Initial Findings: The Integration of Water Loop Heat Pump and Building Structural Thermal Storage Systems

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INITIAL FINDINGS: THE INTEGRATION OF WATER
LOOP HEAT PUMP AND BUILDING STRUCTURAL
THERMAL STORAGE SYSTEMS

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FOREWORD

This report is one in a series of reports describing research activities in support of the U.S. Department of Energy (DOE) Commercial Building System Integration Research Program. The goal of the program is to develop the scientific and technical basis for improving integrated decision-making during design and construction. Improved decision-making could significantly reduce buildings' energy use by the year 2010.

The objectives of the Commercial Building System Integration Research Program are:

- to identify and quantify the most significant energy-related interactions among building subsystems [for example, walls; roofs; windows; heating, ventilation, and air conditioning (HVAC) subsystems and equipment; lighting; power]
- to develop the scientific and technical basis for improving energy-related interactions in building subsystems
- to provide guidance to designers, owners, and builders for improving the integration of building subsystems for energy efficiency.

The lead laboratory for this program is the Pacific Northwest Laboratory. A wide variety of expertise and resources from industry, academia, other government entities, and other DOE laboratories are used in planning, reviewing and conducting research activities. Cooperative and complementary research, development, and technology transfer activities with other interested organizations are actively pursued.

In this report, the interactions of a water loop heat pump system and building structural mass and their effect on whole-building energy performance is analyzed. Comments about the work described in this report will be appreciated by the authors or program managers. The research reports prepared for the program are in a bibliographic list at the back of this report.

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SUMMARY

An earlier study of small office buildings indicated that many commercial buildings need heat in one part of a building while cooling another part. Even more common is the need for heating during one part of the day and cooling during another in the same spaces. If that energy could be economically shifted or stored for later use, significant energy might be saved. It was also hypothesized that if a building's heating and cooling subsystems could be integrated with the building's structural mass and be effectively used to collect, store, and deliver energy, the cost effectiveness of such an approach might be enhanced.

In response to the above problem and hypothesis, researchers at the Pacific Northwest Laboratory (PNL) examined the thermal interactions in a commercial building between the heating, ventilating, and air conditioning (HVAC) system and the building structure. Computer models were developed to simulate this interaction in an existing base building located in Seattle, Washington, in order to find how these building subsystems could be integrated to improve energy efficiency.

The HVAC subsystems in the existing building were modeled. These subsystems consist of decentralized water-source heat pumps in a closed water loop, interconnected to cooling towers for heat rejection during cooling mode and auxiliary boilers for heating. An initial computer model of the base building "as built" was developed. Metered data available for the building was used to calibrate this model to ensure the analysis would provide information closely related to the operation of a real building.

The strategy of HVAC and building structure integration focused on using the concrete floor slabs as thermal storage media. For example, the slabs may be actively charged during off-peak periods with the chilled water in the loop, and either actively or passively discharged into the conditioned space during peak periods. In the computer model this concept was implemented by manifolding an additional water loop to the main HVAC hydronic loop. Tubing in this loop was embedded in the concrete floor slabs of the building. Water was routed to this loop by a controller to charge or discharge thermal energy

to and from the slabs. This integration strategy is referred to as the Building Structural Thermal Storage (BSTS) system.

The building model with the BSTS system was simulated and the results compared to the results of the base case building. Simulations were also performed, for both the base case building model and the building model with the BSTS system, using weather data for five other locations in the United States. The measure of performance was annual HVAC energy consumption of the total building.

The simulations predicted that the annual energy savings using the BSTS system vary significantly with climate, ranging from approximately 3 to 30%. In general, the BSTS system was found to be beneficial where hot and dry summer outdoor air conditions exist. The benefits in predominantly cold climate regions appear to be limited. Future studies are needed to develop generalized design guidelines, control strategies, and costs applicable to building design.

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INITIAL FINDINGS: THE INTEGRATION OF WATER LOOP HEAT PUMP AND BUILDING STRUCTURAL THERMAL STORAGE SYSTEMS

1.0 INTRODUCTION

Previous research on building energy consumption has focused primarily on improving the performance of building subsystems operating independently rather than interactively. From this perspective, many of the potential energy-conserving improvements in individual subsystems have been identified. Understanding how these independent building subsystems are integrated is a key step to further energy conservation, because of the complex and dynamic nature of the energy delivery process in commercial buildings.

An earlier study of small office buildings indicated that many commercial buildings need heat in one part of a building while cooling another part. Even more common is the need for heating during one part of the day and cooling during another in the same spaces. If that energy could be economically shifted or stored for later use, significant energy might be saved. It was also hypothesized that if a building's heating and cooling subsystems could be integrated with the building's structural mass and be effectively used to collect, store, and deliver energy, the cost effectiveness of such an approach might be enhanced.

To test this hypothesis, researchers at the Pacific Northwest Laboratory (PNL)(a) analyzed the integration of heating, ventilation, and air conditioning (HVAC) systems with the mass of a building. This analysis, performed for the U.S. Department of Energy (DOE) Commercial Building System Integration Research Program, included development of a numerical simulation model--the Building Structural Thermal Storage (BSTS) System--and selection of a specific existing building with which to test the integration.

(a) Operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

This report provides a detailed description of PNL's analysis. Background information critical to this analysis appears in Section 2.0. In Section 3.0, the analysis methodology is fully described. Results obtained for the simulated base case building are presented in Section 4.0. The effect that integrating the building mass with the HVAC system has on building performance are discussed in Section 5.0. Information in Section 6.0 describes the effects of climate on HVAC/mass integration. The conclusions and recommendations are presented in Section 7.0. Supporting detailed information is provided in Appendices A and B. Computer code developed for use in this analysis is documented in Appendix C.

2.0 BACKGROUND

This section provides background information that is critical in understanding the analysis that follows later in this report. Section 2.1 describes the nature and purpose of building subsystems interaction research, of which the work reported here is a part. A general discussion of thermal structural storage in buildings, water-source heat pump (WSHP) systems, and the way these two building subsystems can be integrated is given in Section 2.2. Background on the actual test building modeled in this study is given next in Section 2.3. Finally, a discussion of the appropriateness of using a computer simulation code as the primary analytical tool for this study is given in Section 2.4.

2.1 SUBSYSTEM INTERACTION RESEARCH

This investigation is a part of subsystems interaction research, which is one element of the commercial portion of the Building System Integration (BSI) program, a multiyear research endeavor. Subsystems interaction research will develop an understanding of how various materials, components, equipment, and subsystems interact or can be made to interact, and how these interactions affect energy consumption. Examples of subsystems in commercial buildings are the building structure and envelope, the HVAC energy conversion equipment, the HVAC distribution subsystems, and the lighting subsystems. Collectively, they provide enclosure and division of space, temperature and humidity control, ventilation, internal load control, and illumination.

2.2 INTEGRATION OF THE HVAC AND MASS SUBSYSTEMS

Energy storage in building structures occurs passively in all buildings to some extent, and has been shown to have nontrivial energy impacts. When HVAC equipment is shut off or set back during unoccupied periods, the affect of the building mass often results in long temperature recovery time periods. To reduce morning recovery peak in the heating season, some building owners leave the lighting on overnight to maintain the space temperature in a moderate range. For the cooling mode, recent work by researchers at Lawrence Berkeley

Laboratory (Eto 1985) indicates that Monday morning recovery from the passive heat addition to the building mass over a summer weekend negates part of the savings gained by the system shutdown. A Monday morning purging strategy with cool outdoor air is shown to improve performance. However, the efficiency of such a strategy is low compared to active cold storage technologies such as a chilled water storage tank (Eto 1985). As demonstration of this, thermal storage in centralized chiller systems has gained wide acceptance in recent years.

Active thermal storage in building structures, on the other hand, is a relatively new concept. A case study of a Swedish commercial building by Lawrence Berkeley Laboratory (Andersson et al. 1979) discussed the use of a massive floor structure for storage of heat, via an air distribution subsystem, using hollow-core concrete slabs. However, using a water distribution subsystem to charge and discharge the energy stored in the structure appears to have the potential for better control in most applications, because water has a higher heat capacitance than air and thus allows a more thorough purging of stored heat.

The HVAC subsystems used in this study consist of decentralized water-source heat pumps in a closed water loop. This is not a new technology, and it has been recently gaining popularity among designers because of occupant satisfaction (due to excellent zone temperature control) and because of its flexibility in both new design and retrofit applications. A typical water-source heat pump (WSHP) system design is shown in Figure 2.1(a).

Water-source heat pump subsystems with thermal storage have been studied only sporadically. A 1980 Canadian study (Rogers 1980) indicates that adding storage to a water loop heat pump subsystem can substantially improve subsystem performance. In practice, thermal storage can be added by increasing the heat capacitance of the water loop through increasing the amount of water or, in principle, by coupling the loop to the building thermal mass. The structural thermal mass is usable for storage in a water loop heat pump subsystem because

-
- (a) Note that this system corresponds to the base building simulation model described in Section 3.0.

FIGURE 2.1. Typical Water-Source Heat Pump Subsystem

of the inherent dynamics of the system configuration. Thermal mass is known to create time lags in heat transfer, which can be beneficial if properly applied. Because heat pumps can either extract heat from the water loop or reject heat to it, all of the heat capacitance of the distribution piping and fluid, as well as any storage tank or structure coupling, is available for storage.

The drawing in Figure 2.2 shows the water loop for the actual BSTS and water-source heat pump subsystems used in this study^(a). A secondary water loop connects the conventional WSHP water loop to pipes embedded within concrete floor slabs. These pipes are used to transfer heat to and from the structure and the water loop. Practical considerations associated with using the floor slab as the storage medium involve material compatibilities, component connections, and configuration of the piping in the water loop. However, embedding

(a) Figure 2.2 is presented here to illustrate conceptually the integrated design. More detailed descriptions in Section 3.0 will also refer to this figure, because it portrays the actual building subsystems that were simulated.

FIGURE 2.2. Integrated BSTS and Heat Pump Subsystems

water pipes within concrete is a proven concept; thus, many of these considerations have already been addressed in past research. Practical experience has been gained in solar-charged as well as conventional radiant slab heating applications (Solar Heating and Cooling 1979).

The cost of these applications are reasonable in comparison to other HVAC subsystems. Established design criteria for the application include: pipes embedded in floors must be leakproof; long continuous lengths and good flexibility for bending are necessary to minimize the use of any connections and elbows; the pipe must be inert to corrosion, scaling, and electrolysis; and excellent long-term pressure rating and easy installation are needed.

Another important practical consideration for the design and operation of the BSTS system is the effect of structure thermal storage on occupant comfort, which, in turn, affects control strategies in two ways. First, comfort requirements will set limits on the allowable temperature at the surface of the concrete structural elements and, ultimately, on the allowable temperature swings in the water loop, a key determinant of the amount of thermal energy stored and the heat pump efficiency. Second, for the example of cool storage in the structure, the decreased mean radiant temperature of the conditioned space may allow the dry-bulb temperature to be increased and still maintain comfort. Increased space temperature will reduce cooling equipment operating time. Finally, slab temperatures should be moderated to avoid possible condensation on the slab during high wet-bulb temperature conditions.

2.3 TEST BUILDING

The simulation model is based on an existing six-story office building located in Seattle that was monitored by Seattle City Light (SCL) between 1983 and 1985 (Cleary and Crimmin 1986). It is typically occupied 50 hours a week, 8 a.m. to 6 p.m., Monday through Friday; the average occupancy level is 400 people. Built in 1976, the building consists of two rectangular sections, one four stories and the other six. The structure was built on a concrete slab with pre-cast concrete walls. Total floor area is approximately 89,550 ft². Forty-seven percent of the gross wall area is glass.

Heating and cooling are provided by 97 water-source heat pumps that are connected to a common water loop. Two electric boilers are the heat source for the water loop, and a cooling tower is used to reject excess heat during cooling. Ventilation air is provided by a constant-volume supply/exhaust system such that about 20% of the supply air to each zone is outside air. The ventilation system uses a runaround heat recovery system and a resistance duct heater to temper outside air, and operates for 15 hours on weekdays only. There is no economizer (100% outside air) mode in this system; this eliminates the need for larger ducts and fans and for fan capacity modulation. Lighting is predominantly fluorescent with some incandescent task lighting.

2.4 COMPUTER SIMULATION

For this study, PNL developed a computer model for analyzing the integrated system. For a building-level analysis, such as this project, a computer simulation is the most cost-effective and appropriate analysis tool. It can readily provide the researcher with much insight and understanding of the subject by allowing many variations to be examined with relative ease.

Although field monitoring can supply some actual building operation data that are unavailable in simulations, the costs in terms of time and effort involved generally preclude full-scale experiments. In addition, because of the strong influence of independent variables such as weather, consistent comparisons and assessments of alternative subsystems within the building is difficult, if not impossible. In contrast, parametric sensitivity analyses may be readily conducted wherein most variables are held constant while others are varied through a range of physically realistic values.

When using computer simulations as a research tool, care must be taken to appreciate the inherent limitations of mathematical modeling. A model of a complex system can never perform exactly as the real system does in every minute detail. Computer simulation should thus be used to ascertain the relative importance of particular variables to the overall effect under observation.

3.0 ANALYSIS METHODOLOGY

This section describes the analysis methodology followed during the course of the research reported here. The metered data collected by SCL for the existing building are discussed in Section 3.1. The Transient System Simulation Program (TRNSYS), the primary modeling tool employed on this project, is discussed in Section 3.2. A discussion of the development of the base case building simulation model follows in Section 3.3, along with details of the TRNSYS subroutines used and/or developed specifically for modeling the building subsystem and components. Finally, the strategies and methodology employed in introducing and then optimizing the interaction between the HVAC subsystems and the BSTS system are detailed in Section 3.4.

3.1 METERED DATA ANALYSIS

The metered data for the actual base building consist of electricity consumption in amperes and kilowatt-hours for the boilers, cooling tower, heat pumps, supply and exhaust fans, lights, outlets, hot water, and elevators. Although the building's 97 unitary heat pumps operate independently, only the total heat pump electricity consumption measurement was available. In addition, no water temperatures or control signals were monitored. This data aggregation, plus the lack of any building temperature measurements, limited the analysis possibilities.

The 1985 data were analyzed, because the 1983 and 1984 data sets are incomplete. In the 1985 data there are occasional missing hours and a period of approximately 3 weeks of missing data in late November and early December. A total of 507 hours (6%) are missing. Most of the analysis was performed by directly summing various quantities such as the monthly or yearly electricity consumed by a specific piece of equipment or the number of hours of operation.

The primary end-use loads of the actual base building are heating and cooling equipment (47.9% of the total energy consumption), lights (34.4%) and miscellaneous (17.7%). The building consumed the equivalent of 73,460 Btu/yr-ft² in 1985, or a total of 1,413,900 kWh with an average monthly demand of 410 kW (Table 3.1).

TABLE 3.1. Seattle City Light Metered Data Analysis

SCL Building Specifications

Gross floor area	89,550 ft ²
Year built	1976
Shell materials	Concrete
Principal use	Office

Billed Consumption - 1985

kWh	1,413,900
kWh/ft ²	15.8

<u>Electric End-Uses(a)</u>	<u>kWh</u>	<u>kWh/ft²</u>	<u>Percent</u>
HVAC	649,116	7.2	47.9
Lights	466,032	5.2	34.4
Misc equipment	239,148	2.7	17.7
TOTAL	1,354,296	15.1	100.0

(a) Within the precision range of the monitoring equipment.

3.2 TRANSIENT SYSTEM SIMULATION PROGRAM (TRNSYS)

The Transient System Simulation (TRNSYS) Program was selected as the analysis tool for this study because it can perform a dynamic whole building system analysis and it can be readily modified and new building subsystem component models incorporated (University of Wisconsin 1983). TRNSYS was designed with a modular structure. A wide variety of component models are available in the standard TRNSYS library. For the system modeled in this project, assembling the component modules according to the TRNSYS format was a relatively straightforward procedure.

The modular nature of TRNSYS gave the program flexibility and facilitated the addition of user-formulated mathematical models (see Section 3.3.2). Unlike other programs without a modular structure (e.g., DOE-2), the main program of TRNSYS itself does not have to be modified as new models are added.

Available in TRNSYS is a building load model that uses *temperature level control*, a dynamic modeling approach, as opposed to *energy rate control* used in programs such as DOE-2. Depending on the objective of the study, each approach offers different advantages.

In energy rate control, the model calculates the thermal loads based only upon the net thermal gains or losses from the space. The loads are considered to be independent of the HVAC equipment operation. The program determines the heat addition or extraction to maintain the space at specified heating and cooling temperatures (the thermal loads). An HVAC equipment model subsequently calculates the energy required to satisfy these loads. The advantage of the energy rate control is that once the building loads are determined, the researcher may reuse them for various equipment simulations without having to repeat the load calculations. However, in this type of simulation no energy balance is ensured, and much of the detailed dynamics of the equipment, the control, and the building itself are lost.

On the other hand, for temperature level control, the room condition is determined by not only the ambient conditions, but also the heating and cooling equipment inputs. The interactive feedback of the building subsystems is captured. This is a more realistic reflection of the actual thermal responses of the building. The temperature level control requires more complicated modeling schemes, including a controller to command the operation of the building system. In addition, as the building load is no longer assumed to be independent of the instantaneous inputs of its subsystems, it must be calculated for each simulation.

The system under study is complex; its performance is affected by the interactive feedback from the subsystems involved. For example, the energy performance of a water-source heat pump is strongly dependent on the room temperature and humidity, as well as on the water temperature and flow rate. This room condition, in turn, depends on the sensible and latent capacities of the heat pump and the ambient conditions, along with the thermal integrity of the building. The water loop temperature is a function of boiler and cooling tower operation and the coincident operation of other heat pumps that also take heat from or reject heat to the loop. In addition, the operation of

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the duct heater used to temper the ventilation air also affects the operation of the space conditioning equipment. Finally, the use of the building structure for thermal storage and the use of the water loop as its heat source and sink further complicates these interactions by affecting the building load and the water loop temperature. Because the objective of this project was to study the dynamic interaction of the building subsystems, the temperature rate control modeling approach was required. TRNSYS offered such a modeling scheme.

3.3 BASE CASE BUILDING MODEL DEVELOPMENT

As a first stage in the development of the BSTS system model, TRNSYS was used to simulate the existing base case building. To verify that the actual building was being realistically modeled, the input was calibrated using the metered data results. Using the calibrated base case building model as a starting point, the BSTS system could then be implemented. The simulated results of the base case model with the BSTS system would then provide a realistic estimate of the impact of integrating the HVAC subsystems and the building structural mass.

The basic TRNSYS building system modeling approach is discussed in Section 3.3.1. Key component module subroutines used in the base case, some of which were developed specifically for this project, are detailed in Section 3.3.2. Finally, a discussion of modeling uncertainties and the methodology used to calibrate the base case model to achieve close agreement with metered data is covered in Section 3.3.3.

3.3.1 TRNSYS Building System Model

The TRNSYS model can mathematically represent building envelope thermal properties, HVAC subsystems performance, occupant heat and moisture generation, light and equipment convective and radiative heat gains, solar radiation, heat conduction to and from the environment, and other properties for an entire building. However, because of limits on computer speed and memory, it was not practical for this study to simulate the entire base case building. Hence, it was necessary to simplify the system model in several ways.

The first such simplification was to model the entire multistory base case building as a single representative floor. This implies that the heating or cooling loads on all floors are equal, an assumption justified for commercial buildings where the space usage on each floor is roughly identical and the building envelope is homogeneous. When each floor has approximately the same load profile there is no net heat transfer between floors. Furthermore, in most commercial buildings, heat losses from the first-floor slab to the ground are small compared to other losses because the perimeter of a large slab is much smaller than the floor area. Unless the building has large conditioned spaces underground, the effects of ground coupling may be ignored. The roof area, on the other hand, does exchange heat with the environment, and was included in the model. Because the base building has six stories, one-sixth of the roof was modeled and the heat conductance was coupled to the single floor, which represents the entire building.

The next simplifying aggregation was to assume that the single floor can be modeled as a core zone, four perimeter zones, and a common ceiling plenum zone (see Figure 3.1). The core and perimeter zones are each conditioned by a single heat pump that represents the performance of a number of smaller units. In the actual building, each floor contains approximately 16 heat pumps, ranging in capacity from 1 to 3 tons of cooling. In the model, each floor is served by five units sized according to the amount of space served. However, this is only a capacity scaling; the efficiency of the aggregated heat pumps is the same as that of the actual smaller units. Boiler, cooling tower, and other component capacities were scaled by one-sixth as well to maintain the proper fluid temperatures and flow rates. The energy consumption of these components was multiplied by six to produce totals comparable to the actual six-floor building.

Figure 3.2 shows the information flows in the TRNSYS base case building model. Hourly values of temperature, solar radiation, humidity, and wind speed for a Typical Meteorological Year (TMY) imposed loads on the building zones. Internal heat gains from people, lights, and equipment were established by 24-hour weekend and weekday profiles sequenced into a repeating weekly profile. These energy flows plus the supply air temperature and mass flow

FIGURE 3.1. Plan and Elevation Views of the Single Floor (One-Sixth Building) Zone Arrangements Used in the Building Model

FIGURE 3.2. Building System Model Block Diagram

rate were summed, and an energy balance was performed on each zone. From the energy balance, a zone temperature was calculated. This zone temperature, in turn, triggered the room thermostat that commands the heat pump operations. Cooling tower or boiler operation occurs when the water loop temperature exceeds or falls below setpoints of 85°F or 60°F, respectively, as the heat pumps exchange heat with the water loop. Electric energy input to the boiler, cooling tower, heat pumps, fans, pump and duct heater were calculated and output.

Outside air was controlled by a time clock subroutine such that during weekdays, 20% of the total supply air to the zones was tempered fresh air. The outside air was preconditioned by an electric resistance heater and a glycol runaround loop, which exchanges heat with exhaust air that comes from the plenum. The outside air temperature and flow rate were passed to the plenum zone where the mixed air temperature was calculated. Plenum air temperature and return air temperature were input to the heat pumps where heat pump fan and compressor power were calculated.

TRNSYS calculates air and water temperatures that depend on control signals based on these same temperatures. Because this information flow is recursive, TRNSYS iterates through these calculations during each time step until the temperature calculated in successive time steps agrees to within a specified tolerance (a tolerance of 1% was used for this study). Similar iterative calculations are performed throughout the simulation model.

Envelope and equipment characteristics were based on the actual building monitored by SCL for the calibration of the simulation model with an actual building. This model can be modified to simulate other building configurations by scaling to the appropriate dimensions.

3.3.2 Component Modules

In TRNSYS a subsystem model is made up of a number of different component models. The details of individual component models used in this study that are available in the released version of TRNSYS are available in the manual (University of Wisconsin 1983) and will not be repeated here. However, the existing TRNSYS building zone model will be summarized in terms of the approach it uses to model the inside heat exchanges.

