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AN EXPERT SYSTEM FOR THE ANALYSIS OF

BUILDING ENERGY CONSUMPTION

by

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An Expert System for the Analysis of Building Energy Consumption
Thesis directed by Associate Professor David E. Claridge

A significant portion of unnecessary energy consumption in a building can often be attributed to specific operational events, especially in large institutional buildings with complex energy consuming sub-systems. Once identified these events can be tracked automatically with regression techniques and an expert system on a desktop microcomputer using information and observations from daily on-site visits. A prototype methodology, using these techniques, has been able to reduce energy consumption for a pilot building by 15 percent. The pilot building for the application of the methodology is the University of Colorado Recreation Center. This methodology is new because it identifies abnormal energy consumption and relates it to specific operational and maintenance problems using comparative daily consumption estimates and an expert system.

The comparative consumption uses multivariate linearized regression and the expert system was developed with an available proprietary expert system shell. The expert system contains a previously assembled knowledge base which represents the expertise of on-site maintenance personnel, as well as that of the author gained over the six years the building has been under study. The methodology developed, the Building Energy Analysis CONsultant (BEACON) system, has two main components, an energy consumption predictor, and an expert system that analyzes abnormal consumption according to predefined IF-THEN rules.

The Building Energy Analysis Consultant methodology represents the coordination of: building operations from the building administrators, expertise from all building maintenance personnel, a complete energy end-use characterization of all building systems, long term energy auditing, and daily inspections over a one year period. This thesis describes the complete system, its structure and presents results from the application of the methodology to the Rec Center.

**ACKNOWLEDGEMENTS**

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## PREFACE

This work concludes six years of energy conservation studies performed for the University of Colorado Student Recreation Center.

The studies began late in 1980 when the University of Colorado Student Administrators asked Dr. John Dow to perform a solar feasibility study. Since such a feasibility study had previously been performed by Dr. Dow, as well as other studies (Numark and Bartlett, 1981), a comprehensive energy conservation project was recommended, funded, performed and delivered (Dow, 1981).

The second phase of the study began in November 1983, when Dr. Judith Bryant asked that additional energy conservation studies be performed. The building has been under continuous study since.

The third phase of the study, beginning in the summer of 1985, represents the prelude to this work. It originally focused on providing monthly forecasts of energy consumption. Early attempts to deliver such an administrative tool failed because of an insufficient understanding of the inter-related energy consuming subsystems.

This work, beginning in September 1985, finally presented a statisfactory predictor of energy consumption; the results are the regression work described herein. The expert system portion of the work was developed to electronically capture and deliver the expertise of maintenance personnel at Facilities Management as well as the six years of knowledge gained by the author. The work serves as an administrative warning "beacon" that identifies potential problems, and hence the name BEACON.

# CHAPTER 1

## INTRODUCTION

### 1.1. Purpose and Objective

The purpose of the work described in this thesis is to develop an inexpensive prototype expert system that helps building administrators and maintenance personnel responsible for the operation of a building eliminate inefficient operational practices. Results from the prototype application at the University of Colorado Recreation Center (Rec Center) demonstate that such a system reduces annual energy consumption, improves operation and maintenance procedures, and improves institutional memory.

The objective of this thesis is to demonstrate proof-of-concept by developing and documenting a prototype expert system for a pilot building. The system developed for this proof-of-concept employs a regression based energy consumption predictor and an expert system that watch for abnormal consumptions. The expert system makes suggestions as to the cause of the abnormal consumption based on events that have previously ( and are preassembled into the knowledge base contained in the expert system). This knowledge base and the statistically normal consumption are developed from routine daily log-book entries for the pilot building over a one year period. It is believed that this work represents a significant step towards a low cost methodology, applicable to any building, which requires no additional computational hardware beyond currently available desktop microcomputers.

### 1.2. Scope of the Work

The prototype expert system presented draws on developments in four fields of study: building energy auditing, building operation and maintenance, regression analysis and expert system technology. This system was developed to provide a monthly energy consumption predictor that would allow the forecasting of energy costs a year in advance, as required by current University of Colorado budget practices (Bryant, 1985).

The prototype system developed, the Building Energy Analysis CONsultant (BEACON), is the first system known that predicts daily energy consumption, and makes suggestions concerning the cause of the possible abnormal consumption using an expert system. The system uses certain background information describing the building, and daily log book readings to operate. The system has been developed on a IBM Personal Computer and uses a commercially available spreadsheet program (Lotus, 1985) to perform the consumption prediction and an expert system development toolkit to perform the abnormal consumption analysis (Teknowledge, 1985).

### 1.3. Problem Area

Previous energy conservation audits on the pilot building (performed by the author) had shown limited success in reducing energy consumption. These studies had failed to identify certain operational and maintenance problems that were causing abnormal energy consumption (Dow, 1981; Numark and Bartlett, 1981; Claridge, 1984; Claridge et al., 1984a, 1984b, 1985; Madigan, 1984; Hall, 1985; Claridge and Brothers, 1986; Haberl and Claridge, 1985; Haberl et al., 1985). The previous studies had faithfully employed standard energy conservation walk-thru techniques, such as those found in the Department of Energy's Institutional Buildings Conservation Program (COEC, 1983). One effort (Claridge et al., 1984a) even went so far as to simulate the building with the DOE-2.1b program, with limited success. In all, the previous studies failed because they relied on assumptions concerning operational procedures that could not be validated.

The work presented in this thesis has been successful because of the knowledge gained from the intensive inspection required to understand the energy consuming sub-systems well enough to represent them in the expert system knowledge base. This understanding of the building operation is the key to the success of this system. Exposing the pilot building to this level of inspection and measurement uncovered significant operational problems.

**1.4. Significance of the Work**

This work demonstrates proof-of-concept for the application of an expert system that predicts energy consumption for a building, recognizes abnormal consumption and makes suggestions regarding possible reasons for the abnormal consumption. The individual parts of the system, the expert system, the knowledge gained from interviews and intensive inspection, and the consumption predictors are not new. However, the combination of the three components into a prototype system represents a first-of-a-kind effort. The system is a first step towards a cross-cut methodology that incorporates engineering expertise, intensive inspection, administrative and maintenance knowledge and consumption monitoring into an energy conservation action plan.

Simple linearized regression techniques were chosen for the consumption predictors. Suggestions to improve the statistical prediction of consumption are included in the appendix.

Inexpensive data gathering methods (daily log book readings) were employed in order to make the complete methodology applicable to as many buildings as possible. Costly, computerized control and data acquisition were specifically avoided. Computer equipment required was targeted for desktop microcomputers, typical of those found in most administrative offices.

The expert system was kept as simple as possible since the intended users of the system are maintenance and administrative personnel with only moderate computer training. Suggestions concerning the improvement of the expert system are also included in the appendix.

### 1.5. Order of Reporting

This work assumes the reader has some background in energy conservation analysis, Artificial Intelligence (AI), microcomputers and regression based statistical analysis. Therefore, only a brief introductory treatment for each of these areas is contained in the work. Further reading can be found in the references. The next section of this thesis contains an historical perspective, an introduction to AI, intelligent buildings, and a survey of expert system developments in the building energy field. Following this is the body of the work that introduces the BEACON system. A background discussion follows this section. Chapter 4 discusses the application to the Rec Center and presents results for a sample application. Chapter 5 is a wrap-up discussion of the work including the effectiveness, and areas for future research.

The appendices contain a discussion of regression analysis, the knowledge base for the expert system and a description of the spreadsheet and expert system software operation and an index generated with the STARINDX (MicroPro, 1984) program. The data base for the regression analysis is too voluminous to be printed (90+ tables, 1.3 Mbytes) so only a small part is included for discussion purposes.

