Demonstration of Load Shifting and Peak Load Reduction with Control of Building Thermal Mass

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ABSTRACT

In this paper, results of testing at the Iowa Energy Center are presented that demonstrate the potential for load shifting and peak load reduction through precooling of the building structure. This facility is used for performing research on building controls and diagnostics and is very well instrumented and maintained. Cooling loads for individual zones can be determined directly from measurements. A sequence of two week-long tests were performed using a conventional night setup and a simple precooling control strategy. The cumulative occupied load for the test zones was 23% less for the precooling strategy than for night setup control. The simple precooling strategy was not optimized to reduce peak loads since the room temperatures were held constant in the middle of the comfort region during the entire occupied period. Even so, the cumulative peak load of the test zones was reduced by about 9% with the simple precooling strategy. The east test rooms had the largest peak load reductions (15%) because the peaks occur earlier in the day when the thermal mass is cooler and therefore are more effective as a heat sink. The interior rooms also had a significant peak load reduction (12%), whereas the south and west zones had negliglible peak load reductions for the simple strategy that was employed. The building chosen for testing was not considered to be a particularly good candidate for use of building precooling. The results make a strong case for application of control strategies that take advantage of load shifting opportunities from building thermal mass.

Introduction

In order to reduce peak electrical demands, utilities provide price incentives for use of electricity during low demand or off-peak periods. One approach to taking advantage of these incentives involves the use of the existing building structure for storage. The conventional cooling system is used to cool the air and structure during off-peak periods. Then, the zone temperatures are set to higher values during the on-peak period and the cooled structure acts to reduce heat gains to the air leading to lower on-peak electrical requirements for air conditioning. Use of the building structure for thermal storage can provide significant load shifting with minimal initial cost for both new and existing buildings. It is only necessary to change the control strategy that is utilized for adjusting zone temperature setpoints.

Most buildings employ night setup control for zone temperatures, which does not take advantage of building thermal mass. During occupied hours, zone conditions are typically controlled at constant set points that maintain acceptable comfort. During unoccupied times, the setpoints are raised, the equipment turns off, and the zone temperature is allowed to float. Night setup control strategies minimize the effects of building thermal storage. However, in many commercial buildings, the building mass has a significant thermal storage potential.

An optimal controller might precool a building during the unoccupied period and control the storage discharge process by varying the setpoints within acceptable comfort bounds during occupancy.

There have been a number of simulation studies that showed significant reductions of operating costs in buildings by proper precooling and discharge of building thermal storage, including Braun (1990), Andresen and Brandemuehl (1992), Rabl and Norford (1991), Snyder and Newell (1990), and Golneshan and Yaghoubi (1990), and Braun, Montgomery, and Chaturvedi (2001). The savings result from both utility rate incentives (time-of-use and demand charges) and improvements in operating efficiency due to night ventilation cooling and improved chiller performance (lower ambient temperatures and more even loading). The simulation studies demonstrated that the savings potential and 'best' control strategy are very dependent upon the system and particular weather conditions. Improper precooling can actually result in costs that are greater than those associated with conventional control. The importance of developing control strategies for each application has also been demonstrated through experimental evaluations.

Conniff (1991) used a test facility at the National Institute of Standards and Technology (NIST) to study the use of building thermal mass to shift cooling load. The facility was designed to represent a zone in a typical commercial office building and was configured for these tests as an interior zone with no ambient coupling. Several control strategies were considered in these tests. No attempt was made to optimize the control strategies for this facility. The most effective strategy tested for peak reduction did not utilize precooling but used a constant zone temperature for the first seven hours of occupancy followed by a limit on the amount of cooling supplied to the zone. This strategy lowered the peak cooling demand by up to 15% when compared to night setup control. Other strategies that utilized precooling resulted in minimal cooling demand reductions (3%). Since thermal comfort was not evaluated during the tests, additional precooling may have been possible without sacrificing occupant comfort.

Morris, Braun, and Treado (1994) devised and performed a set of experiments at the same facility used by Conniff (1991) in order to validate the potential for load shifting and peak reduction associated with optimal control of building thermal mass. Optimization techniques were applied to a detailed simulation model of the structure in order to determine control strategies used in two separate tests. The first control strategy was designed to minimize total energy costs and resulted in the shifting of 51% of the total cooling load to the off-peak hours. The second control strategy was designed to minimize the peak electrical demand and resulted in a 40% reduction in peak cooling load. In both of these tests, data were collected to measure the occupant thermal comfort. Thermal comfort was maintained within acceptable limits through both of the experiments. The results of Morris, Braun, and Treado (1994) were more encouraging than those of Conniff (1991) for the same test facility because the control was optimized. Another important result of this work was the validation of the model used to develop the optimized control strategies.

