FIELD MEASUREMENTS OF COOLING ENERGY CONSUMPTION IN A MULTI-ZONE OFFICE BUILDING

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ABSTRACT

This paper discusses cooling energy use in a small office building with the objective of developing an understanding of where energy is used and identifying relationships between cooling energy and other energy end uses. Attributes of the building metered are discussed to provide a perspective for the data presented on energy performance of the building with an emphasis on the cooling energy use. The data are reviewed to develop an understanding of cooling loads in the building as well as the HVAC system's response. Despite the detailed instrumentation of the building it is evident that collection of additional data is required to go beyond quantifying the building's energy consumption and explain why the building exhibits its characteristic cooling behavior. Additional data needed are suggested to assist other researchers in developing metering programs. The final section of the paper summarizes a comparison of the metered data with a calibrated DOE 2.1 energy simulation. The results of the calibrated simulation highlight the limitations of simulations in understanding building energy use as well as the need for metering to develop realistic operating schedules.

INTRODUCTION

The data presented in this paper are based upon empirical hourly end-use energy monitoring in a 20,500 square foot office building located in Richland, WA. Hourly end-use energy and microclimate data have been collected for the past two years as a pilot metering project for a larger data collection effort in conjunction with the Building Systems Integration Program managed by Pacific Northwest Laboratory for the U.S. Department of Energy.

The office building metered, called Sigma IV, is a one story 20,500 square foot building built in 1979. This building, part of a four building complex, typifies recent construction: it is a speculative office building leased to a single tenant who pays only moderate attention to energy consumption. Based upon degree days, the climate in Richland can be characterized as temperate: 5299 and 1030 heating and cooling degree days, respectively (base 65 and 70, respectively). Summer daytime highs are typically in the 90's (degrees Fahrenheit) with occasional highs over 100.

OVERVIEW OF BUILDING STRUCTURE

The office building is roughly rectangular, its dimensions being 100 X 200 feet with the longer axis running east-west. The building is built on a 4 inch concrete slab with walls made of concrete block, aluminum studs, 3 1/2 inches of fiberglass insulation and drywall. The windows are 1 inch thick (with the air gap), doubled glazed, solar bronzed glass mounted in fixed aluminum sashes. The building has a large number of divided office spaces with drywall walls extending up to the suspended ceiling. The ceiling is composed of 2 X 5 foot acoustical panels below an unpartitioned plenum. The built up roof deck consists of 2 inches of rigid insulation and tar. There is a 3 foot overhang on all four sides of the building. In addition, there is a 6-inch layer of fiberglass insulation in the roof. A picture of the building is presented in Figure 1.

The mechanical system consists of ten roof mounted air-to-air heat pumps serving five perimeter and five interior zones. The total cooling capacity for the building is 50 tons, approximately one ton for each 400 square feet. This cooling capacity is typical for an office of this size. There are four models of heat pumps ranging from 28 to 88 Btu/hour of cooling capacity. The EERs of these models range from 7 to 8. Eight of the heat pumps are equipped with outside air temperature controlled economizers. Mechanical cooling is locked out on six of the heat pumps when the outside temperature drops below 55°F. The other two heat pumps can use mechanical cooling below 55°F if the thermostat calls for second stage cooling. The heat pumps lock out resistance heating when the outside temperature is above 40°F. Analysis of energy use in the building is complicated by the differences in heat pump capacities and their control strategies. Additional information on the heat pumps will be provided in the analysis section to aid in understanding the energy use.

Information on how the building is used and operated is also essential for understanding energy use. There are no control systems on the building, except for a timer on the outside soffit lights. The building operation is probably atypical in that there are no night-time controls for the fans or night and weekend setbacks of temperatures. The building is typically kept between 70 and 75 degrees F year round and is

