IMPROVING SIMULATION ACCURACY THROUGH THE USE OF SHORT-TERM ELECTRICAL END-USE MONITORING

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ABSTRACT

Hourly simulation programs such as DOE-2, HAP and BLAST can effectively simulate the performance of HVAC systems in response to seasonal weather patterns. However, the schedules of use for key internal loads are often given insufficient consideration, leading to a reduction in accuracy. Schedules are often overly simplified and based on insufficient information about how a building is used. By performing short-term monitoring of key electrical end-uses and extrapolating the measured load profiles over the course of a full year, the magnitude and variability of these loads can be better understood and the accuracy of a building model can be improved in a time-efficient manner.

This paper will describe how short-term monitoring of key internal loads was successfully applied to DOE-2 simulation of a 49,053 square meter commercial office building located in San Diego, California.

INTRODUCTION

While hourly simulation can be applied to a variety of design and research scenarios, achieving high quality results can be difficult as well as time-consuming. As building simulation continues to gain acceptance and is applied to an increasing quantity and diversity of projects, the need has grown for methods of developing accurate models in a time-efficient manner. Ever pressured by the twin demons of budget and schedule, today's energy engineer is expected to produce accurate simulations in a minimum amount of time.

One way to improve the accuracy of a building model is to calibrate specific elements of the model against known data. Some of these methods focus on measuring building response to external loads (solar insolation, wall conduction) in order to evaluate and tune the model's response to varying climatic conditions. In very hot or cold climates, external loads may drive the energy use of the facility, and thus it follows that calibration of external loads can go a long way towards producing an accurate model.

In mild climates, most commercial buildings are internal load-dominated, meaning that the cumulative heat gain contribution of occupants, interior lighting and equipment is greater than the contribution of solar insolation and window and wall conduction (Table 1). In such climates, the effort expended calibrating the model against external load data may be better spent focusing on internal loads, as lighting and equipment use tends to dominate the energy use of such buildings (Table 2). When modeling buildings in mild climates, a reasonable level of accuracy can be achieved using historical weather if the magnitude and usage of internal loads is properly accounted for. When internal loads are physically measured and trend logged the accuracy of the model can be further improved.

Load Component	kW	% of Total
Wall Conduction	74	3%
Window Conduction	98	4%
Window Solar	855	38%
Interior Lighting	536	24%
Plug Load	449	20%
Occupants	218	10%
TOTAL	**2,229**	**100%**

Table 1:
Peak Cooling Load Components for a Large Commercial Office Building in San Diego, California, USA.

This paper addresses the role of short-term energy monitoring as it may be applied to the simulation of an existing building. The focus is on developing accurate simulations in a time-efficient manner; there are certainly other calibration methods that may be used[1], however, short-term monitoring of internal loads is readily achievable for only a modest addition to the project budget and schedule (of particular interest to the consulting engineer). In addition, other research has concluded that model tuning is little

[1] See, for example, "Energy Edge Simulation Tuning Methodologies", prepared by Kaplan Engineering and Portland Energy Conservation, Inc., for Bonneville Power Administration Commercial Technology Section under cooperative agreement #DE-FC79-85BP26683 for a description of other model tuning methods that may be applied to an existing building. Contact Bonneville Power Administration at (800) 282-3713 or via e-mail at comment@bpa.gov for information on obtaining this report.

more than guesswork without valid end-use schedules[2].

CURRENT PRACTICE

In a typical energy simulation, model inputs are developed from a review of as-built drawings, survey of on-site conditions, and interviews with the staff responsible for operating the building. In most cases, physical measurement of building loads does not occur, and model 'calibration' is achieved through making intuitive alterations to model inputs

End Use	GJ/yr	% of Total
Lighting	10,292	29%
Plug Load	8,233	23%
Space Heating	4,346	12%
Space Cooling	2,183	6%
Heat Rejection	403	1%
Pumps	713	2%
Fans	7,232	21%
Water Heating	1,773	5%
TOTAL	**35,175**	**100%**

Table 2:
Annual Energy Consumption by End Use for a Large Commercial Office Building in San Diego, California, USA

to make calculated results more closely match actual profiles (most often without a concrete basis for making such changes). The aggressive budgetary and schedule expectations for typical consulting assignments call for simple, time-efficient strategies to gain insight into building system dynamics. Unfortunately, such strategies can be difficult to come by considering that the consultant usually spends precious few hours in the building for which they are trying to predict performance over an entire year.