There have also been some limited field studies relating to use of building precooling strategies. Ruud, Mitchell, and Klein (1990) performed two precooling experiments on an office building located in Jacksonville, FL. The results showed 18% of the total daytime cooling load was shifted to the night period with no reduction in peak demand. Again, the control strategies used in that study were not optimized for the building considered. Keeney and Braun (1997) demonstrated a simple control strategy that makes use of building thermal mass in order to reduce peak cooling requirements in the event of a loss of a chiller. The control strategy was tested in a 1.4 million square foot (130,000 square meter) office building located near Chicago, IL. The facility has two identical buildings with very similar internal gains and solar radiation loads that are connected by a large separately cooled entrance area. During tests, the east building used the existing building control strategy while the west building used the precooling strategy. Consistent with simulation predictions, the precooling control strategy successfully limited the peak load to 75% of the cooling capacity for the west building, while the east building operated at 100% of capacity. Braun, Montgomery, and Chaturvedi (2001) used data from this same facility to construct an inverse model and then used the model to estimate the savings associated with different control strategies that take advantage of building thermal mass. The model predicted HVAC utility costs for a summer month billing period that were within approximately 5% of actual costs. The best control strategy resulted in approximately a 40% reduction in total cooling costs as compared with night setup control.

Although the savings potential for use of building thermal mass has been demonstrated, there have been very few applications. Part of the reason is that guidelines for the development and application of effective control strategies do not exist. Furthermore, there have only been a limited number of field demonstrations and there is no conclusive evidence that the majority of commercial buildings can take advantage of building thermal mass for load shifting. The objective of the study described in this paper was to demonstrate the potential for load shifting in a building that is not a particularly good candidate for use of building thermal mass. If there is savings potential for this facility, then it will make a strong case for use of building precooling strategies in a broad range of building structures.

The Iowa Energy Center was selected for testing in this project. The facility has four sets of identical zones (two zones facing east, west, and south with external boundary conditions and two internal zones) on two separate air distribution systems. A third air handling unit serves the remainder of the building, including the office spaces adjacent to the test zones. A typical use of the facility involves comparing energy use between test systems while running one test air handling unit and the four zones it serves under one control strategy, and the second air handling unit and set of zones under a different strategy. That was the intent when plans for testing the night setback and building precooling strategies were conceived. Other advantages of testing at this facility include excellent on-site support, excellent instrumentation, and well-documented building construction. However, the building is not a great candidate for use of building thermal mass. It is a single-story structure with a high exterior surface area to volume ratio and there may be significant thermal coupling with the ground and ambient and to adjacent zones within the building. Furthermore, the test zones have no internal furnishings and the floor is carpeted. In order to prepare for testing, detailed simulations of the test zones were developed and used to evaluate the load shifting potential. Through these simulations it was discovered that the thermal coupling between the test zones and adjacent zones was significant. As a result, there would be significant energy transfers between zones that utilize different zone temperature control strategies (e.g., night setup versus precooling strategies). A decision was made to control the entire facility with a uniform control strategy and conduct two tests over two different time periods for the two strategies. Testing was performed during the month of August 2001. This paper describes the test procedures and results of these tests.

Test Description

Figure 1 shows a layout of the Energy Resource Station at the Iowa Energy Center. There are 8 test rooms where internal gains can be controlled and detailed measurements are performed. The rooms are organized in pairs with three sets of zones having one exterior wall (east, east, and south) and one set that is internal. The zones within a pair are identical and labeled 'A' and 'B'.

The building is a single story with a concrete slab on grade. Each zone has a net floor area of 275 ft^2 and the floor is carpeted. The ceiling is suspended with recessed lights. The ceiling height is 8.5 ft and there is a plenum above the suspended ceiling with a height of 5.5 ft. The exterior zones all have 74 ft^2 of window area. The windows are double pane ¼" clear insulating glass and have a shading coefficient of 0.85. During the tests, no blinds or other forms of shading were used. Furthermore, there is no shading from trees or adjacent buildings.

Internal gains within each zone can be simulated using baseboard heat and lights. Both the baseboard heat and lighting have two stages of control. The maximum output of the heaters is 1.8 kW (900 watts per stage) for each test zone. The maximum wattage associated with the lights is 585 W for each room.

There are two separate air-handling systems for the test rooms, one for the A rooms and a separate one for the B rooms. A third separate air-handling unit serves the rest of the building. Each zone has a VAV box with terminal reheat. The air-handling units use chilled water and heated water provided by a central plant.