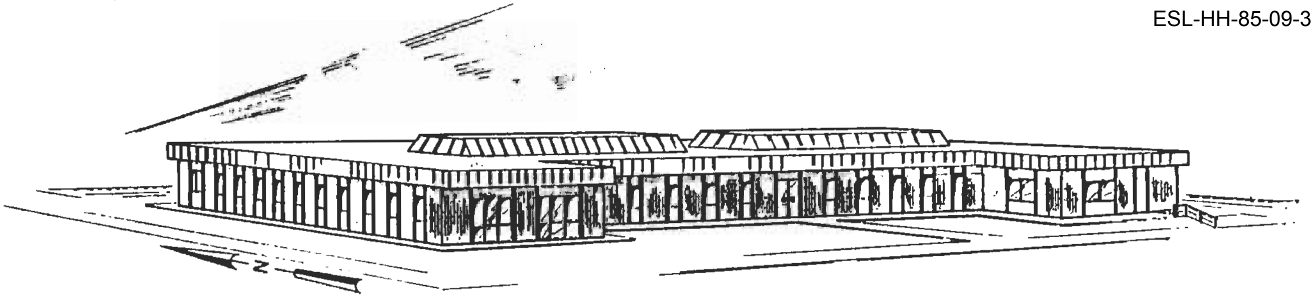

FIGURE 1

continuously ventilated. Office lighting is controlled by switches located in each office, while hall lighting remains on 24 hours a day. The building is occupied by approximately 120 workers, with peak occupancy between 9:00 a.m. and 4:00 p.m. on weekdays. Employees have access to the building 24 hours a day/365 days per year. The building is typically occupied from 6:00 a.m. to 11:00 p.m. on weekdays and during the daytime on weekends. Building cleaning and maintenance is conducted during the working day. Internal maintenance is performed on an as needed basis and HVAC maintenance is done on a quarterly basis by a mechanical contractor.

SUMMARY OF ENERGY CONSUMPTION

The annual end-use energy consumption over the period of May 1984 through April 1985 is summarized in the pie chart in Figure 2. It is surprising to note the small fraction of the total energy use accounted for by cooling. However, it should be recognized that the 24 hour operation of the building results in substantial heating and ventilation energy use. The largest energy end use was lighting representing 38%, or 197,085 kWh. The second largest was ventilation energy at 21%, or 108,887 kWh. Heating and cooling energy were approximately 12% each, 63,368 and 61,097 kWh, respectively. The other major end use was the convenience outlets which accounted for 11%, or 54,777 kWh. The large amount of energy used at the convenience outlets is chiefly due to the large number of personal computers and related equipment in the building. The "other" category consists of two hot water heaters, a copy machine, outside lighting, a mini computer system, and the building fire alarm system.

ANNUAL END USE ENERGY CONSUMPTION

SIGMA IV

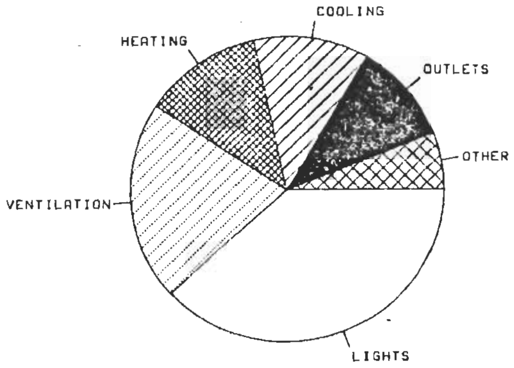

FIGURE 2

On an annual basis, the building uses 86.24 kBTU/Sq.Ft. Internal cooling loads include 32.81 kBTU/Sq.Ft. for lighting, 9.12 kBTU/Sq.Ft. for equipment including computers and the copy machine, and approximately 11.1 kBTU/Sq.Ft. for people (sensible and latent). The rest of this section will describe when and where cooling takes place in the building.

In order to reduce the data to a manageable level, yearly cooling has been divided into four periods based on cooling degree days (CDD) with a base of 70°F. The four periods are: the winter, November through April when there is a total of 1.4 CDD; the swing season, consisting of May and October when there are 24.4 CDD; early and late summer, June and September with 137.2 CDD; and the summer, July and August with 511 CDD. Cooling represents a low of 2.4% of the building's total energy use for the winter period and rises to a high of 31.1% in the summer period. In the swing period, cooling represents 13.0% of the total energy consumption and increases to 19.7% in the early/late summer. Cooling energy use is not significant until the early/late summer and summer periods.

Average hourly cooling energy profiles are shown for each of the four cooling periods in Figure 3. The profiles indicate that between June and September the building operates in a cooling mode even when the building is virtually unoccupied. Peak cooling loads occur between 3:00 and 4:00 in the afternoon.

The cooling energy use is normalized by square feet and cooling degree days in Table 1. The normalized factors are shown to allow comparison with other buildings. However, it is evident that normalizing cooling energy by cooling degree days on a seasonal basis does not result in any insights into cooling loads. This is not surprising since the cooling loads are driven by internal gains, not outside temperature in the winter period and swing season.