SHORTCOMINGS OF CURRENT PRACTICE

Hourly simulation programs can capably estimate the performance of HVAC systems in response to external loads, however, they lend no analytical insight into the magnitude and variability of internal loads. Such usage patterns can be complex, as they are dictated by the collective behavior of all building occupants, each with their own peculiarities. The specific characteristics of lighting, plug load and occupancy patterns must be input by the modeler as accurately as possible in order for them to be properly accounted for in the equipment sizing and energy consumption calculations that the simulation program performs. Of course, trying to predict the behavior of even one occupant with respect to when they are in the building, what equipment they use, and their lighting needs is a tricky proposition, never mind trying to determine the same for the entire building population.

In the absence of measured internal load data, a typical simulation is subject to the following possible sources of error:

- Overestimated Lighting Power Density: Lighting Power Density (LPD) values input in the building model are usually determined by reviewing as-built electrical system drawings, totaling the installed wattage for lighting fixtures, and dividing this value by the affected square footage. While this is a reasonable starting point for a model, it does not account for diversity in lighting use. In a typical office building, many spaces (private offices, conference rooms, storage rooms) are intermittently occupied, and may have their lights shut off at various points throughout the day.

- Overestimated Plug Load: Without load monitoring, it is difficult to accurately estimate the magnitude of electrical loads and usage patterns for computers, copiers, fax machines, and other office equipment. Common modeling mistakes include (1) creating an inventory of such equipment and basing the load for each device upon its nameplate rating, and (2) assuming that the total connected load that the electrical system was designed to accommodate is equal to the actual plug load. Both of these methods will usually greatly overestimate plug loads, often by as much as 200 to 500 percent[3].

- Overly Simplified Usage Schedules: Usage schedules are usually developed based upon interviews with building occupants or the building maintenance staff. As most of the sources of this vital information are not themselves familiar with building simulation, however, their information is often overly simplified and usually does not account for all usage for a given building system. For example, a building engineer may state that lighting is usually on from 6 a.m. until 6 p.m. on typical days, but may neglect to mention that the janitorial crew comes in for a couple hours each

[2] "Energy Edge Simulation Tuning Methodologies", page 50.

[3] See, "Cooling Demands from Office Equipment and Other Plug Loads: Less Than One Watt per Square Foot", Technical Update TU-96-9, published by E Source, Boulder, CO, July 1996, for a more detailed discussion of common myths associated with estimating plug load in office buildings.

evening, and turns on all lights during this period. In addition, typical input from building occupants offers nothing in the way of information on how the load varies throughout the day.

The cumulative result of these sources of error can be difficult to debug. Oftentimes, the overestimated magnitude of internal loads is offset by underestimated hours of operation. This may lead to modeling results that match annual energy consumption within acceptable limits, but do not match month-to-month consumption patterns. Also, these errors will often overestimate peak electrical demand as well as the need for air conditioning during cooler months. The author has observed that many models developed based upon as-built review and operator interviews alone tend to have these problems, exhibiting a "flattened" annual profile for energy consumption and peak demand when compared with actual usage data. This flattened profile is indicative of a model where internal loads have been overestimated, thereby creating a large, non-varying, cooling load each month. The relative contribution of the varying component of the total cooling load – external loads and ventilation – is thus diminished in modeled results, leading to the flattened appearance of the annual profile.

In an effort to account for these known sources of error, an experienced modeler often makes intuitive assumptions about how internal load data should be modified. Typical approaches include:

- Assuming that the plug load density is between 5.4 and 10.8 W/M^2. E Source, ASHRAE, and others have conducted studies concluding that most commercial buildings have plug load densities in this range. In the absence of better data, 8.1 W/M^2 is often an assumed starting point for plug load.

