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EFFECTIVE, LOW-COST HVAC CONTROLS UPGRADE IN A SMALL BANK BUILDING

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by

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ABSTRACT

This report summarizes the measured results from a field study of the performance of a low-cost controls retrofit in a small bank building in Knoxville, TN. The retrofit consisted of a simple upgrade of heating and cooling system controls and new operating strategies. The project was undertaken to better understand how commercial energy use measurement studies should be performed and to demonstrate the effectiveness of a low-cost controls retrofit in a small commercial building. This report describes the details of the project, including building and building system characteristics, the HVAC control changes made, energy end use patterns, and the heating and cooling energy savings achieved.

An improved control strategy involving thermostat setback/setup and on/off control was devised around a single replacement programmable thermostat. The strategy allowed thermostat setback/setup control of the primary HVAC system in the building and provided on/off (time-of-day) control for the two secondary systems. The energy efficiency improvements provided a 33% reduction in heating and a 21% reduction in cooling energy consumptions. Simple payback for the retrofit, including installation cost, was under 1 year. In addition to reducing the energy needs of the building, the replacement electronic thermostat provided improved interior comfort.

INTRODUCTION

Commercial buildings were estimated to account for approximately one-third of the total electrical use in the United States in 1987 (Shepard 1987). Between 1972 and 1986, the growth of commercial electricity use accounted for more than 40% of the growth in U.S. electricity consumption (USDOE 1989). If trends continue, history indicates that future electrical use increases will be largely due to increasing commercial consumption. Small- to medium-size buildings (less than 50,000 ft^2) represent 95% of all U.S. commercial buildings and account for 53% of all commercial floorspace (EIA 1989). These facts indicate that achieving energy savings in small- to medium-size commercial buildings is an important part of reducing national energy use.

While larger businesses often have staff dedicated to the problem of energy conservation and sufficient capital to invest in such projects, smaller businesses usually have neither. The commercial sector, composed of small- to medium-size buildings, has been identified as needing assistance in implementing energy conservation measures. Many electric and gas utilities already extend programs to the commercial sector (Kolb and Hubbard 1988), but many of these programs are not applicable to small buildings or they lack the incentives needed to induce widespread participation. Private companies, such as energy service companies (ESCOs), typically cannot provide services to small businesses due to the small scale of the individual buildings relative to the investment requirements for ESCOs (ACEC 1987).

Affordable, short-payback efficiency improvements promote small business investment and are now encouraging service companies to consider offering wide-scale energy services to smaller buildings. Demonstrating and documenting the benefits of effective, low-cost efficiency improvements in these buildings through field study is an important part of encouraging their implementation.

This paper summarizes the measured results from a field study of the performance of a low-cost controls retrofit in a small bank building in Knoxville, TN. The retrofit consisted of a simple upgrade of heating and cooling system controls and new operating strategies. The study was undertaken to better understand how to meter the energy performance of a small commercial building to determine baseline and improved performance after energy conservation measures are installed and to demonstrate the potential of low-cost improvements in a small commercial building. The project was conducted by a national laboratory as part of the U.S. Department of Energy's program on Existing Buildings Efficiency Research. This paper describes the HVAC (heating, ventilating, and air conditioning) control changes made, energy end-use patterns before and after, the heating and cooling energy savings achieved, and insights learned.

Previous results have been presented from this project on the energy use patterns of buildings (MacDonald and Akbari 1987; MacDonald 1988), electrical energy savings and load impacts during the cooling season (MacDonald and Sharp 1989), and a project summary report (Sharp and MacDonald 1989).

THE BUILDING AND BUILDING SYSTEMS

The building studied for this project was a small stand-alone building housing a branch office of a local bank. The building has one story above ground and a below-ground basement. The building has approximately 4000 ft^2 of conditioned space and 850 ft^2 of unconditioned space. Business is conducted approximately 42 hours a week on weekdays only. The branch office typically has a 12-person staff and averages around 250 to 350 customers per day.

The building has three separate zones -- two office (Zones 1 and 3) and one open business space (Zone 2), as shown in Figure 1. The three zones are heated and cooled by three separate, split-package air conditioners and one central gas-fired boiler which supplies hot water to each air-handling unit. System capacities total approximately 12 tons of cooling and 188,000 Btu/h of heating. Prior to retrofit, conditioning to all zones was controlled by three standard, single-stage mechanical thermostats that were operated at the same setpoints during both occupied and unoccupied periods. Lighting at the site is approximately 70% incandescent and totals approximately 8.3 kW during business hours and 3 kW during non-business hours.

DATA COLLECTION

Data were collected between June 1987 and August 1988. The pre-retrofit period ended on March 1, 1988, and the post-retrofit began on March 2. Since the whole building and all systems were considered as candidates for efficiency improvements, all energy systems at the site were measured as opposed to only measuring a targeted end use. Data were collected under the following end-use classifications: total electricity, cooling, heating, lighting, fans, and miscellaneous energy use. Utility billing data were tracked during the entire monitoring period.

THE EFFICIENCY IMPROVEMENT

The efficiency improvement consisted of replacing the mechanical thermostat on the primary (largest) heating and cooling unit with a programmable thermostat and interfacing it to control the two secondary units. The programmable thermostat has auxiliary contacts which operate as on/off switches triggered by occupied and unoccupied setpoints. On/off system control in the secondary zones was implemented by connecting the auxiliary contacts to relays that control the power to each of the secondary zone thermostats. The new operating strategy consisted of implementing setback/setup control on the primary unit (Zone 2) and on/off control on the two secondary units (Zones 1 and 3). The replacement of all thermostats within the building was avoided to keep costs lower and to leave familiar controls where possible. Hardware and installation costs totaled approximately $600.

The new operating strategy implemented unoccupied setback/setup temperatures of 55°F (heating) and 90°F (cooling). Occupied temperature setpoints were not changed. Occupied hours were programmed for 8 a.m. to 6 p.m. Monday through Thursday and 8 a.m. to 8 p.m. on Friday, totaling 52 hours a week (this includes 2 hours beyond each business day that are allowed for daily cleanup).

Turning off the HVAC systems for the office areas during unoccupied periods is acceptable since the office areas still receive some conditioning through interaction with the primary zone. This strategy and the perimeter location of the offices causes unoccupied space temperatures in Zones 1 and 3 to exceed those in the setback/setup-controlled Zone 2. However, Zone 2 interacts enough with the perimeter zones to minimize the more extreme temperatures that would risk pipe freezing or other problems.

RESULTS

Energy savings resulted from changes made to the HVAC control schemes in each of the three building zones. Previously, all systems operated at normal setpoints continuously (168 hours a week). After the improvement, all systems operated at normal setpoints only 52 hours a week. During the unoccupied period (the remaining 116 hours a week), thermostat setback/setup was implemented in the largest building zone (Zone 2) and complete shutdown of the units occurred in the two secondary zones. The operational changes for the three zones are summarized in Table 1.

Heating Energy Savings

The control changes had a major impact on the amount of gas required for winter heating. The impact to billed gas use is clearly visible in Figure 2. As a rough approximation, if the average gas use rates from these billing data profiles are used to project savings, the retrofit reduced gas use by 37%. Based on the gas use and heating degree-days (HDD) recorded for winter 1988/89 (the mild heating months are excluded), this approximation indicates $400 in heating costs alone were saved during this period.

Linear models (daily gas use as a function of average outdoor temperature) were used to examine changes in energy use patterns and to provide more accurate estimates of the energy savings achieved. The actual data were well represented by the models since all model correlation coefficients (R) were above 0.92 except for the post-retrofit weekend model (0.71). The heating models, model coefficients, and related parameters are summarized in Table 2. The models, shown in Figures 3 and 4, were generated from submetered daily gas use totals and daily average outdoor temperature data. They illustrate the varying impacts of the different control strategies on weekday and weekend gas use. The differing rates of gas use shown in Figure 3 for before-retrofit weekdays and weekends occur due to more internal heat generation (heat added to interior spaces from lights, equipment, and people in this case) during occupied periods. They indicate that the increased internal load during weekdays reduces gas heating needs by approximately 4 therms/day (100 $Btu/ft^2/day$) at all outdoor temperatures.

