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IMPLICATIONS OF OFFICE BUILDING THERMAL MASS AND MULTI-DAY TEMPERATURE PROFILES FOR COOLING STRATEGIES

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IMPLICATIONS OF OFFICE BUILDING THERMAL MASS AND MULTI-DAY TEMPERATURE PROFILES FOR COOLING STRATEGIES

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ABSTRACT

This paper describes a study of the cooling energy requirements that result from thermal storage in building mass, and suggests methods for predicting and controlling its energy cost implications. 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. Increased Monday cooling energy requirements resulting from the weekend shut-down of HVAC systems are documented. Predictors of energy use and peak demands, which account for thermal storage in building mass, are described. Load-shifting, sub-cooling and pre-cooling equipment operating strategies are evaluated with explicit reference to utility rate schedules.

KEYWORDS: Energy Conservation, Commercial Buildings, Thermal Mass, Cooling Energy, Peak Demand

INTRODUCTION

The political and economic events of the last decade have highlighted the importance of research in the field of building energy performance. Computers have figured largely in complementing these interests by providing the researcher with a tool capable of rapidly manipulating large quantities of data. Sophisticated models of heat transfer in buildings can now be implemented to study building energy performance at an unprecedented level of detail. Armed with these tools, detailed results from the research community can now be practically translated into design and operating strategies that reduce energy use and costs. This study uses one such computer-based model to study a specific transient heat transfer phenomenon.

Anecdotal evidence suggests that in the summer many commercial buildings experience peak demands for electricity on Mondays. Preliminary documentation of this phenomenon can be found in the LBL Building Energy-Use Compilation and Analysis for Commercial Retrofits (BECA-CR) data base (*1*). We hypothesize 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 doing so, energy use is increased as is the likelihood of recording a peak demand.

The outline of this paper is as follows. First, we describe our experimental procedure, including the computer model used to estimate thermal storage effects by the mass of a large office building. Second, we document the results of our simulations and develop a crude indicator relating one measure of thermal storage to increases in Monday electricity use and peak demand. Third, we apply these findings by incorporating them into control strategies, which mitigate the energy cost implications of thermal storage in building mass.

EXPERIMENTAL DESIGN

In this section, we describe the design of our experiment to measure and predict the effects of thermal storage in building mass. There are four components to this discussion, the computer model, building prototype, and climate used, and the test procedure.

Modeling Thermal Storage in Building Mass

We use the DOE-2 building energy analysis program (version DOE-2.1C) 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 masses:

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 Tishman (*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.

We made frequent use of the hourly-report features of the program in our study of thermal storage effects. For example, since the strategies we examined affected only the response of the HVAC systems to cooling loads, differences in electricity consumption between the LOADS and PLANT portion of the program represent the net electricity consumption of the HVAC. Hourly reports also allow us to partition energy consumption into differing time-of-use periods and identify peak demands. Finally, hourly temperature data, especially for zones within the building, were used in our development of thermal storage indicators.

Large Office Building Prototype

We selected a large office building prototype for our 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. Skin effects from a lower surface area to volume ratio building might reduce the storage effects we hope to identify. Finally, 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 BEPS 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 levels 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. We note, however, that the bias introduced by this choice of climate can not be determined, *prima facie*; we anticipate future studies for other climates.

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.

Experimental Procedure

The test consisted of simulating the building with and without a weekend equipment shut-down schedule. Cases with weekend shut-downs (5-day operation) followed the operating schedule described above, 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.

Our procedure was to examine daily electricity use and peak demands for each day of the summer cooling months of June, July, and August. Of course, Monday occurs only once a week in a given year of weather. We were able to generate results for every summer day of weather by changing the date of the run period for 7 separate year-long runs. That is, while Monday falls on June 5, 1978, it falls on June 6, 1979. By repeating this procedure for both 5- and 7- day operating schedules, we generated a data set containing results for 91 Mondays with and without weekend operation. Despite our focus on only the summer months, whole-year run periods were specified to eliminate transient effects associated with initialization of the simulations.

Our use of the net electrical consumption of the HVAC system differs from many thermal mass studies. These studies concentrate solely on HVAC load impacts, with little discussion of resulting electrical consumption. We believe that this practice, while appropriate for some 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.

