

# USE OF BUILDING THERMAL MASS TO OFFSET COOLING LOADS

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## ABSTRACT

The use of ice and chilled-water storage systems to reduce peak energy demands is well established. However, relatively few experimental results have been published on the use of building thermal mass to offset demand. The use of off-peak cooling to extract heat from a building structure may increase the total energy use, while at the same time reducing peak cooling loads and cooling costs. This paper describes a project sponsored by ASHRAE TC 4.6 on thermal storage in a building. The purpose of this research project was to evaluate the effect of building thermal energy storage on the peak cooling load.

To study the use of building thermal mass to reduce the peak cooling load, two experiments were performed on the Independent Life Insurance building located in Jacksonville, Florida. The objective of these experiments was to "pre-cool" the building at night and during the weekend to reduce daytime cooling loads. Supply air temperature and flow rate were measured on a floor that was being pre-cooled and on a control floor operated in a normal manner. Temperature and heat flux measurements at the concrete floor surface revealed the extent of charging and discharging of the thermal mass. Diurnal heat capacity calculations were used in analyzing the experimental results. The results showed an 18% reduction in cooling energy supplied during the daytime. There was no reduction in peak demand.

## INTRODUCTION

This paper describes the results of the two experiments performed on the Independent Life Insurance building located in Jacksonville, Florida. The objective of the experiments was to measure the building's response to pre-cooling. Pre-cooling is defined here as the cooling of the building during unoccupied nighttime or weekend periods. In the experiments, the energy supplied both to a floor with pre-cooling and to a floor without pre-cooling was measured. The data were analyzed to determine the effect of building mass in offsetting daytime demand.

## Building Description

The building (ILIB) is 37 stories high and has one million square feet of floor area. The two test stories have a floor area of 14,500 ft<sup>2</sup>. The building is not particularly massive and is typical of modern office buildings. The exterior consists of a glass curtain wall with structural steel supports. The interior construction includes a carpeted concrete floor, gypsum walls, interior partitions, and a concrete block core. A suspended ceiling serves as the return air plenum. It is an office building furnished mainly with desks, filing cabinets, word processors, and other office equipment.

The effective building thermal capacitance was calculated for the components of the test floor, and the relative magni-

tudes are shown in Figure 1. These values are the product of mass and specific heat for each of the components and represent the maximum storage capacity in the building. The

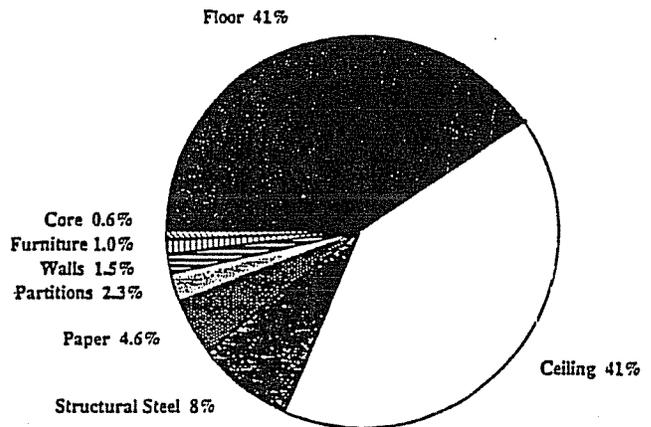


Figure 1 Thermal capacitance of the building

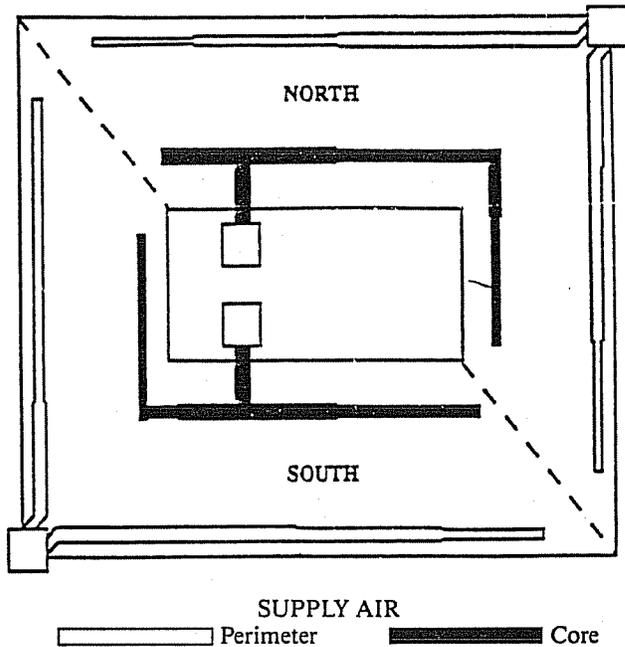


Figure 2 Schematic of HVAC distribution system

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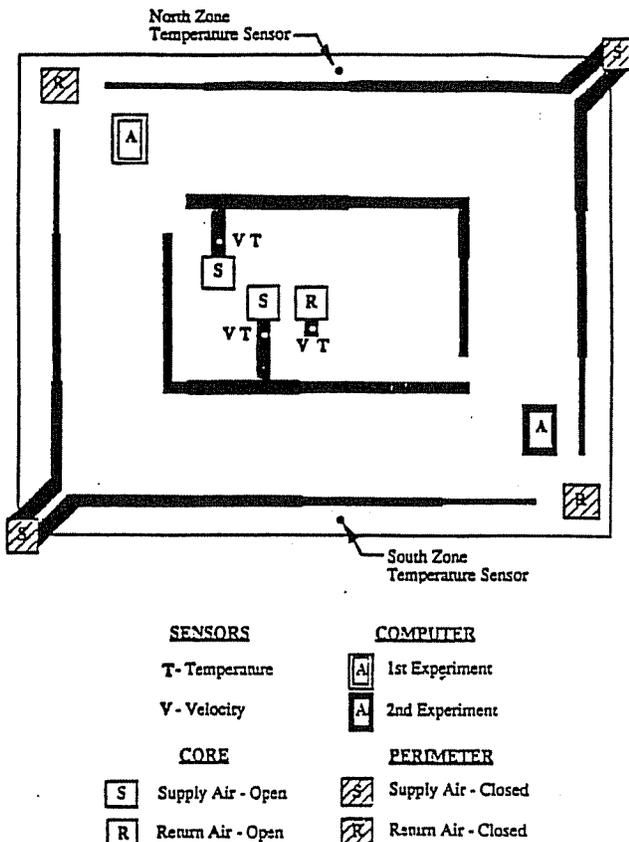


Figure 3 Location of sensors and monitoring station

overall thermal capacitance is about 23 Btu/ft<sup>2</sup>·°F; the main source of thermal mass is the concrete in the floor.