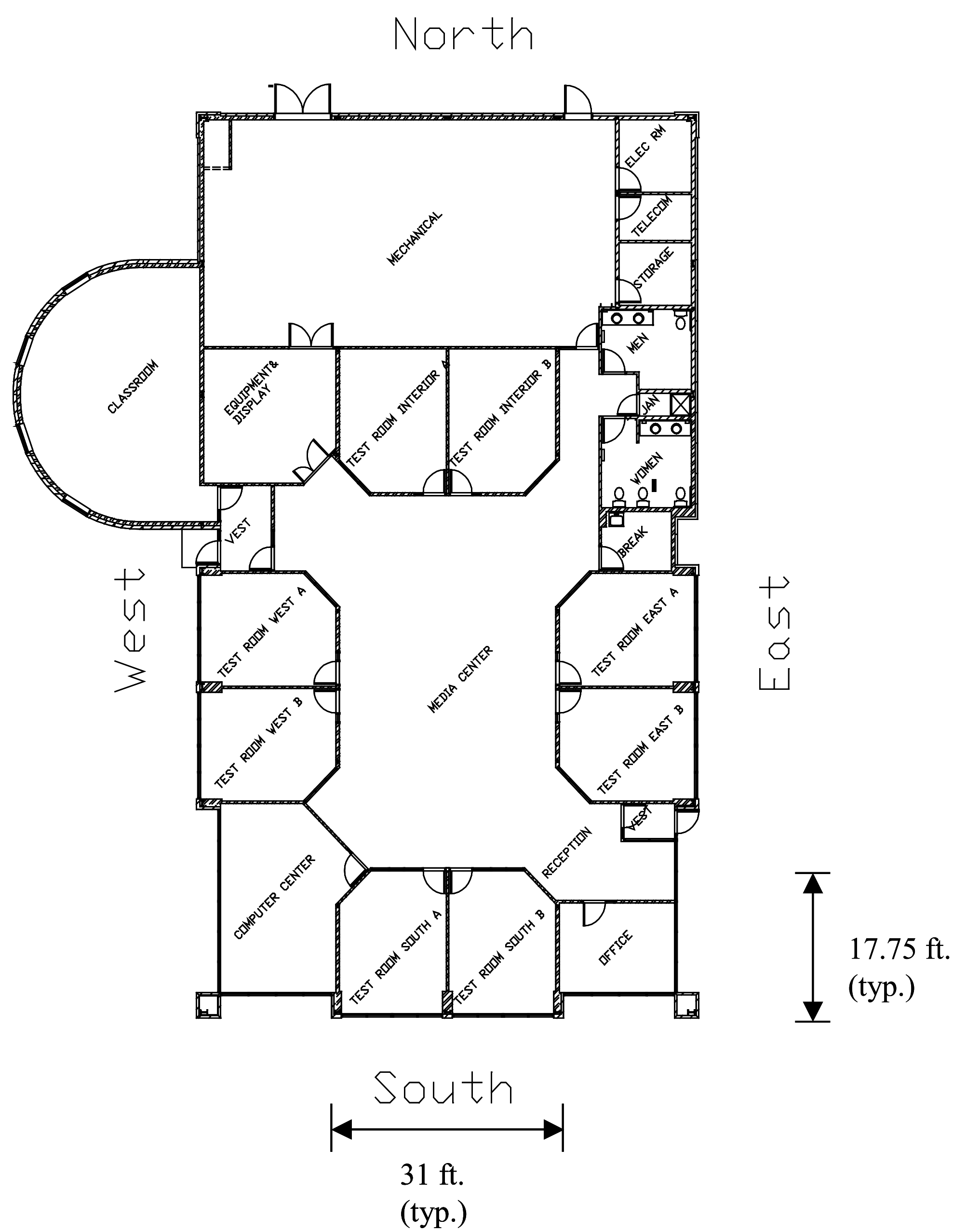
There is an on-site weather station with measurements of outdoor dry bulb, relative humidity, wind speed and direction, total normal solar flux, and global horizontal solar flux. Measurements for each zone include air flow rate, supply air temperature, return air temperature, and reheat power input. Zone sensible cooling requirements are estimated from these measurements.

There were two sets of tests performed with different schedules for temperature setpoints for the test rooms. In order to minimize coupling between zones, the entire facility was controlled with the same setpoints for each test. Each test was supposed to be carried out for 7 days. For both sets of tests, one stage of baseboard heat and two stages of lighting were employed for all of the test zones during a simulated occupied period that extended from 7 am to 6 pm. During the unoccupied period (6 pm to 7 am), heating and lighting were turned off. Additional thermal mass was added to the interior test room A in the form of two rows of standard concrete cinder block, 10 feet long each stacked with three layers of block each. The walls were located near the middle of the test room.

In the first phase of testing (Phase I), the specified strategy for the entire building was night setup control. A setpoint of 74°F was specified during the occupied period (7 am to 6 pm) and a setpoint of 80°F was to be used for the unoccupied period (6 pm to 7 am). The first test began at midnight on 8/3/01. During the first few days of testing, the zone temperature in the west zones exceeded 80°F in the early evening due to solar loads between 6 pm and sundown causing the air-handling system to initiate cooling to maintain the 80°F setpoint. Due to a minimum flow requirement for the VAV boxes and no internal gains at night, the other zones were precooled significantly during these periods resulting in an undesirable representation of night setup control. Raising the unoccupied temperature setpoint to 90°F eliminated this condition and five more days of testing were performed from midnight on 8/9/01 through 8/12/01.

For the second test (Phase II), the entire building was run with a simple precooling strategy. The daytime cooling setpoint was 74°F from 6 am to 6 pm. Then, the temperature was setup to 90ºF from 6 pm to 12 midnight. The nighttime precooling temperature setpoint was 68°F from 12 midnight to 6 am. The precooling test started at midnight on 8/14/01 and ended at the end of the day on 8/20/21.

Figure 1. Energy Resource Station at the Iowa Energy Center



Test Results

Weather Data Comparisons

Figure 2 gives ambient temperature and solar radiation data for the two test periods. In general, the Phase I test period was warmer and sunnier than the Phase II period. However, the weather for the two-day sequence from August 10 to 11 was similar to the weather for August 19 to 20. Furthermore, the weather for the days preceeding these two-day sequences was also fairly similar, which helps to remove any past-history effects. These two-day sequences were chosen as the basis for comparing the cooling loads associated with the night setup and precooling strategies. Figure 3 gives a comparison of the data for these two-day sequences. For the first day of the sequence, the Phase II solar radiation is a little lower, but the ambient temperature is a little higher during the middle of the day. For the second day, both the solar radiation and ambient temperature are lower for Phase II.

