Influence of Air Conditioner Operation on Electricity Use and Peak Demand

Arthur E. McGarity, Daniel Feuermann, Willett Kempton, and Leslie K. Norford

Center for Energy and Environmental Studies
Princeton University, Princeton, N.J.

ABSTRACT

Electricity demand due to occupant controlled room air conditioners in a large master-metered apartment building is analyzed. Hourly data on the electric demand of the building and of individual air conditioners are used in analyses of annual and time-of-day peaks. Effects of occupant schedules and behavior are examined. We conclude that room air conditioners cause a sharp annual peak demand because occupants have strongly varying thresholds with respect to toleration of high indoor temperatures. However, time-of-day peaking is smoothed by air conditioning in this building due to significant off-peak operation of air conditioners by some occupants. If occupants were billed directly for electricity, off-peak use would probably diminish making the peaks more pronounced and exacerbating the utility company's load management problems. Future studies of this type in individually metered apartment buildings are recommended.

INTRODUCTION

TOPICS COVERED IN THIS PAPER

This paper reports on the influence of occupant-controlled room air conditioners on residential electricity use and peak load in a large multifamily building in Trenton, NJ. We use hourly data on whole-building electric demand spanning the entire summer of 1986 to describe both the seasonal and daily peaks and to analyze their meteorological, behavioral, and mechanical determinants. Air conditioning is a very significant component of the electric demand in this building, and measurement of its influence on the load is simplified because energy for domestic hot water and cooking is supplied by natural gas. Thirteen of the ninety air conditioners in the building were monitored, and here we present data on three of those units in order to demonstrate the variety of operating modes that we found in the building and to illustrate types of behavior which exacerbate the daily and seasonal peaks.

We believe that our results can contribute to an understanding of air conditioner loads in other, similar buildings for which lesser amounts of data (monthly or daily) are available. Also, our analyses of hourly data on building electric demand and outdoor temperature illustrate the types of conclusions that can be drawn from such data and suggest a need for monitoring at a similar level in other types of buildings.

This paper presents the macroscopic view of electric loads in the building. Another paper [3] presents the microscopic view by detailing the operation of the thirteen individually monitored units (in eight apartments) and by examining occupant behavior through the analysis of intensive interview material.

REASONS FOR STUDING AN APARTMENT BUILDING

We are trying to understand the peak residential loads of electric utilities by studying how variations in the aggregated load of the apartment building, illustrated in Figure 1, relate to specific loads in the building, especially those in the individual dwelling units. With an apartment building, we are connecting to aggregate demand at a level lower than aggregate data available in most utility data sets, which typically draw on data derived from metering of substations. The substation load is much larger than that of an apartment building, and it is made up of more heterogeneous loads.

Our aggregation at the apartment building level offers some advantages. By aggregating over similar dwelling units and equipment configurations we see a consistent

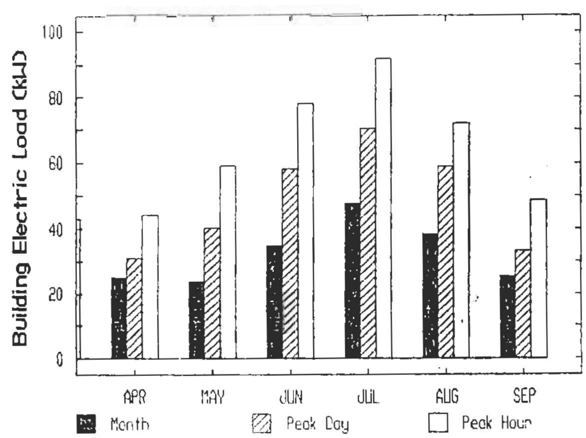

Figure 1. Statistics on total building electric demand: monthly average (shaded), average demand on the peak day of the month (cross hatched) and demand (averaged over one hour) during the peak hour of the month.

Proceedings of the Fourth Symposium on Improving Building Systems in Hot and Humid Climates, Houston, TX, September 15-16, 1987

picture of the effects of equipment, weather, and the behavior of groups of occupants. Yet by combining many apartments, we average out idiosyncrasies in the behavior of individual people. Thus, an apartment building is an ideal location for learning about the behavioral determinants of residential electric demand because it is a microcosm which can be efficiently studied at the level of individual dwellings and at the level of many dwellings.

LITERATURE REVIEW

We are able to explain many features of the electric demand because we have intensively monitored this building for many months. We have also conducted lengthy interviews with some of the occupants. Thus, by combining interview data and hourly load data, we are able to include effects of occupant behavior in a study of electric peak loads due to air conditioning.

Monthly utility meter readings were used in an earlier load study by Hackett and Lutzenhiser which laid groundwork for cooling load studies that include a behavioral component. They documented the reduction of electricity consumption in an air conditioned apartment building after a conversion from master-metering to individual apartment metering, but the effects on peak demand could not be determined without hourly data [2]. McLain, et al. used submetered data of electricity consumed by air conditioners in occupied single family homes to determine parameters for a computer simulation study, but effects of the occupants' life-styles were unknown and had to be simulated by trial-and-error adjustments to the computer model's parameters [5]. Parken, et al. have studied the performance of central air conditioners in three occupied single family homes using data over intervals as short as 5 minutes, but the effects of occupants were deliberately filtered out so that the characteristics of the equipment alone could be determined [6]. Stovall and Kuliasha analyzed hourly electricity consumption data from a large data set which included some information on occupant life-styles in single family residences in different parts of the United States, but their attempt to correlate energy use with roughly quantified "life-style variables" produced limited results [7]. We attempt no such quantification of occupant behavior, but our results help to clarify the effects of different types of behavior and may point towards better definitions of life-style variables.

