons Inc., 1974.

27. Carrier Corporation. "38CQ Split System Heat Pump Outdoor Sections". Catalog No. 523-858, Syracuse, New York, 1978; 40 AQ & 40 AS Direct Expansion Fan Coils, Catalog No. 524-045, Syracuse, New York, 1978; Heat Pump Control, Instructions, Catalog No. 60-0524-3, Syracuse, New York, 1978.

28. Command-Aire Corporation. "Single Package Water to Air Heat Pumps". Series 070-500, Catalog No's. SWP 79330-DB and SWPCAP 79515-5MA, Waco, Texas.

29. Frierson, Beverly. "Data Acquisition and Management for Three Heat Pump Study Homes". M.S. Report, School of Mechanical and Aerospace Engineering, Oklahoma State University, May 1981.

30. Mechanical and Aerospace Engineering Department. "CHLSYM-A Transient Simulation Program". Stillwater: Oklahoma State University, 1979.

31. American Society of Heating, Refrigerating, and Air-Conditioning Engineers. ASHRAE Handbook of Fundamentals. New York 1972.

32. Peavy, B. A. "A Model for Predicting the Thermal Performance of Ventilated Attics". Washington, D.C.: Center for Building Technology, National Bureau of Standards, 1979.

33. Lunde, Peter J. Solar Thermal Engineering. New York: John Wiley & Sons, 1980.

34. Wise, D. M. "Analysis of a Vertical Ground Coil Heat Storage/Source System". M.S. Report, Oklahoma State University, July 1979.

35. Kanchanalai, K. "Numerical Analysis of a Vertical Ground Coil Assisted Heat Pump". M.S. Report, Oklahoma State University, December 1979.

36. Carslaw, H. S. and J. C. Jaeger. Conduction of Heat in Solids. Oxford: Oxford University Press, 1949.

37. Parker, J. D., J. H. Boggs, and E. F. Blick. Introduction to Fluid Mechanics and Heat Transfer. Massachusetts: Addison-Wesley Publishing Co., 1974.

38. Moss, J. T. and P. D. White. "How to Calculate Temperature Profiles in a Water-Injection Well". The Oil and Gas Journal, Vol. 59, (March 9, 1959), pp. 174-178.

39. Shenck, H. Fortran Methods in Heat Flow. New York: The Ronald Press Co., 1963.

40. Dusinberre, G. M. Heat Transfer Calculations by Finite Differences. Scranton, Pennsylvania: International Textbook Co., 1961.

41. Kays, W. M. and M. E. Crawford. Convective Heat and Mass Transfer. New York: McGraw-Hill Book Co., 1980.

42. Croft, D. and D. Lilley. Heat Transfer Calculations Using Finite Difference Equations. London: Applied Science Publishers, 1977.

APPENDIXES

APPENDIX A

PHYSICAL DATA, DIMENSIONS, AND PERFORMANCE DATA FOR THE HEAT PUMP UNITS

Carrier 38C[015 Air-to-Air Heat Pump Physical Data and Dimensions

Outdoor Section

UNIT	38CQ						
	015	020	027	033	039	044	048
OPER WT (lb)	145	160	166	180	210	212	222
REFRIGERANT*	22						
Refrig Control	AccuRater™						
COMPRESSOR	Hermetic						
Cylinders	2						
Rpm (60-Hz)	3500						
FAN	Propeller-Type, Direct Drive						
Air Discharge	Vertical						
Air Qty (cfm)	2000	2000	2600	2800	2800	2600	3400
Motor Hp	1/8	1/8	1/4	1/4	1/4	1/4	1/2
Motor Rpm	1075	1075	1075	1075	1075	1075	1075
COIL (Type)	Plate Fin						
Number	1						1.7
Fins/in.	19						19/15.6
Face Area (sq ft)	7	7	7	10.5	10.5	10.5	13.1
Rows	1.5	1.5	1.5	1.3	1.7	1.9	1.7
DIM. (ft-in.)							
Length A	2-10-1/4						
Width B	1-10						
Height C	1-4-1/8	1-4-1/8	1-4-1/8	2-0-1/8	2-0-1/8	2-0-1/8	2-6-1/8
CONN. (in.)	Compatible Fitting (Suction) & Flare (Liquid)						
Vapor Line†	5/8		3/4				
Liquid Line†	3/8						

*The 38CQ contains correct operating charge for complete system when connected to 40FS/28HQ,VQ; 40AQ or 40DQ indoor units with 25 ft or less of tubing of recommended diameter. Charge adjustment may be required for mix-matches. See Installation, Start-Up and Service Instructions for details.

Indoor Section

MODEL 40AS,AQ		018	024	030	036
OPERATING WT (lb)					
Standard Unit		69	83	100	114
→ Bare Box AQ		59	78	96	110
REFRIGERANT		22			
Refrig Control		Bypass AccuRater™			
FAN		Centrifugal — Direct Drive			
Rpm, 60-Hz		950/850/750			
Air Discharge		Upflow, Horizontal* or Downflow			
Range Cfm		450-600	600-1000	750-1250	900-1500
PSC Motor Hp		1/8	1/4	1/3	1/3
COIL (Rows...Fins/in.)		3...13			
Face Area (sq ft)		1.64	2.02	2.52	3.16
DIMENSIONS (ft-in.)					
Length	A	1-0-3/16	1-2-3/8	1-5-1/4	1-9
Width	B	1-9-1/2			
Height	C	2-9-1/4	3-2-3/8	3-4-11/16	3-6
DUCT INLET (ft-in.)					
	D	0-9-7/8	1-0-1/8	1-2-11/16	1-6-3/8
	E	1-6-3/4			
DUCT OUTLET (ft-in.)					
	F	0-9-13/16	1-0-1/16	1-2-15/16	1-6-5/8
	G	0-9-11/16			
CONNECTIONS (in.)					
Suction ODF†	H	5/8	5/8	3/4	3/4
Liquid ODF†	J	3/8			
Condensate, FPT		3/4			
FILTER‡ (1)		Permanent, 1-in. thick			

Carrier 38CQ015/40AQ018 Air-to-Air Heat Pump Heating and Cooling Performance

INTEGRATED HEATING CAPACITIES*

OUTDOOR UNIT	INDOOR UNIT	TEMPERATURE OF AIR ENTERING OUTDOOR UNIT (Edb)																					
		-10		0		10		17		20		30		40		47		50		60		70	
		Cap.	Kw	Cap.	Kw	Cap.	Kw	Cap.	Kw	Cap.	Kw	Cap.	Kw	Cap.	Kw	Cap.	Kw	Cap.	Kw	Cap.	Kw	Cap.	Kw
38CQ015	40AQ018	4.5	1.3	5.5	1.6	7.0	1.6	8.5	1.7	9.0	1.7	11.0	1.7	13.5	1.3	16.5	2.0	17.5	2.1	20.5	2.2	24.0	2.2

38CQ015/40AQ018

Temp (F) Air Ent Outdoor Unit		Air Ent Indoor Unit — Cfm/BF								
		515/.10			575/.11			645/.12		
		Indoor Unit Ent Air Temp — Ewb (F)								
		72	67	62	72	67	62	72	67	62
85	TC	16.5	15.6	14.7	16.4	15.6	14.9	16.5	15.7	15.2
	SHC	8.4	11.1	13.7	8.4	11.5	14.3	8.7	11.9	14.8
	KW	2.08	2.03	1.98	2.10	2.06	2.02	2.14	2.10	2.07
95	TC	16.4	15.3	14.1	16.4	15.5	14.4	16.6	15.6	14.7
	SHC	8.4	11.4	13.6	8.6	11.9	14.2	8.9	12.4	14.6
	KW	2.23	2.17	2.10	2.25	2.20	2.14	2.30	2.24	2.19
100	TC	16.2	15.0	13.8	16.3	15.1	14.1	16.4	15.3	14.4
	SHC	8.5	11.2	13.4	8.7	11.8	13.9	9.0	12.3	14.4
	KW	2.30	2.23	2.15	2.33	2.26	2.19	2.38	2.31	2.25
105	TC	16.1	14.7	13.4	16.2	14.8	13.7	16.3	15.0	14.1
	SHC	8.5	11.1	13.1	8.8	11.6	13.6	9.1	12.3	14.1
	KW	2.38	2.28	2.20	2.41	2.32	2.25	2.46	2.37	2.31
115	TC	15.8	14.0	12.8	15.9	14.1	13.1	16.1	14.3	13.4
	SHC	8.5	10.8	12.7	8.9	11.4	13.1	9.3	12.1	13.5
	KW	2.53	2.40	2.30	2.58	2.44	2.36	2.61	2.49	2.42

Cap. — Capacity (1000 Btuh), includes fan motor heat and deduction for thermal line losses of 15 ft of piping exposed to outdoor conditions.

Kw — Power input includes compressor motor power input, indoor and outdoor fan motor input.

*Integrated Heating Capacities — Values shown reflect a capacity reduction at those outdoor air temperatures at which frost forms on outdoor coil.

HEATING CAPACITY CORRECTION FACTORS

CFM/TON* ENT INDOOR COIL	CORRECTION FACTORS		TEMP AIR ENT INDOOR COIL (F)	CORRECTION FACTORS	
	Cap.	Power		Cap.	Power
400	.98	.99	65	1.02	.99
450	1.0	1.0	70	1.0	1.0
500	1.02	1.01	75	.98	1.01

*Determine cfm/ton from Combination Rating tables.

COMBINATION RATING NOTES

1. Direct interpolation is permissible. Do not extrapolate.
2. SHC is based on 80 F db temperature of air entering indoor unit. Below 80 F db, subtract (corr factor x cfm) from SHC.
   Above 80 F db, add (corr factor x cfm) to SHC.

BYPASS FACTOR	ENTERING AIR DRY-BULB TEMP (F)					
	79	78	77	76	75	under 75
	81	82	83	84	85	over 85
	Correction Factor					
.10	.98	1.96	2.94	3.92	4.91	Use formula shown below.
.20	.87	1.74	2.62	3.49	4.36	
.30	.76	1.53	2.29	3.05	3.82	

Interpolation is permissible.
Correction Factor = 1.09 x (1 - BF) x (db - 80)

Command-Aire SWP-150 Water-to-Air Heat Pump Physical Data and Dimensions

MODEL: SWP		150
Capacities at ARI Standard Conditions	COOLING	19,500
	EER	8.6
	HEATING (SWP only)	28,000
	COP	3.3
BLOWER: Centrifugal Direct Drive	Dia. & Width	9x7
	CFM Range	450-750
MOTOR:	HP	1/8
	RPM	1075
COIL: Plate Fin	Fins per Inch	13
	Rows	3
	Face Area Ft.²	1.56
FILTER: Throw Away	(1'' thick) SIZE	14½x17¼
	OPERATING WEIGHT	200
	SHIPPING WEIGHT	210
HEAT EXCHANGER:		Tube and shell, 3/4'' Finned Copper Tube, Hydrostatic pressure-tested to 2250 lbs.

MODEL:	BLOWER PERFORMANCE Actual CFM / External Static Pressure	WATER PRESSURE DROP THRU HEAT EXCHANGER GPM/ΔP, PSI
150	800/.15 600/.49 400/.67 700/.35 500/.59	5.0/1.7 4.0/1.2 3.0/.75

Command-Aire SWP-150 Water-to-Air Heat Pump Heating and Cooling Performance

Cooling Performance 150

EWT	600 CFM 80° ENT. DB TEMP.	ENTERING AIR WET BULB TEMP. 3 GPM 63°	3 GPM 67°	3 GPM 71°	4 GPM 63°	4 GPM 67°	4 GPM 71°	5 GPM 63°	5 GPM 67°	5 GPM 71°
80°	TOTAL / SENSIBLE MBH	17.0 / 14.9	18.0 / 12.7	19.2 / 10.4	18.2 / 15.4	19.5 / 13.2	20.8 / 10.8	19.0 / 15.6	20.4 / 13.6	21.8 / 11.3
	COMPRESSOR INPUT KW	2.31	2.44	2.56	2.13	2.23	2.33	2.04	2.11	2.19
	HEAT REJECTED MBH	25.6	27.0	28.6	26.1	27.8	29.4	26.6	28.3	30.0
90°	TOTAL / SENSIBLE MBH	15.9 / 14.4	17.0 / 12.3	17.9 / 9.9	17.1 / 14.9	18.4 / 12.8	19.7 / 10.6	18.0 / 15.2	19.4 / 13.2	20.7 / 10.9
	COMPRESSOR INPUT KW	2.46	2.58	2.70	2.27	2.38	2.48	2.16	2.27	2.35
	HEAT REJECTED MBH	25.0	26.5	27.8	25.5	27.2	28.8	26.1	27.8	29.4
100°	TOTAL / SENSIBLE MBH	14.9 / 14.0	15.8 / 11.8	16.6 / 9.3	16.1 / 14.5	17.2 / 12.3	18.4 / 10.1	16.9 / 14.8	18.2 / 12.7	19.5 / 10.5
	COMPRESSOR INPUT KW	2.62	2.74	2.86	2.43	2.55	2.65	2.32	2.42	2.52
	HEAT REJECTED MBH	24.5	25.8	27.0	25.1	26.6	28.1	25.5	27.1	28.8

Air Volume Factor - Cooling

CFM	400	500	600	700	800
TOT COOL & HT REJ MBH	0.92	0.97	1.00	1.03	1.05
SENSIBLE COOLING MBH	0.83	0.92	1.00	1.07	1.14
COMPRESSOR INPUT KW	0.97	0.99	1.00	1.01	1.02

Air Volume Factor - Heating

CFM	400	500	600	700	800
TOTAL HEATING MBH	0.97	0.98	1.00	1.01	1.02
HEAT EXTRACTED MBH	0.91	0.95	1.00	1.03	1.06
COMPRESSOR INPUT KW	1.21	1.09	1.00	0.93	0.90

Sensible Cooling Factor for Other Dry Bulb Temps.

ENT. W.B.	ENTERING AIR DRY BULB TEMP. 74°	76°	78°	80°	82°	84°	86°
63°	0.82	0.89	0.96	1.00	1.10		
67°		0.83	0.91	1.00	1.07	1.14	1.22
71°				1.00	1.07	1.16	1.25

150 SW - SWP
SWH - SWPH

Heating Performance 150

EWT	600 CFM	ENTERING AIR DRY BULB TEMP. 3 GPM 60°	3 GPM 70°	3 GPM 80°	4 GPM 60°	4 GPM 70°	4 GPM 80°	5 GPM 60°	5 GPM 70°	5 GPM 80°
60°	TOTAL HEATING MBH	21.6	21.0	20.5	23.6	22.9	22.5	24.8	24.1	23.6
	HEAT EXTRACTED MBH	15.3	14.5	13.7	17.0	16.0	15.2	17.5	16.5	15.5
	COMPRESSOR INPUT KW	1.87	1.93	2.02	1.96	2.05	2.15	2.14	2.25	2.39
70°	TOTAL HEATING MBH	23.9	23.2	23.0	26.2	25.6	25.1	27.4	26.7	26.2
	HEAT EXTRACTED MBH	17.2	16.2	15.5	19.0	18.0	17.0	19.5	18.4	17.4
	COMPRESSOR INPUT KW	1.99	2.07	2.22	2.13	2.25	2.39	2.34	2.46	2.59
80°	TOTAL HEATING MBH	26.1	25.9	25.6	28.9	28.4	27.7	30.1	29.5	28.8
	HEAT EXTRACTED MBH	19.0	18.2	17.4	21.1	20.0	18.8	21.5	20.4	19.3
	COMPRESSOR INPUT KW	2.10	2.26	2.42	2.31	2.47	2.63	2.54	2.67	2.80

APPENDIX B

LDSIM INPUT LIST AND PROGRAM LISTING

INPUT LIST AND FORMAT

User's input to LDSIM simulation program is in the NAMELIST format. The input variables are:

/INPT/

IHOUSE - Index identifying the house to be simulated

= 1 (East House)

= 2 (Middle House)

= 3 (West House)

MONTHS - The month in which simulation is to be performed

MDAY1 - The first day of simulation

MDAY2 - The last day of simulation

NPRT - Type of output described

(a) NPRT = 0... Total load for each day

(b) NPRT = 1... a above, plus hour by hour load for each day

(c) NPRT = 2... b above, plus atmospheric dry bulb, wet bulb, humidity differences, sensible, latent and total loads.

(d) NPRT = 3... c above plus individual contributions

(e) NPRT = 4... d above, plus sol-air temp., heat gain through each surface

Note: When NPRT>2 the output will be very large for periods greater than one day.

INWRIT - Index for writing input data

= 0 (input data will not be written)

= 1 (input data will be written)

PRNT - Index for writing loads into the link file

= 0 (loads will not be output to link file)

= 1 (loads will be output to link file)

/NAM4/

NPN - Number of people in the house during nighttime

NPD - Number of people in the house during daytime

CFMN - (Infiltration and ventilation) in CFM During nighttime

CFMD - (Infiltration and ventilation) in CFM during daytime

OFST - Daytime starting hour (e.g. OFST = 8.0)

OFCT - Nighttime starting hour (e.g. OFCT = 17.0)

/NAM5/

QOTSN - Sensible heat loads (e.g., appliances) during nighttime, (Btu/hr)
QOTSD - Sensible heat loads (e.g., appliances) during daytime, (Btu/hr)
QOTLN - Latent heat loads (e.g., appliances) during nighttime, (Btu/hr)
QOTLD - Latent heat loads (e.g., appliances) during daytime, (Btu/hr)
QFLD - Flourescent lights during daytime, KW

/NAM6/

QFLN - Flourescent lights during nighttime, KW

QTLN - Tungsten lights during nighttime, KW

QTLD - Tungsten lights during daytime, KW

TROOM - Room design temperature, F

NHTX - Index for calling HEATX subroutine

(a) NHTX = 0... No call

(b) NHTX = 1... Call HEATX

IHTG - Index for input sensible heat generation

(a) IHTG = 0... sensible heat loads are read from measured data. Values in NAM5 and NAM6 will not be used in the program

(b) IHTG = 1... the user must input values of variables in NAM5 and NAM6

/NAM7/

ERMAX - Maximum capacity of heating/cooling equipment, Btu/hr (negative for heating and positive for cooling)

ERMIN - Minimum capacity of heating/cooling equipment, Btu/hr (negative for heating and positive for cooling)

FLAREA- Total floor area of the building, ft^2

THRANG- Thermostat range - the dead band, F

/NAM8/

THSETD - Thermostat set temperature during daytime, F

THSETN - Thermostat set temperature during nighttime, F

THTIMD - Thermostat set time in the daytime (THTIMD = OFST-1)

THTIMN - Thermostat set time in the nighttime (THTIMN = OFCT)

Note: Other input values concerning building geometry, transfer function coefficients, latitude, longitude, etc. are stored in three files, one for each house. The files are called

'OSU.ACT11451.FF.DATA(EHOUSE)'

'OSU.ACT11451.FF.DATA(MHOUSE)'

'OSU.ACT11451.FF.DATA(WHOUSE)'

These data will be automatically read from the respective files according to the house index specified in the input list.