RESULTS

In this section, we describe the results of our simulations and the development of an indicator of Monday electricity use and peak demand based on a measure of thermal storage in building mass.

The Monday Effect

We find that a Monday Effect exists and that our hypothesis regarding its cause is strongly confirmed by the results of our experiment.

The annual peak demand occurred on a Monday in all seven simulations of the 5-day schedule of operation. Further, monthly peak demands occurred on Mondays for 76 % the 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 increased by a greater percentage than peak demand. Electricity use increased an average of 5 % (standard deviation = 1.6 %), while peak demand increased an average of 3 % (standard deviation = 1.0 %).

Comparisons of weekend interior air temperatures suggest that these increases in electricity use and peak demand were caused by 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, Sunday peak core temperatures were always higher under the 5-day operating schedule. 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).

Developing Indicators of the Monday Effect

We identified three measures of thermal storage and correlated them with Monday electricity consumption and peak demand. The measures were:

1. Peak core zone air temperature;
2. Average Sunday core zone air temperature; and
3. Core Degree-Hours.

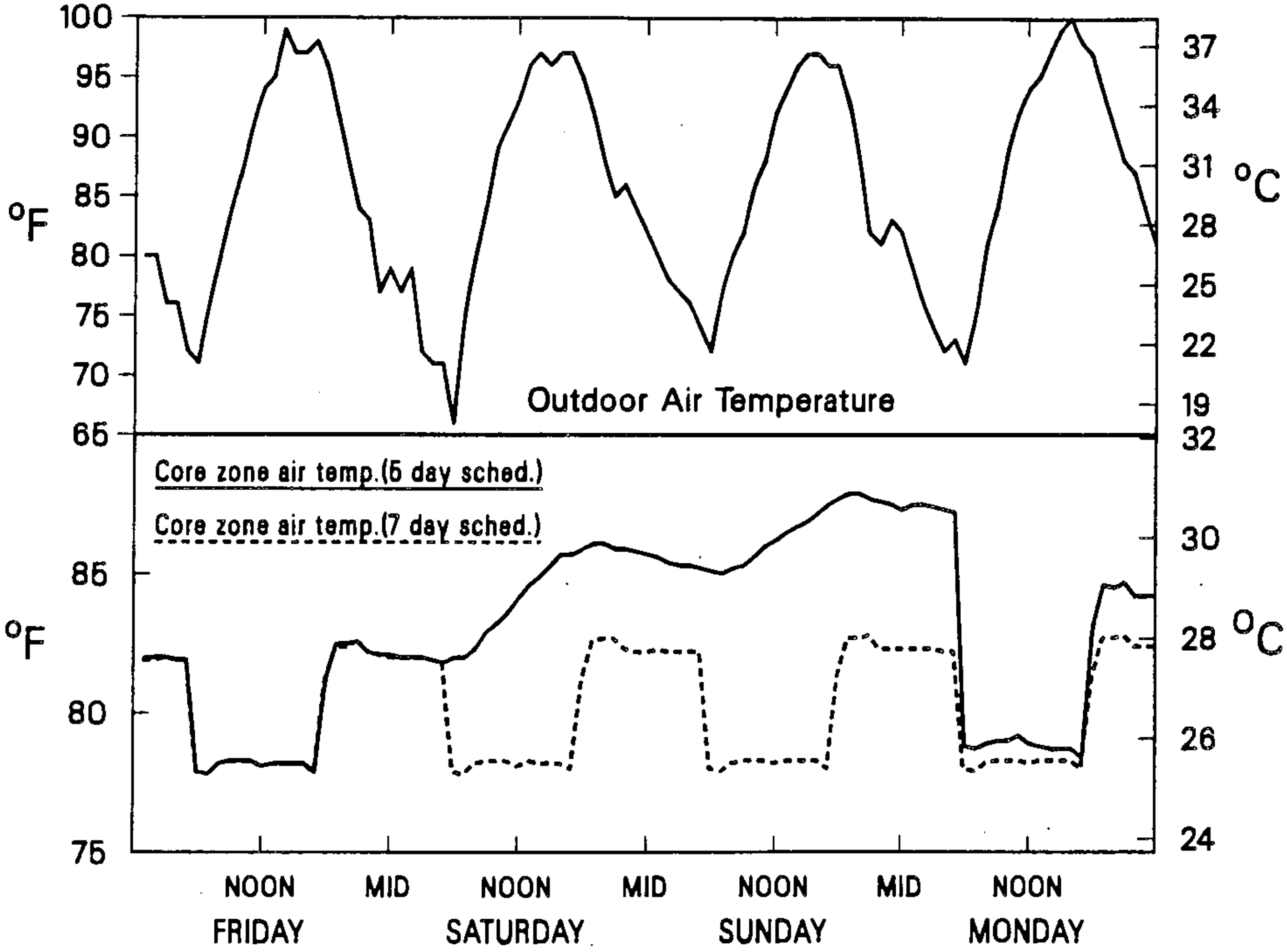

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Figure 1. Outdoor dry-bulb air temperature and indoor core air temperatures for 5- and 7-day schedules of building operation.

The first measure, we speculated, would be a good indicator of the highest level of storage in the building mass. The second and third measures were designed to capture the time-varying effects of thermal storage. The third, the Variable-Base, Core Degree-Hour, was defined in a manner analogous to a Cooling Degree-Day, but the temperature difference was calculated hourly using the air temperature of the core zone. Analytically,