- Assuming a diversity factor for lighting and occupancy. As it is usually not the case that all lighting is simultaneously energized and that all occupants are in the building at the same time, many modelers will assume a diversity factor in their schedules, usually about 80 percent. This means that if the total installed lighting power density is 21.5 W/M^2, the continuous density would never be above 17.2 W/M^2.

- "Ramping" the schedule for the first and last hours of the typical day. In an effort to mimic the varying arrival and departure times of building occupants, the modeler may reduce the scheduled usage for the first and last hours of the day so that a linear increase/decrease is achieved. This is often applied to all internal loads, including occupants, interior lighting, and office equipment.

- "Notching" the schedule during the middle of the day. Most occupants leave their normal work area during lunch, and some even turn their lights off while they are gone. To account for this, some modelers will reduce occupancy, lighting and equipment schedules during this period.

- Using standardized schedules for internal loads, such as those developed for ASHRAE Standard 90. Such schedules may exhibit the hour-to-hour variability that occurs in most buildings, however, this variability is generic and not specific to the building that is being modeled.

While these sorts of changes are based upon reasonable logic and may improve simulation results when compared to known utility data, they are not based on information specific to the building that is being modeled. For this reason, it is difficult to claim that such changes improve the true accuracy of the model, though they give the appearance of improved accuracy.

SHORT-TERM END-USE MONITORING

Conducting short-term physical measurement of key internal loads and then extrapolating this data over the course of a full year can significantly improve the accuracy of simulation results. This strategy reduces much of the uncertainty typically associated with determining the magnitude and variability of interior lighting, equipment, and occupancy schedules.

To accomplish short-term energy monitoring, data loggers with appropriate sensors are installed throughout the building to monitor key loads. The appropriate number of monitoring points for a particular project will vary according to facility size, electrical system design, and the amount of data logging equipment available for use. In the case of high rise buildings with transformers on each floor for lighting and receptacles it is possible to record lighting and plug load usage for an entire floor with only a minimum of equipment. On the other hand, buildings containing a multitude of lighting panels may allow only a few key circuits to be monitored.

An additional consideration in establishing the number of monitoring points is variation in work activities in different parts of the building. For example, in a building containing a legal office, a bank, and a 24-hour per day copy center it will be necessary to monitoring lighting and equipment use in each tenant space in order to accurately predict combined usage. On the other hand, a large office building that primarily houses similar kinds of tenants can probably be monitored in fewer places.

Care must also be taken to select an appropriate duration for the monitoring effort. In general, office buildings that have a stable operating schedule can be monitored for a shorter time period than buildings having significant seasonal variation in operating schedules (for example, a tax preparation service or a retail store). While there is no absolute standard for selecting a monitoring period, when attempting to extrapolate short-term monitored data couple of common sense considerations apply:

- The monitoring period should not be coincident with a holiday season or other period when load profiles may be prone to vary from their normal schedule.
- When possible, monitor for at least two weeks so that load profiles can be compared for consistency. If the profiles for one week are nearly identical to another week, then this suggests that the operating schedules are stable and repeatable.
- If at all possible, monitor for a least a one-week period so that the difference between weekday and weekend operation can be assessed.

A comprehensive discussion of how to prepare a monitoring plan is beyond the scope of this paper, but the importance of proper planning and execution of the monitoring plan cannot be overly emphasized. Specialized software is available that can assist in preparing a monitoring plan, as well as in evaluating the data that is collected[4].

CASE STUDY: SYMPHONY TOWERS

Short term monitoring of lighting, plug load, and occupancy was used to calibrate a DOE-2 simulation for Symphony Towers, a 34-story commercial office building of 49,053 net rentable square meters located in San Diego, California. The author's firm was retained to perform an energy analysis of the facility to (1) identify the magnitude of a cooling capacity shortage, and (2) to provide quantified economic analysis for a variety of retrofit projects for different building systems.

