COOLING STRATEGIES BASED ON INDICATORS OF THERMAL STORAGE IN COMMERCIAL BUILDING MASS

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ABSTRACT

Building thermal mass and multi-day regimes of hot weather are important, yet poorly understood, contributors to cooling energy requirements. This paper develops load-shifting sub-cooling and pre-cooling equipment operating strategies to address a specific instance of this phenomenon, in which thermal storage by building mass over weekends exacerbates Monday cooling energy requirements. The study relies on computer simulations of energy use for a large, office building prototype in El Paso, TX using the DOE-2 building energy analysis program. The economic value of the strategies is evaluated with direct reference to utility rate schedules and a crude measure of thermal storage is related to the energy impacts of the strategies. The indicators are based on core zone air temperatures, which are sampled at night when HVAC systems are not in use. The suggestion is made that the results and proposed strategies could be adapted for use by computerized energy management systems to reduce building energy operating costs.

INTRODUCTION

The energy costs of commercial buildings are strongly determined by electricity requirements for cooling. The costs of meeting these requirements include peak demand and on-peak energy use charges to the user, and capital requirements for investment by the utility. Building thermal mass and multi-day regimes of hot weather are important, yet poorly understood, contributors to cooling energy requirements. With the advent of computers, however, sophisticated models of heat transfer in buildings can be used to study the impact of these factors on building energy performance at an unprecedented level of detail. Armed with these tools, detailed results from the research community can now be applied to the development of operating strategies that reduce energy use and costs. This study uses one such computer-based model to study a specific transient heat transfer phenomenon and suggests techniques to mitigate its impact on commercial building cooling loads.

Anecdotal evidence suggests that in the summer many commercial buildings experience peak demands for electricity on Mondays. In a previous study, this phenomenon was documented with computer simulations (1). The results of this study indicate that on Mondays, the storage of heat in the building mass over the weekend combines with the normal loads imposed by lighting, equipment, and people to exacerbate cooling energy requirements. During the weekend, HVAC systems are not in operation and heat gains (from insolation, conduction, infiltration, and energy-using equipment) are allowed to "charge" the thermal mass of the structure. To maintain comfort conditions on Mondays, HVAC equipment must work harder to compensate for increased heat gains released by the building mass. In so doing, energy use is increased as is the likelihood of recording a peak demand. In the present paper, these results are extended with the development of cooling strategies that are based on measures of thermal storage by building mass.

BACKGROUND

This section describes the components of the study to develop cooling strategies that mitigate the impact of thermal storage in building mass on commercial building cooling loads. Previous work, which provides the context for the development of these strategies, is briefly reviewed.

MODELING THERMAL STORAGE IN BUILDING MASS

The DOE-2 building energy analysis program (version DOE-2.1C) was used to study the effects of thermal mass on commercial building cooling requirements. The DOE-2 program was developed by the Lawrence Berkeley and Los Alamos National Laboratories for the Department of Energy to provide architects and engineers with a state-of-the-art tool for estimating building energy performance (2).

Four features make DOE-2 particularly applicable to the study of thermal storage in building mass:

1. Heating and cooling loads are calculated on an hourly basis.
2. The dynamic effects of structural mass on the thermal storage characteristics of a building are calculated using "weighting factors," which account for the time delay between an instantaneous heat gain and the resultant cooling load. Separate weighting factors are used for solar radiation entering through the windows, general lighting, task lighting, heat generated by people and equipment, and energy entering the room by conduction through the walls (3).
3. The operation of the building can be completely specified by user-inputs.
4. The user can enter a customized utility rate structure to study time-of-day rate schedules

and demand charges with sophisticated ratchet provisions.

The DOE-2 program has been validated in many studies. Perhaps the most comprehensive recent comparison of predicted versus measured results for an office building is described in Tishman Research Corp. (4). This study found excellent correspondence between sub-metered measurements and predicted values. Of particular relevance for the use of DOE-2 in thermal mass studies are shorter studies by McLain, et al. (5) and Birdsall (6). These studies compare DOE-2 predictions with measured data from test cells in New Mexico and Maryland. These test cells were designed to study the effects of thermal mass and have been extensively instrumented.

