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

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Commercial buildings often have extensive periods where one space needs cooling and another heating. Even more common is the need for heating during one part of the day and cooling during another in the same spaces. If a building's heating and cooling system could be integrated with the building's structural mass such that the mass can be used to collect, store, and deliver energy, significant energy might be saved.

Computer models were developed to simulate this interaction for an existing office building in Seattle, Washington that has a decentralized water-source heat pump system. Metered data available for the building was used to calibrate a "base" building model (i.e., nonintegrated) prior to simulation of the integrated system.

In the simulated integration strategy a secondary water loop was manifolded to the main HVAC hydronic loop. Tubing in this loop was embedded in the building's concrete floor slabs. Water was routed to this loop by a controller to charge or discharge thermal energy to and from the slabs. The slabs were also in thermal communication with the conditioned spaces.

Parametric studies of the building model, using weather data for five other cities in addition to Seattle, predicted that energy can be saved on cooling dominated days. On hot, dry days and during the night the cooling tower can beneficially be used as a "free cooling" source for thermally "charging" the floor slabs using cooled water. Through the development of an adaptive/predictive control strategy, annual HVAC energy savings as large as 30% appear to be possible in certain climates.

INTRODUCTION

Energy storage in building structures occurs passively in all buildings to some extent and has been shown to have nontrivial energy impacts. For example, the mass of a building's exterior envelope can produce a time lag and amplitude reduction in the flow of heat through the building's envelope. When coupled with the ability of the building's interior mass to store and then release energy to the interior air, the building's mass influences its energy use. In an appropriate climate (moderate weather with diurnal swings in net flux of energy through the building envelope), a correctly designed building can achieve beneficial passive thermal storage. Unfortunately, in many climates the passive storage effect of a building's thermal mass can have a negative impact on other energy conservation techniques that may be employed. When HVAC equipment is shut off or set back during unoccupied periods, the thermal capacitance effect of the building mass can result in long temperature recovery time periods.

Active thermal storage in building structures, on the other hand, is a relatively new concept. A case study of a Swedish commercial building (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. More recently, research has also looked at "precooling" buildings at night and on weekends with supply air to reduce daytime cooling loads (Ruud et al. 1990); (Braun 1990). 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 and rapid purging of stored heat. In addition, the practical considerations associated with using the floor slab as the storage medium in this manner--i.e., material compatibilities, component connections, and configuration of the piping in the water loop--have already been addressed in past research, as embedding water pipes within concrete is a proven concept.

APPROACH

The interactions of a water loop heat pump system integrated via a water distribution subsystem to the building structural mass were studied, and the effect on whole-building energy performance analyzed. This integration strategy is referred to as the Building Structural Thermal Storage (BSTS) system (Marseille et al. 1989).

A computer model was first developed to simulate an existing base building located in Seattle, Washington. Metered data available for the building were used to calibrate the model to help ensure that the analysis would provide information closely related to the operation of a real building. The building model with the BSTS system added to it (see Figure 1) was then simulated and the results compared to the results of the base case building. Simulations were also performed, for both the base building model and the building model with the BSTS system, using weather data for five other locations in the United States. In the following sections, the simulation methodology, base building model, BSTS building model, energy usage characteristics, and BSTS system optimization considerations are discussed.

SIMULATION METHODOLOGY

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. A building load model is available in TRNSYS that uses *temperature level control*, a dynamic modeling approach, as opposed to *energy rate control* used in programs such as DOE-2. In temperature level control, room conditions are determined by not only the ambient conditions, but also by heating and cooling equipment inputs. The interactive feedback of the building subsystems on building load is thus captured. Because the objective of this project was to study the dynamic interaction of the building subsystems, the temperature level control modeling approach was required. Also, because TRNSYS was designed with a modular structure, it can be readily modified and new building subsystem component models incorporated (Solar Energy Laboratory 1983).

Five new component models not included in the standard TRNSYS library were developed specifically for this study: a cooling tower, heat pump, water boiler, water loop thermostat (used to control cooling tower and boiler operations), and the floor slab used in the BSTS system. The boiler and thermostat are extended versions of existing TRNSYS modules. The heat pump model was entirely new and used a simple extension of an empirical fit to the manufacturer's rating data to determine exit air and water conditions and power consumption. The cooling tower model was developed to compute exit water temperatures by using a simple approach developed by Whillier (1976). Because no data on the actual tower in the building was available, the fill characteristic "factor of merit" used in the model is a value cited as typical by Whillier, based on available data for several commercial cooling towers.