# CHAPTER 2

# BACKGROUND

This background section is intended to introduce the reader to those related areas that have been drawn upon to develop this thesis. An historical perspective is first presented to familiarize the reader with the University of Colorado, Boulder Campus and historical energy conservation efforts. A section reviewing artificial intelligence is next followed by a section introducing the concept of knowledge based system and the building industry.

## 2.1. Historical Perspective

### 2.1.1. Campus Overview

The Boulder Campus of the University of Colorado (the Campus) can be characterized as a centrally laid-out design served by a common utility distribution service. The Physical Plant for the Boulder campus annually consumes $667,805 \times 10^6$ Btu/yr to provide utility services for the buildings on the central campus (Sproul, et al., 1985). The utilities provided to the buildings on campus include: electric, natural gas, steam, potable water (cold) and chilled water. The electricity, natural gas (interruptable) and #6 fuel oil are purchased from local suppliers (primarily the Public Service Company of Colorado) and redistributed through the Campus. Steam and chilled water (for certain buildings) are generated on-site, and likewise distributed to the buildings on the central

Campus. There are two primary categories of buildings on campus: general fund buildings and non-general fund buildings. Energy consumption expenditures in general fund buildings are the responsibility of the Colorado State Legislature; non-general fund buildings are self-financing.

The increasing importance of energy costs can be seen in Table 2-1. In the twelve years between 1972/73 and 1984/85 the rates for electricity (cost per Kwh for the Campus) have increased 458 percent; natural gas rates have increased 1,126 percent (Sproul, et al., 1985). Annual costs for electricity have increased 522 percent; annual costs for heating (i.e., natural gas, #6 fuel oil) have increased 696 percent. Cumulative savings for general fund buildings are $2,203,900 (electric) and $4,915,400 (heating) since 1972/73. Needless to say, energy conservation has been an effective ongoing effort.

**Table 2-1: General Fund Energy Usage and Cost Summary**

| | 1972/73 | 1984/85 | % Change |
|---|---|---|---|
| Electricity ($Kwh/ft^2$) | 14.15 | 13.0 | -8.1 |
| Electricity ($/year) | $434,114 | $2,268,800 | +522 |
| Heating ($Btu/ft^2$) | 177,800 | 111,200 | -37.5 |
| Heating ($/year) | $253,114 | $1,756,700 | +696 |
| Total ($/year) | $687,228 | $4,025,500 | +586 |

Monthly tracking of electric and potable (cold) water are maintained for participating buildings by the Facilities Management department. The proprietary software program "FASER" (Fast Accounting System for Energy Reporting) is used to analyze energy consumption of individual buildings or groups of buildings. FASER is also used to identify questionable meter readings and inoperative meters (OmniComp, 1983).

### 2.1.2. Campus Energy Conservation History

The Campus began a comprehensive energy conservation program during the winter of 1973-74 in response to the Arab oil embargo. Items implemented range from low-cost options, such as the installation of time clocks to control air handling units, to significant-cost options, such as a VAV retrofit in the Engineering Center. A summary of these items is provided in Table 3-4 (Sproul, et al., 1985). The single most important item is the 1982 University-Legislative Memorandum that allows Facilities Management to fund energy conservation efforts with energy savings. Clearly, this has provided the motivation and enthusiasm that has produced significant results.

The effect of the energy conservation program can be seen in

Figure 2-1. According to Sproul et al. (1985) the total cost avoidance attributable to energy conservation is $7,119,300, which consists of $4,915,400 in steam cost avoidance and $2,203,900 in electric cost avoidance. Figure 2-2 is a graphical representation of historical energy usage for the Campus. The squares represent the electrical consumption, pluses represent natural gas consumption and the diamonds are the degree day indicator (x10).

**2.1.3. Rec Center Overview**

The University of Colorado Student Recreation Center (Rec Center), the pilot building for this thesis, is located in the northwest corner of the central campus. The Rec Center, as a part of the centralized utility distribution network, receives steam, natural gas and electricity from the Physical Plant. The operating budget for the Rec Center is allocated by the University of Colorado Student Union (UCSU).

Construction of the Student Recreation Center was completed in 1973. The Rec Center is a large building occupying approximately 150,000 $ft^2$ on two main levels. The upper level (see Figure 2-3) consists of a multipurpose gymnasium, a full-size indoor ice rink with spectator stands, six handball courts, and a lobby overlooking the pool area below. The lower level (Figure 2-4) consists of six additional handball courts, men's and women's locker rooms,

