USE OF METERED DATA ANALYSIS TO IMPROVE BUILDING OPERATION AND MAINTENANCE: EARLY RESULTS FROM TWO FEDERAL COMPLEXES.

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ABSTRACT

Inefficient HVAC operation and maintenance practices have long been suspected of wasting significant amounts of energy in buildings. Such practices can be difficult to track, are usually not uncovered by one-time energy audits and can prove difficult to correct, especially in large buildings where priorities often are centered on other concerns.

Recently, new techniques have begun to appear that allow for continuous analysis of metered data. One approach, adapted from university prototypes (Haberl and Claridge 1986, 1987; Haberl, et al., 1988b, 1988c), is now being evaluated in two federal office complexes (Haberl, 1988). This approach identifies operation and maintenance problems by comparing actual daily energy use to normalized energy use, derived from historical metered data. The approach uses simple daily graphs as posted feedback to identify and correct over-consuming practices.

This paper discusses the approach and presents selected early results from the current applications. Modifications to the original approach are also discussed, including: streamlined construction of the statistical model and expansion of the approach to include hourly comparative analysis.

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1. INTRODUCTION

Metered data analysis of a building's energy consumption is rapidly becoming a vital part of an energy audit. Approaches used vary depending on the purpose of the analysis, the availability, level of detailed information, and the complexity of the building being considered (MacDonald and Wasserman, 1987).

One approach, adapted from a university prototype, has been shown to be capable of identifying operation and maintenance problems by comparing actual energy consumption with normalized energy consumption (Haberl, 1986). This idea, the use of a comparative model to detect abnormal behavior, is at the very heart of intelligent diagnostic systems (Richardson, 1985). A fully developed system has the capabilities of providing continuous monitoring and expert-level diagnostics for complex building energy systems. This paper discusses the application of such an approach to two federal complexes.

2. BACKGROUND

2.1. Use of a Statistical Consumption Model

There are many methods for constructing a model of a building's energy consumption, including: engineering based models (i.e., using DOE-2, BLAST, TRNSYS, etc.), frequency domain models (e.g., BEVA or PSTAR) (Subbarao, 1988), real time optimal models (Cumali, 1988), and simple statistical models. Modeling a building's energy usage characteristics provides valuable insight into current operating conditions, equipment efficiency and operation.

With the advent of inexpensive, powerful microcomputers rapid comparison of modeled consumption and actual consumption is yielding new insight into how buildings are consuming energy. One of the drawbacks of such techniques is the time and effort required in setting-up a model (or taking data) and constantly tuning the model as conditions change. Rapidly assembled, statistical models can significantly reduce this effort and yet offer suitable accuracy. Hence, an approach using a statistical model was chosen for the applications in this study.

In the original approach used at a university Rec Center (Haberl 1986) daily metered data were gathered and recorded in a log book. Readings were checked for errors, normalized to midnight, and converted to energy units and/or monetary values. This procedure continued for a minimum 6 months (1/2 heating and 1/2 cooling season) and served as the basis for regression analysis.

Multiple regressions were then applied to the data set to determine the best coefficients for relating the building's energy consumption to the influencing parameters (e.g. environmental, occupancy & system parameters). Results from the original approach yielded an acceptable statistical model but required significant amounts of analysis .

2.2. Extensions -- Using a PRISM-based Model

The most egregious feature of the original approach was the minimum 6 month period needed to establish the data base for the daily regression analysis. In order for the approach to be viable for a cost conscious application this initial period had to be reduced. Another method needed to be developed that could yield daily components without having to rely on daily data for regressions. After looking at several techniques a PRISM-based approach was selected and the results compared with those from the original method (Haberl et al., 1988c). The resultant PRISM-based model reduced the required historical data to 12 monthly values, which can be obtained from the utility supplier. To add sensitivity from occupant effects a two-step approach was developed. The approach is described here as it was applied to the Forrestal steam consumption. Additional details can be found in the references (Haberl, 1988; Haberl et al., 1988c).

PRISM, the Princeton Scorekeeping Method (Fels, 1986) is a statistical procedure originally developed to measure energy consumption in houses. PRISM requires whole-building metered data and average daily temperatures for a given building at a specific location. PRISM produces a weather-adjusted Normalized Annual Consumption (NAC) that is composed of three primary parameters which describe heating-related and non-heating-related consumption. Details concerning PRISM can be found in Fels (1986).

2.3. Extensions -- Hourly Data Diagnostics

The electricity consumption for both facilities represented the largest (cost-wise) annual energy expense. Both the Forrestal and Germantown facilities have utility-installed, 15-minute electric demand data recorders. The information from these recorders can provide valuable insight into operation and maintenance problems when presented in an informative fashion.

One technique of analyzing this type of data is to look at the hourly profiles displayed in 3-D. Several authors have investigated this approach including Christensen (1984) and Christensen and Ketner (1986) who proposed multicolored energy maps, Milne and Yoshikawa (1978) who created graphic displays of passive solar performance, Reiter (1986) who used hourly profiles to study archetypes in the ELCAP project, and Haberl et al. (1988a) who proposed them as a method for better understanding the DOE-2 building energy simulation program.

We applied these techniques to the hourly electric data and extended them to display annual plots of comparative electrical energy usage. We found the comparative profiles to be helpful in the visualization of operation and maintenance problems.

3. APPLICATION TO TWO FEDERAL OFFICE BUILDINGS

3.1. The U.S.D.O.E. Forrestal Building

The James Forrestal building, located at 1000 Independence Avenue, Washington, D.C., is comprised of interconnected north, south and west wings. The north wing is elevated 4 stories above street level and is comprised mostly of executive offices. The south building is connected to the north building with four aerial walkways and to the west building with underground corridors. The south building surrounds an interior courtyard and contains office space, several small cafeterias and an employee gym. The west building is comprised mostly of a cafeteria and related services.

The Forrestal building is primarily constructed of precast and cast-in-place concrete. Precast recessed window units, encasing 1/4 inch plate glass, are the most prominent feature of the envelope. The main entrance to the complex is located below the north building through automated sliding doors that lead into a glazed vestibule.