LARGE OFFICE BUILDING PROTOTYPE

A large office building prototype was selected for the study because such buildings are good candidates for the implementation of load-shifting cooling strategies that utilize building thermal mass. Large office buildings have substantial thermal mass as well as loads that are typically dominated by internal gains. Importantly, large office buildings often have large cost incentives to reduce on-peak energy use and peak demands.

The prototype was based on an actual building in Indianapolis built in 1981. For this study, only the office tower complex was modeled. The complex consists of 38 floors and two basement levels. The tower is a flattened hexagon in cross-section, with approximately 18,000 square feet (1670 square meters) per floor, that flares out to a larger base at the bottom floors. The building structure is a steel frame with 4 inches (10 cm) of limestone cladding. The tower is about 25% double-paned, bronze-tinted glass, predominantly on the NW and SE faces. Modifications were made to the DOE-2 input file to ensure that the prototype was in compliance with ASHRAE Standard 90-1975 (7).

Building operation followed a typical office schedule. The schedules for occupancy, lighting, equipment, elevators, and fan operation were taken from the Standard Evaluation Technique prepared for the Building Energy Performance Standards program: 8 AM to 6 PM on weekdays, with some evening work, about 30 % occupancy on Saturdays (no evenings), and closed on Sundays and holidays. The zone thermostat settings were 78 F (26 C) cooling and 72 F (22 C) heating with a night and weekend heating setback of 55 F (13 C). Lighting was provided by recessed fluorescent fixtures, which returned 30 % of the lighting heat directly to the plenum. Light loads were estimated at 1.7 W/sqft and equipment was .5 W/sqft.

The perimeter systems were variable air volume (VAV) reheat systems with a minimum stop on the VAV reheat box of 30 %. Separate interior systems were 100 % shut-off VAV, with no reheat coil. Combined motor/fan efficiency was 55 % for the supply air and 47 % for the return air. All air handling units were equipped with drybulb-actuated economizers with a control limit of 62 F (17 C). Heat was furnished by two gas-fired hot water generators. Cooling was furnished by two hermetic centrifugal chillers. Cooling tower water temperatures were allowed to float to a minimum of 65 F (18 C) entering the condensers.

EL PASO WEATHER

The choice of climate reflected a desire to investigate thermal storage effects in a region of the country where cooling requirements are high. The bias introduced by this choice of climate cannot be determined, *prima facie*. Future studies for other climates are anticipated.

The hot, dry climate of El Paso was represented by a WYEC weather tape (8). WYEC data were developed for ASHRAE specifically for energy calculations. In addition to extensive reliance on long-term average weather conditions, actual measurements for solar radiation were used to create a year-long data tape of representative weather.

THE MONDAY EFFECT

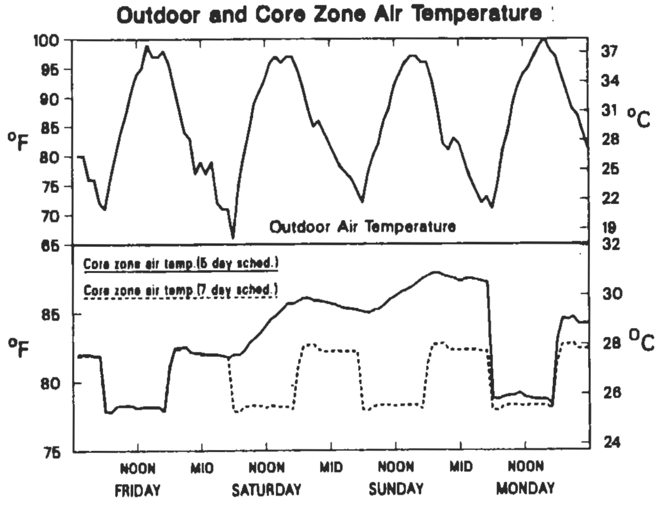
Previous work by Eto and Powell (1) documented the existence of a Monday effect with computer simulations. The test consisted of simulating the building with and without a weekend equipment shutdown schedule. Cases with weekend shut-downs (5-day operation) followed the operating schedule described above, whereas cases without weekend shut-downs followed the Monday thru Friday schedule all week (7-day operation). Differences in Monday peak and total electricity use, therefore, were the result of different operating schedules responding to *identical* weather conditions.