A numerical slab heat transfer model was developed to simulate the building floor slabs and the integrated water piping system within the slabs. The model solves the two-dimensional unsteady conduction equation in a cartesian coordinate space by approximating the temperature field using a central differencing scheme. 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.

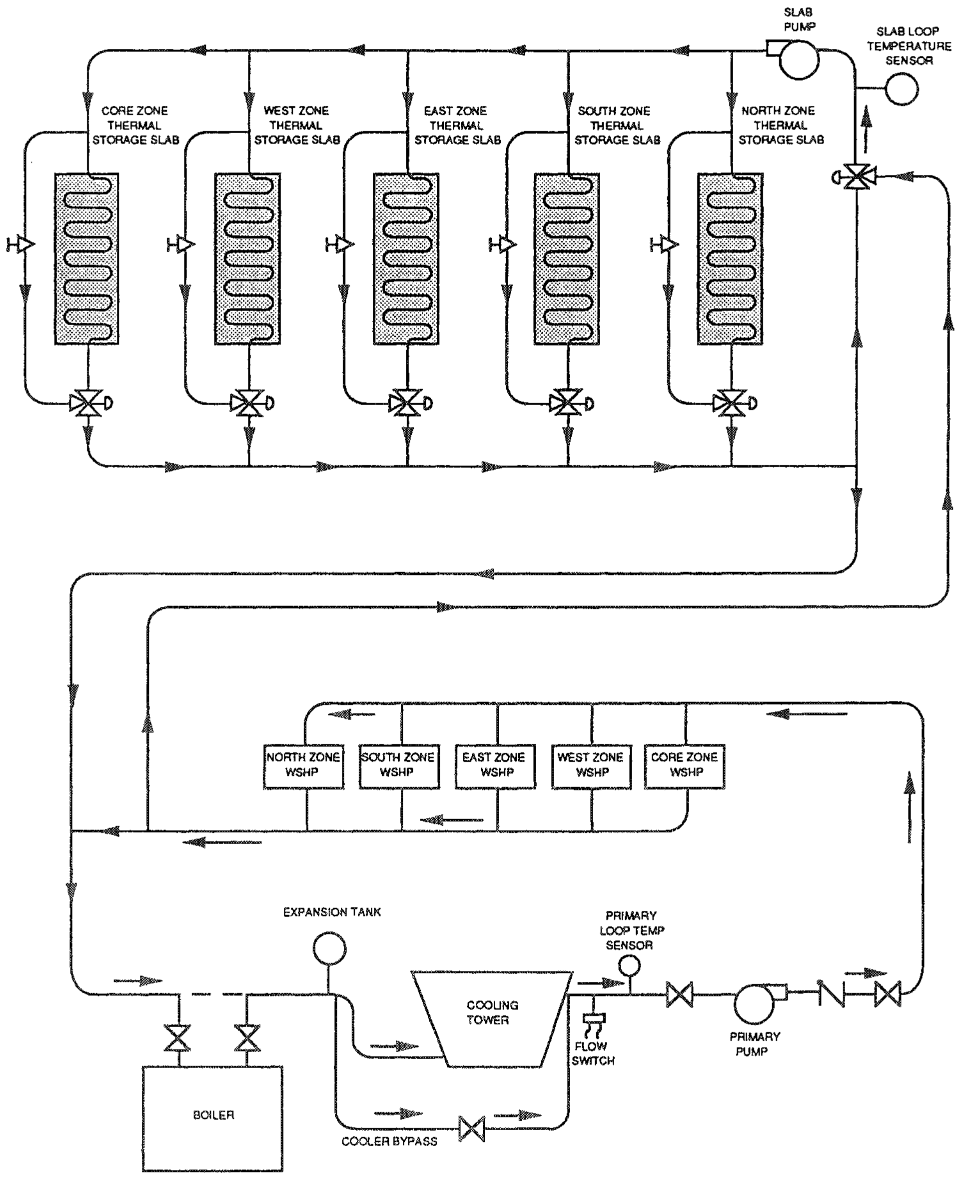

Figure 1. Integrated BSTS and Heat Pump Subsystems

The temperature gradient along the direction of the water flow is not modeled in the numerical solution. Instead, an iterative procedure is used to determine an average temperature (average of slab inlet and outlet temperature) of the water. Because the embedded pipes are typically laid in multiple parallel circuits at high flow rates, assuming the piping to be all at this temperature is reasonable. Also, the resulting symmetries of the piping system meant only the smallest common element (half of the pipe and its associated slab) needed to be analyzed in the numerical model.