LDSIM PROGRAM LISTING

```
000000000111111111122222222223333333333444444444455555555556666666666777777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
C
C***************************************************************************
C                                                                          *
C      BUILDING COOLING AND HEATING LOAD SIMULATION PROGRAM                *
C                                                                          *
C***************************************************************************
C
C
C
C      THIS PROGRAM CALCULATES THERMAL LOAD OF A BUILDING
C      USING TRANSFER FUNCTION TECHNIQUE AND
C      HOURLY WEATHER INFORMATION
C      THIS PROGRAM SIMULATES THE WHOLE PERIOD HOUR BY HOUR
C
C
       INTEGER FLUX
       REAL*8 ORIENT,ZORNT
C
       COMMON/SOL1/ ATCE(24),SOLH(24),XID(24),XIDHV(24),XIT(24)
       COMMON/SOL2/ XLATR,EPR,PSIR,DLONG,IDAY1
       COMMON/SOL3/ SH(24),CH(24),CZ(24),CT(24),CE,RTD
       COMMON/BLOCK1/IIN,IOT,MC,NPRT,INWRIT,TROOM,OFST,OFCT,CFMD,XKT,XLF,
      &        INIT,INHX,MONTH,IDAYM
       COMMON/BLOCK2/QTOTAL(24),PRNT,IHOUSE
C
       DIMENSION PHO(24),RHI(24),HO(24),WV(24),ATWBI(24)
       DIMENSION ATWB(24),DATR(24),DW(24),ALPAJ(8),TAUJ(8)
       DIMENSION SHGF(24),QEW(24),TSW(24),TSWR(10,48),BT(7),DT(7)
       DIMENSION QEWR(10,48),QSSW(48),QSSWR(48),QED(24),QSWR(24)
       DIMENSION QFLS(48),QTLS(24),QPPS(24),QPPL(24),QOTHS(24),QOTHL(24),
      * QIVS(24),QIVL(24),Q30(24),Q31(24),Q34(48),Q35(24)
       DIMENSION SGV(12),CWRV(12),HGLV(12),HGEPRV(12),RTFW(12)
       DIMENSION QSFW(48),Q37(48),Q38(48),Q39(48),QTSHL(24)
       DIMENSION CRATFG(12),CRATFP(12),NDYM(13)
       DIMENSION ZWRL(10),ZWRW(10),ZAD(10),ZAW(10),ZEPR(10),ZPSIR(10),
      1ZHO(10,24),ZHI(10,24),ZRCG(10),ZALP(10),ZEPSWR(10),ZSCG(10),
      2ZUWRA(10),ZUW(10),ZUD(10),ZORNT(10),ZBT(10,7),ZUWRT(10),
      3ZDT(10,7),ZAWR(10),ZXNI(10,24),ZCNS(10),ZCNST(10)
C
       NAMELIST /INPT/IHOUSE,MONTHS,MDAY1,MDAY2,NPRT,INWRIT,PRNT
       NAMELIST /NAM1/NWAR,MC,XLAT,ACLONG,STLONG,XLF
      1    /NAM2/WRL,WRW,AD,AW,EPSILN,PSI,HI,RCG,ALPHWR,EPSWR,SCG,UWRA
      2    ,UW,UD,ORIENT
      3    /NAM3/BT,DT,UWRT
      4    /NAM4/NPN,NPD,CFMN,CFMD,OFST,OFCT
      5    /NAM5/QOTSN,QOTSD,QOTLN,QOTLD,QFLD
      6    /NAM6/QFLN,QTLN,QTLD,TROOM,NHTX,IHTG
C
       DATA SGV/0.2727,-0.3400,0.1169,-0.0064,0.2217,-0.3354,0.1448,
      * -0.0128,0.2155,-0.3712,0.1790,-0.0166/
       DATA CWRV/0.6982,-1.2017,0.6617,-0.1150,0.7108,-1.4456,0.9639,
      * -0.2108,0.7055,-1.5668,1.1378,-0.2698/
       DATA HGLV/0.3178,-0.4507,0.2039,-0.0328,0.2605,-0.4662,0.2819,
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12345678901234567890123456789012345678901234567890123456789012345678901234567890
     * -0.0579,0.2430,-0.5085,0.3547,-0.0825/
      DATA HGEPRV/0.3251,-0.4267,0.1524,-0.0076,0.2574,-0.4036,0.1830,
     * -0.0183,0.2503,-0.4446,0.2255,-0.0245/
      DATA RTFW/0.000,-1.8260,1.0697,-0.2005,0.000,-2.1092,1.4606,
     * -0.3331,0.000,-2.2906,1.7252,-0.4277/
      DATA CRATFG/1.73,-3.50,2.22,-0.45,1.88,-4.22,3.08,-0.74,1.89,
     * -4.55,3.61,-0.95/
      DATA CRATFP/1.000,-1.8260,1.0697,-0.2005,1.000,-2.1092,1.4606,
     * -0.3331,1.000,-2.2908,1.7252,-0.4277/
C
C     COEFFICIENTS FOR REGULAR DS SHEET GLASS
C
      DATA ALPAJ/0.01154,.77674,-3.94657,8.57881,-8.38135,3.01188,0.,0./
      DATA TAUJ/-0.00885,2.71235,-0.62062,-7.07329,9.75995,-3.89922,0.0,
     * 0.0/
C
      DATA  NAT,NSCG,MONTH1,MONTH2/6,0,1,1/
      DATA NDYM/ 1,32,61,92,122,153,183,214,245,275,306,336,366/
C
   10 FORMAT(1X )
   20 FORMAT(/)
   30 FORMAT(1H1)
   40 FORMAT(56X,'LOAD CALCULATIONS')
   50 FORMAT(48X,35('*'))
   70 FORMAT( 3( 2X,8(5X ,I2 ,2X,F5.1 ) ,/))
   80 FORMAT( 5X,'SOLAR INCIDENT ENERGY ON SURFACE',2X,A8,2X,'IN BTU/HR-
     *FT**2')
   90 FORMAT( 5X,'SOL-AIR TEMPERATURE FOR SURFACE',2X,A8,2X,'IN F')
  100 FORMAT( 5X,'SOLAR HEAT GAIN FACTOR FOR WINDOW ON SURFACE',2X,A8,2X
     *,'IN BTU/HR-FT**2')
  110 FORMAT( 5X,'SOL-AIR TEMPERATURE FOR WINDOW ON SURFACE',2X,A8,2X,
     *'IN F')
  120 FORMAT( 5X,'HEAT GAIN THROUGH SURFACE',2X,A8,' IN BTU/HR      AREA=
     * ',F8.0,1X,'SQ.FT.')
  130 FORMAT( 3( 4X,8(2X ,I2,2X,F8.0) ,/))
  150 FORMAT( 5X,'HEAT GAIN THROUGH WINDOW ON SURFACE',2X,A8,' IN BTU/HR
     *      AREA= ',F6.1,' SQ.FT.')
  160 FORMAT( 5X,'HEAT GAIN THROUGH  DOOR  ON SURFACE',2X,A8,5X,'AREA=',
     *F6.1,'FT**2',2X,'IN BTU/HR')
  180 FORMAT( 52X,'INST SENSIBLE HEAT GAIN (BTU/HR)')
  190 FORMAT( 10X,'TIME',3X,'ON-OFF LIGHTS',4X,'ON LIGHTS',6X,'PEOPLE',
     * 9X,'EQUIPMENT',6X,'INFL&VENT', 7X,'SURFACES', 13X,'TOTAL')
  200 FORMAT( 10X,I3,1X,6E15.4, E18.4)
  210 FORMAT( 52X,'LATENT HEAT LOADS (BTU/HR)')
  220 FORMAT( 10X,'TIME',5X,'PEOPLE',9X,'EQUIPMENT',6X,'INFL&VENT',10X,
     *  'TOTAL')
  230 FORMAT( 10X,I3,1X,3E15.4,E18.4)
  240 FORMAT( 35X,'SENSIBLE COOLING LOAD COMPONENTS DUE TO VARIOUS HEAT
     *GAINS (BTU/HR)')
  250 FORMAT( 10X ,'TIME' ,5X,'INSTANT',5X,'LIGHTS ON OFF',5X,'SURFACES'
     * ,5X,'PEOPLE&EQUIP',5X,'WINDOWS UNSH',7X,'TOTAL')
  260 FORMAT( 10X,I4 ,5E15.4,E18.4)
  270 FORMAT( 48X,'TOTAL COOLING/HEATING LOAD (BTU/HR)')
  280 FORMAT( 10X,'TIME',5X,'DB TEMP',3X,'WB TEMP',3X,'HUM DIF',10X,
     $'SENSIBLE',12X,'LATENT',15X,'TOTAL')
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  250 FORMAT( 10X,I4,2F10.1,F13.6,3E20.5)
  300 FORMAT(10X,'THE TOTAL LOAD FOR THE WHOLE DAY',I5,'  OF MONTH',I5,
     $//,10X,'COOLING=',E12.5,2X,'HEATING=',E12.5,5X,'ROOM TEMP=',F5.1)
C
C
C      HOUSE INDEX
C
C      IHOUSE=1     (EAST HOUSE)
C      IHOUSE=2     (MIDDLE HOUSE)
C      IHOUSE=3     (WEST HOUSE)
C
C
       READ(5,INPT)
       RTD=57.29578
       MONTH1=MONTHS
       MONTH=MONTHS
       IIN=5
       IOT=6
       INIT=0
       MC=2
       NWAR=6
       IFLAGD=0
       XLF=0.0
       XKT = 0.0
       XLAT=36.0
       STLONG=90.0
       ACLONG=97.0
       PB=14.696
       DLONG=(STLONG-ACLONG)/15.0
       READ(IHOUSE,NAM1)
       IF(INWRIT.LE.0)  GO TO 310
       WRITE(IOT,30)
       WRITE(IOT,NAM1)
  310  MDAY=1
       NCHECK=96*(1+MDAY2-MDAY1)
       IF(MDAY1.EQ.19) GO TO 320
       KDAY=MDAY1-1
       DO 3131 I=1,18000
       READ(4,2)MDAY,MHR,MIN
    2  FORMAT(5X,I2,6X,I2,6X,I2,/////)
       IF(MDAY.GT.MDAY1) GO TO 919
       IF(MDAY.EQ.KDAY.AND.MHR.EQ.23.AND.MIN.EQ.45) GO TO 320
 3131  CONTINUE
  320  XLATR=XLAT/RTD
       DO 340  NS=1,NWAR
       WRL=0.0
       WRW=0.0
       AD=0.0
       AW=0.0
       PSI=0.0
       EPSILN=90.0
       HI=1.46
       ROG=0.2
       ALPHWR=0.8
       EPSWR=0.9
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         SCG=0.0
         UWRA=0.0
         UW=0.0
         UD=0.0
         DO 342 I=1,7
         BT(I)=0.0
         DT(I)=0.0
  342    CONTINUE
         READ(IHOUSE,NAM2)
         UWRT=UWRA
         READ(IHOUSE,NAM3)
         IF(INWRIT.LE.0)  GO TO 344
         WRITE(IOT,20)
         WRITE(IOT,NAM2)
         WRITE(IOT,20)
         WRITE(IOT,NAM3)
  344    ZWRL(NS) = WRL
         ZWRW(NS) = WRW
         ZAD(NS) = AD
         ZAW(NS) = AW
         ZEPR(NS) = EPSILN/RTD
         ZPSIR(NS) = PSI/RTD
         ZROG(NS) = ROG
         ZALP(NS) = ALPHWF
         ZEPSWR(NS) = EPSWR
         ZSCG(NS) = SCG
         ZUWRA(NS) = UWRA
         ZUW(NS) = UW
         ZUD(NS) = UD
         ZORNT(NS) = ORIENT
         ZAWR(NS) = (WRL*WRW)-AD-AW
         XKT=XKT+(ZAWR(NS)*UWRA)+(AD*UD)+(AW*UW)
         UR = UWRA/UWRT
         ZCNS(NS) =0.0
         DO 346 I=1,7
         ZBT(NS,I)=BT(I)*UR
         ZDT(NS,I)=DT(I)
         ZCNS(NS)=ZCNS(NS)+ZBT(NS,I)
  346    CONTINUE
         ZDT(NS,1)=0.0
  340    CONTINUE
         XKT=XKT/X_F
         FC1=1.0-(0.019*XKT)
         FC2=1.0-(0.016*XKT)
         FC3=1.0-(0.022*XKT)
         FC4=1.0-(0.025*XKT)
         I=(4*MC)-3
         I3=I+3
         IJ=1
         DO 350 J=I,I3
         SGV(IJ)=SGV(J)*FC1
         CWRV(IJ)=CWRV(J)*FC2
         HGLV(IJ)=HGLV(J)*FC3
         HGEPRV(IJ)=HGEPRV(J)*FC4
         RTFW(IJ)=RTFW(J)
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     12345678901234567890123456789012345678901234567890123456789012345678901234567890
           IJ=IJ+1
 350       CONTINUE
           IF(MDAY1.LT.1)  MDAY1=1
           IF(MDAY2.LE.0)  IFLAGD=1
           IF(MDAY1.EQ.1.AND.MDAY2.EQ.1)   MONTH2=MONTH1
           IF(MDAY2.LT.1)  MDAY2=1
           IF(MDAY1.NE.MDAY2)  MONTH2=MONTH1
           IF(IFLAGD.EQ.1)  MDAY2=32
           IF(MONTH2.LT.MONTH1)   MONTH2=MONTH1
           DO 400 MONTH=MONTH1,MONTH2
           INIHX=0
           NPN=0
           NPD=0
           CFMN=0.0
           CFMD=0.0
           QFLN=0.0
           QFLD=0.0
           QTLN=0.0
           QTLD=0.0
           OFST=8.0
           OFCT=17.0
           IENERG=0
           READ(5,NAM4)
           READ(5,NAM5)
           READ(5,NAM6)
           IF(INWRIT.LE.0) GO TO 410
           WRITE(IOT,20)
           WRITE(IOT,NAM4)
 410       WRITE(IOT,30)
           WRITE(IOT,40)
           WRITE(IOT,50)
           DO 405 NS=1,NWAR
           ZCNST(NS)=ZCNS(NS)*TRCOM
   405     CONTINUE
           NDMM=NDYM(MONTH+1)-NDYM(MONTH)
           IF(MDAY2.GT.NDMM)  MDAY2=NDMM
           DO 420  IDAYM=MDAY1,MDAY2
           NKOUNT=0
           IDAY1=0
           IDAYY=NDYM(MONTH)+IDAYM-1
           DO 430 NH=25,48
           I=NH-24
           ITDB=0
           IRHO=0
           IRHI=0
           FLUX=0
           IWV =0
           ITUSE=0
           ICRES=0
           IWHTR=0
           IHSF=0
           DO 431 IJI=1,4
           NKOUNT=NKOUNT+1
           READ(4,1) MDAY,KTOUT,KRHC,KRHE,KRHW,KRHM,KFLUX,KETOT,KWTOT,KMTOT,
          &KWV,KERES,KEWHT,KEHSH,KECOM,KEFAN,KEOFA,KWRES,KWWHT,KWHSH,KWCOM,
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        123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
             &KWFAN,KMRES,KMWHT,KMHSH,KMCOM,KMFAN
           1 FORMAT(5X,I2,19X,I5,48X,/,23X,5(4X,I4),/,7X,
            &3(4X,I4),20X,I4,/,3X,I4,2(4X,I4),8X,3(4X,I4),/,7X,5(4X,I4),/,
            &23X,5(4X,I4))
              ITDB=ITDB+KTOUT
              IWV=IWV+KWV
              IRHO=IRHO+KRHO
              IF(KFLUX.LE.1) KFLUX=0
              FLUX=FLUX+KFLUX
              IF(MDAY.GT.IDAYM.AND.NKOUNT.LT.96) GO TO 939
              IF(IHOUSE.GT.1) GO TO 801
              IRHI=IRHI+KRHE
              ITUSE=ITUSE+KETOT
              ICRES=ICRES+KERES+KECOM
              IWHTR=IWHTR+KEWHT
              IHSF=IHSF+KEHSH+KEFAN+KEOFA
         801  IF(IHOUSE.NE.2) GO TO 802
              IRHI=IRHI+KRHM
              ITUSE=ITUSE+KMTOT
              ICRES=ICRES+KMRES+KMCOM
              IWHTR=IWHTR+KMWHT
              IHSF=IHSF+KMHSH+KMFAN
         802  IF(IHOUSE.LT.3) GO TO 431
              IRHI=IRHI+KRHW
              ITUSE=ITUSE+KWTOT
              ICRES=ICRES+KWRES+KWCOM
              IWHTR=IWHTR+KWWHT
              IHSF=IHSF+KWHSH
         431  CONTINUE
              IF(IHTG.EQ.1) GO TO 637
              QOTHS(I)=3.41215*(24.0*ITUSE-0.72*ICRES-0.9*IWHTR-0.24*IHSF)
         637  WV(I)=IWV/4
              HO(I)=2.2+WV(I)*(0.32+0.001*WV(I))
              ATDB(I)=(ITDB/4.0)*0.18+32.0
              RHO(I)=IRHO/400.0
              IF(RHO(I).GT.1.0) RHO(I)=IRHO/4000.0
              IF(RHO(I).GT.1.0) RHO(I)=1.0
              RHI(I)=IRHI/400.0
              IF(RHI(I).GT.1.0) RHI(I)=IRHI/4000.0
              IF(RHI(I).GT.1.0) RHI(I)=1.0
              SOLH(I)=0.25*FLUX/2.79498
              DATR(I)=ATDB(I)-TROOM
              CALL XMOIST(ATDB(I),ATWB(I),RHO(I),2,PB,HAIR,WSAT,WAIRO,TWALL)
              CALL XMOIST(TROOM,ATWBI(I),RHI(I),2,PB,HAIR,WSAT,WAIRI,TWALL)
              DW(I)=WAIRO-WAIRI
              QSSWR(NH)=0.0
              QSSW(NH)=0.0
        430   CONTINUE
              DO 440 NS=1,NWAR
              EPR=ZEPR(NS)
              PSIR=ZPSIR(NS)
              CALL SOLAR(IDAYY)
              DO 450 IH=25,48
              I=IH-24
              QEW(I)=0.0
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            ZHO(NS,I)=HO(I)
            ZHI(NS,I)=HI
            ZXNI(NS,I)=HI/(HI+HO(I))
            IF(ZAW(NS).LE.0.0)  GO TO 452
            ALPAD=ALPAJ(1)
            TAUD=TAUJ(1)
            DUM=1.0
            DO 454 J=2,NAT
            DUM=DUM*CT(I)
            ALPAD=ALPAD+(ALPAJ(J)*DUM)
            TAUD=TAUD+(TAUJ(J)*DUM)
  454       CONTINUE
            SALPAJ=0.0
            STAUJ=0.0
            DO 456 J=1,NAT
            XJ=1.0/(J+1)
            SALPAJ=SALPAJ+(ALPAJ(J)*XJ)
            STAUJ= STAUJ+(TAUJ(J)*XJ)
  456       CONTINUE
            SHGTC=(XID(I)*TAUD)+(XIDHV(I)*2.0*STAUJ)
            SHGAC=(XID(I)*ALPAD)+(XIDHV(I)*2.0*SALPAJ)
            ALPAW=0.0
            IF(SHGAC.LE.0.0.OR.XIT(I).LE.0.0)  GO TO 458
            ALPAW=SHGAC/XIT(I)
  458       EMEW=ALPAW
            SHGF(I) = SHGTC+ZXNI(NS,I)*SHGAC
            QEW(I) = ZAW(NS)*(ZUW(NS)*DATR(I)+ZSCG(NS)*SHGF(I))
  C
  C         SOL-AIR TEMPERATURE CALCULATIONS
  C
            TSW(I)=ATDB(I)+(ALPAW*XIT(I)/ZHO(NS,I))-(EMEW*20.0*CE/ZHO(NS,I))
  452       TSWR(NS,IH)=ATDB(I)+(ZALP(NS)*XIT(I)/ZHO(NS,I))-(ZEPSWR(NS)*20.0*
           $CE/ZHO(NS,I))
  450       CONTINUE
            IF(INIT.GT.0)  GO TO 480
            DO 490 I=1,24
            IH=I+24
            QEWR(NS,I) = ZUWPA(NS)*(TSWR(NS,IH)-TROOM)
            TSWR(NS,I) = TSWR(NS,IH)
  490       CONTINUE
  480       DO 500 K=25,48
            QEWRT=ZBT(NS,1)*TSWR(NS,K)
            DO 502 J=2,7
            JJ = K+1-J
            QEWRT = (ZBT(NS,J)*TSWR(NS,JJ))-(ZDT(NS,J)*QEWR(NS,JJ))+QEWRT
  502       CONTINUE
            QEWR(NS,K) = QEWRT-ZCNST(NS)
  500       CONTINUE
            DO 510 I=1,24
            IH=I+24
            QEWR(NS,I) = ZAWF(NS)*QEWR(NS,IH)
            QED(I)=ZAD(NS)*ZUD(NS)*(TSWR(NS,IH)-TROOM)
            QSWR(I)=QEWR(NS,I)+QED(I)+QEW(I)
            QSSWR(IH) = QSSWR(IH)+QSWR(I)
            TSWR(NS,I)=TSWR(NS,IH)
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     12345678901234567890123456789012345678901234567890123456789012345678901234567890
 510    CONTINUE
        IF(ZAW(NS).LE.0.0.OR.ZSCG(NS).LT.0.9)  GO TO 520
        NSCG=1
        DO 530 I=1,24
        IH=I+24
        QSSW(IH) = QSSW(IH)+QEW(I)
 530    CONTINUE
 520    IF(NPRT.LT.4)  GO TO 545
        WRITE(IOT,20)
        IF(ZALP(NS).LE.0.0)   GO TO 535
        WRITE(IOT,80)  ZCRNT(NS)
        WRITE(IOT,70)  ((I,XIT(I),I=N,24,3),N=1,3)
        WRITE(IOT,10)
 535    WRITE(IOT,90)  ZCRNT(NS)
        WRITE(IOT,70)  ((I,TSWR(NS,I),I=N,24,3),N=1,3)
        IF(ZAW(NS).LE.0.0)  GO TO 538
        WRITE(IOT,20)
        WRITE(IOT,100) ZCRNT(NS)
        WRITE(IOT,70)  ((I,SHGF(I),I=N,24,3),N=1,3)
        WRITE(IOT,20)
        WRITE(IOT,110) ZCRNT(NS)
        WRITE(IOT,70)  ((I,TSW(I),I=N,24,3),N=1,3)
 538    WRITE(IOT,20)
        WRITE(IOT,120)  ZCRNT(NS),ZAWR(NS)
        WRITE(IOT,130)  ((I,QEWR(NS,I),I=N,24,3),N=1,3)
        IF(ZAW(NS).LE.0.0)  GO TO 540
        WRITE(IOT,20)
        WRITE(IOT,150)  ZCRNT(NS),ZAW(NS)
        WRITE(IOT,130)  ((I,QEW(I),I=N,24,3),N=1,3)
 540    IF(ZAD(NS).LE.0.0)  GO TO 545
        WRITE(IOT,20)
        WRITE(IOT,160)  ZCRNT(NS),ZAD(NS)
        WRITE(IOT,130)  ((I,QED(I),I=N,24,3),N=1,3)
 545    DO 550  I=1,24
        IH=I+24
        QEWR(NS,I)=QEWR(NS,IH)
 550    CONTINUE
 440    CONTINUE
 C
 C   CALCULATION OF HEAT GAIN DUE TO PEOPLE, LIGHTS, OTHER EQUIPMENT,
 C      VENTILATION AND INFILTRATION
 C
        DO 600 I=1,24
        IH=I+24
        XI=I
        CIVL=4840.0*DW(I)
        CFM=CFMN
        XNP=NPN
        QOTS=QOTSN
        QOTL=QOTLN
        QFLE=QFLN
        QTLE=QTLN
        IF(IHTG.EQ.1) GO TO 647
        IF(XI.GT.OFST.AND.XI.LE.OFCT) GO TO 647
        QOTHS(I)=0.95*QOTHS(I)
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         QOTHL(I)=0.10*QOTHS(I)
     647 IF(XI.LE.OFST. OR.XI.GT.OFCT)  GO TO 610
      C
      C   OFFICE HOURS
      C
         CFM=CFMD
         XNP=NPD
         QFLE=QFLD
         QTLE=QTLD
         QOTS=QOTSD
         QOTL=QOTLD
         IF(IHTG.EQ.1) GC TC 610
         QOTHS(I)=0.9*QOTHS(I)
         QOTHL(I)=0.10*QOTHS(I)
      C
      C   CFF OFFICE HOURS
      C
      610  QFLS(IH)=4095.6*QFLE
         QTLS(I)=3413.0*QTLE
         QPPS(I)=250.0*XNP
         QPPL(I)=200.0*XNP
         IF(IHTG.NE.1) GO TO 674
         QOTHS(I)=QOTS
         QOTHL(I)=QOTL
     674 QIVS(I)=CFM*1.08*DATR(I)
         QIVL(I)=CFM*CIVL
         Q30(I)=QIVL(I)+QPPL(I)+QOTHL(I)
         Q31(I)=QTLS(I)+QIVS(I)+(0.5*QPPS(I))+QOTHS(I)
         Q34(IH)=0.5*QPPS(I)
         Q35(I) = Q31(I)+QFLS(IH)+QSSWR(IH)+Q34(IH)
      600  CONTINUE
      C
      C   SENSIBLE COOLING LOAD DUE TO UNSHADED WINDOWS
      C
         IF(INIT.GT.0)  GO TO 620
         DO 630 I=1,24
         IH= I+24
         QFLS(I)=QFLS(IH)
         QSSWR(I)=QSSWR(IH)
         QSSW(I)=QSSW(IH)
         Q34(I)=Q34(IH)
         QSFW(I)=QSSW(IH)
         Q37(I)=QFLS(IH)
         Q38(I)=QSSWR(IH)
         Q39(I)=Q34(IH)
         QSFW(IH)=0.0
      630  CONTINUE
      620  IF( NSCG.NE.1)  GO TO 640
         DO 650 I=25,48
         QSSWR(I)=QSSWR(I)-QSSW(I)
      650  CONTINUE
         DO 660 K=25,48
         QSFWT = SGV(1)*QSSW(K)
         DO 655 J=2,4
         JJ = K+1-J
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      QSFWT = QSFWT+SGV(J)*CSSW(JJ)-RTFW(J)*CSFW(JJ)
 655  CONTINUE
      QSFW(K) = QSFWT
 660  CONTINUE
C
C  SENSIBLE COOLING LOAD DUE TO LIGHTS,SURFACES,AND RAD.FRAC. OF PEOPLE
C
 640  DO 670 K=25,48
      QFWRT=CWRV(1)*QSSWR(K)
      QFFLT=HGLV(1)*QFLS(K)
      QF34T=HGEPRV(1)*Q34(K)
      DO 680 J=2,4
      JJ=K+1-J
      QFFLT = QFFLT+HGLV(J)*QFLS(JJ)-RTFW(J)*Q37(JJ)
      QFWRT=QFWRT+CWRV(J)* QSSWR(JJ)-RTFW(J)*Q38(JJ)
      QF34T=QF34T+HGEPRV(J)*Q34(JJ)-RTFW(J)*Q39(JJ)
 680  CONTINUE
      Q37(K) = QFFLT
      Q38(K) = QFWRT
      Q39(K) = QF34T
 670  CONTINUE
      DO 700 I=1,24
      IH=I+24
      QSSW(I)=QSSW(IH)
      QSSWR(I)=QSSWR(IH)
      Q37(I)=Q37(IH)
      Q38(I)=Q38(IH)
      Q39(I)=Q39(IH)
      QSFW(I)=QSFW(IH)
      QFLS(I)=QFLS(IH)
      Q34(I)=Q34(IH)
 700  CONTINUE
      QTOTFC=0.0
      QTOTFH=0.0
      DO 710 I=1,24
      QTSHL(I)=QSFW(I)+Q37(I)+Q38(I)+Q39(I)+Q31(I)
      QTOTAL(I)=QTSHL(I)+Q30(I)
      IF(QTOTAL(I).GT.0.0)  QTOTFC=QTOTFC+QTOTAL(I)
      IF(QTOTAL(I).LT.0.0)  QTOTFH=QTOTFH+QTOTAL(I)
 710  CONTINUE
      QTOTFH=-QTOTFH
      IF(NPRT.LE.1)  GO TO 800
      IF(NPRT.LE.2)  GO TO 810
C
C  WRITE INSTANTANEOUS SENSIBLE HEAT GAINS
C
      WRITE(ICT,30)
      WRITE(6,180)
      WRITE(6,50)
      WRITE(6,190)
      WRITE(6,20)
      DO 820  I=1,24
      WRITE(6,200) I,QFLS(I),QTLS(I),QPPS(I),QOTHS(I),QIVS(I),QSSWR(I),
     *Q35(I)
      WRITE(6,10)
```