The 1,632,000 sqft. facility contains 315,000 sqft. of parking and 1,317,000 sqft. of office space and corridors. A detailed accounting of the building is contained in the JRB reports (1981). In general, the exterior envelope of the building has minimum insulation. A large portion of the building (668,000 sqft.) is actually below grade. Roofs throughout the building are high mass composite construction with 2 inch rigid insulation.

The Forrestal building receives steam and chilled water from the Central Heating and Refrigeration Plant (located a few blocks to the southwest at 12th and C Streets) operated by the General Services Administration. Steam is metered at the Forrestal building with an electronic, bayonet-type, turbine steam meter; chilled water is metered at the Central plant. Electricity and natural gas are separately metered within the building and are provided by local suppliers (PEPCo, 1987; DOCNG, 1987). Potable water is also metered on-site.

Perimeter heating and cooling is provided by two primary types of systems - four-pipe fan coil units (south and west exposure), and two-pipe fan coil units. Other specialty systems include reheat coils, baseboard units (cafeterias and corridors), north building (fourth floor) hydronic slab heating, heating and ventilating unit heaters (garage), and specialty computer room cooling systems. Ventilation and cooling for the building is also provided by a low pressure air distribution system serviced by air handling units located in 22 mechanical rooms. Hot water is supplied by four domestic water converters. Three supply 105F water for lavatories and one supplies 140F water for kitchen use.

The basic control systems for the Forrestal building are pneumatic. A 995 point, multiplex-type, non-computerized automation system was installed in the mid 1960's, but has been inoperative for many years. At the present time the control of systems at the Forrestal building is provided by effective manual schedules, timeclocks and local pneumatic controllers. Normal business hours for the 3,860 employees are from 8:30 a.m. to 5:00 p.m., Monday through Friday.

The Forrestal building uses approximately 174,300 MBtu per year which is 132,000 Btu/sqft. Utility costs reported for 1985 to 1986 totaled $4,065,785 or about $3.09/sqft.

Figure 1 shows end-use fuel consumption estimates for electric, steam and chilled water (by Btu equivalent, typical year). End-use steam baseload (8.1 %) and steam heating (23.2 %) were derived from monthly data. End-use constant electric baseload (always on) estimates (30.7 %) and the scheduled electric baseload estimates (16.4 %) were derived from hourly data. Chilled water values are as reported by the Central plant. Figure 2 shows historical electric and steam consumption in constant dollars.

Some comments concerning Figure 1. First, the Forrestal building has a significant constant electrical load. Preliminary site measurements have revealed that a large portion of this is for dedicated computer equipment. Second, the chilled water portion is derived from periodic Central plant billing information which reflects system-wide distribution losses that overstate chilled water consumption.

Figure 2 shows a gradual 4.5 % rise in electricity consumption with slight summertime and wintertime peaks caused by additional fan runtimes to account for extreme weather conditions. October 1986, a partial reading, was omitted since due to delegation transfer from GSA to DOE took place at mid-month. Beginning in December 1986 steam consumption shows a significant decrease during heating season. Significant changes in baseload summertime steam consumption is also visible.

3.2. The U.S.D.O.E. Germantown Complex

The U.S.D.O.E. Germantown complex is located on a large 100 acre complex northeast of Washington D.C. in Germantown, Maryland. The main building and support buildings were completed in 1958 for the United States Atomic Energy Commission. The entire complex is composed of a main building, an auditorium, a boiler house, an equipment storage building, a maintenance building, sewer ejector and water pumping stations, a radio building and a large water tower.

The main building is composed of numerous inter-connecting narrow wings of five stories each. The primary construction is masonry and concrete with a brick veneer, single pane glazing and minimal insulation. The main and adjunct buildings comprise 596,000 sqft. of which 390,000 sqft. is office space for administrative personnel and support staff.

The main building at the Germantown complex utilizes steam for heating and chilled water for cooling. Steam is generated in the boiler house and piped a short distance underground to the main complex. Chilled water is provided by two 750 ton chillers and one 350 ton chiller. 350-ton and 1,500-ton condensing towers are provided for the chillers.

The primary heating/cooling systems are perimeter induction units. Ventilation is supplied by air-handling units located throughout the complex. Domestic water heating is provided by steam converters used primarily for restrooms and kitchen usage.

The control systems at the Germantown complex are pneumatic. Well-established manual control schedules predominate. No computerized HVAC control systems have been installed aside from a microprocessor-based steam meter. Additional information concerning the facility can be obtained from the GPC (1987) and VRGW (1987) reports. Normal business hours for the Germantown complex are from 8:30 a.m. to 5:00 p.m., Monday through Friday for the 1,814 employees and contractors.

The Germantown complex uses approximately 104,277 MBtu per year or about 267,250 Btu/sqft. Utility costs for 1986 to 1987 (reconstructed) totaled $1,168,000 or about $2.99/sqft.

Figure 3 shows end-use fuel consumption estimates for electricity and fuel oil (Btu equivalent). End-use fuel oil baseload (32.5 %) and heating estimates (21.5 %) were derived from monthly data. End-use constant electric baseload (28.7 %), scheduled electric baseload (13.6 %) and electric cooling estimates (3.7 %) were derived from hourly data.

Some comments concerning Figure 3. First, the constant and scheduled electric baseloads are very similar to the Forrestal building. The electric cooling portion, when calculated from hourly data, does not include year-round cooling (a considerable amount included in the baseload), and therefore is somewhat understated. Nonetheless, the baseload oil consumption is significantly larger since the Germantown values include the boiler plant inefficiencies and excessive summertime idling of the boilers.

In Figure 4 electricity consumption for Germantown is increasing annually at 9 %, almost twice the rate of Forrestal. Summertime electric cooling is also increasing. A slight summertime oil consumption decrease is visible, however, the considerable summertime baseload oil consumption still remains.

4. USING METERED DATA ANALYSIS

Beginning in September 1986 (Forrestal) and in March 1987 (Germantown) the building operators were asked to begin daily readings of utility meters in addition to their normal programs. Readings were taken at scheduled times and the proper notations made in the facility log book. This information, together with environmental, occupant and system information provided the data base for regressions used to assemble the normalized models.

Periodic meetings were established with the operators where graphs were displayed, analysis techniques, and reasons for differences and ideas for conserving energy were discussed. The primary purpose of these meetings was to improve the awareness of energy consumption and to solicit ideas from the staff as to how improve the day-to-day operation of the building.