Figure 2. Weather Data for Night Setup (Phase I) and Precooling (Phase II) Tests

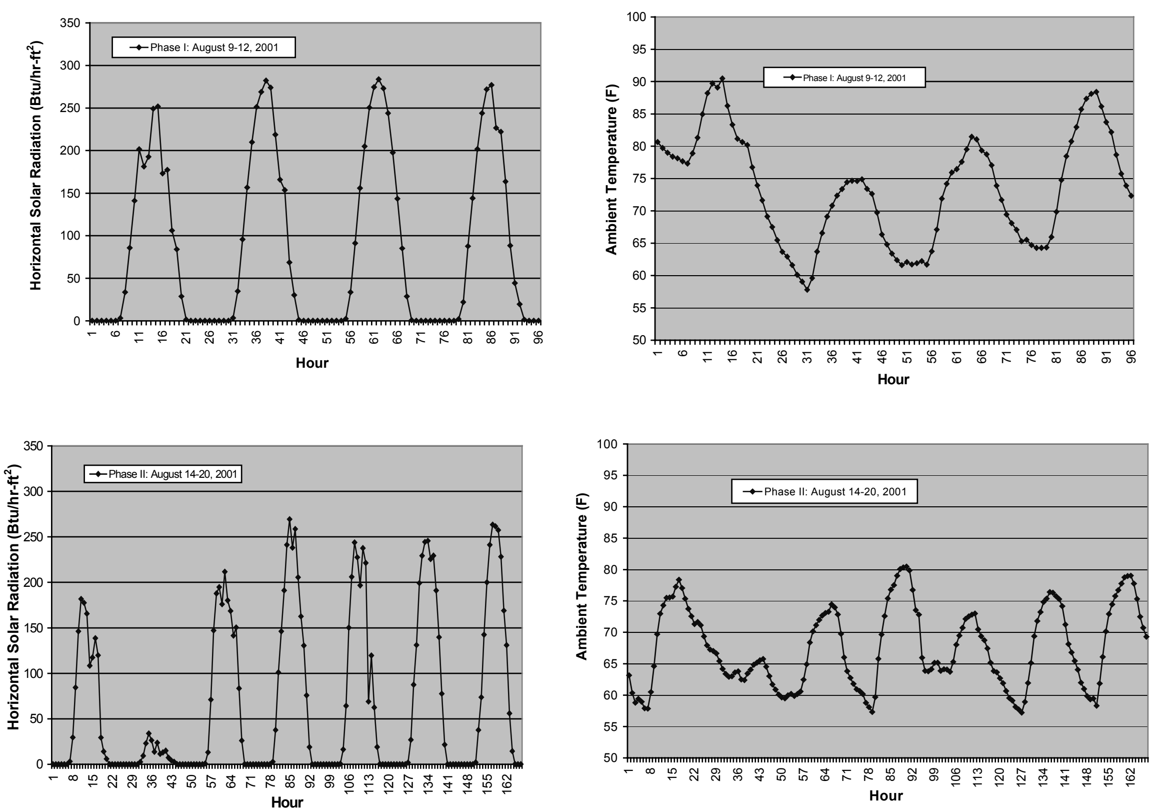
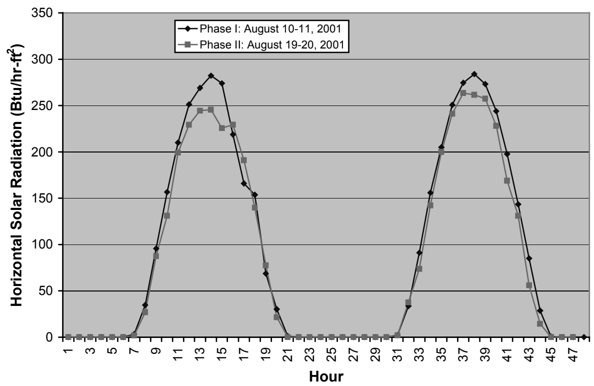
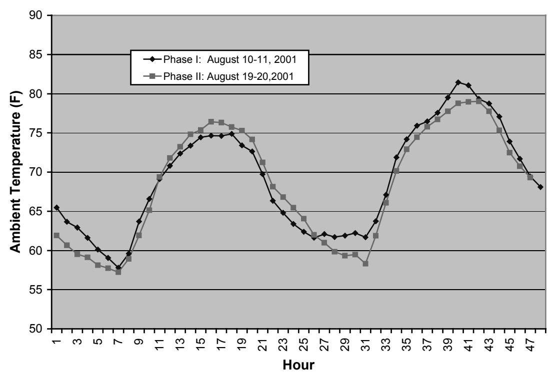


Figure 3. Weather Data for Two-Day Sequences used to Compare Night Setup (Phase I) and Precooling (Phase II) Tests





Interior Test Rooms

Figures 4 and 5 show interior room sensible cooling loads for the Phase I and II testing sequences. The effect of precooling on these zones is quite dramatic. The loads associated with night setup (Phase I) are relatively flat, whereas the precooling strategy (Phase II) results in very low loads during the early hours of occupancy and peak loads at the end of occupancy and start of precooling. The loads for the Phase I sequence are very similar for the two days. However, the loads for the Phase II sequence are somewhat higher on the second day than for the first day, possibly due to higher solar radiation absorbed on the roof. The impact of the added mass for test room A was relatively small.