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00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
820   CONTINUE
C
C   WRITE LATENT HEAT GAINS
C
      WRITE(6,30)
      WRITE(6,210)
      WRITE(6,50)
      WRITE(6,220)
      WRITE(6,20)
      DO 830 I=1,24
      WRITE(6,230) I,QPPL(I),QOTHL(I),QIVL(I),Q30(I)
      WRITE(6,10)
830   CONTINUE
C
C   WRITE SENSIBLE COOLING LOAD DUE TO VARIOUS HEAT GAINS
C
      WRITE(6,30)
      WRITE(6,240)
      WRITE(6,50)
      WRITE(IOT,250)
      WRITE(6,20)
      DO 840 I=1,24
      WRITE(6,260) I,Q31(I),Q37(I),Q38(I),Q39(I),QSFW(I),QTSHL(I)
      WRITE(6,10)
840   CONTINUE
810   CONTINUE
      WRITE(6,30)
      WRITE(6,270)
      WRITE(6,50)
      WRITE(6,280)
      WRITE(6,20)
      DO 850 I=1,24
      WRITE(6,290) I,ATDB(I),ATWB(I),DW(I),QTSHL(I),Q30(I),QTOTAL(I)
      WRITE(6,10)
850   CONTINUE
      WRITE(6,20)
      WRITE(6,300) IDAYM,MONTHS,QTOTFC,QTOTFH,TRCOM
      WRITE(IOT,30)
800   CONTINUE
      IF(NHTX.EQ.1) CALL HEATX
      INIT=1
      INIHX=1
      WRITE(6,30)
      IF(PRNT.EQ.0) GO TO 420
      WRITE(8,900) (QTOTAL(I),I=1,24)
  900 FORMAT(4(E20.5))
420   CONTINUE
400   CONTINUE
      GO TO 959
919   WRITE(6,929)
929   FORMAT(/////,2(10X,72('*')/),10X,5('*'),62X,5('*'),/,10X,5('*'),
     &5X,'DATA FOR THE SPECIFIED SIMULATION PERIOD ARE MISSING',5X,5('*
     &'),/,10X,5('*'),62X,5('*'),/,2(10X,72('*')/))
      GO TO 959
  939 MISS=97-NKOUNT
```

```
        00000000011111111112222222222333333333344444444445555555555666666666677777777778
        12345678901234567890123456789012345678901234567890123456789012345678901234567890
              WRITE(6,949) MISS,IDAYM,MONTH
        949   FORMAT(/////,2(10X,70('*')/),10X,5('*'),60X,5('*'),/,10X,5('*'),5
             &X,'OF THE SIMULATION PERIOD SPECIFIED,',20X,5('*'),/,10X,5('*'),5
             &X,I5,2X,'(15-MINUTE) DATA INTERVALS',22X,5('*'),/,10X,5('*'),5X,'
             &ARE MISSING FOR DAY',I5,2X,'OF MONTH',I5,16X,5('*'),/,10X,5('*'),
             &60X,5('*'),/,10X,5('*'),5X,'CHOOSE ANOTHER SIMULATION PERIOD',22X
             &,5('*'),/,10X,5('*'),60X,5('*'),/,2(10X,70('*')/))
        959   STOP
              END
        C
        C ***********************************************************************
        C *                                                                     *
        C *   SUBROUTINE SOLAR CONVERTS RADIATION FALLING ON HORZONTAL          *
        C *   SURFACE TO THAT ON AN INCLINED SURFACE.                           *
        C *                                                                     *
        C ***********************************************************************
        C
              SUBROUTINE SOLAR(IDAY)
              COMMON/SOL1/ ATDE(24),SOLH(24),XID(24),XIDHV(24),XIT(24)
              COMMON/SOL2/ XLATR,EPR,PSIR,DLONG,IDAY1
              COMMON/SOL3/ SH(24),CH(24),CZ(24),CT(24),CE,RTD
              DIMENSION  SID(24),SIDHV(24)
              SC=429.2
              IF(IDAY.EQ.IDAY1)  GO TO 10
              DAY=IDAY
              IF(DAY.LT.100.)EQTIME=-5.-9.*SIN((2.*DAY-1.)/RTD)
              IF(DAY.GE.100..AND.DAY.LE.242.)EQTIME=-1.+5.*SIN((DAY-100.)/
             &(.395*RTD))
              IF(DAY.GT.242.)EQTIME=-2.5+18.6*SIN((DAY-242.)/(.685*RTD))
              STC=(EQTIME/60.0)+DLONG
              D=(23.45/RTD)*SIN(((IDAY-80.)/370.)*360./RTD)
              SD=SIN(D)
              CD=COS(D)
              SL=SIN(XLATR)
              CL=COS(XLATR)
              CZT=SD*SL
              CDL=CD*CL
              DO 20 I=1,24
              STLTIM=STC+I
              H=3.1416-(0.2618*STLTIM)
              SH(I)=SIN(H)
              CH(I)=COS(H)
              CZ(I)=CZT+(CDL*CH(I))
              IF(CZ(I).LT.0.05)  CZ(I)=0.05
              XKX=SOLH(I)/(SC*CZ(I))
              IF(XKX.GT.0.75)  XKX=0.75
              RATIO=0.5*(1.0+COS(XKX*3.14159))
              SIDHV(I)=RATIO*SOLH(I)
              SID(I)=SOLH(I)-SIDHV(I)
        20    CONTINUE
        10    SE=SIN(EPR)
              CE=COS(EPR)
              SP=SIN(PSIR)
              CP=COS(PSIR)
              CTT=SD*(SL*CE-CL*SE*CP)
```

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         0000000001111111111222222222233333333334444444444555555555566666666667777777777 8
         1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
               DO 30  I=1,24
               CT(I)=0.0
               XIT(I)=0.0
               XID(I)=0.0
               XIDHV(I)=0.0
               IF(SOLH(I).LE.0.0)  GO TO 30
               CT(I)=CTT+(CH(I)*CD)*((CL*CE)+(SL*SE*CP))+(CD*SE*SP*SH(I))
               IF(CT(I).LT.0.0)  CT(I)=0.0
               RB=CT(I)/CZ(I)
               IF(RB.GT.5.0)  RB=1.0
               XIDHV(I)=SIDHV(I)*0.5*(1.0+CE)
               XID(I)=SID(I)*RB
               XIT(I)=XID(I)+XIDHV(I)
         30    CONTINUE
               IDAY1=IDAY
               RETURN
               END
         C
         C
         C
         C**************************************************************************
         C**************************************************************************
         C
               SUBROUTINE XMOIST(TDB,TWB,RH,INDIC,PATM,HAIR,WSAT,WAIR,TWALL)
         C
         C        PURPOSE
         C           TO DETERMINE THE ENTHALPY, SATURATION MOISTURE CONTENT,
         C           AND ACTUAL MOISTURE CONTENT OF MOIST AIR, AND ALSO, THE
         C           NECESSARY WALL TEMPERATURE TO INDUCE MOISTURE REMOVAL,
         C           GIVEN DRY BULB TEMPERATURE AND EITHER WET BULB TEMPERATURE
         C           OR RELATIVE HUMIDITY.
         C           (NOTE : THIS PROGRAM ESSENTIALLY REPRODUCES PSYCHROMETRIC
         C           CHART DATA)
         C
         C        DESCRIPTION OF PARAMETERS
         C         INPUT
         C           TDB     -  DRY BULB TEMPERATURE (F)
         C           TWB     -  WET BULB TEMPERATURE (F)
         C           RH      -  RELATIVE HUMIDITY
         C           INDIC   -  INPUT INDICATOR
         C                      =1, INPUTS ARE TDB, AND TWB
         C                      =2, INPUTS ARE TDB, AND RH
         C           PATM    -  ATMOSPHERIC PRESSURE (PSIA)
         C
         C         OUTPUT
         C           HAIR    -  ENTHALPY OF MOIST AIR (BTU/LBM DRY AIR)
         C           WSAT    -  SATURATION HUMIDITY (LBM WATER/LBM DRY AIR)
         C                      CORRESPONDING TO THE EXISTING WET BULB TEMP.
         C           WAIR    -  ACTUAL HUMIDITY (LBM WATER/LBM DRY AIR)
         C                      CORRESPONDING TO THE GIVEN DRY BULB TEMP.,
         C                      PRES., AND REL. HUMIDITY OR WET BULB TEMP.
         C           TWALL   -  SATURATION OR DEW POINT TEMPERATURE (F)
         C                      CORRESPONDING TO THE GIVEN TDB, PATM, AND TWB, OR
         C
               K=0
```

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0000000001111111111222222222233333333334444444444555555555566666666667777777777 8
1234567890123456789012345678901234567890123456789012345678901234567890123456789 0

            I=1
            IF(INDIC.NE.1)GO TO 30
            T=TWB
      C
      C        DETERMINING SATURATION PARTIAL PRESSURE 'PS' (PSIA)
      C        OF WATER VAPOR AT THE GIVEN TEMPERATURE
         10 T1=273.16/(((T-32.0)/1.8)+273.16)
            A1=-8.29692*((1.0/T1)-1.0)
            A2=4.76955*(1.0-T1)
            A3=10.79586*(1.0-T1)+5.02808*ALOG10(T1)+1.50474E-04*(1.0-10.**A1)
           &+0.42873E-03*((10.0**A2)-1.0)-2.2196
            PS=(10.0**A3)*14.696
            W=1.004*18.01*PS/(28.967*(PATM-PS))
            IF(K.NE.0) GO TO 50
            IF(INDIC.EQ.2) GO TO 40
            IF(I.NE.1) GO TO 20
            I=2
            WSAT=W
            WAIR=WSAT-0.000236*(TDB-T)
            HAIR=0.24*(TWB-32.0)+WSAT*(1060.9+0.444*TWB)
            P=PATM/(1.004*18.01/(28.967*WAIR)+1.0)
            T=TDB
            GO TO 10
      C
      C        FINDING THE CORRESPONDING RELATIVE HUMIDITY, GIVEN
      C        THE WET BULB TEMPERATURE
      C
         20 RH=P/PS
            GO TO 90
         30 T=TDB
            GO TO 10
         40 P=RH*PS
            WAIR=RH*W*(PATM-PS)/(PATM-P)
      C
      C        FINDING THE CORRESPONDING WET BULB TEMPERATURE, GIVEN
      C        THE RELATIVE HUMIDITY
      C
            DT=-10.0
         45 T=T+DT
            K=K+1
            IF(K.GT.30)GO TO 70
            GO TO 10
         50 WS=W-0.000236*(TDB-T)
            IF(ABS(WS-WAIR).LE.0.00005) GO TO 80
            IF(WS-WAIR) 60,80,65
         60 T=T-DT
            DT=DT/2.0
         65 CONTINUE
            GO TO 45
         70 WRITE(6,100)
         80 TWB=T
            WSAT=W
            HAIR=0.24*TDB+WAIR*(1060.9+0.444*TDB)
      C
      C        DETERMINING THE SATURATION OR DEW POINT TEMP. 'TWALL'
```

