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DETERMINATION OF RETROFIT SAVINGS USING A CALIBRATED BUILDING ENERGY SIMULATION MODEL

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ABSTRACT

This paper presents the development of a methodology to determine retrofit energy savings in buildings when few measured preretrofit data are available. Calibration of the DOE-2 building energy analysis computer program for a 250,000 ft^2 building at The University of Texas at Austin, using hourly data for a two-month preretrofit period, is detailed.. The process begins with the identification of the DOE-2 input parameters having the greatest uncertainty. Field measurements then determine those uncertain parameters that have a significant impact on total energy use. Finally, the few remaining parameters are systematically adjusted to match the preretrofit data. Using the calibrated model run for the postretrofit period, energy savings were calculated for whole-building electric, cooling, and heating energy use, and were compared with savings calculated using a regression model developed under the LoanSTAR program. Finally, to validate the model, postretrofit DOE-2 results were compared with measured postretrofit data for a seven-month period.

INTRODUCTION

accrue from an energy conservation retrofit in commercial buildings (Katipamula and Claridge 1991, Wu et al. 1992). Of all the modeling approaches, use of building energy simulation programs is considered most comprehensive. However, owing to the considerable uncertainty involved with various input parameters used in such models, calibration with monitored end use energy data is considered essential for them to predict retrofit energy savings reliably and accurately.

To this end, studies have been conducted to develop detailed procedures for calibrating computer models with monitored data (Bronson 1992). While procedures have been developed in considerable detail to calibrate the non-weather-dependent loads, little has been done to provide a systematic framework to calibrate the more uncertain HVAC loads. This paper presents the results of a study conducted to develop a robust methodology to determine retrofit energy and cost savings in commercial buildings when few measured data are available for the preretrofit condition. Although the study focuses on commercial buildings, it provides a general framework that can be extended to any type of building or facility. The salient feature of our calibration procedure is the systematic approach that we use for isolating, through measured data, the most uncertain input parameters and then adjusting them in the calibration process, as opposed to a trial-and-error process. The process consists of four steps:

a. By direct observation through site visits, identify the most significant end-use energy components and establish the uncertainty with which those values are known,
b. Do not adjust the insignificant parameters, or those which are known with sufficient certainty,
c. Measure as many of the uncertain values as is feasible, and
d. Adjust remaining values through calibration of the model to monitored data.

The study details the calibration of the DOE-2 building energy analysis computer program using hourly preretrofit data for the 250,000 ft^2 Education Building at The University of Texas at Austin. A detailed description of the analysis is found in Reddy

Additionally, the study compares retrofit energy savings predicted by the calibrated DOE-2 model with savings reported using a regression model developed under the Texas LoanSTAR Program. Finally, to validate the calibrated DOE-2 model, postretrofit DOE-2 results were compared with measured data for the June–December 1991 postretrofit period.

BUILDING DESCRIPTION AND PRERETROFIT MODEL

The Education Building on The University of Texas at Austin campus is a five-story structure with concrete floors and walls, and a gross area of about 250,000 ft^2 (Figure 1). Based on an energy audit that was performed on the building, two major energy conservation measures (ECMs) were recommended: retrofit the building's general lighting by replacing the incandescent lamps with high-efficiency fluorescent lamps, and retrofit the fans of the eleven air-handling units with variable speed drives. Also,

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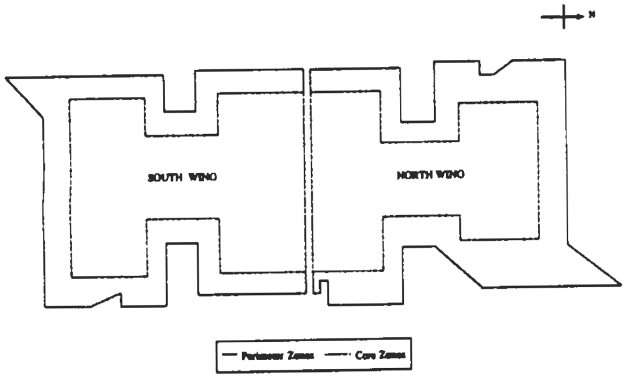

Figure 1. Zoning Configuration: 2nd to 5th Levels

the air mixing boxes were reworked to reduce pressure drops, and the fan motor sizes were reduced. The retrofits were started at the end of the first quarter of 1991 and completed in the subsequent three months.

A tabulation of the parameters used to construct the DOE-2 model of the building is provided in Table 1. The primary sources of this information were the architectural, electrical, and mechanical drawings and specifications available from the Utilities Department at UT-Austin. Additional information was obtained through site surveys and field measurements.

As a first step in the calibration process, we examined the results of the precalibrated DOE-2 model using site weather data for preretrofit building conditions. An hourly time-series plot was made of whole-building electrical energy use for a representative week during the January–February 1991 period. Common weekday, Saturday, and Sunday schedules were applied for all weeks. The results showed that lighting accounts for nearly half of the peak electricity use, followed by a fairly constant fan load during fan operation, with equipment, pump, and vertical transportation accounting for the remaining electricity use. A

Table 1. Preretrofit Doe-2 Model

LOADS:

Occupancy: Open all year and accessible 24 hours a day. Classrooms, labs, and offices closed after normal working hours.

Exterior Envelope: Exterior wall R-value is 2.46; Interior wall R-value is 2.48; Roof and Ceiling R-values are 7.64 and 5.51; Glass U-value is1.49 Btu/h-ft^2-°F, and shading coefficient is 0.5.

Schedule: Weekdays—3 blocks: 8 AM to 6 PM (normal), 6 PM to 10 PM (extended) and 10 PM to 8 AM (closed). Weekends—marginal use between 9 AM and 6 PM. Lighting schedule varies from 100% to 40% to 20%, and equipment from 25% to 5% to 0% for these periods.

Lighting: Building-wide average installed lighting wattage is 2.1 W/ft^2.

Equipment: Building-wide average installed equipment wattage is 0.41 W/ft^2.

People: Design occupancy level in the building is 918 people.

