COMPARISON OF EMPIRICALLY MEASURED END-USE METERED DATA WITH DOE 2.1 SIMULATIONS

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ABSTRACT - This paper examines how well a DOE 2.IB simulation which has been calibrated for a 20,000 square foot building reflects actual end-use energy consumption. Empirically measured data are compared with simulation results for end-use energy consumption, heating and cooling loads by thermal zone and month, monthly energy use, and monthly peak demand. The limitations of the DOE 2.1 code with respect to modeling the heat pump system are discussed and implications analyzed. An examination of-schedules used to model the building highlights the importance of accurate information about building operation and its impacts on the simulation results.

INTRODUCTION

Thermal simulations of commercial buildings are often relied upon for estimating energy consumption of proposed buildings, for research, for developing building standards, and a number of other applications. Recently, the hourly response factor based simulation, DOE 2.1, has been extensively used for developing recommendations for upgrading ASHRAE Standard 90. The accuracy of algorithms in DOE 2.1 has been addressed in a number of research projects. Another aspect of the validity of the code is how well its predicted end-use profiles reflect actual energy consumption in a specific building. This issue is distinguished from the accuracy of the code in that the simulation results are affected by both the code algorithms and the user inputs to the model. Apparent agreement with utility bills may often result from compensating errors.

This paper describes the experiences and results of trying to calibrate (the process of adjusting the inputs) DOE 2.1B to reflect actual energy consumption in a 20,000 square foot office building in Richland, WA. The purpose of this research effort is to establish the appropriate level of confidence in the code for the conditions modeled, to develop guidelines for simulating buildings better, and to assess the usefulness of using simulations for parametric studies of energy conservation strategies for specific buildings.

DESCRIPTION OF BUILDING ANALYZED

Hourly end-use energy monitoring has been conducted for the past 1 1/2 years at an office building, referred to as Sigma IV, located in Richland, WA. Data collected include heating, cooling, and ventilation for each of the building's ten thermal zones as well as lighting and convenience outlet energy consumption. In addition, outdoor meteorological and indoor temperature data have been collected. A brief overview of the physical characteristics of the building as well as the operating schedules are provided as background to the analysis of the building simulations conducted.

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

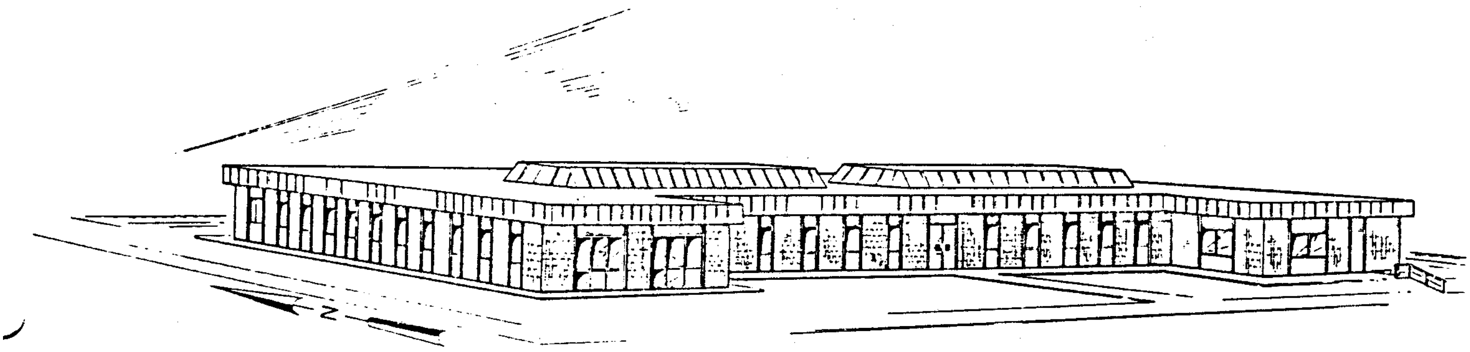

FIGURE 1

The mechanical systems consist of ten roof mounted air-to-air heat pumps serving five perimeter and five interior zones. The total cooling capacity for the building is 50 tons, approximately one ton for each 400 square feet. There are four models ˆ heat pumps installed in the building ranging m 28 to 88 Btu/hour of cooling capacity. The EERs of these models range from 7 to 8. Eight heat pumps are equipped with outside air temperature controlled economizers. Mechanical cooling is locked out on six of the heat pumps when the outside temperature drops below 55 F. The other two economizers allow mechanical cooling below 55 F if the thermostat calls for second stage cooling. The heat pumps lock out resistance heating when the outside temperature is above 40 F.