THE BUILDING

The building, Beechwood Apartments, has 62 units (mostly one-bedroom apartments) on four floors. It was built in the early 1960's. Electricity use is "master-metered" which means that monthly charges for electricity are billed to the building's owner and not to the occupants. Master metering also means that it has a commercial classification for utility rates. This rate involves charges of $0.088/kWh for energy and $10.35/kW for the monthly peak demand.

A disadvantage of master-metered apartments for studies of electric demand is that these buildings are less common than they once were and are, therefore, less representative of buildings in general. However, master metering turns out to be an advantage in Beechwood Apartments because of the type of study we are performing: an innovative load study that explicitly accounts for occupant effects. We have been able to examine the behavior of occupants in the absence of economic factors which might otherwise strongly influence behavior. Our results show behavior that is attributable to factors such as comfort, convenience, safety concerns, and energy conservation concerns. Each of these factors were mentioned by occupants during interviews. Our study can serve as a point of reference for studies of apartment buildings where occupants are charged directly for their electricity. By comparing data from such buildings with our results, estimates can be made of the effects that the economic factor has on load characteristics such as peaking.

ELECTRIC LOADS

Most of the building's electric loads are located in the apartments and are under the control of the occupants. Exceptions are the outside security lighting, hall and staircase lighting, the controls on the natural gas boiler, and the circulating pumps on the hydronic space heating distribution system. Many loads are affected by the level of the occupant activity and vary significantly according to the daily, weekly, and seasonal schedules of the occupants. These loads include room air conditioners, apartment lighting, thermostatically operated refrigerator-freezers, small appliances, home entertainment equipment, portable space heaters in some apartments, and the building's single elevator. Most of the cooking is done with natural gas stoves, but we have noticed that some occupants also use electric toasters and microwave ovens.

The manager of the building has made a deliberate effort to assure that each apartment has at least one functional room air conditioner. Many of the apartments have an additional unit. Most of the units presently in operation are the ones that were installed when the building was new, so they are about 25 years old. We estimate that there are about 90 functional air conditioners in the building. The air conditioners are mounted in a hole cut out of an exterior wall. The units have cooling capacities in

Proceedings of the Fourth Symposium on Improving Building Systems in Hot and Humid Climates, Houston, TX, September 15-16, 1987

the range 8000 - 9000 BTU/hr. We measured power consumption on five units and learned that they typically draw 1100 Watts when the compressor is running and 200 Watts when only the fan is running.

GENERAL FEATURES OF BUILDING ELECTRIC DEMAND

The building's hourly electric demand varies substantially with the time of day and with the time of year. Time-of-day variations are examined in detail in Section 3. The current section presents several important aspects of the electric demand that are shown by plots covering the entire period of mild and hot weather (April - September). In section 2.3, the analysis is extended to include cold weather (January - March).

AVERAGE AND PEAK ELECTRICITY DEMANDS

Figure 1 displays bar graphs of three different statistics on building electricity demand. The solid bars show the average electricity demand for an entire month. The cross-hatched bars show the average demand on the "peak day" of the month, that is, the day having the greatest daily total consumption of electricity. The unshaded bars show the electric demand (averaged over one hour) during the hour of the month with the greatest consumption.

The heights of the monthly average bars determine the energy portion of the utility company's revenue from the building. The heights of the peak day bars indicate the occurrence of sustained periods of greater than average demand. The heights of the peak hour bars indicate the severity of short-term peaks and determine the demand portion of the utility company's revenue. Both types of peaks cause load management problems for utility companies.

Comparing peak-day bars with monthly average bars, we see that sustained greater-than-average demand is much more significant during May through August than in April or September, indicating that sustained peaks accompany hot weather. A similar comparison of peak-hour bars with peak-day bars, provides us with a measure of the severity of the short-term peak. The difference between these bars varies over a limited range of 13 - 20 kW with the larger differences occurring in the hot months. This result indicates that weather has some effect on the severity of the short-term peak, but that it is not the only cause. Further analysis of short-term peak demand indicates that occupant schedules are also very important (see Section 4).

HOURLY DATA: BUILDING ELECTRICITY AND OUTDOOR TEMPERATURE VERSUS TIME

We now present a direct analysis of hourly electric demand data which reveals some other interesting features of the electric demand. Figure 2 displays hourly data for total building electricity demand (lower line) and outdoor temperature (upper line) versus time for April - September.