Infiltration: 0.1 ACH for perimeter zones during occupied hours.

Building Resource: Vertical transportation is 74 kW, and secondary chilled water pump is 40 kW.

SYSTEMS:

Schedules: AHUs are on between 7AM and 1 AM on weekdays, schedule varies on weekends. Cooling set point is 75°F and heating set point is 70°F.

Zone Descriptions: Building-wide average supply air flow rate is 1.46 CFM/ft^2. Thermostat throttling range is 2°F.

Systems Description: Constant volume dual-duct system. Cold deck temperature is 56°F. Hot deck reset schedule is 100° F to 80°F for outside-air temperature varying between 30°F and 72°F, respectively.

PLANT: Chiller Efficiency is 85%; chilled water supply temperature is 40°F.

typical weekday pattern was observed (Fig. 2), consisting of a morning pick-up load, a constant peak of nearly 1,100 kW during regular working hours, a reduction during the extended working hours, followed by a drop to a minimum during the night. Weekend operation reflects morning-only, sparsely occupied conditions, with a peak of about 600 kW.

Hourly plots of heating and cooling coil energy use, as a function of outside ambient temperature, were produced to characterize the heating and cooling patterns during occupied (7 AMto 1 AM) and unoccupied (1 AM to 7 AM) hours. For occupied hours, heating energy use was found to be consistent with the hot deck reset schedule used, with a constant peak at the maximum coil temperature, a constant low load at the minimum coil temperature, and linearly decreasing behavior in between. During unoccupied hours a nearly constant load of about one-fourth the daytime peak was observed.

The cooling coil energy use results for weekdays initially showed a strong dependence on outside-air temperature during occupied hours, and a slight dependence during unoccupied hours. However, because all outside-air dampers are closed (confirmed through field observation), and ventilation requirements are met by infiltration, the building is expected to be internal-load dominated, with little or no dependence on outside-air temperature. The unexpected simulation result of outside-air dependent loads led to the discovery that the DOE-2 default HVAC system control strategy assumes economizer operation. When economizer operation was eliminated, the resulting cooling loads were found to be fairly independent of outside-air temperature. Thus, the user must carefully check all default parameters in the DOE-2 input.

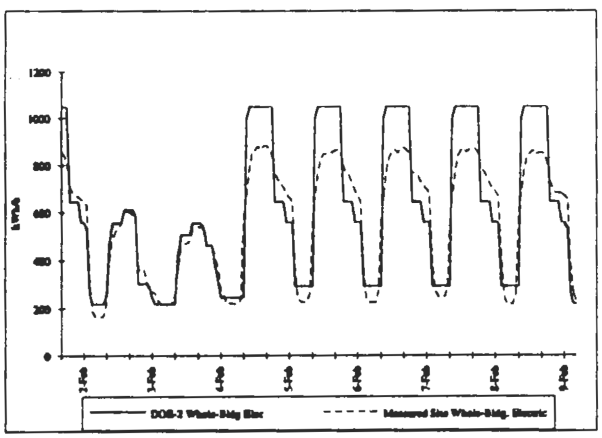

Figure 2. Monitored and Precalibrated DOE-2 Whole Building Electric Energy Use

CALIBRATION OF PRERETROFIT MODEL

As seen in the previous section, despite having extensive information about a building and its operational patterns, simulating the actual building's thermal interaction is difficult because of uncertainty in key input parameters. Comparison with monitored data is perhaps the only method of determining accurate input information.

Whole-Building Electrical Energy Consumption

Calibration of electrical energy use components serves two purposes: (a) it verifies lighting and equipment energy use, whose schedules of operation are not precisely known; (b) because it establishes the internal loads, it also serves as the basis for calibration of heating and cooling energy use. Furthermore, calibration of the fan power verifies the operation of air-handling systems and reduces uncertainty in modeling the HVAC systems operation.

A preliminary investigation of the whole-building electric load profiles revealed that the first week of February 1991 represented an operational pattern typical of the entire preretrofit period. Further, data for this period were complete. Therefore the first week of February's electric load profile is used as the model load pattern for all calibration work.

Figure 2 shows monitored whole-building electric and the corresponding DOE-2 simulated energy use for the same time period in February 1991. It is clear that for weekdays the monitored peak loads are lower than the simulated peak loads, and monitored off-peak values are lower than simulated off-peak values. The weekend profiles, however, match very well. Note that the difference in on-peak values is considerably larger than the difference in off-peak values, indicating a difference in operational pattern that is likely the result of incorrect lighting and equipment schedules. Apart from these, the monitored data show a remarkably consistent load pattern. All weekdays except for Monday, which has lower load in the early hours, and Friday, when loads start reducing earlier than on regular workdays, exhibit similar operation. Saturdays and Sundays differ considerably from the weekday loads, experiencing a much smaller percentage of peak loads. All days have almost the same off-peak loads.

Based on these observations, the following four day types were identified from the first week of February to calibrate electrical energy use for the preretrofit period.

a. Weekday (Wednesday)
b. Monday (day after a weekend)

c. Saturday
d. Sunday

The calibration methodology was then applied using these four day type profiles.

Equipment (Including Building Resource).

Since office equipment loads were small and information on their operating schedules was obtained during surveys of the building, the reliability of the equipment load profile was high enough not to warrant any calibration of its schedule factors. Therefore, the equipment operating schedule was left unchanged. The same was true for vertical transportation equipment, which was simulated by occupancy schedules developed using detailed information of building occupants, their schedules and student populations and class schedules.

Fan and Pump Power.

Fan and pump power constitutes the second largest component of electrical energy use. However, because all fan power draws were verified by one-time field measurements, and the operating schedule was controlled by a time clock, no calibration was applied to fan power. Finally, the electrical load profile of fan power obtained using a one-time measurement (November 1990) of fan power and schedules (time clock) showed an excellent match with the monitored data for the same period, confirming that fan power simulation was reliable and accurate. Therefore, fan power schedules were left unchanged at their designed values. No calibration was required for pump power also because pump energy was metered separately by the monitoring system, and its energy use profile was obtained directly from the monitored data.