At each call during a simulation time step, the slab model uses as its inputs the outputs from other TRNSYS subsystem components, including slab surface temperatures (i.e., top and bottom) and inlet water flow rate and bulk temperature. The amount of heat transferred from the fluid to the slab and that transferred from the slab surfaces is calculated. These then constitute the outputs from the slab component model.

BASE BUILDING MODEL

The base building model is based on an existing six-story office building 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. The structure was constructed in 1976 on a concrete slab with pre-cast concrete walls. Total floor area is approximately 89,550 ft^2. Forty-seven percent of the gross wall area is glass.

The HVAC subsystems used in the reference building consist of decentralized water-source heat pumps in a closed water loop. 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 air economizer mode in this system. Lighting is predominantly fluorescent with some incandescent task lighting.

Because of limits on computer speed and memory, it was necessary to simplify the base building computer 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. 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.

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. 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.

The metered data for the actual base case building consist of electricity consumption measurements for the boilers, cooling tower, heat pumps, supply and exhaust fans, lights, outlets, hot water, and elevators. 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 a total of 1,413,900 kWh in 1985. 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 calibration possibilities.

Monthly overall HVAC energy consumption results for the simulated base building model are compared with the metered data in Figure 2. These comparisons are the most reasonable that could be obtained, given the limitations of the data and the computer model. Monthly simulated energy consumption is within 10% of metered performance except for February, March, April, and November. These larger discrepancies, unresolved by the calibration, were found to be attributable to the difference between the Typical Meteorological Year (TMY) weather data used in the simulation and the actual weather at the building site during 1985. Comparisons were also made for individual HVAC system component consumptions, and the operational trends for each component compared well with the metered data. Major discrepancies again appear to be linked to weather differences. 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.

BUILDING STRUCTURAL THERMAL STORAGE (BSTS) MODEL

In the development of the BSTS system model, the existing HVAC subsystems and controls were left

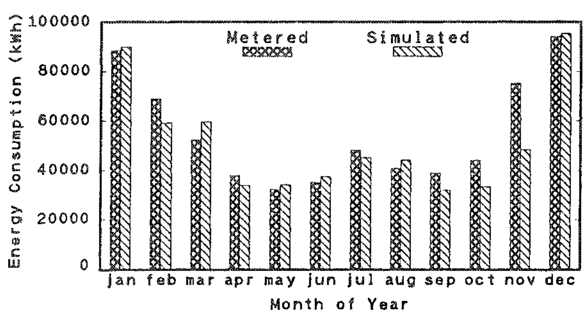

Figure 2. Comparison of Metered Simulated Monthly Total HVAC Energy Consumption

essentially intact. The thermostats were identical to the base case for each of the controlled zones, as was zone night and weekend setback. 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 building model (Figure 1).

Included in the model are five separate slabs, one for each of the four perimeter zones, and one for the core. The total water flow available to each slab equalled the flow rate of the heat pump associated with that slab's zone. Because heat pumps in all zones were nominally sized at 370 ft^2/ton, 3 gpm/ton, this meant water flow to the slab was uniform over the entire floor area. Inlet water temperature to the slabs was based on the overall mixed temperature of water leaving the five zone heat pumps.

Six-inch-thick concrete floor slabs were modeled, having a density of 145 lbm/ft^3, a thermal conductivity of 1.0 Btu/h•ft•°F, and a specific heat capacity of 0.21 Btu/lbm•°F. This relatively heavy concrete material was found to balance the beneficial effects of the slab's thermal capacitance with its ability to quickly store and release energy. The surface conductances selected for the slabs were 0.72 Btu/h•ft^2•°F for the slab top and 1.00 Btu/h•ft^2•°F for the bottom. These values are representative of typical carpet installations. Both the base and BSTS building models included the same concrete material and surface conductances, so that passive effects would not confuse the interpretation of results.

A cooling tower "freecooling" control was also incorporated as part of the BSTS system. During cooling-dominated days, the freecooling controls turn on the cooling tower whenever the outside air wet bulb temperature is low enough that water can be cooled by the tower to temperatures below floor slab bulk temperatures--provided, that is, that (1) the BSTS system controller (described below) calls for cooling, and (2) loop water temperatures are not already low enough that boiler operation would result if the loop water were further cooled.