There are no automated control systems in the building, except for a timer on the outside soffit lights. There are no night and weekend setbacks of temperatures. The building is typically kept between 70 and 75 degrees F year round and is continuously ventilated. Office lighting is controlled by independent switches located in each office, while hall lighting remains on 24 hours a day. Interior lighting is provided by (unvented) fluorescent fixtures recessed into the plenum. Virtually no task lighting is used in the building. Based on a count of the fixtures and a usage factor of 1.18 for rapid start 40 W fluorescent lamps on a 270 V circuit, the installed lighting in the building is 61,172 watts. The outdoor lighting consists of 128 150 watt lamps mounted in the soffit. However, all but four of the soffit lamps are disconnected.

The building is occupied by approximately 120 kers, with peak occupancy between 9:00 a.m. and 4:00 p.m. on weekdays. Employees have access to the building 24 hours a day/ 365 days per year. The building is typically occupied from 6:00 a.m. to 11:00 p.m. on weekdays and during the daytime on weekends. Building cleaning and maintenance is conducted during the working day. Internal maintenance is performed on an as needed basis and HVAC maintenance on a quarterly basis by a mechanical contractor.

SIMULATION OF BUILDING

Building blueprints and visual inspection of the building were used to develop the building description for the loads portion of DOE 2.1B. The building was modeled with ten zones, extending from the floor to the roof, corresponding to the HVAC layout. Since DOE 2.1B is not capable of modeling the common return air plenum, the portion of the plenum above each zone was considered to be a part of that zone. It is recognized that plenum loads affect the performance of the heat pumps, but are not sensed in full by the thermostats. However, since the fans run continuously, the majority of the loads on the plenum are transferred to the conditioned spaces of the building.

The building was modeled with three different sets of schedules for interior lighting and convenience outlets. The first set of schedules was based on the modeler's estimates, the typical procedure. The second set of schedules were taken from the DOE 2.1B library, and the third set was based upon empirical data. An air infiltration rate of 0.15 air changes/hour was assumed for perimeter zones.

Mechanical drawings and manufacturer's data on the heat pumps installed in the building were used to develop the systems input to DOE 2.1B. Inspection of the installed systems indicated that changes in the heat pump models and capacities had been made from the specifications on the mechanical drawings. Manufacturer's data were used to develop bi-quadratic heating and cooling efficiency curves and part load performance curves for the heat pumps. Heating and cooling capacities as well as other parameters were based on manufacturer's data rather than default values provided by DOE 2.1B. Ventilation rates for each zone where based on schedules on the mechanical drawings rather than any actual measurements. There were no records of air balancing of the HVAC system. The plant input for the simulation consisted solely of specifying electric resistance for domestic hot water.

Two problems were encountered in modeling the building. The first, mentioned previously, is the inability of DOE 2.1B to model the common return air plenum for the heat pumps. The second, and perhaps the most significant, is the inability of DOE 2.1B to model economizer operation on air-to-air heat pumps.

WEATHER DATA

In order to directly compare the actual energy consumption with the predicted consumption, the actual weather data was used in the simulation. Due to calibration problems with some of the meteorological data collected at the Sigma IV site, weather data from the Hanford weather station were used. The Hanford weather station is located approximately 22 miles from the Sigma IV building and approximately 700 feet higher in elevation. Both the energy consumption and the weather data are for calender year 1984. The weather data were converted to the Test Reference Year (TRY) format which can be read by the DOE 2.1B weather processor.

COMPARISON OF CALIBRATED VS. ACTUAL ENERGY USE DATA

The goal of the calibrated simulation was to have the DOE 2.1B BEPS output, the yearly summary of energy use by end-use and fuel type, agree with the actual energy consumption. The end-uses on the DOE 2.1 output report are heating, cooling, HVAC auxiliaries, lights, miscellaneous, and domestic hot water. Since hot water energy consumption was metered separately for only part of the year, the domestic hot water and miscellaneous categories were combined.

The first question often asked about calibrated simulations is how well does the predicted energy consumption match actual fuel billing records. (In this study the match was with actual metered data.) In this case, the match is very good. On an annual basis, the actual total site energy use was 1806 MBtu while the predicted energy use was 1740 MBtu. The predicted value is within 4% of the actual value. A month-by-month comparison is illustrated in Figure 2. The differences between monthly estimates and actual monthly consumptions range from 0.3% to 11.4% of the actual energy consumption. The larger discrepancies occur during the peak cooling and heating seasons.