Lighting.

Based on our approach of adjusting the most uncertain parameters, which were deduced through a process of eliminating uncertainty in other parameters through key measurements, it was determined that the lighting schedules comprised the critical calibration area. Since lights constituted the single largest electrical energy use component, and their operating schedules were least certain, lighting schedule factors were adjusted to take up the slack. For the four typical day types identified for calibration, the lighting schedule factors shown in Figure 3 were developed. The schedule factors at each hour were calculated as the ratio of precalibrated DOE-2 whole-building electric energy less the sum of all known/certain loads, and monitored whole-building electric energy less the sum of all known/certain loads. This adjustment was verified by noting that only a portion of the installed fixtures were turned on at any time in most public spaces.

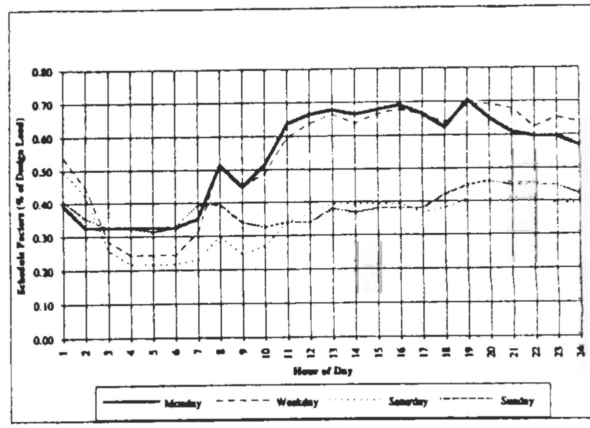

Figure 3. Schedule Factors for Lighting Loads

These lighting schedules were then incorporated into the preretrofit DOE-2 model and the model was run for the months of January and February 1991. Figure 4 compares the calibrated and monitored DOE-2 whole-building electrical energy use profiles for the first week of February. Except for Friday, where a decrease in electrical loads is seen to occur a little early compared to other days, the two sets of data show an excellent match. Figure 4 also shows the new breakdown of electrical energy use after the calibration process, indicating a lower peak load of about 880 kW.

Heating and Cooling Energy Consumption

Steam condensate use represents the building heating coil energy use. Since the preretrofit data were obtained for the months of January and February, heating energy use is expected to be considerable. Also, since the lowest temperatures in Austin are normally recorded in January, the preretrofit data represent peak heating energy use for a typical year.

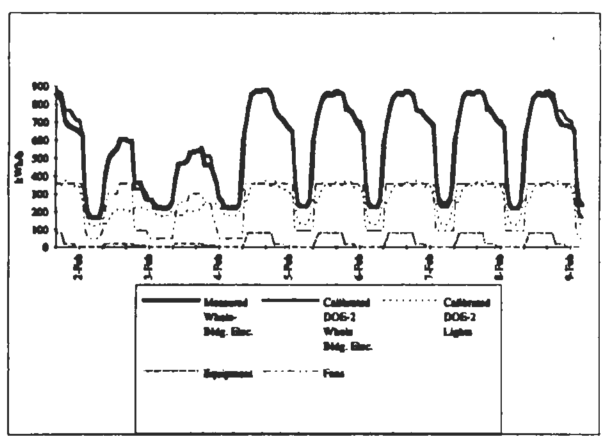

Figure 4. Calibrated DOE-2 vs Monitored Whole-Building Electric for Calibration Week

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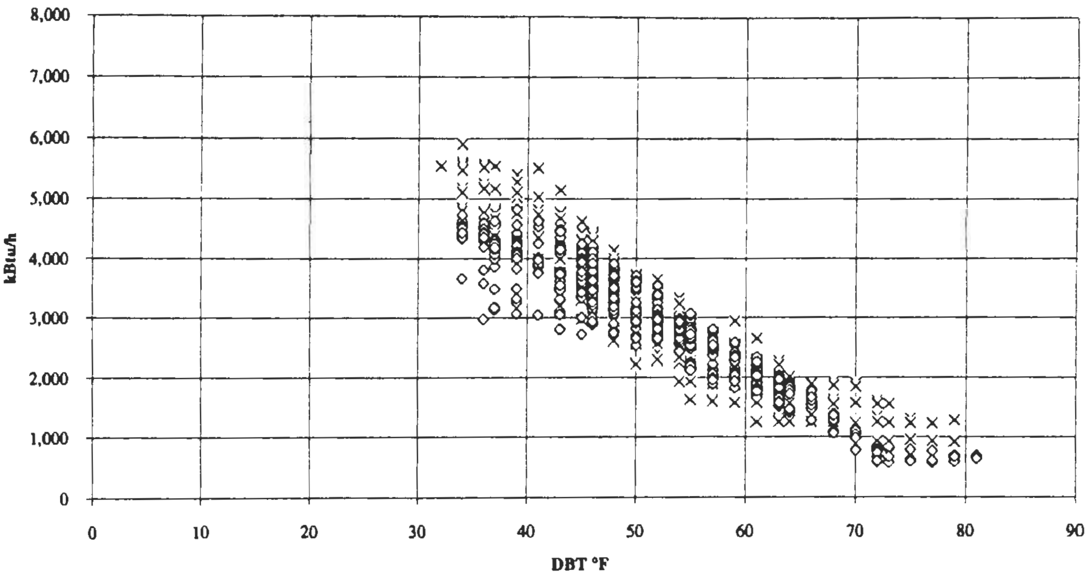

Figure 5a. Monitored and Calibrated Preretrofit DOE-2 Heating Energy: Weekdays (7 AM–1 AM) Occupied Hours, January & February 1991