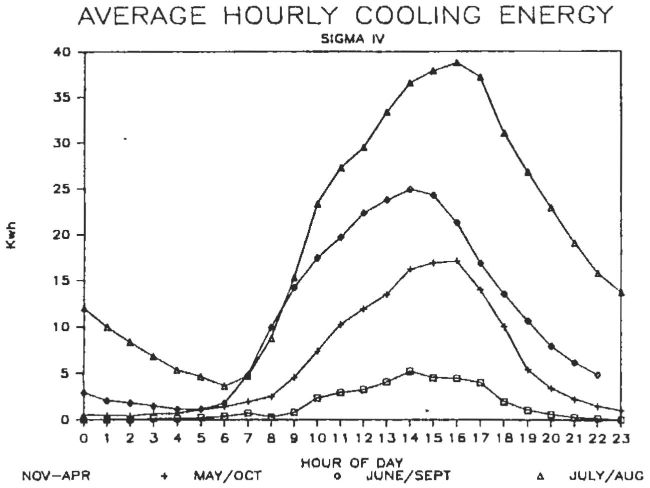

FIGURE 3

Table 1. Normalized Cooling Energy Consumption

Measure *	Winter	Swing	Early/Late Summer	Summer	Total
Watts/sq.ft.	300	492	747	1448	2937
Watts/sq.ft. CDD	214	20.3	5.4	2.8	4.5

* CDD base 70 F

The role of the economizers has been investigated in order to understand the low proportion of cooling energy use. As noted previously, two of the zones, the east and west perimeter zones, do not have economizers. In addition, the heat pump servicing the east zone must be switched manually at the thermostat from heating to cooling. The thermostat is usually switched over to heating from mid November to mid April. In two of the zones, the northwest and southwest interior zones, the heat pumps can operate in a mechanical cooling mode when the temperature is below 55 F if the thermostat calls for second stage cooling.

The contribution of the economizers to serving the cooling demand is illustrated in Figure 4. The total number of heat pump cooling hours and the number of economizer hours are shown by month. The number of hours of economizer operation includes all eight heat pumps with economizers. The total hours of cooling operation include all ten heat pumps. Figure 4 highlights the usefulness of the economizers in the period of November through March. However, it can be seen that these hours represent a small fraction of the annual cooling use.

ANALYSIS OF COOLING ENERGY USE

The summary of energy use highlights the small cooling loads in the office building. Hypotheses for this behavior are proposed in this section, however it becomes evident that insufficient data precludes any conclusions. The low cooling loads

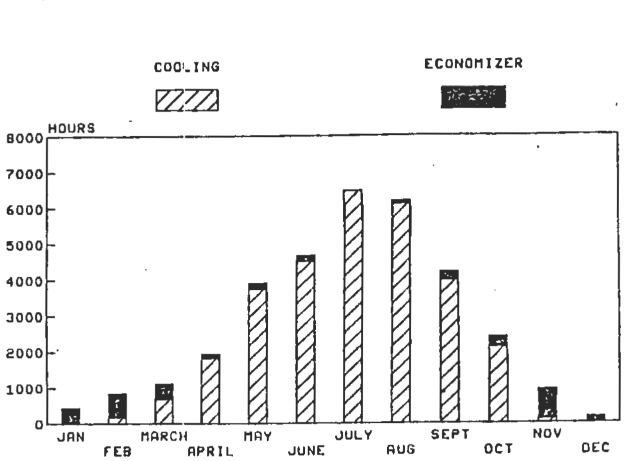

FIGURE 4

might be attributed to the use of economizers. Alternatively, the building construction or operation schedules may be the dominating factor.

Economizer use is investigated in further detail in this section. However, there are no quantitative measurements of the effects of the interior and perimeter zones being coupled to the ground and having a large roof area with only a moderate amount of insulation. The cooling loads during the unoccupied hours of the day can probably be attributed to the hall lighting which remains on all night as well as the large quantity of computer equipment which is typically left on.