A practical consideration in the design and operation of the BSTS system controller is the effect of thermal storage slab temperature on occupant comfort in the adjacent conditioned space. For people wearing appropriate indoor footwear, floor temperatures should be maintained between 65 to 84°F. Extreme slab temperatures could affect the mean radiant temperature to which occupants are exposed, also directly affecting comfort. Both of these concerns were unimportant with the BSTS system, however, because of (1) the carpet's insulating effect and (2) the BSTS controller limited loop water temperatures that could enter the slab.

In the preliminary design of the BSTS system, a simple control scheme that monitored zone temperatures to determine when water should be routed to the slabs from the primary circuit was used. However, energy penalties associated with overcooling the slab were encountered on mild days during initial simulations using this simple control. These penalties were due to the inherent time-delayed response of the BSTS system caused by the heat capacitance of the slab. Overcooling occurs when slab bulk temperatures are reduced such that, though the slab first helps reduce the zone cooling load, mechanical heating is needed later to help offset what eventually becomes a heating load. A BSTS control strategy thus evolved in which the slab bulk temperature rather than the zone temperature became the control point parameter. For this so-called "slab bulk temperature control" strategy, when water is available at the correct temperature range in the primary loop, it is routed to the slabs to help maintain the slab bulk temperature at a predetermined setpoint. For example, in times of high cooling loads, the setpoint would be set to near the zone thermostat heating setpoint; when high heating loads are expected, the setpoint is reset to be near the zone cooling setpoint. By keeping this setpoint within the zone thermostat dead band, the BSTS system cannot accidentally overcool/overheat (i.e., overcharge) the slab. Note though that the slab bulk temperature control setpoint may at times be unattainable because primary loop water temperatures are inappropriate, as would be the case when all of the heat pumps are in heating mode (and thus drawing heat from the water loop).

COMPARISON OF ENERGY USAGE CHARACTERISTICS

A comparison of the monthly energy consumption of the base building model to that of the building with the BSTS system model is shown in Figure 3 for Seattle. Energy savings were found in every month except October. The building annual total HVAC energy consumption for the building with the BSTS system was 556,584 kWh, compared to 612,572 kWh for the base case. The net reduction in annual energy consumption was 10.0%. Heat pump energy consumption followed the same monthly pattern as the overall HVAC energy consumption. Cooling tower energy consumption increased because of the "freecooling" cycle, but was still only a small part of the total HVAC energy consumption. The boiler consumed virtually no energy from May through September and had decreased consumption in each of the remaining months but October, which showed a small increase. This increase was caused because of a poor selection of the slab temperature setpoint for this intermediate month. This limitation in the control scheme is discussed further below.

Although annual and monthly energy consumption were used for comparison of building performance, important insight was gained into the operation of the BSTS system by studying daily temperature and heat transfer profiles in Seattle. Consider first the heat transfer rate and temperature histories for the west zone on the cooling dominated days of July 23rd and 24th, shown in Figures 4 and 5, respectively, for the building with the BSTS system installed. In Figure 4, the use of the BSTS system to

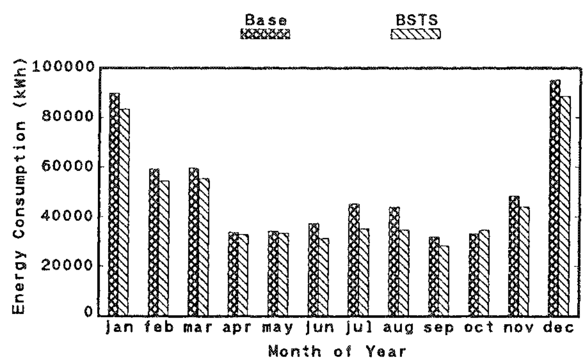

Figure 3. Total HVAC Monthly Energy Consumption for Simulated BSTS Strategies, Seattle