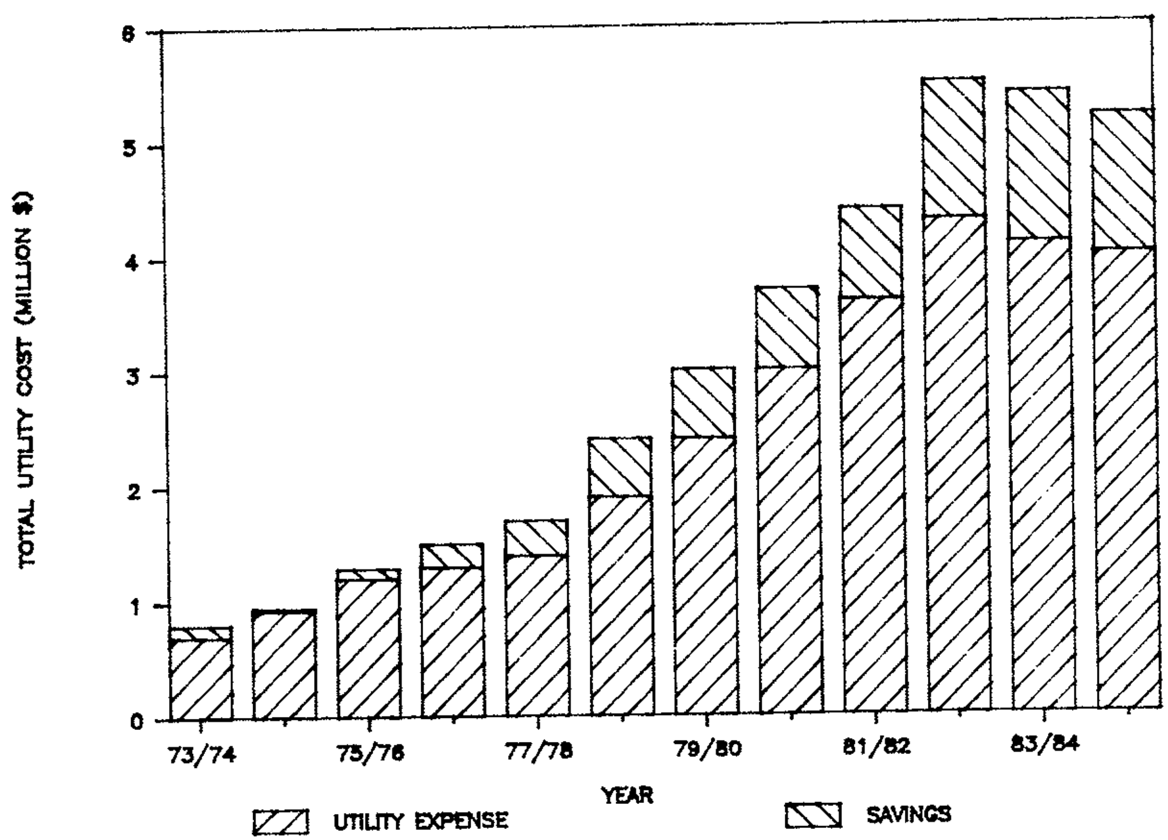



Fig. 2-1: Campus Energy Management Results

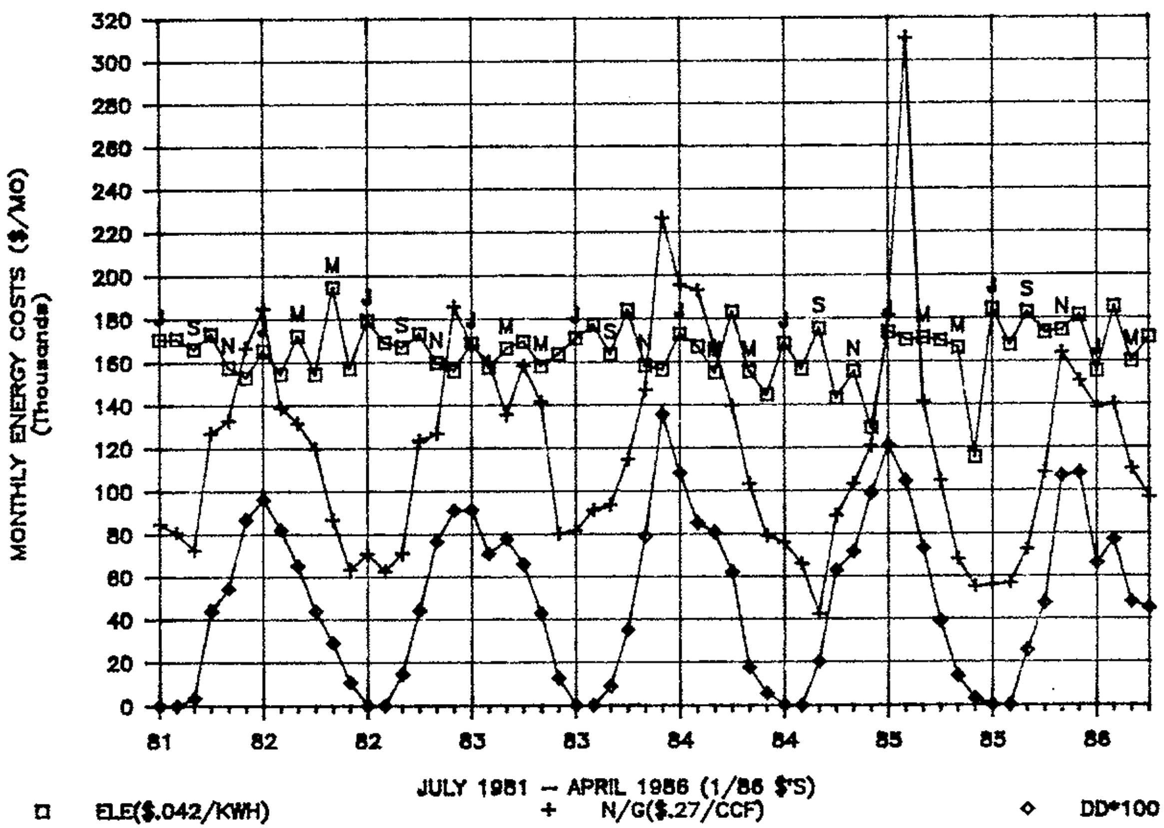



Fig. 2-2: Historical Campus Energy Usage

systems exercise room, free-weight room, training room, equipment checkout area, and administrative offices. On the west end of the lower level (but two stories in height) is the pool area containing separate swimming and diving pools along with spectator bleachers projecting down from the upper level. In addition to the two main levels, there is a basement "tunnel level" containing the entrances to the lower handball courts and mechanical areas for the pool and ice rink and a penthouse area (above the upper handball courts) contains the majority of the heating, ventilating, and air-conditioning (HVAC) equipment (Figure 2-5). Figure 2-6 shows the south (front) elevation of the building.

The Rec Center is a high-mass structure with concrete construction used exclusively throughout the building, with the exception of roofs. Roofs throughout the building are a low-mass composite made up of steel trusses, 1.5 inch corrugated steel decking, 1.5 inch rigid insulation, and built-up asphalt/gravel roofing. The sloped roofs surrounding the gym and pool areas consist of 2.25 inch wood decking with clay tile roofing, The lobby roof is made of 12 inch concrete waffle slab, 8 inch lightweight concrete and built-up roofing.

Exterior walls in most areas are a non-load bearing composite of 8 inch concrete block, 1 inch insulation, and 5 inch sandstone interspersed with 20 inch poured concrete load bearing columns and beams at 20 ft intervals. The pool area uses the same poured concrete columns and beams for support, but the actual walls are of curtain-type glass construction set back approximately 4 ft behind the load bearing structure. Double glazed, tinted glass is

**Table 2-2: Campus Energy Conservation History**

| Year | Cost | Savings | Item |
|---|---|---|---|
| 1973/74 | N/A | N/A | Time Clocks, temperature controls, delamping program. |
| 1976 | N/A | N/A | Experimental computerized fan cycling program (Engineering). |
| 1976 | N/A | N/A | Colorado Commission on Higher Education approves energy monitoring and control for Campus. |
| 1978 | N/A | N/A | Campus Energy Conservation Office created by Vice Chancellor. |
| 1978 | N/A | N/A | In-depth survey of thirty major campus buildings complete. |
| 1978 | $49,500 | N/A | U.S. Department of Energy grants money for insulation projects. |
| 1978 | N/A | N/A | Night-time use of buildings re-evaluated, heatingtemperature (68F), cooling temperature (80F). |
| 1978 | N/A | N/A | Publicity campaigns begun, time clock setting tightened. |
| 1980 | N/A | N/A | Boulder Campus committee on Energy formed. Additional engineer added to EnergyConservationOffice, steam trap maintenance program started. |
| 1980 | $56,500 | $49,200 | Department of Administration State Buildings Division funds chiller unit modification |
| 1980 | N/A | N/A | U.S. Department of Energy begins matching grant program for schools and hospitals. |
| 1982 | N/A | N/A | University-Legislature Memorandum of Understanding makes possible funding of Energy Conservation from utility procurement money. |
| 1982 | $132,200 | $55,000 | Biosciences Heat Recovery. |
| 1982 | $145,000 | $44,600 | Business Building VAV. |
| 1982 | $205,000 | $63,000 | Duane Physics VAV. |
| 1982 | $52,000 | $12,200 | Williams Village boiler economizer. |
| 1982 | $26,400 | $24,000 | Computerized Energy Management (EMS) at Facilities Management. |
| 1982 | $109,000 | $21,000 | EMS installed in UMC. |
| 1983 | $201,000 | $76,200 | EMS - Engineering, Business, Duane, LASP, Muenzinger, Biopsychology. |
| 1984 | $123,800 | $37,500 | Muenzinger VAV. |

**Campus Energy Conservation History (Cont.)**

| Year | Cost | Savings | Item |
|---|---|---|---|
| 1984 | $200,700 | $82,000 | EMS - Norlin, Ekeley, Music, Rec Center, Environmental Design, Law, Chemistry. |
| 1984 | $29,500 | $12,000 | Business Chiller Retrofit. |
| 1985 | $195,400 | $60,000 | EMS - Ramaley, BioScience, Regent, JILA,Fine Arts, Stadium, Fiske. |
| 1985 | $210,000 | N/A | Universityadministration authorizes permanent, annual allocation for energy conservation projects. |
| 1985+ | $173,700 | $210,000 | Steam Trap Maintenance (ongoing). |
| Total* | $2,302,500 | $834,400 | |

* All costs are as reported in (Sproul, et al., 1985).