Comparisons of Figures 3 and 4 show that the weekday gas use rate has been reduced 49% and that the weekend rate was reduced to approximately zero during moderate winter temperatures (40^oF and above). A lack of data on lower- temperature weekends required the post-retrofit weekend model to only represent weekend days with average daily temperatures above 40^oF. At some average outdoor temperature, around 40^oF or lower, the post-retrofit weekend model will experience a slope similar to the weekday model when outdoor temperatures plunge low enough that gas heating is required to maintain the indoor setback temperature. To approximate this gas use, the slope of the post-retrofit weekday model was used to represent the slope of the needed temperature-dependent portion of the post-retrofit weekend model for 40^oF and below (the dashed line in Figure 4). This resulted in a slightly conservative estimate of weekend energy savings since the slope of the temperature-dependent portion of the weekend model will likely be less than that of the weekday model due to the more extreme weekend operating strategy. Error in this approximation should have limited impact on estimated energy savings since the post-retrofit weekend temperature-dependent gas use (since it occurs only on weekends and at daily average temperatures below 40°F) is only a small part of the total post-retrofit gas use.

The linear models shown in Figures 3 and 4 were used to predict gas use for the winter of 1988/89 with and without the retrofit. The models indicated that major heating energy savings were achieved during both weekdays and weekends. Heating energy needs were reduced by approximately 33% ($500 in winter 1988/89) and the savings were approximately equally split between weekdays and weekends.[1]

The hourly impacts of the new control strategy are visible in the two months of data shown in Figure 5. The profile peaks during February (days 32 through 60) typically occur during all hours of the day. In contrast, the new control strategy resulted in peaks being essentially restricted to only occupied periods during March (days 62 through 88). The decrease in profile peaks during business hours when moving from February to March is predominantly due to milder temperatures in March. However, the near elimination of peaks during non-business hours is almost entirely attributable to the new control strategy.

Cooling Energy Savings

The control changes also had a major impact on cooling energy use but the resulting savings are difficult to discern using billing data. Since building cooling is electric-driven, cooling electricity use is

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[1]The 33% heating energy savings is based on gas savings alone and does not include the electric energy savings resulting from the reduced run times of the air distribution fans.

embedded in electric billing data along with baseload electric energy use, i.e., the electric lighting, water heating, refrigeration, and other electric loads that are or are nearly temperature independent. As a result, the reduction in cooling energy use is difficult to discern using billing data in the form presented in Figure 6. Even when baseload electric energy is subtracted out, billing data in this form do not clearly show the cooling energy savings.

The cooling models, model coefficients, and related parameters were generated from submetered daily air-conditioning energy use data and are summarized in Table 3. The varying impacts of the new control strategy on weekday and weekend air-conditioning (AC) energy use are shown in Figures 7 and 8. The higher rate of AC energy use in Figure 7 for pre-retrofit weekdays, as compared to weekends, occurs due to more internal heat generation during occupied periods. More cooling is needed during weekdays to remove heat generated by people, lights, and other sources. The increased internal load during weekdays increases AC energy needs by approximately 32 kWh/day (0.33 W/ft^2). The post-retrofit models (Figure 8) show the change in AC energy use due to the new control strategy. Comparison of Figures 7 and 8 indicates that the weekday energy use rate was reduced only moderately, while the weekend energy use rate decreased substantially (approximately 50%).

The linear cooling models were used to predict cooling energy use for the summer of 1988 with and without the retrofit. The models indicated that most of the cooling energy savings occurred on weekends. Cooling energy needs were reduced by approximately 21% ($300) in 1988.

The hourly impacts of the new control strategy on summer cooling energy use can be seen in the comparison of Figures 9 and 10. Most cooling energy savings are attributable to the near elimination of cooling energy use during weekends (shown by the clearer distinction between the weekday and weekend profiles of the 1988 summer data, Figure 10, as compared to the 1987 data, Figure 9, where valleys in the profile are less deep, indicating higher weekend energy use). Some of the cooling energy savings are also attributable to the near elimination of energy use spikes during unoccupied weekday hours (visible from the comparison of the foregrounds of the two figures). Another noticeable difference between the two profiles is that weekday business hour peaks were higher in 1988. While most of this increase is likely due to 1987 to 1988 temperature variations, part of the increase was found to be due to the replacement of non-working, exterior incandescent floodlamps.

Impacts to Load Profiles

The setback/setup and on/off control scheme altered the daily electric demand profiles for the building, as shown in the comparisons of similar days in Figures 11 and 12. The "smart-start" feature of the thermostat causes the building to begin temperature recovery before the occupied period begins. Recovery causes a higher morning demand than normal and therefore causes the visual time-of-day shift between the before and after daily demand profiles in Figure 11. The "smart-start" feature provides gradual recovery and therefore minimizes the surge in electric demand that would occur if recovery was initiated at the occupied period start when all building lights are switched on. The "smart-start" was not a necessary feature for the thermostat since the electric demand for this building was always far below 50 kW, the level at which the local utility begins to assess electric demand charges.

LESSONS LEARNED

Finding the Best Buildings

The amount of achievable energy savings can vary substantially from building to building. From an economic viewpoint, it is best to target the buildings with the most potential. Identifying these could be costly if a detailed audit is performed on all candidate buildings. This project used a building energy use indicator (billed energy use per ft^2 of conditioned space per billing period day -- $kWh/ft^2/day$) to help identify a building with promising energy improvement potential. In addition to billing data that were readily available from the servicing utility, only knowledge of the building's conditioned ft^2 was required to use this indicator. The indicator was useful in screening out buildings to help minimize the effort expended on evaluating candidate buildings with lower energy-saving potentials.[2]

Increased energy savings in small buildings is needed due to their potential for significantly reducing national energy consumption. If energy management services are to be provided to smaller customers on a wide scale, their savings-to-cost ratio will have to be improved. If wide-scale screening using billing data indicators (and perhaps others) as used here were implemented, small buildings with the most savings potential could be identified at low cost. Targeting these for improvement could increase the cost-effectiveness of the service. Although this approach would not serve all small commercial customers, it could lead to a much greater percentage of customers being served than currently exists and may be the starting point for innovative approaches that could serve even more of the small commercial market.

Energy Use Modeling

For linear modeling of heating and cooling energy use, collecting continuous data is not as important as collecting data representing the broad range of temperatures over which heating and cooling occurs. This happens since the data at the extremes of the linear model have much more control over the model parameters and errors than data recorded near its center. If significant temperature setback/setup or system shutdown is used, an unoccupied day will use energy at a much

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[2]This screening indicator is generally good only on an average basis; specific buildings with a low indicator can have significant energy-saving potentials and, likewise, specific buildings with high indicators may have low potentials. Also, a weather-dependent (e.g., per HDD) indicator may be required if compared buildings experience major weather differences.

different rate than an occupied day. Significantly different energy use rates may require separate weekday and weekend models in order to obtain good model correlations and examine the causes of energy savings.

CONCLUSIONS

Depending on the level of detail, the measurement of energy performance in commercial buildings can easily become complex. Commercial buildings are often complicated by the use of three-phase power, the existence of numerous electrical circuits, and by multiple heating and cooling systems. Multiple systems may lead to the need for collecting more data, which can complicate data collection and processing. The bank building studied here is similar to many commercial buildings in that it has multiple heating and cooling systems that condition different zones of the building. Division of the conditioned zones into office space and open business or other open-area space is also common. As a result, the strategy implemented here is applicable to a large number of small, medium, and perhaps large commercial buildings.