### HVAC System

Air conditioning is supplied centrally, with separate distribution systems for three groups of floors. The air-handling units are divided into core and perimeter systems, as shown in Figure 2. The core and perimeter systems each serve northeast and southwest zones.

The perimeter system delivers heating or cooling at a constant-volume flow rate and is used to maintain the desired air temperatures near the windows. The core system supplies cooling at a variable-volume flow rate and is the main source of cooling for each zone. There are a series of branches (not shown in Figure 2) that deliver air to the individual offices through units mounted in the ceiling.

### Control System

The building has a supervisory energy management and control system (EMCS) for the entire building and HVAC system. Each story has a supply air damper for each zone that is located in the main air duct. The damper setpoint is 73°F. The duct from the supply air damper branches to several slot diffusers in the suspended ceiling, and each diffuser is controlled locally using an adjustable temperature setpoint.

The variable-speed supply air fans are controlled based on the system's static pressure. If a zone damper closes or if the diffusers start to restrict airflow, the system static pressure rises and the speed of the supply fan is reduced. The perimeter system provides cooling only near the windows and is controlled by an outdoor "solar" sensor, consisting of a temperature sensor inside a metal box. The northeast and southwest zones are controlled by separate solar sensors. In order to conduct the experiments, it was necessary to manually override some of these controls.

## EXPERIMENTAL STUDY

The objective of the two experiments was to pre-cool the building at night to reduce daytime cooling loads. Two experiments were performed, the first during the period of June 16 to June 23 and the second during the period of September 8 to September 15, 1989. The objective of the first experiment was to maximize the amount of pre-cooling by cooling during the unoccupied weekend period. Experience gained from the first experiment was used to refine the plan for the second experiment, for which the pre-cooling period was reduced and a warm-up period prior to occupancy was provided.

### Design of the Experiment

Two stories of the building were selected for the experiments. The fifteenth story was the control story and was not pre-cooled. The ninth story was the test story, with stories 8 and 10 also pre-cooled to reduce any interaction between noncooled stories and the test ninth story. Stories 9 and 15 are similar in use and configuration and are assumed to experience similar external (solar and air temperature) and internal (lights, equipment, and people) loads. These stories are not adjacent, so there is no thermal interaction between the two. The core system only was used for pre-cooling and for cooling during the day during the test period. The local diffusers were manually set to open during the pre-cooling period. The two test periods were selected at times for which the perimeter system was not required during the day.

### Measurements

Measurements of supply airflow and temperature were used to calculate the energy supplied to each story. The response to pre-cooling was determined by comparing the energy supplied to the pre-cooled story to the energy supplied to the fifteenth-floor control story.

The locations of the sensors are shown in Figure 3. The building energy management and control system was used to record supply air temperature, supply air velocity, return air temperature, return airflow, room air temperature for the north and south perimeter zones, and outside air temperature and humidity. Additional needed measurements that were not part of the EMCS were made using portable instruments.

Air velocity was measured by a hot wire anemometer installed downstream of the supply air damper for each zone. A temperature sensor was installed next to the velocity sensor to measure the supply air temperature. Velocity and temperature sensors were also installed in the core return air duct on each story. Measurements of zone temperatures on each story were made using the existing north and south zone temperature sensors. These sensors are shielded and mounted on the exterior walls.

A monitoring station was placed on the ninth story and had the capability to record eight analog inputs. Measurements of the local air temperature, return air temperatures, temperature on top of the carpet, and temperature at the concrete surface under the carpet were recorded by the computer. During the first experiment, globe and wall surface temperatures were measured. For the second experiment, a heat flux meter was placed under the carpet at one location to determine local heat flow into and out of the floor. Temperature sensors were placed near the heat flux meter to measure temperatures on top of the carpet and between carpet and floor. In addition, local measurements of temperature, relative humidity, and velocity were taken with a hand-held meter.

All the EMCS temperature sensors used in the experiment were calibrated using a hand-held temperature sensor that had been calibrated against a mercury thermometer. The estimated accuracy is 1°F. Humidity measurements with the hand-held instrument were calibrated using a sling psychrometer.

The installed velocity sensor was a hot wire anemometer located at a fixed position in the center of the duct. It was

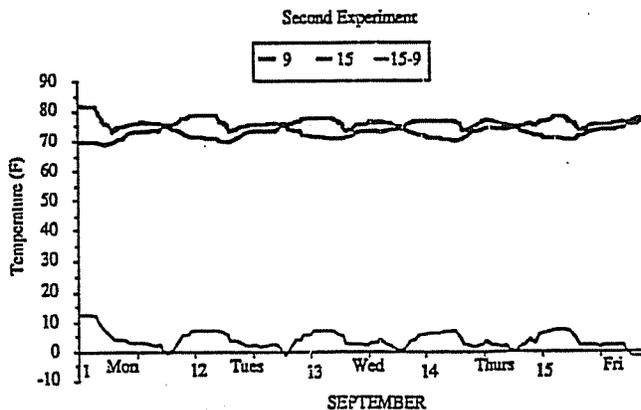
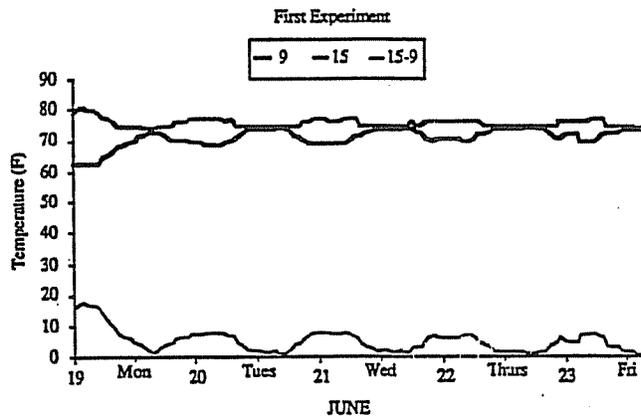