Daily electricity use and peak demands were examined for each day of weather during the summer cooling months of June, July, and August. By changing the calendar year specification for 7 separate year-long runs, results were generated for every summer day of weather. That is, while Monday falls on June 5, 1978, it falls on June 6, 1979. By repeating this procedure 7 times for both 5- and 7-day operating schedules, a data set containing results for Monday operation for every summer day of weather, with and without weekend operation, was produced.

The use of differences in total HVAC electricity consumption differs from many thermal mass studies (9,10). These studies concentrate on HVAC load impacts, with little discussion of resulting electricity consumption. This practice, while highly appropriate for many purposes, can lead to misleading conclusions from the standpoint of evaluating potential operating savings. Economizer cycles and equipment efficiencies must be accounted for in order to determine net energy savings on which to base alternative operating decisions.

The study found that annual peak demand occurred on a Monday in every simulation of the 5-day schedule of operation. Further, monthly peak demands occurred on Mondays for 76 % of the 21 summer months examined. An additional 10 % of the monthly peak demands deserve inclusion since they occurred on Tuesdays following Fourth of July weekends where Monday was a holiday. For the 5-day operating schedule, no monthly peak demand occurred on a Friday, Saturday, Sunday, or Holiday. Finally, every monthly peak demand was greater than the corresponding month's peak demand under the 7-day operating schedule.

Total daily electricity use and peak demand on Mondays were consistently higher under the 5-day schedule of operation. These results were statistically significant at a level of three standard deviations. Total electricity consumption on Monday increased by a greater percentage than peak demand on Monday. Monday electricity use increased an average of 5 % (standard deviation = 1.6 %), while Monday peak demand increased an average of 3 % (standard deviation = 1.0 %).



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Comparisons of weekend interior air temperatures confirmed that increases in Monday electricity use and peak demand are related to thermal storage by the building mass. Net energy gains by the building mass result in higher interior temperatures when the HVAC systems are not in operation. Figure 1 plots one set of core zone air temperatures for each hour from Friday through Monday for both operating schedules. Under the 7-day operating schedule, the core zone air temperature follows a regular pattern as the HVAC system responds to the ambient weather pattern. During operating hours, air temperatures are driven down to the 78 F (26 C) setpoint. During non-operating, hours, temperatures float upward rapidly reaching a plateau around 82 F (28 C). Under a 5-day operating schedule, the core air temperature continues to float upward following Friday operation reaching a maximum of 88 F (31 C) on Sunday, about 6 F (3 C) higher than the maximum reached under the 7-day operation.

Not surprisingly, the average of Sunday peak core temperatures were always higher under the 5-day operating schedule. Average Sunday peak core zone air temperatures averaged 86.2 F (30.1 C) with a standard deviation of 1.2 F (0.7 C). Under the 7-day schedule, the average was 82.3 F (27.9 C) with a standard deviation of 0.3 F (0.2 C).

COOLING STRATEGY DEVELOPMENT AND ANALYSIS

Previous work describes the importance of Monday energy use and peak demands for building operating costs. This section describes how load-shifting cooling strategies can mitigate the energy cost impact of this thermal storage phenomenon.

LOAD SHIFTING COOLING STRATEGIES

Monday on-peak electricity use and peak demands will be reduced by either minimizing thermal gains to the building over the weekend or removing these gains in a timely fashion. The former is largely the response of the building and its HVAC systems to exogenous forces, the weather, and hence is not subject to control by a building operator. The latter approach, therefore, forms the basis for the development of control strategies.

The energy use impact of two overlapping load shifting cooling strategies, pre-cooling and subcooling were examined. Pre-cooling refers to earlier starting times for the HVAC systems. Subcooling, used in conjunction with the first, refers to lower temperature set-points during the pre-cooling period. Under normal operating conditions, the building HVAC systems are scheduled to start at 7 A.M. with a cooling set-point of 78 F (26 C). Pre-cooling start times of 6, 4, and 2 A.M. were combined with sub-cooling set-point temperatures of 78, 75, and 72 F (26, 24, and 22 C) for a total of nine parametric runs for each Monday in the summer.