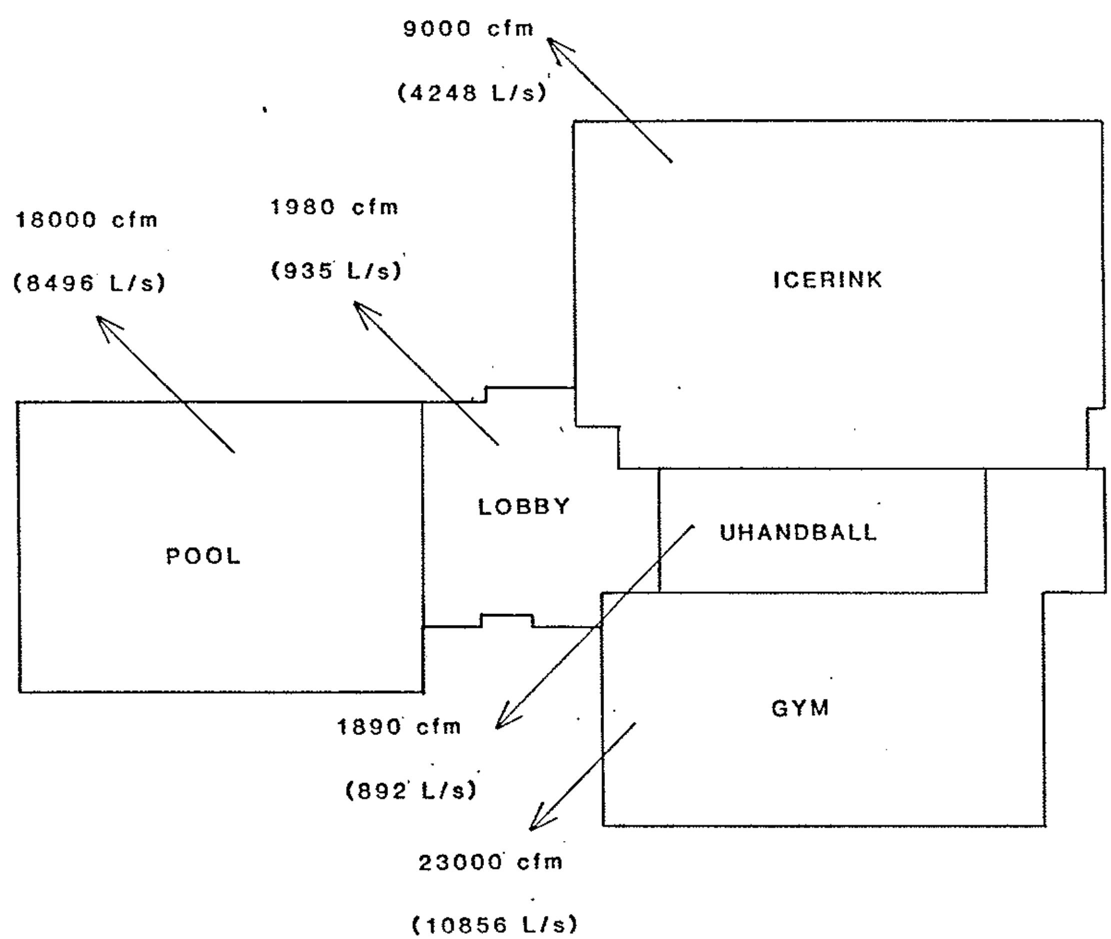



Fig. 2-3: Upper Level Layout of the Rec Center

used in the pool area and in the north wall of the ice rink area. Exterior floor construction is concrete slab on grade with no perimeter insulation. Other areas of glazing include the south wall of the lobby and frosted windows along the perimeter of the locker rooms.

The two main entrances to the building are the main (south) lobby doors and the lower level (east) doors adjacent to the tennis courts. North lobby doors serve as an exit only. The main lobby doors receive the greatest use and are the only doors with an entry vestibule. There are several other exits around the building, all of which receive less frequent use. A loading dock in the south-east corner has a roll-up type overhead door and is used for deliveries. A large set of sliding glass doors lead from the pool area to the south patio area. These are open only during warm weather and provide access to the large patio on the south side of the pool.

Eight heating and ventilating systems and one heating, ventilation and air conditioning system are in the building. Three of these are located in or near the zones they serve with the remainder in the mechanical penthouse. These are all single zone systems. Heating to all zones is provided by steam produced by the campus power plant. Cooling is provided only in the administrative office by a small packaged refrigeration unit.

The Rec Center consumes approximately 30,000 MBtu per year or about 200,000 Btu/ft$^2$ per year. There are four main reasons for the Rec Center's significant energy usage.