In addition, five new component models were developed by PNL researchers specifically for this study: the cooling tower, the heat pump, the water loop boiler, the water loop thermostat (used to control cooling tower and boiler operations), and the floor slab used in the BSTS system. Two of these components, the boiler and thermostat, are extended versions of existing TRNSYS modules. They were modified so that boiler heat output during the simulation would be linearly proportional to inlet water loop temperature over a user specified range above the heating setpoint. The thermostat module was also modified for use in the BSTS system control scheme to turn on the cooling tower to maintain water temperatures at or below 65°F from 4:00 to 6:00 am on summer working days (see Section 3.4.2). The heat pump, cooling tower and floor slab models are, on the other hand, entirely new, and their simulation approaches are described in Sections 3.3.2.2, 3.3.2.2, and 3.4.1, respectively. Appendix C includes a code listing for all five of these component models.

3.3.2.1 TRNSYS Building Zone Model

The component model used to simulate the thermal behavior of the building was the TRNSYS Detailed Zone Model (TRNSYS Type 19). The zone model uses the temperature level control modeling approach discussed in Section 3.3.1. The zone temperature and humidity reflect the ambient conditions, the heating and cooling equipment inputs, and any other thermal inputs (for example, the passive thermal discharge of the thermal storage slab). This model individually simulates the zone subcomponents such as walls, windows, flat roof, doors, and floor. A multizone building such as the one analyzed for this report is simulated through multiple uses of this model.

An energy balance equation for each subcomponent within each zone is formulated to account for the conduction, convection, and radiation heat transfers. These equations are detailed in the TRNSYS manual. Specifically, it should be noted that conduction through walls is modeled using the American Society of Heating, Refrigeration, and Air Conditioning Engineers' transfer function approach (ASHRAE 1985). Convection heat exchange is determined using a constant value of convection heat transfer coefficients and the difference between the surface temperature and the room temperature.

Solar radiation passing through windows is assumed to be isotropic, striking diffusely reflecting gray (i.e., having radiative properties that do not vary with wavelength) interior surfaces within the zone. TRNSYS computes overall exchange factors for solar radiation at the beginning of a simulation using surface reflectivities input by the user and geometric view factors. A simplified method for determining geometric view factors that was available in TRNSYS was used for the base building that computes these factors based on area ratios(a). In TRNSYS all surfaces are assumed to be black (i.e., perfect absorbers) to radiation from lights, people, and equipment, as well as long-wave radiation from other surfaces. Radiative gains from people are assumed to be 70% of their total sensible energy output; the remaining 30% is assumed to be convected directly to the space. Radiation heat transfer from lights, people, and equipment is apportioned evenly over all zone interior surface areas. Long-wave radiation heat transfer is modeled using a linearized radiation heat transfer coefficient. Constant radiative coefficients are calculated for pairs of zone surfaces using average initial surface temperatures and the black body view factors.

An energy balance equation for each subcomponent and the room air is set up in matrix format. For the long-wave radiative and convective exchanges of each interior surface, an equivalent zone temperature is used. This equivalent zone temperature is analogous to the sol-air(b) temperature used for the exterior surfaces to account for both solar and convection heat transfers. The surface temperatures are calculated at each time step by solving the simultaneous equations using direct matrix-inversion (University of Wisconsin 1983).

-
- (a) This simplified approach for computing geometric view factors was used because of uncertainties in the actual geometric configuration of the interior space in the base building. Sensitivity studies of the base case building model were performed, however, that compared results obtained using this approximation to those obtained when approximated user input view factors in the southern exposure zone were used. The differences were found to be insignificant.
  - (b) Sol-air temperature is the inside air temperature which in the absence of long-wave surface radiative exchange results in the same heat transfer as actually occurs.

3.3.2.2 Water-Source Heat Pump Model

The heat pump component model developed for this study was not a detailed equipment model that simulates the individual energy conversion components, such as the compressor and the heat exchangers. Rather, it was an extension of an empirical fit to the manufacturer's rating data.

At given entering water and air conditions, the model calculates the steady-state sensible and latent capacities and power inputs of the heat pump. A time constant is applied to approximate transient performance. The amount of heat rejected or extracted from the water loop is determined by an energy balance on the refrigeration loop. Finally, the exit temperature and humidity of the air, and the exit temperature of the water are calculated based on the heat addition or extraction.

3.3.2.3 Cooling Tower Model

A cooling tower model is used to calculate the exiting water temperature at a given set of conditions. The most commonly used cooling tower model is the Merkel model (ASHRAE 1983). It involves a numerical integration of the heat transfer rate across the two flow streams through the tower. To predict the outlet states of the flow streams, an iterative process is required. In order to reduce the execution time of the model, a simpler approach developed by Whillier (Whillier 1976) was used that follows closely the algorithm used by Braun (Braun, Mitchell, and Kline 1987).

The Whillier model was established based on the assertion that the performance of a cooling tower may be characterized by a single linear function that correlates its effectiveness, E , to its capacity factor, $R(a)$:

$$E = F/[F + (1 - F)R]$$

-
- (a) Cooling tower effectiveness is defined as the ratio of the actual to the maximum possible heat transfer from the water to the air stream. The capacity factor is the ratio of the minimum to maximum thermal capacities of the air and water streams.

where F , a relative factor of merit for the cooling tower, is determined from experimental results or manufacturer's data, while R is directly computed from given air and water inlet conditions. After using the above relation to determine E , the exit state of the water for any off-design conditions is easily determined.

The results calculated by the Whillier model have been compared with the Merkel model. It has been shown that the accuracy of the two models are essentially the same, and they both compare favorably against experimental data (Braun, Mitchell, and Kline 1987). Based on this data, Whillier suggests that for a typical commercial cooling tower an F of 0.65 is reasonable. Because of a lack of specific data for the actual cooling tower in the existing building, this value of F was chosen for the model.

3.3.3 Base Case Uncertainties and Calibration Procedure

In developing the overall building simulation model, physical parameters were required for each of the building components. Parameters are variables that are held constant during the simulation in contrast to inputs that may vary with time. Examples of parameters include the physical dimensions and configuration of the building spaces, zone temperature setpoints, operation schedules, material properties, equipment capacities, distribution of lighting and equipment, and rated efficiencies. Inputs include temperatures, flow rates, humidity, and control signals. Inputs are passed from one component subroutine to another and are calculated based on the outputs from other components, subroutine algorithms, and parameter values. Thus, changing a parameter changes the outputs from the component subroutine, which, in turn, changes the inputs to other components. This ultimately affects the results of the simulation, namely, the equipment energy consumption outputs.

Many parameters in the test building were not known or were not well understood. For those parameters, a sensitivity analysis was performed to establish the model's responsiveness to the parameter value within a physically realistic range. If the model was insensitive, then a high degree of uncertainty was considered permissible, and a reasonable value within the range was selected.

If the model was sensitive to an unknown or uncertain parameter, a variety of methods was used to estimate an appropriate and/or typical value; reasonableness was checked by evaluating the simulation outputs such as zone or water loop temperature fluctuations and total energy consumption. In some cases, a parameter such as interzonal heat and mass transfer was related to a physical process in buildings about which little is known.

Finally, many parameters (such as the manual operation of outside air fans and re-insulation of the roof) were changed seasonally in the actual building, either intentionally or unintentionally,. These changes could have been modeled but were not because of the considerable difficulty in doing so.

Because the final analysis is concerned with the overall energy consumption difference--not individual parameter quantities--between the base building and the building with the BSTS system, these parameters were exploited (within reasonable bounds) during calibration of the base building input so as to obtain the best agreement with metered results. This process entailed an iterative series of parametric simulation runs in which "sensitive" parameters for which actual values were uncertain or unobtainable were varied. Final values of these parameters were established when simulated monthly HVAC energy consumption was found to be within 10% of metered data.

Model deficiencies resulting from uncertain building parameters were uncovered during the calibration that significantly affected the simulation results. These deficiencies, discussed in Section 3.3.3.1 through 3.3.3.3, include

- unknown or inconsistent control or occupant behavior
- uncertainties in equipment operation
- lack of basic data.

3.3.3.1 Unknown/Inconsistent Control or Occupant Behavior

Exact thermostat setpoints for the different zones were unknown. They appeared to be in the range of 70 to 80°F, but were not uniform either with time or location. As there are thermostat controls located in the occupied areas of the actual building, it is likely that they were adjusted by the

occupants. Constant setpoints of 78°F cooling and 71°F heating were chosen during the calibration of the base case.

Occupant use of operable window shading (venetian blinds) was unknown, resulting in uncertainties related to solar gains. The calibration of the test building suggested overall window shading factors were quite low.

Occupancy levels are not known and are subject to changes, resulting in variable internal loads. Sporadic occupancy on Saturdays was not modeled. Constant occupancy during normal building occupied hours was assumed.

The actual monthly lighting and equipment loads varied by a factor of two during 1985, as indicated by metered data. This is probably related to changes in building tenancy, because the metered data indicates electricity consumption jumps roughly 25% in July. Constant lighting and equipment loads were used, the value of which were determined through model calibration. Distribution of these loads in the model were also determined through calibration.

3.3.3.2 Uncertainties in Equipment Operation

Night and weekend thermostat setbacks are inconsistent. The heat pumps are supposed to be shut off each night by disconnecting power to the thermostats, but the January metered data, for example, reveals nighttime heat pump operation that is inconsistent with this strategy. For the model, 24-hour heating operation with a 5°F night setback during nights and weekends was used. The cooling operation mode was shut off nights and weekends.

Constant boiler and cooling tower setpoints of 60°F and 85°F were used in the model, respectively, but may deviate in the actual building due to alteration or drift.

It is not certain from the metered data whether heat pump fans are on all day or cycling with compressors. Because these subsystems are most commonly controlled so heat pump fans are operational whenever the outdoor ventilation fans operate, this operation schedule was used in the model.

The metered data show seasonal control strategy changes, most notably in the supply and exhaust fan operation of the ventilation system. Although

this could have been simulated using individual monthly runs, it was overburdening for annual runs; therefore, these changes were not modeled.

An outside air fraction of 20% was used in the model, but it is not clear how the use of indirect ducting through plenum affects this in the actual building. (The flow rate through a fan is a function of the power input and the static pressure. Because a plenum has an uncertain static pressure, the outdoor air fraction is affected.)

3.3.3.3 Lack of Basic Data

The effective quantity of thermal mass in the zones was unknown. It depends on not only the quantity of heat storage material in the zone (such as furniture), but also its composition, color, and placement, as well as the rate of heat transfer to and from the zone air. This important parameter, which tempers the heating and cooling loads, was estimated using iterative calibration of the test building.

The rates of infiltration, exfiltration, and interzonal air exchange rates were not known. Constant rates of infiltration and exfiltration were assumed; the interzonal air exchange was not explicitly modeled.

The effective thermal mass in the water loop, which also includes the thermal mass of the piping, heat exchanger coils, and cooling tower sump water, was not certain. This parameter was estimated by calculating the total water volume in the loop and comparing it with metered water loop temperature responsiveness.

The effectiveness of the glycol loop outside air heat recovery heat exchanger was unknown because the entering and exiting air temperatures were not metered. The value used in the model is believed to be representative.

Thermal storage effects in glazings (if any) and light fixtures were not accounted for. There are no definitive data on this phenomenon nor on the apportioning of lighting heat gains between the conditioned zones and the plenum and of convective versus radiant heat transfer. The type of glass used in the windows was unknown; thus properties of the glass were considered parametric variables during the calibration of the base case.

Because actual physical floor configurations were unavailable, modeling the heat gains and interzonal air exchange between the core and perimeter was estimated indirectly. The model simplified the interaction by assuming a continuous interior wall separated the core from the perimeter zones. The conductance and other properties of the wall were then established during the calibration of the base case. Because of uncertainties in the actual physical floor configuration and the (somewhat) arbitrary way in which the model was divided into zones, the modeling of radiation heat transfer between interior surfaces had to be simplified. For example, geometric view factors between interior surfaces were computed based on area ratios (see Section 3.3.2).

3.3.3.4 Additional Discrepancies

Replacement of building roof insulation during 1985 added significant thermal resistance to the roof. The thermal resistance of the original insulation was poor and its value unknown because it was partially water-saturated. In the simulation model, it was assumed that the overall resistance of the roof was constant throughout the year.

There was no accounting for holidays in the model. TRNSYS has this simulation capability but it is cumbersome to use. It is uncertain whether occupancy is actually negligible on holidays and likely that many occupants take additional vacation time near holidays.

The use of TMY data for Seattle-Tacoma Airport, rather than local data for 1985 (the latter was not available) resulted in somewhat erroneous instantaneous conductance and solar loads. As shown in Section 4.1, in the long run these errors tend to cancel out unless a seasonal or annual bias occurs, because of significant variations in local average temperatures during the metering period from the typical average.

3.4 BUILDING STRUCTURAL THERMAL STORAGE (BSTS) SYSTEM MODEL DEVELOPMENT

The fourth activity in the analysis was the development of the BSTS system model. The numerical model developed by PNL researchers to simulate the floor slabs used in the BSTS system is discussed in Section 3.4.1. A description of the BSTS system configuration and control strategy used in the building model

is given in Section 3.4.2. Finally, a short description of the parametric simulating studies used to optimize the BSTS system is given in Section 3.4.3.

3.4.1 Thermal Energy Storage in Slab

A numerical heat transfer model was developed by PNL researchers to simulate the thermal charging and discharging of the hot or cold water flowing through 1-in.-diameter polybutylene pipes(a) embedded in the building floor slabs. The model solves for the two-dimensional unsteady conduction equation in a cartesian coordinate space:

$$\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}$$

where T = temperature

t = time

α = thermal diffusivity

Explicit formulas for the temperature field were derived from this relation using the central difference approximation. These formulas are applied in the model at each node in a user specified grid that includes portions of the slab, the pipe wall, and the water.

The model assumes uniform surface temperature at the top and bottom of the slab, consistent with the assumptions of the TRNSYS Zone Model. The temperature gradient along the direction of the water flow is not directly modeled. Instead, an iterative procedure is used to determine an average temperature (average of slab inlet and outlet temperature) of the water. It is then assumed that the water throughout the pipes is at this average temperature. This assumption is justified because these pipes are typically laid in multiple parallel circuits at high enough flow rates to ensure that water of about the same temperature is available at every point of the grid (Shell Chemical 1984). Hence, the entire pipe system is made up of sets of

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(a) Reports on existing radiant slab heating applications using polybutylene confirm the practicality of this material (Shell Chemical 1984).

identical circuits. Figure 3.3 shows a sample pipe pattern for a single circuit. Because of the symmetry of the pipe field, the simulation of only the smallest common element (half of the pipe and its associated slab) is required, simplifying the formulation of the model. Figure 3.3 also shows the portion of the slab being modeled.

At each simulation time step, the model uses the surface temperatures calculated from the Zone Model as inputs. It then calculates the amount of heat transferred from the fluid to the slab, and that transferred from the slab surfaces to the conditioned space (above) and plenum space (below). These heat transfer rates are a function of the fluid temperature and flow through the embedded pipes, as well as of the pipe diameter and spacing, the thickness of the slab, and the surface temperatures. In addition to the heat transfer rates, the cross sectional temperature distribution of the slab, hence the stored energy, is also calculated by the model. At the next time step, the heat transfers at the surfaces are input back to the Zone Model, and the simulation continues.

FIGURE 3.3. Slab with Water Loop Circuit

3.4.2 BSTS System Model and Basic Control Strategy

In incorporating the BSTS system model into the building model, the existing base building subsystems and structure were modified as little as possible for three primary reasons:

- to maintain the integrity of the base building HVAC system design; this was a "design" decision, as it was felt a real building owner would want the capability of running the HVAC system alone
- simplicity in modeling
- interpretation of results; tracing the cause and effect of various system parameter modifications becomes more difficult, the more the basic model is changed.

Thus, the existing HVAC subsystems and controls were left essentially intact. The thermostats were identical to the base case for each of the controlled zones. The HVAC water loop flow rate was the same as in the base case, as were boiler, cooling tower, and heat pump capacities. The primary physical change to the HVAC water loop was the additional secondary piping loop used to route water through the concrete floor of the model (see Figure 2.2).

Included in the actual model are five separate slabs, one for each of the four perimeter zones, and one for the core. The slab water loop parallel circuits were arranged to maintain turbulent water flow (approximately 3 feet/second) at a reasonable pressure drop. The total water flow available to each slab equaled the flow rate of the heat pump associated with the same zone as that slab(a). Inlet water temperature to the slabs was based on the overall mixed temperature of water leaving the five zone heat pumps.

A basic control scheme was used for the slab. Two slab water flow controllers were employed in the model: one sensed the core zone space temperature and the other sensed the volumetrically weighted average perimeter space

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(a) Because heat pumps in all zones were nominally sized at 370 ft²/ton, 3 gpm/ton, this meant water flow to the slab was uniform over the entire floor area.

temperature(a). These temperatures were compared to available water loop temperature to determine if water flow control valves to the slabs should be open or closed and if the slab water pump should be on or off. Night and weekend setback was identical to the base building model for winter heating conditions. During summer cooling, the cooling tower was turned on prior to morning startup to pre-cool the slab and space from 4:00 to 6:00 a.m. This was not used on weekend mornings, because the cooling was shut off.

The two slab water flow controllers, like the zone thermostats, had both heating and cooling setpoints. These setpoints were established so slab heating or cooling would be used (assuming water loop temperatures were appropriate) before the room thermostats signaled the heat pumps to start. For example, during occupied hours the slab water flow controller setpoint for heating was set at 72°F, while zone thermostats (as established by the base case simulation) were set at 71°F. If a zone temperature drops to 72°F during the day, the controller checks the loop temperature to see if water above 72°F is available to help heat the slab associated with the zone in question. If water is available for heating, the controller opens the flow control valve to that zone's slab and the pump is started. Figure 3.4 is a block diagram summarizing the BSTS system control scheme.

The establishment of appropriate slab flow valve controller setpoints is essential for the design. First, to work at all, they must be coupled to the zone thermostat setpoints. A slab water flow controller heating setpoint for a zone that is lower than that zone's heat pump thermostat heating setpoint would be counterproductive, because zone heat pump operation may lower loop water temperatures below a level at which this water can be used for heating in the slab.

Another concern with this control strategy comes about because of the thermal capacitance of the slab. The response time of the slab is slowed by its mass. Thus, although the controller directs warm water to the slab to

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(a) Only two controllers were used because of TRNSYS size limitations. Ideally, individual controllers for each of the four perimeter zone slabs would have been used.

LEGEND	
T_C	- ZONE THERMOSTAT COOLING SETPOINT
T_H	- ZONE THERMOSTAT HEATING SETPOINT
T_Z	- TEMPERATURE OF ZONE
T_{CS}	- SLAB COOLING SETPOINT
T_{HS}	- SLAB HEATING SETPOINT
T_W	- TEMPERATURE OF WATER AVAILABLE TO SLAB
δ_P	- SLAB WATER PUMP RELAY SIGNAL
δ_V	- SLAB WATER CONTROL VALVE SIGNAL

FIGURE 3.4. Block Diagram of BSTS System Control Scheme

help heat the space before the thermostat starts the heat pump, by the time this heat is available to radiate from the slab to the space, the zone temperature may have dropped so that the heat pump comes on anyway. Or, the zone temperature may rise of its own accord as outside air temperatures rise, so that the heat transferred to the slab is no longer needed, or perhaps even serves to overheat the space so cooling is required.

Finally, with the thermal storage slab coupled to the conditioned space, the allowable range of slab temperatures was dictated by occupant thermal comfort considerations. Hence, the surface temperatures played an important role in the feasibility of the integration control strategy. Two comfort criteria related to surface temperatures were identified:

- The mean radiant temperature (MRT) is as important as air temperature in affecting thermal comfort. MRT is calculated as the area-weighted average surface temperature.
- For people wearing appropriate indoor footwear, the floor temperature should be maintained between 65 to 84°F.

3.4.3 Parametric Studies

Various strategies were tested using a series of parametric simulations, beginning with the base case building with the BSTS system described in Section 3.4.2. The general procedure was similar to that employed in the parametric studies for the base case: key parameters of the BSTS system were individually modified to gauge their impact/sensitivity; then, a series of optimizing simulations to find the most favorable combination of realistic values was performed. The strategies fell primarily into three categories: slab modifications, water loop variations, and control setpoint modifications.

The motivation behind the slab modification parametric studies was to alter the total heat capacity and/or capacitance of the slab to the most energy-conserving design. Thermal parameters that were changed to accomplish this are density, specific heat, and thermal conductivity. Physical changes in the slab that were examined included slab thickness. The conductance of the insulating materials such as carpeting, which cover the top and bottom of the slab, were also varied.

4.0 BASE CASE BUILDING MODEL CALIBRATION RESULTS

An important step in this investigation was the calibration of the base case building model with metered data (see Section 3.3.3), because it helps verify that the actual building was realistically modeled. This, in turn, provides confidence that the simulated results of the building model with the BSTS system added (see Section 5.0) provides a reasonable estimate of the impact of integrating the HVAC system and the building structural mass.

The simulated monthly overall HVAC energy consumption results are compared with the available corresponding metered data in Figure 4.1. These comparisons are the most reasonable that could be obtained, given the limitations of the data and the computer model (see Section 3.3.3). Monthly simulated energy consumption is within 10% of metered performance except for February, March, April, and November. These larger discrepancies, unresolved by the calibration, can primarily be attributed to the difference between the Typical Meteorological Year (TMY)(a) weather data used in the simulation and the actual weather at the building site during 1985. For example, as indicated in Figure 4.2, the TMY average monthly temperature was approximately 11°F higher in November than National Oceanic and Atmospheric Administration (NOAA) temperature data for 1985 (measured at Seattle-Tacoma airport). For February and April the differences were 3°F. These differences correlate with the discrepancies between metered and simulated building energy consumption. No attempt was made to use NOAA weather data for 1985 because solar radiation data is not included, and the merging of TMY data with NOAA data would produce numerous hours when solar radiation and temperatures were inconsistent.

In Figures 4.3 through 4.5, the simulated monthly energy consumption of the major HVAC components is compared to the metered data. Although differences are not within 10% for many of the months, the operational trends for each component compare well, as does the overall annual energy consumption.

(a) The TMY weather data represents "typical" values of temperatures, solar radiation, and wind speed in a year.

FIGURE 4.1. Comparison of Metered Simulated Monthly Total HVAC Energy Consumption

FIGURE 4.2. Comparison of National Oceanic Atmospheric Administration and Typical Meteorological Year Average Monthly Temperatures

FIGURE 4.3. Metered Versus Simulated Monthly Heat Pump Energy Consumption

FIGURE 4.4. Metered Versus Simulated Monthly Boiler Energy Consumption

FIGURE 4.5. Metered Versus Simulated Monthly Cooling Tower Energy Consumption

Figures 4.6 and 4.7 summarize the simulated monthly and annual energy consumption of the HVAC components. These also indicate that the energy consumption of the HVAC components is distributed in a manner characteristic of this type of commercial building, both on a monthly and annual basis.