The changes made to the HVAC control strategy were very effective in reducing energy use and provided an attractive payback of less than one year. Although savings were achieved during weekdays, weekend non-business days were responsible for most cooling savings. In contrast, heating energy savings were approximately evenly split between weekdays and weekends. This type of efficiency improvement is most effective for commercial buildings having a weekday business schedule where manual or automatic setback/setup is not already providing savings. The dramatic reduction in the annual run times of the two secondary units as a result of the new control strategy will pay off in terms of saved energy (avoided energy costs) and perhaps in extending the life of these units.

The temperature setback/setup and on/off control strategies as implemented in this building impact building energy use profiles. If a building pays demand charges or at times operates near that point, caution should be used in implementing these types of control strategies. Demand costs, if increased, can easily negate much of the costs avoided by reduced energy consumption. The new operating strategy shifted the electric demand profile slightly, but was not a concern for the business since typical building loads were well below the point where the electric utility assessed demand charges (50 kW).

Upgrading controls in commercial buildings having multiple heating and cooling systems does not necessarily require the replacement of all existing controls or the installation of costly energy management control systems. The new operating strategy here required replacement of only one of the three existing thermostats. Thus, the upgrade was done with little impact on existing system controls. Simple, low-cost control changes and modified control strategies can be implemented affordably and can provide substantial energy use and cost reductions for small commercial buildings.

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Table 1. Weekly HVAC operational hours: before and after retrofit.

Units	Weekly Operational Status
1 & 3 -	Before: 100% Normal On
	After : 30% Normal On & 70% Off
2 -	Before: 100% Normal On
	After : 30% Normal On & 70% Setback/Setup On

Table 2. Space heating energy regression modeling results.

*Model: Daily Space Heating Gas Use = m x T_{avg} + b

	R	n (days)	m	Std. Error	b	Std. Error	Balance Point Temp.** (°F)
			(therms/day/°F)		(therms/day)		
Before							
Weekdays	0.93	16	-0.572	(0.062)	34.4	(2.7)	60.0
Weekends	0.95	6	-0.530	(0.086)	35.7	(2.9)	67.3
After							
Weekdays	0.93	20	-0.293	(0.028)	18.7	(1.4)	63.8
Weekends***	0.71	8	-0.018	(0.007)	0.9	(0.4)	49.7

*Models based on data recorded between February 1 and March 28, 1988. A baseload (temperature-independent) gas use equal to 2.55 therms/day was used to maintain boiler water temperature, however, this gas use did not contribute to space heating and is therefore not reflected in the models shown.

**Balance point temperature = -(b/m).

***This model represents data recorded at winter daily average temperatures of 40°F and above. At these temperatures, this model indicates approximately zero space heating energy use.

Table 3. Cooling energy regression modeling results.

*Model: Daily Cooling Energy Use = m x T_{avg} + b

	R	n (days)	m	Std. Error (therms/day/°F)	b	Std. Error (therms/day)	Balance Point Temp.** (°F)
Before							
Weekdays	0.90	76	8.36	(0.47)	-462	(35)	55.3
Weekends	0.91	30	8.84	(0.75)	-533	(56)	60.3
After							
Weekdays	0.95	30	6.20	(0.40)	-310	(29)	50.0
Weekends***	0.61	33	3.70	(0.86)	-257	(64)	69.5

*Models based on data recorded between May and September of each year.

**Balance point temperature = -(b/m).

***Model based on total electric energy measurements due to lack of submetered cooling energy data at extreme summer temperatures (daily cooling energy use = daily total electric energy use - daily electric baseload)

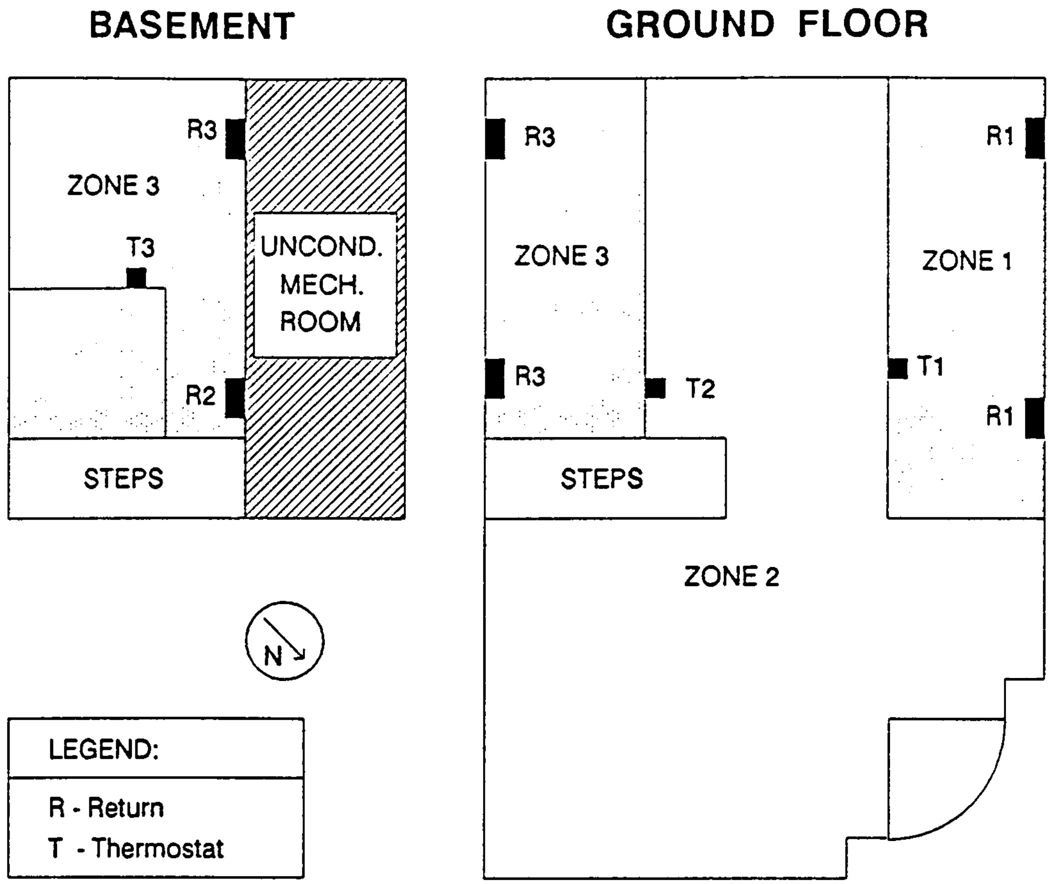

Figure 1. HVAC zoning and controls.