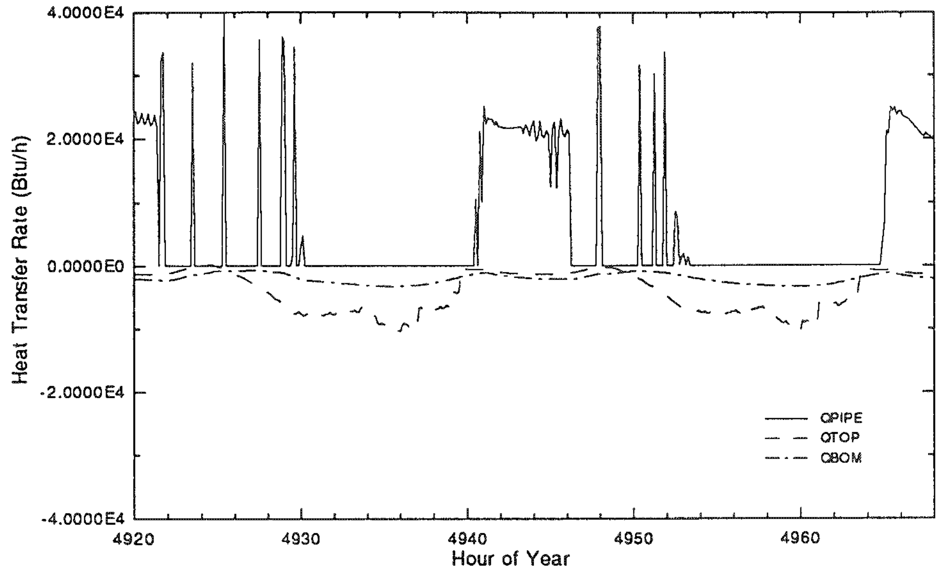

Figure 4. July 23rd and 24th Heat Transfer Rate History for the West Zone of the BSTS Building

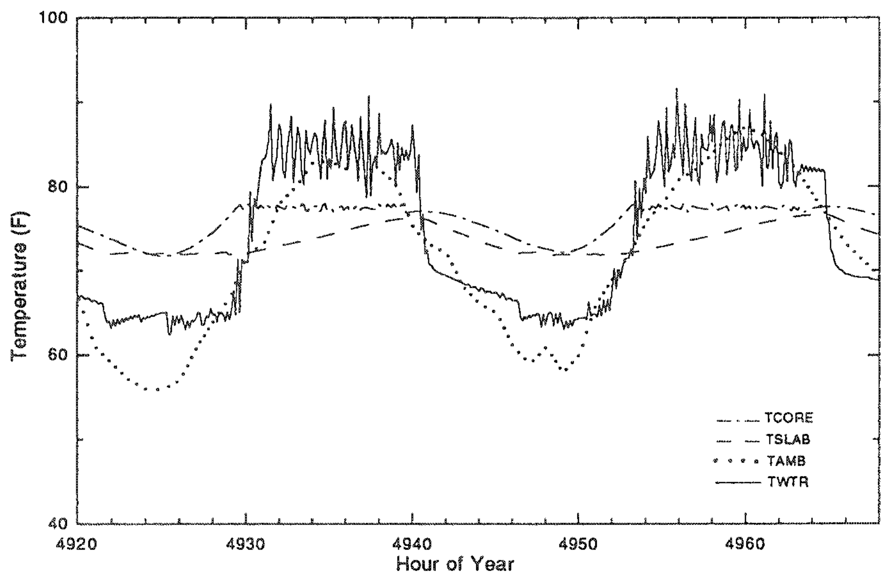

Figure 5. July 23rd and 24th Temperature History for the West Zone of the BSTS Building

cool the slab is clearly illustrated by intermittent peaks in slab-to-pipe heat transfer (QPIPE). The majority of the BSTS operation can be seen to occur during nighttime hours (e.g., hours 4940 to 4949 correspond to 8:00 p.m. to 5:00 a.m.), because lower nighttime wet-bulb temperatures and reduced cooling loads allow the freecooling cycle to reduce water loop temperatures (TWTR) to below the slab bulk temperature (TSLAB), as shown in Figure 5. Slab temperatures are roughly periodic with time of day, lagging the more pronounced periodic changes in the ambient (TAMB) and zone (TROOM) temperatures because of the slab's thermal capacitance. Irregularities in the slab temperature history are caused by the BSTS system.