```
00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
C         CORRESPONDING TO THE GIVEN PRESSURE, DRY BULB TEMPERATURE,
C         AND RELATIVE HUMIDITY OR WET BULB TEMP.
C
    90 IF(P.LE.0.0185) TWALL=(P-0.0185)/0.00077
       IF(P.GT.0.0185) TWALL=(P-0.0185)/0.00124
       IF(P.GT.0.0309) TWALL=(P-0.0113)/0.00196
       IF(P.GT.0.0505) TWALL=(P+0.0129)/0.00317
       IF(P.GT.0.0885) TWALL=(P+0.0441)/0.004145
       IF(P.GT.0.1217) TWALL=(P+0.10394)/0.005641
       IF(P.GT.0.17811) TWALL=(P+0.21284)/0.007819
       IF(P.GT.0.2563) TWALL=(P+0.3845)/0.01068
       IF(P.GT.0.3681) TWALL=(P+0.6435)/0.01438
       IF(P.GT.0.5069) TWALL=(P+1.0235)/0.01913
       IF(P.GT.0.6982) TWALL=(P+1.5508)/0.0251
   100 FORMAT(' ***** ITERATION IN XMOIST DOES NOT CONVERGE')
       RETURN
       END
C
C
C*************  SUBROUTINE HEATX COMPUTES THE HEAT EXTRACTION RATES
C
C
       SUBROUTINE HEATX
C
       COMMON/BLOCK1/IIN,IOT,MC,NPRT,INWRIT,TROOM,OFST,OFCT,CFMD,XKT,XLF,
      &         INIT,INIHX,MONTH,IDAYM
       COMMON/BLOCK2/QTOTAL(24),PRNT,IHOUSE
       DIMENSION G(4),P(4),ZG(12),ZP(12)
       DIMENSION XI(24),QTOT(48),ER(48),T(48)
       NAMELIST/NAM7/ERMAX,ERMIN,FLAREA,THRANG
      &         /NAM8/THSETD,THSETN,THTIMD,THTIMN
       DATA ZG/1.73,-3.5,2.22,-0.45,1.88,-4.22,3.08,-0.74,1.89,-4.55,3.61
      &         ,-0.95/
       DATA ZP/1.000,-1.8260,1.0697,-0.2005,1.000,-2.1092,1.4606,-0.3331,
      &         1.000,-2.2908,1.7252,-0.4277/
    10 FORMAT(1X )
    20 FORMAT(/)
    30 FORMAT( 51X,31('*'),//)
    35 FORMAT(52X,'HEAT EXTRACTION RATES (BTU/HR)')
    36 FORMAT(52X,'HEAT  ADDITION RATES (BTU/HR)')
    40 FORMAT( 3( 2X,8(5X, I2 ,2X,F5.1 ),/))
    50 FORMAT(5X,'ROOM AIR TEMPERATURES 1-24 HRS',5X,'THERMOSTAT SETTING'
      &,F5.1,1X,'F',1X,'AT',F4.0,'HRS',3X,F5.1,1X,'F',1X,'AT',F4.0,'HRS')
    60 FORMAT(5X,'HEAT EXTRACTION RATES 1-24 HRS',5X,'ERMIN=',G13.6,2X,
      &         'ERMAX=',F9.0,2X,'BTU/HOUR')
    61 FORMAT(5X,'HEAT ADDITION RATES 1-24 HRS',5X,'ERMIN=',G13.6,2X,
      &         'ERMAX=',F9.0,2X,'BTU/HOUR')
    70 FORMAT(3(4X,8(2X,I2,1X,F9.0),/))
    80 FORMAT(5X,'TOTAL COOLING LOAD PROVIDED DURING THE 24 HRS =',E14.6,
      &         1X,'BTU/DAY')
    81 FORMAT(5X,'TOTAL HEATING LOAD PROVIDED DURING THE 24 HRS =',E14.6,
      &         1X,'BTU/DAY')
    90 FORMAT(5X,'TOTAL COOLING LOAD FROM BEGINING (OF MONTH) TO TODAY',
      &         '=',E14.6,1X,'BTU')
    91 FORMAT(5X,'TOTAL HEATING LOAD FROM BEGINING (OF MONTH) TO TODAY',
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000000000111111111122222222223333333333444444444455555555556666666666777777777778
123456789012345678901234567890123456789012345678901234567890123456789012345678900
     &         '=',E14.6,1X,'ETU')
 100 FORMAT(5X,'MONTH= ',I2,5X,'DAY = ',I3,/)
      IF(INIHX.GT.0) GC TO 200
      IFLAGH=0
      ERTOPC=0.0
      ERTOPH=0.0
      ERMIN=0.0
      ERMAX=0.0
      FLAERA=0.0
      THRANG=2.0
      IF(INIT.GT.0) GO TO 205
      I=4*MC-3
      IP3=I+3
      IJ=1
      DO 210 J=I,IP3
      G(IJ)=ZG(J)
      P(IJ)=ZP(J)
      IJ=IJ+1
 210  CONTINUE
      SUMP=P(1)+P(2)+P(3)+P(4)
      DO 215 I=1,24
      QTOT(I)=QTOTAL(I)
      ER(I)=QTCTAL(I)
 215  CONTINUE
 205  CONTINUE
      THSETD=TROOM
      THSETN=TROOM
      THTIMN=OFCT
      THTIMD=CFST-1.0
      READ(IIN,NAM7)
      READ(IIN,NAM8)
      ITIMD=THTIMD
      ITIMN=THTIMN
      IF(INWRIT.GE.1) WRITE(IOT,NAM7)
      IF(INWRIT.GE.1) WRITE(IOT,NAM8)
      IF(ERMAX.LT.0.0) IFLAGH=1
      ID=THTIMD
      IN=THTIMN
      G(1)=(G(1)*FLAREA)+(((XKT*XLF)+(CFMD*1.08))*SUMP)
      G(2)=G(2)*FLAREA
      G(3)=G(3)*FLAREA
      G(4)=G(4)*FLAREA
      SUMG=G(1)+G(2)+G(3)+G(4)
      DO 220 I=1,24
      T(I)=THSETN
      IF(I.GE.ID.AND.I.LT.IN) T(I)=THSETD
      T(I+24)=T(I)
 220  CONTINUE
      ED=ERMAX-ERMIN
      S=ED/THRANG
      S=ABS(S)
      WN=(ED/2.0)-S*THSETN
      WD=(ED/2.0)-S*THSETD
      DUM=1.0/(S+G(1))
      GT1=G(1)*DUM
```

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000000000111111111122222222223333333333444444444455555555556666666666777777777778
123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
      ST1=S*DUM
  200 CONTINUE
      DO 300 I=1,24
      QTOT(I+24)=QTOTAL(I)
  300 CONTINUE
      KOUNT=1
      II=25
      IL=ID-1+24
  340 WT=WN
  330 DO 310 K=II,IL
      XIT=0.0
      DO 320 J=2,4
      JJ=K+1-J
      XIT=XIT-G(J)*T(JJ)+P(J)*QTOT(JJ)-P(J)*ER(JJ)
  320 CONTINUE
      KJ=K-24
      XI(KJ)=XIT+TFCOM*SUMG+P(1)*QTOT(K)
      ER(K)=(GT1*WT)+(ST1*XI(KJ))
      IF(IFLAGH.EQ.1)GO TO 325
      IF(ER(K).LT.ERMIN) ER(K)=ERMIN
      IF(ER(K).GT.ERMAX) ER(K)=ERMAX
      GO TO 315
  325 IF(ER(K).GT.ERMIN) ER(K)=ERMIN
      IF(ER(K).LT.ERMAX) ER(K)=ERMAX
  315 T(K)=(XI(KJ)-ER(K))/G(1)
  310 CONTINUE
      KOUNT=KOUNT+1
      II=IL+1
      IL=IN+24
      WT=WD
      IF(KOUNT.EQ.2) GO TO 330
      IL=48
      IF(KOUNT.EQ.3) GO TO 340
      ERTOTC=0.0
      ERTOTH=0.0
      DO 350 I=1,24
      IP24=I+24
      QTOT(I)=QTOT(IP24)
      ER(I)=ER(IP24)
      T(I)=T(IP24)
  350 CONTINUE
      IF(NPRT.EQ.0) GO TO 360
      IF(IFLAGH.EQ.1) GO TO 370
      DO 365 I=1,24
      ERTOTC=ERTOTC+ER(I)
  365 CONTINUE
      ERTOPC=ERTOPC+ERTOTC
      WRITE(IOT,20)
      WRITE(IOT,35)
      WRITE(IOT,30)
      WRITE(IOT,100) MONTH,IDAYM
      WRITE(IOT,50) THSETD,THTIMD,THSETN,THTIMN
      WRITE(IOT,10)
      WRITE(IOT,40) ((I,T(I),I=N,24,3),N=1,3)
      IF(PRNT.EQ.0) GO TO 3761
```