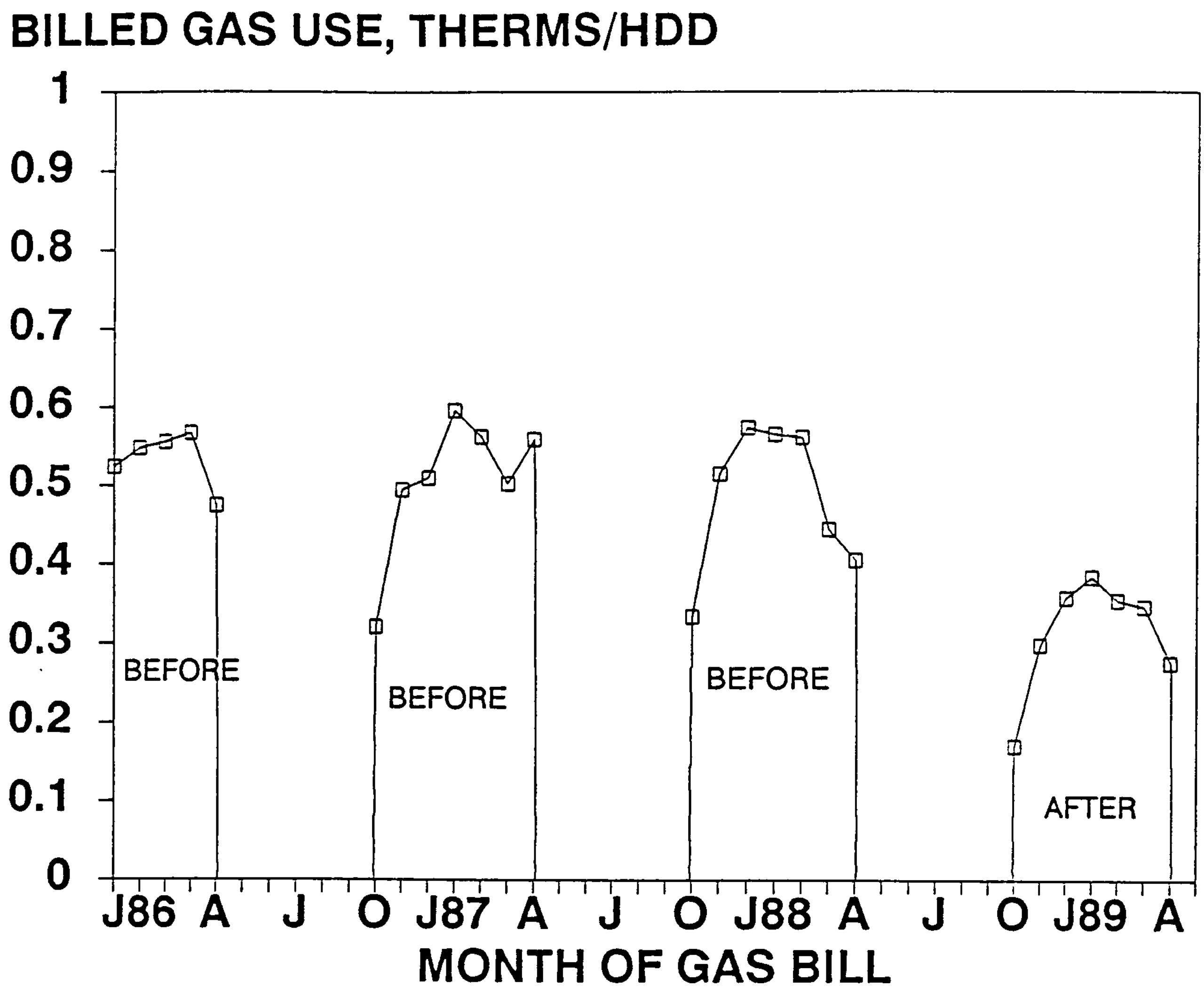

Figure 2. Billed energy use for pre-retrofit and post-retrofit winters.

Fig. 2

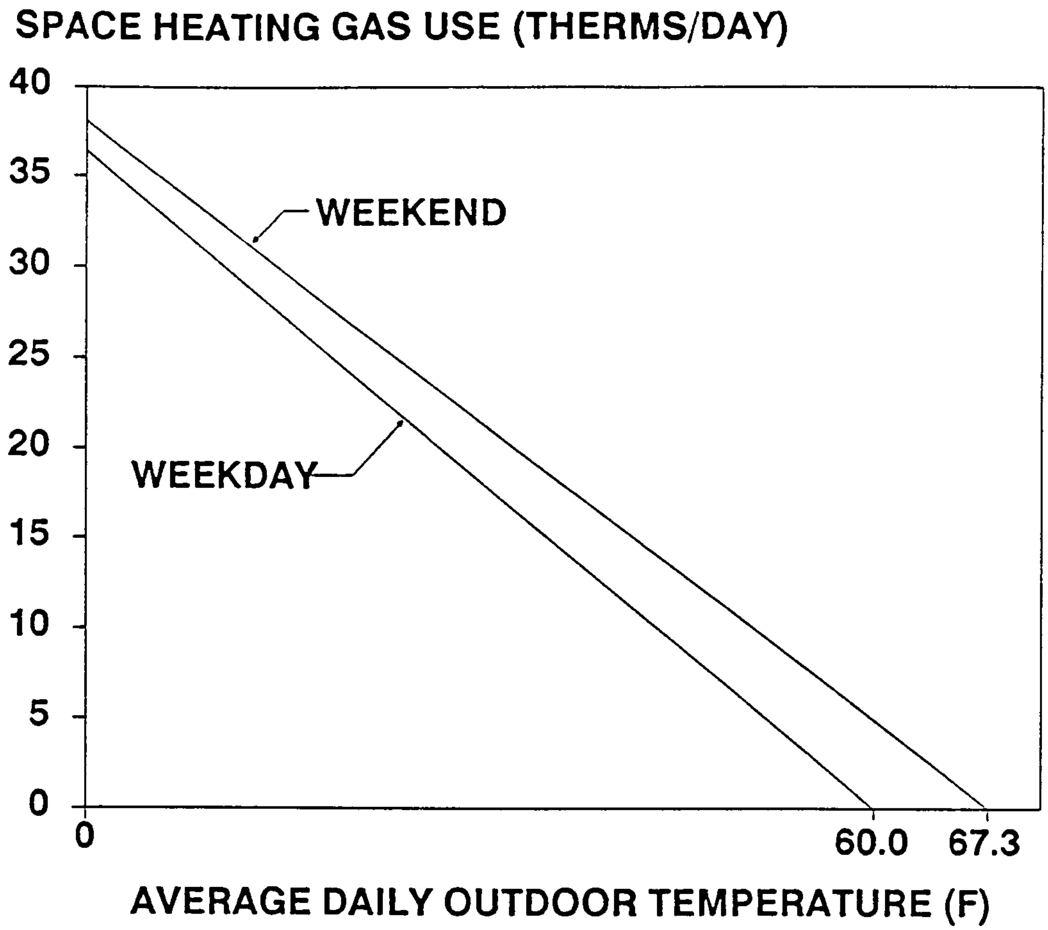

Figure 3. Pre-retrofit gas consumption models.