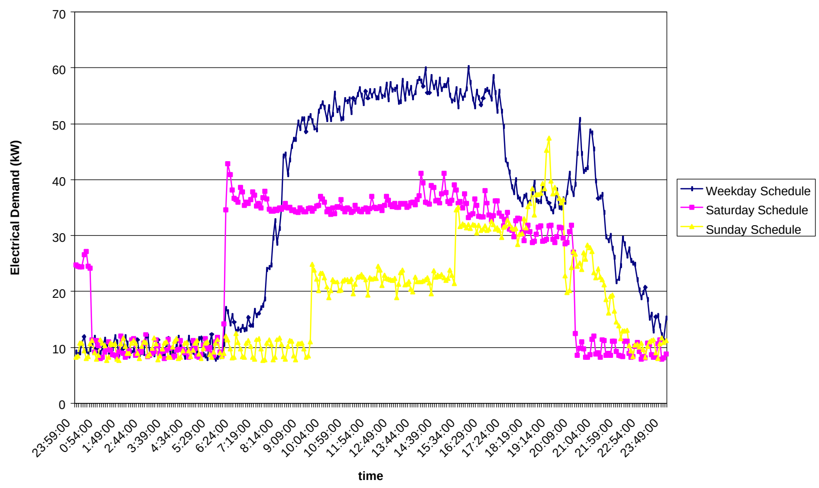
METHODOLOGY

Even though preliminary cooling load calculations indicated that solar insolation was the single largest load component at Symphony Towers, the audit team decided to monitor lighting and equipment usage on two full floors of the building in order to obtain calibration data. Reasons for this decision included:

- Lighting and plug load cumulatively represent more than fifty percent of total annual energy use for the facility, and since the goal of the project was to accurately estimate the overall energy use of the facility it made sense to focus on monitoring the largest end uses.
- Lighting system schedule control is automated, and thus it was thought that usage measured during a two-week period could be accurately extrapolated for a full year simulation.
- Most of the tenants at the building are in similar lines of business (primarily legal and professional services), and have similar needs for copiers, printers, fax machines and personal computers. It was felt that plug load measurements conducted on representative floors of the building could be extrapolated for the rest of the facility.
- DOE-2 is capable of simulating the thermal behavior of a building, however, it lends no analytical insight into the magnitude and variability of internal loads. Therefore, it was felt that physical measurement of internal loads could improve elements of a DOE-2 model most prone to be overly simplified by user inputs.
- Plug load is perhaps the least understood of all energy end uses in terms of coincident load levels and usage patterns, and the project team felt that monitoring would provide much needed insight into the dynamics of equipment use in this building.
- Even though solar insolation is the single largest load component, it would be difficult to substantially improve our simulation in this area within the confines of the imposed budget and schedule. This is because various tenants in the building have different habits with regards to when and how they use interior shading devices throughout the day, and it would be a major undertaking to establish detailed DOE-2 inputs to reflect such habits. In the absence of detailed data regarding interior shading device usage, we used DOE-2's standard probability-based method of controlling these devices. We assumed that blinds will be closed when incoming insolation reaches 126 W/M^2, and that there is a 50% probability that occupants will reopen the blinds after insolation drops below this threshold.

[4] Such a product is a software program called Enforma, developed by Architectural Energy Corporation, 2540 Frontier Avenue, Suite 201, Boulder, CO 80301, (303) 444-4149, (303) 444-4304 fax, www.archenergy.com.

Figure 1: Measured Weekday and Weekend Schedules for Lighting Use



The monitoring plan consisted of installing two four-channel data loggers in electrical rooms on two of the thirty-four floors in the building. Electrical demand from lighting and receptacle transformers was monitored for a period of ten days.

At the conclusion of the monitoring period, the data was transferred back to a PC and then imported into a spreadsheet as ASCII text. From this data, "typical" daily profiles were established for lighting and receptacle load for weekdays, Saturdays and Sundays (see Figure 1). This data was then formatted for use with the DOE-2 model.

CALIBRATION METRICS

Because Symphony Towers is a relatively new building that is in good operating condition, it was felt that energy simulation calibration goals should be reasonably ambitious. Two statistical metrics, Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), were used to measure model calibration against actual energy usage. The targeted levels of calibration for the base case model were as follows:

- Mean Bias Error: ±5 percent for annual electrical consumption, and ±10 percent for peak electrical demand;

- Coefficient of Variation of RMS Error: ±10 percent for annual electrical consumption (compared at monthly intervals) and ±10 percent for the sum of monthly peak electrical demand level.