Finally, prototype software templates were developed. They were installed on the available microcomputers and the administrative staff was trained to use them. Typically, the meters are read once-per-day by the maintenance staff, recorded in the log book and checked by the maintenance supervisor. Readings are then transferred once-per-week to the template where the majority of the analysis is performed in the template spreadsheet. Graphs (and printouts when needed) are produced and posted on the bulletin board for review by the operation and maintenance staff.

4.1. Daily Metered Data Analysis — Forrestal Building

The normalized regression-based model for the Forrestal steam consumption began with a PRISM analysis and added sensitivity to day-of-the-week variations as follows. First, average daily coefficients were obtained from PRISM. Next, daily residuals were obtained by subtracting the expected daily PRISM consumption from the actual daily consumption. These residuals were then sorted according to heating and non-heating season by day-of-the-week. Daily adjustments above or below the average PRISM values were then calculated. The complete model is then composed of a baseload or non-heating coefficient (a), a combined heat loss coefficient (B) for a specific balance point temperature (t_{bp}), and an occupancy adjustment for each weekday for heating and non-heating season. The coefficients for the Forrestal building are listed in Table 1.

Figure 5 is a scatter plot of the Forrestal daily steam ($/day using $15.50/Mlb) consumption versus outside temperature. The data labels represent the day-of-the-week (0 = Saturday). The Forrestal PRISM-based model (Table 1) is superimposed over the data points as shown. Figure 6 is another way of viewing the normalized model of the steam consumption. In Figure 6 outside temperature and day-of-the-week form the x-y plane. Consumption ($/day) is represented by the height above the plane. Daily consumption can be determined by tracing a path on the surface shown.

Figure 7 is an example of a posted graph for the period March 1, 1988 through March 24, 1988. The actual and estimated energy usage (in constant $) form the upper lines, the difference between the two forms the lower line. The upper numeric data-label is the day-of-the-month and the lower alphanumeric data label is the weekday. This particular format was chosen, after numerous trials, as the most readable and easily understood.

In a similar fashion to the steam graphs, comparative electricity consumption graphs were produced. Figure 8 illustrates the actual, estimated and comparative electric usage for March 1, 1988 through March 24, 1988. The labeling in the graph is similar to that of Figure 8.

4.2. Hourly Metered Data Analysis

3-D annual, hourly profiles were found to be useful in identifying operational and maintenance problems when they were presented as comparative plots. Such plots display problems as profiles which can be identified by archetype and time-of-occurrence. Comparative plots were produced by selecting representative swing-season weeks in the fall and spring, calculating average hourly values for each day-of-the-week and extending this as a baseload for the entire year. Actual hourly electricity usage was then compared (hour by hour) to the average baseload by simple subtraction -- yielding comparative hourly plots.

Figure 9 shows the 3-D annual profile of Forrestal's actual electricity use. The day-of-the-year and hour-of-the-day form the bottom x-y plane. The electric demand (kWh/h) is the height of surface above the x-y plane and the electric energy usage (kWh) is the volume traced out by the surface. The dominant scheduled loads for the Forrestal building can be clearly seen. This type of annual profile is typical of those shown by Reiter (1986) and Akbari et al. (1988).

Figure 10 illustrates the hourly average, baseload electricity usage created for the Forrestal building from the representative spring and fall swing-season periods.

Figure 11 shows the annual weekend only, electric comparison profile for the Forrestal building. This figure was created by subtracting the hourly baseload electric usage from the actual electric usage and displaying positive values only (over-consumptions) for weekends. One can clearly see three types of archetype weekend over-consumptions. First, in January 1987, a constant weekend over-consumption typical of a system left on 24 hours is visible. Second, scheduled weekend over-consumptions occurs in two, four week periods (beginning in March 1987 and in July 1986). Third, second-order weekend cooling and seasonality is visible as very small summertime constant loads. Finally, during the second week of December 1986, a weekend cooling archetype over-consumption occurs.

Figure 12 is the comparative electricity usage for Forrestal for weekdays and weekends (positive only) with occupied hours suppressed. The primary features of this graphs show additional fan runtimes during extreme heating and cooling seasons.

In a similar fashion the annual electric profile for Germantown is shown in Figure 13. The electric cooling loads are clearly visible from April to October. Figure 14 is the weekend comparative annual electric profile (positive only). Cooling season related weekend over-consumptions dominate this comparative plot.

5. SUMMARY

5.1. Impact

We found that metered data analysis has provided the administrative and maintenance staffs with useful information about energy consumption. This information has assisted efforts to reduce energy consumption by providing immediate graphic feedback and by allowing a common communication media that is understandable by the administrative, maintenance, and technical staffs.

In the Forrestal building the actual steam consumption was reduced by $259,773 during the first 12 months beginning September 1986. Figures 15 and 16 illustrate the steam consumption and savings during this period. The majority of these savings are due to intensive steam trap maintenance and repair efforts by the Forrestal staff -- which were prompted by discussions that used the graphs as a means of displaying consumption. In addition to steam trap maintenance and retubing of the main converters certain operational procedures have also been changed -- for example, in the Forrestal building, beginning in July 1987, the steam is turned off (using the main building valve) on Friday night and turned back on Monday morning. This procedure is now followed for all weekends when N.W.S. forecasts do not indicate freeze problems.

Figure 16 illustrates the illusive nature of the cumulative steam savings. This figure shows high and low estimates of cumulative steam savings and daily steam savings. The low cumulative savings represent steam savings calculated by comparing actual consumption with normalized 1985/86 consumption. Accordingly, one can see that the largest savings accumulated in the first 7 months, leveled out slightly during the summer and began again during the next heating season. Also apparent are numerous, single-day events that can gain (or lose) significant amounts of steam. The importance of consistent operation and maintenance is readily apparent in this figure.

The high cumulative savings reflects our estimate of steam savings that account for inaccuracies in the main steam meter. This estimate reflects baseload steam consumption of about 53,000 lbs/day (measured in October 1986 before the steam trap maintenance program) versus a baseload of 15,000 lbs/day calculated with questionable metered data. The actual reported, steam savings fall about midway between our low and high estimates. The difference between these amounts has accrued as steam savings to the GSA Central plant (which have been confirmed through conversations with the Central plant staff).