Figure 4 Variation of zone temperature during the first and second experiments

TABLE 1  
Duct Area and Traverse Correction Factors

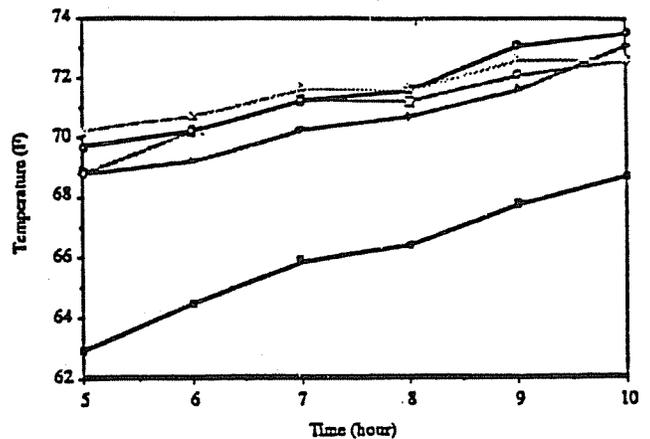
Supply Air Duct	Duct Area (ft <sup>2</sup> )	Traverse Correction Factors	
		Damper Open	Damper Closed
9 South	5.074	0.986	0.972
9 North	3.792	1.131	0.590
15 South	4.174	1.020	0.481
15 North	4.076	0.806	0.760

calibrated using a hand-held hot wire anemometer that had been calibrated using a pitot tube in a wind tunnel. Calibration of the flow rate from the installed velocity sensors involved taking a traverse across each duct. Due to the bends in the supply duct and the damper upstream of the sensor, the velocity profile was not uniform, and a velocity profile correction factor was determined. Measurements of the cross-sectional duct area were taken at the flow sensor location. The flow rate was then computed as the product of velocity and duct area and estimated to be accurate to within 10% to 20%. The correction factors and duct areas are listed in Table 1.

Recordings were made by the EMCS system at 15-minute intervals and printed out by a line printer. Recordings were made at five-minute intervals by the monitoring station. Readings of temperature and humidity were made by the hand-held instrument on an hourly basis.

## EXPERIMENT I

The first experiment was conducted from June 16 to June 23, 1989. Cooling was initiated on the ninth story through the weekend to reduce the amount of energy stored in the ninth story. During the week, the ninth story was cooled at night beginning at 5 p.m. and continuing until 5 a.m. The supply air



Mon	$Y = 57.590 + 1.1257X$	$R^2 = 0.983$
Tues	$Y = 64.343 + 0.8343X$	$R^2 = 0.965$
Weds	$Y = 65.724 + 0.7057X$	$R^2 = 0.934$
Thurs	$Y = 65.529 + 0.8029X$	$R^2 = 0.975$
Fri	$Y = 67.757 + 0.5057X$	$R^2 = 0.941$

Figure 5 Daytime temperature rise of test floor for experiment I

temperatures were set to 50°F for the entire period. The fifteenth story received no cooling at night nor during the weekend during this period.

The zone temperatures during the period are shown in Figure 4 for the ninth and fifteenth floors. The upper curves are the temperatures and the lower curve is the difference in temperature between the two floors. The relative humidity fluctuated around the 40% level. During the weekend, the ninth floor temperature was lower than the normal set temperature. The fifteenth floor temperature, which was allowed to float, was higher than the setpoint. During the week, the ninth floor temperature dropped during the night due to pre-cooling, while the fifteenth floor temperature rose. On the average, the daytime zone temperature of the ninth floor was within about 2°F of that of the fifteenth floor and at night it was about 7°F cooler.

A number of factors led to corrections of the data. On Monday morning, the perimeter system was inadvertently turned on. Inspection also revealed that the ninth story dampers were open and the fifteenth story dampers were closed. This allowed additional unmeasured cooling to be supplied to the ninth story on Monday. On Tuesday, the supply dampers to the ninth story were locked in the closed position.

Attempts to calibrate the ninth floor return air sensor revealed that this sensor was faulty. A replacement sensor was not installed until 4 p.m. on Thursday. The average of the north and south zone temperatures was found to be a good approximation for the return air temperature (Ruud 1989). This approximation was used to replace the data from the faulty sensor readings.

The computer monitoring system was set up to record eight temperatures at 15-minute intervals. Originally it was thought that the data disk could record up to five days of data at 15-minute intervals. When the data disk was removed for backup on Tuesday, it was discovered that the data from 4 a.m. Sunday to 10 a.m. Tuesday were not recorded. This left about a two-day gap in the data. For the remainder of the week the disks were backed up daily.

Numerous complaints were received from occupants on the eighth, ninth, and tenth stories on Monday morning. An overcast, cool morning, coupled with the large amount of weekend pre-cooling, caused the zone temperature to remain uncomfortably cold throughout the morning. It was

**TABLE 2**  
**Carpet and Surface Resistances (h·ft<sup>2</sup>·°F/Btu)**

Experiment	Carpet	Surface	Sum
1	1.02	1.02	2.04
2	0.77	1.59	2.36

apparent that a warm-up period following pre-cooling would be necessary to make the zone comfortable.

Weekend pre-cooling had been turned off at 5 o'clock Monday morning to allow the zone temperature to warm up before occupants arrived, but the zone temperature was still low. At 5 a.m., the average zone temperature was 62.9°F, at 8 a.m., 66°F, and at noon it had reached 70°F.

Figure 5 shows the change in temperature from 5 a.m. to 10 a.m. for each day of the week. A linear regression gave the slope for a straight line approximation to the data. The rate of temperature rise is a measure of the internal gains in the zone. These values were used in the second experiment to estimate the time required to warm up the zone prior to occupancy.

## EXPERIMENT II

The second experiment was conducted from September 8 to September 15, 1989, and was similar in design to the first experiment. However, less weekend pre-cooling was supplied. To limit the amount of pre-cooling, the ninth floor zone temperature was not allowed to fall below 66°F during the weekend pre-cooling period. During the week, pre-cooling was initiated at 5 p.m. and was turned off at 5 a.m.

The data taken during the second experiment were more complete than those taken during the first experiment. However, trends in the fifteenth story supply temperatures revealed a faulty south supply air temperature sensor. Fortunately, data from the first experiment showed that south and north supply air temperatures are reasonably close (Ruud 1989). The north supply air temperature readings were used to replace data from the faulty south supply air temperature sensor.

The ninth floor zone temperatures were monitored Monday morning to ensure enough warmup time before occupancy. Estimates of warmup time were based on the average value of temperature rise in Table 2. Warmup time was calculated according to

$$\text{Hours Warmup Time} = \frac{(\text{Zone Temperature} - \text{Target Temperature})}{(\text{Rate of Temperature Rise})} \quad (1)$$

where the target temperature was the desired zone temperature for occupancy and equal to 70°F. By allowing for sufficient warmup time, no complaints were received from occupants on the eighth, ninth, and tenth stories on Monday morning or during the rest of the week. During this experiment, the zone temperatures for the ninth and fifteenth floors were similar to those for Experiment I, as shown in Figure 4.

## ANALYSIS OF DATA

The data analysis involved use of data from the EMCS, the monitoring station, and the hand-held instrument. Hourly values were transcribed from the 15-minute printouts and were evaluated to be representative. Data from the EMCS were available only on printouts; therefore, more than 9000 data points were manually transferred from EMCS printouts to a computer spreadsheet. Data from the spreadsheet and from the computer monitoring station were used to produce plots of all measured variables, which were then analyzed for errors and trends. Data that appeared to be in error for the reasons discussed above were discarded and replaced by appropriate estimates.