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         0000000001111111111222222222233333333334444444444555555555566666666667777777777 8
         1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
               WRITE(8,93) THSETD,THSETN,THRANG,ITIMD,ITIMN
               WRITE(8,92) (T(I),I=1,24)
          3761 WRITE(IOT,20)
               WRITE(IOT,60) ERMIN,ERMAX
               WRITE(IOT,10)
               WRITE(IOT,70) ((I,ER(I),I=N,24,3),N=1,3)
               WRITE(IOT,20)
           380 WRITE(IOT,80) ERTOTC
               WRITE(IOT,20)
               WRITE(IOT,90) ERTOPC
               WRITE(IOT,20)
               RETURN
           370 ERMAXH=-ERMAX
               ERMINH=ABS(ERMIN)
               DO 375 I=1,24
               XI(I)=-ER(I)
               ERTOTH=ERTOTH+XI(I)
           375 CONTINUE
               ERTOPH=ERTOPH+ERTOTH
               WRITE(IOT,20)
               WRITE(IOT,36)
               WRITE(IOT,30)
               WRITE(IOT,100) MONTH,IDAYM
               WRITE(IOT,50) THSETD,THTIMD,THSETN,THTIMN
               WRITE(IOT,10)
               WRITE(IOT,40) (( I,T(I),I=N,24,3),N=1,3)
               IF(PRNT.EQ.0) GO TO 376
               WRITE(8,93) THSETD,THSETN,THRANG,ITIMD,ITIMN
            93 FORMAT(3F10.1,2I10)
               WRITE(8,92) (T(I),I=1,24)
            92 FORMAT(4(F20.1))
           376 WRITE(IOT,20)
               WRITE(IOT,61) ERMINH,ERMAXH
               WRITE(IOT,10)
               WRITE(IOT,70) (( I,XI(I),I=N,24,3),N=1,3)
               WRITE(IOT,20)
           390 WRITE(IOT,81) ERTOTH
               WRITE(IOT,20)
               WRITE(IOT,91) ERTOPH
               WRITE(IOT,20)
               RETURN
           360 WRITE(IOT,100) MONTH,IDAYM
               IF(IFLAGH.EQ.1) GO TO 390
               GO TO 380
               END
         $ENTRY
          &INPT IHOUSE=3,MONTHS=12,MDAY1=21,MDAY2=21,NPRT=3,INWRIT=1,PRNT=1,&END
          &NAM4 NPN= 0,NPD= 0,CFMN= 81.5,CFMD=120.0,OFST=11.0,OFCT=20.0,&END
          &NAM5 QOTSN=  0.0,QOTSD=  0.0,QOTLN=  0.0,QOTLD=  0.0,QFLD=0.0,&END
          &NAM6 QFLN=  0.0,CTLN=  0.0,QTLD=  0.0,TRCOM=70.0,NHTX=1,IHTG=0,&END
          &NAM7 ERMAX=-24000.0,ERMIN=0.0,FLAREA=1240.0,THRANG=2.0, &END
          &NAM8 THSETD=70.0,THSETN=68.0,THTIMD=11.0,THTIMN=20.0,&END
         $IBSYS
```

APPENDIX C

HPSIM INPUT LIST, FLOWCHARTS AND PROGRAM LISTING

INPUT LIST AND FORMAT

User's input to the heat pump simulation model is in the NAMELIST format. The input variables are,

/INPUT/

MONTH - Month of simulation

MDAY1 - First day of simulation

MDAY2 - Last day of simulation

INDEX - Index specifying type of measured incident solar incident solar radiation

= 1, input is radiation incident on a horizontal surface

= 2, input is radiation incident on a vertical surface

KPRINT - Index for printing the temperature distribution in the soil

= 0, no temperature distribution printout

= 1, temperature distribution will be printed

Note: If the simulation period is more than one day and KPRINT is set = 1, then the printout will be very large.

IHOUSE - Index identifying the house to be simulated

= 1, East House

= 2, Middle House

= 3, West House

IDP - index for output format

= 0, hourly average heat pump performance data are printed

= 1, 15-minute performance data are printed

The measured environmental data are stored into OSU library files. At the present the data stored are as follows:

Month	Days	Name of the File
November	(whole month)	'OSU.ACT11451.NOVDATA.DATA'
August	(4 - 6)	'OSU.ACT11864.AUGDATA.DATA'
December	(19-21)	'OSU.ACT11451.DECDATA.DATA'

These data will be automatically read from the respective files according to the month and days of specified into the input list. The cooling/heating loads as computed by LDSIM are automatically input into the program through a link file named 'OSU.ACT11451.CHLOAD.DATA'.

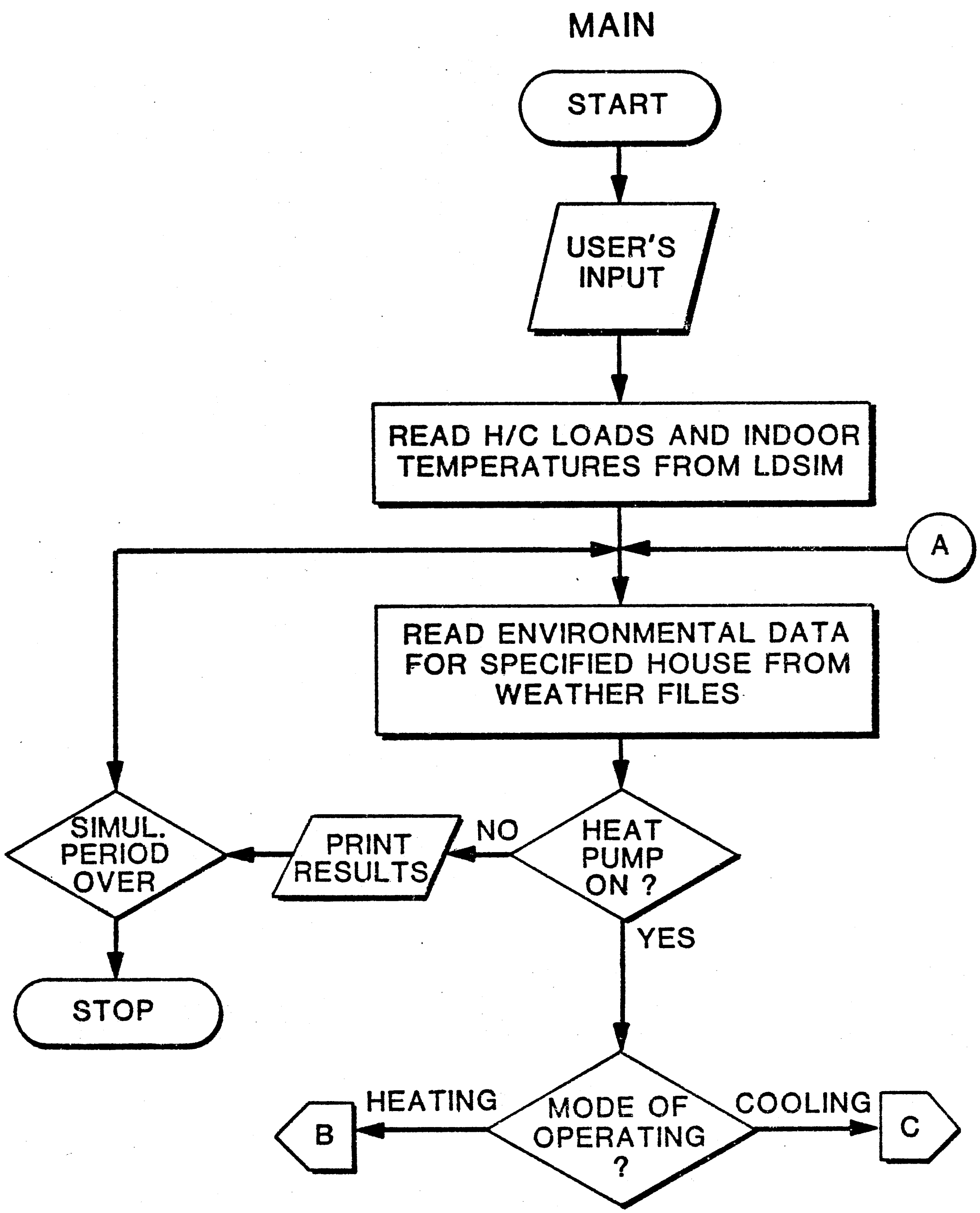

Figure 18. Main Program Flowchart

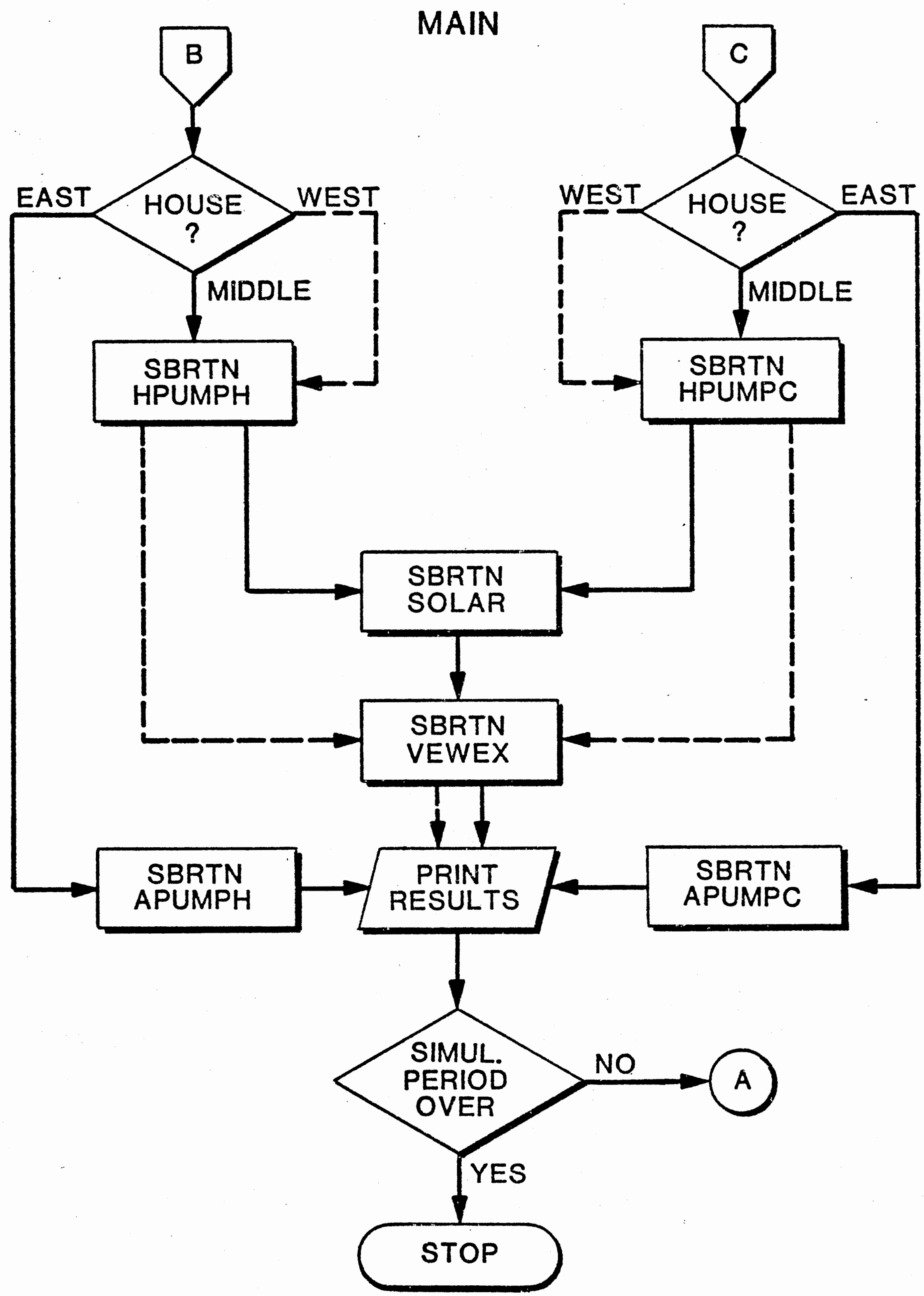

Figure 18. (continued)

HEAT PUMP CAPACITY SUBROUTINES

HPUMPC HPUMPH
APUMPC APUMPH

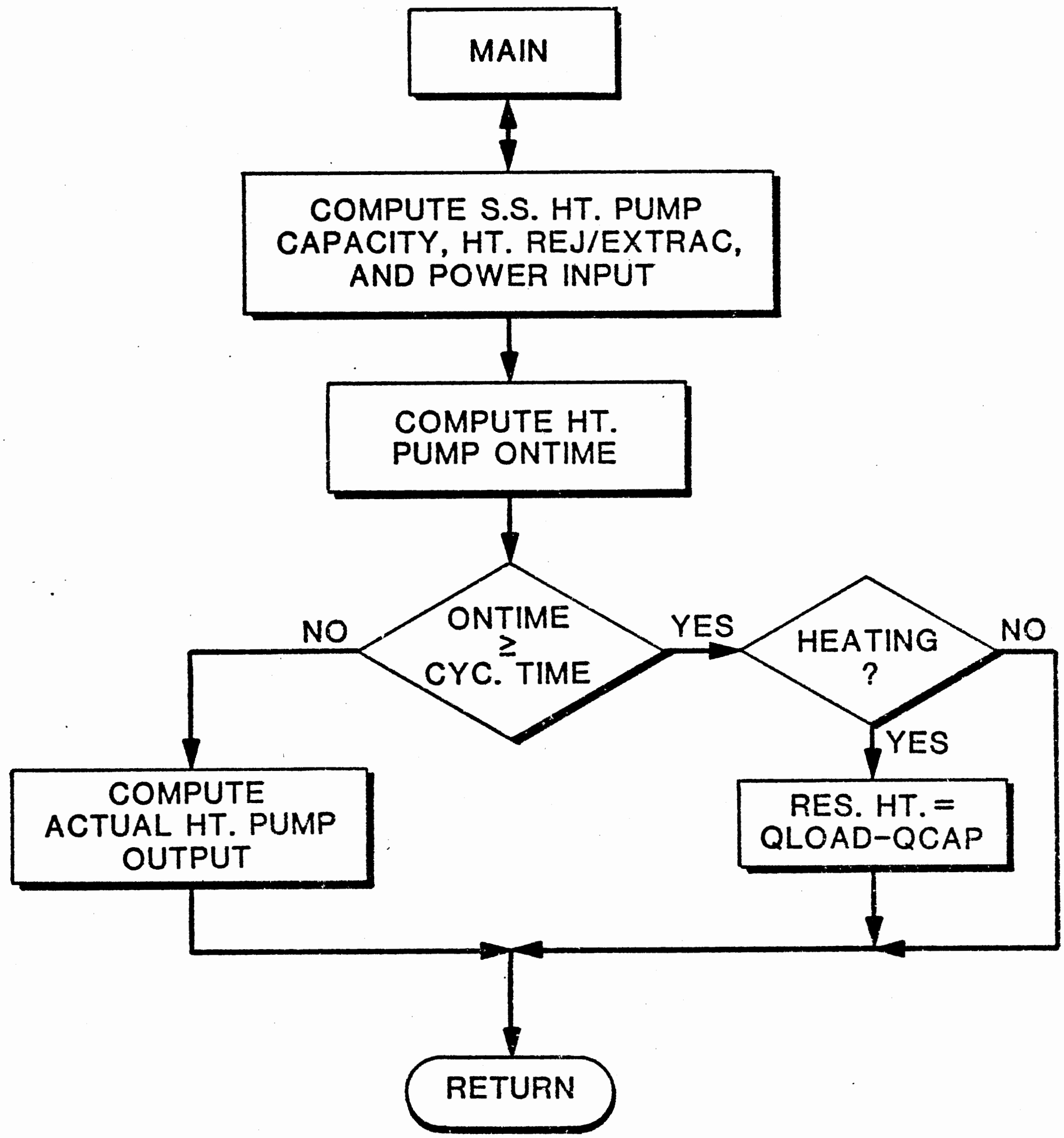

Figure 19. Flowchart for Heat Pump Subroutines

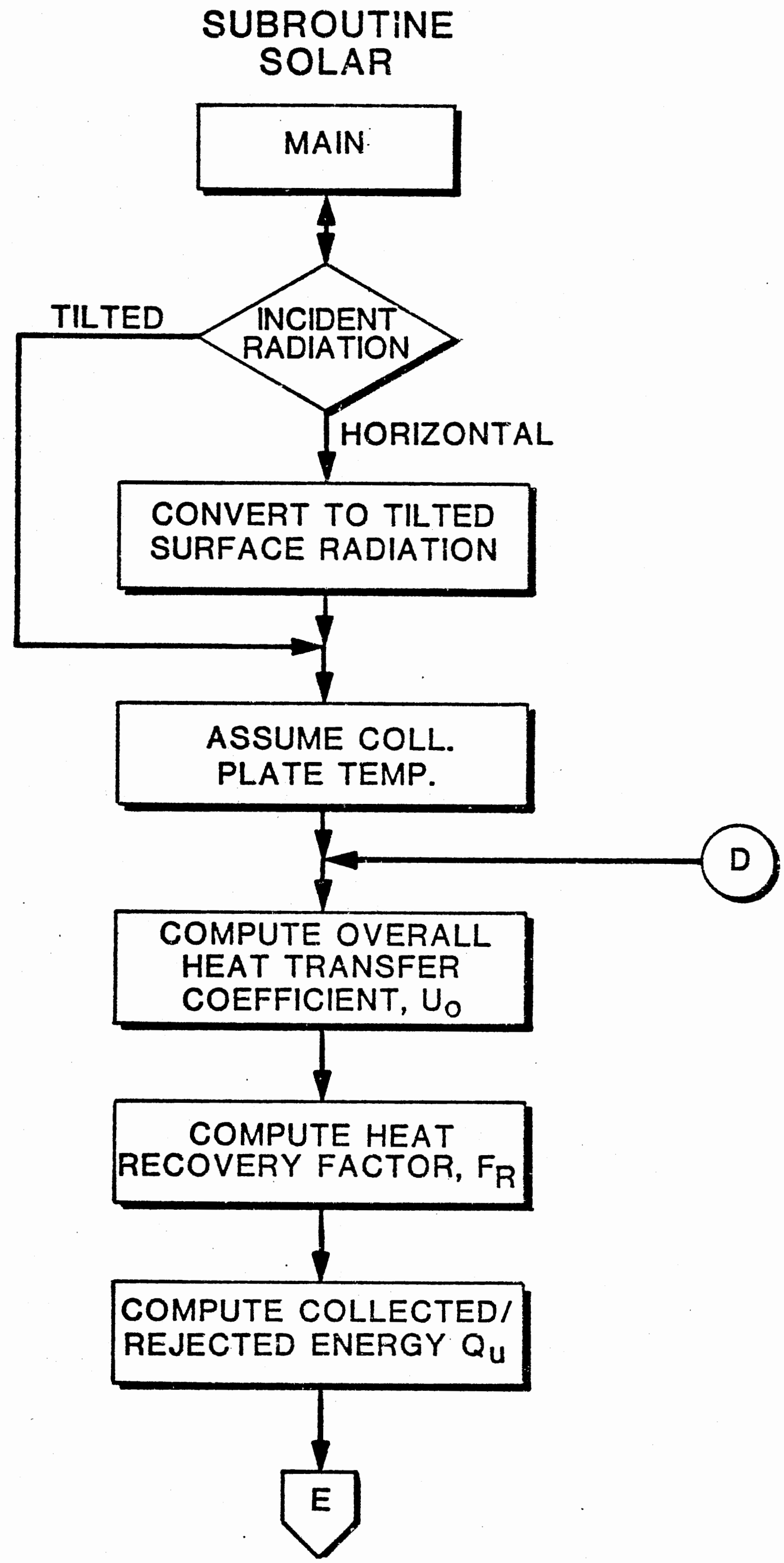

Figure 20. Subroutine SOLAR Flowchart

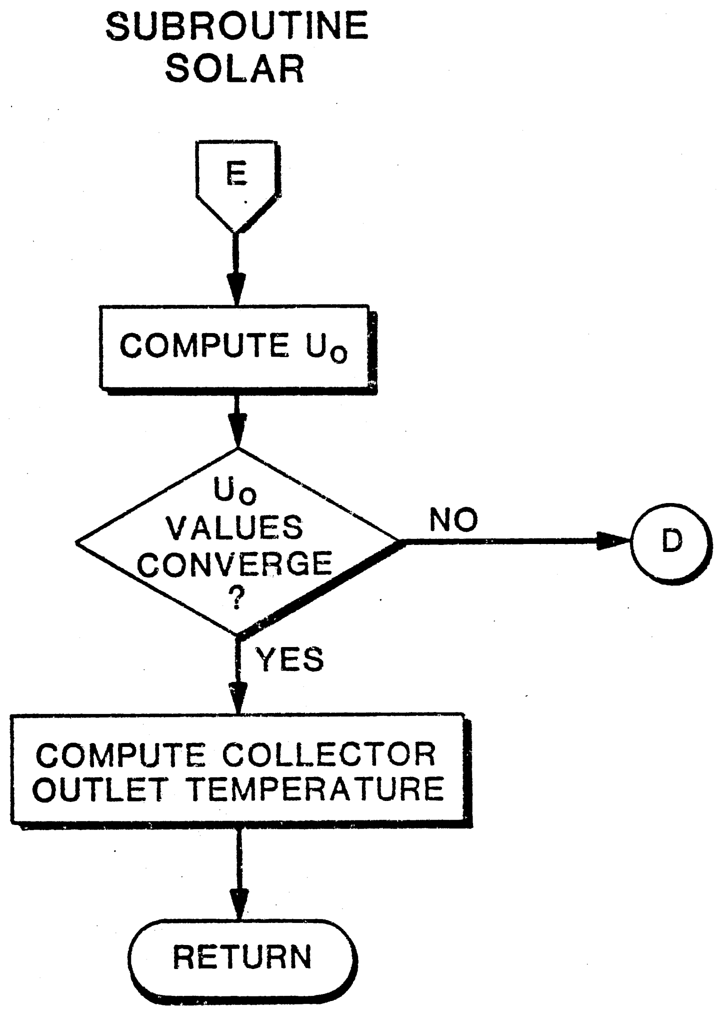

Figure 20. (continued)

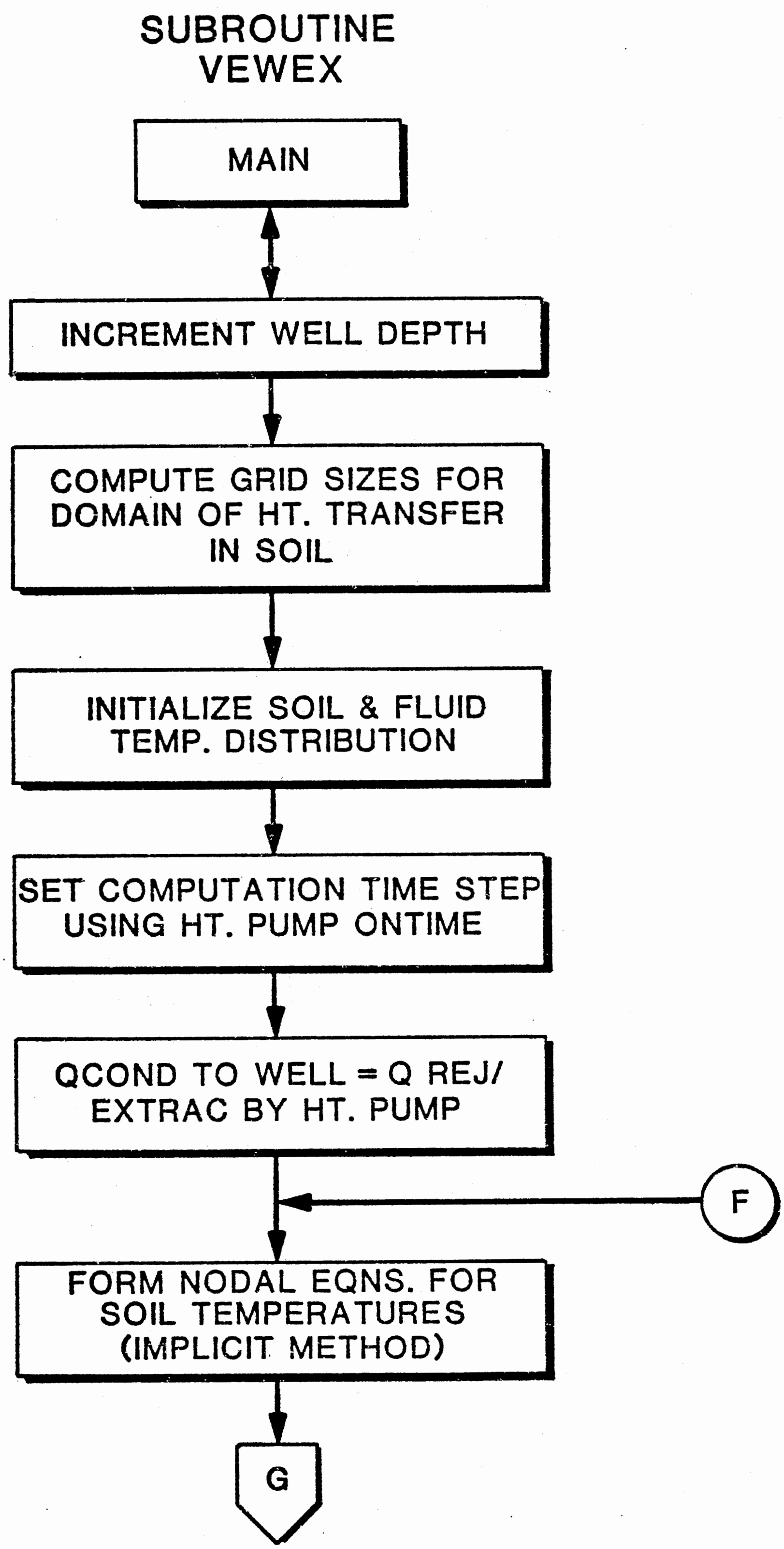

Figure 21. Subroutine VEWEX Flowchart

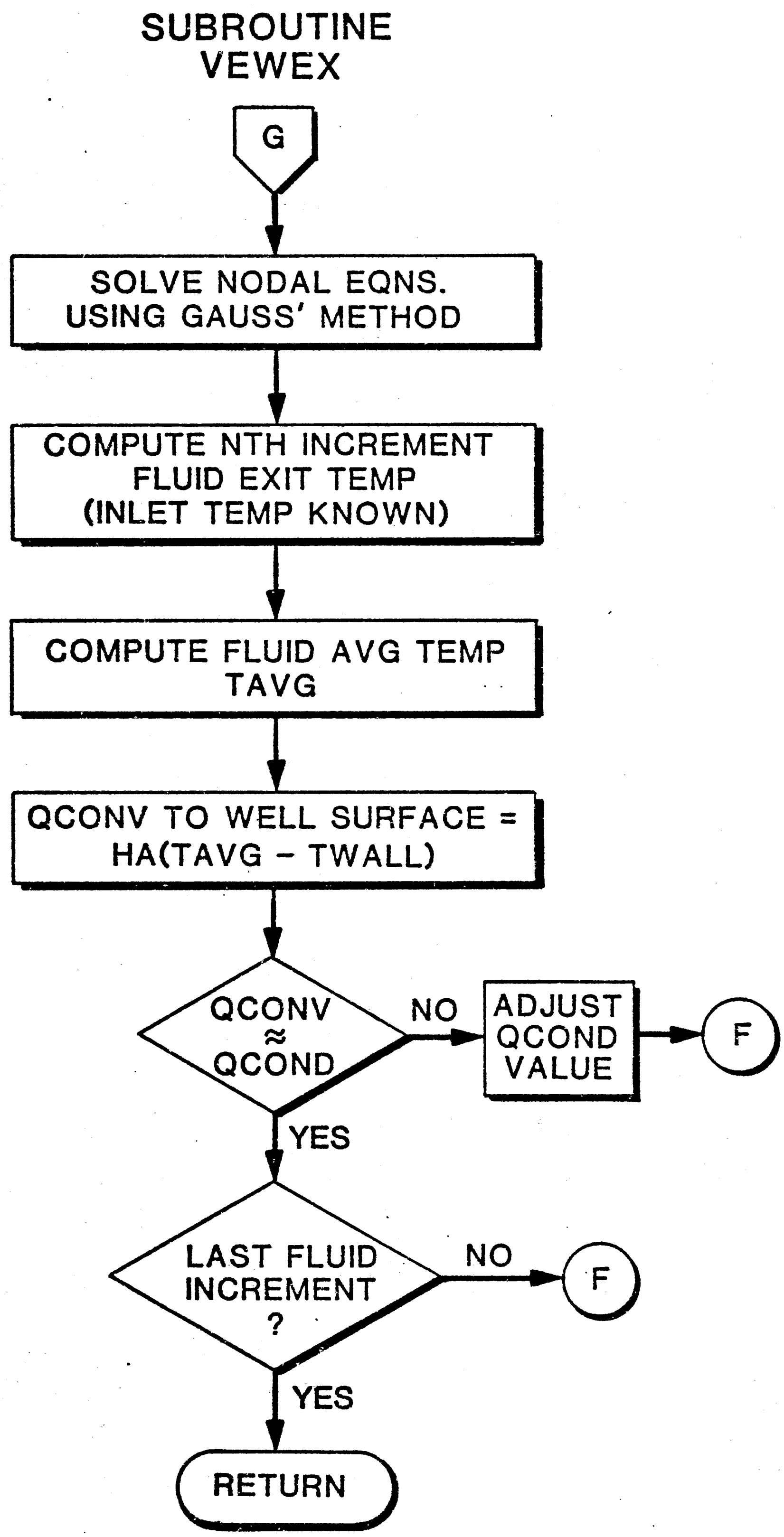

Figure 21. (continued)

HPSIM PROGRAM LISTING

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00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
C
C
C
C    ******************************************************************
C    ******************************************************************
C    *                                                                *
C    *                                                                *
C    *                          ( H P S I M )                         *
C    *                                                                *
C    *                                                                *
C    *       THIS PROGRAM SIMULATES THE CYCLIC PERFORMANCE OF A SOLAR *
C    *       ASSISTED-GROUND SOURCE/SINK AND AN AIR-TO-AIR HEAT PUMP  *
C    *       SYSTEMS.                                                 *
C    *       ENVIRONMENTAL DATA ARE READ FROM MONTHLY WEATHER FILES   *
C    *       COMPILED FOR THE PERKINS HOUSES.                         *
C    *                                                                *
C    *                                                                *
C    ******************************************************************
C    ******************************************************************
C
C
      COMMON FLOW
      COMMON /BLOCK/ GGPM,KPRINT
      DIMENSION GLCAD(24),GSLCF(24),QFORT(24)
      DIMENSION TRCCM(24),TSLCP(24)
      NAMELIST/INPUT/MONTH,MDAY1,MDAY2,INDEX,KPRINT,IHOUSE,IDP
      DATA CPF,CPG,EXE,ALPHA/1.0,0.34,0.63,0.95/,KTIM1/1/
      DATA HS1,HS2,HS22,HS3/'EAST','MIDD','LE','WEST'/
    1 FORMAT('1')
    2 FORMAT(/////,49X,'HEAT PUMP PERFORMANCE CALCULATION',/,57X,
     &'FOR THE ',A4,' HOUSE',/,50X,'FOR DAY',I5,'  OF MONTH',I5,/,
     &49X,34('*'),////)
    3 FORMAT(/////,49X,'HEAT PUMP PERFORMANCE CALCULATIONS',/,56X,
     &'FOR THE ',A4,A2,' HOUSE',/,51X,'FOR DAY',I5,'  OF MONTH',I5,/,
     &49X,34('*'),////)
    4 FORMAT(' ',10X,'TIME',3X,'OUTDOOR',5X,'INDOOR',7X,'HOUSE',7X,
     &'HT PUMP',5X,'HT PUMP',7X,'RES.',5X,'COMP. &',5X,'HEAT',/,19X,
     &'DB TEMP',5X,'DB TEMP',7X,'LOAD',8X,'ON TIME',6X,'CAPACITY',6X,
     &'HEAT',6X,'FANS',7X,'PUMP',/,10X,'(HR)',7X,'(F)',9X,'(F)',9X,
     &'(BTU)',8X,'(HR)',9X,'(BTU)',8X,'(KWH)',6X,'(KWH)',6X,'COP',/)
    5 FORMAT(5X,'TIME',3X,'OUT DB',4X,'IN DB',6X,'HOUSE',5X,'HT PUMP',4
     &X,'HT PUMP',7X,'RES.',4X,'COMP &',5X,'HEAT',5X,'SOLAR',7X,'GR COIL
     &',4X,'GR COIL',
     &/,13X,'TEMP',6X,'TEMP',6X,'LOAD',6X,'ON TIME',4X,'CAPACITY',4X,'
     &HEAT',5X,'FAN',7X,'PUMP',5X,'LOOP Q',5X,'IN TEMP',4X,'OUT TEMP',/,
     &5X,'(HR)',5X,'(F)',5X,'(F)',7X,'(BTU)',6X,'(HR)',7X,'(BTU)',8X,'(K
     &WH)',3X,'(KWH)',6X,'COP',5X,'(BTU/HR)',8X,'(F)',8X,'(F)',/)
   10 FORMAT(5X,I2,2(6X,I2),3(12X,I4),4X,I4,/,11X,I4,////)
   11 FORMAT(/,41X,'HEAT PUMP AVERAGE COP =',14X,F10.2)
   12 FORMAT(////,38X,'TOTAL HEAT PUMP OPERATING TIME =',11X,F10.2,//,
     138X,'TOTAL COMPRESSOR & FAN(S) KWH CONSUMPTION =',F10.2,//,38X,
     3 'HEAT PUMP AVERAGE COEFF. OF PERFORMANCE =',2X,F10.2)
   15 FORMAT(4F20.0)
```