Finally, numerous meetings and conversations with the administration and maintenance staff have revealed another important impact of the work. They report that they feel as though they have now regained some control over the building -- and can track different conservation, operation and control strategies.

5.2. Problems

First, obtaining historical data for any study is not a simple matter. Utility information prior to September 1986 was kept by a different government agency (in quarterly format) and contained missing data and unexplained adjustments.

Second, the accuracy of steam data prior to September 1986 could not be assured. This is evident when one considers the PRISM analysis of PRE and POST data. Values for the PRE PRISM analysis show considerable error terms and an R^2 of 0.865. Values for the POST PRISM analysis show significant improvement of all error terms and an improved R^2 of 0.966. Further, we have additional evidence that indicates that the meter might have been seriously out of calibration (by a factor of 2 to 3). We have included a high cumulative savings estimate to reflect what we believe to be the total steam savings that accrued to the Department of Energy and to the Central plant. Further analysis will be needed of the Central plant steam production reports to resolve this discrepancy. To avoid meter drift in the future DOE will be installing condensate meters to meter the steam usage.

Third, although significant steam savings did occur, significant electric savings could not be observed — even though the maintenance records show that numerous ballasts, lamp replacements and other measures have been implemented to reduce electric usage. Not unexpectedly, electricity usage has increased for Forrestal by an average 4 % per year and for Germantown by 9 % per year. There are many possible reasons for this one of which we call the "PC factor". The PC factor is the enormous amount of desktop microcomputing equipment that is being added to these facilities each month. We believe that this accounts for a significant portion of the observed electric increase and obscures any electric conservation efforts.

5.3. Discussion

The use of feedback has been shown by many others to be an effective means of providing useful information to building operators about their energy consumption. We wanted to investigate this approach in a large office building to see if it could also be used to guide an energy conservation program. We used monthly, daily and hourly feedback graphs presented at periodic meetings with the building operators to discuss procedures for improving the operation of the building. Although this study was not intended to be behavioral analysis of the effectiveness of posted feedback we found that significant operational problems could only be revealed by the persons who maintain the building. To this extent we found that an understanding the engineering characteristics of the building had to be augmented by some sense of how the building was being operated -- hence the emphasis on the team approach.

We did find that existing institutional barriers can prevent achieving high savings, and thus deter rapid payback. For example, a lack of calibrated meters is seen as one such problem. Lack of incentive and bonuses for motivating building personnel is also seen as a barrier.

Finally, this work supports the idea that energy audits should be diagnostic in nature, making use of extensive metered data analysis rather than a prescriptive, fill-in-the-blank approach that prevails today. Also, this work seems to show that significant energy savings require both good energy conservation measures and a means of continuously measuring the savings in order to assure long term results.

6. REFERENCES

Akbari, H., Heinemeier, K., Flora, D., LeConiac, P. 1988. "Analysis of commercial whole building 15 minute interval electric load data", ASHRAE

Transactions, V. 94, Pt. 2.
Christensen, C. 1984. "Digital and color energy maps for graphic display of hourly data.", Solar Energy Research Institute, SERI Report No. SERI/TP-253-2461, and Proceedings of the 9th annual Passive Solar Conference - 1984, Columbus, Ohio, September 25-27, 1984.
Christensen, C., and Ketner, K. 1986. "Computer graphic analysis of Class B hourly data.", Proceedings of the 11th National Passive Solar Conference - 1986, Boulder, Colorado, June 9 - 11 1986.
Cumali, Z. 1988. "Global Optimization of HVAC system operations in real time", ASHRAE Transactions, Vol. 94, Pt. 1, 1988.
DOCNG 1987, District of Columbia Natural Gas Company, P.O. Box 2432, Washington, D.C., 20081.
Fels, M. 1986. "Measuring Energy Savings" The Scorekeeping Approach", Energy and Buildings, Vol. 9, #1 - 2.
GPC 1987a, Germantown Heating and Refrigeration - Plant Operation Manual., Vol. 1-3, Prepared for the General Services Administration by General Physics Corporation, May, 1987.
Haberl, J. 1986. "An expert system for the analysis of building energy consumption", Ph.D. Thesis, Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder.
Haberl, J. 1988. "United States Department of Energy Pilot Program: Forrestal and Germantown Facilities Metered Data Consumption Analysis", Summary Report - Volumes 1 & 2, Management Information Support, Lakewood, Colorado.
Haberl, J., and Claridge, D. 1986. "A statistical building energy usage prediction methodology", Proceedings of the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Volume 9, August 1986, Santa Cruz, CA.
Haberl J. and Claridge D. 1987, "An expert system for building energy consumption analysis: Prototype results",ASHRAE Transactions, V. 93, Pt. 1, 1987.
Haberl, J., MacDonald, M., Eden, A. 1988a. "An overview of 3-D graphical analysis using DOE-2 hourly simulation data", ASHRAE Transactions, V. 94, Pt. 1.
Haberl, J., Smith, L., Cooney, K., Stern, F. 1988b, "An expert system for building energy consumption analysis: applications at a university campus", ASHRAE Transactions, V. 94, Pt. 1, 1988.
Haberl, J. Smith, L., Kreider, J. 1988c, "Metered data analysis and knowledge based methods that reduce HVAC operational and maintenance problems", Fifth Annual Symposium on Improving Building Energy Efficiency in Hot and Humid Climates, Texas A&M, September 13-14, 1988, Houston, Texas, in preparation.
JRB, 1981."Utility Conservation and Fuels Analysis Study - Forrestal Building, Final Report and Appendices A-D", GSA Contract No. GS-03B-89044, JRB Associates, 8400 Westpark Drive, McLean, Virginia, 22102.
MacDonald, M. and Wasserman, D. 1987. "Metered Data Analysis Methods for Commercial, Institutional, and Large Multifamily Buildings", Oak Ridge National laboratory, Draft Report, ORNL/CON/XXX - to be published.
Milne, M., and Yoshikawa, S. 1978. "Solar-5, an interactive computer-aided passive solar building design system", Proceedings of the Third National Passive Solar Conference - 1978, Vol. #, Newark, Delaware.
NOAA 1987, "Local Climatological Data - Washington D.C., National Airport", National Oceanic and Atmospheric Administration - National Climatic Data Center, Ashville, North Carolina.
NAP 1987, National Airport Weather Station, National Oceanic and Atmospheric Administration, Washington, D.C., personal communications.
PEPCo 1987, Potomac Electric Power Company, 1900 Pennsylvania Ave., N.W., Washington, D.C. 20068-0001.
Reiter, P. D. 1986. "Early results from commercial ELCAP buildings: Schedules as primary determinant of load shapes in the commercial sector." ASHRAE