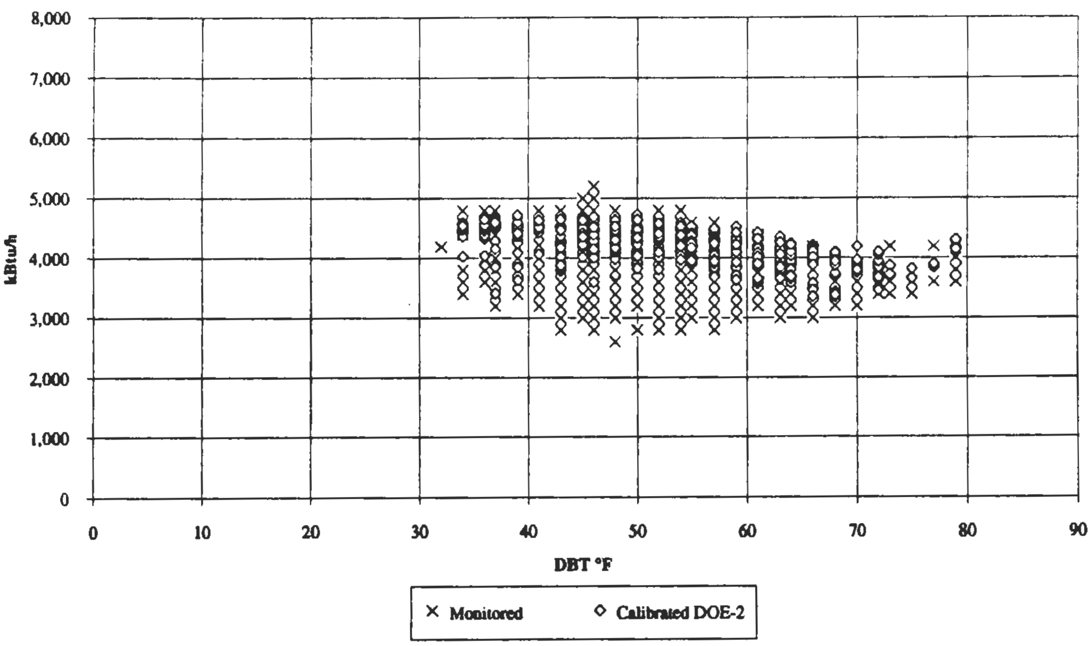

Figure 5b. Monitored and Calibrated Preretrofit DOE-2 Cooling Energy: Weekdays (7 AM–1 AM) Occupied Hours, January & February 1991

Figure 5a shows that monitored heating energy use increases along a constant slope as outside-air temperature drops below 60°F. The slope, however, is not so steep at higher temperatures, with heating energy use remaining nearly constant above 72°F. The constant use at temperatures above 72°F is consistent with the hot deck schedule. Peak energy use for the time period is 6,000 kBtu/h, while the minimum is about 1,000 kBtu/h. Figure 6 shows heating energy use during unoccupied hours to be minimal and nearly constant.

Similarly, chilled water consumption represents the building cooling energy use. Despite the cool weather prevailing during the preretrofit period, because of high internal loads cooling energy use is significant. Since this building has no outside-air

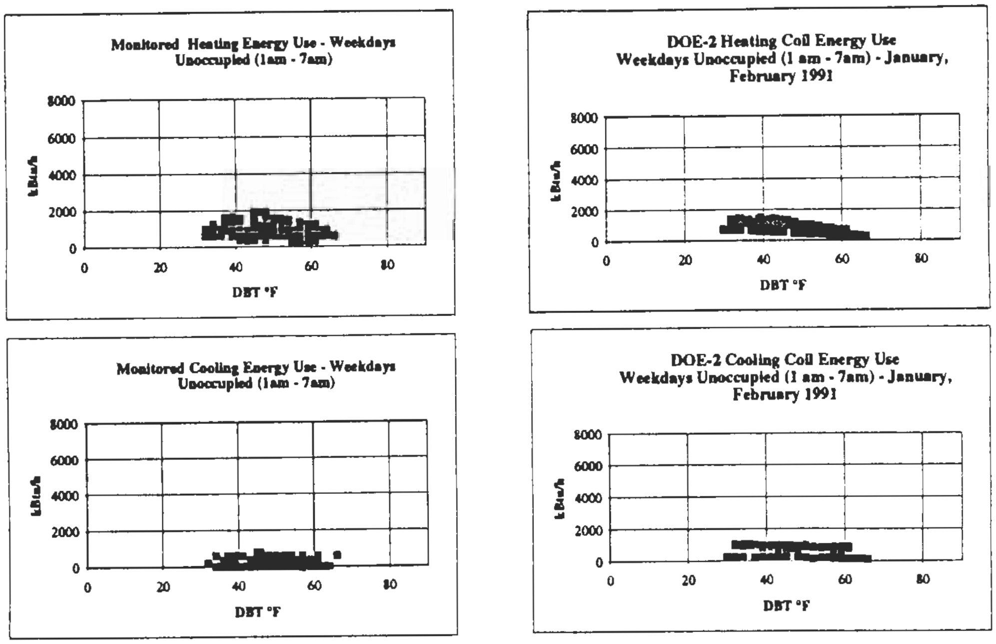

Figure 6. Monitored and Calibrated Preretrofit DOE-2 Heating and Cooling Energy Use: Weekdays (1 AM–7 AM) Unoccupied Hours, January & February 1991

supply except through infiltration, a weak dependence on outside-air temperature is expected. This is corroborated by Figure 5b which shows monitored cooling energy to be fairly constant over the temperature range of 30°F to 80°F. Peak cooling use is about 5,000 kBtu/h; the scatter in cooling energy use is attributed to the diversity in the building operation. Figure 6 shows cooling energy use during unoccupied hours to be minimal and largely independent of temperature.

Comparison of DOE-2 simulated and the monitored heating energy use values indicated that although both heating and cooling energy use during unoccupied hours and peak values during occupied hours were about the same in both cases, during occupied hours, heating energy use predicted by DOE-2 increased more rapidly with decreasing temperature. The heating use above 72°F also showed differing patterns. Furthermore, DOE-2–predicted cooling energy use was considerably higher than the monitored values during occupied hours. Therefore, calibration of the model was necessary.

Applying the same approach for calibration of heating and cooling energy use as was used for the whole-building electric data, calibration was achieved through a process of parametric runs, in which the following parameters were successively adjusted in the calibration process:

a. Infiltration
b. Supply Air Flow Rates
c. Hot Deck Reset Schedule
d. Space Thermostat Set Point

<u>Infiltration</u>.