The effects of building orientation were investigated and the data have been summarized in Figure 5 by zone, orientation, and location as well as season. The energy use has been normalized to watts/sq.ft./month to remove the effects of different zone sizes and the longer time period for the winter season. The location and size of each of the zones along with the cooling capacity

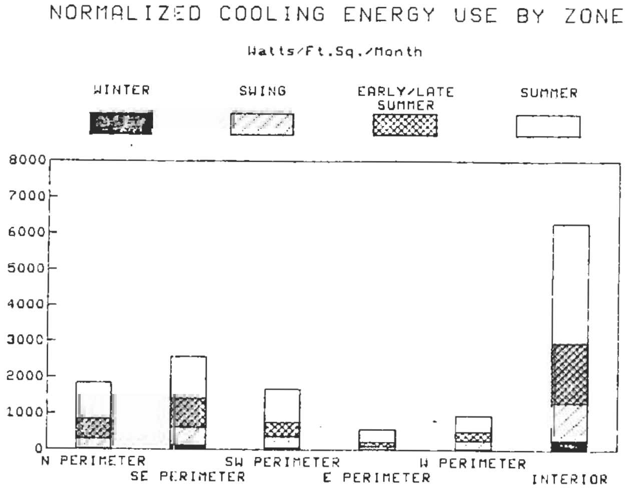

FIGURE 5

of its corresponding heat pump are shown in Figure 6. The east perimeter zone has the smallest heat pump followed by the heat pump in the west perimeter zone. The cooling capacities of the east and west perimeter zones are less than the north and south perimeter zones.

The north and south exterior zones follow the expected pattern for the winter and swing season: the southern two zones use more energy, on a square foot basis than the northern zone. In the early through late summer it is surprising that the north perimeter zone uses more cooling energy than the southwest perimeter zone. One possible explanation is that there is a higher ratio of glass to wall area for the northern zone than the southwestern zone as well as the role of the overhang in reducing solar loads on the southern face. The east and west perimeter zones use significantly less energy than the other perimeter zones for all seasons except during the winter for the west perimeter zone. This result is surprising, especially since the east and west perimeter zone heat pumps do not have economizers. The low cooling energy consumption in these zones suggests the importance of the interaction of equipment sizing. The interior zones exhibited the same cooling behavior.

It is difficult to provide a detailed explanation of the difference in the performance of the different zones due to the limitations of the data collected. While the heat pumps all have similarly rated efficiencies, any differences in the installed performance of the heat pumps might explain some of the zonal variations. In addition, the performance of the individual zones is affected by the mixing of the return air from all the zones in the plenum.

Sigma IV Floor Plan

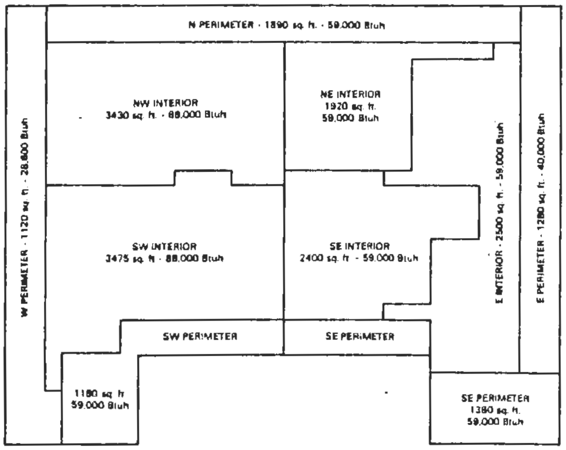

FIGURE 6

Economizer operation was investigated and is summarized in Figures 7 and 8 on a zone by zone basis for the four defined cooling periods. Figure 7 shows the fraction of hours during which the economizers were used as a percent of total hours when the thermostat called for cooling. Figure 8 shows the percent of hours of economizer operation of the total hours in the time period. These figures should be viewed in the context of the building's operational characteristics. The building systems operate 168 hours a week as opposed to a typical office building which is operated approximately 80 hours a week. Cooling is rarely required during the extended hours of building operation due to the combination of low nighttime temperatures and relatively low internal loads. Therefore, these percentages are likely to be significantly higher in a building with a typical operating schedule. No economizer operation is shown for the southeast interior zone. The metered data indicate that the economizer was not working.