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      00000000011111111112222222222333333333344444444445555555555666666666677777777778
      12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
         20 FORMAT(5X,I2,6X,I2,6X,I2,3X,I5,23X,I4,/,3X,I4,
        &         16X,6(4X,I4),/,43X,I4,4X,I4,///)
        601 FORMAT('0',3X,F5.2,3X,F5.1,5X,F5.1,3X,E12.5,3X,F5.3,3X,E12.5,3X,
           &F5.2,3X,F5.2,5X,F5.3,3X,E12.5,3X,F5.1,6X,F5.1)
        602 FORMAT('0',10X,F5.2,5X,F5.1,7X,F5.1,4X,E12.5,5X,F5.3,4X,E12.5,
           &5X,F5.2,5X,F5.2,5X,F5.2)
        607 FORMAT(////,2(10X,72('*')/),10X,5('*'),62X,5('*'),/,10X,5('*'),
           &5X,'DATA FOR THE SPECIFIED SIMULATION PERIOD ARE MISSING',5X,5('*
           &'),/,10X,5('*'),62X,5('*'),/,2(10X,72('*')/))
        701 FORMAT(/////,2(10X,70('*')/),10X,5('*'),60X,5('*'),/,10X,5('*'),
           &5X,'OF THE SIMULATION PERIOD SPECIFIED,',20X,5('*'),/,10X,5('*'),
           &5X,I5,2X,'(15-MINUTE) DATA INTERVALS',22X,5('*'),/,10X,5('*'),5X,
           &'ARE MISSING FOR DAY',I5,2X,'OF MONTH',I5,15X,5('*'),/,10X,5('*')
           &,60X,5('*'),/,10X,5('*'),5X,'CHOOSE ANOTHER SIMULATION PERIOD',23
           &X,5('*'),/,10X,5('*'),60X,5('*'),/,2(10X,70('*')/))
        702 FORMAT('1')
        703 FORMAT(////,41X,'COMPRESSOR OPERATING TIME =',10X,F10.2,//,41X,
           1'COMPRESSOR & FAN(S) KWH CONSUMPTION =',F10.2)
        704 FORMAT(/,41X,'RESISTANCE HEAT (KWH) =',14X,F10.2,//,41X,
           &'HEAT PUMP AVERAGE COP =',14X,F10.2)
        707 FORMAT(////,33X,'TOTAL HEAT PUMP OPERATING TIME =',11X,F10.2,//,
           138X,'TOTAL COMPRESSOR & FAN(S) KWH CONSUMPTION =',F10.2,//,38X,
           2'TOTAL RESISTANCE HEAT =',20X,F10.2,//,38X,
           3'HEAT PUMP AVERAGE COEFF. OF PERFORMANCE =',2X,F10.2)
        708 FORMAT(////,45X,39('*'),/,45X,'*',37X,'*',/,45X,'*',4X,
           1'TOTALS FOR DAY ',I2,' OF MONTH ',I2,4X,'*',/,45X,'*',37X,'*',/,
           245X,39('*'))
        709 FORMAT('1',15(/),34X,63('*'),/,34X,'*',61X,'*',/,34X,'*',4X,
           1'PERFORMANCE SUMMARY FOR THE ',I3,'-DAY SIMULATION PERIOD',4X,'*',
           2/,34X,'*',61X,'*',/,34X,63('*'))
            GGPM=5.5
            FLOW=12.0
            XMCW=497.3*CPF*GGPM
            XMCG=518.1*CPG*FLOW
            TMID=62.0
            AVGCOP=0.0
            SUM5=0.0
            SUM6=0.0
            SUM7=0.0
            SUM8=0.0
            KMODE=0.0
      C
      C          INDEX FOR THE HOUSE TO BE SIMULATED
      C
      C          IHOUSE=1        ( EAST HOUSE )
      C          IHOUSE=2        ( MIDDLE HOUSE )
      C          IHOUSE=3        ( WEST HOUSE )
      C
      C
            READ(5,INPUT)
            IF(MDAY1.EQ.4) GO TO 600
            KDAY=MDAY1-1
            DO 500 I=1,18000
            READ(1,10) MDAY,AHR,MIN,KTF,KTM,KTWW,KTW,KTWM
            IF(MDAY.GT.MDAY1) GO TO 606
```

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00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
        IF(MDAY.EQ.KDAY.AND.MHR.EQ.23.AND.MIN.EQ.45) GO TO 600
  500 CONTINUE
  600 DO 3000 J=MDAY1,MDAY2
      NKOUNT=0
      SUM1=0.0
      SUM2=0.0
      SUM3=0.0
      SUM4=0.0
      WRITE(6,1)
      IF(IHOUSE.EQ.1) WRITE(6,2) HS1,J,MONTH
      IF(IHOUSE.EQ.2) WRITE(6,3) HS2,HS22,J,MONTH
      IF(IHOUSE.EQ.3) WRITE(6,2) HS3,J,MONTH
      IF(IHOUSE.EQ.1) WRITE(6,4)
      IF(IHOUSE.EQ.2.OR.IHOUSE.EQ.3) WRITE(6,5)
      NDOM=J
      READ(2,6) TSETD,TSETN,THRANG,ITIMD,ITIMN
    6 FORMAT(3F10.1,2I10)
      READ(2,7) (TROOM(I),I=1,24)
    7 FORMAT(4F20.1)
      READ(2,15) (QLOAD(I),I=1,24)
      DO 1200 KR=1,24
      QFORT(KR)=QLOAD(KR)/4.0
 1200 CONTINUE
      DO 1300 KS=1,23
      QSLOP(KS)=QFORT(KS+1)-QFORT(KS)
      TSLOP(KS)=TROOM(KS+1)-TROOM(KS)
 1300 CONTINUE
      QSLOP(24)=QFORT(24)-QFORT(1)
      TSLOP(24)=TROOM(24)-TROOM(1)
      DO 2900 I=1,24
      TOSUM=0.0
      HPOSUM=0.0
      RUNSUM=0.0
      SUMKWH=0.0
      SUMRES=0.0
      QSLSUM=0.0
      WTISUM=0.0
      WTOSUM=0.0
      TISET=TSETN
      IF(I.GT.ITIMD.AND.I.LT.ITIMN) TISET=TSETD
C
C         INPUT BUILDING LOAD AND INDOOR TEMPERATURES COMPUTED BY LDSIM
C
      DO 2000 JJ=1,4
      QBLDG=QFORT(I)+QSLOP(I)*(JJ-KTIM1)/4.0
      TDB=TROOM(I)+TSLOP(I)*(JJ-KTIM1)/4.0
      KON=0
      NKOUNT=NKOUNT+1
C
C         INPUT DATA FROM WEATHER FILES
C
      READ(1,20) MDAY,KHOUR,KMIN,KTOUT,KTWW,KTWM,KRHO,KRHE,
     &           KRHW,KRHM,KSRH,KSRV,KWD,KWV
      HOUR=KHOUR+KMIN/60.0
      TWW=KTWW*0.18+32.0
```

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0000000001111111111222222222233333333334444444444555555555566666666667777777778
1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
CARD
      TWM=KTWM*0.18+32.0
      TAMB=KTOUT*0.18+32.0
      RHO=KRHO/100.0
      IF(RHO.GT.1.0) RHO=RHO/10.0
      IF(RHO.GT.1.0) RHO=1.0
      WV=KWV
      WDR=KWD
      IF(KSRH.LE.1) KSRH=0
      IF(KSRV.LE.1) KSRV=0
      IF(INDEX.EQ.1) SR=KSRH/2.79458
      IF(INDEX.EQ.2) SR=KSRV/2.17036
      IF(IHOUSE.GT.1) GO TO 401
      RHI=KRHE/100.0
  401 IF(IHOUSE.NE.2) GO TO 402
      RHI=KRHM/100.0
  402 IF(IHOUSE.LT.3) GO TO 403
      RHI=KRHA/100.0
  403 IF(RHI.GT.1.0) RHI=RHI/10.0
      IF(MDAY.GT.J.AND.NKOUNT.LT.96) GO TO 700
      IF(JJ.LE.1.AND.I.LE.1.AND.J.EQ.MDAY1) TCI=TDB
      IF(JJ.LE.1.AND.I.LE.1.AND.J.EQ.MDAY1.AND.IHOUSE.EQ.2) TFOUT=TWM
      IF(JJ.LE.1.AND.I.LE.1.AND.J.EQ.MDAY1.AND.IHOUSE.EQ.3) TFOUT=TWW
C
C          INDEX FOR HEAT PUMP MODE OF OPERATION
C
C          IMODE = 1     ( HEAT PUMP IS IN THE HEATING MODE )
C          IMODE = 2     ( HEAT PUMP IS IN THE COOLING MODE )
C          IMODE = 3     ( HEAT PMUP IS OFF )
C
      RATIO=1.0
      ONTIME=0.0
      QCAP=0.0
      CKWH=0.0
      COP =0.0
      QSCL=0.0
      QRES=0.0
      IMODE=3
      IF(QBLDG.GT.0.0)IMODE=2
      IF(QBLDG.LT.0.0).OR.TAMB.LT.60.0) IMODE=1
      IF(QBLDG.GT.0.0.AND.TAMB.LT.50.0) IMODE=3
      IF(IMODE.EQ.1.AND.TDB.GE.(TISET+THRANG/2.0)) IMODE=3
      IF(IMODE.EQ.2.AND.TDB.LE.(TISET-THRANG/2.0)) IMODE=3
      IF(ABS(QBLDG).LT.100.0) IMODE=3
      IF(IMODE.EQ.2) KMODE=1
      IF(IHOUSE.EQ.1) GO TO 507
      IF(IMODE.EQ.3) GO TO 504
      IF(IMODE.EQ.2) GO TO 501
      CALL HPUMPH (TFOUT,TDB,GGPM,QBLDG,QGRUND,QCAP,CKWH,COP,ONTIME,
     &             RATIO,QRES)
      GO TO 502
  501 CALL XMOIST (TDB,TWB,RHI,2,1+.696,HAIR,WSAT,WAIR,TWALL)
      CALL HPUMPC (TFOUT,TDB,TWB,GGPM,QBLDG,QGRND,QCAP,CKWH,COP,ONTIME,
     &             RATIO)
  502 TFHP=TFOUT+QGRND/XMCW
  504 IF(IMODE.EQ.3) TFHP=TFOUT
```

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         00000000011111111112222222222333333333344444444445555555555666666666677777777778
         12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
               HO=2.2+WV*(0.32+0.001*WV)                                            00002230
               TSA=TAMB+ALPHA*SR/HO                                                 00002240
               DO 2500 ITIME=1,2                                                    00002250
               IF(ITIME.GE.2)TFHP=TFOUT                                             00002260
               IF(ITIME.GE.2.AND.IMODE.LT.3.AND.CNTIME.GE.1.0)                      00002270
              &    TFHP=TFOUT+QGROND/XMCW                                           00002280
               IF(IHOUSE.EQ.3.OR.(IMODE.EQ.1.AND.SR.LE.0.0)) GO TO 511              00002290
               IF(KON.EQ.1) GO TO 512                                               00002300
         C                                                                          00002310
         C        CONTROL STRATEGY FOR TURNING THE SOLAR LOOP PUMP ON.              00002320
         C                                                                          00002330
               IF(IMODE.EQ.1.AND.(TSA-TMID).LT.20.0) GO TO 511                      00002340
               IF(IMODE.EQ.3.AND.KMODE.EQ.0.AND.(TSA-TMID).LT.20.0) GO TO 511       00002350
               IF(IMODE.EQ.2.AND.(TMID-TSA).LT.20.0) GO TO 511                      00002360
               IF(IMODE.EQ.3.AND.KMODE.EQ.1.AND.(TMID-TSA).LT.20.0) GO TO 511       00002370
           512 CALL SOLAR (TAMB,WDR,WV,SR,INDEX,HOUR,MONTH,NODM,TCI,TCO,QU,TC,      00002380
              &             ITIME)                                                  00002390
               QSOL=EXE*XMCW*(TCO-TFHP)                                             00002400
               TCI=TCO-QSOL/XMCG                                                    00002410
               TFIN=TFHP+QSOL/XMCW                                                  00002420
         C                                                                          00002430
         C        CONTROL STRATEGY FOR TURNING THE SOLAR LOOP PUMP OFF.             00002440
         C                                                                          00002450
               KON=1                                                                00002460
               IF(IMODE.EQ.1.AND.(TC-TMID).GE.5.0) GO TO 506                        00002470
               IF(IMODE.EQ.3.AND.KMODE.EQ.0.AND.(TC-TMID).GE.5.0) GO TO 506         00002480
               IF(IMODE.EQ.2.AND.(TMID-TC).GE.5.0) GO TO 506                        00002490
               IF(IMODE.EQ.3.AND.KMODE.EQ.1.AND.(TMID-TC).GE.5.0) GO TO 506         00002500
           511 TFIN=TFHP                                                            00002510
               KON=0                                                                00002520
               QSOL=0.0                                                             00002530
               TCI=TDB                                                              00002540
           506 QEXC=XMCW*(TFIN-TFOUT)                                               00002550
               IF(ITIME.LE.1) TWIN=TFIN                                             00002560
               CALL VEWEX (TFIN,QEXC,RATIO,TMID,TFOUT,UNTIME)                       00002570
               WTISUM=WTISUM+TFIN                                                   00002580
               WTOSUM=WTOSUM+TFOUT                                                  00002590
          2500 CONTINUE                                                             00002600
               IF(IOP.LE.0) GO TO 1900                                              00002610
               WRITE(6,601) HOUR,TAMB,TDB,QBLDG,UNTIME,QCAP,QRES,CKWH,COP,QSOL,     00002620
              &             TWIN,TFOUT                                              00002630
               GO TO 1900                                                           00002640
           507 IF(IMODE.EQ.3) GO TO 609                                             00002650
               IF(IMODE.EQ.2) GO TO 508                                             00002660
               CALL APUMPH (TAMB,TDB,QBLDG,QCAP,CKWH,COP,UNTIME,QRES)               00002670
               GO TO 609                                                            00002680
           508 CALL XMOIST (TDB,TWB,PHI,2,14,696,HAIR,WSAT,WAIR,TWALL)              00002690
               CALL APUMPC (TAMB,TDB,TWB,QBLDG,QCAP,CKWH,COP,UNTIME)                00002700
               IF(IOP.LE.0) GO TO 1900                                              00002710
           609 WRITE(6,602) HOUR,TAMB,TDB,QBLDG,UNTIME,QCAP,QRES,CKWH,COP           00002720
          1900 TOSUM=TOSUM+TAMB                                                     00002730
               HPQSUM=HPQSUM+QCAP                                                   00002740
               RUNSUM=RUNSUM+UNTIME                                                 00002750
               SUMKWH=SUMKWH+CKWH                                                   00002760
               SUMRES=SUMRES+QRES                                                   00002770
```

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000000000111111111122222222223333333333444444444455555555556666666666777777777778
123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
      QSLSUM=QSLSUM+QSOL
 2000 CONTINUE
      IF(SUMKWH.LE.0.0) GO TO 2001
      AVGCOP=HPOSUM/(3412.15*SUMKWH)
 2001 TOAVG=TOSUM/4.0
      QSLAVG=QSLSUM/4.0
      WTIAVG=WTISUM/8.0
      WTOAVG=WTOSUM/8.0
      ZZ=I
      IF(IOP.GE.1) GO TO 2002
      WRITE(6,601)ZZ,TOAVG,TRCON(I),QLOAD(I),RUNSUM,HPOSUM,SUMRES,
     &SUMKWH,AVGCOP,QSLAVG,WTIAVG,WTOAVG
 2002 SUM1=SUM1+HPOSUM
      SUM2=SUM2+RUNSUM
      SUM3=SUM3+SUMRES
      SUM4=SUM4+SUMKWH
 2900 CONTINUE
      IF(SUM4.LE.0.0) GO TO 2901
      DAVCOP=SUM1/(3412.15*SUM4)
 2901 WRITE(6,708) J,MONTH
      WRITE(6,703) SUM2,SUM4
      IF(KMODE.EQ.1) GO TO 2902
      WRITE(6,704) SUM3,DAVCOP
      GO TO 2903
 2902 WRITE(6,11) DAVCOP
 2903 SUM5=SUM5+SUM1
      SUM6=SUM6+SUM4
      SUM7=SUM7+SUM3
      SUM8=SUM8+SUM2
 3000 CONTINUE
      SAVCOP=SUM5/(3412.15*SUM6)
      IPRIOD=NDAY2-NDAY1+1
      WRITE(6,709) IPRIOD
      IF(KMODE.EQ.1) GO TO 3001
      WRITE(6,707) SUM8,SUM6,SUM7,SAVCOP
      GO TO 3002
 3001 WRITE(6,12) SUM8,SUM6,SAVCOP
 3002 WRITE(6,702)
      GO TO 99
  606 WRITE(6,607)
      GO TO 99
  700 MISS=97-NKOUNT
      WRITE(6,701) MISS,J,MONTH
   99 STOP
      END
C
C
C
C
C
C
C***********************************************************************
C****                                                               ****
C****      COOLING, WATER-TO-AIR HEAT PUMP: SUBROUTINE(HPUMPC)      ****
C****                                                               ****
```