The weather in April and May is characterized by a mixture of cool, mild, and warm

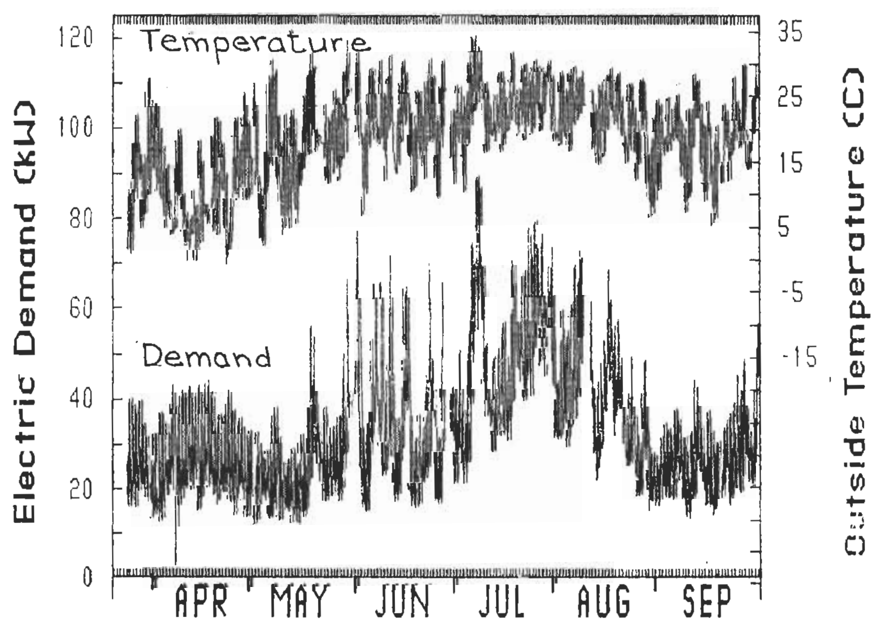

Figure 2. Hourly data for total building electric demand (lower line) and outdoor temperature (upper line) versus time for six months.

Proceedings of the Fourth Symposium on Improving Building Systems in Hot and Humid Climates, Houston, TX, September 15-16, 1987

temperatures. The bottom of the demand envelope, defined by the daily minima, increases noticeably during the cool weather (from 12-15 kW to 20 kW) when there are changes in loads that are usually constant, such as switching on of the 4 kW circulator pump on the hydronic space heating system. Occupants who use supplemental electric space heaters during cool weather may also contribute to an increase in the daily demand minima. However, analysis of winter data (not presented here) suggests that the occupants tend not to use the space heaters while they are sleeping or while they are away from their apartments and that supplemental space heaters have more effect on the daily maxima than the daily minima.

The plot in Figure 2 begins with mild weather during the first week of April. During this period, daily minima are about 13 kW. Cooler weather occurred during the rest of April and the space heating system operated most of the time until the first week of May when it was shut off completely. Mild weather dominated the first half of May, and during most of this period, the building's load varied daily between 13 kW and 27 kW. However, this period contains a brief increase in peak demands which we attribute to the first use of air conditioners.

Note the weather conditions which motivated some of the occupants to begin using their air conditioners during the first week of May: for the first time the daily maximum temperatures were above 25 C for three consecutive days and the daily minimum temperatures were above 12 C for two consecutive days. During this period, electricity demand peaked at about 40 kW and, for the first time, a demand peak corresponded to a temperature peak rather than a temperature dip. A warm period at the beginning of April was almost as warm, but there is no evidence that air conditioning use began at that time. Note also that there was a warm spell in the middle of May that was only slightly warmer and slightly longer, but electricity demand increased substantially to a peak of 55 kW.

We believe that the lag phenomenon we observe during the transition between cold and hot weather is due primarily to the behavior of the occupants rather than the physical properties of the building. During the first warm spell, perhaps no one turned on an air conditioner. During the second, a few air conditioners were used. During the third, many more occupants turned on units. The thermal lag of the building may also contribute to this behavior. However, we rule it out as the major factor because the outdoor temperature immediately preceding the third warm spell is lower than it is for the first and second. A significant thermal lag in this case would diminish the need for air conditioning. We do not mean to imply that thermal lag is not significant in this massive masonry building. Rather, we argue that our data show evidence of a more significant dynamic effect due to the behavior of the occupants.

Data from our interviews with occupants suggests that some people have a "behavioral inertia" which delays their use of air conditioning. They speak of the air conditioner as something they have to "deal with," and this response suggests that having to operate the unit can be bothersome. Perhaps it is particularly bothersome at the beginning of the cooling season when occupants are required to refamiliarize themselves with the control panel. Our interview data suggest that most people do not understand the controls. Another theory which may help to explain the lag phenomenon is based on the observation that people are less tolerant of hot weather after having been exposed to air conditioning. Lutzenhiser describes this phenomenon as being like an "addiction" [4]. Perhaps occupants are exposed to air conditioning outside their homes with increasing frequency throughout the transition period and gradually reach the point where they are uncomfortable without it.

The demand pattern during the remainder of the summer is characterized by a jagged envelope with large changes in both the maximum and the minimum from day-to-day corresponding to changes in the outdoor temperature. The large variations in the daily minima create a sharp contrast with the pattern associated with mild weather in April and May. Apparently, many occupants leave air conditioners running while they are sleeping and while they are out of their apartments.