$$Core\ Degree\text{-}Hours = \sum_{i=1}^{24} (Core\ T_i - Base\ T) \tag{1}$$

$$where\ (Core\ T - Base\ T) > 0$$

No measure was completely successful in explaining Monday energy use. Among the three measures, Sunday peak core temperature showed the best correlation with electricity use and peak demand. Figures 2 and 3 illustrate these correlations. Total electrical consumption was better correlated with peak core temperature than was peak electrical demand.

The correlations for average core air temperature and Core Degree-Hours were less robust. Not surprisingly, the Core Degree-Hour correlations did improve slightly with higher base temperatures. That is, the asymptotic limit of the Core Degree-Hour statistic is zero as the reference or base temperature approachs the peak core temperature.

It should come as no surprise that our indicators of thermal storage provided, at best, only a partial explanation for Monday energy use. Thermal storage is only one component of the Monday cooling energy requirements of buildings. An obvious contributor that we did not examine was the weather on Monday. Finally, we used the DOE-2 building energy analysis tool primarily to replicate anecdotal evidence regarding the existence of a Monday effect; we are less confident with regard to the use of intermediate program outputs to predict the Monday Effect.

AN APPLICATION

We have documented a relationship between the storage of heat in the mass of the building over weekends and the energy performance of HVAC systems on Monday. The value of this information will now be illustrated with an example of how load-shifting cooling strategies can mitigate the impact of this thermal storage phenomena.

Load-Shifting Cooling Strategies

Monday on-peak electricity use and peak demands will be reduced by control strategies that either minimize the thermal gains to the building over the weekend or remove these gains in a timely fashion. The former is a largely the response of the HVAC systems to exogenous forces, the weather. In this section, we discuss the energy and cost implications of the latter set of