```
         00000000011111111112222222222333333333344444444445555555555666666666677777777778
         12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
      C***********************************************************************
      C
      C
            SUBROUTINE HPUMPC (EWT,EDB,TWB,GPM,QBLDG,QREJ,QCAP,CKWH,COP,CNTIME
           &                 ,RATIO)
            DATA CFM/600.0/
            DATA CFST0,CFST1,CFST2,CFST3,CFST4,CFST5/8.3597,-0.23243,
           &     1.05873E-03,-3.724E-02,1.73322E-05,1.06562E-03/
            DATA CFC0,CFC1,CFC2,CFC3,CFC4/-0.9313,1.18511E-02,-2.84E-05,
           &     3.08627E-08,-1.25126E-11/
            DATA CFS0,CFS1,CFS2,CFS3,CFS4/0.72047,-1.31175E-03,6.96749E-06,
           &     9.17738E-09,4.17127E-12/
            DATA CKW0,CKW1,CKW2,CKW3,CKW4/0.23951,4.54523E-03,-1.04679E-05,
           &     1.08445E-08,-4.17146E-12/
            DATA C0,C1,C2,C3,C4,C5,C6,C7/566.06,-73.96,-0.339,303.25,-0.3472,
           &     2542.8,-255.56,0.11636/
            DATA SC0,SC1,SC2,SC3,SC4,SC5,SC6,SC7/25582.0,-14.7,-0.278,208.84,
           &     -8.503,737.24,-94.44,776.64/
            DATA CP0,CP1,CP2,CP3,CP4,CP5,CP6,CP7/-5.4522E-02,2.223E-03,
           &     3.333E-05,5.5769E-02,-2.0333E-04,-.45262,4.1667E-02,-6.84E-06/
            DATA HR0,HR1,HR2,HR3,HR4,HR5,HR6,HR7/1434.6,-58.31,-0.1667,459.8,
           &     -1.04167,831.1,-100.0,0.10355/
      C
      C
            QLOAD=QBLDG
            CFCHR=1.0
            CFSC=1.0
            CFKW=1.0
            CFSCT=1.0
            X1=EWT
            X2=TWB
            X3=GPM
            X4=X1*X1
            X5=X2*X2
            X6=X3*X3
            X7=X1*X2*X3
            B=CFM/100.0
            SP=21.35-14.03667*B+3.49*B*B-0.37833*B*B*B+0.015*B*B*B*B
      C
      C        CORRECTION FACTORS FOR TOTAL COOLING CAPACITY, HEAT REJECTION
      C        RATE, SENSIBLE COOLING CAPACITY AND COMPRESSOR POWER INPUT,
      C        RESPECTIVELY, WHEN AIR VOLUME RATE NE. 600 CFM.
      C
            IF(CFM.EQ.600.0) GO TO 101
            Z1=CFM
            Z2=Z1*Z1
            Z3=Z1*Z2
            Z4=Z2*Z2
            CFCHR=CFC0+CFC1*Z1+CFC2*Z2+CFC3*Z3+CFC4*Z4
            CFSC=CFS0+CFS1*Z1+CFS2*Z2+CFS3*Z3+CFS4*Z4
            CFKW=CKW0+CKW1*Z1+CKW2*Z2+CKW3*Z3+CKW4*Z4
        101 IF(EDB.EQ.80.0) GO TO 102
      C
      C        CORRECTION FACTOR FOR SENSIBLE COOLING CAPACITY WHEN THE
      C        ENTERING DRY BULB TEMPERATURE IS NE. 80 F.
```

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0000000001111111111222222222233333333334444444444555555555566666666667777777778
1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
C
      Y1=EDB
      Y2=Y1*Y1
      CFSCT=CFST0+CFST1*X2+CFST2*X3+CFST3*Y1+CFST4*Y2+CFST5*X2*Y1
C
C        COMPUTE THE STEADY STATE COOLING CAPACITY (BTUH), SENSIBLE
C        COOLING CAPACITY (BTUH), HEAT REJECTION RATE (BTUH), AND
C        COMPRESSOR POWER INPUT, RESPECTIVELY.
C
  100 Q=CFCHR*(C0+C1*X1+C2*X4+C3*X2+C4*X5+C5*X3+C6*X6+C7*X7)
      QSCSS=CFSC*CFSCT*(SC0+SC1*X1+SC2*X4+SC3*X2+SC4*X5+SC5*X3+SC6*X6
     &                  +SC7*X7)
      QHRSS=CFCHR*(HR0+HR1*X1+HR2*X4+HR3*X2+HR4*X5+HR5*X3+HR6*X6+HR7*X7)
      CPOWER=CFKW*(CP0+CP1*X1+CP2*X4+CP3*X2+CP4*X5+CP5*X3+CP6*X6+CP7*X7)
      QPART=0.25*Q
      ONTIME=0.25
C
C        CHECK IF THE HEAT PUMP WILL CYCLE ON-OFF
C
      RATIO=QLOAD/QPART
      ONTIME=0.25*RATIO
      IF(ONTIME.GT.0.25) ONTIME=0.25
      IF(ONTIME.LT.0.06) ONTIME=0.06
      TIMEC=-ONTIME/ALOG(0.005)
      QCYCLE=Q*(ONTIME-TIMEC*(1.0-EXP(-ONTIME/TIMEC)))
      QPART=QCYCLE
      QREJ=QHRSS
      QCAP=QPART
      FP=9.395E-04*SP*CFM
      CKWH=(CPOWER+FP+0.075)*ONTIME
      COP=QPART/(3412.15*CKWH)
      RETURN
      END
C
C
C
C
C***********************************************************************
C****                                                               ****
C****     HEATING, WATER-TO-AIR HEAT PUMP: SUBROUTINE(HPUMPH)       ****
C****                                                               ****
C***********************************************************************
C
C
      SUBROUTINE HPUMPH (EWT,EDB,GPM,QBLDG,QEXT,QCAP,CKWH,COP,ONTIME,
     &                   RATIO,QRES)
      DATA CFM/600.0/
      DATA CFH0,CFH1,CFH2,CFH3,CFH4/2.48131,-1.08012E-02,2.79006E-05,
     &    -3.08633E-08,1.25129E-11/
      DATA CHE0,CHE1,CHE2,CHE3,CHE4/3.20227,-1.70532E-02,4.53358E-05,
     &     -5.0885E-08,2.08555E-11/
      DATA HKW0,HKW1,HKW2,HKW3,HKW4/3.24123,-1.17673E-02,2.64E-05,
     &     -2.9195E-08,1.25121E-11/
      DATA H0,H1,H2,H3,H4,H5,H6,H7/1903.4,175.32,0.556,-135.8,0.556,
     &     5962.5,-544.4,1.6715E-02/
```

```
0000000001111111111222222222233333333334444444444555555555566666666667777777777B
12345678901234567890123456789012345678901234567890123456789012345678901234567890
      DATA HE0,HE1,HE2,HE3,HE4,HE5,HE6,HE7/-2620.4,170.28,0.278,-117.5,
     &     0.278,5339.6,-622.2,-0.0525/
      DATA CI0,CI1,CI2,CI3,CI4,CI5,CI6,CI7/1.2965,5.99063E-03,4.444E-05
     &     ,-7.73159E-03,9.444E-05,-0.10627,0.02111,2.464E-05/
C
C
      QLOAD=-QBLDG
      CFHC=1.0
      CFHE=1.0
      CFKWH=1.0
      QRES=0.0
      X1=EWT
      X2=EDB
      X3=GPM
      X4=X1*X1
      X5=X2*X2
      X6=X3*X3
      X7=X1*X2*X3
      B=CFM/100.0
      SP=21.35-14.03667*B+3.69*B*B-0.37833*B*B*B+0.015*B*B*B*B
C
C         CORRECTION FACTORS FOR TOTAL HEATING CAPACITY, HEAT EXRACTION
C         RATE AND COMPRESSOR POWER INPUT, RESPECTIVELY.
C
      IF(CFM.EQ.500.0) GO TO 101
      Z1=CFM
      Z2=Z1*Z1
      Z3=Z1*Z2
      Z4=Z2*Z2
      CFHC=CFH0+CFH1*Z1+CFH2*Z2+CFH3*Z3+CFH4*Z4
      CFHE=CHE0+CHE1*Z1+CHE2*Z2+CHE3*Z3+CHE4*Z4
      CFKWH=HKW.0+HKW1*Z1+HKW2*Z2+HKW3*Z3+HKW4*Z4
C
C         COMPUTE THE STEADY STATE HEATING CAPACITY (BTUH), HEAT
C         EXTRACTION RATE (BTUH), AND COMPRESSOR POWER INPUT (KW),
C         RESPECTIVELY.
C
  101 Q=CFHC*(H0+H1*X1+H2*X4+H3*X2+H4*X5+H5*X3+H6*X6+H7*X7)
      QHESS=CFHE*(HE0+HE1*X1+HE2*X4+HE3*X2+HE4*X5+HE5*X3+HE6*X6+HE7*X7)
      CPOWER=CFKWH*(CI0+CI1*X1+CI2*X4+CI3*X2+CI4*X5+CI5*X3+CI6*X6
     &              +CI7*X7)
      QPART=0.25*Q
      ONTIME=0.25
C
C         CHECK IF THE HEAT PUMP WILL CYCLE ON-OFF
C
      RATIO=QLOAD/QPART
      IF(RATIO.GT.1.0) QRES=(QLOAD-QPART)/3412.15
      ONTIME=0.25*RATIO
      IF(ONTIME.GT.0.25) ONTIME=0.25
      IF(ONTIME.LT.0.06) ONTIME=0.06
      TIMEC=-ONTIME/ALOG(0.005)
      QCYCLE=Q*(ONTIME-TIMEC*(1.0-EXP(-ONTIME/TIMEC)))
      QPART=QCYCLE
      QEXT=-QHESS
```

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0000000001111111111222222222233333333334444444444555555555566666666667777777778
1234567890123456789012345678901234567890123456789012345678901234567890
      QCAP=QPART
      FP=9.395E-04*SP*CFM
      CKWH=(CPOWER+FP+0.075)*CNTIME
      COP=QPART/(3412.15*(CKWH+QRES))
      RETURN
      END
C
C
C**********************************************************************
C****                                                              ****
C****       COOLING, AIR-TO-AIR HEAT PUMP: SUBROUTINE(APUMPC)      ****
C****                                                              ****
C**********************************************************************
C
C
      SUBROUTINE APUMPC (TAMB,TDB,TWB,QBLDG,CCAP,CKWH,COP,CNTIME)
      DATA CFM /575.0/
      DATA C0,C1,C2,C3,C4,C5,C6,C7/31793.8,36.78393,-0.7037,-528.723,
     &     4.93333,-13.24353,4.7619E-03,1.55021E-03/
      DATA U0,U1,U2,U3,U4,U5,U6,U7/2.33606,1.04283E-02,-2.381E-05,
     &     -3.43148E-02,2.8E-04,-1.33345E-03,6.5E-07,1.9E-07/
      DATA S0,S1,S2,S3,S4,S5,S6,S7/-21778.0,75.67,-0.84127,1494.7,
     &     -15.867,-2.03211,-4.7619E-03,2.12277E-03/
C
C
      QLOAD=QBLDG
      X1=TAMB
      X2=TWB
      X3=CFM
      X4=X1*X1
      X5=X2*X2
      X6=X3*X3
      X7=X1*X2*X3
      CNTIME=0.25
C
C     CORRECTION FACTOR FOR THE SENSIBLE COOLING CAPACITY WHEN THE
C     ENTERING DRY BULB IS NE. 80.0 F.
C
      BF=0.0212+1.5354E-04*X3
      QCF=1.09*X3*(1.0-BF)*(TDB-80.0)
C
C     COMPUTE THE HEAT PUMP STEADY STATE TOTAL CAPACITY (BTUH),
C     SENSIBLE CAPACITY (BTUH), AND POWER INPUT (COMPRESSOR,INDOOR,
C     AND OUTDOOR FANS) (KW).
C
      Q=C0+C1*X1+C2*X4+C3*X2+C4*X5+C5*X3+C6*X6+C7*X7
      QS=QCF+S0+S1*X1+S2*X4+S3*X2+S4*X5+S5*X3+S6*X6+S7*X7
      UKW=U0+U1*X1+U2*X4+U3*X2+U4*X5+U5*X3+U6*X6+U7*X7
      QPART=0.25*Q
C
C     CHECK IF THE HEAT PUMP WILL CYCLE ON-OFF
C
      RATIO=QLOAD/QPART
      IF(RATIO.LE.0.06) RATIO=0.06
      CNTIME=0.25*RATIO
```

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0000000001111111111222222222233333333334444444444555555555566666666667777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
      IF(CNTIME.GT.0.25) CNTIME=0.25
      TIMEC=-ONTIME/ALOG(0.005)
      QCYCLE=Q*(ONTIME-TIMEC*(1.0-EXP(-ONTIME/TIMEC)))
      QPART=QCYCLE
      QCAP=QPART
      CKWH=UKW*CNTIME
      COP=QPART/(3412.15*UKW*CNTIME)
      RETURN
      END
C
C
C
C
C***********************************************************************
C****                                                              ****
C****     HEATING, AIR-TO-AIR HEAT PUMP: SUBROUTINE(APUMPH)        ****
C****                                                              ****
C***********************************************************************
C
C
      SUBROUTINE APUMPH (TAMB,TDB,QBLDG,QCAP,CKWH,COP,CNTIME,QRES)
      DATA CFM/575.0/
      DATA H0,H1,H2,H3,H4,H5,H6/5393.4,187.435,2.39421,-0.47104,
     &    2.04404E-02,-3.20595E-04,1.71E-06/
      DATA C0,C1,C2,C3,C4/1.59131,1.45083E-02,-1.11042E-03,3.365E-05,
     &    -2.7E-07/
C
C
      QLOAD=-QBLDG
      CFC=1.0
      CKW=1.0
      TCF=1.0
      TKW=1.0
      QRES=0.0
      X1=TAMB
      X2=X1*X1
      X3=X1*X2
      X4=X1*X3
      X5=X1*X4
      X6=X1*X5
      ONTIME=0.25
C
C        CORRECTION FACTOR FOR DIFFERENT VALUES OF CFM AND IDOOR DRY
C        BULB TEMPERATURE.
C
      CFC=0.77+0.0004*CFM
      CKW=0.335+0.0002*CFM
      TFC=1.28-0.004*TDB
      TKW=0.86+0.002*TDB
C
C        COMPUTE THE HEAT PUMP STEADY STATE PERFORMANCE AND POWER
C        INPUT (COMPRESSOR, INDOOR & OUTDOOR FANS).
C
      Q=CFC*TFC*(H0+H1*X1+H2*X2+H3*X3+H4*X4+H5*X5+H6*X6)
      UKW=CKW*TKW*(C0+C1*X1+C2*X2+C3*X3+C4*X4)
```

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00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
C
C          CHECK IF THE HEAT PUMP WILL CYCLE ON-OFF
C
      QPART=0.25*Q
      RATIO=QLOAD/QPART
      IF(RATIO.GT.1.0) QRES=(QLOAD-QPART)/3412.15
      ONTIME=0.25*RATIO
      IF(ONTIME.GT.0.25) ONTIME=0.25
      IF(ONTIME.LT.0.06) ONTIME=0.06
      TIMEC=-ONTIME/ALOG(0.005)
      QCYCLE=Q*(ONTIME-TIMEC*(1.0-EXP(-ONTIME/TIMEC)))
      QPART=QCYCLE
      QCAP=QPART
      COP=QPART/(3412.15*(UKW*ONTIME+QRES))
      CKWH=UKW*ONTIME
      RETURN
      END
C
C
C ********************************************************************
C ********                                                    ********
C ********            S U B R O U T I N E   S O L A R          ********
C ********                                                    ********
C ********************************************************************
C
C
      SUBROUTINE SOLAR (TAMB,WDR,WV,SR,INDEX,HOUR,MONTH,NDOM,TCI,TCO,QU,
     &                  TC,ITIME)
C
C
C     PURPOSE:
C             TO COMPUTE THE COLLECTOR EXIT TEMPERATURE AND THE RATE OF
C             HEAT EXCHANGE BETWEEN THE COLLECTOR AND THE AMBIENT FOR A
C             SOLAR ENERGY LOOP.  THE LOOP CONSISTS OF A BARE COLLECTOR
C             PANEL(S), A HEAT EXCHANGER AND A CIRCULATING PUMP.
C             HORIZONTAL OR TILTED SURFACE SOLAR RADIATION CAN BE INPUT
C             IF HORIZONTAL SOLAR RADIATION IS THE INPUT, THE SUBROUTINE
C             WILL CONVERT IT TO THAT INCIDENT ON A TILTED SURFACE.
C
C             DESCRIPTION OF PARAMETERS:
C             INPUT-
C                  TAMB - DRY BULB TEMPERATURE OF THE AMBIENT (F)
C                  WV   - WIND VELOCITY (MILE/HR)
C                  WDR  - WIND DIRECTION (DEGREES)
C                  SR   - SOLAR RADIATION INCIDENT ON THE SURFACE
C                         (BTU/HR-FT**2)
C                  INDEX- INDEX IDENTIFYING THE TYPE OF SOLAR RADIATION
C                         INPUT
C                       = 1  (HORIZONTAL SURFACE SOLAR RADIATION)
C                       = 2  (TILTED SURFACE SOLAR RADIATION)
C                  HOUR - LOCAL STANDARD TIME (HOURS)
C                  MONTH- MONTH OF THE YEAR (E.G. 1,2,.....12)
C                  NDOM - NUMBER OF DAY THE OF MONTH (E.G. 1,2,....,30)
C                  TCI  - COLLECTOR INLET TEMPERATURE (F)
C
```

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          00000000011111111112222222222333333333344444444445555555555666666666677777777778
          12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
      C          OUTPUT-
      C                    TCO  - COLLECTOR OUTLET TEMPERATURE (F)
      C                    QU   - RATE OF ENERGY EXCHANGE BETWEEN COLLECTOR AND
      C                           AMBIENT (BTU/HR)
      C                    TC   - COLLECTOR PLATE TEMPERATURE (F)
      C
      C
      C
            COMMON FLOW
            DIMENSION CST(14),NDYM(12)
            DATA CST/0.057,0.058,0.06,0.071,0.097,0.121,0.134,0.136,0.122,
           &    0.092,0.073,0.063,0.057,0.058/
            DATA NDYM/0,31,59,90,120,151,181,212,243,273,304,334/
            DATA RAD,TZ,ACLONG,XLAT,REF,TILT/.01745,6.,97.,36.017,.2,90./
            DATA SIGMA,CHITE,AC,EF,W/0.1712E-08,7.0,140.0,0.90,.333/
            DATA DI,PI,CB,ALPHA,HFI/0.04342,3.14159,38.52,0.95,100.0/
            DATA EW,TN,TL,DO/0.4,60.0,70.0,0.05208/,CPG/0.84/
            DATA D0,D1,D2,D3,D4,D5,D6/8.53633E-02,-1.8859E-04,2.76608E-07,
           &3.05179E-09,-4.04333E-11,1.93653E-13,-3.32374E-16/
            DATA C0,C1,C2,C3,C4,C5,C6/1.31069E-02,2.63437E-05,2.03083E-08,
           &-9.33445E-10,1.07258E-11,-5.20563E-14,9.11518E-17/
            DATA V0,V1,V2,V3,V4,V5,V6/0.4553,1.79714E-03,2.42925E-06,
           &-3.32359E-08,3.50757E-10,-1.0353E-12,2.8E-15/
            DATA P0,P1,P2,P3,P4,P5,P6/0.72204,-2.01553E-04,-1.1113E-06,
           &5.87489E-08,-7.49793E-10,3.85345E-12,-7.03039E-15/
      C
      C
      C
      C
            IF(ITIME.EQ.1.AND.HOUR.LE.0.0) HOUR=24.0
            IT=SR
            HUR=HOUR
            G=FLOW*518.1/AC
            XMCG=518.1*CPG*FLOW
            IF(ITIME.EQ.2) HUR=HUR+0.125
            IF(INDEX.EQ.2) GO TO 77
      C
      C***  CONVERT HORIZONTAL SURFACE RADIATION TO THAT OF A TILTED SURFACE
      C
            NM=MONTH
            NDY=NDYM(NM)+NDOM
            NM=NM+1
            NM1=NM
            DNDOM=21-NDOM
            IF(DNDOM.LT.0.0) NM=NM+1
            CSTT=(CST(NM)-CST(NM-1))/30.5
            IF(NDY.LT.100) EQT=-5.0-9.0*SIN((2.0*NDY-2.0)*RAD)
            IF(NDY.GE.100.AND.NDY.LE.242) EQT=-1.+5.0*SIN((NDY-100.)*RAD/.395)
            IF(NDY.GT.242) EQT=-2.5+18.6*SIN((NDY-242.)*RAD/0.685)
            C=CST(NM1)-(CSTT*DNDOM)
            D=23.45*SIN((NDY-30.0)*360.0*RAD/370.0)
            STIME=HUR+TZ-(ACLONG/15.0)+EQT/60.0
            HANGLE=(STIME-12.0)*15.0
            SINA=COS(XLAT*RAD)*COS(D*RAD)*COS(HANGLE*RAD)+SIN(XLAT*RAD)*
           &     SIN(D*RAD)
```

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000000000111111111122222222223333333333444444444455555555556666666666777777777778
1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
      HDN=HT/(SINA+C)
      COSTH=COS((XLAT-TILT)*RAD)*COS(D*RAD)*COS(HANGLE*RAD)+
     &        SIN((XLAT-TILT)*RAD)*SIN(D*RAD)
      HDRECT=HDN*COSTH
      HDIFUZ=0.5*HDN*(C*(1.0+COS(TILT*RAD))+REF*(C+SINA)*
     &          (1.0-COS(TILT*RAD)))
      HT=HDRECT+HDIFUZ
C
C          BEGIN CALCULATION FOR THE COLLECOR USEFUL HEAT GAIN/LOSS AND
C          THE COLLECTOR OUTLET TEMPERATURE
C
   77 TC=200.0
      UCHK=0.0
      IF(WDR.LT.90.0.OR.WDR.GT.270.0.AND.WV.GT.100.0) WV=5.0
      HW=0.8+0.23*WV
      FS=0.5*(1.0+COS(TILT*RAD))
   88 TAVG=(TC+TAMB)/2.0
      TREF=TC+0.38*(TAMB-TC)
      X2=TAVG*TAVG
      X3=X2*TAVG
      X4=X3*TAVG
      X5=X4*TAVG
      X6=X5*TAVG
      TCR=TC+460.0
      TAMBK=((TAMB-32.0)/1.8)+273.0
      TSKYR=1.8*(0.0552*(TAMBK**1.5))
      TAMBR=TAMB+460.0
      HRPS=SIGMA*EP*FS*(TCR*TCR+TSKYR*TSKYR)*(TCR+TSKYR)
      HRPG=SIGMA*EP*FS*(TCR*TCR+TAMBR*TAMBR)*(TCR+TAMBR)
      HRPW=SIGMA*(TCR*TCR+TAMBR*TAMBR)*(TCR+TAMBR)/(1.0/EP+1.0/EW-1.0)
      ROTA=D0+D1*TAVG+D2*X2+D3*X3+D4*X4+D5*X5+D6*X6
      ROTR=D0+D1*TREF+D2*TREF**2.+D3*TREF**3.+D4*TREF**4+D5*TREF**5.
     &       +D6*TREF**6.0
      VISC=(V0+V1*TAVG+V2*X2+V3*X3+V4*X4+V5*X5+V6*X6)/3.6E03
      PRN=P0+P1*TAVG+P2*X2+P3*X3+P4*X4+P5*X5+P6*X6
      AIRK=C0+C1*TAVG+C2*X2+C3*X3+C4*X4+C5*X5+C6*X6
      BETA=ROTA*((1.0/ROTR-1.0/ROTA)/(TREF-TAVG))
      GRL=32.2*BETA*ABS(TC-TAMB)*(CHITE**3.)/(VISC*VISC)
      HNC=0.021*(AIRK/CHITE)*((PRN*GRL)**0.4)
      UT=HW+HRPS+HRPG
      UB=HRPW+HNC
      UL=UT+UB
      IF(ABS(UL-UCHK).LE.0.001) GO TO 99
      UCHK=UL
      AM=SQRT(UL/0.00948)
      DUM=0.5*AM*(W-DC)
      FEFF=TANH(DUM)/DUM
      DUM1=UL*(DC+FEFF*(W-DC))
      F1=1.0/((W*UL)*(1.0/DUM1+1.0/CB+1.0/(PI*DI*HFI)))
      DUM2=G*CPG/UL
      FR=DUM2*(1.0-EXP(-F1/DUM2))
      QU=AC*FR*(HT*ALPHA-UL*(TCI-TAMB))
      TFM=TCI+(1.0-FR/F1)*QU/(AC*UL*FR)
      TC=TFM+QU*(1.0/(HFI*FI*DI*TN*TL))
      GO TO 88
```