1. The Rec Center contains several special systems

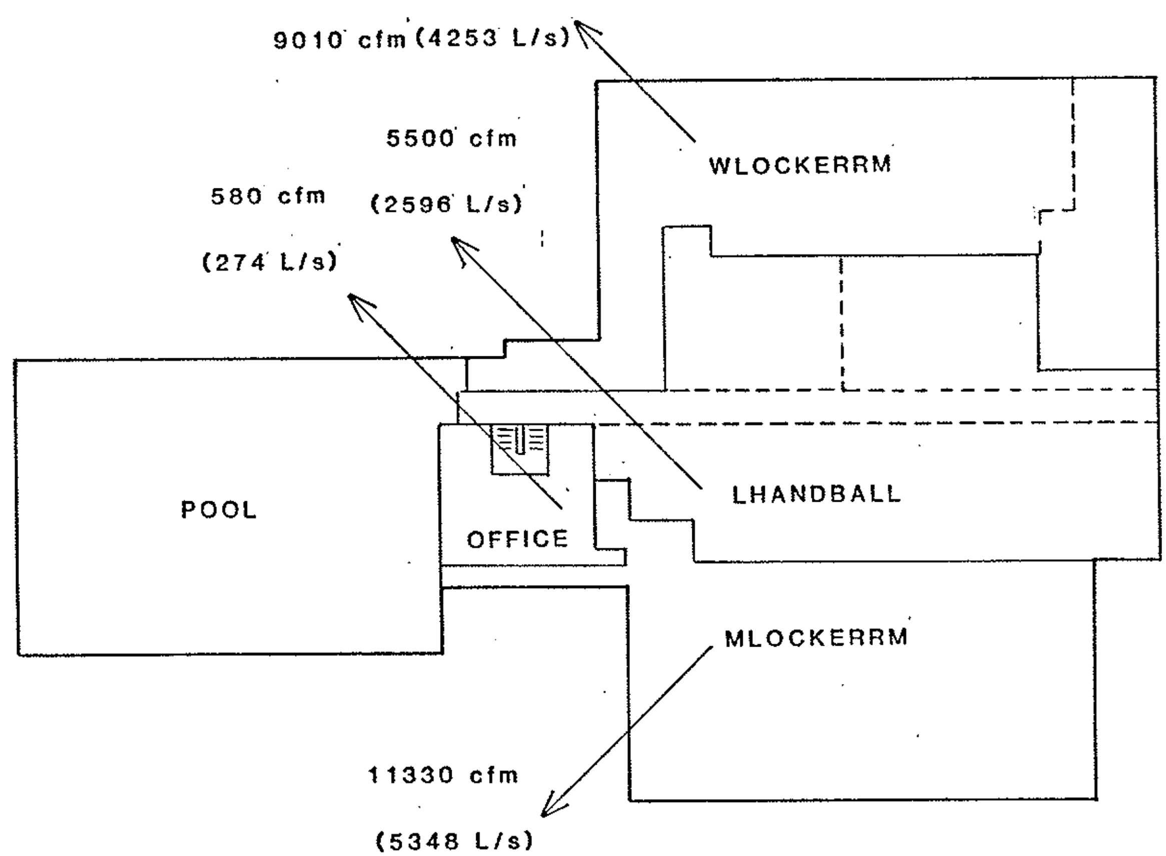



Fig. 2-4: Lower Level Layout of the Rec Center

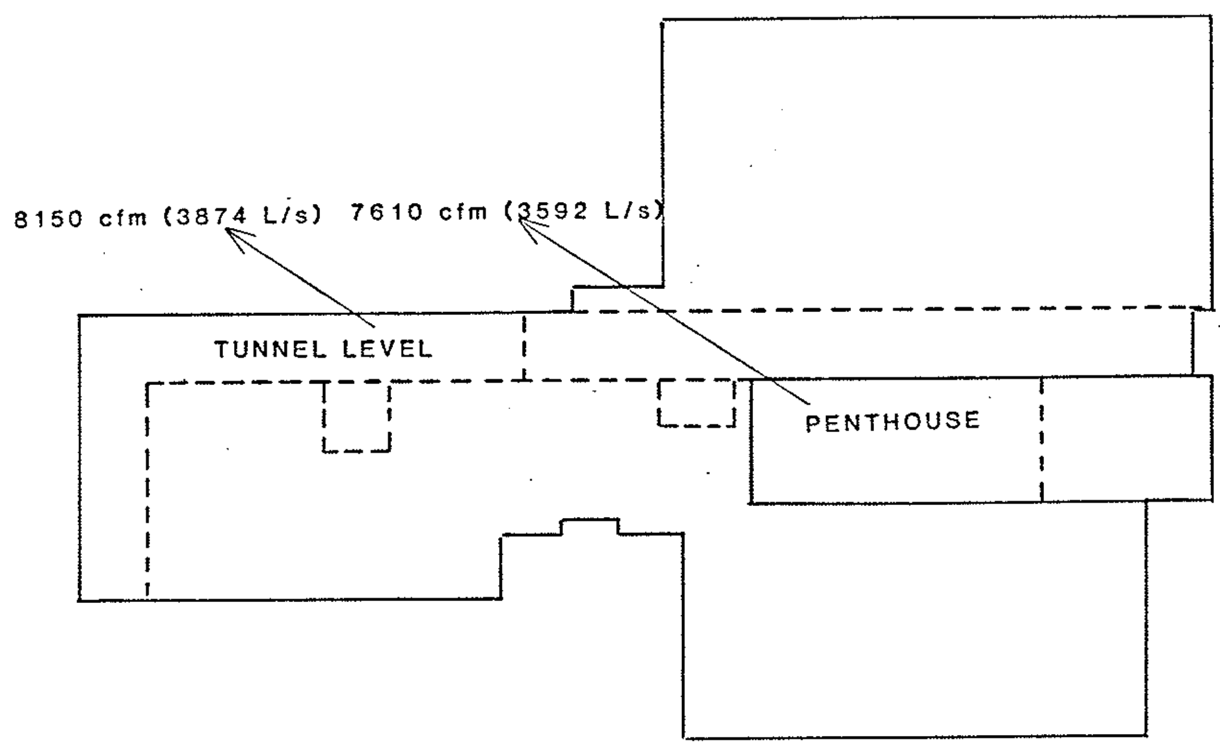



Fig. 2-5 Penthouse and Tunnel Levels of the Rec Center

that are not contained in 'normal' buildings, such as the ice rink and the swimming pool.

2. The Rec Center requires large amounts of ventilation air due to the significant requirements for fresh air (gym, locker room, etc.).

3. The Rec Center was designed in an era when energy conservation received little consideration and therefore, is an inefficient user of energy.

4. Aging energy consuming systems require constant inspection and fine-tuning beyond the capabilities of current maintenance contracts.

During the period from 7/82 to 6/83, the Rec Center utility costs totaled $256,149. These costs are shown in Figure 2-7. The Breakdown of the utility expenditures, as simulated by the DOE-2.1b program is shown in Figure 2-8 (Haberl and Claridge, 1985).

There are several different lighting systems within the Rec Center. Table 2-3 summarizes the dominant lighting type for each area along with the demand in KW. Most lights are on whenever the Rec Center is open. Lights in the pool and ice rink are often shut off during daylight hours when natural lighting is sufficient. The building is open throughout the year, but receives its greatest use during the spring and fall semesters. Average weekly occupancy declines considerably during the summer and during the semester breaks. This is due to both reduced use and reduced hours of

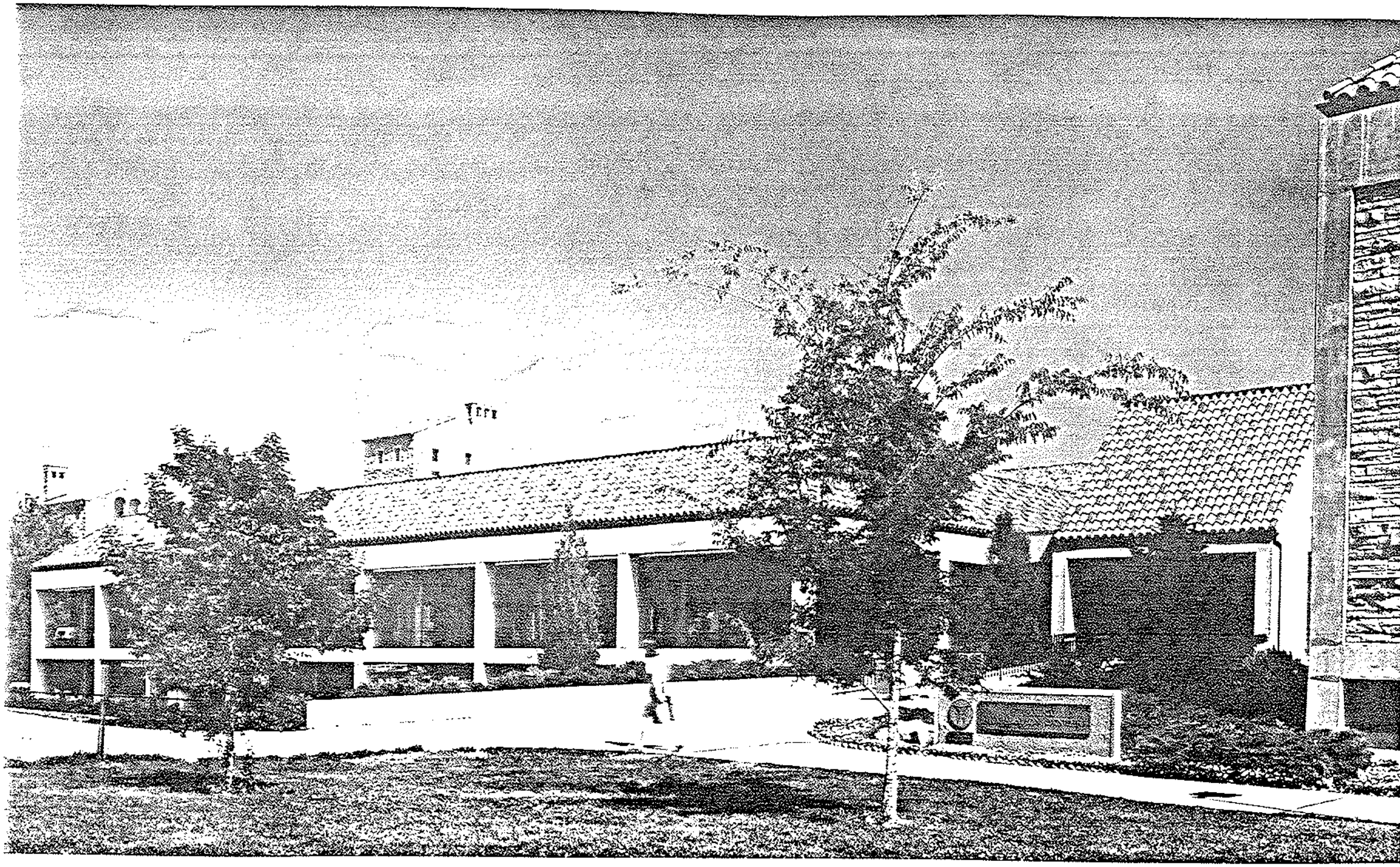


Fig. 2-6: Front Elevation of the Rec Center

operation. Figure 2-9 illustrates the daily occupancy rates during the most recent year.

The Rec Center has extremely high exhaust air volumes Figures 2-3, 2-4 and 2-5 for each zone.