The peak electricity demand of the nine month period occurs in early July on the day of the seasonal maximum outdoor temperature (35 C). The peak of 92 kW is about three times the average demand (31 kW) over the period.

ELECTRICITY DEMAND VERSUS OUTDOOR TEMPERATURE

In Figure 3 we include data from January, February, and March and plot the building's electricity demand averaged over each day versus the corresponding average outdoor temperature for each day for the period January - September. The plot appears to be comprised of three different segments corresponding to three different temperature ranges. For daily average temperatures below 5°C (41 F), average demand is virtually constant at about 30 kW (about 720 kWh per day). Between 5°C and 15°C (59 F), the plot slopes gently downward to about 22 kW. Above 15°C, average load increases sharply with temperature. The data from the "shoul-

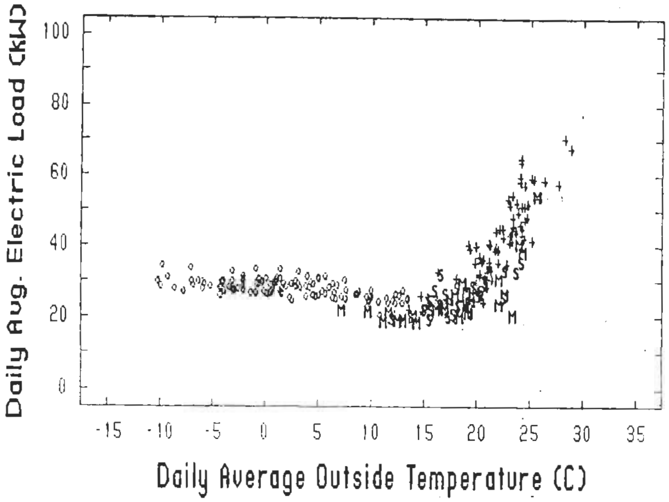

Figure 3. Daily average electric demand versus outdoor temperature for 9 months: January - September. Data for cold months (Jan.-Apr.) are indicated by "O"; hot months (Jun.-Aug.) are indicated by "+"; May and September are indicated by "M" and "S", respectively.

der months" of the cooling season are indicated by "M" for May and "S" for September.

The flatness of the plot below 5°C suggests that the daily average load of the occupants' electric space heaters is fairly constant once cold weather sets in. The 8 kW drop between daily average temperatures of 5 and 15°C is caused by declining use of the space heaters and the cut-out of a 4 kW central heating circulator pump on days when the temperature rises above 18°C for portions of the day.

When the daily average temperatures rise above 15°C, the apartments become warm during portions of the day and some occupants begin to use their air conditioners. The data from May and September contribute to the scatter in this portion of the plot. The May data for temperatures between 20 and 25°C provide another view of the occupant's behavior discussed in Section 2.2. Three points from May are distinctly below the trend at temperatures of 22, 23, and 24°C. Two of these points are from the first period of air conditioner use in the first week of May, and the third is from the first day of the mid-month warm spell. Data points from September create additional scatter. Warm September days have electric demand below the trend and some of the cooler September days have electric demand above the trend. It is possible that some occupants stopped using air conditioners after periods cool weather began to occur early in the month. Also, considering the abrupt changes in outdoor temperature that initiated the September cool spells, is possible that stored thermal energy in the building kept interior temperatures high causing air conditioners to continue operating on some mild days.

Analysis of our data from individual apartments, including occupant interviews, indicates that occupants have a variety of "threshold" weather conditions which determine air conditioner use. Some occupants said that they prefer to open windows or use fans in mildly warm weather. During warmer weather, more people decide to turn on air conditioners and a greater portion of the building is cooled. This gradual increase in the total cooling load with increasing outdoor temperature should create an increasing positive slope over the warm weather portion of Figure 3. If we examine the summer points that remain after the shoulder months are removed, (points indicated by "+"), we see a distinct knee in the plot below 20°C, but above this point, the trend appears to be linear. However, much scatter remains and upward curvature can not be ruled out.

TIME OF DAY PROFILES: SELECTED MILD AND HOT WEEKS

In this section, we closely examine a week in the middle of May when there was negligible space heating or air conditioning load. Electric load data from this week provide us with a measure of the building's base load, i.e. the electric demand due to loads other than space heating and air conditioning. Analysis of hourly data yields a time-of-day profile for the base load. Additional data, obtained from occupants, the building superintendent, and additional measurements enable us to estimate the components of the base load. Then, we examine a typical week of hot weather in late July and compare the electric load profile with that of the mild week. This comparison, combined with our analysis of the base load, enables us to draw conclusions about the time-of-day profile of the air conditioning load and to estimate the number of air conditioners that were in use.