Overall, it was concluded that the calibration approach provided a model which compares reasonably well with metered data. Major discrepancies appear to be linked primarily to a difference between the weather data used in the simulation and the actual conditions in 1985 at the building site. Since this is a deficiency in basic data not related to the building itself, the discrepancy in no way invalidates usefulness of the model as a tool for studying the integration of the HVAC subsystems and building structural mass.

B = Boiler D = Duct Heaters C = Cooling Tower
H = Heat Pumps P = Pumps F = Fans

FIGURE 4.6. Simulated Monthly Energy Consumption of HVAC Components

FIGURE 4.7. Simulated Annual Energy Consumption of HVAC Components

FIGURE 4.6. Simulated Monthly Energy Consumption of HVAC Components

FIGURE 4.7. Simulated Annual Energy Consumption of HVAC Components

5.0 EVALUATION OF BUILDING STRUCTURAL THERMAL STORAGE SYSTEM PERFORMANCE

After the base case building model was established for the Seattle location, study of the interaction between the HVAC system and building mass began. Results of the BSTS system simulation are presented and interpreted in Sections 5.1 and 5.2. A discussion of the limitations noted in the system follow in Section 5.3.

5.1 SIMULATION RESULTS

The BSTS system was simulated with the temperate Seattle weather data first to provide a basis for determining whether to continue simulations in other locations. Trends in energy consumption and sensitivities of the BSTS system operation were found at this stage of the testing, which included brief sensitivity analysis simulations and full annual simulations. The sensitivity simulations used portions of the January and July months, with which trends in peak heating and cooling operation were found. Slab thermal properties and water loop control parameters were altered in the sensitivity analyses, providing information on the best-performing BSTS system configuration.

Comparisons of simulated building base case and simulated building with the BSTS system results for Seattle are shown in Figures 5.1 through 5.4. Definite energy-conserving patterns were found for the Seattle location, suggesting further study of the BSTS system in other locations (see Section 6.0). The first measure of performance noted was the building total HVAC energy consumption for a year. The BSTS system energy consumption was 585,435 kWh, as compared to 637,748 kWh for the base case. On a monthly basis for total HVAC, shown in Figure 5.1, energy savings were found in every month for the period of April through November. Additional energy was consumed during December, January, February, and March; however, the net reduction in annual energy consumption shown in the above results was 8.2%.

Heat pump energy consumption (see Figure 5.2) followed the same monthly pattern as the overall HVAC energy consumption described above. The boiler consumed virtually no energy from May through September; however, the boiler

SEATTLE TOTAL MONTHLY

FIGURE 5.1. Total HVAC Monthly Energy Consumption for Simulated BSTS Strategies, Seattle

SEATTLE HEAT PUMP

FIGURE 5.2. Heat Pump Monthly Energy Consumption for Simulated BSTS Strategies, Seattle

FIGURE 5.3. Boiler Monthly Energy Consumption for Simulated BSTS Strategies, Seattle

FIGURE 5.4. Cooling Tower Monthly Energy Consumption for Simulated BSTS Strategies, Seattle

consumption pattern for remaining months is essentially the same as that for the overall HVAC. Cooling tower energy consumption for the BSTS system is only slightly less than the base case for most months of operation, as shown in Figure 5.4. As was illustrated in Figures 4.6 and 4.7, cooling tower energy consumption is a small part of the total HVAC energy consumption. Because this component is providing economical cooling through the night "purge" cycle in summer, small changes in energy consumption patterns are acceptable.

5.2 DIURNAL RESPONSE

The BSTS system was studied for diurnal response characteristics in order to better understand operation of this system. Although annual and monthly energy consumption was used for comparison of building performance in this work, important insight was gained into the operation of the BSTS system by studying daily temperature and heat transfer profiles. A series of zone temperature and heat transfer rate histories for different days of the year are presented in this section for the building, both with and without the BSTS system.

In each of the temperature history figures the applicable zone temperature, bulk temperature of the slab adjacent to the zone(a), outdoor air ambient, and water loop temperature available to the slab are presented. In each of the heat transfer rate histories the heat transfer rates from the zone to the top of the slab, the plenum to the bottom of the slab, and from the slab to the water loop piping are presented.

Consider first the temperature and heat transfer rate histories for the core zone on January 5th, shown in Figures 5.5 and 5.6 for the building with the BSTS system installed. In Figure 5.5, the use of the BSTS system to help cool the core is clearly illustrated by two sharp peaks in slab-to-pipe heat transfer at 12:00 to 14:30 hours and at 16:15 to 18:45 hours. As shown in Figure 5.6, core zone temperatures at these times have risen to 74°F (the slab

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(a) The "bulk" slab temperature is computed in subroutine THESIS (see Appendix C) by taking the arithmetic average of each discretely defined numerical node.

FIGURE 5.5. January 5th Heat Transfer Rate History for the Core Zone of the Simulated Building with the BSTS System

FIGURE 5.6. January 5th Temperature History for the Core Zone of the Simulated Building with the BSTS System

controller cooling setpoint), while water loop temperatures range from 60 to 65°F. Because the water is cooler than the zone, the slab controller directs water through the slab to help slow the rise in temperature in the core as it approaches the zone thermostat cooling setpoint of 75°F.

A comparison of the core temperature and heat transfer histories on January 5th, in the building with the BSTS system installed, to those in the base case building, given in Figure 5.7 and 5.8, illustrates several other phenomena. For example, in Figure 5.8, the irregularity of the core zone temperature around its cooling setpoint of 75°F from 12:15 to 18:00 hours indicates the core heat pump in the base case building is operating during this time in the cooling mode. For the BSTS system building, Figure 5.6 indicates heat pump operation in cooling mode only from 14:15 to 14:30 hours, illustrating clearly that the use of the BSTS system reduces heat pump operation in the afternoon. Also, note that the water loop temperature for the BSTS system building is lower than in the base case building in the second half of the day, because less heat is rejected by the core heat pump due to less frequent operation in cooling mode.

On the other hand, use of the BSTS system in the core also results in an energy penalty at some times when compared to the base case building. As can be seen in Figure 5.6 or Figure 5.8, core zone temperatures drop at night when the building is unoccupied, due to reduced internal heat gains and the setback of adjacent perimeter zone control temperatures to 67°F. By using the BSTS system to cool the slab late in the afternoon (and especially after 18:00 hours when cooling is shut off anyway) the zone temperature in the morning at the beginning of the warmup is lower than in the base case building; thus, more heat pump and boiler operation is required. This penalty could probably be avoided or reduced with the implementation of a more sophisticated slab control scheme in the simulation model which accounts for time of year, time of day, and/or weather conditions.

The January 5th south zone temperature and heat transfer histories for the BSTS system building and base case building are shown in Figures 5.9 through 5.12. Zone temperatures are seen to be essentially the same throughout the day. No heat transfer from the water loop to the slab occurs in the BSTS system

FIGURE 5.7. January 5th Heat Transfer Rate History for the Core Zone of the Simulated Base Case Building

FIGURE 5.8. January 5th Temperature History for the Core Zone of the Simulated Base Case Building

FIGURE 5.9. January 5th Heat Transfer Rate History for the South Zone of the Simulated Building with the BSTS System

FIGURE 5.10. January 5th Temperature History for the South Zone of the Simulated Building with the BSTS System

FIGURE 5.11. January 5th Heat Transfer Rate History for the South Zone of the Simulated Base Case Building

FIGURE 5.12. January 5th Temperature History for the South Zone of the Simulated Base Case Building

building, because the zone temperature is essentially always at the heating setpoint, and the slab controller senses water loop temperatures are too low to help heat the zone through the slab. Comparing Figure 5.10 with Figure 5.12, the increased thermal capacitance of the 25% higher density slab used in the BSTS system building can be clearly observed by the slower response of the slab bulk temperature to changes in zone temperature during morning warmup and night setback. The generally lower slab temperatures during occupied hours in the BSTS system building, when compared to the base case building slab, result in an increased heat loss in the south zone and therefore an increase in heat pump operation in heating mode. This increase in heat pump operation in the south zone caused by the more massive slab used in the BSTS system building applies to all perimeter zones and, along with the additional heating penalty caused by overcooling the core zone slab late in the day discussed above, appears to account for why the overall energy consumption in cold winter months, shown in Figure 5.1, is higher in the building with the BSTS system installed than in the base case simulated building. As was mentioned before, a more sophisticated slab control scheme should limit these energy penalties(a).

By inspecting temperature and heat transfer histories for typical days in July and April, additional limitations on the potential of the BSTS system for conserving energy, caused by the simple slab control scheme utilized in the model, can be observed. For example, on April 3, Figure 5.13 shows that the water loop is being used to cool the core zone slab from 10:00 to 12:15, and then to heat the slab intermittently from 12:15 to 15:00 hours. However, core zone temperatures shown in Figure 5.14 indicate cooling is required on a continual basis from 10:00 to 18:00 hours. The reversal from slab cooling to slab heating occurs because water loop temperatures exceed the bulk slab temperature after 12:15 hours, but are still below the zone temperature; thus, the slab controller, which only compares water loop temperature with zone

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- (a) Reducing the slab density in the BSTS system building was found in the sensitivity studies to degrade improvements in summer performance more than it helped in winter; therefore this option for the BSTS system building model was not used.

FIGURE 5.13. April 3rd Heat Transfer Rate History for the Core Zone of the Simulated Building with the BSTS System

FIGURE 5.14. April 3rd Temperature History for the Core Zone of the Simulated Building with the BSTS System

temperature, sends water to the slab, raising the slab temperature and reducing its potential as a heat sink for the core.

This same characteristic can also be observed in Figures 5.15 and 5.16 for July 5th in the core zone. In addition, the use of the cooling tower from 4:00 to 6:00 hours can be clearly seen by the drop in water loop temperature to the 65°F cooling tower summer morning setpoint. The accompanying drop in slab temperature indicates the slab controller has sensed the lower water temperatures and, since zone temperatures are above 74°F (the slab cooling setpoint in the core), has routed water through the slab. Interestingly, a second drop in water loop temperature down to 60°F occurs at 6:00 hours. As Figures 5.17 and 5.18 for the south zone indicate, this second water loop temperature drop is caused by perimeter heat pump operation in the heating mode, used to raise cool perimeter zone temperatures to their daytime heating setpoint of 71°F. That this morning warmup occurs even in July suggests that the summertime boiler operation, observed in Figure 5.3 to occur in the BSTS system building but not in the base case building, is caused because the cooling tower has lowered water loop temperatures to 65°F during the morning purge cycle; thus, less heat pump operation in heating mode in the BSTS system building is needed when compared to the base case building to drop water loop temperatures below the boiler setpoint.

5.3 LIMITATIONS

Size limits of the TRNSYS code allowed the use of only two microprocessors for water loop flow control: one for the core slab water control valve and one for all four perimeter zone water control valves. Five would be preferable, which would allow one for each of the four perimeter zones. More exotic or flexible hydronic loop arrangements (e.g., variable flow) were not modeled due to TRNSYS size and execution limitations.

Observations of the diurnal response in Section 5.2 indicate the BSTS system needs more effective control schemes that would vary heating and cooling setpoints on a monthly, weekly, or daily basis. Additional improvements would be gained by using controls that dynamically respond to the needs of the zones. As modeled, water is supplied to the slab based on current zone temperature

FIGURE 5.15. July 5th Heat Transfer Rate History for the Core Zone of the Simulated Building with the BSTS System

FIGURE 5.16. July 5th Temperature History for the Core Zone of the Simulated Building with the BSTS System

FIGURE 5.17. July 5th Heat Transfer Rate History for the South Zone of the Simulated Building with the BSTS System

FIGURE 5.18. July 5th Temperature History for the South Zone of the Simulated Building with the BSTS System

and current water loop temperature. The controls ignore the time-delayed response inherent in the heat capacitance of the slab when deciding whether routing available water to the slab would be beneficial.

and current water loop temperature. The controls ignore the time-delayed response inherent in the heat capacitance of the slab when deciding whether routing available water to the slab would be beneficial.

6.0 EFFECTS OF CLIMATE ON BUILDING STRUCTURAL THERMAL STORAGE SYSTEM PERFORMANCE

Additional simulations modeling the same building were performed using TMY weather data from five additional cities; Los Angeles, Houston, El Paso, Washington, and Milwaukee. These cities were chosen because of their unique climatic conditions when compared to the temperate climate found in Seattle. Specifically, Milwaukee has a predominantly cold climate, El Paso and Los Angeles are hot and dry, Houston is hot and humid, while Washington is hot and humid in summer and cold in winter. Together, these cities typify fairly well the range of climatic conditions found across the U.S.; thus, performing the simulations in each of these locations provided quantitative insight as to where a BSTS system can be most effectively applied.

The approach used for assessing the effectiveness of the BSTS system in these different locations was as follows. First, the Seattle base case building model (reported on in Section 4.0) was simulated for an entire year in a new location with no other changes. The capacities for the boiler, cooling tower, and heat pumps were then adjusted if necessary so that zone temperature set-points could be maintained during peak load conditions, and the simulation rerun. Next, the BSTS system used for the Seattle simulation (reported in Section 5.0) was incorporated into this adjusted base case model for the new location. Simulations were then performed in the new location for short winter and summer peak load periods to establish appropriate values for slab thermal properties and those water loop control parameters identified as being highly sensitive during the Seattle studies (see Section 5.0). Finally, an annual simulation of the building with this modified BSTS system was performed, and these results were compared to the base case building annual simulation results in the new location.

Figures 6.1 through 6.5 compare the total simulated HVAC monthly energy consumption for the base building in each of the five new locations to that of the same building with the BSTS system. In Figure 6.6, the total HVAC annual energy consumption is compared for all of the locations. Additional comparisons are shown in Appendix A and B for individual HVAC subsystem components.

FIGURE 6.1. Total HVAC Monthly Energy Consumption for Simulated BSTS System Strategies, Los Angeles

FIGURE 6.2. Total HVAC Monthly Energy Consumption for Simulated BSTS System Strategies, El Paso

FIGURE 6.3. Total HVAC Monthly Energy Consumption for Simulated BSTS System Strategies, Houston

FIGURE 6.4. Total HVAC Monthly Energy Consumption for Simulated BSTS System Strategies, Washington, DC

FIGURE 6.5. Total HVAC Monthly Energy Consumption for Simulated BSTS System Strategies, Milwaukee

FIGURE 6.6. Total HVAC Annual Energy Consumption for Simulated BSTS System Strategies

The energy-conserving effects of the BSTS system were found to be most pronounced in the hot, dry climates. El Paso and Los Angeles benefited greatly, with annual energy savings on the order of 30%. A substantial fraction of these energy savings occurred during the May through September cooling period. Although also a hot climate, Houston did not fair as well because the higher wet-bulb temperatures found in Houston limited the ability of the cooling tower to reject heat; thus, water loop temperatures were higher, and the performance of the BSTS system was decreased. Energy savings in Washington D.C. were low due to cold winter conditions and high summer wet-bulb temperatures. The building with the BSTS system showed only minimal improvement in the cold climate of Milwaukee, achieving on the order of 3% annual energy savings. As was the case in Seattle, the BSTS system was found to actually increase energy consumption in winter months for Milwaukee and Washington, D.C.

This poor winter performance raised questions about winter operation of the BSTS system. It was observed through the simulations that though high slab mass improved summer performance, it hindered winter performance. This negative effect was in large part due to the fact that the higher slab mass meant additional heat was needed to warmup the space in the morning from the night setback point of 67°F. In addition, a low cooling load was observed in the core zone in the coldest climates in winter. Because loop water temperatures were far below the BSTS system cooling setpoint, water would be routed through the slab to help cool the zone under these conditions. The time-lag caused by the thermal capacitance of the slab could often result in a significant overcooling of the slab, and thus the zone, to the point where heating would eventually be required by the heat pumps. This cycling between heating and cooling was due to limitations in the BSTS control scheme (see Section 5.3). To limit these winter penalties on performance, the BSTS system was shut off during cold winter months and the slab mass was chosen which provided the best tradeoff of summer and winter performance.

The energy-conserving effects of the B2S2 system were found to be most pronounced in the hot, dry climate of Paso and Los Angeles benefited greatly with annual energy savings on the order of 30%. A substantial fraction of these energy savings occurred during the May through September cooling period. Although also a hot climate, Houston did not fare as well because the higher wet-bulb temperatures found in Houston limited the ability of the cooling tower to reject heat; thus, water loop temperatures were higher, and the performance of the B2S2 system was decreased. Energy savings in Washington, D.C. were low due to cold winter conditions and high summer wet-bulb temperatures. The building with the B2S2 system showed only minimal improvement in the cold climate of Milwaukee, achieving on the order of 3% annual energy savings. As was the case in Seattle, the B2S2 system was found to actually increase energy consumption in winter months for Milwaukee and Washington, D.C. This poor winter performance raised questions about winter operation of the B2S2 system. It was observed through the simulations that though high slab mass improved summer performance, it hindered winter performance. This negative effect was in large part due to the fact that the higher slab mass meant additional heat was needed to warm the space in the morning from the night set-back point of 67°F. In addition, a low cooling load was observed in the core zone in the coldest climates in winter. Because loop water temperatures were far below the B2S2 system cooling setpoint, water would be routed through the slab to help cool the zone under these conditions. The time-lag caused by the thermal capacitance of the slab could often result in a significant overcooling of the slab, and thus the zone, to the point where heating would eventually be required by the heat pumps. This cycling between heating and cooling was due to limitations in the B2S2 control scheme (see Section 5.3). To limit these winter penalties on performance, the B2S2 system was shut off during cold winter months and the slab mass was chosen which provided the best tradeoff of summer and winter performance.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The BSTS system was shown to be an energy-conserving system for the building modeled in this study when compared to identical buildings without the BSTS system. The HVAC annual energy savings predicted by the Transient System Simulation Program (TRNSYS) simulations for the building with the BSTS system used were found to vary significantly with climate, ranging from approximately 3% to 30%. The BSTS system performed best in the hotter, drier climates of Los Angeles and El Paso, where summer cooling at lower ambient wet bulb temperatures dominate building energy use. More moderate benefits were achieved in Houston, Seattle, and Washington, D.C. Little gain in annual performance was found in the Milwaukee climate simulation. In general, the BSTS system is beneficial whenever hot and dry summer outdoor air conditions exist. The benefits in cold climate regions, on the other hand, appear to be limited.

Further energy savings may be possible if every facet of the BSTS system was optimized fully for every climate region tested. The optimization for each climate of all important BSTS system model parameters identified using sensitivity studies for the Seattle climate region was beyond the scope of this research. Thus, when a new climate was studied after the Seattle simulations, building models of both the reported base case building and the building with the BSTS system added were essentially those used in Seattle.

Indeed, a truly optimized BSTS system is still needed even for Seattle, because of the limitations inherent in the computer model used. Improved HVAC control schemes were desired, but could not be constructed from modules available in TRNSYS, primarily because of size limitations and excessive computer processing time. The interactions of the BSTS system occurring in the winter mode and cold climates were sensitive to the controls employed. Intelligent, adaptive/predictive controls for truly thermally efficient water loop flow control in core and perimeter zones would improve performance, but would entail significant new code development.

Mean radiant temperatures (MRT) were not analyzed. The space temperature set points used in the simulations do not take into account the MRT effect of

the floor slab system. An analysis of this is recommended to determine if the effect of MRT would further reduce energy consumption.

Another issue not addressed by this study is the effect of the BSTS system on cooling/heating peak electrical demand, because actual building electrical billing rates are dependent on both demand and total overall consumption. Although thermal storage did occur, it was low temperature storage and it is uncertain if this could significantly shift energy consumption during peak hours to off-peak hours.

Finally, it should be reiterated that the BSTS system has been applied to only a single building with a single type of HVAC subsystem. Future studies must address the potential cost and energy effectiveness of the BSTS system in other building designs, so that designers and owners will be able to determine whether integrating the HVAC subsystems with the building mass makes sense for their needs.

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APPENDIX A

MONTHLY ENERGY CONSUMPTION FOR HVAC COMPONENTS

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MONTHLY ENERGY CONSUMPTION FOR HVAC COMPONENTS

The following bar graphs portray simulated monthly energy consumption results of HVAC system components for five U.S. cities in both the base case building model and the base case building model with the Building Structural Thermal Storage (BSTS) system added. This information is supplementary to Section 6.0 of the main report, in which total building energy consumption results are presented. The five cities are Los Angeles, El Paso, Houston, Washington, and Milwaukee.

In Figures A.1 through A.5, the total heat pump monthly energy consumption for each city is presented. Following these, Figures A.6 through A.9 are for the boiler (no boiler operation was required in Los Angeles), and Figures A.10 through A.14 are for the cooling tower.

FIGURE A.1. Heat Pump Monthly Energy Consumption for Simulated BSTS System Strategies, Los Angeles

FIGURE A.2. Heat Pump Monthly Energy Consumption for Simulated BSTS System Strategies, El Paso

FIGURE A.3. Heat Pump Monthly Energy Consumption for Simulated BSTS System Strategies, Houston

FIGURE A.4. Heat Pump Monthly Energy Consumption for Simulated BSTS System Strategies, Washington, D.C.

FIGURE A.5. Heat Pump Monthly Energy Consumption for Simulated BSTS System Strategies, Milwaukee

FIGURE A.6. Boiler Monthly Energy Consumption for Simulated BSTS System Strategies, El Paso

FIGURE A.7. Boiler Monthly Energy Consumption for Simulated BSTS System Strategies, Houston

FIGURE A.8. Boiler Monthly Energy Consumption for Simulated BSTS System Strategies, Washington, DC

FIGURE A.9. Boiler Monthly Energy Consumption for Simulated BSTS System Strategies, Milwaukee

FIGURE A.10. Cooling Tower Monthly Energy Consumption for Simulated BSTS System Strategies, Los Angeles

FIGURE A.11. Cooling Tower Monthly Energy Consumption for Simulated BSTS System Strategies, El Paso

FIGURE A.12. Cooling Tower Monthly Energy Consumption for Simulated BSTS System Strategies, Houston

FIGURE A.13. Cooling Tower Monthly Energy Consumption for Simulated BSTS System Strategies, Washington, DC

FIGURE A.14. Cooling Tower Monthly Energy Consumption for Simulated BSTS System Strategies, Milwaukee

FIGURE A.13. Cooling Tower Monthly Energy Consumption for Simulated BSTS System Strategies, Washington, DC

APPENDIX B

ANNUAL ENERGY CONSUMPTION FOR THE HVAC COMPONENTS

The following bar graphs portray simulated annual energy consumption results of HVAC system components for six U.S. cities in both the base case building model and the base case building model with the Building Structural Thermal Storage (BSTS) system added. This information is supplementary to Section 6.0 of the main report, in which total building energy consumption results are presented. The six cities are Seattle, Los Angeles, El Paso, Houston, Washington, and Milwaukee.

In Figures B.1 the total heat pump annual energy consumption for each city is presented. Figure B.2 is for the boiler, and Figure B.3 is for the cooling tower.