By comparing these heat transfer rate and temperature histories to those of the base building (given in Figures 6 and 7), other phenomena are illustrated. For example, the base building west zone temperature (TROOM) remains near its cooling setpoint of 78°F continuously, with some irregularity in its profile indicating operation of the zone heat pump. For the BSTS system building (Figure 5) zone temperatures reach the cooling setpoint only during

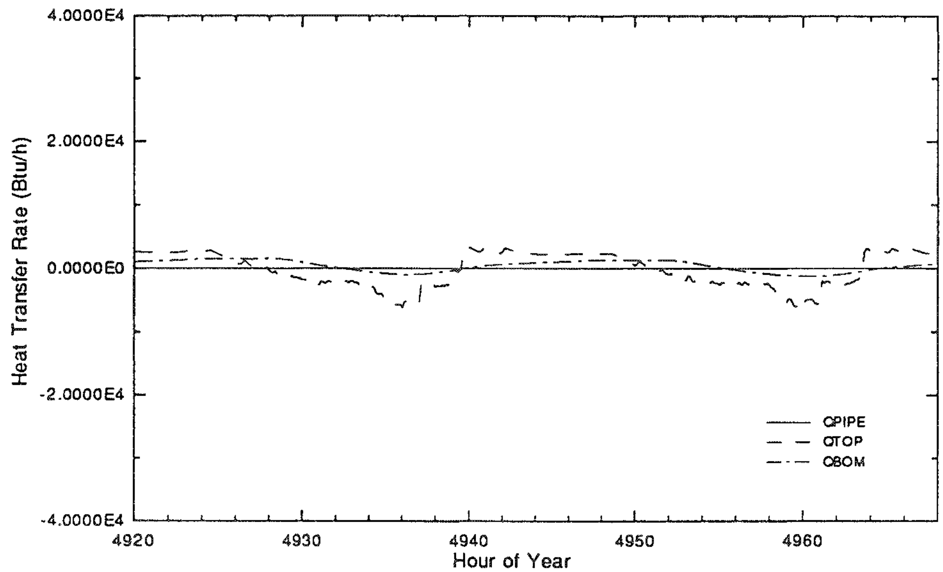

Figure 6. July 23rd and 24th Heat Transfer Rate History for the West Zone of the Base Building

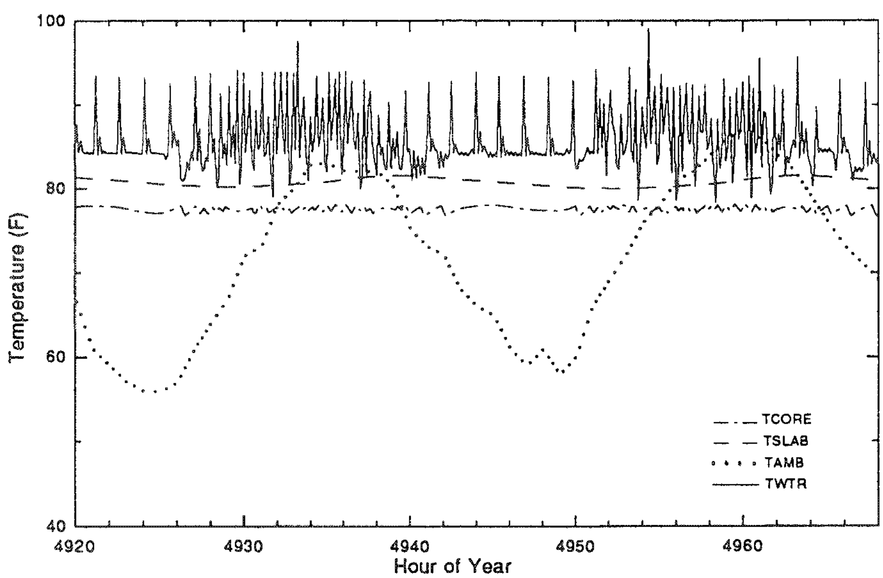

Figure 7. July 23rd and 24th Temperature History for the West Zone of the Base Building

portions of occupied hours, clearly showing that the use of the BSTS system reduces total heat pump operation. The slab temperature history for the base building (TSLAB in Figure 7) shows none of the irregularities found for the BSTS building, but instead is smoothly periodic with time of day at a temperature that is also consistently higher than the zone. Because of this higher temperature, the slab contributes to the cooling load during occupied hours (QTOP and QBOM in Figure 6), in contrast to the slab in the BSTS system (QTOP and QBOM in Figure 4).

Additional simulations modeling the same building were performed using TMY weather data from five additional cities: El Paso, Houston, Los Angeles, Milwaukee, and Washington D.C.. These cities were chosen because of their unique climatic conditions when compared to the temperate climate found in Seattle. 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 some quantitative insight as to where a BSTS system can be most effectively applied.