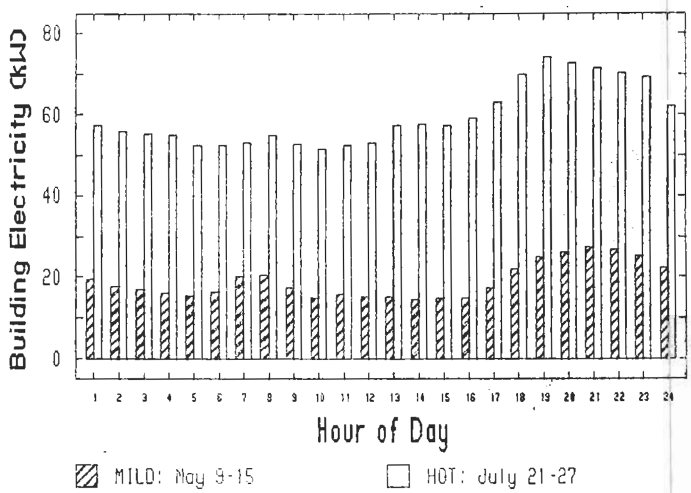

Figure 4. Time-of-day profiles of building electric demand for a mild week in May (cross-hatched bars) and for a hot week in July (unshaded bars).

Proceedings of the Fourth Symposium on Improving Building Systems in Hot and Humid Climates, Houston, TX, September 15-16, 1987

Figure 4 presents time-of-day profiles for both weeks. The figure is created by averaging building electricity demand for each hour of the day over the entire week. Each cluster of bars shows average demands for a particular hour of the day (the hour preceding the indicated time) Time is displayed in daylight savings time (one hour later than standard time). The weather was fairly uniform throughout both weeks; average outdoor temperatures were 12.9oC (55 F) and 24.4oC (76 F) during the mild and hot weeks, respectively.

Table 1 presents minima, maxima, and ranges of daily variation for the two weeks.

TABLE 1: Comparisons of Electricity Demand for Two Weeks

Type of Week	Average Demand (kW)	Daily Minimum (kW)	Time of Minimum	Daily Maximum (kW)	Time of Maximum	Range (Min-Max) (kW)
Mild	19	15	9AM-4PM	27	8-10 PM	12
Hot	60	52	4AM-Noon	74	6-7 PM	22

MILD-WEEK: COMPONENTS OF THE BASE LOAD

First, we discuss what we know about the components of the base load during the middle of the night when we can assume that most apartment lighting was off and very few appliances were in use. The minimum <u>nighttime</u> demand during the this week occurred between 3:00 and 5:00 AM and the average value was 15.9 kW.

Hallway and staircase lighting created a constant load of 2.5 kW. Nighttime security lighting consisted of 1.8 kW operated by a timer and 1.3 kW switched manually. Seasonal adjustments can be made to the timer, but we believe that it was not adjusted between December, 1985 and September, 1986, based on spot checks. Thus this load was probably present between 5:00 PM and 9:00 AM daylight time (hours 1 - 9 and 18 - 24 in Figure 4) during the mild and hot weeks. The manually switched security lights are located at the front and rear entrances and are controlled by switches located just inside the doors. We are confident that these lights were turned on at night, but we do not know whether they were always turned off during the day, although the superintendent claims that they usually were. Summing all nighttime lighting loads in common areas, we obtain 5.6 kW.

We measured the power consumed by two of the refrigerators for one week in July and obtained an average of 80 Watts. We believe that these refrigerators are representative of most units in the building (the units are provided and maintained by the building's owner). During mild weather, the consumption would have been less than in July by perhaps as much as 18% [1]. We shall assume, therefore, that the nighttime refrigerator load averaged 66 Watts per apartment, or about 4.1 kW for the building.

Miscellaneous loads we know about, including our own data acquisition system, total about 500 Watts, so we have accounted for all but 5.7 kW of the nighttime base load (92 Watts per apartment). We have no additional measurements, but we speculate that the remaining base load includes all-night lighting in some apartments, equipment that consumes electricity while off such as instant-on televisions, and occasional use of the elevator during these hours. Also, the superintendent and the occupant of one of the apartments we monitored have small freezers (the refrigerators have only a small freezer compartment), and the superintendent believes that there are about five small freezers in use in the building. In the analysis that follows, we must assume that the magnitude and time-of-day profile of these unknown loads were the same during the mild and hot weeks.

We now estimate the magnitude of the occupant-controlled base load at three times of the day: morning peak (hours 7 and 8), midday minimum (hours 10 - 16), and evening peak (hours 21 and 22). Since all of the security lighting is likely to be on during the morning peak, we subtract the entire 15.9 kW nighttime base load from the morning peak load of 20.4 kW to estimate that 4.5 kW or 73 Watts per apartment is the peak load due to the morning activities of the occupants. We assume that all of the security lighting is off during the middle of the day, so we subtract 3.1 kW from the nighttime base load to obtain a daytime constant base load of 12.8 kW. Subtracting this value from the actual midday consumption of 15 kW, we can estimate that occupants who are at home during the day consume 2.2 kW for daytime lighting, appliances, and entertainment equipment. During the evening peak, the security lighting is on, so we subtract the nighttime base load from the evening peak (27 kW) to obtain 11.1 kW or 180 Watts per apartment as an estimate of the daily peak load due to occupant activity.