Comparison of the precalibrated DOE-2 model and monitored cooling energy use indicated that the DOE-2 predicted values were higher than the monitored data, but heating energy use was lower than monitored values. Apart from the minimal infiltration rate of 0.1 ACH assumed for the perimeter zones, the building has no other mode of ventilation. The higher cooling energy use and lower heating energy use suggest a higher effective infiltration rate.

Since typical commercial buildings can have infiltration rates varying from 0.1 to almost 0.8 air changes per hour, a series of simulations was run varying the infiltration rates between these two values. Results indicated that increasing infiltration rates produced slightly increased heating energy use; the effect on cooling energy use was minimal. An infiltration rate of 0.5 air changes per hour in all perimeter zones resulted in the best match of heating and cooling energy use and was therefore used for all future simulations.

<u>Supply Air Flow Rate</u>.

Considerable uncertainty exists as to the supply air flow rates for the fan systems. Because occupancy rates and use patterns may change over several years of building operation, design values of supply air flows, taken from as-built drawings and specifications, are generally not reliable. Therefore, we attempted a direct measurement of the supply air flows for each of the eight air handlers using handheld anemometers. Unfortunately, malfunctioning instruments rendered these field measurements unusable.

In addition, we took one-time measurements of supply fan electric power, static pressure drop across the fans, coupled with fan speed measurements. Applying these results to the fan curves supplied by the manufacturer, we calculated supply flow rates that were then used in the DOE-2 model. Using these flow rates resulted in a good match with both the hourly heating and cooling coil energy use profiles, but the cooling energy use magnitude was overpredicted, suggesting that the supply air flow rates determined in this fashion were too high.

Because the fan power and pressure drop measurements were believed to be reliable, these were combined with an estimated fan efficiency of 70% (the DOE-2 default value for dual-duct systems) in the DOE-2 fan model to determine the supply air flow rates. This resulted in an average supply air flow rate of 1.56 cfm/ft^2. Using these values in the DOE-2 model resulted in an excellent match with the heating and cooling energy use data (see Figure 5), although the heating energy use at low outside-air temperatures was slightly lower than the measured values and cooling energy use was slightly higher.

<u>Hot Deck Reset Schedule</u>.
Since heating energy use at the lowest outside-air temperatures was slightly lower than the monitored values, the hot deck set point was examined further. Discussion with maintenance staff indicated that although the maximum set point was 105°F for design conditions, it was overridden and increased to about 110°F on some occasions. The model was updated with this information.

<u>Heating and Cooling Thermostat Set Points</u>.
Finally, the thermostat set points for heating and cooling were examined. Since the model predicted higher cooling energy use and lower heating energy use, indicating an upward shift in both cooling and heating set point temperatures, data logs of the preretrofit field measurements were consulted. It was found that return air temperatures were recorded at an average of about 76 °F for all air-handling systems. Since these measurements were made during the heating season, the heating thermostat set point was raised to 75°F, with the remaining temperature differential assumed to be caused by internal loads. A similar reasoning was applied to the set point for cooling, which was increased to 76°F.

After incorporating all these changes in the model, a final composite case was run, with the results presented in Figures 5 and 6. It is evident that the DOE-2 model's heating and cooling energy use match very well with the monitored data for all hours and all day types with the monitored data. To confirm the model calibration and to present an overall picture of heating and cooling energy use for different day types, four sets of data each for heating and cooling energy use, representing weekday and weekend calibrated DOE-2 model and monitored values were plotted against daily average dry-bulb temperatures as shown in Figures 7a and 7b. The good match between the calibrated model and measured data validates the calibration.

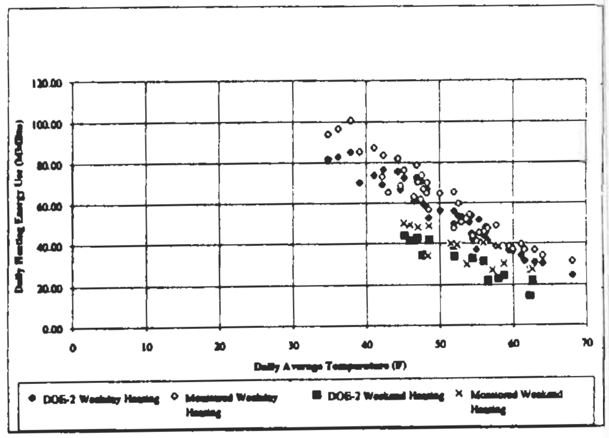

Figure 7a. Calibrated Preretrofit DOE-2 Model vs Monitored Data for Preretrofit Period (January & February 1991): Heating

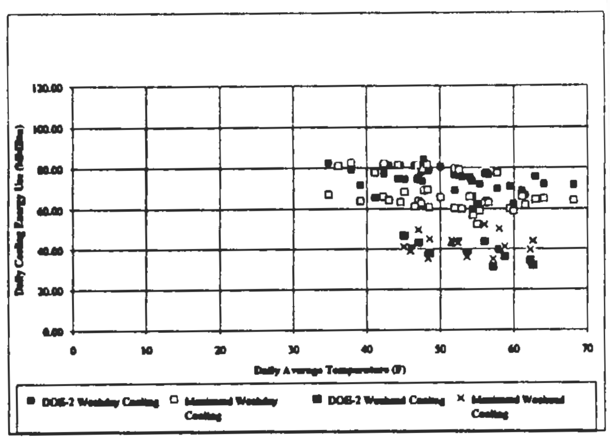

Figure 7b. Calibrated Preretrofit DOE-2 Model vs Monitored Data for Preretrofit Period (January & February 1991): Cooling

RETROFIT SAVINGS AND COMPARISON WITH REGRESSION MODEL

Results of Calibrated Model Run for Postretrofit Period

The calibrated DOE-2 model now represents the Education Building in its preretrofit condition. Therefore, results predicted by the model run for the postretrofit period using site weather data indicate what the energy use would have been, had the retrofits not been incorporated. Thus, retrofit savings would be the difference between these DOE-2 results and the monitored data for this period. For the purpose of this analysis, June through December 1991 was chosen to represent the postretrofit period. Site weather data for this period were incorporated into TMY weather format, and a DOE-2 simulation was performed. Figures 8, 9, and 10 show results of the simulation for daily whole-building electric use, heating energy use, and cooling energy use, respectively.