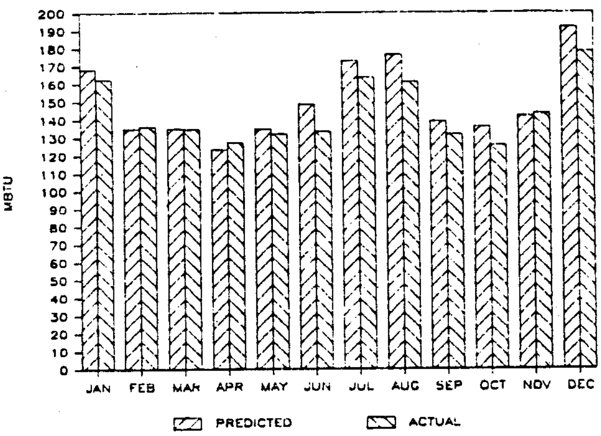

FIGURE 2

Accurate estimates of peak demand are important in developing conservation strategies in locations with high utility energy demand charges. A comparison of the predicted and actual building peak demand is illustrated in Figure 3. Due to metering equipment problems, actual peak demand is not available for the months of August and September. The simulated peak demands for these months are 478 and 427 KBtu/hr, respectively.

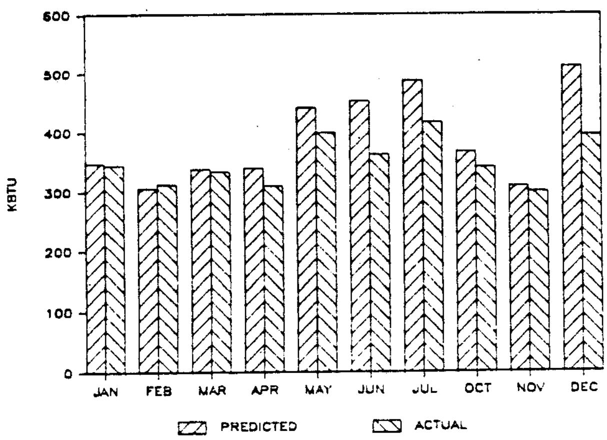

FIGURE 3

The simulation overestimates peak demand by 23% and incorrectly identifies the building as winter peaking while the actual peak is in the summer. According to DOE 2.1B, the annual peak demand, occurring in December, is 512 kBtu/hr. The summer peak demand is 488 kBtu/hr and occurs in July. The metered data indicate that the peak demand occurs in July and is 416 kWh, while a winter peak demand of 394 kWh occurs in December.

A comparison of actual versus predicted annual energy consumption by end-use is depicted graphically in Figure 4. Even though there is a good correlation between actual and predicted total energy use, a more detailed review of the data indicates major discrepancies between the actual and predicted data for the HVAC systems. The lighting, domestic hot water, and the miscellaneous equipment are within 1% of their metered values, as these are calibrated inputs.

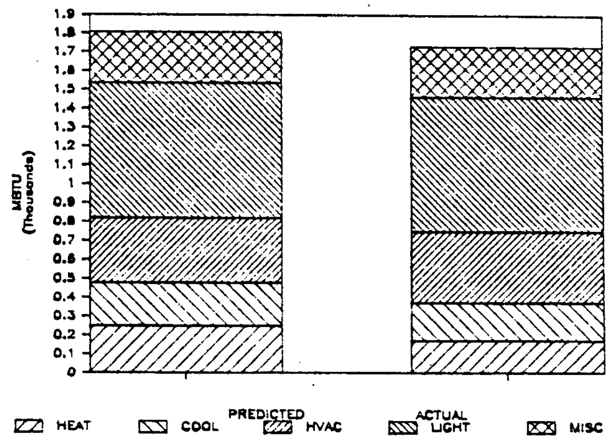

FIGURE 4

The HVAC system did not fair as well in the simulation. DOE 2.1B over-predicted the heating and cooling energy use by 42% and 15% respectively. The HVAC auxillary energy (the fans) was under--predicted by 9%. A slight overestimate of the cooling energy was expected since DOE 2.1B did not account for the heat pumps' economizer operation. The large overestimate of the heating loads was surprising. It is possible that the components of the heat pumps are not performing according to the manufacturer's specifications. In that case the most probable result would be a decrease in efficiency resulting in under- predicting heating and cooling energy consumption. However, heating and cooling were over-predicted. Other explanations of the discrepancies between predicted and actual energy consumption were reviewed in greater detail through a zone-by-zone comparison of the heat pumps' performance.