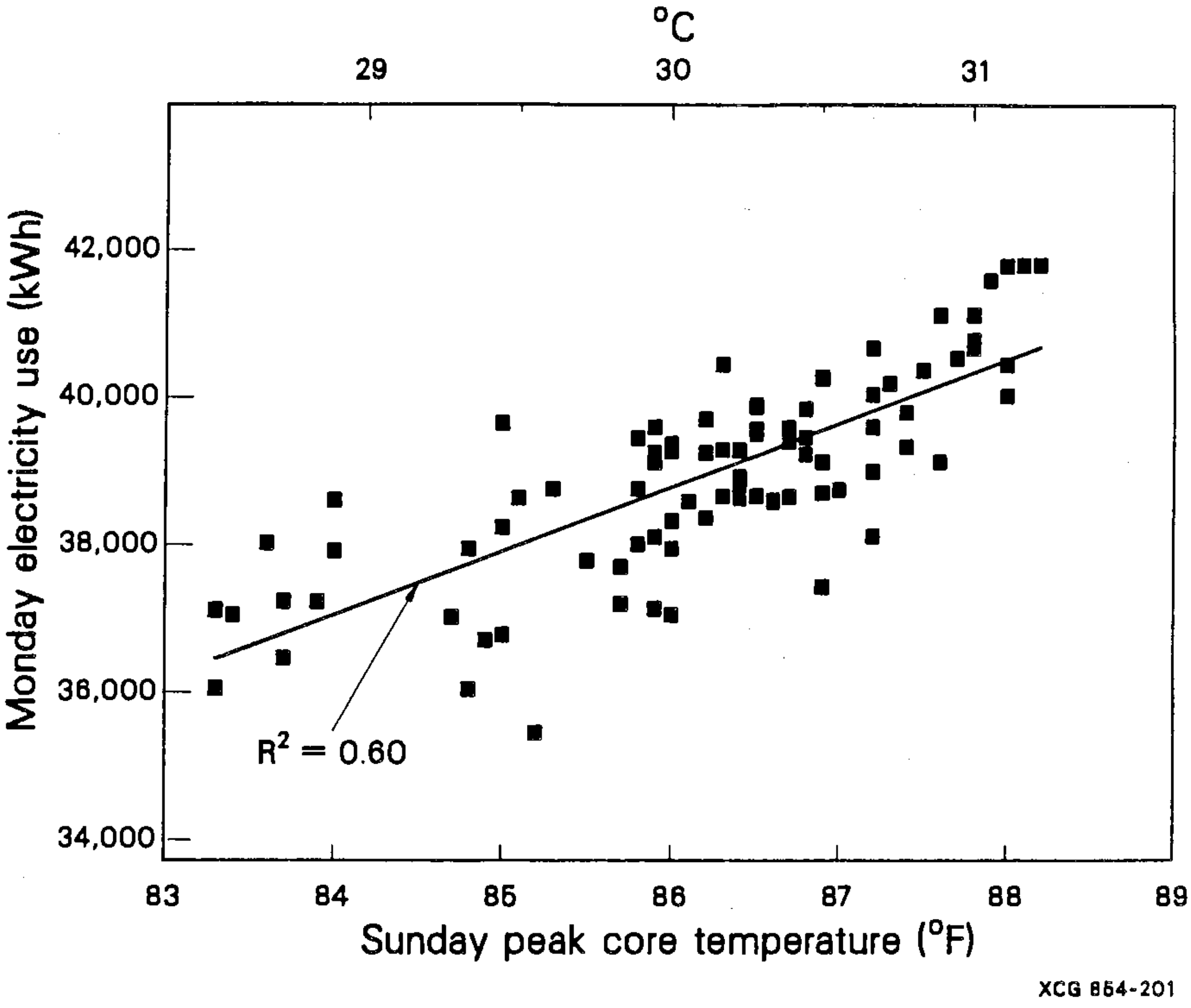

Figure 2. Sunday peak core zone air temperature correlation with Monday total electricity use.