Fig. 3

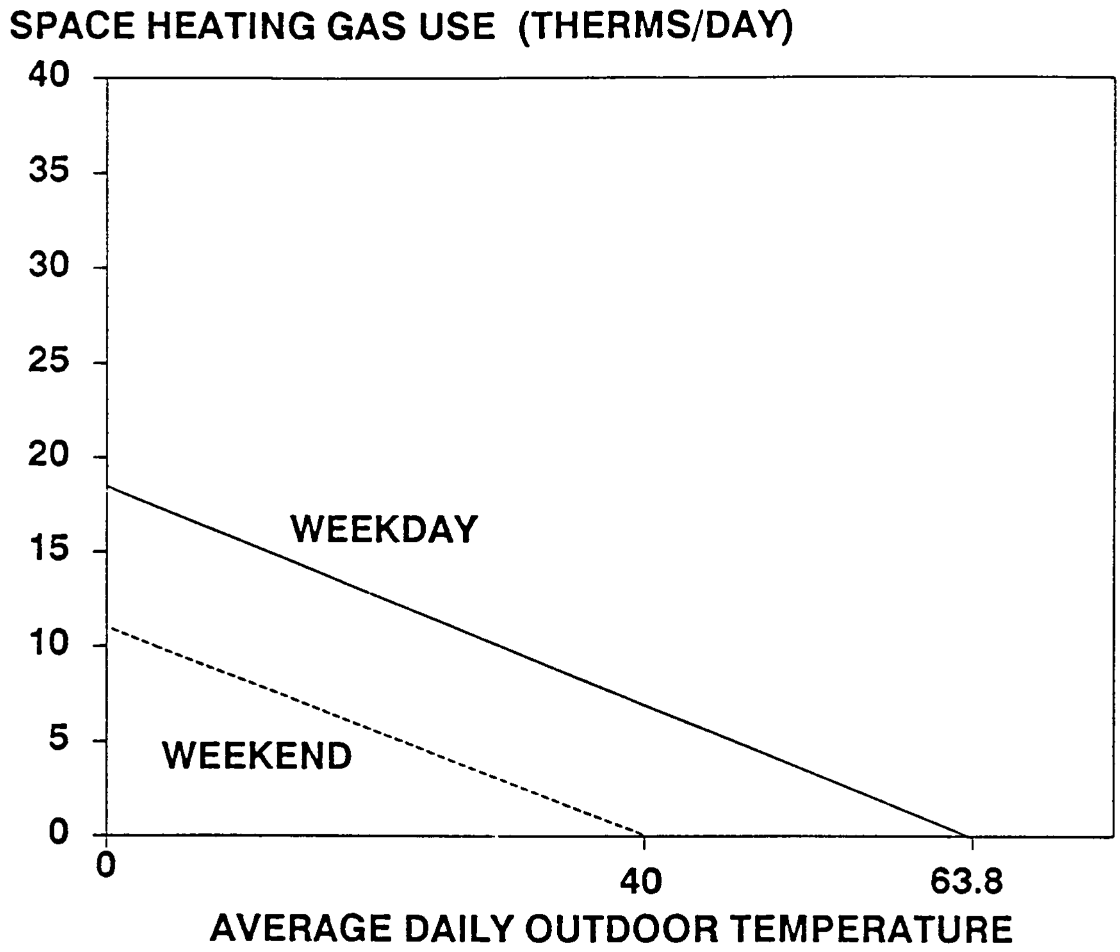

Figure 4. Post-retrofit gas consumption models.

Fig. 4

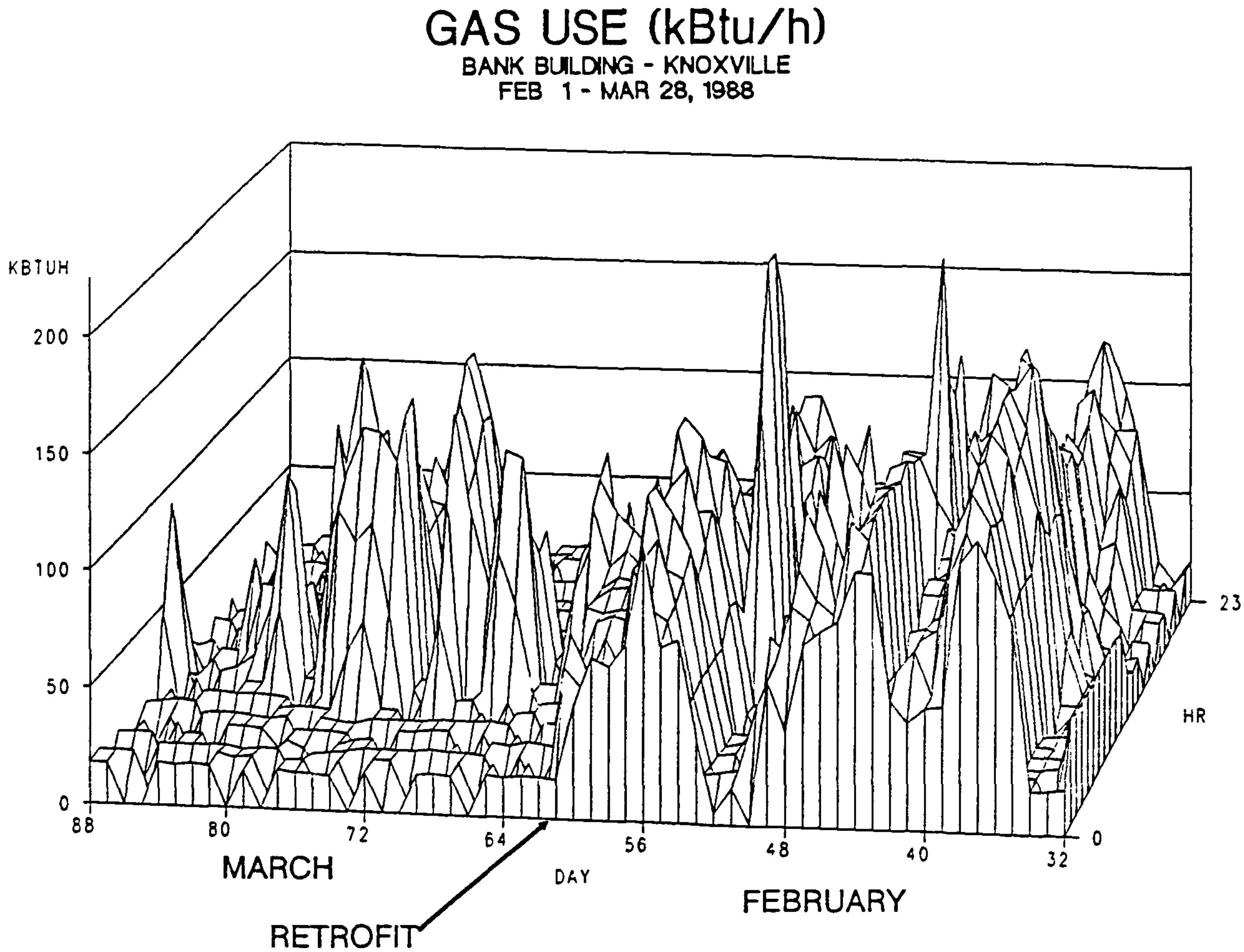

Figure 5. Hourly gas consumption profile one month before and after retrofit.