A zone-by-zone comparison of the predicted and actual annual heating energy use is shown in Figure 5. (The building zones are labeled in Figures 5, 6 and 7, with the following convention: the cardinal orientation of the zone is listed first and a notation of whether the zone is on the building's perimeter (P) or interior (I) follows the hyphen.) This figure illustrates how DOE 2.1B dramatically overestimated the heating energy use for seven of the building's ten zones. In one e heating energy was dramatically ..uerestimated. There is no apparent explanation for why the estimation of heating loads differ so much from actual loads. The metered consumption for the southeast interior zone also indicates an anomaly for that heat pump. With the limited amounted of metered data on the building it is difficult to determine the source of the discrepancies; what is due to problems with the simulation as opposed to problems associated with the installation and operation of the heat pumps.

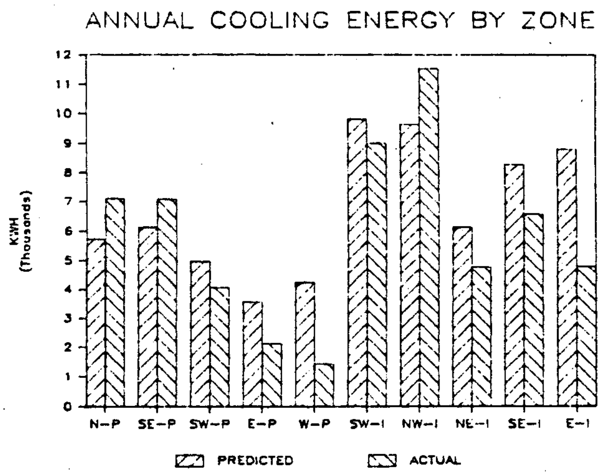

FIGURE 5

A comparison of the actual and predicted cooling loads on a zone-by-zone basis is shown in Figure 6. As noted earlier, DOE 2.1B does not account for economizer operation so one would expect that cooling loads would be overestimated. Cooling loads are overestimated in seven of the building's zones. Two of the heat pumps do not have economizers, the east and west perimeter zones marked "E-P" and "W-P" in Figure 6. However, the simulation still overestimates cooling energy consumption for these zones. The three zones where cooling loads are underestimated have economizers. Therefore, DOE 2.1B's inability to simulate economizers does not directly explain the 15% overestimate of cooling energy use.

The final component of the HVAC system reviewed on a zone-by-zone basis is the ventilation energy use. Actual fan energy consumption is compared with the predicted HVAC auxiliary energy consumption in Figure 7. The actual (metered) fan energy consumption is based upon assigning energy used by the fans to the fan category regardless of whether the heat pump is operating in the heating, cooling, or economizer mode. In eight of the ten zones fan energy consumption is under-estimated. The estimates for fan energy are off by more than 70% for the two zones with the smallest heat pumps.

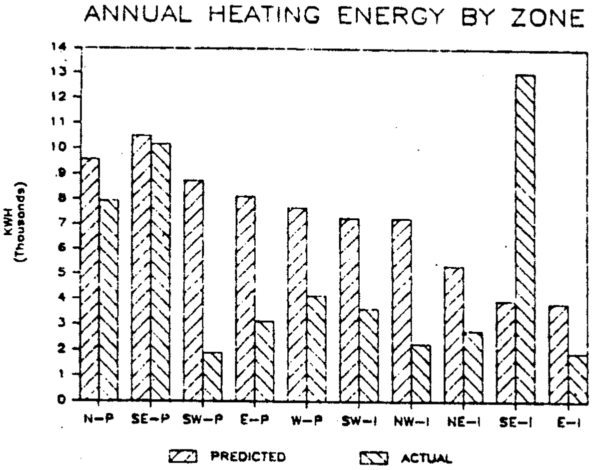

FIGURE 6

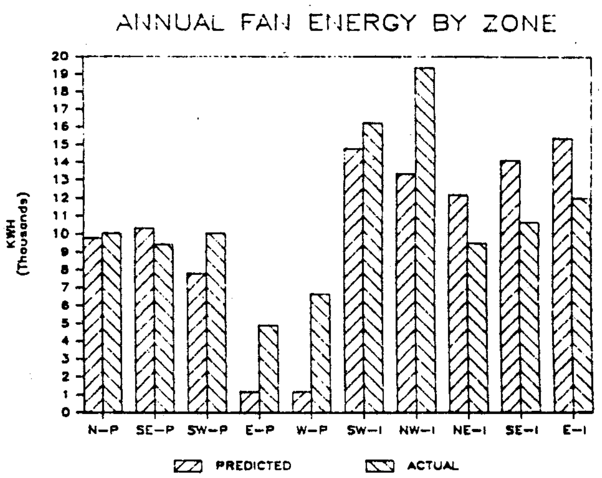

FIGURE 7

The ability of DOE 2.1 to track HVAC loads on a monthly basis was examined for one of the building's zones. The southeast perimeter zone was selected since it had the best correlation between metered and predicted energy consumption on an annual basis. The predicted and actual energy consumption are listed in Table 1.