It was considered important to consider both MBE and CV(RMSE) as calibration metrics because MBE values may be artificially low due to offsetting positive and negative errors on a month-to-month basis. CV(RMSE) accounts for how well simulated results match measured monthly data on an absolute basis.

RESULTS

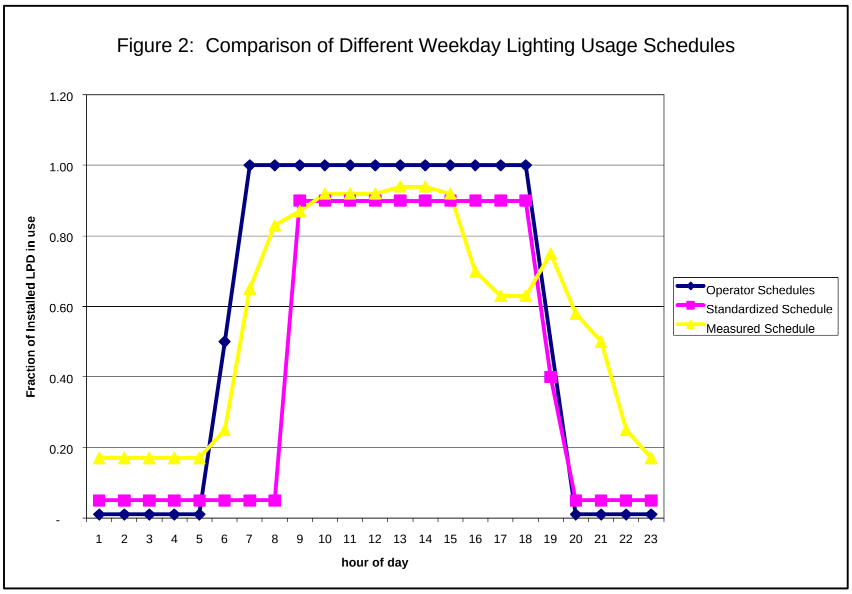
The DOE-2 model was evaluated with three types of schedule data for lighting and plug load:

1. Using schedule information provided by building operating staff;
2. Using standardized schedules using for energy code compliance calculations in the State of California;
3. Using schedules developed from the short-term monitoring of key internal loads.Figure 2 depicts different schedules for lighting that were developed based on the three different sources for data. Both the operating staff as well as the standardized schedules have a block-like shape, and do not contain the hour to hour variability that the monitored data showed.

Table 3 shows how the simulated peak electrical demand and consumption compared with actual month-to-month data when using internal load schedules developed from monitored data. These results are presented graphically in Figures 3 and 4, as well. Overall, Mean Bias Error values of –2.3% for demand of 2.0% for consumption were achieved, and CV(RMSE) values of 7.3% for demand and 4.1% for consumption were achieved. These levels were all within the calibration limits previously described, and thus the base case simulation was considered suitably tuned for use in subsequent analysis.

It was learned after the project was completed that some unusual activities in the building[5] in the month

[5] A mishap with the fire alarm system turned all of the HVAC off for a period of several hours during the middle of the day. The resulting "pull down" load led to an unusually high peak demand for this month.



of December resulted in higher than expected peak electric demand for the facility. The single greatest monthly error for electrical demand was during this month, with the model predicting a peak demand that was 350 kW lower than what was actually experienced. Correcting the actual utility data for this anomaly would improve correlation between measured and simulated data.