For both interior zones, the total cooling load during the occupied period (7 am to 6 pm) is about 31% lower for the Phase II sequence. The peak load during the occupied period is about 12% lower for Phase II. Much greater peak load reductions would be possible if the zone temperature were adjusted within the comfort zone rather than being held constant in the middle of the comfort region. The total cooling requirement associated with the Phase II sequence is about 6% lower than for the Phase I sequence. This could be due to lower solar radiation incident upon the roof during the Phase II sequence.

Figure 4. Interior Test Room A Sensible Loads for Two-Day Sequences

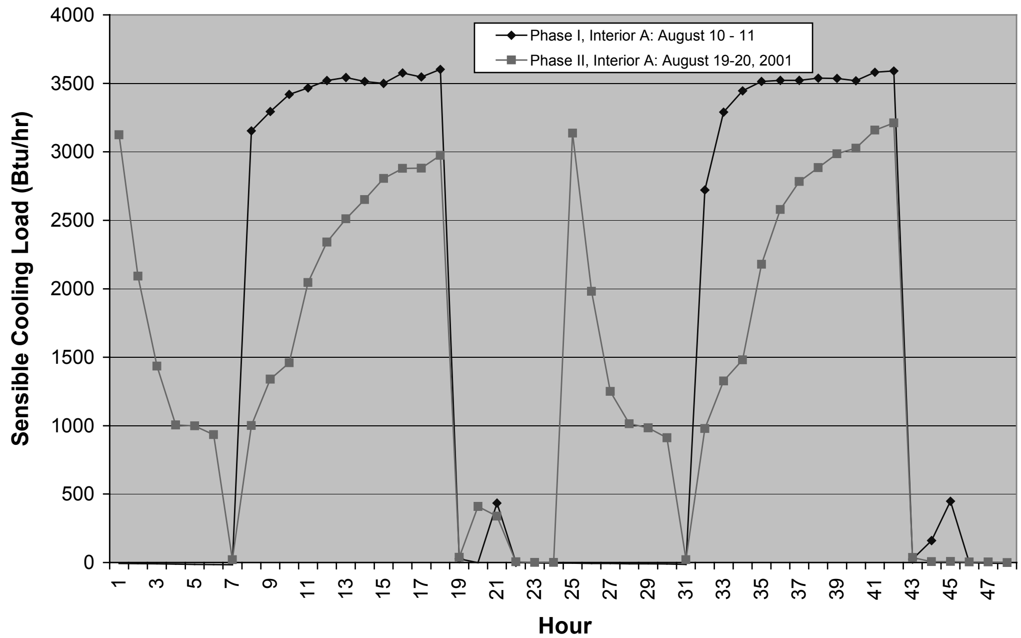
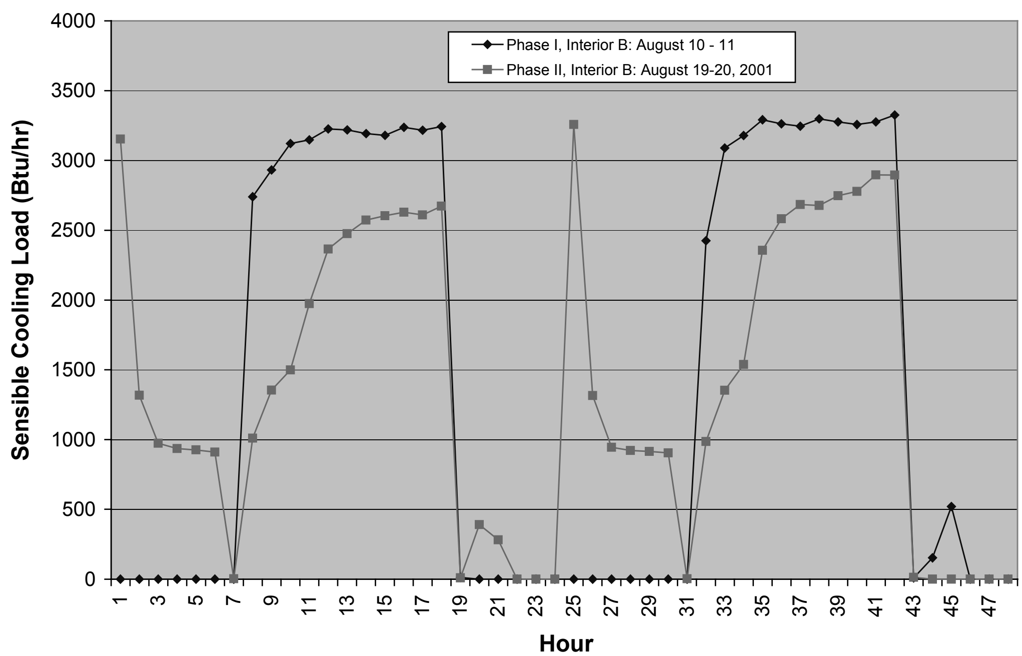