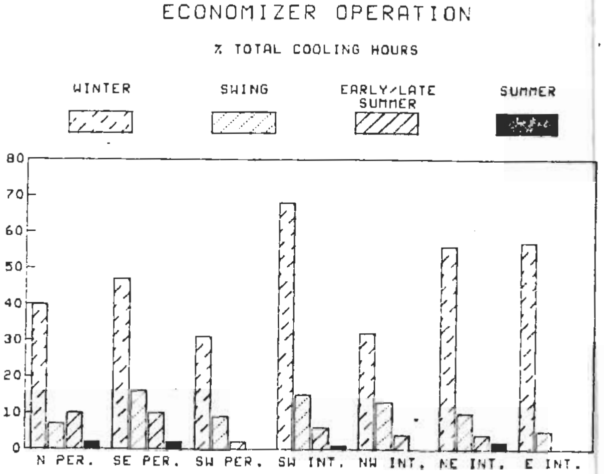

FIGURE 7

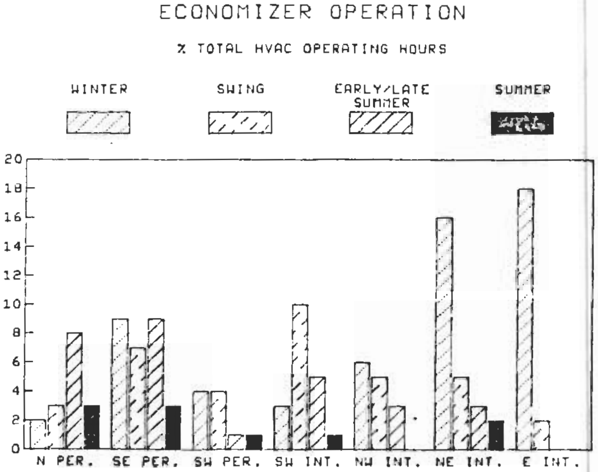

FIGURE 8

Except for the southeast interior zone, the economizer operation serves a significant portion of the cooling demand during the winter season. When these data are examined by month it is evident that the economizers account for almost 100% of the cooling demand for the period of December through March. In April the demand for cooling, as called for at the thermostat, represents a large proportion of the total cooling hours for the six month period. In addition, the daytime temperature rises above 55^{o}F thus requiring mechanical cooling. The second column illustrates that the percent of hours where cooling is needed, either mechanical or free, is a small percent of the time period. In the summer, the contribution of the economizers becomes negligible.

ADDITIONAL DATA REQUIRED

There is no "correct" amount of instrumentation required to meter a commercial building. Instrumentation requirements are established by study objectives, study budget, and hardware limitations. Data summarizing end-use energy consumption are valuable to identify actual consumption patterns and to help confirm or refute common expectations and/or the results of thermal simulations. The Sigma IV metering research project indicates the importance of knowing about the performance of the HVAC system. Either continuous, or one-time, measurements of equipment efficiency would be useful to help explain variations in energy use by building zone. Monitoring of part load performance would also be useful. Measurements of insolation in the perimeter zones could be used to further assess the impacts of building orientation as well as the effectiveness of the building's overhangs. Finally, the ability to adjust the building's operating schedules to study the associated impact would aid in developing an understanding of cooling energy use in the building.

COMPARISON WITH COMPUTER SIMULATION

The availability of metered data at this level of detail can provide valuable insights into possible building energy conservation strategies. Since the data are collected hourly, the building energy use can be compared to estimates from an unlimited number of energy analysis methodologies and tools. Discussed briefly here is an attempt to model the energy consumption in Sigma IV with the DOE 2.1B energy analysis program.

DOE 2.1B is a public domain, hour-by-hour computer simulation that has been widely used by building designers, engineers, and researchers. The validity of its algorithms and methodologies has been demonstrated in a number of studies. Nevertheless, many designers, engineers, and researchers alike are skeptical of its accuracy and suitability for assessing design strategies. The intent of this work was not to validate the program or prove its accuracy, but rather to lend insight into its suitability for developing energy conservation strategies in a specific building, and to highlight potential user errors and pitfalls in modeling a building. Of particular interest here is the process of compiling input estimates of building use schedules. The availability of hourly data allows close scrutiny of such estimates.

In order to directly compare the metered data for a particular year with a computer simulation, it is necessary to use the same weather year for input into the simulation. The availability of such data at Pacific Northwest Laboratory (PNL) has made this possible. Hourly weather observations from 1982 through 1984 were obtained from the PNL weather station. These data were converted to Test Reference Year (TRY) format which can be read by the DOE 2.1B weather processor. Since the metered data cover a period from November, 1983 through April, 1985, the full measurement year can be directly compared.