Transactions, Vol. 92, Part 2.
Richardson, J. 1985. Artificial intelligence and maintenance. Noyes Publications, Park Ridge, New Jersey.
Subbarao, K. 1988. "A Method of Robust Determination of Dynamic Thermal Characteristics from Short-Term Tests" ASHRAE Seminar Presentation — Building Thermal Analysis Based on Dynamic Short-Term Test Data:, Ottawa, Canada.
VRGW, 1987. "Building Condition Report - Forrestal Building", GSA Contract No. GS-11B-47036, Velsey Architects, 4401 East West Highway, Suite 400, Bethesda, MD, 20814.

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Table 1 - Forrestal PRISM results

PRE	POST
October 1985 to September 1986	October 1986 to September 1987
a = 40.16 (29.64) Mlbs/day	a = 24.06 (8.34) Mlbs/day
B = 14.19 (4.53) Mlbs/day-F	B = 9.82 (1.49) Mlbs/day-F
T_{bp} = 59.0 (7.52) F	T_{bp} = 58.6 (3.10) F
NAC = 56,425.37 (6,501.57) Mlbs/year	NAC = 36,979.68 (1,936.59) Mlbs/year
R^2 = 0.865	R^2 = 0.966

(Weather N.W.S. National A.P. 1982 - 1988)
(Occupancy factors — Heating season)

Monday = +24,259 lbs., Tuesday = +73,220 lbs.,
Wednesday = +51,050 lbs., Thursday = +47,967 lbs.
Friday = - 3567 lbs.,
Saturday/Sunday = $-7112(T_{bp}$ - Tout) lbs/^{o}F-day,

(Occupancy factors — non-heating season)

Saturday = -10658 lbs, Sunday = -6650 lbs,
Monday = +8538 lbs, Tuesday = 16715 lbs,
Wednesday = 9690 lbs, Thursday = 9820 lbs,
Friday = - 1361 lbs.

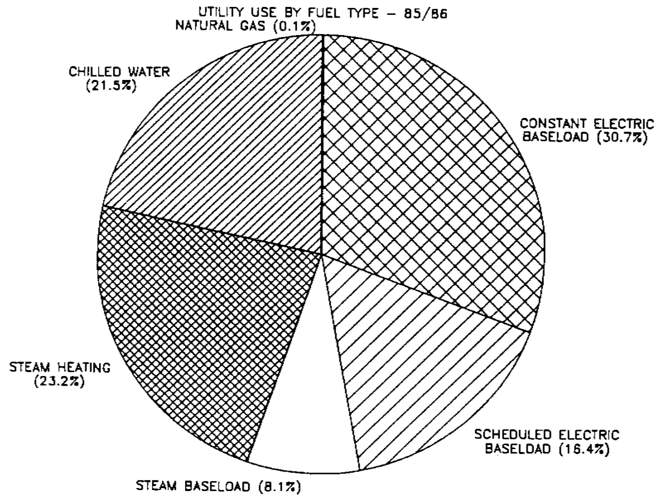

Figure 1 – Forrestal End-Use Energy Consumption Estimates These are estimates that show end-use energy consumption in Btu equivalents. Constant electric and scheduled electric were calculated from hourly data. Steam heating and baseload estimates were calculated from monthly estimates. Chilled water represents thermal requirements (C.O.P. = 1) from GSA.

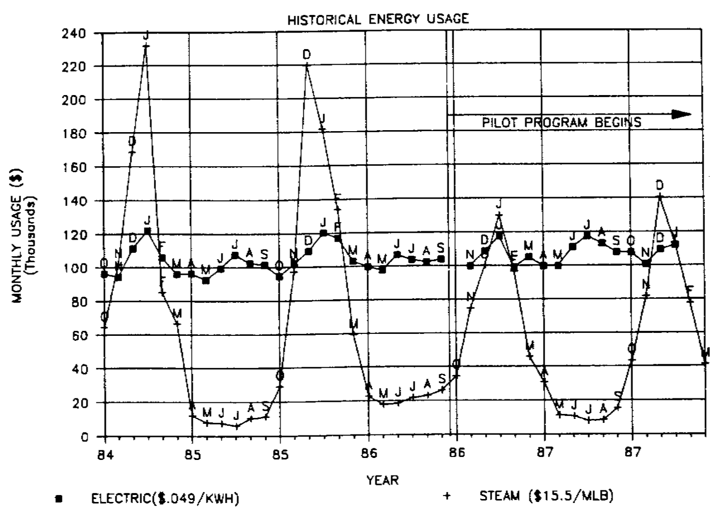

Figure 2 – Forrestal Historical Energy Use These values are monthly electricity (kWh) and steam (Mlbs) usage displayed as constant costs. The pilot effort began in October 1986. Reductions in peak and summertime usage are apparent. Steam values prior to September 1986 may contain significant errors due to the main steam meter being out of calibration.

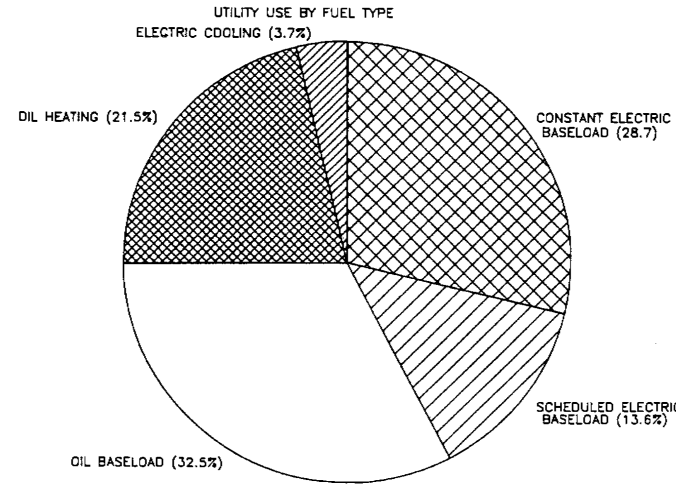

Figure 3 – Germantown End-Use Energy Consumption Estimates These are estimates that show end-use energy consumption in Btu equivalents. Constant electric and scheduled electric were calculated from hourly data. Oil heating and baseload estimates were calculated from monthly deliveries. The small electric cooling estimate does not reflect year-around cooling (unfortunately) included in the electric baseload portions.