Month	kW (M-S)	KWh (M-S)
Jan-98	(160)	(4,752)
Feb-98	(235)	88,314
Mar-98	195	1,541
Apr-98	(230)	38,736
May-98	(83)	1,663
Jun-98	(252)	(3,574)
Jul-98	(97)	(3,255)
Aug-98	(7)	(27,372)
Sep-98	(56)	24,360
Oct-98	(151)	29,091
Nov-98	34	61,591
Dec-98	350	6,467
Σ (M-S)	(692)	212,810
Σ M	29,855	10,431,816
MBE	**-2.3%**	**2.0%**
CV(RMSE)	**7.3%**	**4.1%**

Table 3:
Monthly Correlation between Measured (M) and Simulated (S) Peak Demand and Consumption using Measured Usage Schedules

Table 4 shows that using monitored data to develop schedules for lighting and equipment usage provided much more accurate results than schedules obtained

from the building engineer or from using a generic office schedule. It is worthwhile to note that the results shown in Table 4 for the two non-monitored cases would not have provided acceptable accuracy for our purposes, and therefore the model inputs

would have been adjusted. The adjustment, however, would not have necessarily been based upon real operating data. As shown in Figure 4, all three schedule scenarios provided reasonable matching with the demand profile (considering that historical and not actual weather data was used for this region). Based on this, our changes would have been focused on hours of operation and not load intensity in order to increase energy consumption without drastically altering the demand profile.

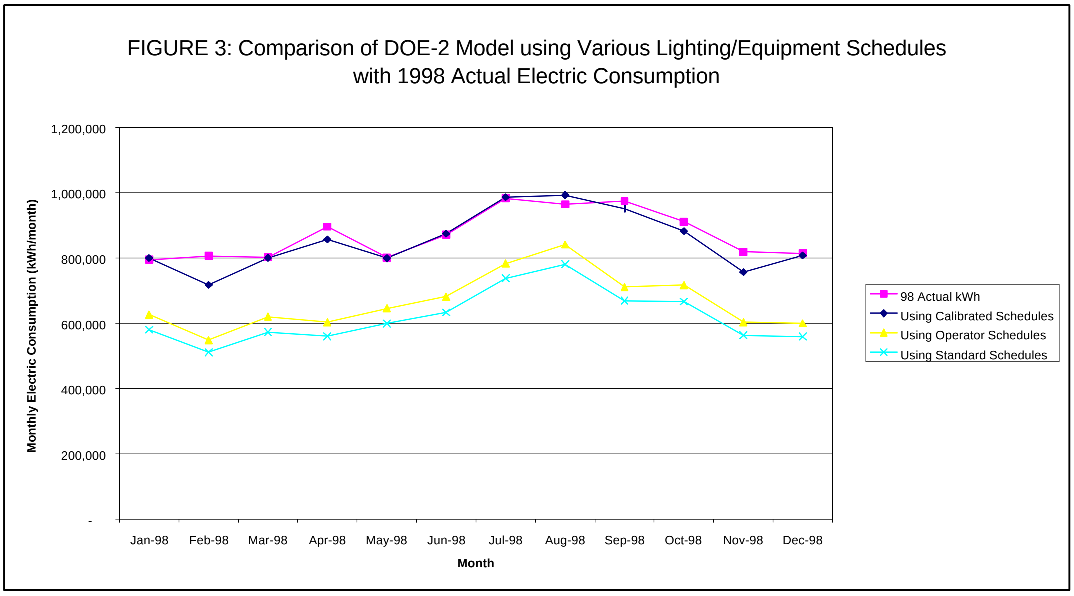
Case	MBE	CV(RMSE)
Monitored Data	2.0%	4.1%
Operator Schedules	23.6%	24.1%
Standard Schedules	28.8%	29.2%

Table 4:
Comparison of Monthly Energy Consumption Correlation for Different Internal Load Schedule Inputs

LESSONS LEARNED

While the project team considered short-term monitoring to be an essential part of the success of the project, there were a number of lessons learned that we will consider for future efforts. We suggest that others who are considering the use of short-term monitoring consider the following possible pitfalls:

- Inquire about planned equipment outages that may be scheduled to occur during the monitoring period. During our monitoring period, we monitored fan electric demand for two of the four main air handling units. Unfortunately, during most of the monitoring period one of the two chillers that serve the building was off-line for annual preventive maintenance, resulting in



unusual fan energy patterns. As a result, the monitored fan data was only useful for verifying start and stop times.