FIGURE B.1. Heat Pump Annual Energy Consumption for Simulated BSTS System Strategies

FIGURE B.2. Boiler Annual Energy Consumption for Simulated BSTS System Strategies

FIGURE B.3. Cooling Tower Annual Energy Consumption for Simulated BSTS System Strategies

APPENDIX C

COMPUTER CODES

APPENDIX C

COMPUTER CODES

This appendix contains code listings of the five component modules developed by Pacific Northwest Laboratory researchers specifically for this study: the cooling tower, the heat pump, the water loop boiler, the water loop thermostat (used to control cooling tower and boiler operation), and the floor slab used in the BSTS system.

Each module is written as a FORTRAN subroutine. These subroutines were linked after compilation with the main TRNSYS source code and those additional existing TRNSYS component modules also required for the model to create executables used for the simulations described in the main report.

BOILER

```
      SUBROUTINE TYPE40 (TIME,XIN,OUT,T,DTDT,PAR,INFO)
C
C *** BOILER MODEL MODIFIED FOR PROPORTIONAL CONTROL (11/23/87)
C
C THIS SUBROUTINE MODELS AN AUXILIARY HEATER.  WHENEVER THE INPUT
C CONTROL FUNCTION IGAM NOT = 0.0, HEAT IS ADDED AT A RATE BETWEEN
C 0.0 TO QMAX DETERMINED BY 'IGAM'
C IN ORDER TO BRING THE FLOWSTREAM TEMPERATURE UP TO TSET.
      DIMENSION XIN(10),OUT(20),PAR(10),INFO(10)
      REAL IGAM
C
      IF (INFO(7).GE.0) GO TO 100
C FIRST CALL OF SIMULATION
      INFO(6)=3
      INFO(9)=0
      CALL TYPECK(1,INFO,3,3,0)
C SET PARAMETER AND INPUT VARIABLES
100  QMAX=PAR(1)
      TSET=PAR(2)
      CP=PAR(3)
      TIN=XIN(1)
      FLOW=XIN(2)
C *** IGAM = 0 TO 1
      IGAM=XIN(3)
      IF (FLOW .GT. 0.) GO TO 10
C NO FLOW
      OUT(2) = 0.
      OUT(3) = 0.
```



```

      RETURN
C CHECK INLET TEMPERATURE AND CONTROL FUNCTION
C *** IGAM = 0 TO 1
10  IF (TIN .LT. TSET .AND. IGAM .GT. 0) GO TO 20
C HEATER OFF
    TOUT = TIN
    QAUX = 0.
    GO TO 50
C HEATER ON
C *** QMAX PROPORTIONAL - 0 TO QMAX
20  TOUT = TIN + (QMAX*IGAM)/(FLOW*CP)
    TOUT = AMIN1 (TSET, TOUT)
    QAUX = (FLOW*CP)*(TOUT-TIN)
C SET OUTPUTS
50  OUT(1)=TOUT
    OUT(2)=FLOW
    OUT(3)=QAUX
    RETURN
    END

```

COOLING TOWER

SUBROUTINE TYPE42 (TIME,XIN,OUT,T,DTDT,PAR,INFO)

```
C
C      *****
C      *                  COOLING TOWER                  *
C      *****
C
C MODEL MODIFIED FOR PROPORTIONAL CONTROL (11/23/87)
C
C *** WHILLIER MODEL TO CALCULATE PERFORMANCE OF COOLING TOWER
C   4 CELLS MAXIMUM
C
C *****
C
C *** ONE COOLING TOWER PER SIMULATION ***
C
C PARAMETERS: 6
C
C   1 FANMAX = MAXIMUM FAN CAPACITY, FOR ONE CELL (CFM)
C   2 POWMAX = MAXIMUM FAN POWER REQUIREMENT, FOR ONE CELL (KW)
C   3 NCELL = TOTAL NUMBER OF CELLS (DIMENSIONLESS)
C             (MIN=1, MAX=4)
C   4 A = COEFFICIENT 'A' (DIMENSIONLESS)
C   5 B = COEFFICIENT 'B' (DIMENSIONLESS)
C       FOR EQUATION  $E = A + B * R$ 
C       where E = COOLING TOWER EFFECTIVENESS (DIMENSIONLESS)
C              R = COOLING TOWER CAPACITY FACTOR (DIMENSIONLESS)
C   6 TAU = COOLING TOWER CAPCITY TIME CONSTANT (MIN)
C           (SET TO 0 FOR NEGLIGIBLE TRANSIENT DELAY)
C
C INPUTS: 5+NCELL
C
C *** FOR PROPORTIONAL CONTROL, INPUT(1) & INPUT(6) SHOULD BE
C   CONNECTED TO THE SAME SAME PROPORTIONAL SIGNAL ***
C   1 ITOWER = COOLING TOWER ON-OFF INDEX (PROPORTIONAL - 0 TO 1)
C   2 TDB = AMBIENT DRY-BULB TEMPERATURE (F)
C   3 TWB = AMBIENT WET-BULB TEMPERATURE (F)
C   4 TCWR = INLET WATER TEMPERATURE (F)
C   5 FLCW = INLET WATER MASS FLOWRATE (LB/HR)
C   6 to 5+NCELL
C       FRAC = FRACTIONAL FAN OPERATION FOR EACH CELL (DIMENSIONLESS)
C           (FANS ARE ASSUMED TO OBEY THE FAN LAW)
C       * IF ITOWER, FLCW, OR ALL FRAC = 0, TOWER IS OFF *
C
C OUTPUTS: 5
C
C   1 TCWS = OUTLET WATER TEMPERATURE (F)
C   2 DT = RANGE (F)
C   3 POWER = TOTAL FAN POWER (KW)
```

```

C      4 QAVG = TOWER CAPACITY AVERAGED OVER TIME STEP (KBTUH)
C      5 QNEW = TOWER CAPACITY AT THE END OF TIME STEP (KBTUH)
C
C *****
C
C      DIMENSION XIN(9),OUT(5),PAR(6),INFO(9),FRAC(4)
C      COMMON/SIM/TIME0,TFINAL,DELT
C      DATA CPW/1./
C
C *** FIRST CALL OF SIMULATION
C      IF(INFO(7) .NE. -1)GO TO 100
C          NI=INFO(3)
C          NP=INFO(4)
C          INFO(6)=5
C          CALL TYPECK(1,INFO,NI,NP,0)
100  CONTINUE
C
C *** SET PARAMETERS & INPUTS -- FANMAX IN CFM, FLCW IN GPM
C      FANMAX=PAR(1)*60.
C      POWMAX=PAR(2)
C      NCELL=PAR(3)
C      A=PAR(4)
C      B=PAR(5)
C      TAU=PAR(6)/60.
C
C * FOR PROPORTIONAL CONTROL
C      ITOWER=0
C      IF(XIN(1) .GT. 0)ITOWER=1
C      TDB=XIN(2)
C      TWB=XIN(3)
C      TCWR=XIN(4)
C      FLCW=XIN(5)
C      DO 2 I=1,NCELL
2      FRAC(I)=XIN(5+I)
C      IF(INFO(7) .LE. 0)QOLD=OUT(5)
C
C      FDUM=0.
C      POWER=0.
C      DO 5 I=1,NCELL
C          FDUM=FDUM+FRAC(I)
5      POWER=POWER+POWMAX*(FRAC(I))**3
C
C      DT=0.
C      IF(ITOWER .EQ. 0 .OR. FDUM .LE. 0 .OR. FLCW .LE. 0.)GO TO 800
C      CALL PSYCH(TCWR,TCWR,H,SCWR,VDUM,WDUM)
C      CALL PSYCH(TDB,TWB,H,SA,VA,WA)
C      WRITE(6,1050)TDB,TWB,TCWR,SA,SCWR,VA,WA,FLCW,FRAC(1),
C      & FRAC(2),QOLD
C1050 FORMAT(3F4.0,2F6.2,F6.2,F6.4,E8.2,2F4.2,E8.2/)
C      DO 20 I=1,NCELL

```



```

      IF (FRAC(I) .GT. 0.) THEN
        FLA = FANMAX * FRAC(I) / VA
        QAMAX = AMAX1 (FLA * (SCWR - SA), 1.E-5)
        QWMAX = AMAX1 (FLCW * CPW * (TCWR - TWB) / NCELL, 1.E-5)
        R = AMIN1 (QAMAX, QWMAX) / AMAX1 (QAMAX, QWMAX)
        R = AMIN1 (1., AMAX1 (0., R))
        EPS = A + B * R
        IF (EPS .GT. 1.) EPS = 1.
        DTC = EPS * NCELL * AMIN1 (QAMAX, QWMAX) / FLCW / CPW
        DT = DT + DTC
C      WRITE (6, 1000) FLCW, FLA, QAMAX, QWMAX, R, EPS, DTC, DT
C1000    FORMAT (4E9.3, 2F9.4, 2F9.2/)
      ENDIF
20    CONTINUE
      DT = DT / NCELL
      QSS = FLCW * DT
      IF (TAU .NE. 0.) THEN
        QNEW = QSS - (QSS - QOLD) * EXP (-DELT / TAU)
        QAVG = QSS - (QSS - QOLD) * (TAU / DELT) * (1. - EXP (-DELT / TAU))
        DT = QAVG / FLCW
      ELSE
        QNEW = QSS
        QAVG = QSS
      ENDIF
      TCWS = TCWR - DT
      GO TO 900
C
C800    TCWS = TCWR
      POWER = 0.
      QAVG = 0.
      QNEW = 0.
900    CONTINUE
C
C      WRITE (6, 1100) TCWS, DT, POWER, QAVG, QNEW, QSS
C1100    FORMAT (2F6.2, 4E8.2/)
C      WRITE (6, 1200)
C1200    FORMAT ('*****' /)
C
C *** SET OUTPUTS
      OUT (1) = TCWS
      OUT (2) = DT
      OUT (3) = POWER
      OUT (4) = QAVG
      OUT (5) = QNEW
C
      RETURN
      END
C
C *****
C * PSYCHROMETRIC FUNCTION *

```

```

C *****
C
C   SUBROUTINE PSYCH(TDB,TWB,H,S,V,W)
C   DATA P/14.7/
C
C   T=(TWB-32.)/1.8+273.15
C   PSAT=EXP(-5800.2206/T+1.3914993-0.04860239*T
&     +0.41764768E-4*T**2-0.14452093E-7*T**3+6.545967*ALOG(T))
C   PSAT=PSAT*0.000145
C   WSAT=0.62198*PSAT/(P-PSAT)
C   IF(ABS(TDB-TWB) .GT. .01) THEN
C     W=((1093.-0.556*TWB)*WSAT-0.24*(TDB-TWB))/(1093.+.444*TDB-TWB)
C   ELSE
C     W=WSAT
C   ENDIF
C   V=.3705*(TDB+460.)*(1.+1.6078*W)/P
C   H=.24*TDB+W*(1061.+.444*TDB)
C   S=H-W*1.003*TWB
C
C   RETURN
C   END

```

PROPORTIONAL CONTROL THERMOSTAT

```
      SUBROUTINE TYPE43(TIME,XIN,OUT,T,DTDT,PAR,INFO)
C
C      *****
C      * PROPORTIONAL CONTROL THERMOSTAT *
C      *****
C
C *** MAXIMUM 5 THERMOSTATS
C
C MODIFIED 8/16/88 BY T. J. MARSEILLE
C COOL ON/OFF INDEX HARDWIRED TO BE 1.0
C DURING 4-6 A.M. PERIOD OF THE SUMMER, UNLESS
C THE LOOP WATER TEMPERATURE DROPS BELOW 65 F,
C OR ON SATURDAY OR SUNDAY.
C THIS MODULE SHOULD ONLY BE USED WITH THESE MODIFICATIONS
C WHEN THE HVAC/MASS INTERACTION MODEL IS BEING USED TO
C PULLDOWN THE BUILDING IN THE MORNING.
C
C *****
C
C      PARAMETERS: 6
C
C      1 TH = HEATING SETPOINT (F) - TEMP WHEN HEATING FIRST COMES ON
C      2 TC = COOLING SETPOINT (F) - TEMP WHEN COOLING FIRST COMES ON
C      3 TDELH = HEATING THROTTLING RANGE (F)
C              *** HEATING=MAX @ TEMP=TH-TDELH ***
C      4 TDELC = COOLING THROTTLING RANGE (F)
C              *** COOLING=MAX @ TEMP=TC+TDELC ***
C      5 TSETBK = HEATING SETBACK TEMPERATURE DIFFERENCE (F)
C              (* ENTER 0 FOR NO SETBACK*)
C      6 TCW = NON-SUMMER COOLING TOWER SETPOINT (F)
C
C      INPUTS: 3
C      1 TEMP = TEMPERATURE WHICH COMMANDS THE T'STAT (F)
C      2 ISETBK = HEATING SETBACK SCHEDULE (0=NO SETBACK, 1=SETBACK)
C      3 IWK = WEEKEND OVERRIDE OF HVAC /MASS COOLDOWN LOGIC
C
C      OUTPUTS: 3
C      1 HEAT = HEATING ON/OFF (0.0-1.0)
C      2 COOL = COOLING ON/OFF (0.0-1.0)
C      3 SLAB = RESET SLAB COOLING CONTROL (0 OR 1)
C
C *****
C
C      DIMENSION PAR(15), XIN(10), OUT(20), INFO(10)
C      COMMON/SIM/TIME0,TIMEF,DELT
C      COMMON/LUNITS/LUR,LW,LW,IFORM
C
C *** FIRST CALL OF SIMULATION
```



```

        IF (INFO(7) .GE. 0) GO TO 100
        NI=INFO(3)
        NP=INFO(4)
        INFO(6)=2
        CALL TYPECK(1,INFO,NI,NP,0)
100    CONTINUE
C
C *** SET PARAMETERS
        SLAB = 0.
        TSETH=PAR(1)
        TSETC=PAR(2)
        IF((TIME-2884.) .LT. 0. .OR. (TIME-6534.) .GT. 0.) TSETC=PAR(6)
        TDELH=PAR(3)
        TDELC=PAR(4)
        TBACK=PAR(5)
C
C *** SET INPUTS
        TEMP=XIN(1)
        IBACK=INT(XIN(2))
        IWEK=INT(XIN(3))
C
C *** ADJUST HEATING SETBACK TO ACCOUNT FOR SETBACK, IF ANY
        TSETH=TSETH-TBACK*IBACK
C
C *** TEMP FOR MAX(1) AND MIN(0) SIGNALS
        TQMAXH=TSETH-TDELH
        TQMAXC=TSETC+TDELC
        TQMINH=TSETH
        TQMINC=TSETC
C
C *** ERRORS
        IF((TQMAXH .GT. TQMINH) .OR. (TQMINH .GT. TQMINC) .OR.
&      (TQMINC .GT. TQMAXC)) THEN
            WRITE(*,1000)
            WRITE(LUW,1000)
1000    FORMAT('** TYPE43 ERROR -- INCORRECT THERMOSTAT SETTINGS **')
            CALL TYPECK(4,INFO,0,0,0)
            ENDIF
C
C *** ON/OFF CONTROL SIGNAL
        IHEAT=0
        ICOOL=0
        IF(TEMP .LT. TQMINH) THEN
            IHEAT=1
        ELSE
            IF(TEMP .GT. TQMINC) ICOOL=1
        ENDIF
C
C *** PROPORTIONAL CONTROL SIGNAL
        HEAT=0.0

```

```

COOL=0.0
IF(IHEAT .NE. 0)THEN
  IF(TQMAXH .EQ. TQMINH)THEN
    HEAT=1
  ELSE
    HEAT=(TEMP-TQMINH)/(TQMAXH-TQMINH)
    IF(HEAT .GT. 1.)HEAT=1.
  ENDIF
ELSE
  IF(ICOOOL .NE. 0)THEN
    IF(TQMAXC .EQ. TQMINC)THEN
      COOL=1
    ELSE
      COOL=(TEMP-TQMINC)/(TQMAXC-TQMINC)
      IF(COOL .GT. 1.)COOL=1.
    ENDIF
  ENDIF
ENDIF
ENDIF
C  HVAC/MASS LOGIC USED FOR MORNING COOLDOWN OF WATER
C  IN SUMMER
  IF(IWEEK.EQ.0)GO TO 2000
  IF((TIME-2884.).LT.0..OR.(TIME-6534.).GT.0.)GO TO 2000
  HOUR = TIME - (AINT(TIME/24.)*24.)
  IF(HOUR.GE.4.0.AND.HOUR.LE.6.0.AND.TEMP.GE.65.)THEN
    COOL = 1.0
    SLAB = 1.
  ENDIF
2000 CONTINUE
C
C *** OUTPUTS
  OUT(1)=HEAT
  OUT(2)=COOL
  OUT(3)=SLAB
C
  RETURN
END

```

THERMAL ENERGY STORAGE IN SLAB

```
      SUBROUTINE TYPE47 (TIME,XIN,OUT,T,DTDT,PAR,INFO)
C
C      *****
C      *              THESIS              *
C      *  THERMAL ENERGY STORAGE IN SLAB  *
C      *****
C *** THE MODEL ASSUMES ALL FLUID AT THE AVERAGE INLET AND OUTLET
C      TEMPERATURE. AVERAGE TEMPERATURE SOLVED BY ITERATION.
C *** MAXIMUM THESIS UNITS PER TRNSYS SIMULATION = 4
C *** MAXIMUM NUMBER OF NODES = 25 X 25
C *****
C
C  PARAMETERS: 26
C  * NOTE * PAR(4), PAR(22) & PAR(24) MUST BE CONSISTENT, AS FOLLOWS:
C            PAR(4)*PAR(24) = TRNSYS TIME STEP (IN SECONDS)
C            PAR(22) & PAR(24) MUST SATISFY STABILITY REQUIREMENT
C
C  1  IU = THESIS UNIT INDEX (1-4)
C
C  PIPE CIRCUITING:
C  2  EQTPL = PIPE LENGTH FOR EACH PARALLEL CIRCUIT (FT)
C  3  NPARLL = NUMBER OF CIRCUITS IN PARALLEL
C
C  4  NTERAT = NUMBER OF NUMERICAL TIME STEPS WITHIN EACH TRNSYS TIME
C            STEP ([DELTS] * [NTERAT] = [TRNSYS TIME STEP])
C
C  FLUID TEMP CONVERGENCE:
C  5  MAXIT = MAXIMUM NUMBER OF ITERATION (FOR EACH CIRCUIT IN EACH
C            TRNSYS RUN TIME STEP) FOR CONVERGENCE OF AVG FLUID TEMP
C            BEFORE TERMINATION OF RUN
C  6  ERROR = TOLERANCE OF AVERAGED WATER TEMPERATURE IN EACH CIRCUIT
C            FOR INTERATION CONVEGENCE (F)
C
C  7  TINIT = INITIAL SLAB TEMPERATURE (F)
C
C  SLAB:
C  8  COND = CONDUCTIVITY OF SLAB (BTU/HR-FT-F)
C  9  RHO = DENSITY OF SLAB (LB/CU FT)
C 10  CP = SPECIFIC HEAT OF SLAB (BTU/LB-F)
C 11  THICK = TOTAL THICKNESS OF SLAB (INCH)
C
C  SURFACE INSULATION:
C 12  CONDT = THERMAL CONDUCTANCE OF INSULATION (CARPETING, ETC.)
C            ABOVE THE SLAB (BTU/HR-SQ FT-F)
C 13  CONDB = THERMAL CONDUCTANCE OF INSULATION UNDER THE SLAB
C            (BTU/HR-SQ FT-F)
```


C   * NOTE * CONDT & CONDB ARE FOR A GIVEN THICKNESS OF
 C   INSULATION (LESS THAN OR EQUAL TO 0.00 IF NONE)
 C
 C PIPES:
 C 14 CONDP = THERMAL CONDUCTIVITY OF PIPE (BTU/HR-FT-F)
 C 15 RHOP = DENSITY OF PIPE (LB/CU FT)
 C 16 CPP = SPECIFIC HEAT OF PIPE (BTU/LB-F)
 C 17 R = OUTER RADIUS OF PIPE (INCH)
 C 18 RIP = INNER RADIUS OF PIPE (INCH)
 C 19 S = PIPE SPACING, CENTER-TO-CENTER (INCH)
 C
 C FLUID FLOW HEAT TRANSFER:
 C 20 CONV1 = CONVECTION HEAT TRANSFER COEFFICIENT OF WATER IN PIPE
 C   -- W/FLOW (BTU/HR-SQ FT-F)
 C 21 CONV2 = CONVECTION HEAT TRANSFER COEFFICIENT OF WATER IN PIPE
 C   -- NO FLOW (BTU/HR-SQ FT-F)
 C
 C NUMERICAL SOLN SPEC.:
 C 22 DELX = LENGTH (WIDTH) OF EACH NODE (INCH)
 C   * NOTE * DELX SHOULD BE LESS THAN R.
 C   PARTIAL NODE IS NOT ALLOWED => [THICK/DELX]
 C   SHOULD BE AN INTEGER, OTHERWISE THE TOTAL THICKNESS
 C   OF THE NODES WILL BE SOMEWHAT GREATER THAN [THICK].
 C   THE SAME APPLIES TO [S/2/DELX].
 C 23 NCEN = NODE NUMBER FOR THE PIPE-FIELD PLANE. THE PIPES SHOULD ALWAYS
 C   BE EMBEDDED IN THE SLAB. ENTER 0 IF CENTERED, BUT IF THE
 C   NUMBER OF NODES ALONG THE THICKNESS OF SLAB IS EVEN, THEY
 C   WILL BE SLIGHTLY OFF-CENTERED.
 C   (NODE NUMBER BEGINS WITH 1 AT THE BOTTOM OF SLAB)
 C
 C 24 DELTS = NUMERICAL ITERATION TIME STEP (SEC)
 C   MUST BE LESS THAN TRNSYS TIME STEP AND
 C   [DELTS] * [NTERAT] = [TRNSYS TIME STEP]
 C   * NOTE * DELX & DELTS MUST SATISFY STABILITY REQUIREMENT !
 C
 C 25 FRAC = AVERAGE CROSS-SECTIONAL AREA OF NODES AROUND PIPE WALL
 C   (FRACTION OF AREA OF WHOLE INTERIOR NODES)
 C 26 RADD = ADDITIONAL THERMAL RESISTANCE FOR NODES AROUND PIPE WALL
 C   (HR-FT-F/BTU)
 C
 C INPUTS: 5
 C
 C 1 TTOP = TOP SURFACE TEMPERATURE (F)
 C 2 TBOM = BOTTOM SURFACE TEMPERATURE (F)
 C 3 TFINEQ = ENTERING FLUID TEMPERATURE (F)
 C 4 FLOW = MASS FLOW RATE OF WATER (LB/HR)
 C   (IF FLOW=0 => BYPASS)
 C * AS THE TEMP GRADIENT ALONG THE DIRECTION OF FLOW IS NOT DIRECTLY
 C   SIMULATED, IF TFINEQ IS VERY LONG &/OR FLOW IS
 C   VERY SMALL, THE FLUID TEMPERATURE WILL NOT CONVERGE *

```

C      5 ICONV = INDEX TO DETERMINE IF CONVECTION TO PIPE
C              IS TO BE INCLUDED
C
C      OUTPUTS: 7
C
C      * ALL HEAT TRANSFER RATES ARE FOR TOTAL NUMBER OF CIRCUITS
C        AND TOTAL PIPE LENGTH *
C      1 QTZ = AVERAGED HEAT TRANSFER RATE FROM FLUID TO SLAB (BTUH)
C              (+ = HEAT GAIN TO WATER, - = HEAT LOSS FROM WATER)
C      2 QTOPTZ = AVERAGED HEAT TRANSFER RATE FROM TOP SURFACE TO
C              ROOM (BTUH)
C              (+ = HEAT GAIN TO ROOM, - = HEAT LOSS FROM ROOM)
C      3 QBOMTZ = AVERAGED HEAT TRANSFER RATE FROM BOTTOM SURFACE
C              TO ROOM (BTUH)
C              (+ = HEAT GAIN TO ROOM, - = HEAT LOSS FROM ROOM)
C      4 TFOUT = TEMPERATURE OF FLUID LEAVING SERIS-CIRCUITS AT THE END OF
C              TRNSYS TIME STEP (F)
C      5 TBULK = BULK/AVERAGED TEMPERATURE OF SLAB (F)
C              (IT IS ONLY AN APPROXIMATION ... ALL NODES ARE WEIGHED
C              EQUALLY)
C      6 IRUN = NUMBER OF ITERATION BEFORE THE AVG FLUID TEMP CONVERGED
C      7 TFLUID = AVG FLUID TEMP USED FOR FINAL NUMERICAL SOLN (F)
C
C      *****
C
C      DIMENSION PAR(26),XIN(5),OUT(7),INFO(9),TDUMP(4,25,25)
C      DIMENSION IPIPE(4,25,25),TT(25,25),TTNEW(4,25,25),CONST(4,26)
C      COMMON/FLXDUM/JTDUM,CTDUM,JBDUM,CBDUM
C      COMMON/CONSTN/AA,BB,CCTOP,DDTOP,CCBOM,ddbom,CTF,CT3,CTT,CWATER
C      COMMON/NODESP/IPPIPE,M,N,MSP,NBP,NTP,NCEN,NIPIPE,ICOUNT
C      COMMON/SIM/TIMEO,TFINAL,DELT
C      COMMON/LUNITS/LUR,LUW,IFORM
C      DATA PI/3.1416/
C
C      *** FIRST CALL OF SIMULATION
C      IF(INFO(7) .EQ. -1)THEN
C          TEMPH = PAR(20)
C          NI=INFO(3)
C          NP=INFO(4)
C          INFO(6)=7
C          CALL TYPECK(1,INFO,NI,NP,0)
C      ENDIF
C
C      *** INITIALIZATION
C      IU=INT(PAR(1))
C      EQTPL=PAR(2)
C      NPARLL=INT(PAR(3))
C      NTERAT=INT(PAR(4))
C      MAXIT=INT(PAR(5))
C      ERROR=PAR(6)