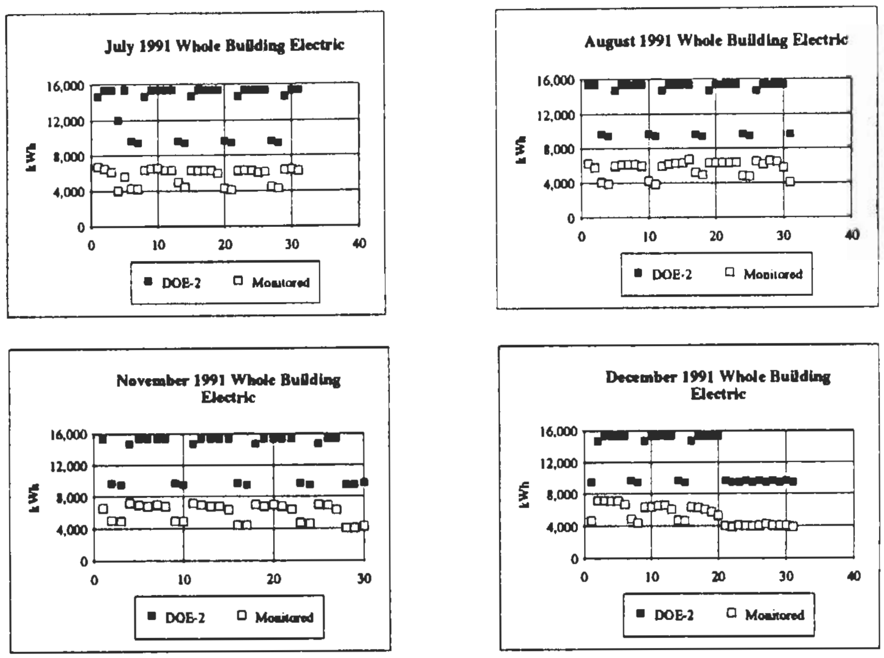

Figure 8. Calibrated DOE-2 Simulation Run for Postretrofit Period (June–December 1991): Whole Building Electric [Figure Shows Only Two Representative Summer and Winter Months Each]

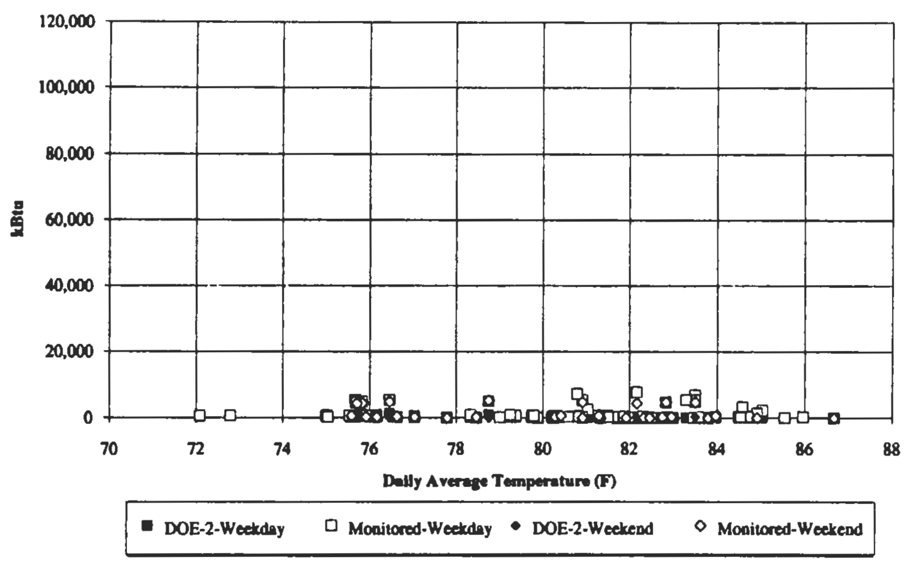

Figure 9a. Calibrated DOE-2 Simulation Results for Postretrofit Period vs Postretrofit Monitored Data: Daily Heating Energy Use (June–September 1991)

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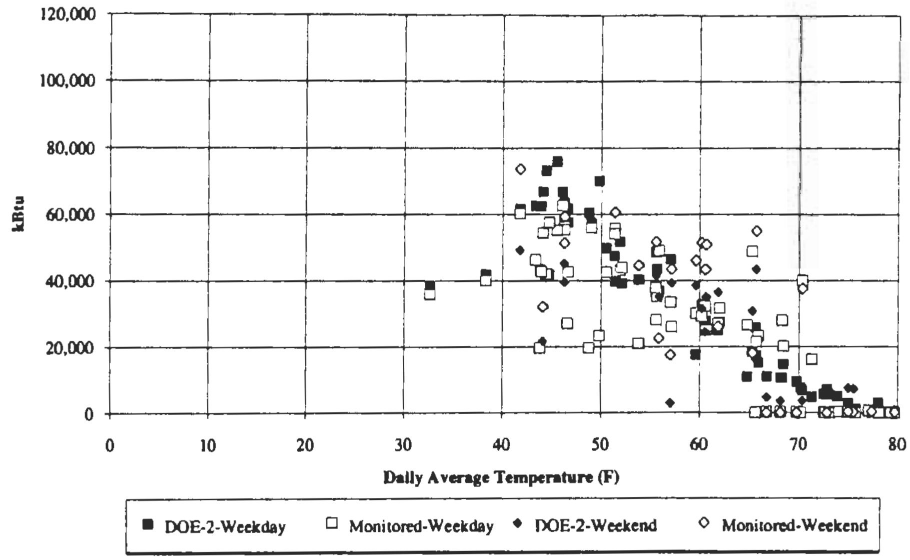