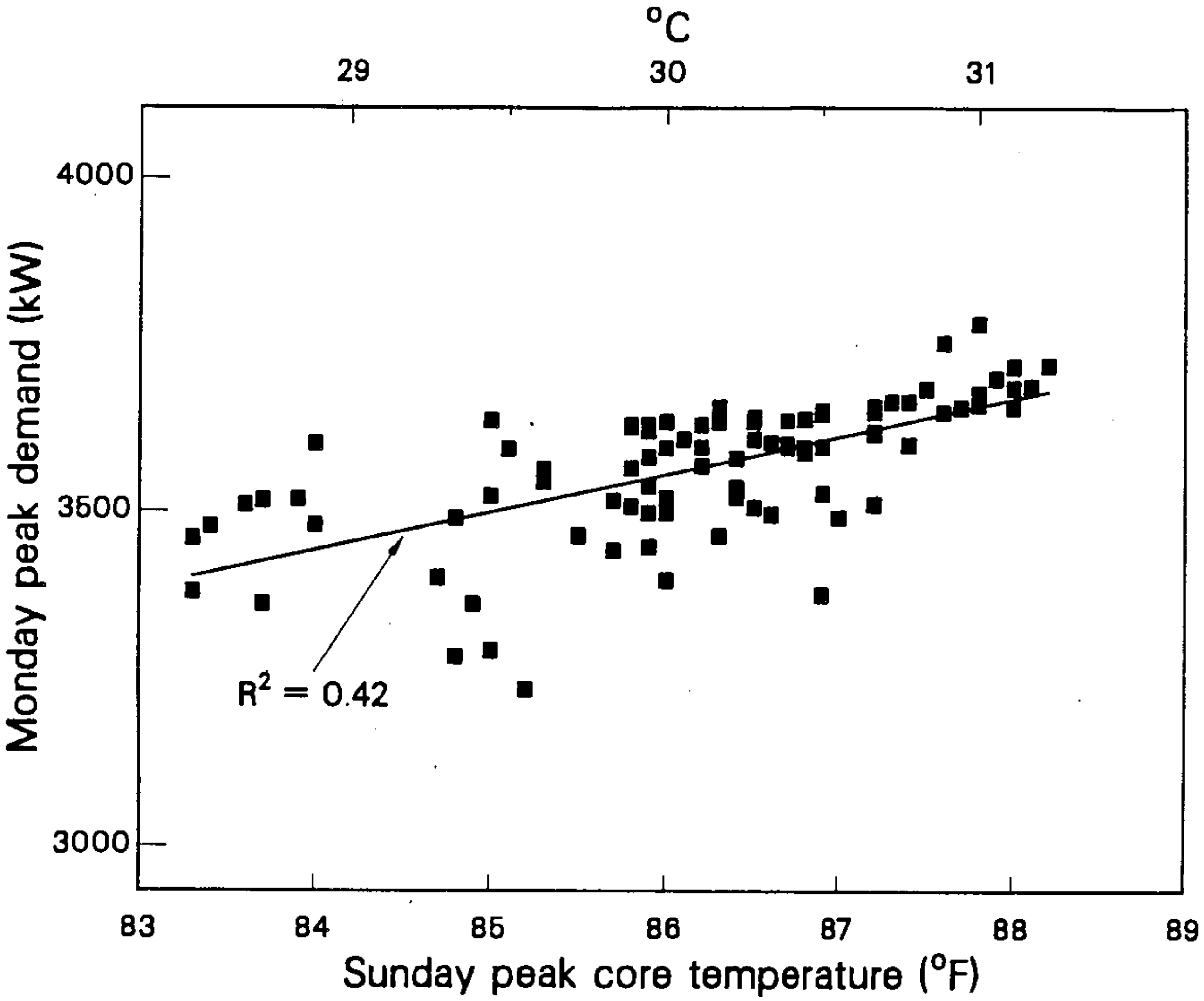

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Figure 3. Sunday peak core zone air temperature correlation with Monday peak electrical demand.

control strategies.

The load shifting cooling strategies we examined are called pre-cooling and sub-cooling. The first starts the HVAC system earlier, at the normal temperature set point. The second, used in conjunction with the first, lowers space temperatures even further during the pre-cooling period. 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. Under normal operating conditions, the building HVAC systems were scheduled to start at 7 A.M. with a cooling set-point of 78 F (26 C).

An examination of the trade-offs between fan power and chiller operation was implicit in choice of these parametric runs. Both ventilation rates (duration) and the temperature of the ventilation air contribute to the removal of heat from the building mass. Figure 4 illustrates the effect of this trade-off for one set of pre-cooling strategies.

Table 1 summarizes the reductions in peak electricity demand and the on- and off-peak changes in electricity consumption for one Monday. Earlier start times and lower temperature set-points 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 Jun 10

		A	B	C	D	Threshold Values	
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)	*Off-peak (=D)*. On-peak (=C)	*Peak Demand (=B)* Electricity (=A)
6	78	+ 458	+ 4	- 299	+ 757	2.532	.00873
4	78	+1,774	-15	- 558	+2,332	4.179	.00846
2	78	+3,033	-29	- 761	+3,795	4.987	.00956
6	75	+ 451	- 2	- 370	+ 821	2.219	.00443
4	75	+1,955	-30	- 732	+2,687	3.671	.01535
2	75	+3,316	-52	-1,014	+4,330	4.270	.01568
6	72	+ 582	- 6	- 422	+1,005	2.382	.01031
4	72	+2,370	-40	- 867	+3,238	3.735	.01688
2	72	+4,123	-69	-1,209	+5,332	4.410	.01674

Base case electricity consumption = 40,346 kWh; peak demand = 3682 kW.
Base case operating conditions: fan start 7 AM, set-point 78 F.
On-peak hours are 8 AM - 6 PM.