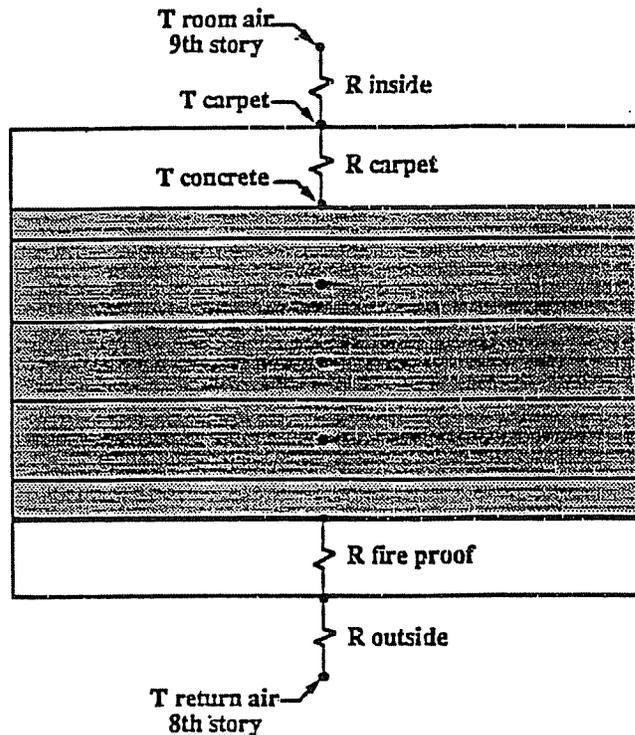


Figure 6 Finite difference model for floor

## Floor Heat Flow

The concrete floor is the largest storage component for pre-cooling. The major resistances to heat flow into and out of the floor are the surface convective coefficient and the carpet thermal resistance. The data were analyzed to evaluate the resistance using a one-dimensional finite difference model, shown in Figure 6. This model was constructed to calculate floor heat flux from temperatures measured at the surface of the carpet and under the carpet and to determine the two major unknown resistances.

The properties of the 4.75-in.-thick-concrete floor were calculated (Balcomb 1983) as:

- density: 110 lbm/ft<sup>3</sup>
- specific heat: 0.22 Btu/lbm·°F
- thermal conductivity: 0.45 Btu/h·°F

The average thickness of the fireproofing was assumed to be 3/4 in., and an estimate of the thermal resistance for the fireproofing is 2.5 h·ft<sup>2</sup>·°F/Btu.

The convective resistance ( $R_{outside}$ ) between the fireproofing and the eighth floor return air plenum was estimated, using ASHRAE (1989) correlations for heat flow, to be 0.77 h·ft<sup>2</sup>·°F/Btu.

For the first experiment, the finite difference solution was obtained using the measured temperatures on either side of the carpet. The heat flux into and out of the floor was calculated using the temperature measured between carpet and floor. This heat flux was then used together with the measured temperatures in the air and on top of the carpet to obtain the two resistances.

The results for the periodic behavior of the temperature and heat flux for the first experiment are shown in Figure 7. Heat flux is defined as positive into the floor (discharging) and negative out of the floor (charging). In the second experiment, a heat flux sensor was available, and results from the finite difference model were also compared to measurements from the heat flux sensor. Figure 8 shows the results and demonstrates that the finite difference results are consistent with the heat flux sensor readings. The results also show that maximum heat fluxes of 2 to 3 Btu/h·ft<sup>2</sup> (0.6 to 1.0 W/ft<sup>2</sup>) are obtained during discharging of the floor.

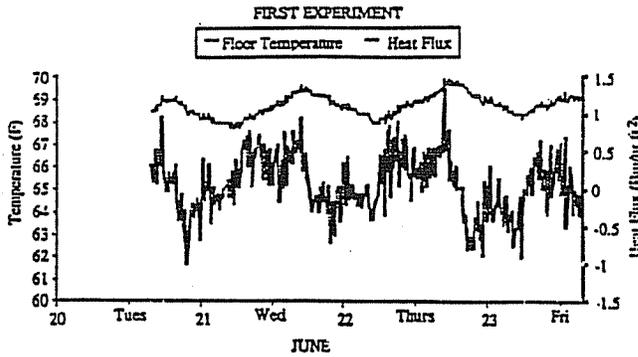


Figure 7 Measured temperature and heat flux for floor

Using the calculated or experimental heat flux values, the experimental values for the carpet resistance and the floor surface convective resistance were determined. Table 2 lists the experimental values of the resistances and their sum. There was no significant difference between the measured convective resistance values for daytime and nighttime. The standard deviation of the data about the mean is about 30% for the carpet and 50% for the convective resistance.

Since the finite difference results from the second experiment were checked against the heat flux sensor, and since the first experiment is missing some of the weekly data, the results from the second experiment are more reliable. These resistance values were used in the analysis of the effective storage capacity described later.

### COOLING ENERGY USE

The cooling energy supplied to each story over the test period was calculated from measured supply air velocities and supply and return temperatures. The return airflow through the core return air duct is less than the supply due to leakage through the perimeter return air dampers, elevators, stairwells, mail conveyor, and along the perimeter at the windows. All the air entering the room at the supply air temperature ( $T_s$ ) is assumed to leave the room at the return air temperature ( $T_r$ ). The sensible energy supplied ( $E_s$ ) is then:

$$E_s = 1.10 VCA(T_r - T_s)(\text{Btu/h}) \quad (2)$$

where

- $V$  = measured air velocity (fpm),
- $C$  = correction factor for velocity profile, and
- $A$  = measured duct area (ft<sup>2</sup>).

With a pre-cooling strategy, the air conditioning on the ninth story is on during the night, while on the fifteenth story the cooling is off. Since nighttime zone temperatures on the ninth story are lower than on the fifteenth story and the ambient temperatures are higher than the zone temperatures, the envelope losses ( $Q_{env}$ ) on the ninth story are greater than on the fifteenth story. Also, since the ninth story has a recirculation airflow, exfiltration energy losses ( $Q_{inf}$ ) on the ninth story will be greater than on the fifteenth story. Some of the energy ( $Q_{store}$ ) supplied to the ninth story will lower the temperature of the thermal mass. On the fifteenth story,  $Q_{store}$  represents the energy into the mass due to the zone increasing in temperature at night when the air conditioning is off and the "pull down" period in the morning. Therefore, during the night charging period, energy use for the ninth story is greater than for the fifteenth story. The difference in energy use between the ninth and fifteenth stories is, then:

$$(E_9 - E_{15}) = \quad (3)$$

$$(Q_{env9} - Q_{env15}) + (Q_{inf9} - Q_{inf15}) + (Q_{store9} - Q_{store15})$$

During the daytime, both stories are ventilated and controlled to maintain a zone temperature of 73°F. If both stories