```
0000000001111111111222222222233333333334444444444555555555566666666667777777777 8
1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
CARD
    99 TCC=TCI+QJ/XMCG
       RETURN
       END
C
C
C
C
C**************************************************************************
C****                                                                 ****
C****        PSYCHROMETRIC PROPERTIES: SUBROUTINE(XMOIST)             ****
C****                                                                 ****
C**************************************************************************
C
C
      SUBROUTINE XMOIST(TDB,TWB,RH,INDIC,PATM,HAIR,WSAT,WAIR,TWALL)
C
C        PURPOSE
C           TO DETERMINE THE ENTHALPY, SATURATION MOISTURE CONTENT,
C           AND ACTUAL MOISTURE CONTENT OF MOIST AIR, AND ALSO, THE
C           NECESSARY WALL TEMPERATURE TO INDUCE MOISTURE REMOVAL,
C           GIVEN DRY BULB TEMPERATURE AND EITHER WET BULB TEMPERATURE
C           OR RELATIVE HUMIDITY.
C           (NOTE : THIS PROGRAM ESSENTIALLY REPRODUCES PSYCHROMETRIC
C           CHART DATA)
C
C        DESCRIPTION OF PARAMETERS
C         INPUT
C           TDB     -  DRY BULB TEMPERATURE (F)
C           TWB     -  WET BULB TEMPERATURE (F)
C           RH      -  RELATIVE HUMIDITY
C           INDIC   -  INPUT INDICATOR
C                      =1, INPUTS ARE TDB, AND TWB
C                      =2, INPUTS ARE TDB, AND RH
C           PATM    -  ATMOSPHERIC PRESSURE (PSIA)
C
C         OUTPUT
C           HAIR    -  ENTHALPY OF MOIST AIR (BTU/LBM DRY AIR)
C           WSAT    -  SATURATION HUMIDITY (LBM WATER/LBM DRY AIR)
C                      CORRESPONDING TO THE EXISTING WET BULB TEMP.
C           WAIR    -  ACTUAL HUMIDITY (LBM WATER/LBM DRY AIR)
C                      CORRESPONDING TO THE GIVEN DRY BULB TEMP.,
C                      PRES., AND REL. HUMIDITY OR WET BULB TEMP.
C           TWALL   -  SATURATION OR DEW POINT TEMPERATURE (F)
C                      CORRESPONDING TO THE GIVEN TDB, PATM, AND TWB, OR
C
      K=0
      I=1
      IF(INDIC.NE.1)GO TO 30
      T=TWB
C
C        DETERMINING SATURATION PARTIAL PRESSURE 'PS' (PSIA)
C        OF WATER VAPOR AT THE GIVEN TEMPERATURE
   10 T1=273.16/(((T-32.0)/1.8)+273.16)
      A1=-3.29692*((1.0/T1)-1.0)
      A2=4.76955*(1.0-T1)
```

```
000000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
      A3=10.79586*(1.0-T1)+5.02808*ALOG10(T1)+1.50474E-04*(1.0-10.**A1)
     &+0.42873E-03*((10.0**A2)-1.0)-2.2196
      PS=(10.0**A3)*14.696
      W=1.004*18.01*PS/(28.967*(PATM-PS))
      IF(K.NE.0) GO TO 50
      IF(INDIC.EQ.2) GO TO 40
      IF(I.NE.1) GO TO 20
      I=2
      WSAT=W
      WAIR=WSAT-0.00236*(TDB-T)
      HAIR=0.24*(TWB-32.0)+WSAT*(1060.9+0.444*TWB)
      P=PATM/(1.004*18.01/(28.967*WAIR)+1.0)
      T=TDB
      GO TO 10
C
C        FINDING THE CORRESPONDING RELATIVE HUMIDITY, GIVEN
C        THE WET BULB TEMPERATURE
C
   20 RH=P/PS
      GO TO 90
   30 T=TDB
      GO TO 10
   40 P=RH*PS
      WAIR=RH*W*(PATM-PS)/(PATM-P)
C
C        FINDING THE CORRESPONDING WET BULB TEMPERATURE, GIVEN
C        THE RELATIVE HUMIDITY
C
      DT=-10.0
   45 T=T+DT
      K=K+1
      IF(K.GT.30)GO TO 70
      GO TO 10
   50 WS=W-0.000236*(TDB-T)
      IF(ABS(WS-WAIR).LE.0.00005) GO TO 80
      IF(WS-WAIR) 60,80,65
   60 T=T-DT
      DT=DT/2.0
   65 CONTINUE
      GO TO 45
   70 WRITE(6,100)
   80 TWB=T
      WSAT=W
      HAIR=0.24*TDB+WAIR*(1060.9+0.444*TDB)
C
C        DETERMINING THE SATURATION OR DEW POINT TEMP. 'TWALL'
C        CORRESPONDING TO THE GIVEN PRESSURE, DRY BULB TEMPERATURE,
C        AND RELATIVE HUMIDITY OR WET BULB TEMP.
C
   90 IF(P.LE.0.0185) TWALL=(P-0.0185)/0.00077
      IF(P.GT.0.0185) TWALL=(P-0.0185)/0.00124
      IF(P.GT.0.0309) TWALL=(P-0.0113)/0.00196
      IF(P.GT.0.0505) TWALL=(P+0.0129)/0.00317
      IF(P.GT.0.0885) TWALL=(P+0.0441)/0.004145
      IF(P.GT.0.1217) TWALL=(P+0.1394)/0.005641
```

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0000000001111111111222222222233333333334444444444555555555566666666667777777777 8
1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
CARD
      IF(P.GT.0.17811) TWALL=(P+0.21284)/0.007819
      IF(P.GT.0.2563) TWALL=(P+0.3345)/0.01068
      IF(P.GT.0.3681) TWALL=(P+0.6435)/0.01438
      IF(P.GT.0.5069) TWALL=(P+1.0235)/0.01913
      IF(P.GT.0.6982) TWALL=(P+1.5603)/0.0251
  100 FORMAT(' ***** ITERATION IN XMOIST DOES NOT CONVERGE')
      RETURN
      END
C
C
C
C
C
C     ************************************************************************
C     ****                                                                ****
C     ****  VERTICAL EARTH-WATER HEAT EXCHANGER: SUBROUTINE(VEWEX)         ****
C     ****                                                                ****
C     ************************************************************************
C
C
       SUBROUTINE VEWEX (TFIN,QEXC,RATIO,TMID,TFOUT,CNTIME)
C
C
C          PURPOSE:
C              TO COMPUTE THE WELL EXITING FLUID TEMPERATURE, THE HEAT
C              TRANSFER RATE BETWEEN THE FLUID AND THE SOIL, AND THE
C              TEMPERATURE PROFILE IN THE SOIL SURROUNDING THE WELL.
C
C        NOTE: THE PHYSICAL PROPERTIES OF THE SOIL ARE ASSUMED CONSTANT
C              IN THIS PROGRAM.
C
C
C          DESCRIPTION OF INPUT/OUTPUT PARAMETERS:
C          INPUT-
C                TFIN  - TEMPERATURE OF THE FLUID EXITING THE WELL. (F)
C                QEXC  - HEAT REJECTED (COOLING MODE) OR EXTRACTED (HEAT
C                        ING MODE) BY THE HEAT PUMP AFTER SOLAR LOOP
C                        CONTRIBUTION.  IN THIS SUBROUTINE, IT IS USED AS
C                        A FIRST ESTIMATE OF THE HEAT CONDUCTED TO OR
C                        FROM THE SOIL. (BTU/HR)
C                RATIO - FRACTION OF THE HEAT PUMP CYCLE THE HEAT PUMP
C                        IS ON.
C               CNTIME- PERIOD OF TIME THE HEAT PUMP IS OPERATING. (HR)
C
C
C         OUTPUT-
C                TMID - TEMPERATURE OF THE FLUID AT THE CENTER OF WELL.(F)
C                TFOUT - TEMPERATURE OF THE FLUID EXITING THE WELL. (F)
C
C
      COMMON /BLOCK/GGPM,KPRINT
      DIMENSION R(33),DR(50),RL(50),FA(50),CV(50),A(50),TAVG(50),TAV(50)
      DIMENSION B(50),C(50,50),CC(50,50),D(50),TF(50),TGROND(12)
      DATA KOUNT,KOUNT1,CYTIME/0,0,0.25/
      DATA PHI,N,RRL,EPSP/3.14159,32,30.0,1.1/
```

```
0000000001111111111222222222233333333334444444444555555555566666666667777777778
1234567890123456789012345678901234567890123456789012345678901234567890123456780
CARD
      C
      C          WELL PARAMETERS
      C
            DATA RO,ALPHA,DEPTH,CCND,DELTAZ,CPF/0.20833,0.0290,250.0,0.82
           &                   ,50,0.1.0/,RHO/62.0/
      C
      C
      C
        199 FORMAT('1',//////,54X,'VALUES OF NON-UNIFORM GRID',//)
        201 FORMAT(5X,'THE WATER TEMPERATURE=',F8.2,10X,'THE HEAT CONDUCTED',
           &          ' TO OR FROM EARTH=',F10.0,'BTU.',/)
        202 FORMAT(5X,'THE SOIL TEMPERATURES ARE.',/)
        203 FORMAT(4(15X,8(F8.2,1X),/))
        204 FORMAT(55X,'THE TOTAL HEAT TO, OF FROM THE SOIL IS',F10.0,'BTU'/)
        300 FORMAT(' ',////,10X,'TEMPERATURE DISTRIBUTION',F6.1,'  FEET FROM'
           &          ,' THE BOTTOM OF THE WELL',3X,///)
        301 FORMAT(4(5X,8('DR(',I2,')=',F7.4,2X),///))
        302 FORMAT(////,54X,'THE RADIUS VALUES',//)
        303 FORMAT(5(5X,8('R(',I2,')=',F7.4,2X),///))
        304 FORMAT('1')
        305 FORMAT(//,10('*'),'VEWEX DOES NOT CONVERGE AFTER 20 ITERATIONS')
      C
      C
            Q=QEXC
            TF(1)=TFIN
            FLRATE=497.3*GGFM
            GFLUX=FLRATE/(PHI*RO*RO)
            WMU=8.3574-.18457*TFIN+.2332E-02*TFIN**2.-.17931E-04*TFIN**3.0
           &     +.81845E-07*TFIN**4.-.20274E-09*TFIN**5.+.20919E-12*TFIN**6.
            WPR=27.51876-.65809*TFIN+.65557E-02*TFIN**2.-.66433E-04*TFIN**3.
           &     +.30315E-06*TFIN**4.-.74791E-09*TFIN**5.+.7675E-12*TFIN**6.
            WK=WMU*CPF/WPR
            RED=2.0*GFLUX*RO/WMU
            IF(RED.LE.2000.0) H=4.364*WK/(2.0*RO)
            IF(RED.GT.2000.0.AND.QEXC.GT.0.0) H=0.023*(RED**0.8)*(WPR**0.3)
           &                                   *WK/(2.0*RO)
            IF(RED.GT.2000.0.AND.QEXC.LE.0.0) H=0.023*(RED**0.8)*(WPR**0.4)
           &                                   *WK/(2.0*RO)
            IF(KOUNT.GE.1) GO TO 500
      C
      C          SET THE VALUE OF RADIUS AND RADIUS INTERVALS.
      C          DOMAIN SIZE=30.0 FT. FROM WELL SURFACE.
      C
            NP1=N+1
            DRAPP=RRL/N
            R(1)=0.0
            DO 100 I=2,NP1
            R(I)=R(I-1)+DRAPP
            DRAPP=DRAPP*EPSR
        100 CONTINUE
            FACTOR=RRL/R(NP1)
            DO 101 I=2,NP1
            R(I)=R(I)*FACTOR
            DR(I)=R(I)-R(I-1)
        101 CONTINUE
```

```
         00000000011111111112222222222333333333344444444445555555555666666666677777777778
         12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
            IF(KPRINT.EQ.0) GO TO 111
      C
      C        PRINT THE VALUES OF NON-UNIFORM GRID
      C
            WRITE(6,199)
            WRITE(6,301) (I,DR(I),I=2,NP1)
        111 DO 122 I=1,NP1
            R(I)=R(I)+RC
        122 CONTINUE
            IF(KPRINT.EQ.0) GO TO 113
      C
      C        PRINT THE VALUES OF RADIUS
      C
            WRITE(6,302)
            WRITE(6,303) (I,R(I),I=1,NP1)
            WRITE(6,304)
      C
      C        BUILD UP RADIUS AND FACE AREA OF LEFT FACE OF CONTROL VOLUME
      C
        113 RL(1)=R(1)
            DO 102 I=2,NP1
            RL(I)=(R(I)+R(I-1))/2.0
            FA(I)=2.0*PHI*RL(I)
        102 CONTINUE
      C
      C        BUILD UP CONTROL VOLUME
      C
            CV(1)=PHI*(RL(2)*RL(2)-RL(1)*RL(1))
            DO 104 I=2,N
            CV(I)=PHI*(RL(I+1)*RL(I+1)-RL(I)*RL(I))
        104 CONTINUE
            K=(DEPTH/DELTAZ)
            DDPTH=K
      C
      C        INITIAL TEMPERATURE DISTRIBUTION
      C
            DO 106 J=1,K
            TGROND(J)=63.0-0.5*(J-1)
            TAV(J)=TGROND(J)
            DO 106 I=1,NP1
        106 CC(J,I)=TGROND(J)
            DO 108 I=2,K
            TF(I)=TGROND(I)
        108 CONTINUE
            AREA=2.0*PHI*RO*DELTAZ
            VOL=PHI*RO*RO*DELTAZ
        500 QTOTAL=0.0
      C
      C        SET UP CALCULATION ACCORDING TO HEAT PUMP CYCLING
      C
            IF(RATIO.GE.1.0) GO TO 991
            IF(KOUNT1.EQ.1) GO TO 990
            DTIME=ONTIME
            MSET=1.0
            GO TO 992
```

```
0000000001111111111222222222233333333334444444444555555555566666666667777777777 8
1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
CARD
  990 MSET=0
      DTIME=CYTIME-ONTIME
      GO TO 992
  991 DTIME=0.125
C
C         BUILD UP COEFFICIENTS OF TMDA
C
  992 X=2.0*FLRATE*DTIME/(RHO*VOL)
      Y=H*AREA*DTIME/(RHO*VOL*CFF)
      XX=X-Y-1.0
      YY=X+Y+1.0
      DO 37 KK=1,K
      KCHECK=0
  300 DO 109 I=1,NP1
  109 C(KK,I)=CC(KK,I)
      A(1)=-(ALPHA*DTIME*FA(2)/(CV(1)*DR(2)))
      B(1)=0.0
      C(KK,1)=C(KK,1)+(Q*ALPHA*DTIME)/(DELTAZ*COND*CV(1))
      D(1)=1.0-A(1)
      DO 200 I=2,N
      B(I)=-(ALPHA*DTIME*FA(I)/(CV(I)*DR(I)))
      A(I)=-(ALPHA*DTIME*FA(I+1)/(CV(I)*DR(I+1)))
      D(I)=1.0-B(I)-A(I)
  200 CONTINUE
      C(KK,N)=C(KK,N)-A(N)*C(KK,N+1)
      A(N)=0.0
C
C         TRIDIAGONAL SYSTEM GAUSS ELIMINATION
C
C         COMPUTE THE NEW MATRIX.  SOLUTION WILL BE STORED IN C ARRAY
C
      DO 25 I=2,N
      RR=B(I)/D(I-1)
      D(I)=D(I)-RR*A(I-1)
      C(KK,I)=C(KK,I)-RR*C(KK,I-1)
   25 CONTINUE
C
C         BACK SUBSTITUTION
C
      C(KK,N)=C(KK,N)/D(N)
      DO 35 I=2,N
      J=N-I+1
      C(KK,J)=(C(KK,J)-A(J)*C(KK,J+1))/D(J)
      IF(C(KK,N).LT.TGROND(KK)) C(KK,N)=TGROND(KK)
   35 CONTINUE
C
C         BEGIN ITERATION FOR VERTICAL TEMPERATURE VARIATION
C
      TF(KK+1)=(XX/YY)*TF(KK)+(2.0/YY)*(TAV(KK)+Y*C(KK,1))
      TAVG(KK)=(TF(KK)+TF(KK+1))/2.0
      QCONV=H*AREA*(TAVG(KK)-C(KK,1))
      IF((ABS(Q)-ABS(QCONV)).LE.10.0) GO TO 1100
      IF(QCONV.GT.Q) Q=Q+(QCONV-Q)/2.0
      IF(Q.GT.QCONV) Q=Q-(Q-QCONV)/2.0
      KCHECK=KCHECK+1
```

```
         0000000001111111111222222222233333333334444444444555555555566666666667777777777 8
         1234567890123456789012345678901234567890123456789012345678901234567890123456789 0
CARD
               IF(KCHECK.GE.20.0) WRITE(6,305)                                  00011030
               IF(KCHECK.GE.20.0) GO TO 40                                      00011040
               GO TO 300                                                        00011050
         1100  QCOND=Q*DTIME                                                    00011060
               QTOTAL=QTOTAL+QCOND                                              00011070
               TAV(KK)=TAVG(KK)                                                 00011080
               DO 107 I=1,NPI                                                   00011090
          107  CC(KK,I)=C(KK,I)                                                 00011100
               TFOUT=TF(KK+1)                                                   00011110
               HZ=KK*DELTAZ                                                     00011120
               WMU=3.3374-.15457*TAVG(KK)+.2332E-02*TAVG(KK)**2.                00011130
              &-.17931E-04*TAVG(KK)**3.0                                        00011140
              &     +.81845E-07*TAVG(KK)**4.-.20274E-09*TAVG(KK)**5.            00011150
              &     +.20919E-12*TAVG(KK)**6.                                    00011160
               WPR=27.51876-.55809*TAVG(KK)+.05657E-02*TAVG(KK)**2.             00011170
              &-.56433E-04*TAVG(KK)**3.                                         00011180
              &     +.30315E-06*TAVG(KK)**4.-.74791E-09*TAVG(KK)**5.            00011190
              &     +.7675E-12*TAVG(KK)**6.                                     00011200
               WK=WMU*CPF/WPR                                                   00011210
               IF(RED.LE.2000.0) H=4.364*WK/(2.0*RO)                            00011220
               IF(RED.GT.2000.0.AND.QEXC.GT.0.0) H=0.023*(RED**0.8)*(WPR**0.3)  00011230
              &                                    *WK/(2.0*RO)                 00011240
               IF(RED.GT.2000.0.AND.QEXC.LE.0.0) H=0.023*(RED**0.8)*(WPR**0.4)  00011250
              &                                    *WK/(2.0*RO)                 00011260
         C          PRINT THE RESULTS                                           00011270
         C                                                                      00011280
               IF(KPRINT.EQ.0) GO TO 37                                         00011290
               WRITE(6,300) HZ                                                  00011300
               WRITE(6,201) TF(KK+1),QCOND                                      00011310
               WRITE(6,202)                                                     00011320
               WRITE(6,203) (CC(KK,I),I=1,32)                                   00011330
           37  CONTINUE                                                         00011340
               TMID=TAVG(3)                                                     00011350
         C                                                                      00011360
         C          RETURN TO FORWARD ANOTHER TIME STEP                         00011370
         C                                                                      00011380
               KOUNT=KOUNT+1                                                    00011390
               IF(KPRINT.EQ.1) WRITE(6,204) QTOTAL                              00011400
               IF(RATIO.GE.1.0) GO TO 40                                        00011410
               KOUNT1=1                                                         00011420
               IF(MSET.EQ.0) KOUNT1=0                                           00011430
           40  RETURN                                                           00011440
               END                                                              00011450
         //GO.SYSIN DD *                                                        00011460
          &INPUT MONTH=08,MDAY1=04,MDAY2=06,INDEX=2,KPRINT=0,IHOUSE=2,IOP=1,&END 00011470
         $ENDLIST                                                               00011510
         //**                                                                   00011520
         //                                                                     00011530
```

2

VITA

Faisal Ibrahem Al-Juwayhel

Candidate for the Degree of

Doctor of Philosophy

Thesis: SIMULATION OF THE DYNAMIC PERFORMANCE OF AIR-SOURCE, EARTH-SOURCE, AND SOLAR ASSISTED EARTH SOURCE HEAT PUMP SYSTEMS

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