**Table 2-3: Rec Center Lighting Summary**

| AREA | WATTAGE (KW) | LIGHTING TYPE |
|---|---|---|
| Pool | 17.75 | Mercury Vapor/Incand. |
| Gymnasium | 44.35 | Incandescent/HP Sodium |
| Ice Rink | 13.67 | HP Sodium/Incandescent |
| Lobby | 1.65 | Fluorescent/Incandescent |
| Upper Handball | 27.00 | Incandescent |
| Lower Handball | 52.79 | Fluorescent/Incandescent |
| Men's Locker Room | 13.50 | Fluorescent |
| Women's Locker Room | 15.50 | Fluorescent |
| Administrative Offices | 3.70 | Fluorescent |
| Tennis Courts | 96.00 | Quartz |
| Total | 285.91 kw | |

(approximately 97,000 cfm). This design was meant to insure that no stuffiness or odor problem occurs within the space. Exhaust fans are a considerable distance from the intake ductwork, thereby making heat exchange between the two expensive. Exhaust rates are shown in

**2.1.4. Rec Center Energy Conservation History**

Steady increases in the cost of energy to the Rec Center combined with the transfer of the responsibility for the payment of the utility costs from the General Fund to UCSU prompted the UCSU

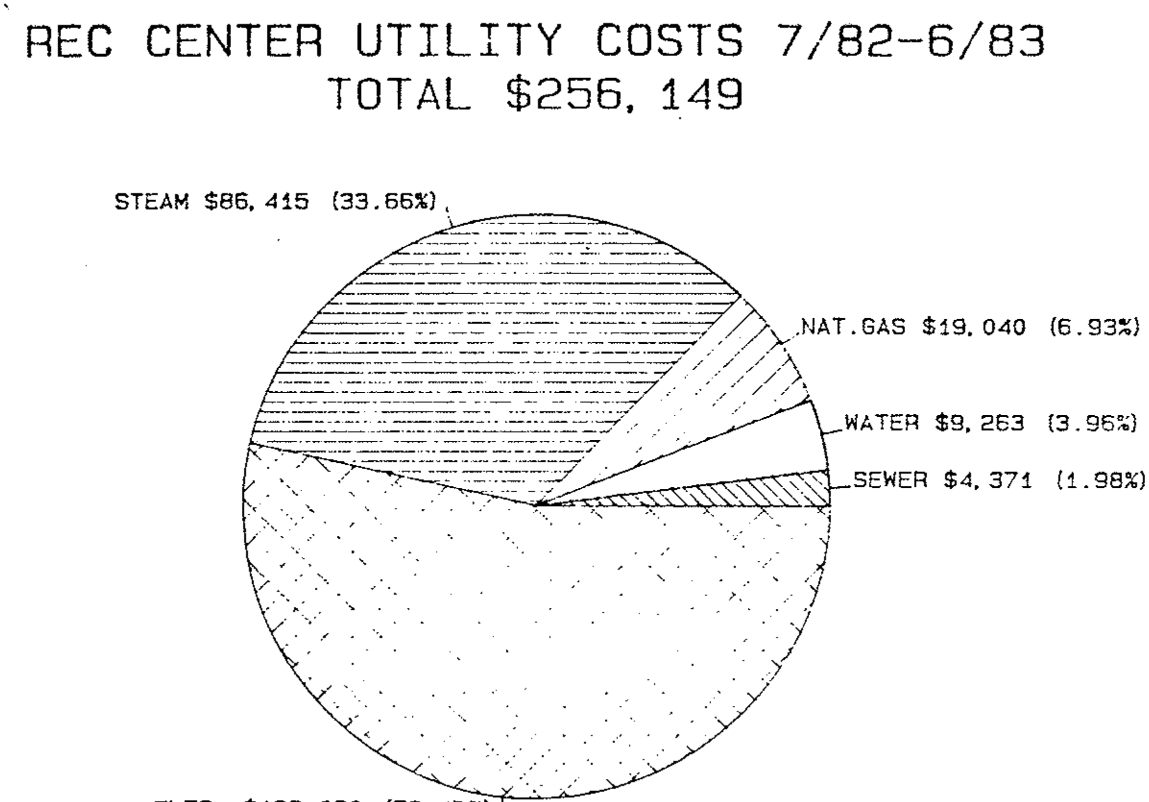



Fig. 2-7: Rec Center Utility Costs 7/82-6/83

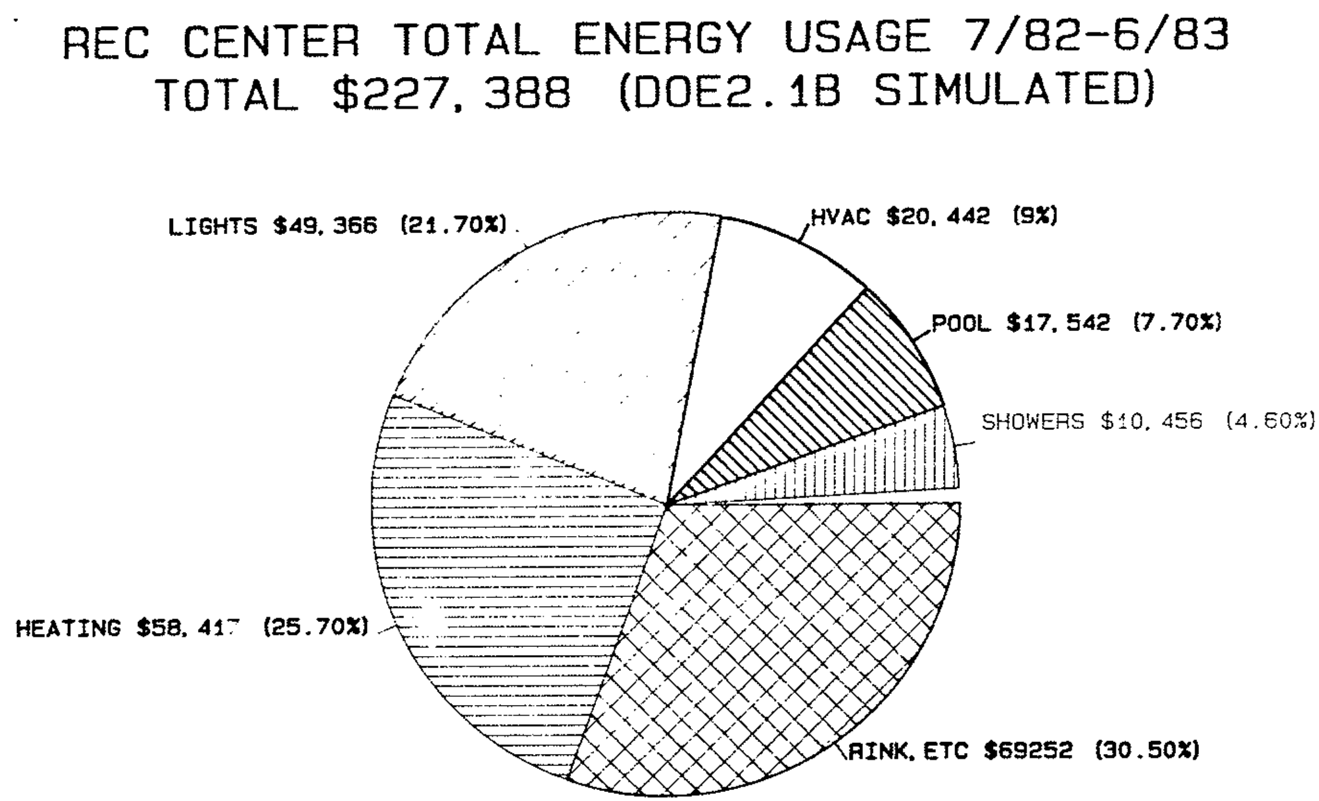



Fig. 2-8: Rec Center Simulated Energy Usage 7/82-6/83

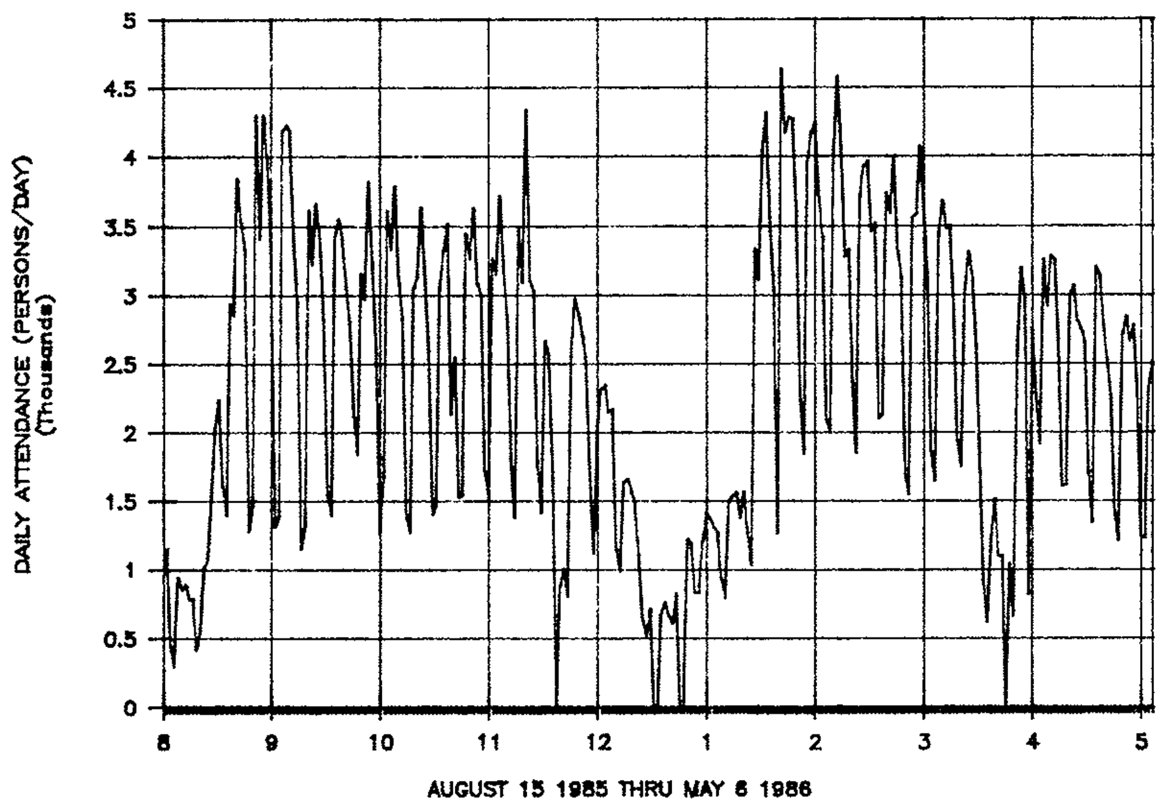



Fig. 2-9: Rec Center Occupancy Measurements

representatives and the Rec Center administrators to finance a series of energy conservation studies performed by the faculty and students of the Building Systems Program in the Civil, Environmental and Architectural Engineering Department. The purpose of these studies was to recommend energy conservation measures that would significantly reduce the financial burden of the annual utility costs (Dow, 1981).

Table 2-4 presents an historical perspective of energy conservation measures implemented at the Rec Center. Cost figures included in this table approximate actual expenditures.

**2.1.5. Energy Conservation Effectiveness**

Historical Rec Center energy consumption for the period July 1980 to February 1986 is shown in Figures 2-10 and 2-11. Figure 3-19 represents monthly utility usage as recorded at the University of Colorado Facilities Management department. Figure 2-10 shows the historical energy costs expressed in terms of March 1986 fuel costs and dollars. All billings are plotted as though they were being charged at today's rates.