Figure 5. Interior Test Room B Sensible Loads for Two-Day Sequences



East Test Rooms

Figure 6 gives sensible cooling loads for both east facing test rooms during the Phase I and II sequences. The peak loads for these rooms occur during the morning hours due to solar radiation coming through the windows. The night setup and precooling strategies result in similar load shapes. However, for the Phase II sequence the total load and peak load for the occupied period were about 21% and 15% less, respectively. The load shifting percentage is less than for the interior rooms because of greater coupling to the ambient. Precooling results in greater heat gains which reduces the load shifting potential. The peak load reduction is larger than for the interior rooms because the peak occurs during the morning hours when the effect of the cooled thermal mass is greatest. Even greater peak load reductions would be possible if the room temperature was varied within the comfort region rather than being held constant. The total cooling requirement associated with the Phase II sequence is about 4% lower than for the Phase I sequence. This could be due to lower solar radiation during the Phase II sequence, which offsets the effect of precooling.

South Zones

Figure 7 gives sensible cooling loads for both south facing test rooms during the Phase I and II sequences. The peak loads for these rooms occur during the late afternoon hours where the effects of thermal mass precooling are largely diminished. Most of the load reduction associated with precooling occurs during the morning hours when the loads are lower. The total load and peak load for the occupied period were about 18% and 4% less for the Phase II sequence. Again, much greater peak load reductions would be possible if the room temperature was varied within the comfort region rather than being held constant. The total cooling requirement associated with the Phase II sequence is about 1% larger than for the Phase I sequence. This is due to the increased gains associated with precooling, which offsets the effect of smaller solar radiation.

Figure 6. Sensible Loads for East Test Rooms for Two-Day Sequences

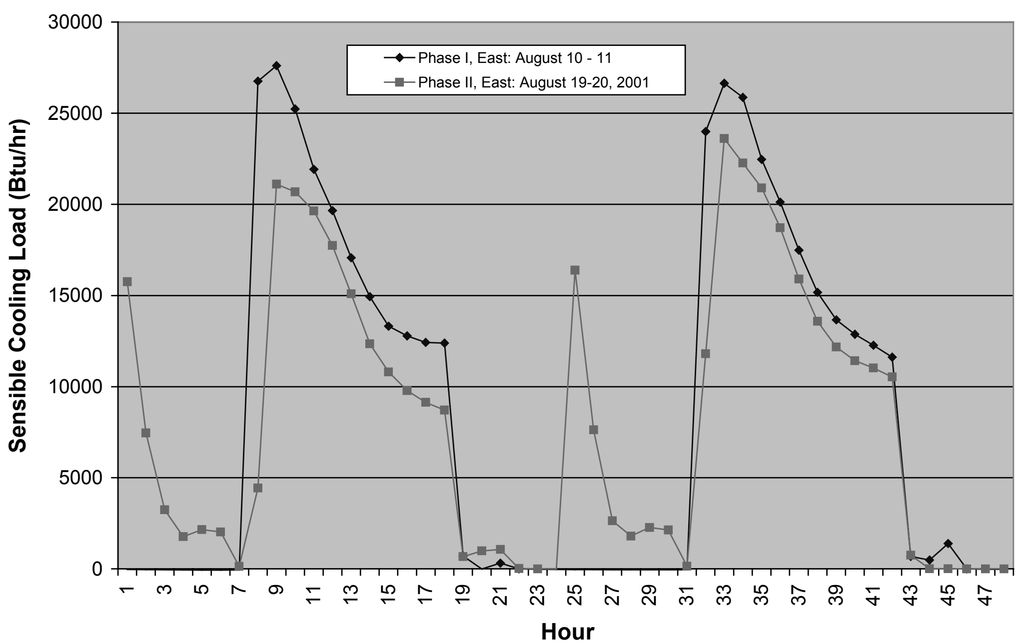
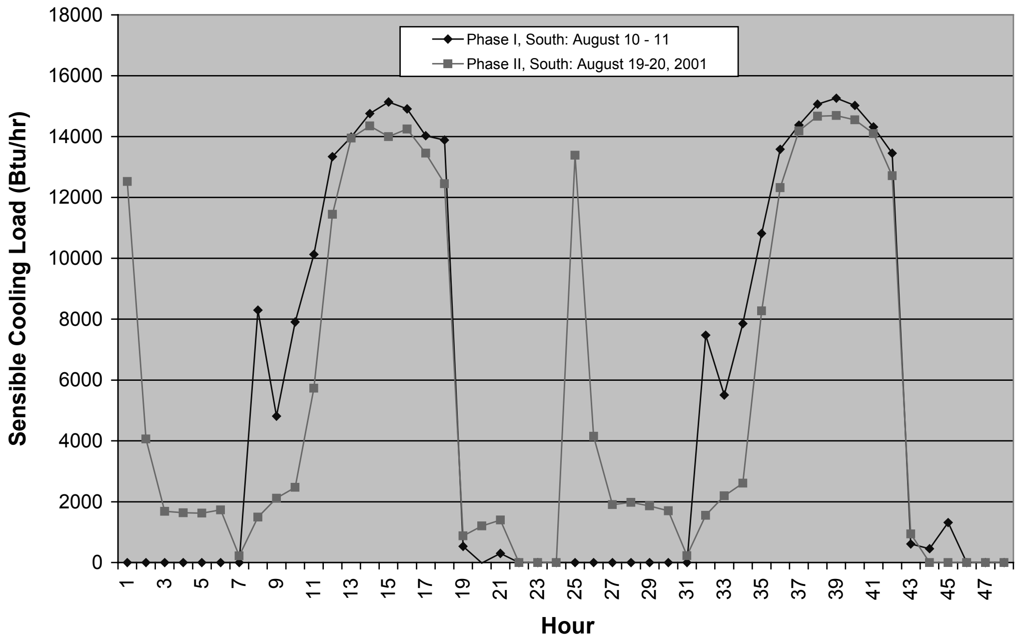