Figure 9b. Calibrated DOE-2 Simulation Results for Postretrofit Period vs Postretrofit Monitored Data: Daily Heating Energy Use (October–December 1991)

Results for selected months (Fig. 8) show that lighting retrofits and the installation of variable frequency drives on fan motors resulted in a drop in the peak value of whole-building energy use from about 16,000 kWh/day to about 7,000 kWh/day, a reduction of more than 50% in weekday electrical use. The pattern was observed for weekends and holidays as well. Heating demands were very small for the warmer months of June through September 1991 (Fig. 9a), but increased substantially in the cooler months of October through December 1991 (Fig. 9b). It is apparent that there is no significant decrease in heating energy use with the retrofits in place. Even though the system was retrofitted with a VAV system, the decrease in internal loads resulted in higher heating demands, negating savings resulting from the decrease in air flow volumes to be heated. However, because of reduced internal loads due to lighting retrofits, and lower cooling coil loads due to the variable air volume system, the difference in the magnitudes of DOE-2 and monitored cooling energy use is considerable for both summer and winter (Fig. 10).

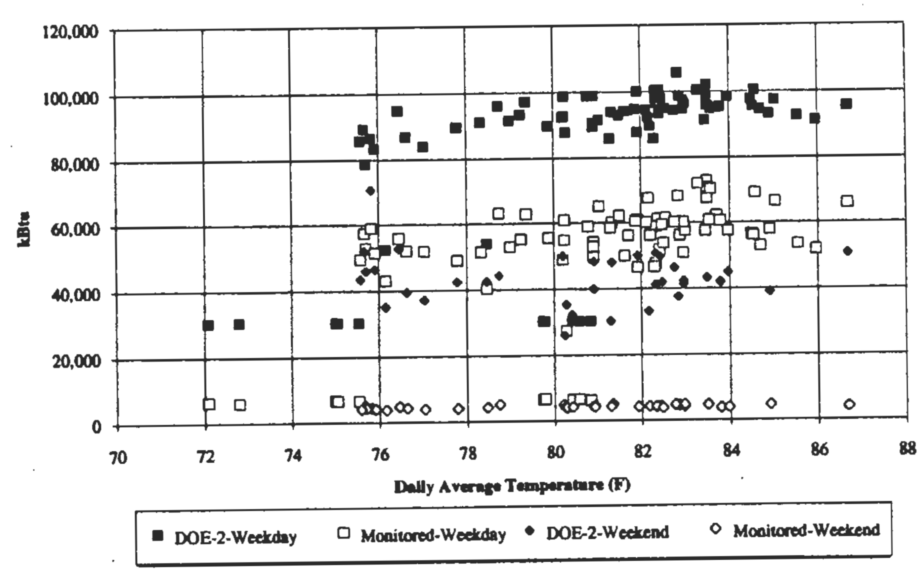

Figure 10a. Calibrated DOE-2 Simulation Results for Postretrofit Period vs Postretrofit Monitored Data: Daily Cooling Energy Use (June–September 1991)

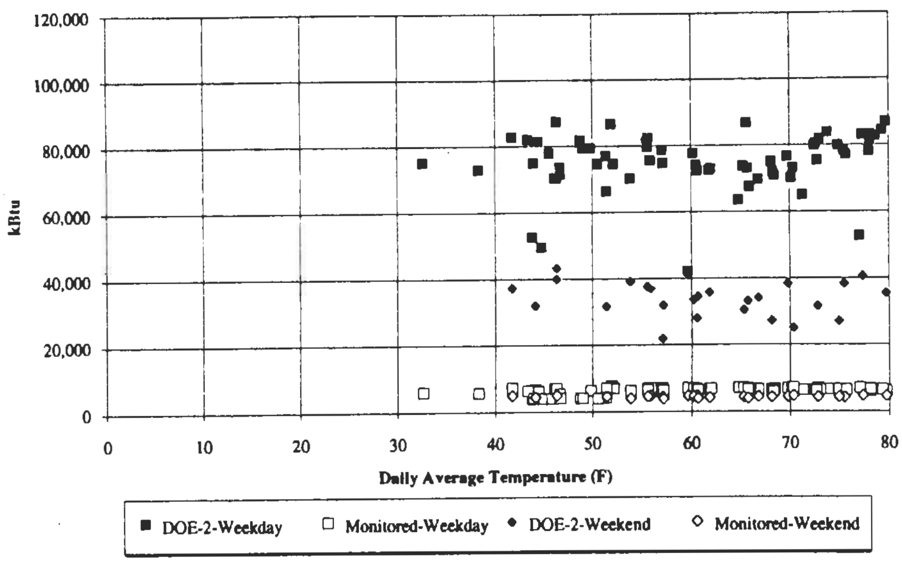

Figure 10b. Calibrated DOE-2 Simulation Results for Postretrofit Period vs Postretrofit Monitored Data: Daily Cooling Energy Use (October–December 1991)

Retrofit Savings

Savings were calculated for each day as the difference between the daily sum of hourly energy use for the DOE-2 results and the monitored data and were aggregated to determine total monthly savings. Table 2 shows the retrofit savings for the June–December 1991 postretrofit period. A utility rate schedule appropriate to UT-Austin, was used to calculate the energy savings (see bottom of the table). Since UT-Austin generates its own electrical power, no demand charges/savings are applicable.

The table shows that a mean savings of approximately $10,000 in electrical energy use is achieved each month due to the energy efficiency retrofits. Heating cost savings fluctuate during the summer months because the small values appear magnified when expressed relatively; however, the effect is not significant on an absolute scale. As temperatures drop and heating demands rise in October and December, net heating energy savings result. The deviation of heating energy costs from this trend in November is attributed to the mild weather prevailing during this month.

Comparison of DOE-2 Retrofit Savings with Savings Predicted from Regression Model

Table 2 also compares retrofit savings determined using the calibrated DOE-2 model and savings based on a regression model developed under the Texas LoanSTAR Program (Kissock et al. 1991).