In Figures 2-10 and 2-11 the uppermost line (square) represents the total energy bill, inclusive of electric, steam, and natural gas. The remaining symbols in Figure 2-10 and 2-11 represent the following: (plus) represents the electrical consumption; (diamond) represents the steam consumption; (triangle) represents the natural gas consumption, (line) represents the recorded monthly degree days (65F base) for the campus. The x-axis of Figures 2-10 and 2-11 are the month numbers from 7/80 to 2/86. The y-axis is the monthly dollar costs for the different fuel types. Monthly letters

**Table 2-4: Rec Center Energy Conservation History**

| Year | Cost | Item |
|---|---|---|
| 1981 | $6,000 | CEAE Energy Conservation Study, Phase I. |
| 1983 | $300 | Insulation jacket on ice rink chiller. |
| 1983 | $0 | Reschedule cleaning crew. |
| 1983 | $25,000 | Shower heat reclaim from ice rink. |
| 1983 | $60,000 | Reinsulate women's locker room ceiling. |
| 1984 | $1,000 | Delamp overlite areas. |
| 1984 | $500 | Natural gas meter recalibrated. |
| 1984 | $10,000 | Energy Conservation Study, Phase II. |
| 1984 | $500 | Use of Tennis Court lights as security lighting discontinued, replaced w/ H.I.D. security light. |
| 1985 | $2,500 | Separate pool steam meter installed |
| 1985 | $0 | Modify snow melt, outdoor ramp. |
| 1985 | $12,500 | Pool covers. |
| 1985 | $0 | Discontinue incandescent usage in gym. |
| 1985 | $0 | Raise ice rink brine temperature. |
| 1985 | $100 | Pool leak discovered in surge tank. |
| 1985 | $0 | Brine circulation problem corrected. |
| 1985 | $0 | Gutter heat tape usage reduced. |
| 1985 | $250 | Cross-wiring problem with men's locker room corrected. |
| 1985 | $0 | Shower heat reclaim from ice rink fine-tuned by adjusting flow configuration. |
| 1985 | $0 | Shower heat reclaim reactivated from condensate heat exchanger. |
| 1985 | $0 | Flooding of floor in steam metering room resolved by repositioning waste pipe. |
| 1985 | $12,000 | Energy Conservation Study, Phase III. |
| 1986 | $200 | Use cold water for Zamboni ice resurfacing. |
| 1986 | $50,968 | Matching grant from DOE approved ($25,424). |
| Total* | $181,818 | |

* Total includes $25,424 grant from DOE.