HOT WEEK: PROFILE OF AIR CONDITIONER USE

The analysis in this section assumes that the loads due to occupant activity were the same during the hot week as they were during the mild week. Seasonal differences in lighting loads have been reported in the literature [1], but we argue that there was little difference in lighting loads between

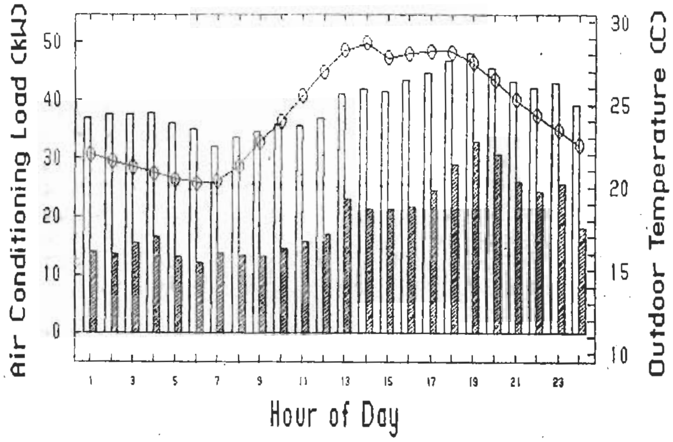

Figure 5. Time-of-day profiles during the hot week in July for the air conditioning load. Entire building air conditioning load (unshaded bars) is estimated. Aggregated compressor load for ten air conditioners (shaded bars, scaled by a factor of 10) is from direct measurements of individual units. A line plot of the outdoor temperature profile is also shown.

our mild week and our hot week because the daylight period differed by only 18 minutes between these two weeks. Among the other components of the base load, only the refrigerator loads are likely to have differed significantly between the two weeks. Here, we assume that the load of each refrigerator increased 14 Watts during the hot week (i.e. to the measured value of 80 Watts) for a total increase of 840 Watts in the building. We add this value to each hour of the mild week time-of-day loads to create an adjusted base load profile. Then, by subtracting the adjusted base loads for each hour from the hot week time-of-day loads, we create a time-of-day profile for the building's air conditioning load.

Figure 5 displays the time-of-day profile of the building's air conditioning load calculated as described above (unshaded bars). The figure also shows data derived from the air conditioners we monitored (ten units during the hot week). The shaded bars show the profile for the hot week of the aggregated power consumed by the compressors (scaled by a factor of 10). The similarity of the two profiles suggests that the assumptions we have made to calculate the building air conditioning load profile are reasonable.

Note that the air conditioning load is substantial at night while people are sleeping and during the middle of the day when most occupants are away from home. Minimum air conditioning load occurs at the time of the minimum temperature (hour 7) which is also the time of the morning peak in occupant activity. Thus, the morning peak in apartment lighting and appliance loads is offset by the dip in air conditioning load, and the result is the virtual elimination of the morning demand peak (see Figure 4).

We can estimate the number of units in use at various times of day by calculating the power that a single unit draws when it is on and by dividing the load by this number. This calculation requires an estimate of the percentage of time the compressor operates when a unit is turned on. We have used data from the units we monitored to estimate a compressor operating percentage for each hour of the day. We use the following equation to calculate the power:

Average Air Conditioner Power =

[(% of time * power):compressor+fan]

+ [(% of time * power):fan only]

For example, between 3:00 and 5:00 AM, the compressors in the units that were turned on (among those we monitored) operated 80 percent of the time. Thus, we estimate that the average unit operating at this time consumed:

$$(0.80)(1.1\text{ kW}) + (1-0.80)(0.2\text{ kW}) = 0.92\text{ kW}.$$

The air conditioning load at this time was 37 kW, so we estimate that the number of air conditioners in use while occupants were sleeping was 40 or 44% of the functional units in the building. Table 2 presents results for this and other times of day.

Table 2: Air Conditioner Load and Number of Units on at Certain Times of Day

Hour of Day	A/C Load (kW)	Compressor Operation (%)	Number of Units On	Percentage of Total
4-5	37	80	40	44
7	32	66	40	44
14-15	41	80	45	50
19	47	83	49	54

PEAK DEMAND: ANNUAL VERSUS DAILY

COMPARISON OF ANNUAL AND TIME-OF-DAY PEAKS

Table 3 shows four different measures of the severity of the annual peak and the time-of-day peaks during the mild and hot weeks. The annual results are calculated on the basis of a nine-month average demand of 31 kW, the annual minimum demand of 12 kW in late March, and the annual maximum demand of 92 kW in early July.

Table 3: **Measures of Peak Severity: Annual and Time-of-Day**

Type of Peak	Time Period	Range (Min-Max) (kW)	Ratio: Maximum / Minimum	Ratio: Maximum / Average	Ratio: Range / Average
Annual	Jan.-Sep.	80	7.7	2.97	2.58
Time of Day	Mild Week	12	1.8	1.42	0.63
	Hot Week	22	1.4	1.23	0.37

One conclusion we draw from Table 3 is that the annual peak is much more severe than the time-of-day peaks according to all measures of severity. Of course the annual range and the annual maximum-to-minimum ratios must be at least as great as the corresponding time-of-day measures. (The annual values could be nearly equal to the time-of-day values if the annual minimum and maximum both occurred during one of the three weeks.) However, both of these measures are around four times greater in the annual case than they are in the time-of-day case because of the magnitude of the peak air conditioning load during the hottest weather.