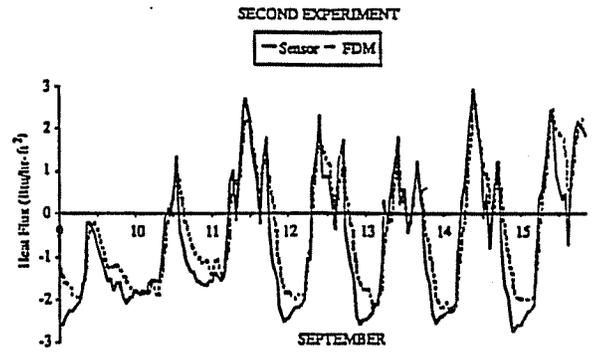


Figure 8 Comparison of heat flux from sensor and by finite difference method

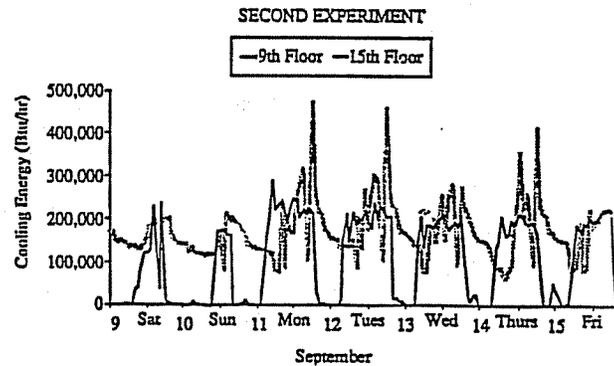
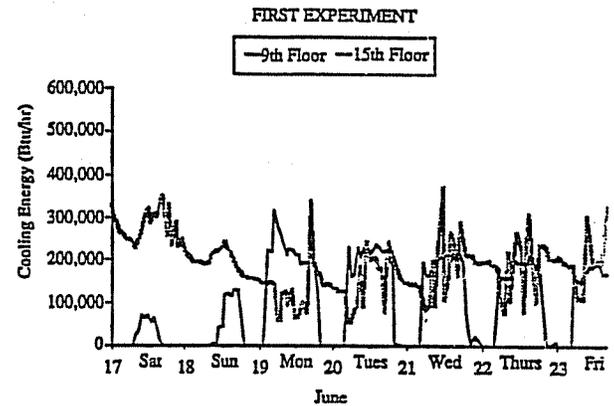


Figure 9 Energy supplied to test and control floors

are approximately at the same temperature and infiltration is assumed to be the same for both stories, then the difference in energy can be attributed to the thermal energy that goes into and out of storage:

$$(E_9 - E_{15}) = Q_{store9} - Q_{store15} \quad (4)$$

Discharging of the cool thermal mass reduces the ninth story's cooling load. Energy stored in the fifteenth story thermal mass during the night or weekend is released during the day, causing increased cooling loads.

Figure 9 is a plot of cooling energy supplied to the ninth and fifteenth stories for the first and second experiments. The energy values are calculated from Equation 2 using the instantaneous readings taken every hour from the EMCS system. The energy supplied to the fifteenth floor is relatively constant during the daytime, while that supplied to the ninth floor varies as the floor heats up and then is pre-cooled. Spikes in the energy supplied to the ninth story can be attri-

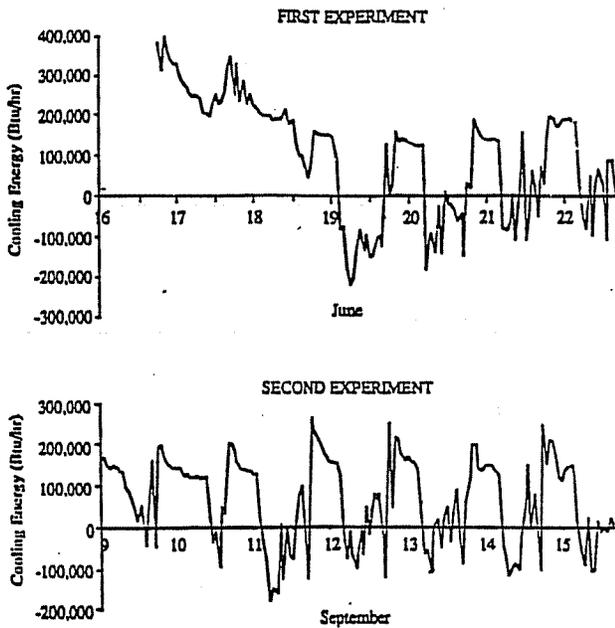


Figure 10 Difference in energy supplied to test and control floors

TABLE 3  
Cooling Energy Use Ratios

	Week (M-F)	Total Period
$(E_9/E_{15})$		
Experiment I	1.36	2.04
Experiment II	1.34	1.61
$E_{discharge}/E_{charge}$		
Experiment I	0.42	0.19
Experiment II	0.40	0.26

buted to the opening and closing of supply dampers on other stories. Since the ninth story supply dampers were locked open for the experiment, the closing or opening of supply dampers on other stories causes the flow to surge.

A comparison of the energy supplied to the two stories can be seen more clearly in Figure 10. In this figure, the cooling energy supplied to the fifteenth story is subtracted from that supplied to the ninth story. The ninth story shows a large energy input during the weekend. During the week, the ninth story uses less energy during the day when the building capacitance is discharging and more energy at night when the floor is being charged.

The cooling energy supplied to the ninth floor relative to that for the fifteenth floor was calculated for the total period and for during the week (Monday through Friday). These values are given in Table 3. The total cooling energy supplied to the ninth story during the first experiment was about twice the amount supplied to the fifteenth story for the first experiment and 60% greater for the second. During the weekdays, the energy supplied to the ninth story was about 35% greater than the amount supplied to the fifteenth story for both experiments. The agreement for the weekdays indicates that the greater amount of weekend cooling in the first experiment had little effect on reducing the weekday cooling loads.

The difference in total energy between the two experiments is due to the shorter pre-cooling period for experiment II. The results for the week are very close since the control strategies are the same. The greater cooling energy attributed to the ninth floor is presumably due to environmental gains. The ambient temperature was, on the average, 5°F to 10°F warmer than the zone temperature during the experiments.

The difference between the ninth and fifteenth floor cooling energy subtracts the internal gains and reflects the energy into and out of storage and the increased external gains. The ratio of discharge energy (when the difference is negative) to the charging energy (when the difference is positive) is also a measure of thermal storage efficiency. These ratios, given in Table 3, range from 19% for the entire period to 42% for the week.