Between the two strategies, we make two general observations:

1. Pre-cooling has a greater impact on consumption than sub-cooling.

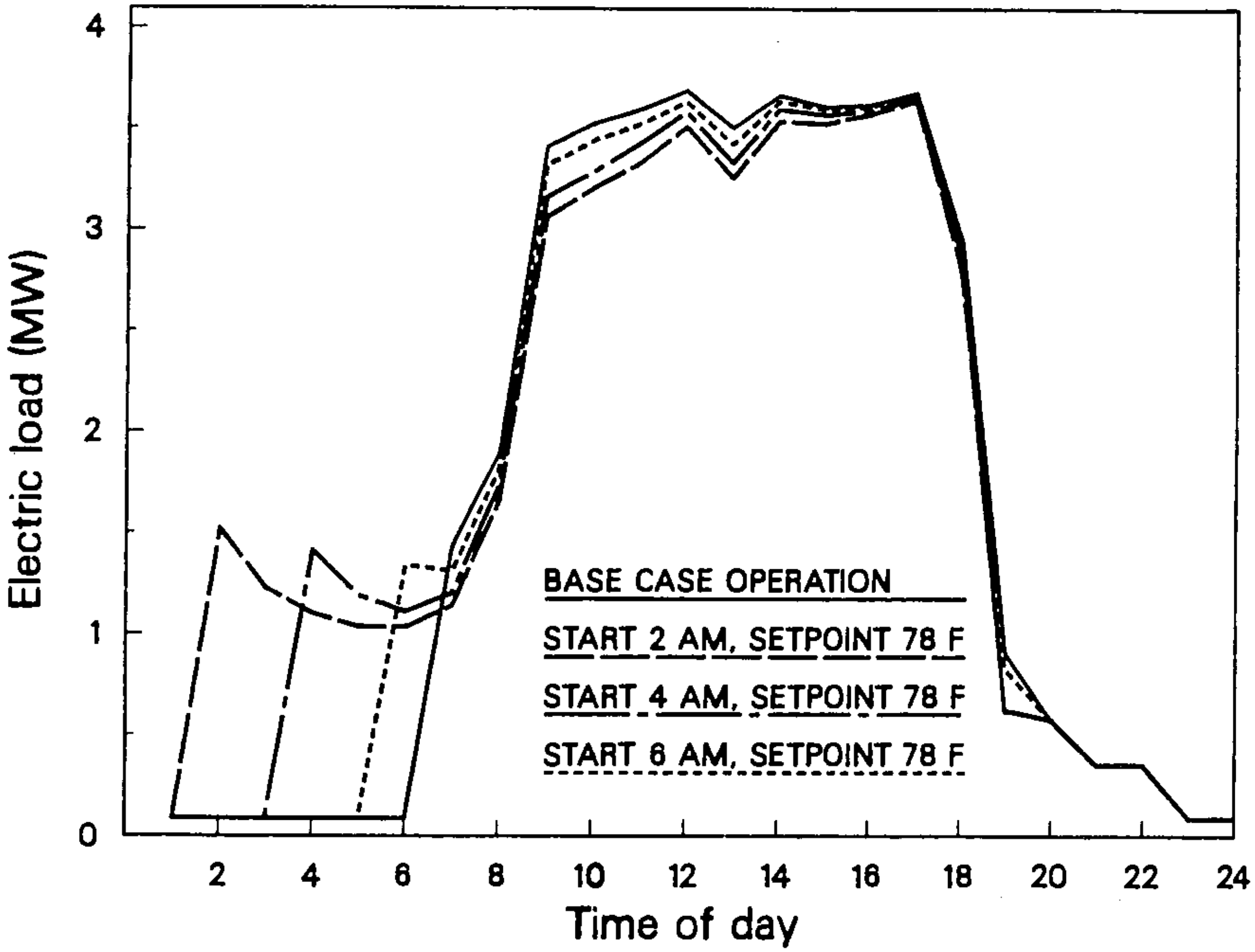

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Figure 4. Electric load profiles for load-shifting, pre-cooling strategies.

2. Peak demands appear to be more sensitive to the load-shifting strategies than electricity consumption, as measured by percentage changes.