```

```

      TTOP=XIN(1)
      TBOM=XIN(2)
      TFINEQ=XIN(3)
      TFIN=TFINEQ
      FLOW=XIN(4)
      IDEBUG=0
      ICONV = INT(XIN(5))
      IF(ICONV.NE.1)THEN
      PAR(20) = .000001
      ELSE
      PAR(20) = TEMPH
      ENDIF
C
C *** FIRST CALL OF SIMULATION--CALCULATE & STORE CONSTANTS
      CALL INITIAL(INFO,PAR,CONST,IU,IDEBUG)
C
C *** RETRIEVE STORED CONSTANTS
      AA=CONST(IU,1)
      BB=CONST(IU,2)
      CCTOP=CONST(IU,3)
      DDTOP=CONST(IU,4)
      CCBOM=CONST(IU,5)
      DDBOM=CONST(IU,6)
      IF(FLOW .GT. 0.)THEN
      RESISP=CONST(IU,7)
      CTF=CONST(IU,9)
      CTT=CONST(IU,12)
      ELSE
      RESISP=CONST(IU,8)
      CTF=CONST(IU,10)
      CTT=CONST(IU,13)
      ENDIF
      CT3=CONST(IU,11)
      JTDUM=INT(CONST(IU,14))
      CTDUM=CONST(IU,15)
      JBDUM=INT(CONST(IU,16))
      CBDUM=CONST(IU,17)
      M=INT(CONST(IU,18))
      N=INT(CONST(IU,19))
      MSP=INT(CONST(IU,20))
      NTP=INT(CONST(IU,21))
      NBP=INT(CONST(IU,22))
      NCEN=INT(CONST(IU,23))
      ICOUNT=INT(CONST(IU,24))
      CWATER=CONST(IU,25)
C
C *** RESET NODAL TEMPERATURE AT FIRST CALL OF THE TIME STEP
      IF(TIME .EQ. 0. .OR. INFO(7) .EQ. -1)THEN
      TINIT=PAR(7)
      DO 5 I=1,M

```



```

DO 5 J=1,N
  IF(IPIPE(IU,I,J) .EQ. 0)THEN
    TDUMP(IU,I,J)=TFIN
    TT(I,J)=TFIN
    TTNEW(IU,I,J)=TFIN
  ELSE
    TDUMP(IU,I,J)=TINIT
    TT(I,J)=TINIT
    TTNEW(IU,I,J)=TINIT
  ENDIF
5  CONTINUE
  QT=0.
  QTOPT=0.
  QBOMT=0.
  TFOUT=TFIN
  TBULK=TINIT
  IRUN=0
  TFLUID=TFIN
  GO TO 999
ELSE
  IF(INFO(7) .EQ. 0)THEN
    DO 10 I=1,M
    DO 10 J=1,N
10   TDUMP(IU,I,J)=TTNEW(IU,I,J)
    CONST(IU,26)=OUT(7)
  ENDIF
ENDIF
C
20  IRUN=0
    TFLUID=TFIN
C
C *** START ITERATION FOR EACH CIRCUIT
25  CONTINUE
    IRUN=IRUN+1
C
C *** INITIALIZE TEMPERATURE
    IF(FLOW .LE. 0.)TFLUID=CONST(IU,26)
    DO 50 I=1,M
    DO 50 J=1,N
      IF(IPIPE(IU,I,J) .EQ. 0)THEN
        TT(I,J)=TFLUID
      ELSE
        TT(I,J)=TDUMP(IU,I,J)
      ENDIF
50  CONTINUE
C * AT TOP & BOTTOM SURFACE
    DO 100 I=1,M
      IF(CCBOM .EQ. 0.)TT(I,1)=TBOM
      IF(CCTOP .EQ. 0.)TT(I,N)=TTOP
100  CONTINUE

```

```

C
  IF(IDEBUG .EQ. 1)THEN
    WRITE(LUW,*)'*****'
    WRITE(LUW,1000)TIME,INFO(7),IU
    WRITE(LUW,*)' INITIAL CONDITIONS'
    WRITE(LUW,2490)TTOP
    DO 182 J=N,1,-1
      WRITE(LUW,2500)(TT(I,J),I=1,M)
182  CONTINUE
    WRITE(LUW,2490)TBOM
  ENDIF
C
  CALL NUMERC(TT,TTNEW,TTOP,TBOM,FLOW,TFNEW,
&            NTERAT,TFLUID,TBULK,QT,QTOPT,QBOMT,IDEBUG,
&            IPRTB,IPRTE,RESISP,IU)
C
C *** CALCULATE EXIT FLUID TEMPERATURE
  IF(FLOW .LE. 0.)GO TO 887
  TFOUT=(2.*NPARLL*QT*EQTPL)/(FLOW*1.)+TFIN
  TFAVG=0.5*(TFIN+TFOUT)
  TERROR=ABS(TFAVG-TFLUID)
  IF(ABS(TERROR) .GT. ERROR)THEN
    IF(IRUN .LT. MAXIT)THEN
      TFNEW=TFAVG
      IF(IDEBUG .EQ. 1)WRITE(LUW,2000)QT,QTOPT,QBOMT,TFLUID,
&      TFOUT,TFAVG,TFIN,TBULK,IRUN,TERROR
      TFLUID=TFNEW
      GO TO 25
    ELSE
      WRITE(*,*)' EXECUTION TERMINATED-WATER TEMP DID NOT CONVERGE!'
      WRITE(LUW,*)' EXECUTION TERMINATED-WATER TEMP DID NOT CONVERGE'
      STOP
    ENDIF
  ENDIF
  GOTO 888
C
887  TFOUT=TFNEW
     TFLUID=TFNEW
888  CONTINUE
C
C *** CONVERT HEAT TRANSFER RATES TO PER TOTAL PIPE LENGTH & SPACING
  QT=QT*EQTPL*NPARLL*2.
  QTOPT=QTOPT*EQTPL*NPARLL*2.
  QBOMT=QBOMT*EQTPL*NPARLL*2.
C
C *** OUTPUTS
999  OUT(1)=QT
     OUT(2)=QTOPT
     OUT(3)=QBOMT
     OUT(4)=TFOUT

```

```

      OUT(5)=TBULK
      OUT(6)=REAL(IRUN)
      OUT(7)=TFLUID
C
1000 FORMAT(' TIME, INFO(7), IU ',F10.4,2I5)
2000 FORMAT(' *MAIN*'/,
      &      ' QT QTOPT QBOMT TFLUID TFOUT TFAVG',
      &      ' TFIN TBULK RUN ERROR'//,8F8.2,I4,F8.4/)
2010 FORMAT(I3)
2490 FORMAT(F6.2)
2500 FORMAT(13F6.2)
      RETURN
      END
C
C *****
C
      SUBROUTINE INITAL(INFO,PAR,CONST,IU,IDEBUG)
C
C *** CALCULATES & STORES PARAMETERS
C
      REAL MCPN,MCPP
      DIMENSION IPIPE(4,25,25),INFO(9),PAR(26),CONST(4,26)
      COMMON/FLXDUM/JTDUM,CTDUM,JBDUM,CBDUM
      COMMON/CONSTN/AA,BB,CCTOP,DDTOP,CCBOM,ddbom,CTF,CT3,CTT,CWATER
      COMMON/NODESP/IPICE,M,N,MSP,NBP,NTP,NCEN,NPIPE,ICOUNT
      COMMON/LUNITS/LUR,LUW,IFORM
      DATA PI/3.1416/,RHOW/62.4/,CPW/1./
C
      COND=PAR(8)
      RHO=PAR(9)
      CP=PAR(10)
      THICK=PAR(11)
      CONDT=PAR(12)
      CONDB=PAR(13)
      CONDP=PAR(14)
      RHOP=PAR(15)
      CPP=PAR(16)
      R=PAR(17)
      RIP=PAR(18)
      S=PAR(19)
      CONV1=PAR(20)
      CONV2=PAR(21)
      DELX=PAR(22)
      NCEN=INT(PAR(23))
      DELTS=PAR(24)
      FRAC=PAR(25)
      RADD=PAR(26)
C
C *** CALCULATE NODAL PARAMETERS
      DELY=DELX

```



```

M=NINT((S/2/DELX)+0.4999)+1
N=NINT((THICK/DELY)+0.4999)+1
IF(M.GT. 25 .OR. N.GT. 25)THEN
  WRITE(*,*)' EXECUTION TERMINATED - TOO MANY NODES! ',M,M
  WRITE(LUW,*)' EXECUTION TERMINATED - TOO MANY NODES! ',M,N
  STOP
ENDIF
IF(NCEN.LE. 0)NCEN=NINT((N+1)+0.4999)/2
NBP=NCEN-NINT(RIP/DELY+0.4999)
NTP=NCEN+NINT(RIP/DELY+0.4999)
MSP=NINT(RIP/DELX+0.4999)+1
IF(NTP.GE. N .OR. NBP.LE. 1 .OR. MSP.GE. M)THEN
  WRITE(*,*)'EXECUTION TERMINATED - INVALID NODE ARRANGEMENT!'
  WRITE(LUW,*)'EXECUTION TERMINATED - INVALID NODE ARRANGEMENT!'
  STOP
ENDIF
THICK=THICK/12.
R=R/12.
RIP=RIP/12.
S=S/12.
DELX=DELX/12.
DELY=DELX
DELT=DELTS/3600.
ALPHA=COND/(RHO*CP)
AA=(ALPHA*DELT)/(DELX*DELX)
BB=1.-4.*AA
C
C *** SET UP DUMMY PARAMETERS FOR CALCULATING HEAT FLUX
IF(CONDT.LE. 0.)THEN
  JTDUM=N-1
  CTDUM=COND
  CCTOP=0.
  DDTOP=0.
ELSE
  JTDUM=N
  CTDUM=CONDT*DELX
  CCTOP=CONDT*2*DELT/(RHO*CP*DELX)
  DDTOP=1-4.*AA-CCTOP
ENDIF
IF(CONDB.LE. 0.)THEN
  JBDUM=2
  CBDUM=COND
  CCBOM=0.
  DDBOM=0.
ELSE
  JBDUM=1
  CBDUM=CONDB*DELX
  CCBOM=CONDB*2*DELT/(RHO*CP*DELX)
  DDBOM=1-4.*AA-CCBOM
ENDIF

```

```

C
C *** PIPE WALL
CALL PIPE(RIP,DELX,DELY,IDEBUG,IU)
C
C *** THERMAL RESISTANCE OF PIPE PER ADJACENT NODE
RDUM=2*NPIPE*(ALOG(R/RIP)/(2.*PI*CONDP))+RADD
RESIS1=RDUM+2*NPIPE/(2.*PI*RIP*CONV1)
RESIS2=RDUM+2*NPIPE/(2.*PI*RIP*CONV2)
C
C *** AVERAGED AREA OF NODES ADJACENT PIPE
MCPN=RHO*(FRAC*DELX*DELX)*CP
MCPN=RHO*(PI*(R**2-RIP**2))*CPP/(2*NPIPE)
CTF1=DELT/((MCPN+MCPN)*RESIS1)
CTF2=DELT/((MCPN+MCPN)*RESIS2)
CT3=COND*DELT/(MCPN+MCPN)
CTT1=1.-CTF1-3.*CT3
CTT2=1.-CTF2-3.*CT3
C
C *** WATER
CWATER=2*DELT/(RHOW*PI*RIP**2)
C
IF(IDEBUG .EQ. 1)
& WRITE(LUW,3000)AA,BB,CCTOP,DDTOP,CCBOM,DDBOM,CTF1,CT3,CTT1,
& RESIS1,CTF2,CTT2,RESIS2,JTDUM,CTDUM,JBDUM,CBDUM,
& CWATER
C
C *** CHECK FOR SYSTEM INSTABILITY
IF((BB .LT. 0.) .OR. (CTT1 .LT. 0.) .OR. (CTT2 .LT. 0.) .OR.
& (DDTOP .LT. 0.) .OR. (DDBOM .LT. 0.))THEN
WRITE(*,*)' EXECUTION TERMINATED - SYSTEM UNSTABLE!'
WRITE(LUW,*)' EXECUTION TERMINATED - SYSTEM UNSTABLE!'
STOP
ENDIF
C
C *** STORE CONSTANTS
CONST(IU,1)=AA
CONST(IU,2)=BB
CONST(IU,3)=CCTOP
CONST(IU,4)=DDTOP
CONST(IU,5)=CCBOM
CONST(IU,6)=DDBOM
CONST(IU,7)=RESIS1
CONST(IU,8)=RESIS2
CONST(IU,9)=CTF1
CONST(IU,10)=CTF2
CONST(IU,11)=CT3
CONST(IU,12)=CTT1
CONST(IU,13)=CTT2
CONST(IU,14)=REAL(JTDUM)
CONST(IU,15)=CTDUM

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```

CONST(IU,16)=REAL(JBDUM)
CONST(IU,17)=CBDUM
CONST(IU,18)=REAL(M)
CONST(IU,19)=REAL(N)
CONST(IU,20)=REAL(MSP)
CONST(IU,21)=REAL(NTP)
CONST(IU,22)=REAL(NBP)
CONST(IU,23)=REAL(NCEN)
CONST(IU,24)=REAL(ICOUNT)
CONST(IU,25)=CWATER
C
3000 FORMAT(' *INITAL*'/,
&          '      AA      BB CCTOP DDTOP CCBOM DDBOM',
&          '      CTF1     CT3  CTT1 RESIS1'/,10F7.4/,
&          '      CTF2     CTT2 RESIS2 JTDUM CTDUM JBDUM CBDUM',
&          '      CWATER'/,3F7.4,2(17,F7.4),F7.4)
      RETURN
      END
C
C *****
C
      SUBROUTINE PIPE(R,DELX,DELY,IDEBUG,IU)
C
C *** CALCULATES PIPE NODE CONFIGURATIONS
C
      DIMENSION IPIPE(4,25,25),IPIPEZ(25,25)
      COMMON/NODESP/IPIPE,M,N,MSP,NBP,NTP,NCEN,NPIPE,ICOUNT
      COMMON/LUNITS/LUR,LUW,IFORM
C
      IF(IDEBUG .EQ. 1)WRITE(LUW,1200)M,N,MSP,NBP,NTP,NCEN,IU
      DO 150 I=1,M
      DO 150 J=1,N
        IPIPEZ(I,J)=2
150    IPIPE(IU,I,J)=2
C
      DO 250 I=1,MSP
        YDUM=R*R-((I-1)*DELX)**2
        IF(YDUM .LE. 0.)THEN
          YR=0.
        ELSE
          YR=SQRT(YDUM)
        ENDIF
      DO 250 J=1,MSP
250    IF(YR .GT. (J-1)*DELY)IPIPEZ(I,J)=0
C
C * IPIPE=0=FLUID,=1=PIPE WALL,2=SLAB
      DO 300 I=1,MSP
        IDUM=0
      DO 300 J=1,MSP
        IF(IPIPEZ(I,J) .EQ. 2 .OR. IPIPEZ(I,J) .EQ. 1)THEN

```



```

        IDUM=IDUM+1
        IF(IDUM .EQ. 1)IPIPEZ(I,J)=1
    ENDIF
300    CONTINUE
        DO 350 J=1,MSP
            IDUM=0
            DO 350 I=1,MSP
                IF(IPIPEZ(I,J) .EQ. 2 .OR. IPIPEZ(I,J) .EQ. 1)THEN
                    IDUM=IDUM+1
                    IF(IDUM .EQ. 1)IPIPEZ(I,J)=1
                ENDIF
            350    CONTINUE
C
C *** TRANSFER CENTER OF ORIGIN BACK TO LOWER LEFT CORNER
        DO 800 I=1,MSP
            DO 800 J=1,MSP
                IPIPE(IU,I,J+NCEN-1)=IPIPEZ(I,J)
            800    IPIPE(IU,I,-J+NCEN+1)=IPIPEZ(I,J)
C
C *** SUM PIPE NODES
        NIPIPE=-1
        DO 810 I=1,MSP
            DO 810 J=NBP,NTP
            810    IF(IPIPE(IU,I,J) .EQ. 1)NIPIPE=NIPIPE+1
C
C *** SUM ALL NODES
        ICOUNT=0
        DO 814 I=1,M
            DO 814 J=1,N
            814    IF(IPIPE(IU,I,J) .NE. 0)ICOUNT=ICOUNT+1
C
        IF(IDEBUG .EQ. 1)THEN
            WRITE(LUW,1400)NIPIPE,ICOUNT
            DO 904 J=N,1,-1
            904    WRITE(LUW,3000)J,(IPIPE(IU,I,J),I=1,M)
        ENDIF
C
1200 FORMAT(' *PIPE*   M   N MSP NBP NTP NCEN',//,7X,614,' IIIUUU ',I4)
1400 FORMAT(' *PIPE*  NIPIPE  ICOUNT',//,7X,218)
3000 FORMAT(1X,' IP ',22I3)
        RETURN
        END
C
C *****
C
        SUBROUTINE NUMERC(TT,TTNEW,TTOP,TBOM,FLOW,TFNEW,
&            NTERAT,TFLUID,TBULK,QT,QTOPT,QBOMT,IDEBUG,
&            IPRTB,IPRTE,RESISP,IU)
C
C *** NUMERICAL SOLUTION

```

```

C
  DIMENSION IPIPE(4,25,25),TTNEW(4,25,25),TT(25,25)
  COMMON/FLXDUM/JTDUM,CTDUM,JBDUM,CBDUM
  COMMON/CONSTN/AA,BB,CCTOP,DDTOP,CCBOM,ddbom,CTF,CT3,CTT,CWATER
  COMMON/NODESP/IPICE,M,N,MSP,NBP,NTP,NCEN,NIPICE,ICOUNT
  COMMON/LUNITS/LUR,LW,LW,IFORM
C
C *** ITERATION
  ITERAT=0
  QT=0.
  QTOPT=0.
  QBOMT=0.
  DO 180 I=1,M
  DO 180 J=1,N
180   TTNEW(IU,I,J)=TT(I,J)
C
  50   ITERAT=ITERAT+1
C
C * ALONG PIPE WALL
  DO 200 I=2,MSP
  DO 200 J=NBP,NTP
    IF(1PIPE(IU,I,J) .EQ. 1)THEN
      DUM=0.
      DO 190 IDUM=I-1,I+1,2
190       IF(1PIPE(IU,IDUM,J) .NE. 0)DUM=DUM+TT(IDUM,J)
      DO 192 JDUM=J-1,J+1,2
192       IF(1PIPE(IU,I,JDUM) .NE. 0)DUM=DUM+TT(I,JDUM)
      TTNEW(IU,I,J)=CTF*TFLUID+CT3*DUM+CTT*TT(I,J)
    ENDIF
200   CONTINUE
  DO 240 J=NBP,NTP
    IF(1PIPE(IU,1,J) .EQ. 1)THEN
      DUM=0.
      DO 230 JDUM=J-1,J+1,2
230       IF(1PIPE(IU,1,JDUM) .NE. 0)DUM=DUM+TT(1,JDUM)
      TTNEW(IU,1,J)=CTF*TFLUID+CT3*(2*TT(2,J)+DUM)+CTT*TT(1,J)
    ENDIF
240   CONTINUE
C
C * LEFT & RIGHT BOUNDARY
  DO 310 J=2,NBP-1
    TTNEW(IU,1,J)=AA*(2*TT(2,J)+TT(1,J+1)+TT(1,J-1))
    & +BB*TT(1,J)
310   CONTINUE
  DO 315 J=NTP+1,N-1
    TTNEW(IU,1,J)=AA*(2*TT(2,J)+TT(1,J+1)+TT(1,J-1))
    & +BB*TT(1,J)
315   CONTINUE
  DO 320 J=2,N-1
    TTNEW(IU,M,J)=AA*(2*TT(M-1,J)+TT(M,J+1)+TT(M,J-1))

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```

      & +BB*TT(M,J)
320  CONTINUE
C
C *** INTERIOR NODES
DO 400 I=2,MSP
DO 400 J=2,N-1
  IF(IPIPE(IU,I,J) .NE. 2)GO TO 400
  TTNEW(IU,I,J)=AA*(TT(I-1,J)+TT(I+1,J)+TT(I,J-1)
    & +TT(I,J+1))+BB*TT(I,J)
400  CONTINUE
DO 500 I=MSP+1,M-1
DO 500 J=2,N-1
  TTNEW(IU,I,J)=AA*(TT(I-1,J)+TT(I+1,J)+TT(I,J-1)
    & +TT(I,J+1))+BB*TT(I,J)
500  CONTINUE
C
C *** TOP & BOTTOM OF SLAB
IF(CCTOP .EQ. 0.)THEN
DO 510 I=1,M
510  TTNEW(IU,I,N)=TTOP
ELSE
DO 515 I=2,M-1
515  TTNEW(IU,I,N)=2*AA*TT(I,N-1)+AA*(TT(I-1,N)+TT(I+1,N))
    & +CCTOP*TTOP+DDTOP*TT(I,N)
    & TTNEW(IU,1,N)=2*AA*TT(1,N-1)+2*AA*TT(2,N)+CCTOP*TTOP
    & +DDTOP*TT(1,N)
    & TTNEW(IU,M,N)=2*AA*TT(M,N-1)+2*AA*TT(M-1,N)+CCTOP*TTOP
    & +DDTOP*TT(M,N)
ENDIF
C
IF(CCBOM .EQ. 0.)THEN
DO 520 I=1,M
520  TTNEW(IU,I,1)=TBOM
ELSE
DO 525 I=2,M-1
525  TTNEW(IU,I,1)=2*AA*TT(I,2)+AA*(TT(I-1,1)+TT(I+1,1))
    & +CCBOM*TBOM+DDBOM*TT(I,1)
    & TTNEW(IU,1,1)=2*AA*TT(1,2)+2*AA*TT(2,1)+CCBOM*TBOM
    & +DDBOM*TT(1,1)
    & TTNEW(IU,M,1)=2*AA*TT(M,2)+2*AA*TT(M-1,1)+CCBOM*TBOM
    & +DDBOM*TT(M,1)
ENDIF
C
C *** TOTAL HEAT TRANSFER FROM FLUID
QIT=0.
DO 540 I=2,MSP
DO 540 J=NBP,NTP
540  IF(IPIPE(IU,I,J) .EQ. 1)QIT=QIT+(TT(I,J)-TFLUID)/RESISP
DO 560 J=NBP,NTP
560  IF(IPIPE(IU,1,J) .EQ. 1)QIT=QIT+(TT(1,J)-TFLUID)/RESISP/2.