Figures 8 through 12 compare the simulated total HVAC monthly energy consumption for the base building in each of the five additional test locations to that of the same building with the BSTS system. In Figure 13, the total HVAC annual energy consumption is compared for all locations, including Seattle. The energy-conserving effects of the BSTS system were found to be most pronounced in warm, dry climates. Annual energy savings in El Paso and Los Angeles were 18.6% and 12.7%, respectively. Although also a cooling dominated climate, Houston fared poorly, with annual energy savings of only 4.9%, because the generally higher wet-bulb temperatures in this location limited the cooling tower freecooling effect. Energy savings in Washington were also lower due to its longer winter and high summer wet-bulb temperatures. The BSTS system provided little benefit during cold winter months because no "freeheating" source was available and core cooling-load requirements for the test building were small. Improvements in annual energy consumption in Milwaukee were thus quite limited (2.4%).

Simulation results indicated the BSTS system has no discernible effect on summer/winter peak electrical demands for the test building in any of the climate regions. On summer days, the BSTS system only served to reduce morning heat pump operation, both because of the limited thermal capacity and delivery capabilities of the slabs, and because the higher afternoon wetbulb temperatures meant the cooling tower's freecooling effect could not be utilized. Further, because there is no comparable "freeheating" source, the winter peak demand that occurs during morning warmup was found to be unaffected by the BSTS system.

BSTS SYSTEM OPTIMIZATION CONSIDERATIONS

The simulations reported above were made using only a single value for each of the summer and winter BSTS slab bulk temperature control setpoints, with a preselected changeover between the two setpoints in the spring and fall. In fact, for a truly optimized system the control setpoints would probably be varied on a monthly, daily, or even hourly basis because of widely varying weather conditions, particularly during fall and spring times. On cooling load dominated days, knowing precisely how far to cool the slabs while still avoiding overcooling could greatly improve system performance. The impact such an adaptive/predictive control algorithm might have on system performance was therefore examined. The procedure entailed iteratively determining optimal setpoints for "average" days of each month of the year through an extensive series of short parametric simulations, using knowledge of each day's weather to help make "smart" control setpoint decisions manually. Results indicated significant additional savings could be obtained on some days, suggesting that development of a control algorithm that dynamically controls BSTS slab bulk temperature setpoints based on predicted building loads and past performance would be highly beneficial. For example, extrapolation of these average day results for El Paso suggested annual energy savings as high as 30% might be obtainable.

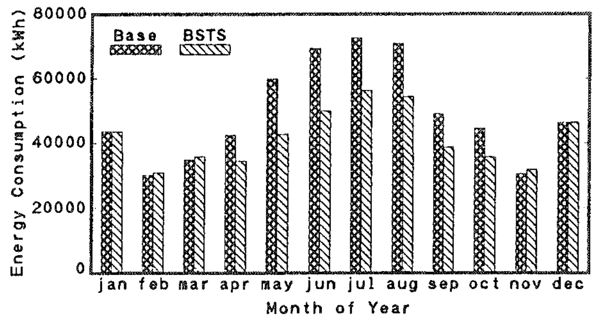

Figure 8. Total HVAC Monthly Energy Consumption for BSTS and Base Buildings, El Paso

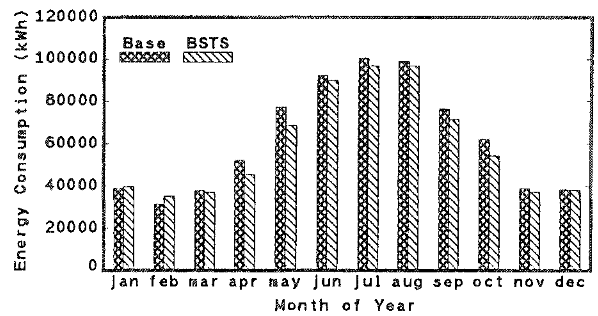

Figure 9. Total HVAC Monthly Energy Consumption for BSTS and Base Buildings, Houston

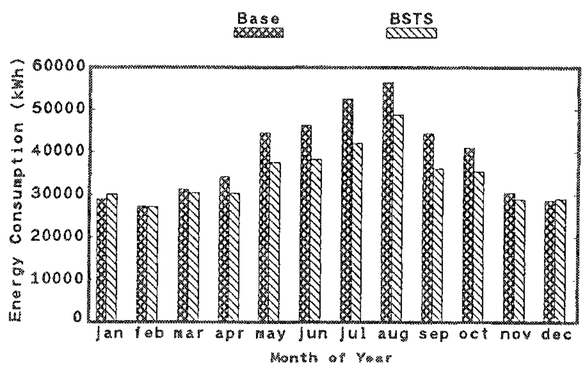

Figure 10. Total HVAC Monthly Energy Consumption for BSTS and Base Buildings, Los Angeles