Figure 7. Sensible Loads for South Test Rooms for Two-Day Sequences



West Test Rooms

Figure 8 gives sensible cooling loads for both west facing test rooms during the Phase I and II sequences. The peak loads for these rooms occur at the end of the day due to solar radiation coming through the windows. At this point the effect of the thermal mass precooling is largely diminished. For the night setup control, a second smaller peak occurs during the early morning hours due to the solar gains from the end of the previous day. Most of the load reduction associated with precooling occurs during the morning hours. The total load and peak load for the occupied period were about 27% and 3% less for the Phase II sequence. Again, much greater peak load reductions would be possible if the room temperature was varied within the comfort region rather than being held constant. The total cooling requirement associated with the Phase II sequence is about 3% larger than for the Phase I sequence. This is due to the increased gains associated with precooling, which offsets the effect of smaller solar radiation.

Combined Zones

Figure 9 gives total sensible cooling loads for all of the test rooms during the Phase I and II sequences. For night setup control, the loads are relatively flat during the occupied period with a peak load near the end of the day. The total load and peak load were about 23% and 9% less for the Phase II sequence. Of course, much greater peak load reductions would be possible if the room temperature was varied within the comfort region rather than being held constant. The total cooling requirement associated with the Phase II sequence is about 1% smaller than for the Phase I sequence.

Figure 8. Sensible Loads for West Test Rooms for Two-Day Sequences

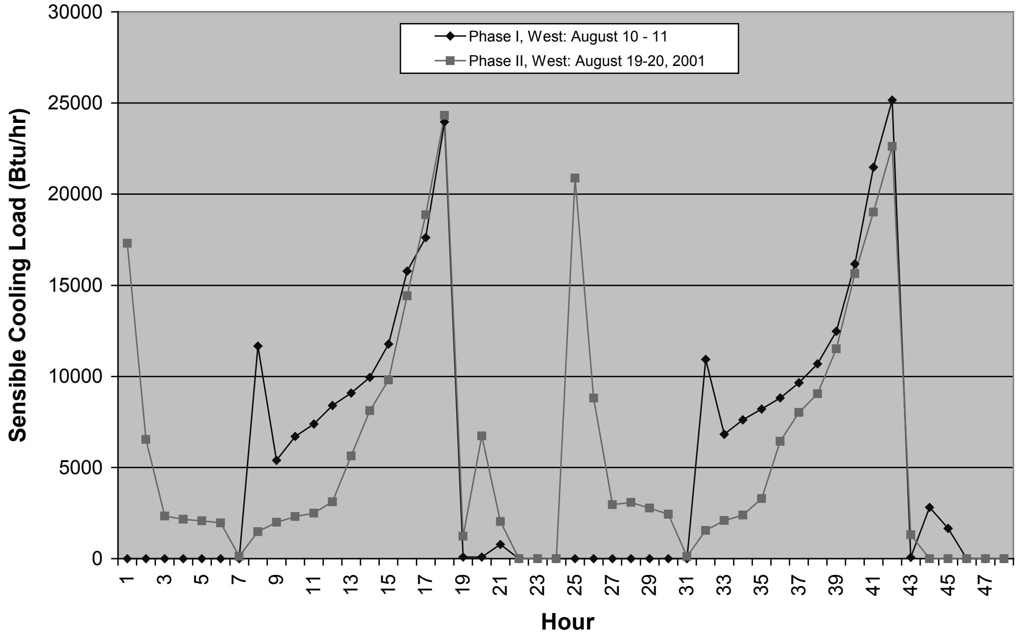
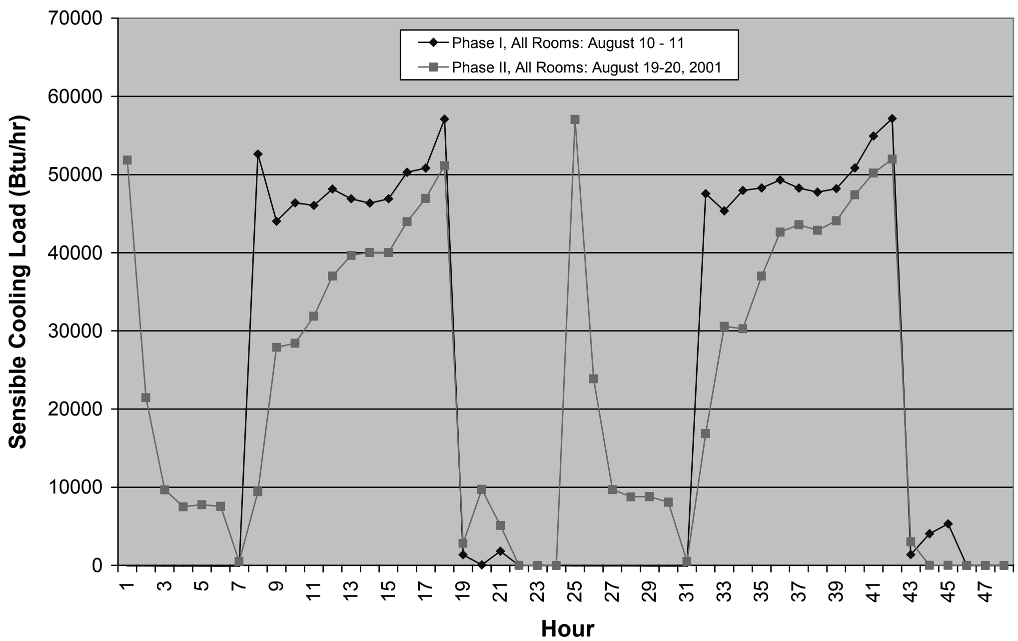