The experimental results demonstrate a difference in the total cooling energy supplied to the test and control floors. However, the totals should be essentially equal, since pre-cooling energy offsets air conditioning that is required later. There is only some increase in cooling energy required due to the increased environmental gains, since the cooled zone is lower in temperature than the non-cooled zone.

The heat conducted through the double-pane windows of the test floor during the pre-cooling period was estimated. The pre-cooling occurs during the nighttime for 12 hours. For the second experiment, the zone temperature was about 7°F lower than the ambient. The increase in cooling load required to offset the resulting gain is about 8% of the total cooling supplied to the zone. For a week with a weekend pre-cooling period, the total cooling requirement is increased about 15%. These values represent the energy penalty for the pre-cooling strategy employed in this building.

For the experiments conducted in this study, there were additional energy increases not directly attributable to the pre-cooling strategy. Only the eighth, ninth, and tenth floors were pre-cooled. Infiltration from the warmer surrounding floors was possible, since there are no seals between floors at the perimeter. An estimate of the infiltration rate from warmer floors that could account for the measured discrepancy is about 50% of the total supply airflow rate. This agrees with measurements showing that the flow through the return air duct was only about 50% of the supply airflow rate. For a building that would be totally pre-cooled, infiltration would be between floors equally cooled and would not increase the energy consumption.

The time distributions of the difference in energy between the ninth and fifteenth floors represent the shifting of load due to storage. Figure 11 shows the weekly sum of  $(E_9 - E_{15})$  during each hour of the week for the two experiments. For example, the value at 1:00 is the sum of  $(E_9 - E_{15})$  for Monday through Friday between 12:00 and 1:00 p.m.

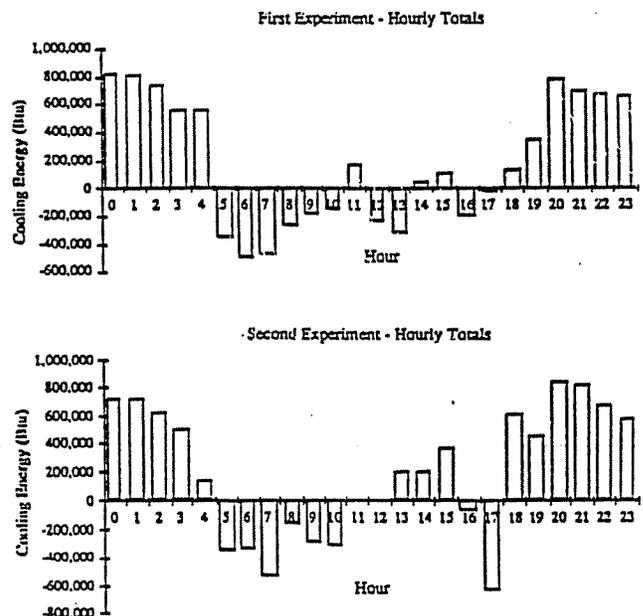


Figure 11 Hourly distribution of difference in cooling energy supplied to test and control floors

Figure 11 shows that the reduction in cooling load occurs mainly in the morning between 5 a.m. and noon. Some reduction in afternoon cooling loads occurred in the first experiment. The reduction at 17:00 hours (5 p.m.) in the second experiment is an artifact and occurred because the air conditioning on the ninth story was turned off while the fifteenth story air conditioning was still on.

Most of the cooling load reduction occurred shortly after the pre-cooling period ended in the early morning. The effect of pre-cooling for this building appears to last only for a short period that is less than eight hours due to the limited amount of thermal capacitance in the building. Extensive pre-cooling (charging) over the weekend does not appear to be effective in reducing weekday cooling loads, since the daytime profiles for the two experiments are similar. The time distribution of loads also reveals that for some daytime hours there is no difference in cooling load between the two floors. Comparison with Figure 9 shows that this occurs often during the time when loads are high in the afternoon.

The total reduction in the cooling load during the daytime hours (8 a.m. to 6 p.m.) is about 18% of the total cooling load. The rate of cooling supplied during the afternoon is about the same for both of the floors, and the electrical demand is the same. If typical time-of-use rates were in effect, there would be a savings in energy charge due to load shifting but no demand charge reduction.

For this building with a low thermal capacitance, a pre-cooling strategy can be recommended to provide some peak load reduction. The cooling load reduction occurs only in the hours immediately after the pre-cooling period ends. To provide a reduction during the peak (afternoon) hours, the temperature of the thermal mass should be maintained as low as possible before the peak period begins. The temperatures during the occupied periods must remain within an acceptable comfort region, which covers a temperature range of about 7°F (ASHRAE 1989). During occupied off-peak periods, then, cooling should be provided to maintain the zone temperature at the low end of the comfort region. During peak periods, the cooling should be modulated to allow the temperature to rise but not exceed the high end of the comfort range.

A pre-cooling strategy must also consider the requirements of rate schedules, which define peak periods of comfort criteria during occupied periods and zone temperatures necessary to prevent condensation during unoccupied periods. The current time-of-use rate schedule applicable to the building has the summer peak period between April and October (Plicque 1989), but the building is not currently on this schedule.

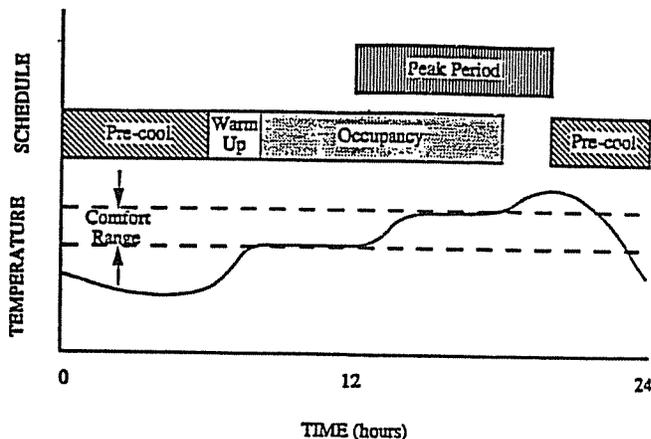


Figure 12 Pre-cooling strategy

Figure 12 illustrates the pre-cooling strategy that would satisfy the requirements. Within these constraints, effective pre-cooling becomes an optimization problem. Pre-cooling may be supplied through the use of mechanical refrigeration or by ventilation with cool outdoor air. For mechanical refrigeration, the supply air temperature and flow rate can be adjusted to obtain maximum peak reductions at minimum cooling cost. With outdoor ventilation, the enthalpy of the outdoor air and the flow rate affects the benefit and cost of pre-cooling. Moisture in the outdoor air may increase the latent loads while the sensible load is decreased (Ruud 1989; Oussama 1989). The duration of the pre-cooling (charging) period is also a factor. For example, the experiments on the building indicate that longer term (weekend) pre-cooling was not effective. Buildings with higher thermal capacitance could be expected to benefit more from pre-cooling.