- Be aware of known variations in operating schedules. After we reviewed the results for the model, we saw that our model greatly underestimated energy consumption during the month of March. A consultation with the building engineer made us aware of the fact that this is a busier than usual time for most tenants in the building because this is the month that most companies prepare their income tax returns (which are due on April 15th each year in the U.S.).

- Carefully select the areas that you intend to monitor. You should consider whether there really is any such thing as a "typical" tenant in the building. If not, care must be exercised when extrapolating the monitored data to develop schedules for other, non-monitored spaces.

- Carefully develop your monitoring plan before you arrive on-site to install monitoring equipment. When possible, bring along extra sensors and data loggers to accommodate occasional equipment failures. We had to make several trips back to Symphony Towers because of various equipment malfunctions that necessitated replacing components.

CONCLUSIONS

Based on the results of the short-term monitoring and the subsequent DOE-2 analysis, the following conclusions were reached:

- The lighting power density for the monitored floors had a maximum value of about 10.8 W/M^2 during the monitoring period. In absence of any monitored data, we would have assumed a maximum value of 13.5 W/M^2 based upon site survey results, which would have overstated the peak demand for this end use.

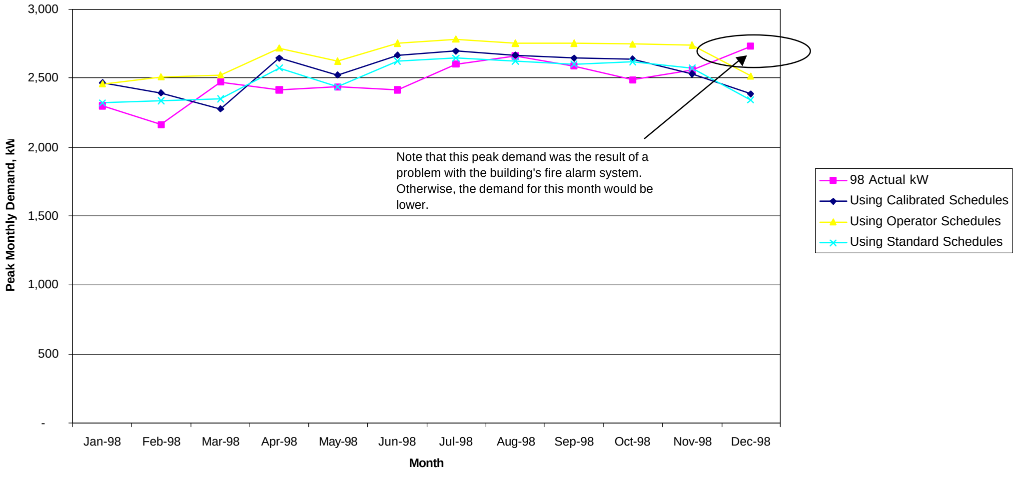
- The receptacle load had a maximum value of about 7.5 W/M^2 during the monitoring period. In absence of monitored data, we would have assumed 8.1 W/M^2, which would have still allowed us to achieve a moderate level of accuracy.

- Using schedules of operation provided by the building operating staff would have overestimated lighting and equipment use during the day and underestimated energy use during the evening. In particular, weekend usage was under-predicted by the operators.

- Using standardized schedules for lighting and equipment would have underestimated energy consumption for these end uses, but would have provided a good match for peak demand.

Based upon our experience with applying short-term monitoring of internal loads to this particular building, we intend to continue to perform simulation of existing buildings this way. The budgetary impact is small as long as the monitoring plan is well conceived, and the potential improvement in model accuracy makes it worth the extra effort.

Figure 4: DOE-2 Model Comparison with Actual 1998 Peak Electric Demand



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REFERENCES

1 Kaplan Engineering and Portland Energy Conservation, Inc **, "Energy Edge Simulation Tuning Methodologies**", prepared for Bonneville Power Administration Commercial Technology Section under cooperative agreement #DE-FC79-85BP26683.

2 "**Cooling Demands from Office Equipment and Other Plug Loads: Less Than One Watt per Square Foot**", Technical Update TU-96-9, published by E Source, Boulder, CO, July 1996 (contact E SOURCE at (303) 440-8500 for information about obtaining this report.