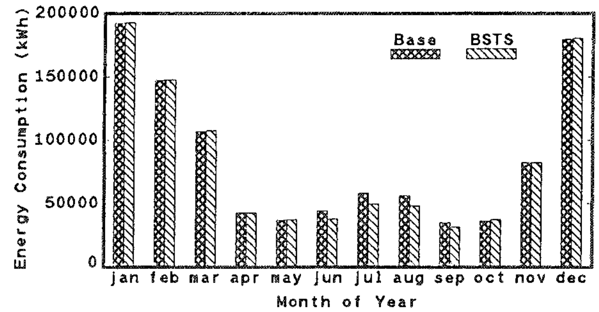

Figure 11. Total HVAC Monthly Energy Consumption for BSTS and Base Buildings, Milwaukee

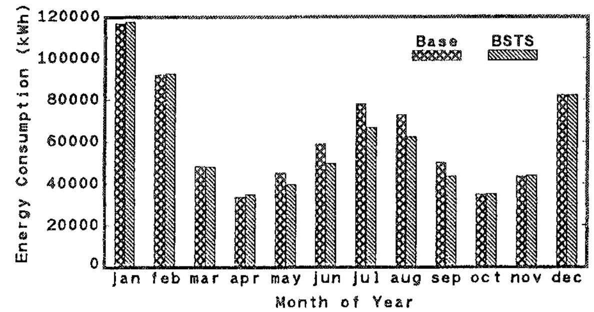

Figure 12. Total HVAC Monthly Energy Consumption for BSTS and Base Buildings, Washington, DC

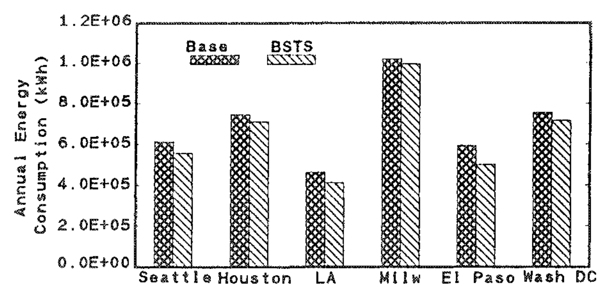

Figure 13. Total HVAC Annual Energy Consumption for BSTS Buildings

Besides optimization of the BSTS system control logic, it would also be desirable to select slab parameters so that the total heat capacity and/or capacitance of the slab give the most energy-important include density, specific heat capacity, and thermal conductivity. The product of these values, the thermal penetration property ((Btu/ft^2•°F)^2/h) (Childs et al. 1983), provides an indication of the speed with which energy can penetrate the slab during a thermal transient. Hence, selection of the value of this product was considered during sensitivity studies, as was the conductance of the slab's top and bottom insulating materials.

In general, it was found that selection of a more massive slab could improve overall energy savings during cooling-load dominated months, as it maximized the thermal capacitive benefits of the BSTS system. For example, a larger amount of incident solar loads could be absorbed into a more massive slab throughout the day, and then effectively be purged from the building at night using the tower freecooling cycle. However, economic and structural considerations would probably impose practical limits on the slab mass in an actual application. Increasing the conductance of slab insulating materials was found to diminish the beneficial thermal lag of the slab, and was thus not pursued.

CONCLUSIONS

The BSTS system was found to be an energy-conserving system for the building modeled in this study when compared to an identical building without the BSTS system. Annual energy savings ranged from approximately 2.4% to 18.6%, depending on climate. The BSTS system performed best using weather data for the moderate, drier climates of Los Angeles and El Paso, where cooling-loads at lower ambient wet-bulb temperatures dominate building HVAC energy use. More modest energy savings were obtained in Seattle, Houston, and Washington, D.C. Little gain in annual performance was predicted using Milwaukee weather data. Contrary to some conventional thermal storage systems, the BSTS system was also found to have negligible effect on summer/winter peak electrical demands.

Further energy savings may be possible if every facet of the BSTS system was optimized fully for every climate region tested. However, such an optimization, though feasible, may in fact be impractical for actual applications. Because significant additional energy savings was obtained by optimizing the slab temperature control setpoints on a daily basis, an adaptive/predictive control algorithm would be invaluable.

Future work must address the potential cost and energy effectiveness of the BSTS system in the test building as well as 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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