## EFFECTIVE STORAGE CAPACITY

The total storage capacity of a structure calculated from the mass and specific heat of the component assumes that all of the mass is at the same temperature during charging and discharging. However, the thermal resistances between the room air and the components and the internal thermal resistance inside the structures create temperature differences throughout the structure. The thermal effectiveness of the mass is thus reduced.

The total heat capacity ( $TC$ ) is the maximum amount of thermal energy stored or released due to a uniform change in temperature of the material, and is given by

$$THC = \rho cV \quad (5)$$

where

$\rho$  = density,  $c$  = specific heat, and  $V$  = volume.

The diurnal heat capacity (DHC) is a measure of the effective thermal capacity of a building component exposed to periodically varying temperatures (Balcomb 1983). The DHC is the amount of thermal energy stored ( $\Delta Q$ ) for a change in temperature ( $\Delta T$ ) over half of a 24-hour daily cycle and is less than the total heat capacity. The amount of energy stored due to heat flow into the thermal mass will reduce the amount of energy required for cooling. The amount of thermal energy stored is given by

$$\Delta Q = \Delta T DHC \quad (6)$$

The method for calculating DHC values is similar to the way UA values are calculated for a building (Balcomb 1983). The determination of the DHC values for this building is given in Ruud (1989). These were obtained from the material properties and the estimated mass of the components. Convection coefficients were taken from ASHRAE (1989). Table 4 lists the calculated DHC values for the components of the ninth story of the building, which are also shown in Figure 13. The temperature difference is computed using Equation 9. The angle given in Table 4 indicates the phase angle between the driving temperature and the heat flux.

TABLE 4  
Diurnal Heat Capacity

	DHC (Btu/°F)	Phase Angle (°)
Floor	29,870	19.9
Ceiling	15,805	18.9
Walls	5,380	83.3
Partitions	8,098	85.2
Core Concrete	356	26.4
Steel Supports	751	47.7
Steel Risers	194	9.1
Metal Furniture	3,646	90.0
Paper	15,731	90.0
Total	66,641	47.1

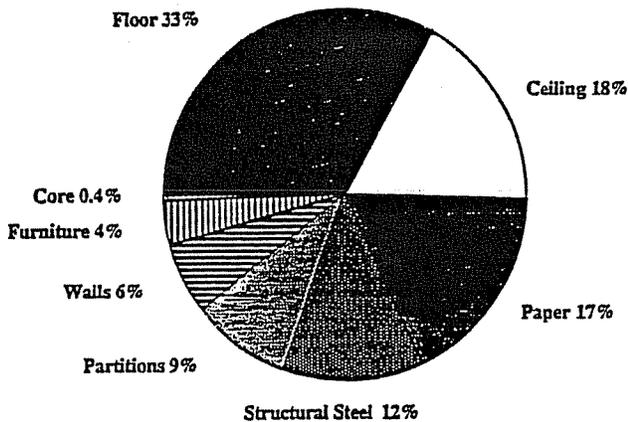


Figure 13 Distribution of diurnal heat capacity

The values of the DHC are useful in estimating the maximum benefit to storage and determining which are the significant storage components. The values of the DHC were combined with the measured temperature changes of the zones and the measured reductions in cooling load to verify the reasonableness of the values.

The total reduction in cooling load ( $\Delta E$ ) is the amount of energy supplied to the fifteenth story ( $E_{15}$ ) less the amount of energy supplied to the ninth story ( $E_9$ ) during the daytime when the difference is greater than zero.

An energy balance on each story gives the total cooling energy ( $E$ ) as

$$E = Q_{cplg} + Q_{surf} + Q_{conv} + Q_{inf} + Q_{sens} \quad (7)$$

where

- $Q_{cplg}$  = gains due to coupling with adjacent stories,
- $Q_{surf}$  = convective gains from surfaces,
- $Q_{conv}$  = internal convective gains,
- $Q_{inf}$  = gains from infiltration, and
- $Q_{sens}$  = net sensible gain.

During the daytime occupied period, both the ninth story and fifteenth story are maintained at a temperature of approximately 73°F.  $Q_{cplg}$ ,  $Q_{conv}$ ,  $Q_{inf}$ , and  $Q_{sens}$  are assumed to be approximately the same during the day for the ninth and fifteenth stories. Since the ninth story was cooled at night while the fifteenth story was not, the total calculated reduction in daytime cooling load ( $\Delta E_{calc}$ ) should equal the amount of energy removed from the thermal mass

$$\Delta E_{calc} = \int (E_{15} - E_9)^+ dt \quad (8)$$

where the "+" indicates only positive values of the integral are used. The integral was evaluated assuming that the temperature varied periodically over the course of the day. The daily measured peak-to-peak temperature difference for the ninth floor was used as the amplitude.

$$\Delta T = \text{Max}(T_9) - \text{Min}(T_9) \quad (9)$$

Table 5 compares the calculated thermal storage capacity ( $\Delta E_{calc}$ ) to the measured reduction in cooling ( $\Delta E_{meas}$ ) from the second experiment using the total DHC value in Table 5.

The average values of the calculated and measured storage terms differ by 4%. The values for each day differ more than the average values. Some of the difference may be attributable to interactions between stores and systematic differences between the ninth and fifteenth stories. Comparisons of daily values would improve if the peak-to-peak temperature difference was more periodic with an equal variation from one day to the next. Still the DHC method provides a good prediction of the average reduction in cooling for the week.

TABLE 5  
Temperature Difference and Thermal Storage

	$\Delta T$ (°F)	$\Delta E_{calc}$ (Btu)	$\Delta E_{meas}$ (Btu)
Monday	13.7	912,981	1,020,956
Tuesday	13.6	906,317	502,250
Wednesday	7.4	493,143	442,850
Thursday	7.4	493,143	665,371
Friday	8.6	573,113	882,572
Average	10.14	675,739	702,800

Comparisons were not made with the energy values from the first experiment. The additional perimeter cooling that was present in the first experiment makes these values difficult to interpret. Cooling reductions due to the thermal mass are confounded with the unmeasured perimeter cooling supplied to the ninth story.

The effectiveness of the thermal storage components of the building can also be determined. The thermal effectiveness parameter ( $\eta$ ) relates the diurnal thermal capacity to the maximum thermal capacity.

$$\eta = \frac{\text{DHC}}{\text{THC}} \quad (10)$$

Table 6 lists the effectiveness values calculated for the ninth story of the building. The overall effectiveness of storing energy in the building mass on a daily basis is only 19.8%. The effectiveness of the floor is low due to the carpet and convective resistance between the concrete surface and the room air. The ceiling is even lower in effectiveness due to the resistance of the fireproofing. The paper and metal furniture show a high effectiveness. Overall, only about one-quarter of the mass is effective in storing energy.