Table 2. Retrofit Energy Cost Savings

	ELECTRIC		HEATING		COOLING		TOTAL	
Month	DOE-2	Regression	DOE-2	Regression	DOE-2	Regression	DOE-2	Regression
Jun-91	$9,641	--	($727)	--	$7,705	--	$16,619	$9,341
Jul-91	$11,199	--	($213)	--	$9,032	--	$20,019	$12,207
Aug-91	$11,186	--	($274)	--	$8,819	--	$19,731	$19,034
Sep-91	$10,483	--	$582	--	$10,989	--	$22,055	$17,249
Oct-91	$10,892	$10,543	$836	$3,503	$14,069	$8,606	$25,797	$22,652
Nov-91	$9,781	$9,999	($60)	$1,153	$12,264	$8,041	$21,985	$19,194
Dec-91	$9,889	$11,368	$569	$1,649	$13,634	$9,719	$24,092	$22,737

Electrical Unit Cost = $0.04550 / kWh
Chilled Water Cost = $7.425 / MMBtu
Steam Condensate Cost = $6.20 / MMBtu

Savings from individual energy use components were not reported separately for this regression model for the months of June through September 1991; therefore only aggregated savings are shown. For the three months of complete data, the following observations can be made.

Electrical savings predicted by the calibrated DOE-2 model and the regression model compare very closely for October and November; however, DOE-2 predicts considerably lower savings in December. For the three-month period, electrical energy savings predicted by the regression model are about 4.2% higher than those predicted by the calibrated DOE-2 model.

However, the regression model appears inadequate in modeling heating and cooling loads in a large commercial building. Comparison of DOE-2 and regression model savings for October–December 1991 indicate that while DOE-2 predicts very small or negative heating energy cost savings, the regression model predicts significant (369% higher) savings. On the other hand, cooling energy cost savings predicted by DOE-2 are substantially higher than those predicted by the regression model. Evidently the impact of reduced internal loads is more accurately represented in the calibrated DOE-2 model.

Savings predicted by the regression model for cooling were 34% lower for this same period, whereas the total electric, heating, and cooling savings for all seven months were 18.5% lower than those predicted by the calibrated DOE-2 model. Although the total savings difference is not very large, the effect of overestimating heating savings and underestimating cooling savings by the regression model cancels out when the two savings are aggregated; erroneous conclusions can be drawn if the heating and cooling energy savings are not properly modeled.

A possible explanation for the disparity between DOE-2 and regression model energy use values could be provided by the results of a study conducted to determine the effect of short data periods on the prediction accuracy of temperature-dependent regression models (Kissock et al. 1993). The study indicates that regression models based on monitored data obtained during heating season tend to overpredict annual heating energy use, and those based on data obtained during the cooling season overpredict annual cooling energy use. Table 2 verifies this reasoning because it shows higher heating savings and lower cooling savings, confirming the regression model bias.

DOE-2 MODEL VALIDATION

To validate the calibrated DOE-2 model, the postretrofit simulation results were compared with measured postretrofit electric, heating, and cooling energy use. The postretrofit model, developed by incorporating the energy conservation measures into the calibrated preretrofit model, was run for the postretrofit period of June 1991 through December 1991 using site weather data for that period.

Table 3 compares results of the postretrofit model and monitored site data for all seven months of the postretrofit period. It shows that the whole-building electric energy use matches very well, with monitored data being 4.5% lower than DOE-2 values for the whole period, but with monthly variations ranging up to 9%. It appears that the model has a slight bias. Heating energy calculations show that monitored data are about 2.8% lower than values predicted by DOE-2 for the period, indicating an excellent match between the model and measured data. However, large monthly differences are apparent for June through October; because the absolute energy use values are so small the high percentages are not significant. The difference between the two data sets for cooling energy use is

Table 3. Comparison of Postretrofit DOE-2 Model with Postretrofit Monitored Data

	Electric (kWh)		(DOE-2 - Monitored) / Monitored	Cooling (MMBtu)		(DOE-2 - Monitored) / Monitored	Heating (MMBtu)		(DOE-2 - Monitored) / Monitored
	DOE-2	Monitored		DOE-2	Monitored		DOE-2	Monitored	
Jun-91	185,348	189,080	-2.0%	1,177	1,303	-9.7%	95	110	-13.2%
Jul-91	186,916	177,832	5.1%	1,262	1,301	-3.0%	21	12	81.0%
Aug-91	191,109	176,418	8.3%	1,208	1,287	-6.1%	17	11	63.4%
Sep-91	185,438	170,336	8.9%	515	516	-0.3%	20	12	63.8%
Oct-91	198,566	188,542	5.3%	182	189	-3.3%	240	121	98.6%
Nov-91	182,169	180,116	1.1%	173	180	-4.0%	1,080	1,108	-2.5%
Dec-91	173,177	164,716	5.1%	170	165	3.1%	1,242	1,270	-2.2%
Totals	1,302,723	1,247,040	4.5%	4,687	4,941	-5.1%	2,716	2,643	2.8%

also small, with monitored data being 5.1% higher than DOE-2 predicted values, with monthly variations ranging up to 10%. The model consistently predicts lower cooling energy use than the monitored data, indicating a slight bias in the model.

CONCLUSIONS

Based on the experience gained during the course of this study, the following conclusions can be drawn:

1. The most critical step in accurately determining retrofit savings is the development of a complete and accurate preretrofit computer simulation model. Obtaining firsthand knowledge of the building being modeled and acquiring a feel for its overall operation reduce the degree of uncertainty associated with most model input parameters.
2. Distinguishing between several operational day types and time periods, and using one-time field measurements and hourly plots for systematically calibrating all loads through a process of adjusting the most uncertain parameters, are effective methods of constructing an accurate model of the building.
3. When modeling large commercial buildings to determine retrofit savings, sophisticated analysis tools such as DOE-2, provided they are carefully calibrated against monitored hourly data, are more reliable than single-variable regression models.
4. Finally, comparison of postretrofit DOE-2 model (derived from a preretrofit calibration) results with monitored data for the postretrofit period show the reliability of retrofit savings predicted by the calibrated model.

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