```



```

      QT=QT+QIT
C
C *** NO FLOW CONDITIONS
      IF (FLOW .LE. 0.) TFNEW=TFLUID+QIT*CWATER
C
C *** CALCULATE HEAT TRANSFER RATE AT TOP AND BOTTOM SURFACE
      BFLUX=0.
      DO 850 I=2,M-1
850      BFLUX=BFLUX+(TT(I,JBDUM)-TBOM)
      BFLUX=BFLUX+(TT(1,JBDUM)+TT(M,JBDUM)-2*TBOM)/2.
      QBOM=BFLUX*CBUM
      QBOMT=QBOMT+QBOM
C
      TFLUX=0.
      DO 900 I=2,M-1
900      TFLUX=TFLUX+(TT(I,JTDUM)-TTOP)
      TFLUX=TFLUX+(TT(1,JTDUM)+TT(M,JTDUM)-2*TTOP)/2.
      QTOP=TFLUX*CTDUM
      QTOPT=QTOPT+QTOP
C
C *** UPDATE TEMPERATURE
      DO 600 I=1,M
      DO 600 J=1,N
          IF (FLOW .LE. 0. .AND. IPIPE(IU,I,J) .EQ. 0) THEN
              TT(I,J)=TFNEW
          ELSE
              TT(I,J)=TTNEW(IU,I,J)
          ENDIF
600      CONTINUE
      IF (FLOW .LE. 0.) TFLUID=TFNEW
C
C *** CALCULATE BULK SLAB TEMPERATURE
      TBULK=0.
      DO 940 I=1,M
      DO 940 J=1,N
940      IF (IPipe(IU,I,J) .NE. 0) TBULK=TBULK+TT(I,J)
      TBULK=TBULK/ICOUNT
C
      IF (IDEBUG .EQ. 1) THEN
          WRITE(LUW,2000) ITERAT,QIT,QTOP,QBOM,QT,QTOPT,QBOMT,TBULK,TFLUID
          WRITE(LUW,2490) TTOP
          DO 602 J=N,1,-1
602      WRITE(LUW,2500) (TT(I,J),I=1,M)
          WRITE(LUW,2490) TBOM
      ENDIF
C
C *** END OF ITERATION
      IF (ITERAT .LT. NTERAT) GO TO 50
      QT=QT/NTERAT
      QTOPT=QTOPT/NTERAT

```

```

      QBOMT=QBOMT/NTERAT
C
800  CONTINUE
2000 FORMAT(/,'  ITERAT      QIT      QTOP      QBOM',
      &      '      QT      QTOPT      QBOMT      TBULK  TFLUID'/,18,8F8.2)
2010 FORMAT(I3)
2490 FORMAT(F6.2)
2500 FORMAT(13F6.2)
      RETURN
      END

```

HEAT PUMPS

```
      SUBROUTINE TYPE50 (TIME,XIN,OUT,T,DTDT,PAR,INFO)
C
C      *****
C      *   WATER SOURCE HEAT PUMP   *
C      *****
C      *****
C      *** MAXIMUM 10 HEAT PUMPS PER SIMULATION ***
C
C      PARAMETERS:  9
C
C      1  CAPTN(1) = NOMINAL CAPACITY - HEATING (KBTUH)
C              (*** POSITIVE ***)
C      2  POWN(1) = NOMINAL POWER - HEATING (KW)
C      3  CAPTN(2) = NOMINAL TOTAL CAPACITY - COOLING (KBTUH)
C              (*** NEGATIVE ***)
C      4  CAPSN(2) = NOMINAL SENSIBLE CAPACITY - COOLING (KBTUH)
C              (*** NEGATIVE ***)
C      5  POWN(2) = NOMINAL POWER - COOLING (KW)
C      6  TAU = CAPACITY TIME CONSTANT (MIN)
C              SET TO 0 FOR NEGLIGIBLE TRANSIENT DELAY
C      7  POWFN = NOMINAL FAN POWER (KW)
C      8  CFMN = NOMINAL AIR FLOWRATE (CFM)
C      9  MGPHN = NOMINAL WATER FLOWRATE (LB/HR)
C
C      INPUTS: 11
C
C      1  IH = HEATING ON-OFF CONTROL INDEX
C      2  IC = COOLING ON-OFF CONTROL INDEX
C      3  IFAN = FAN ON-OFF CONTROL INDEX
C      4  MGPH = WATER MASS FLOWRATE (LB/HR)
C      5  TWI = ENTERING WATER TEMPERATURE (F)
C      6  TRDB = INDOOR/ROOM DRY-BULB TEMPERATURE (F)
C      7  WR = INDOOR/ROOM HUMIDITY RATIO (LB/LB)
C      8  TADB = OUTDOOR/AMBIENT DRY-BULB TEMPERATURE (F)
C      9  WA = OUTDOOR/AMBIENT HUMIDITY RATIO (LB/LB)
C      10 CFM = INDOOR FAN FLOWRATE (CFM)
C      11 FRACA = VOLUMETRIC FRACTIONAL OUTDOOR AIR ENTERING INDOOR COIL
C              (DIMENSIONLESS)
C
C      OUTPUTS: 12
C
C      1  CAPTF = HEATING/COOLING TOTAL CAPACITY AT THE END OF THE
C              TIME STEP (KBTUH)
C              (HEATING=POSITIVE; COOLING=NEGATIVE)
C      2  CAPTAV = HEATING/COOLING TOTAL CAPACITY, AVERAGED OVER THE
C              TIME STEP (KBTUH)
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```

C      (HEATING=POSITIVE; COOLING=NEGATIVE)
C 3 CAPSF = HEATING/COOLING SENSIBLE CAPACITY AT THE END OF THE
C      TIME STEP (KBTUH)
C      (HEATING=POSITIVE; COOLING=NEGATIVE)
C 4 CAPSAV = HEATING/COOLING SENSIBLE CAPACITY, AVERAGED OVER THE
C      TIME STEP (KBTUH)
C      (HEATING=POSITIVE; COOLING=NEGATIVE)
C 5 TODB = AIR TEMPERATURE LEAVING INDOOR COIL (F)
C 6 WO = AIR HUMIDITY RATIO LEAVING INDOOR COIL (LB/LB)
C 7 MAIR = SUPPLY AIR MASS FLOW RATE (LB/HR)
C 8 POW = COMPRESSOR POWER (KW)
C 9 HRAV = HEAT TRANSFER TO THE WATER LOOP (KBTUH)
C      (HEAT REJECTION=POSITIVE; HEAT ABSORPTION=NEGATIVE)
C 10 TWO = LEAVING WATER TEMPERATURE (F)
C 11 POWF = FAN POWER (KW)
C 12 IHP = HEAT PUMP INDEX
C      (1 TO 10, MAXIMUM)

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NOMENCLATURES

```

C      ??S=STEADY-STATE, UNADJUSTED VALUES
C      ??J=STEADY-STATE, ADJUSTED VALUES
C      ??N=NOMINAL VALUES @ ARI POINT
C      ??I=INITIAL VALUES
C      ??F=FINAL VALUES
C      ??AV=AVERAGED OVER TIME STEP
C      X(I,J,K)  I:1=M,2=A1,3=A2, FOR Y=M+A1*X1+A2*X2;
C                  J:1=UNADJUSTED, 2=ADJ. FOR INDOOR TEMP, 3=ADJ. FOR CFM
C                  K:IHC=0=NO HEATING/COOLING, 1=HEATING, 2=COOLING
C                  X:CT=TOTAL CAP, CS=SENSIBLE CAP, PW=POWER

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*****

```

C      REAL MW,MAIR,MGPH,MGPHN,MA,MR
C      DIMENSION XIN(11),OUT(12),PAR(9),INFO(9),CT(3,3,2),CS(3,3,2),
C      &          PW(3,3,2),CAPTN(2),CAPSN(2),POWN(2),CAPTI(10),
C      &          CAPSI(10)
C      COMMON/SIM/TIMEO,TFINAL,DELT
C      COMMON/LUNITS/LUR,LUW,IFORM
C      DATA CAPTI/10*0./,CAPSI/10*0./,IHP/0/,NHPU/0/,IWARN/0/
C      &      CT/0.4101,0.0763,0.0073,1.3366,-0.0048,0.,
C      &      0.8545,0.1455,0.,
C      &      1.1274,0.0355,-0.0019,-0.1294,0.,0.0169,
C      &      0.8605,0.1395,0./,
C      &      CS/0.,0.,0.,0.,0.,0.,0.,0.,0.,
C      &      0.9659,-0.0003,0.0004,0.8834,0.0429,-0.0495,
C      &      0.6898,0.3102,0./,
C      &      PW/0.6885,0.0410,0.0039,0.6438,0.0051,0.,
C      &      1.14,-0.14,0.,
C      &      0.5904,-0.0960,0.0059,0.6446,0.,0.0053,

```

```

      &      0.8401 ,0.1599 ,0./
C
C *** FIRST CALL OF SIMULATION
      IDEBUG=0
      IF(INFO(7) .NE. -1)GO TO 100
      NI=INFO(3)
      NP=INFO(4)
      INFO(6)=12
      CALL TYPECK(1,INFO,NI,NP,0)
      NHPU=NHPU+1
      OUT(12)=NHPU
      IF(NHPU .GT. 10)CALL TYPECK(6,INFO,0,0,0)
100  CONTINUE
C
C *** SET PARAMETERS AND INPUTS
      IHP=INT(OUT(12)+0.1)
      CAPTN(1)=PAR(1)
      CAPSN(1)=CAPTN(1)
      POWN(1)=PAR(2)
      CAPTN(2)=PAR(3)
      CAPSN(2)=PAR(4)
      POWN(2)=PAR(5)
      TAU=PAR(6)/60.
      POWFN=PAR(7)
      CFMN=PAR(8)
      MGPHN=PAR(9)
      GPMN=MGPHN/(60.*8.333)
C
      IH=INT(XIN(1))
      IC=INT(XIN(2))
      IF(IH .EQ. 1 .AND. IC .EQ. 0)IHC=1
      IF(IH .EQ. 0 .AND. IC .EQ. 1)IHC=2
      IF(IH .EQ. 0 .AND. IC .EQ. 0)IHC=0
      IF(IH .EQ. 1 .AND. IC .EQ. 1)CALL TYPECK(3,INFO,0,0,0)
      IFAN=INT(XIN(3))
      MGPH=XIN(4)
      GPM=MGPH/8.333/60.
      TWI=XIN(5)
      TRDB=XIN(6)
      WR=XIN(7)
      TADB=XIN(8)
      WA=XIN(9)
      CFM=XIN(10)
      FRACA=XIN(11)
      POWF=0.
C
C      Set IFAN = 1 if IHC = 1 (so fan always operates when hp needed)
C
      IF(IHC .NE. 0)IFAN = 1
      IF(IFAN .NE. 0)POWF=POWFN*(CFM/CFMN)**3

```

```

C      IF(IHC+IFAN .EQ. 0)GO TO 800
C
C *** CALCULATE MIXED-AIR CONDITIONS ENTERING INDOOR COIL
VR=0.0252*(TRDB+460)*(1.+1.6078*WR)
MR=CFM*(1.-FRACA)/VR*60.
VA=0.0252*(TADB+460)*(1.+1.6078*WA)
MA=CFM*FRACA/VA*60.
MAIR=MR+MA
TIDB=(MA*TADB+MR*TRDB)/MAIR
WI=(MA*WA+MR*WR)/MAIR
C
C      IF(IHC .EQ. 0)GO TO 700
C
C *** SET INITIAL VALUES
IF(INFO(7) .LE. 0)THEN
  CAPTI(IHP)=OUT(1)
  CAPSI(IHP)=OUT(3)
ENDIF
C
C *** CALCULATE WET-BULB TEMP
C * (NOTE: EQUATIONS ASSUME AVG NORMAL ROOM CONDITION)
H=0.5583*TIDB+WI*(1.0328*TIDB+2467.9511)-17.8667
IF((H+17.68) .LE. 0.)THEN
  WRITE(*,*)
  & ' PSYCHROMETRIC PROBLEM IN TYPE 50, CHECK TEMP & HUMIDITY'
  WRITE(*,1060)TIME,INFO(1),TADB,WA,TRDB,WR,TIDB,WI,H
  WRITE(LUW,*)
  & ' PSYCHROMETRIC PROBLEM IN TYPE 50, CHECK TEMP & HUMIDITY'
  WRITE(LUW,1060)TIME,INFO(1),TADB,WA,TRDB,WR,TIDB,WI,H
ENDIF
Y=ALOG(H+17.68)
TIWB=80.1415+Y*(-78.192+Y*(25.0362-Y*1.7586))
IF(TIWB .GT. TIDB)TIWB=TIDB
C
C *** CALCULATE ADJUSTED, STEADY-STATE PERFORMANCE
C
CAPTS=CT(1,1,IHC)+CT(2,1,IHC)*GPM/GPMN+CT(3,1,IHC)*TWI
CAPTJ=CAPTS
& *(CT(1,2,IHC)+CT(2,2,IHC)*TIDB+CT(3,2,IHC)*TIWB)
& *(CT(1,3,IHC)+CT(2,3,IHC)*CFM/CFMN)
C
IF(IHC .EQ. 1)THEN
  CAPSS=CAPTS
  CAPSJ=CAPTJ
ELSE
  CAPSS=CS(1,1,2)+CS(2,1,2)*GPM/GPMN+CS(3,1,2)*TWI
  CAPSJ=CAPSS
  & *(CS(1,2,2)+CS(2,2,2)*TIDB+CS(3,2,2)*TIWB)
  & *(CS(1,3,2)+CS(2,3,2)*CFM/CFMN)

```



```

ENDIF
C
POWS=PW(1,1,IHC)+PW(2,1,IHC)*GPM/GPMN+PW(3,1,IHC)*TWI
POWJ=POWS
&    *(PW(1,2,IHC)+PW(2,2,IHC)*TIDB+PW(3,2,IHC)*TIWB)
&    *(PW(1,3,IHC)+PW(2,3,IHC)*CFM/CFMN)
C
IF( (POWJ .LE. 0. .OR. POWJ .GE. 3.0)
& .OR. (CAPTJ .LE. 0. .OR. CAPTJ .GE. 3.0)
& .OR. (CAPSJ .LE. 0. .OR. CAPSJ .GE. 3.0)) THEN
    IWARN=IWARN+1
    WRITE(*,*)' ERROR IN HEAT PUMP COEFFICIENT IN TYPE 50'
    WRITE(*,1070)TIME,INFO(1),TIDB,TIWB,TWI,MGPH,CFM,POWJ,CAPTJ,
&    CAPSJ
    WRITE(LUW,*)' ERROR IN HEAT PUMP COEFFICIENT IN TYPE 50'
    WRITE(LUW,1070)TIME,INFO(1),TIDB,TIWB,TWI,MGPH,CFM,POWJ,
&    CAPTJ,CAPSJ
    IF(IWARN .GE. 10) THEN
        WRITE(*,*)' EXECUTION TERMINATED - TYPE 50 ERROR'
        WRITE(LUW,*)' EXECUTION TERMINATED - TYPE 50 ERROR'
    ENDIF
ENDIF
ENDIF
C
C *** CALCULATE TRANSIENT & AVERAGE PERFORMANCE
POW=POWN(IHC)*POWJ
CAPT=CAPTN(IHC)*CAPTJ
CAPS=CAPSN(IHC)*CAPSJ
IF(ABS(CAPS) .GT. ABS(CAPT))CAPS=CAPT
C
C *** VERY SHORT TIME CONSTANT, FINAL & AVG = STEADY STATE VALUES
IF(TAU .GT. 0.0001) THEN
    AA=DELT/TAU
    BB=EXP(-AA)
    CC=(1./AA)*(1.-BB)
ELSE
    BB=0.
    CC=0.
ENDIF
CAPTF=CAPT-(CAPT-CAPTI(IHP))*BB
CAPTAV=CAPT-(CAPT-CAPTI(IHP))*CC
IF(IHC .EQ. 1) THEN
    CAPSF=CAPTF
    CAPSAV=CAPTAV
ELSE
    CAPSF=CAPS-(CAPS-CAPSI(IHP))*BB
    IF(ABS(CAPSF) .GE. ABS(CAPTF))CAPSF=CAPTF
    CAPSAV=CAPS-(CAPS-CAPSI(IHP))*CC
    IF(ABS(CAPSAV) .GE. ABS(CAPTAV))CAPSAV=CAPTAV
ENDIF
GO TO 750

```

```

C
C *** ONLY FAN OPERATING
700 CAPTF=0.
    CAPTAV=0.
    CAPSF=0.
    CAPSAV=0.
    POW=0.

C
C *** CALCULATE HEAT ABSORBED/REJECTED & OUTLET TEMP OF WATER AND AIR
750 HRAV=POW*3.4121-CAPTAV
    TWO=TWI+HRAV*1000./MGPH
C * INCLUDE FAN HEAT
    IF(IHC .EQ. 1)THEN
        CAP=CAPTAV+POWF*3.4121
        MW=0.
    ELSE
        IF(IHC .EQ. 2)THEN
            CAP=CAPSAV+POWF*3.4121
            MW=(CAPTAV-CAPSAV)*1000./1061.
        ELSE
            CAP=POWF*3.4121
            MW=0.
        ENDIF
    ENDIF
    WO=WI+MW/MAIR
    HI=(0.24+0.444*WI)*TIDB
    HO=HI+CAP*1000./MAIR
    TODB=HO/(0.24+0.444*WO)
    GO TO 810

C
C *** NO HEATING OR COOLING
C
800 CAPTF=0.
    MAIR=0.
    CAPTAV=0.
    CAPSF=0.
    CAPSAV=0.
    POW=0.
    POWF=0.
    HRAV=0.
    TWO=TWI
    WO=WI
    TODB=TIDB

C
C *** OUTPUT
810 OUT(1)=CAPTF
    OUT(2)=CAPTAV
    OUT(3)=CAPSF
    OUT(4)=CAPSAV
    OUT(5)=TODB

```

```

OUT(6)=W0
OUT(7)=MAIR
OUT(8)=POW
OUT(9)=HRAV
OUT(10)=TWO
OUT(11)=POWF
OUT(12)=IHP

```

C

```

      IF (IDEBUG .EQ. 1) THEN
      WRITE(LUW,1040)
1040  FORMAT(' *-----*')
      WRITE(LUW,1030) IHP, TIME, INFO(7), INFO(8), (XIN(I), I=1, 11)
1030  FORMAT(/' IHP', I4/,
      &      F6.4, 2I3, 3F3.0, F7.0, 2F6.2, F6.4, F6.2, F6.4, F6.0, F4.2/)
      WRITE(LUW,1000) CAPTI(IHP), CAPTS, CAPTJ, CAPT, CAPTF, CAPTAV,
      &      CAPSI(IHP), CAPSS, CAPSJ, CAPS, CAPSF, CAPSAV,
      &      POWS, POWJ, POW
1000  FORMAT(F10.2, 2F10.4, 3F10.2/, F10.2, 2F10.4, 3F10.2/, 2F10.4, F10.2/)
      WRITE(LUW,1010) (OUT(I), I=1, 12)
1010  FORMAT('OUT', 5F10.2/, 3X, F10.6, 6F10.2/)
      WRITE(LUW,1020) AA, BB, CC, VR, MR, VA, MA, TIDB, WI, TIWB
1020  FORMAT('A,B,C', 4F7.3, F7.0, F7.3, F7.0, F7.3, F6.4, F6.2/)
      WRITE(LUW,1025) CAPTI(IHP), CAPSI(IHP)
1025  FORMAT(' CAPI', 2F10.4/)
      ENDIF
1060  FORMAT('      TIME UNIT      TADB      WA      TRDB      WR',
      &      '      TIDB      WI      H' /,
      &      F8.2, I5, 3(F8.0, F8.4), F10.2/)
1070  FORMAT('      TIME UNIT TIDB TIWB TWI      GPM      CFM',
      &      '      POWJ CAPTJ CAPSJ' /,
      &      F8.2, I5, 3F6.0, 2F8.0, 3F8.2/)