TABLE 6  
Thermal Effectiveness

	THC (Btu/°F)	DHC (Btu/°F)	Effectiveness (%)
Floor	137,504	29,870	21.7
Ceiling	137,504	15,805	11.5
Walls	5,417	5,380	99.3
Partitions	8,125	8,098	99.7
Core Concrete	2,475	356	14.4
Steel Supports	12,180	751	6.1
Steel Risers	14,716	194	1.3
Metal Furniture	3,646	3,646	100.0
Paper	15,731	15,731	100.0
Overall	337,298	66,641	19.8

In order to demonstrate how a design change could affect storage, the diurnal heat capacity of the floor was recalculated without including the carpet resistance. The DHC increases to 48,285 Btu/°F and the effectiveness to 25.2%. The potential energy storage of the floor would increase by 13% by removing the carpet.

## CONCLUSIONS

Results from the experiments at an office building show that the maximum cooling load reduction occurred shortly after the pre-cooling period ended. The daytime cooling load was reduced about 18%, but there was no reduction in peak demand. Excessive pre-cooling over the weekend was found not to be effective in reducing weeknight cooling loads.

During unoccupied times when the ambient temperature is higher than the building's set temperatures, pre-cooling both meets environmental gains and cools the structure. For this building, significant energy was used to meet the gains.

Diurnal heat capacity calculations provide a method for estimating the potential for thermal storage in a building. Com-

parisons with the experiments show good agreement between calculated and measured values of energy storage. The effectiveness of the mass in storing energy on a daily basis was found to be 19.8%. Design changes, such as reducing the large thermal resistance, can significantly increase the effectiveness. Calculations showed that eliminating the carpet would increase the floor effectiveness by 13%.

The limited results on this building show that precooling was not effective. The uncertainties in the experiments preclude drawing broad conclusions, and it is recommended that further research be conducted into control strategies that utilize building mass.

## ACKNOWLEDGMENTS

This project was sponsored by ASHRAE Committee TC 4.6, Building Operations Dynamics. The experiments performed at the Independent Life Insurance building would not have been possible without the support and assistance of Ed Cavin, Fred Wheeler, Dan Frey, and the many other helpful building operators. The financial support of the ASHRAE Grant-in-Aid program is greatly appreciated.

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## DISCUSSION

**Ron Judkoff, Senior Architectural Engineer, SERI, Golden, CO:** On this particular building, pre-cooling was not an effective strategy. However, you should point out that in some climates pre-cooling could be accomplished with an economizer (outside air) and that this might be cost-effective.

**J.W. Mitchell:** I agree that precooling with outside air may be an appropriate strategy in some climates. The Jacksonville climate is very humid, and simulations we made showed that the reduction in sensible load due to cooling of the structural mass was offset by the increase in latent load due to moisture in the building interior furnishings. The strategy you suggest would be more beneficial in drier climates.

**Bent A. Borresen, Techno Consult, Sandvika, Norway:** For years I have been working with building thermal dynamics, first as a researcher, now more as a designer of HVAC loads and systems, for instance in glazed atria. Computer simulations are important to verify measurements. Are you planning work on simulations?

Activation of the thermal mass means that you have to allow for temperature variations during the day. If you keep a constant room air temperature, a significant part of the storage capability will be wasted. Did you take aspects of this kind into account?

Heat transfer between rooms within a building through the internal structure is significant due to large surface areas and rather high U-values. How did you run the floors above and below your test floor?

You showed cooling energy differences between your test floor and a "standard" floor. Site measurements are very difficult—but they are very important. I have problems understanding why the precooled floor has higher cooling energy use in the afternoon. Could this indicate difficulties that occur when measuring "real life"—and do you believe that the precooled floor has a higher advantage than you stated?

**Mitchell:** At our laboratory, we have developed a program for simulating the dynamics of buildings and HVAC plants. We have simulated the dynamics of the present building in order to evaluate cooling with outside air. We have complemented many of our previous experimental studies with simulations.

In the experiments conducted on this building, the temperature of the interior mass varied about 10°F over the course of the day. I agree that the structure temperature must vary if storage is to be useful. However, there are lower and higher temperature limits due to occupant comfort.

The floors on either side of the test floor were precooled in the same manner as the test floor. This effectively eliminated conduction between the test floor and the surrounding floors. However, there appears to have been a significant convective flow on the inside along the glass windows that brought warm air from the lower seven floors into the test (ninth) floor.

The differences in cooling energy between the test and control floors in the afternoon are probably not significant. It was our perception that the temperature of the test floor structure was essentially equal to that of the control floor in the afternoon, and that the cooling requirements were probably about equal. There was not a consistent increase in use from day to day. The significant differences occurred in the morning.

**Hal Levin, Research Architect, Hal Levin & Associates, Santa Cruz, CA:** Did you consider envelope loss as trivial? Do you believe the conclusion applies to a concrete structure also? Have you investigated the physical characteristics of the fireproofing to determine its theoretical resistance to heat transfer?

Also, have you reviewed the work of Axley, where core mass is investigated in concrete structures, for potential relevance to your conclusions regarding the steel frame building you studied?

**Mitchell:** The envelope of the building is mainly glass with a relatively high conductance. We estimated that the envelope gain during the test period increased the cooling energy of the test floor by about 15%. An insulated concrete envelope could reduce this effect.

We did estimate the thermal resistance of the fireproofing and estimated the thermal resistance under the floor to be about 50% greater than that on top of the floor. Thus, there is probably significant heat flow into and out of the bottom of the floor. The experimental results include the effect of heat transfer from the bottom on the cooling load since the floor below the test floor (eighth floor) was also cooled.

Increased mass of the core could increase the storage capacity of the structure. However, the convective resistance between air and core mass, and the internal resistances in the core mass itself, may limit the amount of energy that may be stored.

**Edna Shaviv, Professor, Israel Institute of Technology, Haifa:** Your experiment was carried out in an existing building, where you could not optimize the required thermal mass. Suppose the building does not possess enough

thermal mass to store all the required energy from the pre-cooling night hours to daytime; in this case, pre-cooling should be performed for a shorter time and only before office hours. I presume that this suggested strategy would result in better savings and a reduction of peak demand?

**Mitchell:** Optimal control strategies for buildings with low thermal mass are certainly effective. A paper by J.E. Braun

in the next session shows that, even with a small amount of structure mass, maintaining the building at a low temperature during the early part of the working day and then using storage in the afternoon is effective in reducing peak loads and shifting cooling to off-peak periods. This strategy would have been more appropriate for this building.