Fig. 5

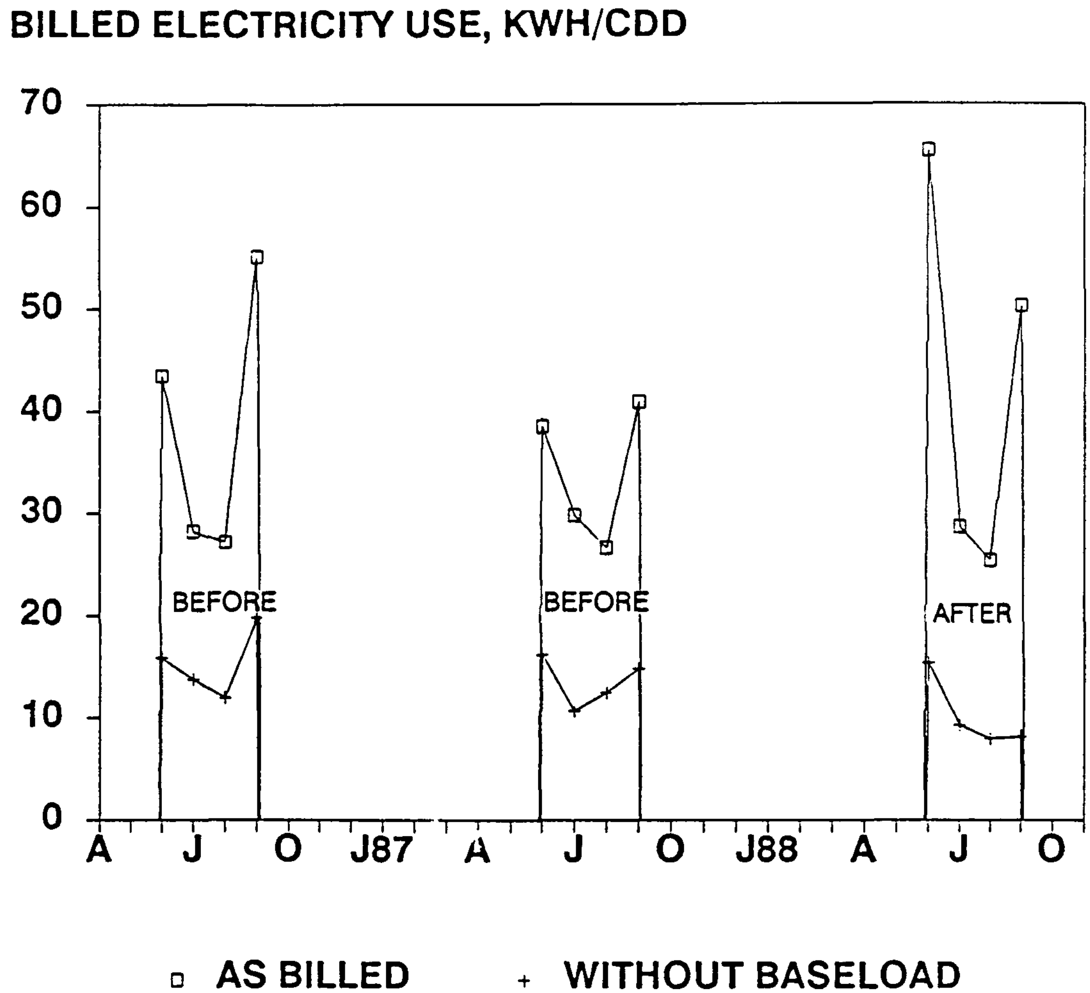

Figure 6. Billed electric energy use for pre-retrofit and post-retrofit summers.

Fig. 6

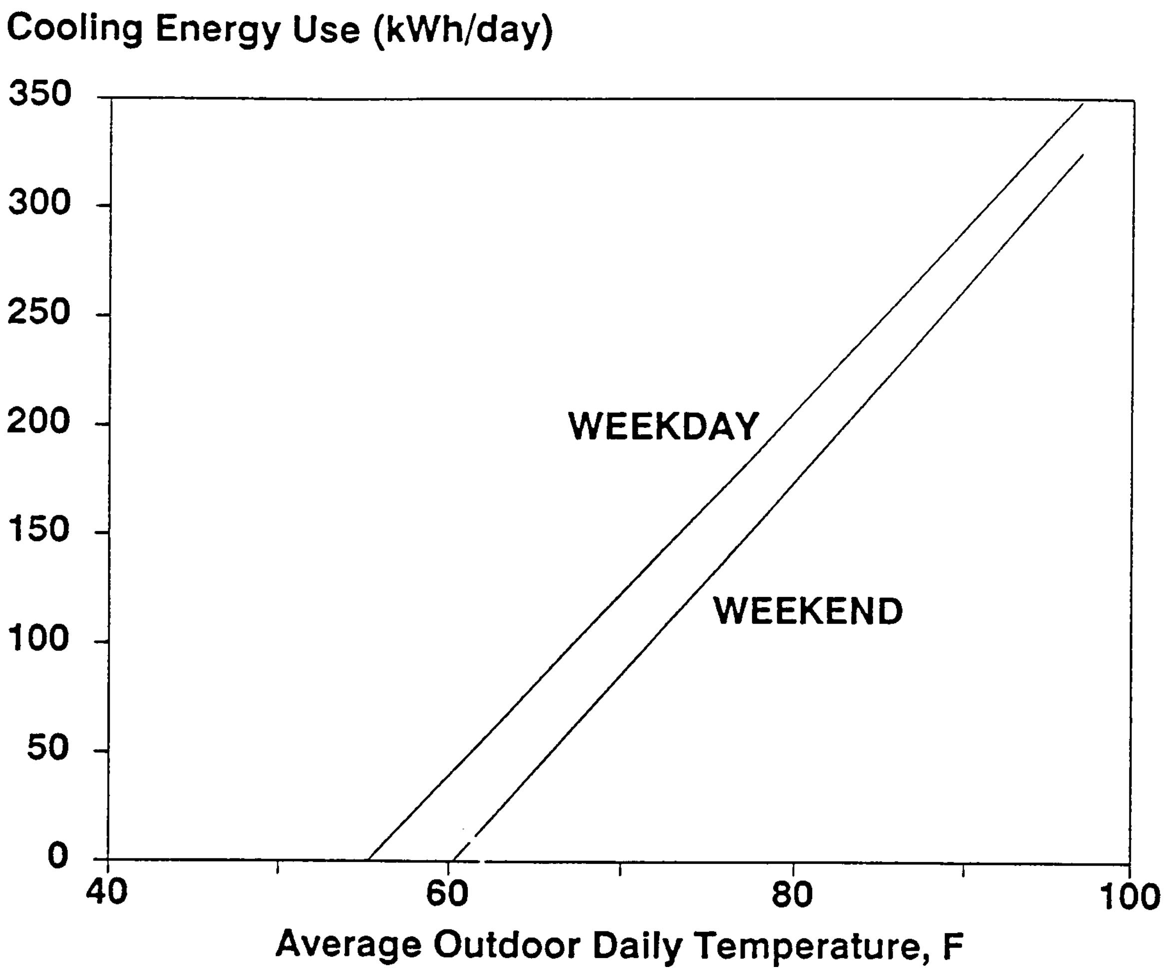

Figure 7. Pre-retrofit air conditioning models.