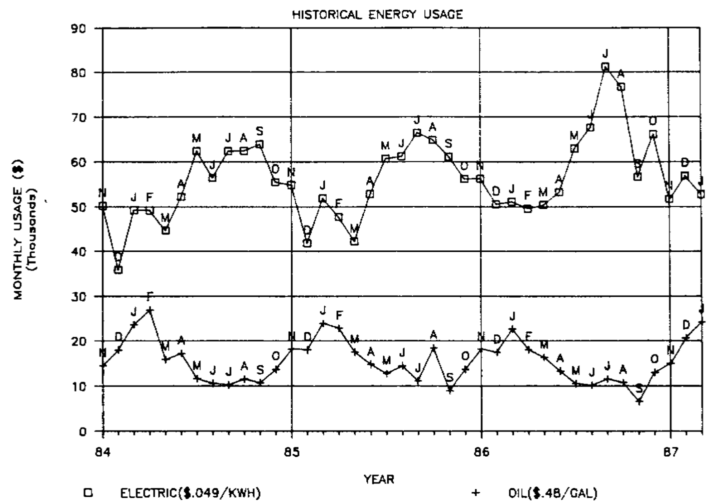

Figure 4 – Germantown Historical Energy Use These values are monthly electricity (kWh) and oil (gal) usage displayed as constant costs. The pilot effort began in March 1987.

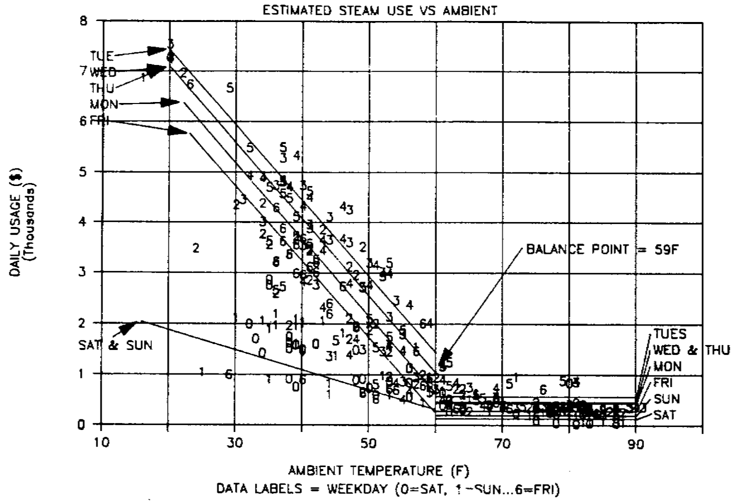

Figure 5 - Forrestal Steam & PRISM-based model vs. Outside Air This figure shows the steam consumption versus average daily ambient temperature. The data labels represent the day-of-the-week (0=Sat...6=Fri). The PRISM-based model is graphically represented by the solid lines. The balance point temperature is 59F which serves to separate heating and non-heating seasons.

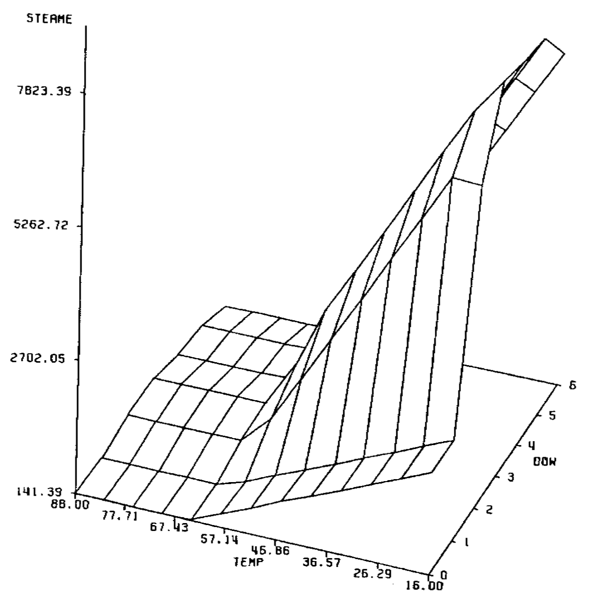

Figure 6 - Normalized Forrestal Steam Model vs. O/A & D.O.W. This figure displays the Forrestal normalized steam model as a surface floated above the two primary influences forming the lower x-y plane. The height of an individual point on the surface is the amount of daily steam consumption.

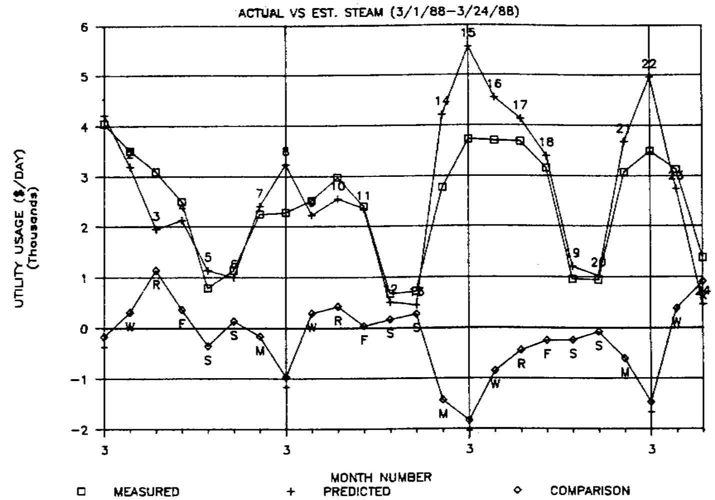

Figure 7 - Forrestal Comparative Steam Usage This figure shows the measured, predicted (calculated) and comparative daily steam consumption. The data labels above the predicted consumption are the day-of-the-month, the data labels below the comparative consumption are the weekday. The apparent under-consumption on 3/14-3/18 and 3/21-3/22 are due to over-prediction by the model which occurs at temperatures near the balance point. Further adjustments and the use of dummy variables (e.g., steam valved on/off) are needed to improve the accuracy.