An examination of the trade-offs between fan power and chiller operation is implicit in the choice of these parametric variations. Both ventilation quantities and the temperature of the ventilation air contribute to the removal of heat from the building mass. Figure 2 illustrates the effect of this trade-off for one set of pre-cooling strategies.

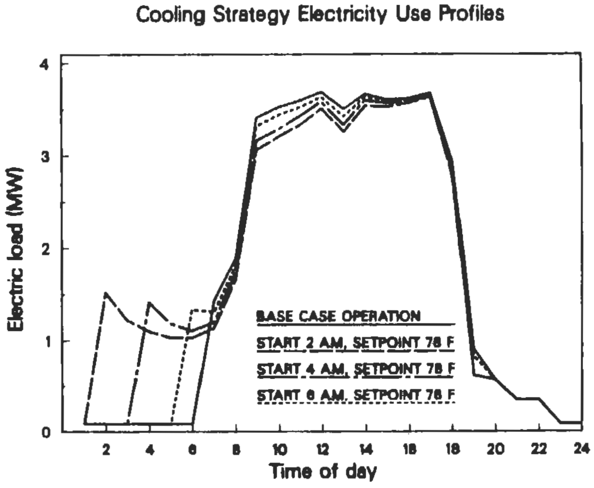

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Table 1 summarizes the changes in on- and off-peak electricity consumption for one Monday. Earlier start times and lower temperature set-points appear to reduce on-peak energy consumption and peak demand in a predictable fashion; the space cooling load has been shifted to an earlier time in the day, but the shifts have increased total electricity consumption.

Table 1. Load-shifting Cooling Results for July 22, 1985

Fan Start Time (AM)	Set-Point Temp (F)	Change in Electricity (kWh)	Change in Peak Demand (kW)	Change in On-Peak (kWh)	Change in Off-peak (kWh)
6	78	+ 507	- 29	- 311	+ 819
4	78	1886	48	629	2515
2	78	3278	62	820	4098
6	75	488	35	388	876
4	75	2039	62	802	2841
2	75	3489	84	1100	4590
6	72	634	39	444	1078
4	72	2530	71	923	3453
2	72	4312	100	701	5013

Base case electricity consumption = 37840 kWh; peak demand = 3552 kW.
Base case operating conditions: fan start 7 AM, set-point 78 F.
On-peak hours are 8 AM - 6 PM.

Table 2 summarizes the impact on on- and off-peak electricity consumption for all of the Mondays in a single summer season. On-peak energy decreases are related directly to off-peak energy increases and expressed as a ratio. The form of this presentation illustrates the efficiency of the building mass as a thermal storage device. Compared to ice or chilled water thermal storage devices, which are physically distinct from the building structure, the magnitude of the loads shifted and associated efficiencies are low. Nevertheless, there is no additional capital cost associated with this form of thermal storage.

Table 2. Summary of Load-shifting Cooling Strategy Impacts

Change in On-peak Energy/Change in Off-peak Energy

Start Time (AM): Set Point (F):	6 78	4 78	2 78	6 75	4 75	2 75	6 72	4 72	2 72
June 3	.233	.174	.153	.317	.213	.197	.310	.210	.197
June 10	.395	.239	.201	.451	.272	.234	.420	.268	.227
June 17	.102	.095	.088	.182	.152	.137	.217	.182	.157
June 24	.388	.265	.217	.461	.295	.246	.457	.280	.234
July 1	.218	.165	.156	.284	.203	.191	.292	.199	.187
July 8	.412	.210	.218	.493	.297	.251	.446	.282	.238
July 15	.287	.186	.160	.353	.229	.202	.341	.227	.201
July 22	.380	.250	.200	.443	.282	.240	.412	.267	.140
July 29	.208	.154	.139	.273	.200	.178	.270	.198	.178
Aug 5	.268	.187	.162	.331	.227	.204	.316	.224	.202
Aug 12	.256	.209	.183	.325	.242	.220	.320	.237	.210
Aug 19	.174	.173	.129	.240	.189	.170	.259	.145	.174
Aug 26	.358	.240	.200	.407	.274	.238	.388	.265	.230

Table 3 presents average impact and standard deviations for the nine strategies. These statistics indicate that each strategy has a characteristic load impact and that these impact follow a consistent pattern.