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 two idealized rate schedules and illustrate how the value of a strategy can be calculated. These schedules are intended to represent the end-points in the spectrum of utility rate structures; intermediate cases fall naturally within this framework. The first is a time-of-day schedule with an on- and off-peak energy charge and no demand charge. The second is an energy and demand schedule with a flat rate for both electricity consumption and peak demand.

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,

$$Savings = \sum_{i=1}^{n} (E_i - E_i') \times \mathrm{P}_i \tag{2}$$

where:

i = Time-of-day period

E = Base case electricity consumption

E' = Strategy case electricity consumption

P = Price of electricity

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 on- and off-peak electricity prices.

$$Threshold\ \ Value = \frac{(\mathrm{E}_{off\text{-}peak} - \mathrm{E}'_{off\text{-}peak})}{(E'_{on\text{-}peak} - \mathrm{E}_{on\text{-}peak})} = \frac{\mathrm{P}_{on\text{-}peak}}{\mathrm{P}_{off\text{-}peak}} \tag{3}$$

In this expression, comparing the ratio of the loads shifted to the ratio of prices determines the desirability of a strategy. Substituting the appropriate quantities for 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 1 also converts the load-shifting impacts of each strategy for a single Monday to its threshold value.

We note for this example that under typical U.S. utility rate schedules *no* strategy is cost-effective. Most time-of-use price differentials are too small to justify the implementation of any load shifting strategy; 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 $ 0.06/kWh, then the threshold value is 2.0, which is far below the threshold values for any of the strategies on Table 1.

Utility rate schedules with demand charges in addition to an energy charge can be used to evaluate the profitability of load-shifting strategies in exactly the same manner, with three qualifications. First, demand charges are calculated by reference to the highest demand for power in the billing period. If the peak demand for a Monday is reduced, but that Monday does not happen to be the day of the monthly peak (for example, the previous Monday was the monthly peak), there are no demand charge savings. Second, even if the Monday is the day of the monthly peak, many utilities have ratchets built into their schedules. In this case, if the ratchet is greater than the monthly peak, the demand charge will again remain unchanged by the load-shifting. Third, even if the Monday is both the monthly peak and the demand upon which a ratchet would otherwise be based, the peak demand reduction on this Monday may only receive partial credit. Here, the credit will be the difference between the demand that would otherwise have been recorded and the *next* highest monthly/ratchet demand and this demand may be recorded some other day (another Monday, perhaps). All of these subtleties make the selection of the appropriate load shifting strategy more complicated.

If we ignore these subtleties for the moment, we can calculate a threshold point in exactly the same manner as before.

$$\textit{Threshold Value} = \frac{(\text{Peak Demand} - \text{Peak Demand}')}{(\textit{Elect. Use}' - \text{Elect. Use})} = \frac{P_{\text{elect.}}}{P_{\text{demand}}} \tag{4}$$

Table 1 also summarizes these threshold values.

For a typical demand charge rate schedule, many strategies do become cost-effective. If, for example, demand charges are $ 7 /kW-mo and energy is $ .10 /kWh, the threshold value is .0143. From Table 1, several strategies appear to be cost-effective for this threshold value, notably the lowest temperature sub-cooling cases with the earliest pre-cooling start times. Again, we ignore the subtleties of demand charges noted above.

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, predicts a range of likely energy use and peak demand for the following Monday by reference to a characteristic slope of the sort illustrated in Figures 2 and 3 (the slope, of course, would be unique to each building). This information triggers a search of the data base of potential building responses. That is, for a given range of predicted energy use and peak demand, there is an associated matrix of energy impacts for available load-shifting strategies. Based on the current rate schedule, the strategy that maximizes energy cost savings is selected.

SUMMARY

We have used a computer model to study the thermal storage impacts of commercial building thermal mass on cooling energy use and costs. We documented the anecdote that many commercial buildings experience increased electricity use and peak electrical demands on Mondays and explained these phenomena by noting that the building mass acts as a thermal storage device during the weekend shut-down of HVAC systems. We developed crude indicators of thermal energy storage in building mass and correlated them with subsequent electricity use and peak demands. Finally, we presented an application of this relationship in the form of load-shifting strategies that modify Monday energy use and peak demands and developed a simple framework for ranking these strategies based on explicit consideration of utility rate structures. In doing so, we noted the peculiar features of the assessment of demand charges and its implications for the load shifting strategies.

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