The maximum-to-average ratio is a rough indicator of the amount of utility generating capacity required per unit of revenue derived from energy charges. Of course, the actual effect that Beechwood Apartments has on the local utility company depends on the nature of the overall demand in the company's service area.

The range-to-average ratio is an indicator of the amount of utility load fluctuation per unit of energy revenue derived. Fluctuations in time-of-day demand may add to the utility company's costs if generating capacity must frequently be brought on-line and taken off-line. Of course, fluctuations in annual demand will also add to costs if peaking generators that are expensive to operate are necessary to supply annual peak loads.

Comparisons of load ratios for the mild and hot weeks indicate that, although the air conditioners cause annual load management problems for the utility company, they improve load management on the daily time scale. The off-peak air conditioning load has a smoothing effect on daily fluctuations.

EFFECTS OF SPECIFIC OCCUPANT BEHAVIOR ON SEASONAL AND DAILY PEAKS

Here, we present results from continuous monitoring of air conditioning operation in three apartments. The behavior exhibited by occupants in each of these apartments illustrates the effects that different people can have on peak demands and utility revenue. Figure 6 shows contrasts in the effects of individual occupants as measured by use of air conditioners during the entire cooling season: part A; use during time-of-day peak: part B; and use during the annual peak: part C. The labels to the left of each horizontal bar show the apartment number (e.g. 2K) and the room of the monitored unit, with "L" indicating living room and "B" indicating bedroom.

Part A shows the total number of hours (as percentages of the entire season) that each unit was switched on (total length of bars) and the total hours of compressor operation (shaded portion of bars). Each unit was monitored 2755 hours or about 115 days. To the right of each bar is an estimate of the total energy that was consumed during the season including the fan and the compressor of each unit. Part B shows what portion of each unit's seasonal compressor operation occurred during the hours of high demand (6 - 11 PM). Part C shows what portion of each unit's seasonal compressor operation occurred during the week of peak demand (July 5 - 11).

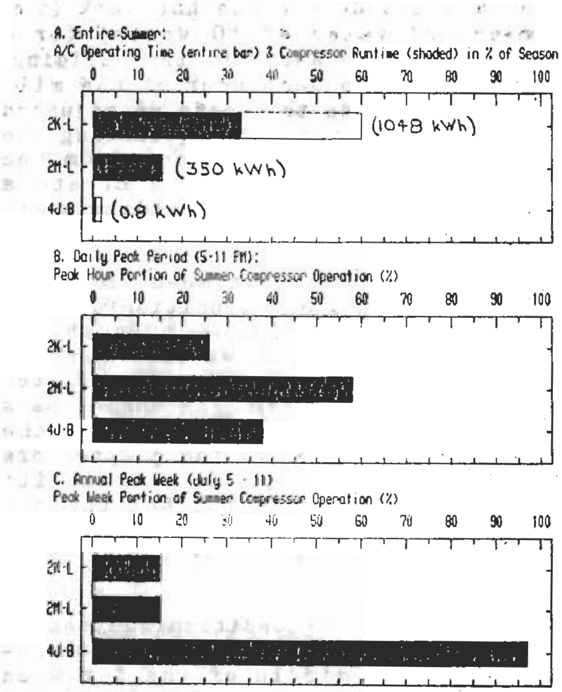

Figure 6. Air conditioner use of selected occupants and distributions of use during daily and annual peak **periods. Part A shows air conditioner operating time (entire bar) and compressor operating time (shaded portion) for the entire summer.** Total energy consumed **by each unit is shown to the right of each bar.** Parts **B and C show the percentages of** the annual compressor **operation that occurred during** the daily peak periods **and during the annual peak week.**

Proceedings of the Fourth Symposium on Improving Building Systems in Hot and Humid Climates, Houston, TX, September 15-16, 1987

Table 4 displays information on the average operating conditions of each unit. The first column shows the comfort temperature, the average temperature in the room while the air conditioner was operating. The second column shows the level of air conditioner operation (the percentage of time that the compressor operated while the unit was switched on).

Table 4: Average Operating Conditions

A/C Unit	Comfort Temperature	Level of Operation
2K-L	24°C (75 F)	53%
2M-L	25°C (77 F)	97%
4J-B	28°C (82 F)	31%

The occupant of apartment 2K worked at home and ran the living room unit most of the time. The person in 2M worked a typical 8 AM - 5 PM weekday schedule and ran the living room unit for several hours each evening after work. The occupants of 4J ran their bedroom unit on only two days during the summer, and one of those days was the one on which the building's total electricity demand reached its annual peak.

Unit 2K-L used the most energy and created the most revenue for the utility company. Unit 2M-L used much less energy and unit 4J used almost none. However, units 2M-L and 4J-B both affected the building's peak demand and thereby had an effect on the amount of generating capacity the utility company had to provide.

Figure 6 shows that the peak-hour portion of unit 2K-L's compressor operation (about one-quarter of total operation) is the same as that period's portion of the day (6 hours or one-quarter of the day). In contrast, unit 2M-L's compressor operation during peak hours is disproportionate: more than half of the unit's total operation. Clearly, in apartment 2M, we have monitored behavior of an occupant whose schedule and mode of air conditioner use combine to produce behavior which exacerbates the daily peak electric demand.