Table 3. Average Impact of Load-shifting Cooling Strategies

Set Point (F) Start Time (AM)	78		75		72	
6	.283	(.097)	.351	(.095)	.342	(.076)
4	.196	(.046)	.237	(.045)	.230	(.042)
2	.170	(.038)	.208	(.034)	.198	(.030)

Standard deviation in parentheses

From this information, we can make the following general observations:

1. For the range of variation examined, earlier start-times (pre-cooling) have greater impacts on consumption than lower set-points (sub-cooling).
2. The effect of earlier start-times is to diminish the efficiency of the thermal storage; off-peak consumption increases faster than the decrease in on-peak consumption.
3. The 75 F (22 C) set-point appears to represent a local maximum for sub-cooling.
4. The most efficient strategies are also the least well-defined; they have the largest standard deviation.

Future studies to further develop and characterize the energy impact of these and other load-shifting cooling strategies are envisioned.

ECONOMIC ANALYSIS

The value of these shifts in load and, hence, the desirability of selecting one of these strategies is completely determined by the rate schedule of the local utility. We now consider a hypothetical time-of-day electric rate schedule and illustrate how the value of a strategy can be calculated.

Under time-of-day rates, the price of electricity is determined by consumption during utility-defined time periods. The desirability of one load-shifting strategy over another is determined by the magnitude of electricity shifted and the price differential of that electricity. Analytically,

$$Savings = \sum_{i=1}^{n} (E_i - E_i') \times \mathrm{P_i} \qquad (1)$$

where:

E = Base case electricity consumption
E′ = Strategy case electricity consumption
P = Price of electricity
i = Time-of-day period
n = Number of time-of-day periods

A more convenient expression for our idealized on- and off-peak rate structure involves the solution for a threshold value. In the formulation for our time-of-use rate, the threshold value is defined by the ratio of off- to on-peak electricity prices.

$$\text{Threshold Value} = \frac{(E_{on\text{-}peak} - E'_{on\text{-}peak})}{(E'_{off\text{-}peak} - E_{off\text{-}peak})} = \frac{P_{off\text{-}peak}}{P_{on\text{-}peak}} \qquad (2)$$

In this expression, comparing the ratio of the loads shifted to the ratio of prices determines the desirability of a strategy. mass studies (9,10). Substituting the appropriate quantities for the on- and off-peak price of electricity determines the threshold value. If the ratio of the load shifted falls below this value, the strategy is not profitable; the further above this threshold, the more profitable the strategy. Intuitively, the threshold value may be thought of as the point where on-peak electricity cost reductions just equal off-peak electricity cost increases. Table 2, therefore, also represents the threshold value of the load-shifting impact of each strategy.

For this example, few strategies are cost-effective under typical U.S. utility rate schedules. Most time-of-use price differentials are too small to justify the implementation of these load shifting strategies; the on-peak energy savings are always smaller than the off-peak energy cost increases. For example, if on-peak energy charges are $ 0.12/kWh and off-peak charges are $ 0.05/kWh, then the threshold value is 0.417, which is above the corresponding values of most of the strategies.

IMPLEMENTING LOAD-SHIFTING COOLING STRATEGIES

This section describes the development of a crude mechanism for implementing the load-shifting cooling strategies developed in the last section. The mechanism is based on a measure of thermal storage in building mass. The development of this indicator provides the linkage between the load shifting cooling strategies previously examined and the Monday Effect they seek to address.

The work by Eto and Powell previously cited identified several measures of thermal storage and correlated them with Monday electricity consumption and peak demand (1). Sunday peak core temperature was found to yield the best correlation with electricity use and peak demand. Total electrical consumption was better correlated with peak core temperature than was peak electrical demand.

This earlier finding was used as a starting point for the development of correlations for each of the cooling strategies. The ratio of the changes in on- to off-peak energy use was regressed against Sunday peak core temperatures. Table 4 summarizes the results of these regressions.