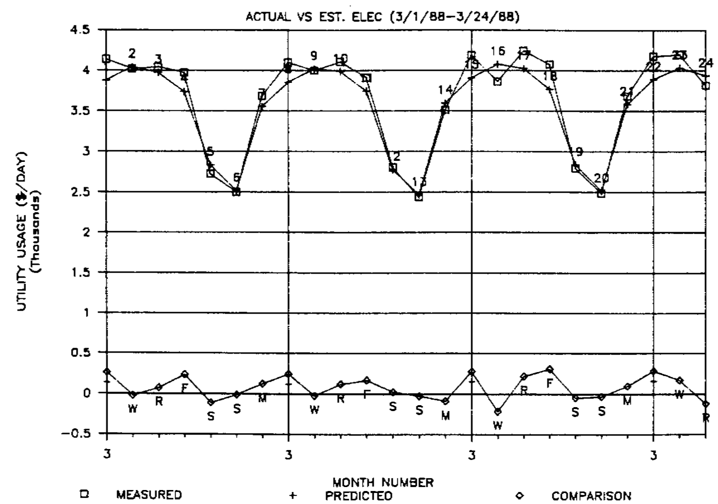

Figure 8 - Forrestal Comparative Electric Usage This figure shows the measured, predicted and comparative whole-building electricity usage. The nomenclature for this figure is identical to Figure 7. Electricity usage, for the most part, is well described by the model.

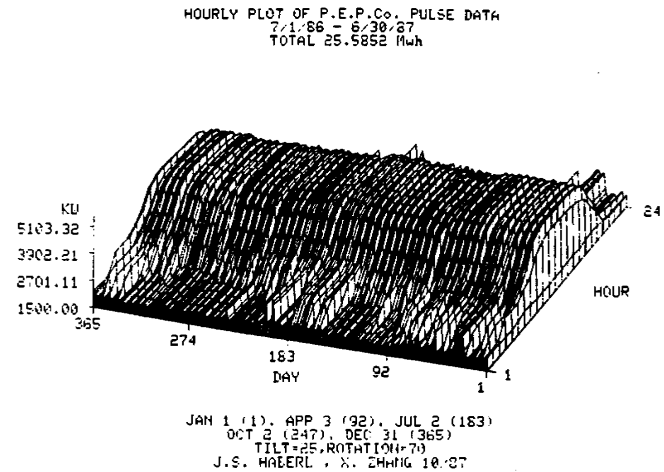

Figure 9 - Forrestal Annual Electric Profile This figure is an annual electricity usage profile for the period 7/1/86 to 6/30/87. Chronologically, the data begins in the middle of the proceeds until December and then begins again in January and proceeds until June. The dominate scheduled loads are apparent.

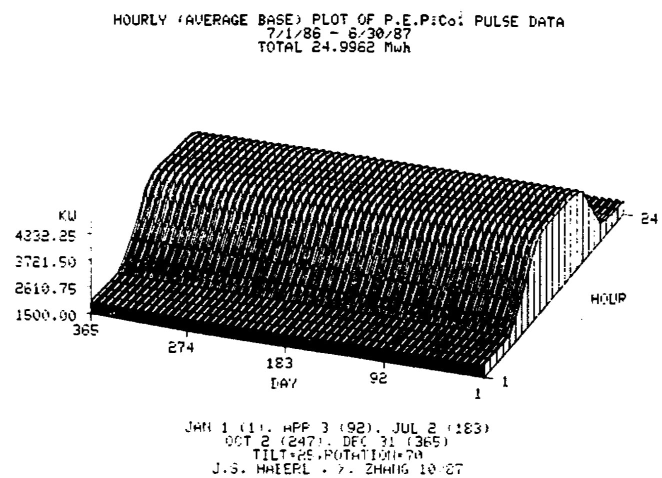

Figure 10 - Forrestal Baseload Electric Profile This figure shows the average baseload displayed for all 52 weeks. All 52 weeks are identical. Each week is composed of average hourly values for all 7 days, calculated from swing season (non-heating/non-cooling) periods.

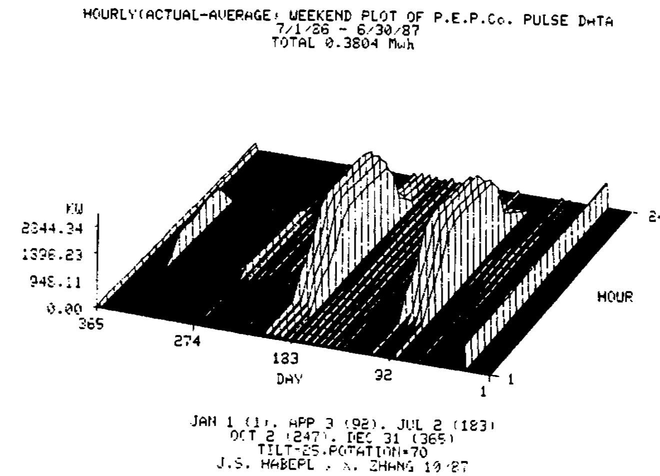

Figure 11 - Forrestal Comparative Electric Profile (Weekend) This comparative figure shows the results of subtracting the data in Figure 10 (hour-by-hour) from the data in Figure 11. This figure shows weekend values (positive only). The apparent shapes represent intervals when the actual consumption deviated from the average baseload.