Table 1. Predicted Vs. Actual Energy Consumption Southeast Perimeter Zone - KWH

	Predicted	Actual
Heating	10596	10168
Cooling	6135	7100
HVAC Aux	10332	9462
Total	27063	26730

The monthly comparison is shown in Figure 8. The horizontal axis is labelled with the first letter of the month, consecutively listed, followed by a hyphen and either a "P" to designated the predicted value, or a "A" to designate metered data. The stacked bar chart illustrates that there are compensating errors on a monthly level which result in good annual correlations. However, in five of the months (February, June, August, September, and November) there are good correlations between actual and predicted heating, cooling, and ventilation loads.

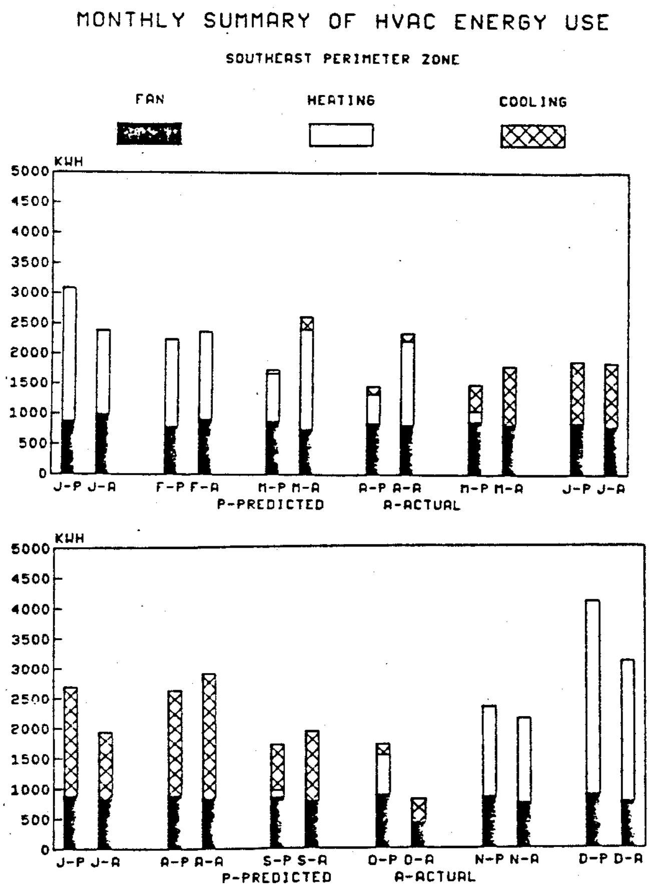

FIGURE 8

STEPS IN THE CALIBRATION PROCESS

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

The Sigma IV building was modeled three times, varying the assumed lighting and equipment power densities and use schedules. The first simulation used power densities estimated by counting the connected fixtures and equipment, and use schedules developed from the consensus of a number of persons familiar with the building and its operation. The second simulation utilized the same power densities, but used the typical or "standard" lighting and equipment schedules contained in the DOE 2.1B Reference Manual library. The final simulation was calibrated so that lighting and equipment schedules and peak densities were as close as possible to the actual data. The results of the three simulations are shown in Figure 9.