The peak-week portions of unit 2K-L's and unit 2M-L's compressor operation are both about 15 percent of the seasonal operation although the peak week is only 6 percent of the season. Of course, we expect to see increased levels of use during such a hot week. However, Unit 4J-B's compressor operation during the peak week is disproportionate: almost all of the unit's total operation. In apartment 4J, we have monitored behavior that exacerbates the annual peak and could contribute to upward curvature in a plot of electric load versus outdoor temperature.

CONCLUSIONS AND RECOMMENDATIONS

This paper reports results from a field study of electricity demand in a multifamily building that was intensively monitored for nine months. Data, recorded hourly, on environmental variables and on electricity consumption (in the entire building and in individual apartments) have been analyzed in a variety of ways in order to understand the components of the building's electric load, particularly air conditioning. We have augmented the hourly data with information obtained through contact with the building superintendent, several occupants of the building, and spot measurements. Our findings should be of interest to others who are studying electricity use in buildings without the benefit of hourly data, particularly in other master-metered buildings including hotels. Also, the methods we have used to analyze hourly data illustrate how such data can be used when it is available.

Our major findings concern the effects of room air conditioning on electric demand in this building. During a hot week, the average load due to air conditioning was approximately 3 times the base load (the average load during a mild week). The ratio of the peak annual electric demand to the base load was 4.8, or, when compared to the average yearly load, annual peak demand was 3 times greater.

Air conditioning load clearly dominates summer electric demand and causes a sharp annual peak. One cause for the sharpness of the annual peak can be found in the behavior of occupants who have strongly varying thresholds with respect to toleration of high indoor temperatures. It is significant that such variation exists in a master-metered building because there is no economic benefit in avoiding air conditioner use. Apparently, some people are not uncomfortable until the temperature is quite high. Also, there are non-economic factors such as the desire for fresh air, irritation by air conditioner noise, and concern for energy conservation which cause many people to avoid using the air conditioner until they are particularly uncomfortable. We have also learned, on the other hand, that air conditioning in this building tends to flatten the time-of-day peak because of substantial off-peak use of air conditioners. It is possible that a large part of the off-peak use is by occupants who lack motivation to turn the units off when they are not needed because there is no cost.

We recommend future studies in an apartment building where occupants are billed directly for electricity used to air condition individual apartments. Results from such a study can be compared with our findings to measure the importance of the cost of electricity in determining patterns of air conditioner use.

In a building with individual apartment metering, we would expect to see sharper peaks (both annual and time-of-day) as measured by the peak-to-average ratio; off-peak use of air conditioners (which contributes substantially to the average load) is likely to be less significant than in Beechwood, but peak use (which occurs when high temperatures correspond with high levels of occupant activity) is likely to be about as significant as it is in Beechwood. We would also expect to see significantly lower utility revenues per air conditioner resulting from reduced off-peak use and from the absence of a peak demand charge. Residential rate classification is used when apartments are metered individually, and, presently, this rate includes no demand charge. If the peak demand per air conditioner is unaffected by individual metering, the utility company's revenue derived per unit of generating capacity will be lower. Additional studies can help to clarify the effects that conversions from master-metering to individual apartment metering have on electricity use and peak demand, and whether changes in rate classifications are necessary to accommodate the trend towards more individually metered apartment buildings.

ACKNOWLEDGEMENTS

We acknowledge the following colleagues for helpful comments during the writing and review of this paper: Margaret Fels, Douglas Flemming, and Robert H. Socolow at the Center for Energy and Environmental Studies, Princeton University. This research was funded by the New Jersey Energy Conservation Laboratory of Princeton University.

REFERNCES

1. Fels, M.F., M.L. Rachlin, and R.H. Socolow, "Seasonality of Non-heating Consumption and Its Effect on PRISM Results", Energy and Buildings, Vol. 9, Nos. 1&2, (Feb./May, 1986).

2. Hackett, Bruce and Loren Lutzenhiser, "Energy Billings, Cultural Variation, and Residential Energy Consumption", Proceedings of the ACEEE 1986 Summer Study on Energy Efficiency in Buildings (August, 1986).

3. Kempton, Willett, D. Feuermann, A.E. Mc Garity, "Air Conditioner User Behavior in a Master-Metered Apartment Building", Proceedings of Symposium on Improving Building Energy Efficiency in Hot and Humid Climates (this volume) Houston, TX (September, 1987).

4. Lutzenhiser, Loren. Personal Communication (July, 1987).

5. McLain, H.A., D. Goldberg, M.A. Karnitz, S.D. Anderson, S.Y. Ohr. Benefits of Replacing Residential Central Air Conditioning Systems, Oak Ridge National Laboratory, ORNL/CON-113 (April 1985).

6. Parken, Walter H., David A. Didion, Paul H., Wojciechowski, Lih Chern, Field Performance of Three Residential Heat Pumps in the Cooling Mode, National Bureau of Standards, NBSIR 85-3107 (March 1985).

7. Stovall, T.K. and M.A. Kuliasha, An Analysis of Lifestyle Effects on Residential Energy Use, Oak Ridge National Laboratory, ORNL/CON-170, (February 1985).