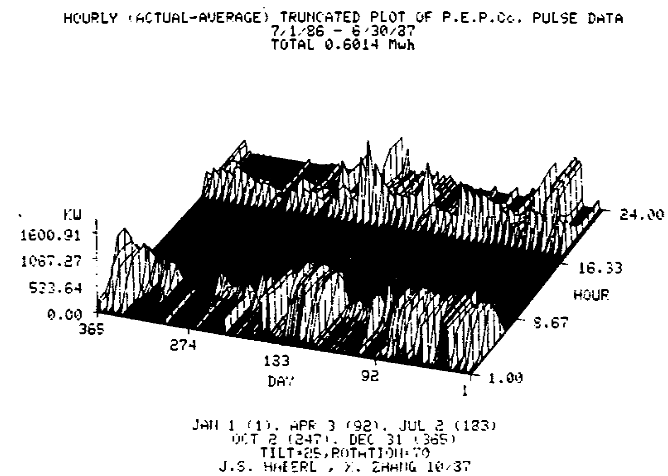

Figure 12 - Forrestal Comparative Electric Profile (All days, unoccupied periods) This comparative annual profile shows the differences between the actual electricity usage and the average baseload usage for all weekdays during unoccupied periods only (positive values only). Primarily, what is shown is the extended runtimes of the AHU's during extreme heating and cooling conditions.

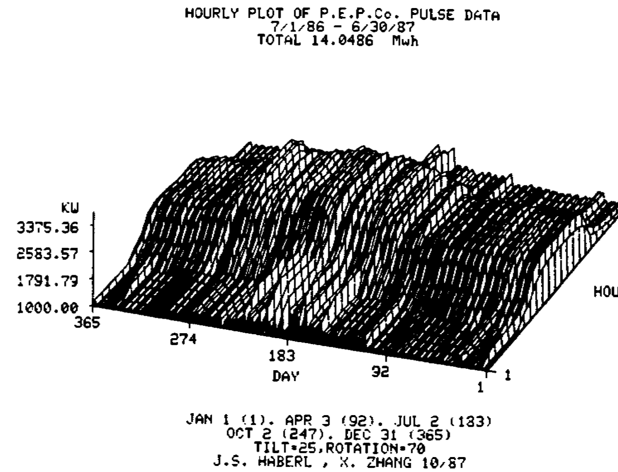

Figure 13 - Germantown Annual Electric Profile This figure shows the actual electricity usage for the period 7/1/86 to 6/30/87. The cooling load is readily apparent when one compares this graph to Figure 9.

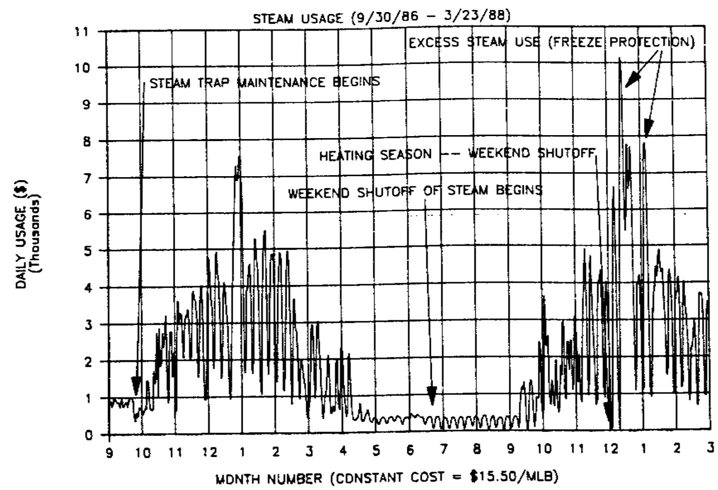

Figure 15 - Forrestal Daily Steam Usage This figure shows the daily steam consumption for the Forrestal building. The high level of steam usage (apx. $750 to $1,000 per day) in September 1986 is visible in the lower left portion of the graph. Other program milestones are noted.

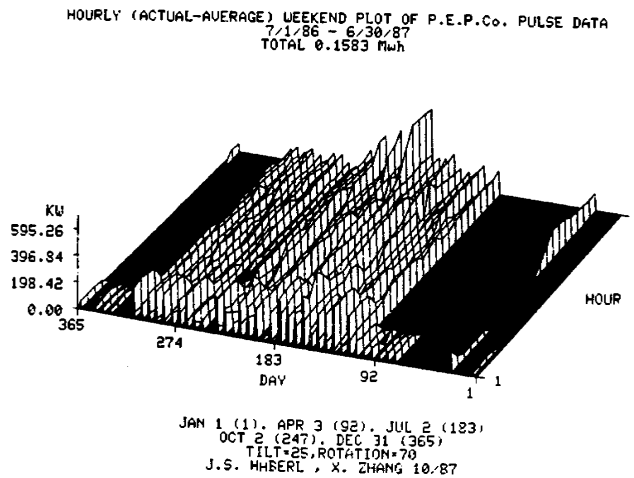

Figure 14 - Germantown Comparative Electric Profile (Weekend) This figure was constructed in an identical fashion to that of Figure 11 (i.e., comparative weekend, positive only). The dominating feature of this plot is the electricity usage for cooling purposes. Some simultaneous heating and cooling is also apparent.

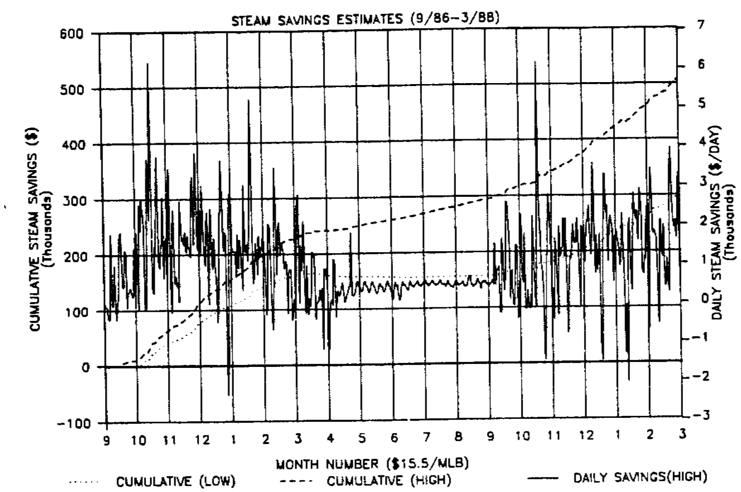

Figure 16 - Forrestal Estimated Steam Savings This figure shows calculated daily, high and low cumulative estimates of steam savings. Actual monthly steam savings fall between the the high and low estimates. The high cumulative savings represent an estimate of the steam savings that accrued to both the Forrestal building and to the GSA Central plant. The daily steam savings represent the high estimate. A calibration problem with the main steam meter is the primary source of differences shown.