```

C

```

      RETURN
      END

```


TRNSYS SIMULATION DECK

```
* YEAR RUN *****
* EXECUTED ON 9/01/88 USING MAIN.EXE;32 AND NEWSLAB73.COM
* CONNECTED SLABS; MANIFOLDS BEFORE AND AFTER SLABS
*
* SIX ZONE MODEL WITH TWO 6 inch SLABS DENS AND COND CHANGED
* TOP & BOTTOM INSULATION (COND=.72 , 1) WITH FLOW
*
* TWO TANKS USED TO MODEL HYDRONIC LOOP STORAGE 20 cuft ea.
* 20 % outside air
* RADIATION VIEW FACTORS NOT USED!!!!
* 5F SETBACK, HEATING, WEEKEND SHUTOFF FOR COOLING
* cooling tower FULL size TAU = 20, 25 HP, 75%EFF
* FURNITURE/AIR THERMAL MASS: RHO*CP=15*AIR
* THERMOSTAT setpts at 71 and 78 (75 core), 1F deadband
*****
* new module TYPE 13 added (originally TYPE 40 microprocessor)
* for core (UNIT 16) and also for perimeter (lumped as single zone for
* control purposes--UNIT 50). These controls, along with the
* software modifications made to modules TYPE 43 and TYPE 47 allow
* for semi-smart control of loop water--i.e., when it is used in the
* slabs, or when it is bypassed. The logic checks the loop water
* temperature to see if it can act as an energy sink/source to the
* zones before turning on heat pumps/boiler to maintain space temperature.
*
* Also, in Summer months (MAY-September) the cooling tower will come on
* to bring loop temperature down to 70F from 4-6A.M.--this water is then
* used by the slabs to precool the space (i.e. purging building).
*
*****
* LOOSE BLDG, 1 ACPH INTERZONAL, Ug=.55,hci=.55
* DHT setpt at 57 ambient air(!) HIGH LIMIT 68
*****
* BOILER 250000 SETPT 59.5 COOL TOWER SETPT 85
*****
* HP FAN ON W/VENTILATION, and whenever cooling or heating is required!
* DHT only operates when ventilation fans operating
* CORE ISOLATED FROM PERIMETER BY REDUCING ADJACENT WALL AREAS
* BY A FACTOR OF 10, AND CEILING BY FACTOR OF 100
* Window shading set to mormal .50; .25 during "sunny" hours
* INTERIOR HEAT GAINS INCREASED SLIGHTLY, AND REDISTRIBUTED
*
* ***** SIMULATION CONTROL AND WEATHER DATA READER *****
*
SIMULATION 0 8760 .125 * hour start hour stop timestep
TOLERANCES .02 .02
LIMITS 40 300
WIDTH 72
```

UNIT 1 TYPE 9 TMY WEATHER DATA READER * converts SI to English
 PARAMETERS 16 * no. hourly Iht:KJ/m2 Tdb:C Tdp:C windsp:m/s device
 7 1 -4 .0889 0 5 .18 32 6 .18 32 7 .2237 0 3 0

UNIT 2 TYPE 16 SOLAR RADIATION PROCESSOR * Erbs correlation: use Iht
 PARAMETERS 7 * mode track dayofyr lat. solarconst. shift soltime
 ***** January *****

3 1 1 47 430 0 -1
 * 3 1 91 47 430 0 -1
 * 3 1 212 47 430 0 -1

INPUTS 12
 1,4 1,19 1,20 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0
 0 0 0 .2 90 0 90 90 90 180 90 -90

UNIT 3 TYPE 33 PSYCHROMETRICS
 PARAMETERS 2 *mode units
 3 2
 INPUTS 2 * Tdb Tdp output: w, Twb, h
 1,5 1,6
 50 40

***** OCCUPANCY, LIGHTING AND EQUIPMENT SCHEDULES *****

UNIT 7 TYPE 14
 PARAMETERS 40 * 200 SQ FT/PERSON
 3
 6 0 0 8 0 8 30 17 30 17 0 24 0
 6 0 0 8 0 8 13 17 13 17 0 24 0
 6 0 0 8 0 8 8 17 8 17 0 24 0
 * 1=CORE-OCC, 3=WEST/EAST, 2=NORTH,SOUTH

UNIT 9 TYPE 14 * (1.7 w/sf lts + 0.5 w/sf eqp)
 PARAMETERS 53
 4
 6 0 1584 8 1584 10 15840 17 15840 20 1584 24 1584
 6 0 360 8 360 10 3600 17 3600 20 360 24 360
 6 0 216 8 216 10 2160 17 2160 20 216 24 216
 6 0 1260 8 1260 10 12600 17 12600 20 1260 24 1260
 * 1=CORE(C) LITE, 2=NORTH,SOUTH LITE, 3=W/E LITE, 4=PLENUM(PL) LITE

UNIT 8 TYPE 41 INTERNAL LOAD PROFILE SEQUENCER
 PARAMETERS 8 * 10% LITES ON WEEKEND
 7 1 1 1 1 1 2 2 *FULL YR
 INPUTS 14
 *C-0 C-LT SN-0 NS-LT E/W-0 E/W-L PLM-LT
 7,1 9,1 7,2 9,2 7,3 9,3 9,4
 0,0 0,0 0,0 0,0 0,0 0,0 0,0
 0 0 0 0 0 0 0

0 1000 0 400 0 240 1400

***** ZONE DESCRIPTIONS *****

UNIT 10 TYPE 19 CORE ZONE

PARAMETERS 10

*mode units vol ac/h k2 k3 furn.cap #surf Tinit winit(40%)
2 2 52800 .1 0 0 14000 5 71 .0075

INPUTS 11 *Tamb wamb Tvin mdot wvin wint Nocc actv Qrad Qint wind
17,1 17,2 41,5 41,7 41,6 0,0 8,1 0,0 8,2 8,2 1,7
50 0 71 0 0 0 0 4 0 0 0

PARAMETERS 5 * CORE ZONE FLOOR

*no. type area refl hc
1 4 6600 0 1.08

INPUTS 1

40,2

0

PARAMETERS 17 * CORE ZONE CEILING (LOW MASS SUSPENDED)

*no. type area refl abs icoef hc Nb Nc Nd
2 3 66 0 0 4 1.63 3 3 1
.23317 .08172 .00004 .41976 -.1049 .00006 -.00493

INPUTS 3 *Tsurf,eq Tplenum UAadd'l
19,11 19,1 0,0
71 71 0

PARAMETERS 20 * NORTH INTERIOR WALL

*no. type area refl abs icoef hci Nb Nc Nd
3 3 88 0 0 4 1.46 4 4 2
.07203 .15211 .01584 0 .90068 -.72764 .06757 -.00002 -.39984 .02094

INPUTS 3 *Tsurf,eq Tnorth UAadd'l
12,13 12,1 0,0
71 71 0

PARAMETERS 20 * SOUTH INTERIOR WALL

*no. type area refl abs icoef hci Nb Nc Nd
4 3 88 0 0 4 1.46 4 4 2
.07203 .15211 .01584 0 .90068 -.72764 .06757 -.00002 -.39984 .02094

INPUTS 3 *Tsurf,eq Tsouth UAadd'l
17,13 17,1 0,0
71 71 0

PARAMETERS 20 * WEST INTERIOR WALL

*no. type area refl abs icoef hci Nb Nc Nd
5 3 48 0 0 4 1.46 4 4 2
.07203 .15211 .01584 0 .90068 -.72764 .06757 -.00002 -.39984 .02094


```

INPUTS 3      *Tsurf,eq  Tsouth  UAadd'l
              14,13      14,1      0,0
              71         71         0

```

```

*PARAMETERS 20      *      EAST INTERIOR WALL
*no. type area refl abs icoef hci Nb Nc Nd
* 6   3   48   0   0   4  1.46  4  4  2
*.07203 .15211 .01584 0   .90068 -.72764 .06757 -.00002  -.39984 .02094
*

```

```

*INPUTS 3      *Tsurf,eq  Tsouth  UAadd'l
*              15,13      15,1      0,0
*              71         71         0

```

```

PARAMETERS 1      *      VIEW FACTORS--NOT USED
0
*2 .822 .0584 .0307 .0584 .0307 .0584 .0307 .0584 .0307 .0392 .0452
* .0392 .0719 .0115 .0392

```

```

PARAMETERS 11 * OPTIONAL OUTPUTS--EQUIVALENT ROOM TEMP. OF ADJ. ZONE
5 1 1 2 2 2 3 2 4 2 5

```

```

***** NORTH ZONE *****

```

```

UNIT 11 TYPE 14 WINDOW SHADING ALL ZONES (TRANSMITTANCE MODIFIER)

```

```

PARAMETERS 45      * time1 tau1 time2 tau2 ...
4 6 0 .50 6 .50 6 .25 18 .25 18 .50 24 .50
6 0 .50 12 .50 12 .25 18 .25 18 .50 24 .50
2 0 .50 24 .50
6 0 .50 6 .50 6 .25 12 .25 12 .50 24 .50

```

```

UNIT 12 TYPE 19 NORTH PERIMETER ZONE

```

```

PARAMETERS 10
*mode units vol ac/h k2 k3 cap #surf Tinit winit
2 2 20800 .1 .0128 .031 5550 5 71 .0075

```

```

INPUTS 11
*Tamb wamb Tvin mdot wwin wint Nocc actv Qrad Qint wind
1,5 3,1 43,5 43,7 43,6 0,0 8,3 0,0 8,4 8,4 1,7
50 0 71 0 0 0 0 4 0 0 0

```

```

PARAMETERS 29      *      EXTERIOR WALL NORTH ZONE
*no. type area refl abs icoef hc Nb Nc Nd
1 1 300 .5 .7 4 1.2 7 7 5
0 .00078 .00387 .00267 .00032 .00001 0
.79537 -1.65181 1.09955 -.24727 .01184 -.00005 0
-1.46336 .63577 -.09710 .00401 .00002

```

```

INPUTS 1      * total incident solar radiation
2,14

```

0

PARAMETERS 5 * NORTH ZONE FLOOR

*no. type area refl hc
2 4 2600 0 1.08

INPUTS 1

42,2

0

PARAMETERS 17 * NORTH ZONE CEILING

*no. type area refl abs icoef hc Nb Nc Nd
3 3 2600 0 0 4 1.63 3 3 1
.23317 .08172 .00004 .41976 -.1049 .00006 -.00493

INPUTS 3 *Tsurf,eq Tplenum UAadd'l

19,12 19,1 0,0
71 71 0

PARAMETERS 20 * INTERIOR WALL SEPARATING CORE FROM NORTH ZONE

*no. type area refl abs icoef hc Nb Nc Nd
4 3 88 .5 .7 4 1 4 4 2
.07203 .15211 .01584 0 .90068 -.72764 .06757 -.00002 -.39984 .02094

INPUTS 3 *Tsurf,eq Tcore UAadd'l

10,13 10,1 0,0
71 71 0

PARAMETERS 8 * NORTH WINDOW

*no. type area mode taud hci NI sl
5 5 900 1 .8 .55 1 2

INPUTS 5 *IT IbT Tau Ug fk1

2,14 2,15 11,3 0,0 0,0
0 0 .86 .55 1

PARAMETERS 1 * VIEW FACTORS--NOT IN PROBLEM!

0

*2 .411 .325 .136 0 .646 .156 .111 .156 .126 .136

PARAMETERS 7 * OPTIONAL OUTPUTS--EQUIVALENT ROOM TEMP. OF ADJ. ZONE

3 1 2 2 3 2 4

***** WEST PERIMETER ZONE *****

UNIT 14 TYPE 19 WEST PERIMETER ZONE

PARAMETERS 10

*mode units vol ac/h k2 k3 cap #surf Tinit winit
2 2 12800 .1 .0128 .031 3400 5 71 .0075

INPUTS 11

*Tamb wamb Tvin mdot wvin wint Nocc actv Qrad Qint wind
1,5 3,1 47,5 47,7 47,6 0,0 8,5 0,0 8,6 8,6 1,7

50 0 71 0 0 0 0 4 0 0 0

PARAMETERS 5 * WEST ZONE FLOOR

*no. type area refl hc
1 4 1600 0 1.08

INPUTS 1

29,2

0

PARAMETERS 17 * WEST ZONE CEILING

*no. type area refl abs icoef hc Nb Nc Nd
2 3 1600 0 0 4 1.63 3 3 1
.23317 .08172 .00004 .41976 -.1049 .00006 -.00493

INPUTS 3 *Tsurf,eq Tplenum UAadd'l

19,14 19,1 0,0
71 71 0

PARAMETERS 29 * EXTERIOR WALL WEST

*no. type area refl abs icoef hc Nb Nc Nd
3 1 200 .5 .7 4 1.2 7 7 5
0 .00078 .00387 .00267 .00032 .00001 0
.79537 -1.65181 1.09955 -.24727 .01184 -.00005 0
-1.46336 .63577 -.09710 .00401 .00002

INPUTS 1

2,11

0

PARAMETERS 20 * INTERIOR WALL SEPARATING CORE FROM WEST ZONE

*no. type area refl abs icoef hc Nb Nc Nd
4 3 48 .5 .7 4 1.63 4 4 2
.07203 .15211 .01584 0 .90068 -.72764 .06757 -.00002 -.39984 .02094

INPUTS 3 *Tsurf,eq Tcore UAadd'l

10,15 10,1 0,0
71 71 0

PARAMETERS 8 * WEST WINDOW

*no. type area mode taud hci NI sl
5 5 600 1 .8 .55 1 1

INPUTS 5 *IT IbT Tau Ug fkl
2,11 2,12 11,2 0,0 0,0
0 0 .86 .55 1

PARAMETERS 1 * VIEW FACTORS--NOT IN PROBLEM!

0

*2 .411 .325 .136 0 .646 .156 .111 .156 .126 .136

PARAMETERS 7 * OPTIONAL OUTPUTS--EQUIVALENT ROOM TEMP. OF ADJ. ZONE

3 1 1 2 2 2 4

***** EAST PERIMETER ZONE *****

UNIT 15 TYPE 19 EAST PERIMETER ZONE

PARAMETERS 10

*mode	units	vol	ac/h	k2	k3	cap	#surf	Tinit	winit
2	2	12800	.1	.0128	.031	3400	4	71	.0075

INPUTS 11

*Tamb	wamb	Tvin	mdot	wvin	wint	Nocc	actv	Qrad	Qint	wind
1,5	3,1	48,5	48,7	48,6	0,0	8,5	0,0	8,6	8,6	1,7
50	0	71	0	0	0	0	4	0	0	0

PARAMETERS 5 * EAST ZONE FLOOR

*no.	type	area	refl	hc
1	4	1600	0	1.08

INPUTS 1

33,2

0

PARAMETERS 17 * EAST ZONE CEILING

*no.	type	area	refl	abs	icoef	hc	Nb	Nc	Nd
2	3	1600	0	0	4	1.63	3	3	1
.23317	.08172	.00004	.41976	-.1049	.00006	-.00493			

INPUTS 3 *Tsurf,eq Tplenum UAadd'l

19,15	19,1	0,0
71	71	0

PARAMETERS 29 * EXTERIOR WALL EAST

*no.	type	area	refl	abs	icoef	hc	Nb	Nc	Nd
3	1	200	.5	.7	4	1.2	7	7	5
0	.00078	.00387	.00267	.00032	.00001	0			
.79537	-1.65181	1.09955	-.24727	.01184	-.00005	0			
-1.46336	.63577	-.09710	.00401	.00002					

INPUTS 1 * total incident solar radiation

2,17

0

*PARAMETERS 20 * INTERIOR WALL SEPARATING CORE FROM EAST ZONE

*no.	type	area	refl	abs	icoef	hc	Nb	Nc	Nd
* 4	3	48	.5	.7	4	1.63	4	4	2
*.07203	.1521	.01584	0	.90068	-.72764	.06757	-.00002	-.39984	.02094

*INPUTS 3 *Tsurf,eq Tcore UAadd'l

* 10,16	10,1	0,0
* 71	71	0

PARAMETERS 8 * EAST WINDOW

```

*no. type area mode taud hci NI s1
  4   5   600   1   .8   .55 1   1
INPUTS 5 *IT IbT   Tau   Ug   fk1
        2,17 2,18 11,4  0,0  0,0
        0     0   .86   .55   1

```

PARAMETERS 1 * VIEW FACTORS--NOT IN PROBLEM!

0

*2 .411 .325 .136 0 .646 .156 .111 .156 .126 .136

PARAMETERS 5 * OPTIONAL OUTPUTS--EQUIVALENT ROOM TEMP. OF ADJ. ZONE

2 1 1 2 2

***** SOUTH PERIMETER ZONE *****

UNIT 17 TYPE 19 SOUTH PERIMETER ZONE

PARAMETERS 10

```

*mode units vol ac/h k2 k3 cap #surf Tinit winit
  2   2   20800 .1 .0128 .031 5550 5 71 .0075

```

INPUTS 11

```

*Tamb wamb Tvin mdot wvin wint Nocc actv Qrad Qint wind
  1,5 3,1 45,5 45,7 45,6 0,0 8,3 0,0 8,4 8,4 1,7
  50   0   71   0   0   0   0   4   0   0   0

```

PARAMETERS 29 * EXTERIOR WALL SOUTH

```

*no. type area refl abs icoef hc Nb Nc Nd
  1   1   300   .5   .7   4   1.2 7 7 5

```

```

0 .00078 .00387 .00267 .00032 .00001 0
.79537 -1.65181 1.09955 -.24727 .01184 -.00005 0
-1.46336 .63577 -.09710 .00401 .00002

```

INPUTS 1 * total incident solar radiation

2,6

0

PARAMETERS 5 * SOUTH ZONE FLOOR

```

*no. type area refl hc
  2   4  2600   0 1.08

```

INPUTS 1

27,2

0

PARAMETERS 17 * SOUTH ZONE CEILING

```

*no. type area refl abs icoef hc Nb Nc Nd
  3   3  2600   0   0   4   1.63 3 3 1

```

```

.23317 .08172 .00004 .41976 -.1049 .00006 -.00493

```

INPUTS 3 *Tsurf,eq Tplenum UAadd'l

```

      19,13      19,1      0,0
      71         71         0

```

PARAMETERS 20 * INTERIOR WALL SEPARATING CORE FROM S ZONE
 *no. type area refl abs icoef hc Nb Nc Nd
 4 3 88 .5 .7 4 1.2 4 4 2
 .07203 .15211 .01584 0 .90068 -.72764 .06757 -.00002 -.39984 .02094

INPUTS 3 *Tsurf,eq Tcore UAadd'l
 10,14 10,1 0,0
 71 71 0

PARAMETERS 8 * SOUTH WINDOW
 *no. type area mode taud hci NI sl
 5 5 900 1 .8 .55 1 2
 INPUTS 5 *IT IbT Tau Ug fk1
 2,6 2,7 11,1 0,0 0,0
 0 0 .86 .55 1

PARAMETERS 1 * VIEW FACTORS--NOT IN PROBLEM!
 0
 *2 .411 .325 .136 0 .646 .156 .111 .156 .126 .136

PARAMETERS 7 * OPTIONAL OUTPUTS--EQUIVALENT ROOM TEMP. OF ADJ. ZONE
 3 1 2 2 3 2 4

***** PLENUM ZONE *****

UNIT 19 TYPE 19 COMMON PLENUM ZONE
 PARAMETERS 10 *1500 s.f. x 3.5 ft.
 *mode units vol ac/h k2 k3 cap #surf Tinit winit
 2 2 52500 0.1 0.0128 .031 26300 15 71 .0075
 INPUTS 11
 *Tamb wamb Tvin mdot win wint Nocc actv Qrad Qint wind
 1,5 3,1 32,1 32,2 3,1 0,0 0,0 0,0 8,7 8,7 1,7
 50 0 71 0 0 0 0 4 0 0 0

PARAMETERS 29 * SOUTH EXTERIOR WALL PLENUM ZONE
 *no. type area refl abs icoef hc Nb Nc Nd
 1 1 600 .5 .7 4 1.2 7 7 5
 0 .00078 .00387 .00267 .00032 .00001 0
 .79537 -1.65181 1.09955 -.24727 .01184 -.00005 0
 -1.46336 .63577 -.09710 .00401 .00002

INPUTS 1 * total incident solar radiation
 2,6
 0

PARAMETERS 29 * PLENUM ZONE WEST EXTERIOR WALL
 *no. type area refl abs icoef hc Nb Nc Nd
 2 1 400 .5 .7 4 1.2 7 7 5
 0 .00078 .00387 .00267 .00032 .00001 0

.79537 -1.65181 1.09955 -.24727 .01184 -.00005 0
 -1.46336 .63577 -.09710 .00401 .00002

INPUTS 1 * total incident solar radiation
 2,11
 0

PARAMETERS 29 * PLENUM ZONE NORTH EXTERIOR WALL
 *no. type area refl abs icoef hc Nb Nc Nd
 3 1 600 .5 .7 4 1.2 7 7 5
 0 .00078 .00387 .00267 .00032 .00001 0
 .79537 -1.65181 1.09955 -.24727 .01184 -.00005 0
 -1.46336 .63577 -.09710 .00401 .00002

INPUTS 1 * total incident solar radiation
 2,14
 0

PARAMETERS 29 * PLENUM ZONE EAST EXTERIOR WALL
 *no. type area refl abs icoef hc Nb Nc Nd
 4 1 400 .5 .7 4 1.2 7 7 5
 0 .00078 .00387 .00267 .00032 .00001 0
 .79537 -1.65181 1.09955 -.24727 .01184 -.00005 0
 -1.46336 .63577 -.09710 .00401 .00002

INPUTS 1 * total incident solar radiation
 2,17
 0

PARAMETERS 17 * ZONE CEILING: ADJ. TO CORE
 *no. type area refl abs icoef hc Nb Nc Nd
 5 3 66 0 0 4 1.63 3 3 1
 .23317 .08172 .00004 .41976 -.1049 .00006 -.00493

INPUTS 3 *Tsurf,eq Tcore UAadd'l
 10,12 10,1 0,0
 71 71 0

PARAMETERS 17 * ZONE CEILING: ADJ. TO NORTH PERIMETER ZONE
 *no. type area refl abs icoef hc Nb Nc Nd
 6 3 2600 0 0 4 1.63 3 3 1
 .23317 .08172 .00004 .41976 -.1049 .00006 -.00493

INPUTS 3 *Tsurf,eq Tsouth UAadd'l
 12,12 12,1 0,0
 71 71 0

PARAMETERS 17 * ZONE CEILING: ADJ. TO SOUTH PERIMETER ZONE
 *no. type area refl abs icoef hc Nb Nc Nd
 7 3 2600 0 0 4 1.63 3 3 1

.23317 .08172 .00004 .41976 -.1049 .00006 -.00493

INPUTS 3 *Tsurf,eq Tsouth UAadd'l
17,12 17,1 0,0
71 71 0

PARAMETERS 17 * ZONE CEILING: ADJ. TO WEST PERIMETER ZONE

*no.	type	area	refl	abs	icoef	hc	Nb	Nc	Nd
8	3	1600	0	0	4	1.63	3	3	1
.23317	.08172	.00004	.41976	-.1049	.00006	-.00493			

INPUTS 3 *Tsurf,eq Tsouth UAadd'l
14,12 14,1 0,0
71 71 0

PARAMETERS 17 * ZONE CEILING: ADJ. TO EAST PERIMETER ZONE

*no.	type	area	refl	abs	icoef	hc	Nb	Nc	Nd
9	3	1600	0	0	4	1.63	3	3	1
.23317	.08172	.00004	.41976	-.1049	.00006	-.00493			

INPUTS 3 *Tsurf,eq Tsouth UAadd'l
15,12 15,1 0,0
71 71 0

PARAMETERS 5 * CORE ZONE FLOOR

*no.	type	area	refl	hc
10	4	6600	0	1.08

INPUTS 1
40,3
0

PARAMETERS 5 * NORTH PERIMETER ZONE FLOOR

*no.	type	area	refl	hc
11	4	2600	0	1.08

INPUTS 1
42,3
0

PARAMETERS 5 * SOUTH PERIMETER ZONE FLOOR

*no.	type	area	refl	hc
12	4	2600	0	1.08

INPUTS 1
27,3
0

PARAMETERS 5 * WEST PERIMETER ZONE FLOOR

*no.	type	area	refl	hc
13	4	1600	0	1.08

INPUTS 1
29,3

0

PARAMETERS 5 * EAST PERIMETER ZONE FLOOR

*no. type area refl hc
14 4 1600 0 1.08

INPUTS 1

33,3

0

PARAMETERS 29 * ROOF ABOVE PLENUM ZONE (EXT WALL CONSTRUCTION)

*no. type area refl abs icoef hc Nb Nc Nd * 1/6 of building total

15 1 2500 .5 .7 4 1.2 7 7 5

0 .00078 .00387 .00267 .00032 .00001 0

.79537 -1.65181 1.09955 -.24727 .01184 -.00005 0

-1.46336 .63577 -.09710 .00401 .00002

INPUTS 1 * total horizontal solar radiation

2,4

0

PARAMETERS 1 * VIEW FACTORS PUT BACK IN?