Fig. 7

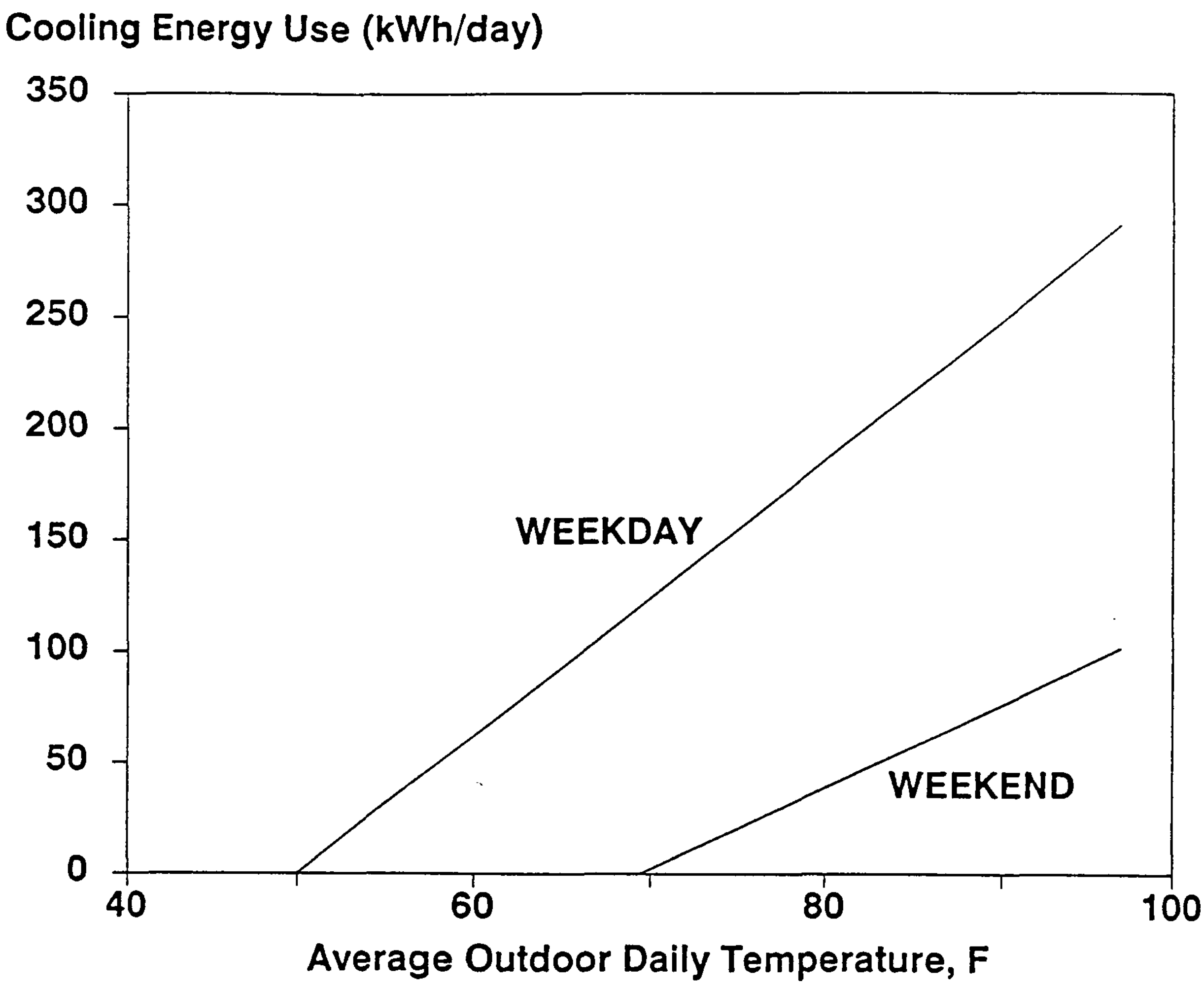

Figure 8. Post-retrofit air conditioning models.

Fig. 8

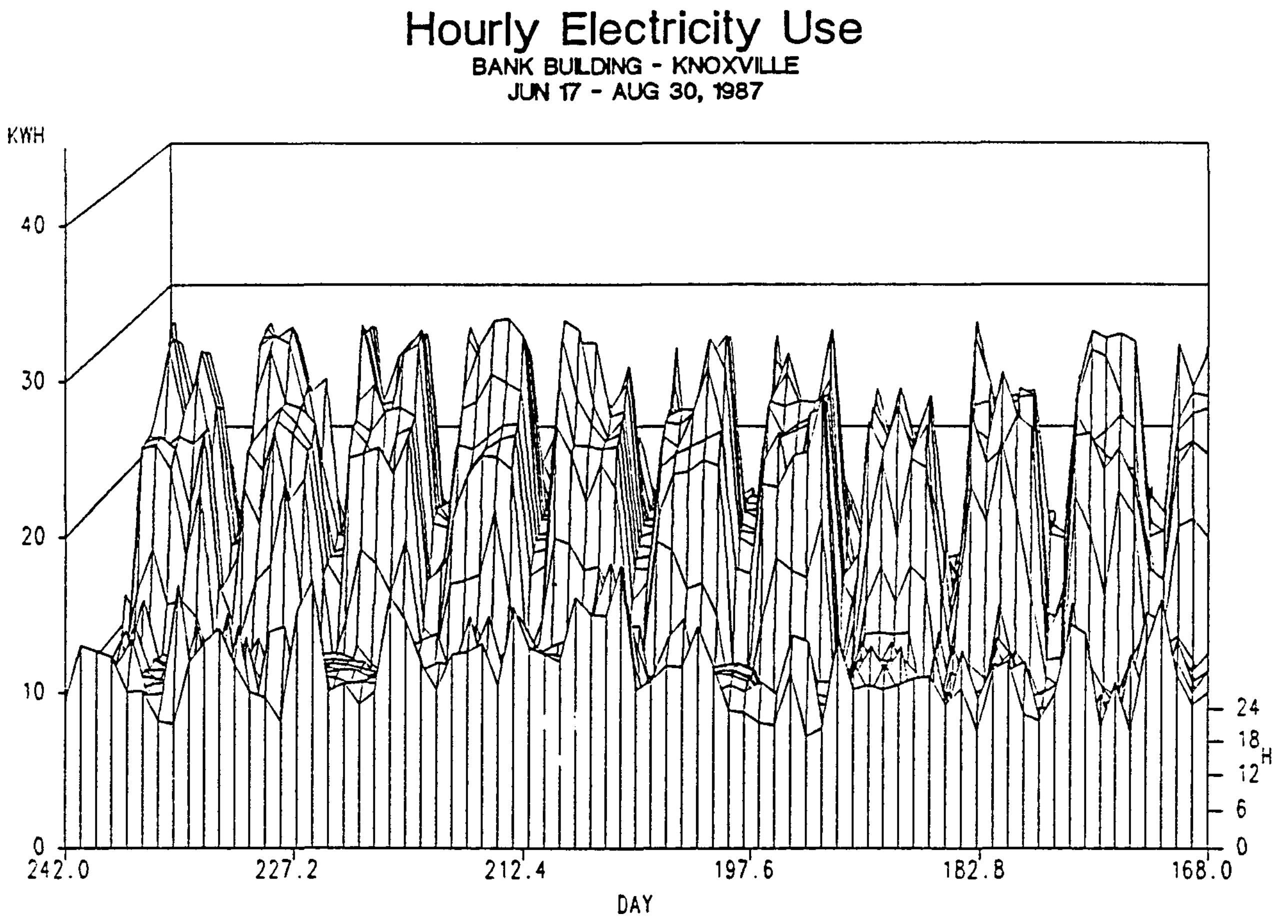

Figure 9. Hourly total electricity use profile for the pre-retrofit summer.