Table 4. Cooling Strategy Impact as a Function of Sunday Peak Core Temperature

Change in On-peak/Change in Off-peak = A + B*(Sunday Peak Core Temperature)

Set Point (F)	Start Time (AM)	A	B	R-square
78	6	-10.583	.132	.48
78	4	- 5.501	.069	.58
78	2	- 4.886	.061	.67
75	6	- 9.813	.123	.44
75	4	- 5.152	.065	.55
75	2	- 4.131	.053	.62
72	6	- 7.611	.096	.42
72	4	- 4.082	.052	.41
72	2	- 2.568	.034	.32

The low R-squared terms associated with these regressions indicate that Sunday peak core temperatures provide only a partial explanation for the on- and off-peak energy use impact of the cooling strategies. This was not an unexpected result. Thermal storage over the weekend is only one component of the Monday cooling energy requirements of buildings. An obvious contributor not examined was the weather on Monday.

Monday weather, nevertheless, is outside the boundary of the present work. The present work seeks to develop cooling strategies, which are deployed in anticipation of impending increases in energy use based on indicators of thermal storage. It is, in this respect, too late to deploy a strategy once Monday has arrived.

A possible outcome of this work can be easily visualized: A computerized energy management system, upon the receipt of information from temperature sensors on Sunday, calculates load impact for a range of potential cooling strategies via regression equations of the type developed from our simulations. The equations, of course, would be unique to each building. Then, based on the current rate schedule, the strategy that maximized energy cost savings would be implemented.

SUMMARY

A computer model was used to study the thermal storage impact of commercial building thermal mass on cooling energy use and costs. Load-shifting cooling strategies were developed to mitigate the impact of increased electricity use and peak electrical demands on Mondays. An earlier study demonstrated the importance of Monday energy demands by documenting how the building mass acts as a thermal storage device during the weekend shut-down of HVAC systems. A simple framework was developed to evaluate the economic value of these strategies with direct reference to time-of-day electric rate schedules. Finally, a crude indicator of thermal energy storage in building mass was related to the load-shifting cooling strategies. It is suggested that correlations of this type could be used by computerized energy management systems to reduce building operating energy costs.

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REFERENCES

1. Eto, J, and Powell, G. "Implications of Office Building Thermal Mass and Multi-day Temperature Profiles for Cooling Strategies", Proceedings of the 1985 ASME/AIChE National Heat Transfer Conference, Denver, CO, August 4-7, 1985.

2. Curtis, R., Birdsall, B., Buhl, W., Erdem, E., Eto, J., Hirsch, J., Olson, K., and Winkelmann, F., The DOE-2 Building Energy Use Analysis Program, Lawrence Berkeley Laboratory, LBL-18046, April, 1984.

3. Kerrisk, J., Weighting Factors in the DOE-2 Computer Program, Los Alamos National Laboratory, LA-8886-MS, June, 1981.

4. Tishman Research Corporation, DOE-2: Comparison with Measured Data, U.S. Department of Energy, DOE/CS/20271-5, March, 1984.

5. McLain, H., Christian, J., Ohr, S., and Bledsoe, J., Simulation of the SWTMS Test Cells Using DOE-2.1A Model, Oak Ridge National Laboratory, 1984 (draft).

6. Birdsall, B., A Comparison of DOE-2.1C Prediction with Thermal Mass Test Cell Measurements Lawrence Berkeley Laboratory, LBL-18981, January, 1985.

7. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., ASHRAE Standard 90-75: Energy Conservation for Buildings, 1975.

8. Crow, L., Development of Hourly Data for Weather Year for Energy Calculations (WYEC), Including Solar Data at 21 Stations Throughout the United States, ASHRAE Research Project 239, 1980.

9. Carroll, W., Webster, T., Mertol, A., and Kammerud, R., The Effect of Envelope Thermal Mass on Building Heating and Cooling Loads, Lawrence Berkeley Laboratory, LBL-16358, 1983.

10. Goodwin, S., and Catani, M., "The Effect of Mass on Heating and Cooling Loads and on Insulation Requirements of Buildings in Different Climates," ASHRAE Transactions, v. 85, PH-79-11, No. 1, 1979.