Two significant difficulties were encountered in modeling the Sigma IV building for this study. Both involve limitations of the ability of DOE 2.1B to model the performance of heat pumps. The first, and the most critical to this study, is the inability of DOE 2.1B to model economizer operation on an air-to-air heat pump. The second problem is the inability of DOE 2.1B to model the common return air plenum for the ten heat pumps.

One of the first steps in modeling a building is the development of building use schedules. Since energy use in larger buildings is typically driven dominantly by internal loads, this step is extremely important. Unfortunately, these assumptions are often given only minimal thought. Even when carefully developed, these assumed schedules may not be accurate, as was demonstrated by this study.

The Sigma IV building was modeled three times, first with estimated lighting and equipment densities and schedules, then with "standard" lighting and equipment schedules from the DOE 2.1B Reference Manual, and finally with the actual power densities and schedules derived from the metered data. The estimated power densities were developed by counting the installed light fixtures and equipment. Estimated occupancy, lighting, and equipment schedules were developed through the consensus of a number of persons familiar with the building. The "standard" occupancy, lighting, and equipment schedules from the DOE 2.1B Reference Manual were used in conjunction with the estimated power densities for the second simulation. The final simulation was calibrated so that lighting and equipment energy use were as close as possible to the actual consumption. The results of these simulations are shown in Figure 9.

Upon first examination, the results appear to compare favorably. For example using the estimated use schedules the lighting energy consumption was predicted with an error of less than ten percent of metered consumption. However, closer examination reveals some interesting differences. The count of connected lighting fixtures amounted to 3.01 Watts/sq.ft. However, the actual peak density revealed by the metered data was 2.37 Watts/sq.ft, indicating that all the lights are never on or working at the same time. The estimated schedule assumed that the minimum lighting use (during the night) was approximately 5 percent of the peak. The data revealed that this base is almost 30 percent. Had the peak density been estimated correctly, the annual lighting energy would have been predicted with an error of almost 30 percent. Cooling energy would have been predicted with a difference of 11 percent from the original estimate, and 17 percent from the actual metered consumption.

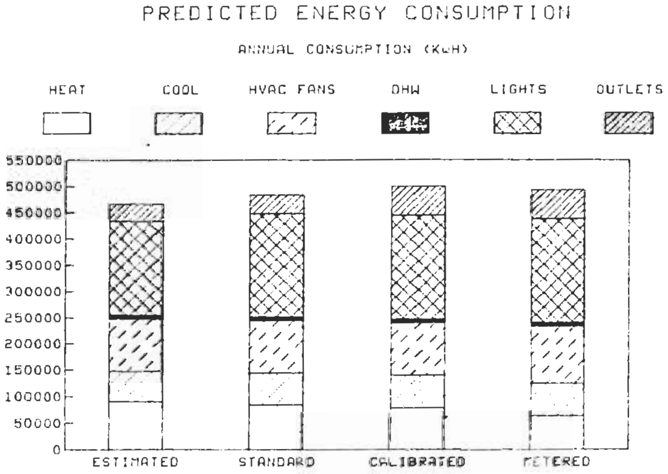

FIGURE 9

Similarly, convenience outlet (equipment) schedules and power densities were not estimated correctly. The differences in predicted cooling consumption resulting from these errors could result in detrimental energy conservation strategies if the simulation were used as the primary input for decision-making. In any particular situation, the magnitude of errors resulting from faulty building use assumptions might easily equal or exceed the calculated savings from any proposed energy conservation strategies.

CONCLUSIONS

Hourly end-use energy data were collected and analyzed for a one year period. Cooling energy was found to represent approximately 12 percent of the total annual electricity consumption. Economizer operation was shown to provide a relatively small portion of annual cooling requirements. The difficulty of explaining the causes of the loads were highlighted. The low cooling requirements as well as the cooling behavior of the different perimeter zones could not be directly coupled to the issues of proper equipment sizing, operating schedules, and building construction. This revelation, while disappointing, emphasizes the need for careful design of metering studies developed to identify strategies to reduce total energy use as well as peak energy demand.

The experience gained from the calibrated energy simulation highlighted the care and caution required when using this approach for analyzing energy use in specific buildings. The metering effort has revealed that accurate operating schedules are of utmost importance. The analyst should devote the time and expense necessary to correctly estimate schedules and internal load densities before attempting to determine conservation strategies. Periodic spot measurements at the electric panel are probably warranted.

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