Fig. 9

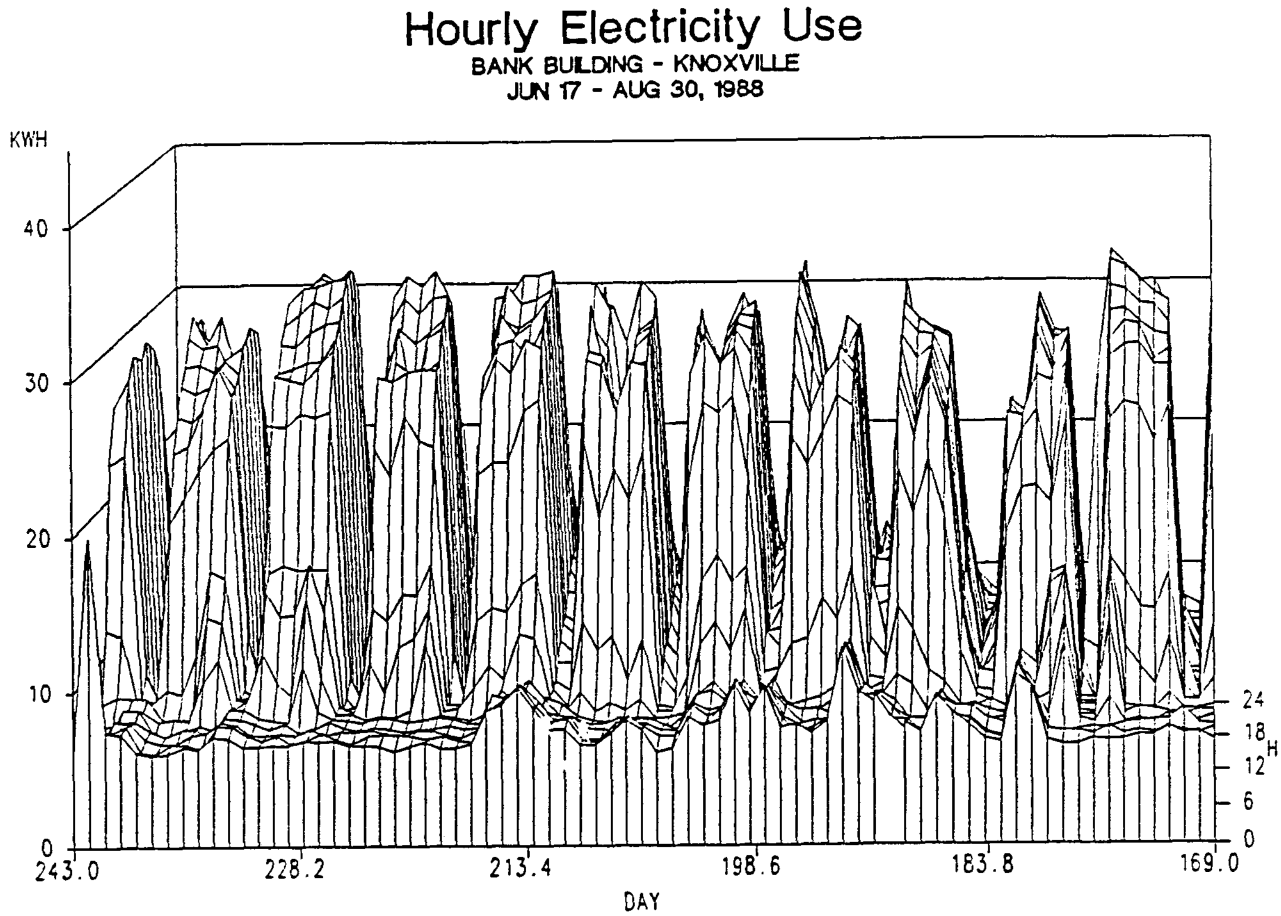

Figure 10. Hourly total electricity use profile for the post-retrofit summer.

Fig. 10

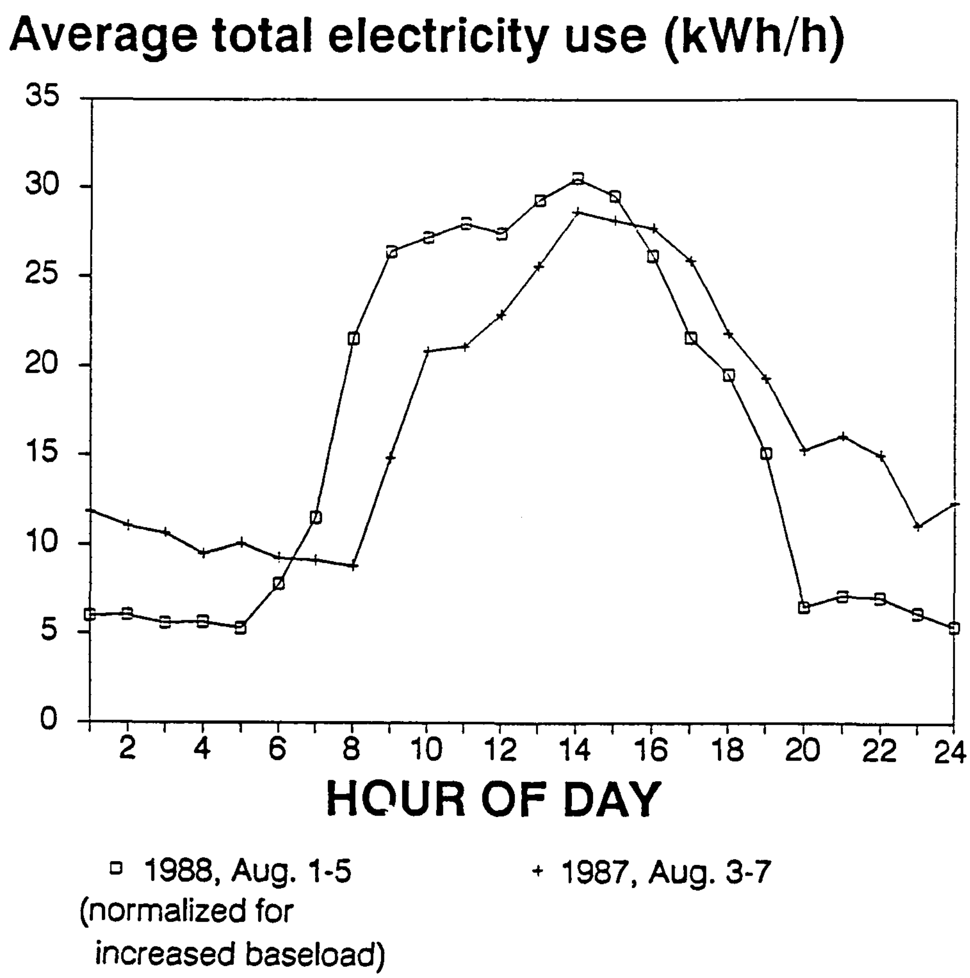

Figure 11. Average electricity energy use profiles before and after thermostat setup for weekdays with peak summer temperatures.

Fig. 11

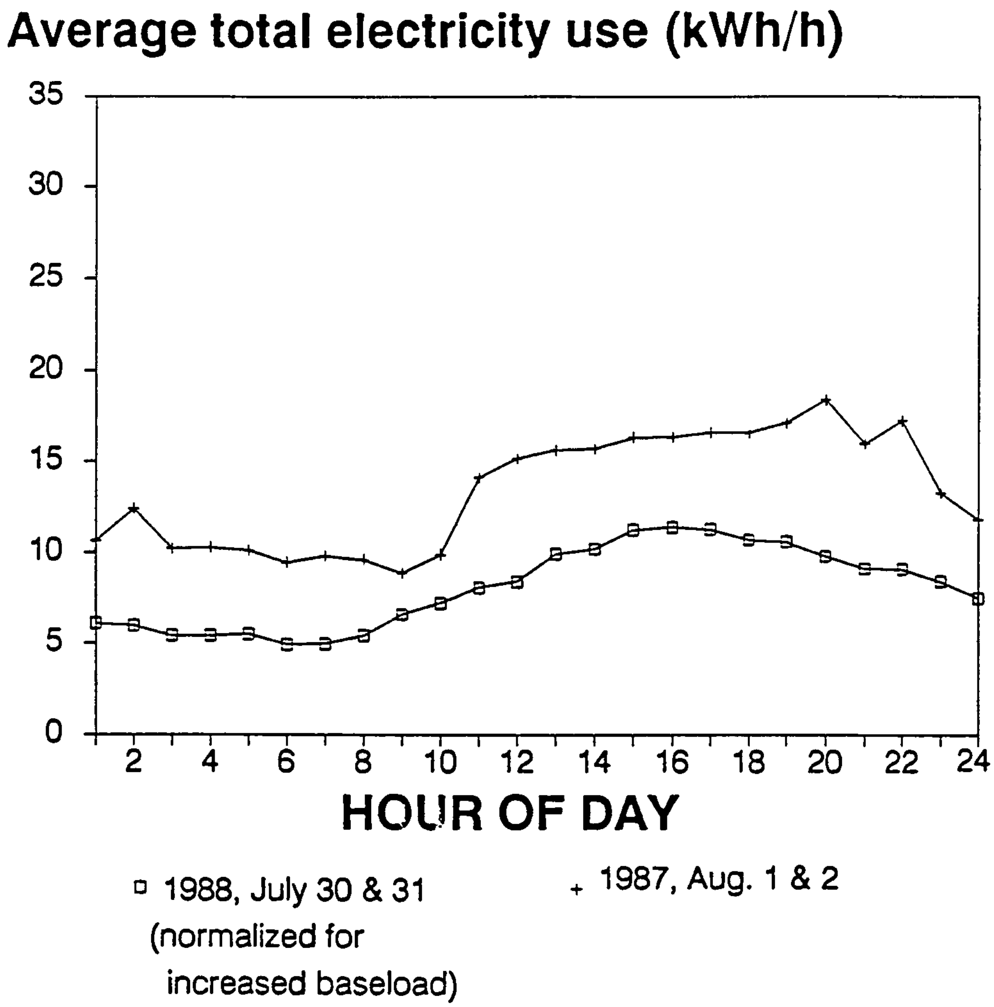

Figure 12. Average electricity energy use profiles before and after thermostat setup for weekends with peak summer temperatures.

Fig. 12