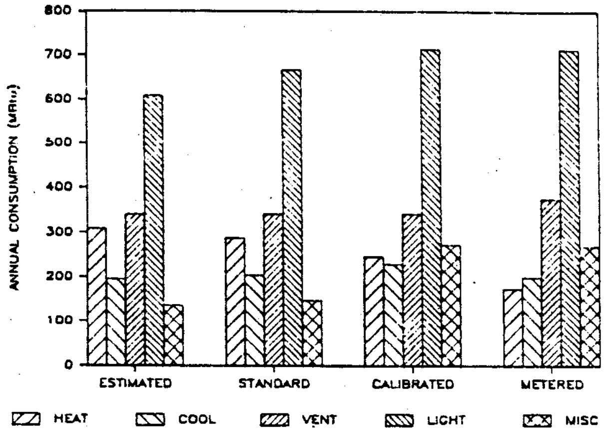

FIGURE 9

As can be seen, the original (estimated) internal loads were grossly underestimated. Table 2 shows the percent difference between various predicted values and their actual counterparts. The annual lighting and miscellaneous equipment loads were underestimated by roughly 15% and 49%, respectively. The effect on predicted heating energy consumption was significant. The estimated internal loads resulted in heating energy being over predicted by 78%. Following calibration of the lighting and equipment loads, the discrepancy became roughly 42%. Predicted cooling energy, however, appeared to be worsened by the calibration. Cooling energy, under the estimated internal load scenario, was predicted within roughly 2% of the actual value. Calibration resulted in a cooling energy prediction of roughly 15% high with the explanation being the inability of DOE 2.1B to account for economizer operation in this system type.

Table 2. Percent Differences Between Predicted Values and Actual Values

Category	Estimated	Standard	Calibrated
Heating	78.33	66.46	42.23
Cooling	-2.21	2.15	14.91
Vent.	-8.74	-8.74	-8.74
Lights	-14.71	-6.38	.00
Misc.	-49.49	-45.48	1.31

The source of the errors in estimated internal loads is two-fold. First, the estimated peak density of lighting, obtained from a count of installed fixtures, was roughly 3.0 W/ft^2. The actual peak obtained from the metered data was 2.39 W/ft^2. The second discrepancy, which partially offset the first, involved the estimation of the minimum lighting load (occurring at night and on weekends). This base load was estimated to be 5% of the peak. In reality, the lighting level never dropped below

28% of the peak. The differences between the assumed schedule, the "standard" schedule for office buildings from the DOE 2.1B Reference Manual, and the actual schedule are illustrated in Figure 10. Similarly, miscellaneous equipment loads were incorrectly estimated.

The impact of these user input errors is significant on the predicted heating and cooling loads. Using the results of the original simulation to steer conservation strategies could result in detrimental measures being adopted, particularly those related to peak load management.

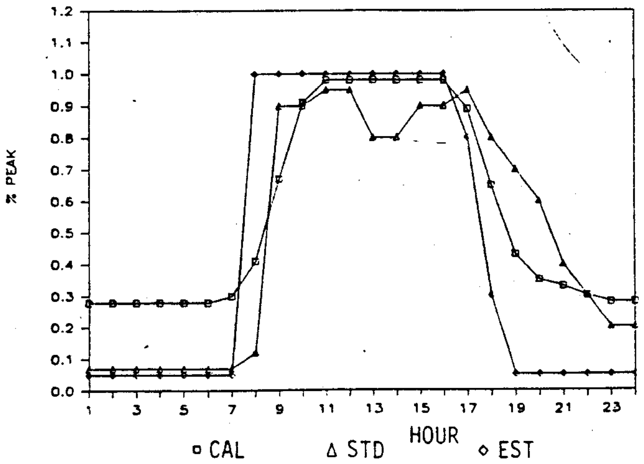

FIGURE 10

CONCLUSIONS

It was not possible to obtain a well calibrated DOE 2.1 simulation of the building based upon metered end-use energy consumption data. While adjustments of the lighting and equipment loads and their corresponding schedules resulted in accurate calibration of those end uses, use of manufacturer's data on the building's heat pumps was not adequate for accurate modeling of heating, cooling, and ventilation energy uses. Possible variations between the actual performance of the building's ten heat pumps and their rated performance may account for some of the difficulties in accurately modeling the HVAC system. However, more important are the limitations of the DOE 2.1B code that preclude accurate characterization of the HVAC system due to its inability to model the economizers and the return air plenum.

Compensating errors resulted in an indication that the building was successfully calibrated based upon the building's annual energy use. However, their were significant discrepancies between actual and predicted heating, cooling, and ventilation energy uses as well as peak energy demand. Based upon this analysis the authors suggest extreme caution in use of the DOE 2.1 code for assessing energy conservation measures for existing buildings with heat pumps.

The analysis of the impact of building schedules, lighting levels, and miscellaneous equipment use highlights the importance of careful attention to these simulation inputs. It was also evident that even careful review of the building's blueprints and careful observation of the building's operating characteristics may not be sufficient for accurately setting these inputs. While the analyst's experience with using the simulation code will have a significant impact on the accuracy of the simulation, at least limited metering of a building appears to be necessary to confidently simulate an existing building.

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