Figure 9. Sensible Loads for All Test rooms for Two-Day Sequences



Conclusions

Testing was performed at the Iowa Energy Center in order to demonstrate the load shifting potential associated with building precooling. This is not a particularly good candidate structure for application of building precooling since it has a single story with a relatively high exterior surface area to volume ratio, no internal furnishings, and a carpeted floor. However, the load shifting potential is still significant. The greatest potential exists for interior zones. For the interior test rooms, the total occupied period load was approximately 31% less for a simple precooling strategy compared to a night setup control. The load shifting was less for exterior zones with the west, east, and south zones having occupied period loads for precooling that were 27%, 21%, and 18% less than those associated with night setup control. Cumulatively, the occupied period load for the zones was 23% less than that associated with night setup control. The simple precooling strategy was not optimized to reduce peak loads since the room temperatures were held constant in the middle of the comfort region during the entire occupied period. Even so, the cumulative peak load associated with the test zones was reduced by about 9% with the simple precooling strategy. The east test rooms had the largest peak load reductions (15%) because the peaks occur earlier in the day when the thermal mass is cooler and therefore are more effective as a heat sink. The interior rooms also had a significant peak load reduction (12%), whereas the south and west zones had negliglible peak load reductions for the simple strategy that was employed.

References

Andresen, I. and Brandemuehl, M.J., 1992, "Heat Storage in Building Thermal Mass: A Parametric Study," ASHRAE Transactions, Vol. 98, Part 1, pp. 496-504.

Braun, J.E., 1990, "Reducing energy costs and peak electrical demand through optimal control of building thermal storage," *ASHRAE Transactions*, Vol. 96, Pt. 2, pp. 876-888.

Braun, J.E., Montgomery, K.W., and Chaturvedi, N. "Evaluating the Performance of Building Thermal Mass Control Strategies," International Journal of Heating, Ventilating, Air-Conditioning and Refrigeration Research, Vol. 7, No. 4, pp. 403-428, 2001.

Coniff, J.P., 1991, "Strategies for reducing peak air conditioning loads by using heat storage in the building structure," *ASHRAE Transactions*, Vol. 97, pp. 704-709.

Golneshan, A.A. and Yaghoubi, M.A., 1990, "Simulation of Ventilation Strategies of a Residential Building in Hot Arid Regions of Iran," *Energy and Buildings* 14: 201-205.

Keeney, K.R. and Braun, J.E., 1997, "Application of Building Precooling to Reduce Peak Cooling Requirements," *ASHRAE Transactions*, Vol. 103, Pt. 1, pp. 463-469.

Montgomery, Kent W., 1998, "Development of Analysis Tools for the Evaluation of Thermal Mass Control Strategies," Report No. HL98-17, Herrick Laboratories, Purdue University, West Lafayette, Indiana.

Morris, F.B., Braun, J.E., and Treado, S.J., 1994, "Experimental and simulated performance of optimal control of building thermal storage," *ASHRAE Transactions*, Vol. 100, Pt. 1, pp. 402-414.

Rabl, A. and Norford, L.K., 1991, "Peak Load Reduction by Preconditioning Buildings at Night," *International Journal of Energy Research* 15: 781-798.

Ruud, M.D., Mitchell, J.W., and Klein, S.A., 1990, "Use of building thermal mass to offset cooling loads," *ASHRAE Transactions*, Vol. 96, Pt. 2, pp.820-829.

Snyder, M.E. and Newell, T.A., 1990, "Cooling cost minimization using building mass for thermal storage," *ASHRAE Transactions*, Vol. *96*, Pt. 2, pp. 830-838.