0

PARAMETERS 21 * OPTIONAL OUTPUTS--EQUIVALENT ROOM TEMP. OF ADJ. ZONE

10 2 5 2 6 2 7 2 8 2 9 1 10 1 11 1 12 1 13 1 14

***** ZONE SYSTEM CONTROLS *****

UNIT 20 TYPE 14 TIME CLOCKS

PARAMETERS 27 * heat setback, VENT fans

2

6 0 1 6 1 6 0 18 0 18 1 24 1

6 0 0 7 0 7 1 18 1 18 0 24 0

UNIT 23 TYPE 41 WEEKEND SETBACK SEQUENCER

PARAMETERS 8

8 1 1 1 1 1 2 2 * FULL YR

INPUTS 16 * HP SETBACK, VENT FANS, 2 X HP COOLING

20,1 20,2 25,3 26,3 5,3 21,3 49,3 0,0

0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0

0 0 0 0 0 0 0 1

1 0 0 0 0 0 0 0

UNIT 25 TYPE 8 CORE ZONE THERMOSTAT

PARAMETERS 8 * nstk istg Tmin Tcool Theat1 Theat2 dTset dTdband

15 0 199 75 73.5 71 5 1

INPUTS 3 * Tzone Tsource sbcontrol

10,1 0,0 23,1

71 99 0

UNIT 5 TYPE 8 SOUTH PERIMETER ZONE THERMOSTAT
PARAMETERS 8 * nstk istg Tmin Tcool Theat1 Theat2 dTset dTdband
15 0 199 78 73.5 71 5 1
INPUTS 3 * Tzone Tsource sbcontrol
17,1 0,0 23,1
71 99 0

UNIT 21 TYPE 8 WEST PERIMETER ZONE THERMOSTAT
PARAMETERS 8 * nstk istg Tmin Tcool Theat1 Theat2 dTset dTdband
15 0 199 78 73.5 71 5 1
INPUTS 3 * Tzone Tsource sbcontrol
14,1 0,0 23,1
71 99 0

UNIT 49 TYPE 8 EAST PERIMETER ZONE THERMOSTAT
PARAMETERS 8 * nstk istg Tmin Tcool Theat1 Theat2 dTset dTdband
15 0 199 78 73.5 71 5 1
INPUTS 3 * Tzone Tsource sbcontrol
15,1 0,0 23,1
71 99 0

UNIT 26 TYPE 8 NORTH PERIMETER ZONE THERMOSTAT
PARAMETERS 8 * nstk istg Tmin Tcool Theat1 Theat2 dTset dTdband
15 0 199 78 73.5 71 5 1
INPUTS 3 * Tzone Tsource sbcontrol
12,1 0,0 23,1
71 99 0

***** VENTILATION SYSTEM & CONTROL *****

UNIT 30 TYPE 3 SUPPLY/EXHAUST FAN
PARAMETERS 2 * maxflow maxKW
7350 .932
INPUTS 3 * Tin lb/hr contrl
1,5 0,0 23,2
50 10000 1

UNIT 31 TYPE 17 OUTSIDE AIR PREHEATER (WASTE HEAT RECOVERY)
PARAMETERS 15 * glycol runaround loop overall eff = .64 const.
*#hx mdot Cp stick tol mode Eff1 Cpc ctrl dTmin mode Eff2 Cp2 ctrl dTmin2
2 44000 .94 5 1 4 .8 .24 1 1 4 .8 .24 1 1
INPUTS 4 *Tin1 Min1 Tin2 Min2 (ALL RECOVERED HEAT FROM CORE EXHAUST)

30,1 30,2 10,1 30,2
50 0 71 0

- * Change duct heater so it only works when ventilation fan is on;
- * also change the air it senses to be the air leaving the preheater.

UNIT 22 TYPE 8 DUCT HEATER THERMOSTAT
PARAMETERS 6 * nstk istg Tmin Tcool Theat1 Theat2
15 0 199 72 71 57
INPUTS 2 * Tair Tsource ctrl
1,5 0,0 23,2
50 99 1

UNIT 32 TYPE 6 DUCT (OUTSIDE AIR) HEATER (123 KW/6)
PARAMETERS 3 *BTU/H Tmax Cp
70000 68 .24
INPUTS 3 *Tin mdot on/off
31,1 31,2 22,2
71 0 0

***** HEAT PUMPS & THERMAL STORAGE SLABS *****

UNIT 41 TYPE 50 HEAT PUMP CORE ZONE * sizing basis: 370 sf/ton,3 gpm/ton
PARAMETERS 9 *hcap hpwr ccaptot csens cpwr Tauh fKWn cfmn Mwatn
265.4 19.7 -226.8 -170.8 19 2 2.05 8250 28724
INPUTS 11
*heat cool fanON Mwat Twat Tdbra wra Tplen wplen cfm OAfrac
25,2 23,3 23,2 0,0 37,1 10,1 10,2 19,1 19,2 0,0 0,0
* 0,0 0,0 0,0 0,0 37,1 10,1 10,2 19,1 19,2 0,0 0,0
0 0 0 28724 71 71 0 71 0 8250 .2
*out: tcap avcap scap avscap Tsupp wsupp Msupp CompKW Qloop Tloop fanKW index

UNIT 43 TYPE 50 HEAT PUMP NORTH PERIM ZONE * sizing basis: 370 sf/ton,3 gpm/ton
PARAMETERS 9 *hcap hpwr ccaptot csens cpwr Tauh fKWn cfmn Mwatn
101.5 7.6 -84.6 -63.7 7.3 2 .715 3285 10914
INPUTS 11
*heat cool fanON Mwat Twat Tdbra wra Tplen wplen cfm OAfrac
26,2 23,4 23,2 0,0 37,1 12,1 12,2 19,1 19,2 0,0 0,0
* 0,0 0,0 0,0 0,0 37,1 12,1 12,2 19,1 19,2 0,0 0,0
0 0 0 10914 71 71 0 71 0 3285 .2

*out: tcap avcap scap avscap Tsupp wsupp Msupp CompKW Qloop Tloop fanKW index

UNIT 45 TYPE 50 HEAT PUMP SOUTH PERIM ZONE * sizing basis: 370 sf/ton,3
gpm/ton

PARAMETERS 9 *hcap hpwr ccaptot csens cpwr Tauh fKWn cfmn Mwatn
101.5 7.6 -84.6 -63.7 7.3 2 .715 3285 10914

INPUTS 11

*heat cool fanON Mwat Twat Tdbra wra Tplen wplen cfm OAfrac
5,2 23,5 23,2 0,0 37,1 17,1 17,2 19,1 19,2 0,0 0,0
* 0,0 0,0 0,0 0,0 37,1 12,1 12,2 19,1 19,2 0,0 0,0
0 0 0 10914 71 71 0 71 0 3285 .2

*out: tcap avcap scap avscap Tsupp wsupp Msupp CompKW Qloop Tloop fanKW index

UNIT 47 TYPE 50 HEAT PUMP WEST PERIM ZONE * sizing basis: 370 sf/ton,3
gpm/ton

PARAMETERS 9 *hcap hpwr ccaptot csens cpwr Tauh fKWn cfmn Mwatn
62.48 4.69 -52.1 -39.2 4.5 2 .44 2021.7 6716.2

INPUTS 11

*heat cool fanON Mwat Twat Tdbra wra Tplen wplen cfm OAfrac
21,2 23,6 23,2 0,0 37,1 14,1 14,2 19,1 19,2 0,0 0,0
* 0,0 0,0 0,0 0,0 37,1 12,1 12,2 19,1 19,2 0,0 0,0
0 0 0 6716.2 71 71 0 71 0 2021.7 .2

*out: tcap avcap scap avscap Tsupp wsupp Msupp CompKW Qloop Tloop fanKW index

UNIT 48 TYPE 50 HEAT PUMP EAST PERIM ZONE * sizing basis: 370 sf/ton,3
gpm/ton

PARAMETERS 9 *hcap hpwr ccaptot csens cpwr Tauh fKWn cfmn Mwatn
62.48 4.69 -52.1 -39.2 4.5 2 .44 2021.7 6716.2

INPUTS 11

*heat cool fanON Mwat Twat Tdbra wra Tplen wplen cfm OAfrac
49,2 23,7 23,2 0,0 37,1 15,1 15,2 19,1 19,2 0,0 0,0
* 0,0 0,0 0,0 0,0 37,1 12,1 12,2 19,1 19,2 0,0 0,0
0 0 0 6716.2 71 71 0 71 0 2021.7 .2

*out: tcap avcap scap avscap Tsupp wsupp Msupp CompKW Qloop Tloop fanKW index

UNIT 28 TYPE 15 NOT-SO-SIMPLE MANIFOLD

PARAMETERS 32

0 -11 3 -12 3 -12 3 -13 3 -3

-11 -14 1 -11 -15 1 3 -12 -16 1 3 -12 -17 1 3 -13 -18 1 3 -7 2 -4
 INPUTS 8
 0,0 0,0 0,0 43,10 45,10 47,10 48,10 41,10 *DISCONNECTED SLAB N S W E CORE
 10914 6716.2 28724 0 0 0 0 0 0 *out: total flow, mixed temp

UNIT 18 TYPE 15 SLAB ALGEBRAIC OPERATOR
 PARAMETERS 43
 0 -17 -17 3 -18 3 -18 3
 -11 -17 1 -12 -17 1 3 -13 -18 1 3 -14 -18 1 3
 -7 2 -4
 -1 77 -15 -1 3 1 4 -4
 -1 72 -16 -1 4 1 4 -4 -4
 INPUTS 8
 *PERIMETER ZONE TEMPS: N S E W , CLG TOWER INDEX, HEATING STBACK INDEX
 12,1 17,1 15,1 14,1 24,3 23,1 0,0 0,0
 71 71 71 71 0 0 20800 12800

UNIT 16 TYPE 13 CORE SLAB FLOW PROCESSOR
 PARAMETERS 67
 4 0 -.9 0 -.9 2 .1 2 .1
 9 1 0 0 0 1 0 1 0 1 0 0 1 0 0 0 1
 0 0 0 0 0 1 0 0 0 1 1 0 0 1 0 1
 1 0 0 1 0 0 0 0 1 0
 4 0 0 0 0 0 0 0 0 0 0 2
 INPUTS 8
 * core temp compared to cooling setpoint, heating setpoint, and loop wtr temp
 10,1 0,0 18,3 10,1 28,2 10,1 10,1 28,2
 71 74 71 71 71 71 71

UNIT 50 TYPE 13 PERIMETER SLAB FLOW PROCESSOR
 PARAMETERS 67
 4 0 -.9 0 -.9 2 .1 2 .1
 9 1 0 0 0 1 0 1 0 1 0 0 1 0 0 0 1
 0 0 0 0 0 1 0 0 0 1 1 0 0 1 0 1
 1 0 0 1 0 0 0 0 1 0
 4 0 0 0 0 0 0 0 0 0 0 2
 INPUTS 8
 * core temp compared to cooling setpoint, heating setpoint, and loop wtr temp
 18,1 18,2 18,3 18,1 28,2 18,1 18,1 28,2
 71 77 73 71 71 71 71
 * REDUCE RHO TO DECREASE IMPACT OF MASS--MAKING LIKE STANOARD FLOOR

UNIT 40 TYPE 47 CORE ZONE THERMAL ENERGY STORAGE SLAB

PARAMETERS 26

```
*no eqpft nparl nterat maxit ertol tinit cond rho cp thk contop conbot
* 1 508 13 9 5 1 71 1.0 50 .21 6 .72 1.00
1 507.7 13 9 5 1 71 1.0 50 .21 6 .72 1.00
*cndpipe rhop cpp radout radin space fconv nconv delx ncen delts frac radd
.125 75 .48 .57 .50 12 400.000 10 1 0 50 .75 0
```

***** NOTE fconv CHANGE *****XXXXXXXX*****

INPUTS 5 * Ttop Tbot Tfin flow iconv

10,11 19,16 28,2 0,0 16,1

71 71 50 28724 1

*out: Qtrans Qtop Qbot Tfout Tbulk Irun Tavg

TRACE 4396 4416

UNIT 42 TYPE 47 NORTH PERIMETER ZONE THERMAL ENERGY STORAGE SLAB

PARAMETERS 26

```
*no eqpft nparl nterat maxit ertol tinit cond rho cp thk contop conbot
* 2 520 5 9 5 1 71 1.0 50 .21 6 .72 1.00
2 520 5 9 5 1 71 1.0 50 .21 6 .72 1.00
*cndpipe rhop cpp radout radin space fconv nconv delx ncen delts frac radd
.125 75 .48 .57 .50 12 400.000 10 1 0 50 .75 0
```

***** NOTE fconv CHANGE *****XXXXXXXX*****

INPUTS 5 * Ttop Tbot Tfin flow iconv

12,11 19,17 28,2 0,0 50,1

71 71 50 10914 1

*out: Qtrans Qtop Qbot Tfout Tbulk Irun Tavg

TRACE 4396 4416

UNIT 27 TYPE 47 SOUTH PERIMETER ZONE THERMAL ENERGY STORAGE SLAB

PARAMETERS 26

```
*no eqpft nparl nterat maxit ertol tinit cond rho cp thk contop conbot
* 2 520 5 9 5 1 71 1.0 50 .21 6 .72 1.00
3 520 5 9 5 1 71 1.0 50 .21 6 .72 1.00
*cndpipe rhop cpp radout radin space fconv nconv delx ncen delts frac radd
.125 75 .48 .57 .50 12 400.000 10 1 0 50 .75 0
```

***** NOTE fconv CHANGE *****XXXXXXXX*****

INPUTS 5 * Ttop Tbot Tfin flow iconv

17,11 19,18 28,2 0,0 50,1

71 71 50 10914 1

*out: Qtrans Qtop Qbot Tfout Tbulk Irun Tavg

UNIT 29 TYPE 47 WEST PERIMETER ZONE THERMAL ENERGY STORAGE SLAB

PARAMETERS 26

```
*no eqpft nparl nterat maxit ertol tinit cond rho cp thk contop conbot
* 2 533.3 3 9 5 1 71 1.0 50 .21 6 .72 1.00
```



```

4 533.3 3 9 5 1 71 1.0 50 .21 6 .72 1.00
*cnpipe rhop cpp radout radin space fconv nconv delx ncen delts frac radd
.125 75 .48 .57 .50 12 400.000 10 1 0 50 .75 0
***** NOTE fconv CHANGE *****XXXXXXXXXXXXXXXXXXXX*****
INPUTS 5 * Ttop Tbot Tfin flow iconv
14,11 19,19 28,2 0,0 50,1
71 71 50 6716 1
*out: Qtrans Qtop Qbot Tfout Tbulk lrun Tfavg

```

```

UNIT 33 TYPE 47 EAST PERIMETER ZONE THERMAL ENERGY STORAGE SLAB
PARAMETERS 26
*no eqpft nparl nterat maxit ertol tinit cond rho cp thk contop conbot
* 2 533 3 9 5 1 71 1.0 50 .21 6 .72 1.00
4 533.3 3 9 5 1 71 1.0 50 .21 6 .72 1.00
*cnpipe rhop cpp radout radin space fconv nconv delx ncen delts frac radd
.125 75 .48 .57 .50 12 400.000 10 1 0 50 .75 0
***** NOTE fconv CHANGE *****XXXXXXXXXXXXXXXXXXXX*****
INPUTS 5 * Ttop Tbot Tfin flow iconv
15,11 19,20 28,2 0,0 50,1
71 71 50 6716 1
*out: Qtrans Qtop Qbot Tfout Tbulk lrun Tfavg

```

```

UNIT 44 TYPE 15 NOT-SO-SIMPLE MANIFOLD
PARAMETERS 32
0 -11 3 -12 3 -12 3 -13 3 -3
-11 -14 1 -11 -15 1 3 -12 -16 1 3 -12 -17 1 3 -13 -18 1 3 -7 2 -4
INPUTS 8
0,0 0,0 0,0 42,4 27,4 29,4 33,4 40,4 *CONNECTED SLAB N S W E CORE
10914 6716.2 28724 0 0 0 0 0 0 *out: total flow, mixed temp

***** AUXILIARY WATER SYSTEM & CONTROLS *****

```

```

UNIT 34 TYPE 4 STRATIFIED THERMAL STORAGE TANK 1(400 gal. water/floor)
PARAMETERS 6 *mode cuft Cp dens Ut height
2 20 1 62.4 1 1
INPUTS 5 *Thot Mhot Tret Mret Tenv
44,2 44,1 34,1 44,1 1,5
71 0 71 0 71 *out: Tsource Msource Tload Mload
DERIVATIVES 1 *Tinit
71

```

UNIT 24 TYPE 43 WATER LOOP HEATER AND COOLING TOWER
 * PROPORTIONAL CONTROL THERMOSTAT
 PARAMETERS 6 * Th Tc Tdelh Tdelc Tsetbk Tcw
 * 71 71 11 14 0
 59.5 75 1 5 0 85
 INPUTS 3 * Tloop Tsource Iweek
 34,1 0,0 23,8
 71 0 0 *out:heat(on-off) cool(on-off)

UNIT 35 TYPE 40 WATER LOOP HEATER (2*128 KW/6)
 PARAMETERS 3 *BTU/H Tmax Cp
 * 65000 65 1
 * 250000 90 1
 250000 65 1
 * 480000 90 1
 INPUTS 3 *Tin mdot status
 34,3 34,4 24,1
 71 0 0

UNIT 36 TYPE 42 COOLING TOWER (BAC Model VXT 150)/6
 PARAMETERS 6 *fanmax powmax ncell a b tau
 * 2800 1.24 1 1.0899 -.44565 20
 5575 4.14 1 1.0899 -.44565 20
 INPUTS 6 *status Tdb Twb Twat mdot frac
 24,2 1,5 3,2 35,1 35,2 0,0
 0 50 50 71 0 1

UNIT 37 TYPE 4 STORAGE TANK 2
 PARAMETERS 6 *mode cuft Cp dens Ut height
 2 20 1 62.4 1 1
 INPUTS 5 *Thot Mhot Tret Mret Tenv
 36,1 34,4 37,1 34,4 1,5
 71 0 71 0 71 *out:Tsource Msource Tload Mload
 DERIVATIVES 1 *Tinit
 71

***** OUTPUT *****

UNIT 4 TYPE 46 CAPACITY & ENERGY SUMMER
 PARAMETERS 1 * FLOOR
 6
 INPUTS 36 * 5X IH, 5X IC, 5X IFO, 5X Q, 5X COMP, 5X FAN, B, DHT, CT FAN
 * CORE-NORTH-EAST-WEST-SW-SE

25,2	26,2	49,2	21,2	5,2	23,3	23,4	23,7	23,6	23,5		
23,2	23,2	23,2	23,2	23,2	41,2	43,2	48,2	47,2	45,2		
41,8	43,8	48,8	47,8	45,8	41,11	43,11	48,11	47,11	45,11		
35,3	32,3	36,3	30,3	16,1	50,1						
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0

UNIT 6 TYPE 24 QUANTITY INTEGRATOR

PARAMETERS 1

-1 * resets each month -- leave alone for all runs

INPUTS 10

4,2	4,3	4,4	4,5	4,6	4,7	4,8	4,9	4,10	4,11
0	0	0	0	0	0	0	0	0	0

*CL CAP, HT_HP, CL_HP, FN_HP, TOT_HP, BOIL, DHT, TOWER, FAN, PUMP

*UNIT 13 TYPE 24 QUANTITY INTEGRATOR

*PARAMETERS 1

*1 * integrates each hour -- leave alone for all runs

*INPUTS 11

*4,1	4,2	4,3	4,4	4,5	4,6	4,7	4,8	4,9	4,10	4,11
*0	0	0	0	0	0	0	0	0	0	0

**HT CAP, CL CAP, HT_HP, CL_HP, FN_HP, TOT_HP, BOIL, DHT, TOWER, FAN, PUMP

***** PRINTERS *****

UNIT 13 TYPE 25 P1 INTEGRATED ENERGY QUANTITY PRINTER

PARAMETERS 4 * interval start stop lu

*-1 0 8760 50 * FULL YEAR or month

*120 0 720 50 * JANUARY

24 0 8760 13 * daily totals

INPUTS 9

6,6	6,7	6,8	6,2	6,3	6,4	6,5	6,9	6,10
0	0	0	0	0	0	0	0	0

*BOIL, DHT, TOWER, HP HEAT, HP COOL, HP VENT, TOT_HP, FAN, PUMP

UNIT 39 TYPE 25 P2 WATER LOOP TEMP

PARAMETERS 4

1 0 8670 39

INPUTS 7

37,1	40,4	42,4	27,4	29,4	33,4	44,2	34,1
HP IN	OUT_C	OUT_N	OUT_S	OUT_W	OUT_E	OUT_MAN	TANK1

```

UNIT 38  TYPE 25    P3 ZONE TEMPS
PARAMETERS 4
1  0  8670  38
INPUTS 6
*12,16   19,16   12,1   42,2   42,3   43,2
*  0      0      0      0      0      0
*TTOP    TBOM    TZONE    QTOP    QBOM    QHP
*
12,1     10,1     19,1     14,1     15,1     17,1
TZONE_N  TZONE_C  TZONE_PL TZONE_W  TZONE_E  TZONE_S

```

```

*UNIT 46  TYPE 25    P4 SLAB TEMPS
*PARAMETERS 4
*1  0  8670  46
*INPUTS 5
**12,16   19,16   12,1   42,2   42,3   43,2
**  0      0      0      0      0      0
**TTOP    TBOM    TZONE    QTOP    QBOM    QHP
**
*40,5     42,5     27,5     29,5     33,5
*SLAB_C   SLAB_N   SLAB_S   SLAB_W   SLAB_E

```

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END

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