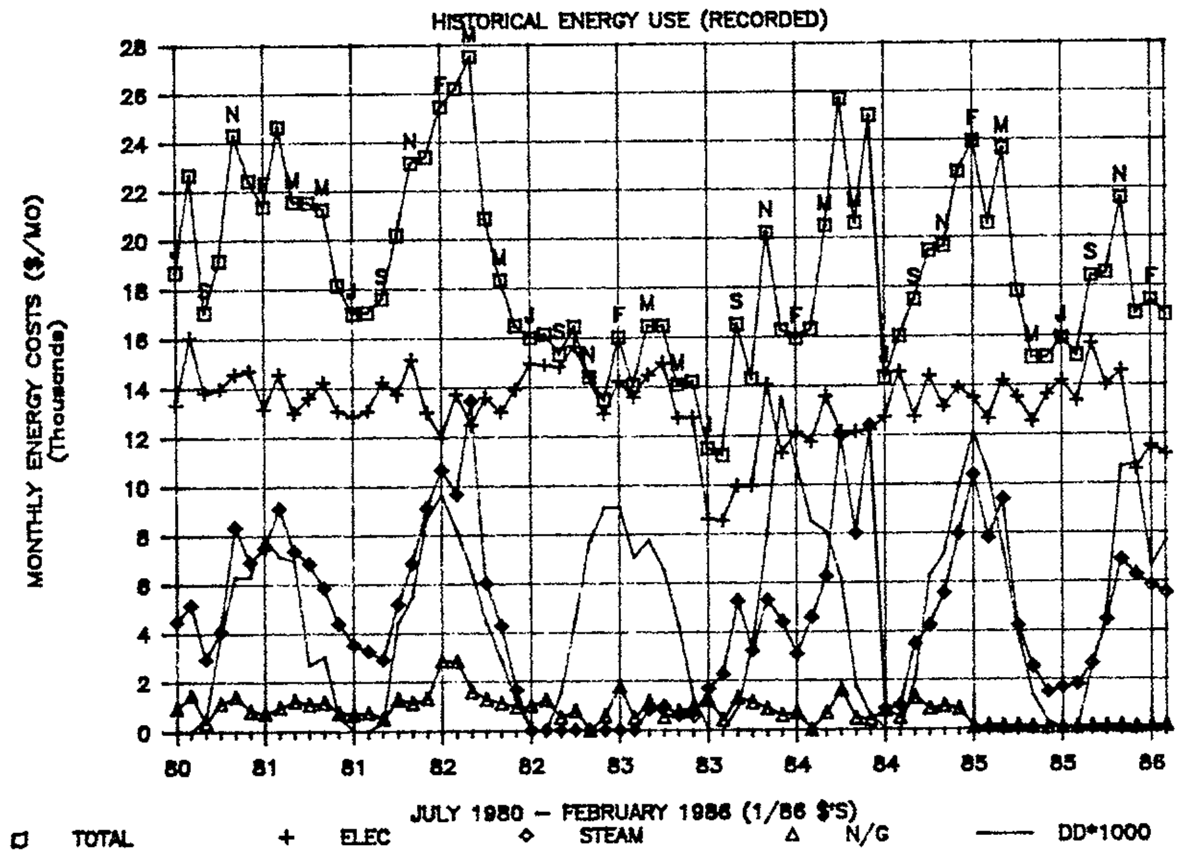



Fig. 2-10: Rec Center Historical Energy Usage (Levelized)

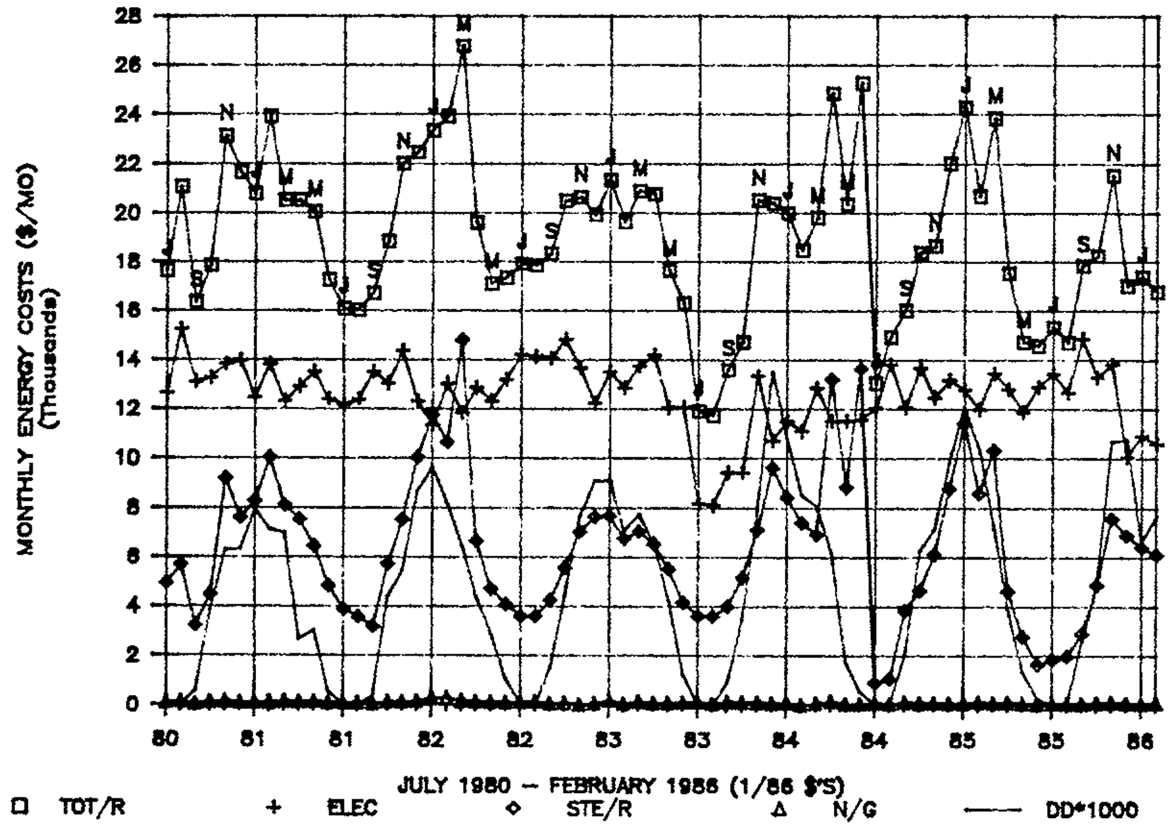



Fig. 2-11: Rec Center Historical Energy Usage (Reconstructed)

(i.e., J, F, M, etc.) are indicated along the top of the total energy consumption.

The steam meter readings for the period 6/82 through 2/83 are meaningless because the steam meter was inoperative and all steam consumed went unmetered. Values reported for the period 3/83 through 2/84 are inconsistent with previous and subsequent readings and were therefore discarded. The reconstructed values for the steam span the entire section from 6/82 through 2/84. These values were reconstructed from heating degree day (65F) regressions using 7/80-5/82 and 3/84-2/86 information.

The natural gas readings for the period 7/80 through 12/84 overstated the actual consumption due to an inaccurate meter constant. Calibration of the meter (Claridge, 1984) and on site field tests of actual consumption showed that the previous meter constant was a factor of ten high. All natural gas readings in Figure 2-11 have been reset to unity (x1). These readings are also shown in Figure 2-10 from the period 1/85 through 2/86. The total (the "plus" symbol) consumption values in Figure 2-11 reflect both the reconstructed steam and the natural gas corrections.

The reconstructed values of Figure 2-11 yield the most insight into potential energy conservation candidates. One of these is the occasional "double-spike" that occurred in the years 1980, 1982 and 1984. The first spike seems to correspond to cold weather but the second spike tends to occur in the spring or early summer. Conversations with the pool manager indicated that the pools were drained and cleaned during periods that corresponded with the second spike. Each time the pools are filled, the 400,000+ gallons of cold city water (40-50F) requires heating to the 78F pool temperature. This use of energy is significant and indicates a consumption of $3,000 to $4,000 in wasted steam costs not to mention the purchased water. A modification suggested by the author was to clean one pool at a time, draining only one of the pools, and transfer the water from one pool to the other upon completion of the cleaning of the first pool. This would save approximately 200,000 gallons of water at a savings of $280 for the water and sewer costs and an estimated $1,500 to $2,000 in steam costs.

Four other significant features can be noted in Figure 2-11. First, the drop in the electrical consumption during the period 7/83 to 10/83 is due to the rebuilding of the ice rink. Second, the summertime steam consumption for 1985 is clearly below that of previous years. This, most likely, represents the savings from the shower heat reclaim system installed since July 1983 on the ice rink refrigerant condensing system.

Third, the steam consumption for the months 11/85 thru 2/86 is below previous consumption figures. This is due in part to a number of factors: weather conditions for January and February were warmer than normal, the fine-tuning of the shower heat reclaim system, use of pool covers and resetting of the shower setpoint temperature from 140F to 110F. Finally, the electric consumption for the months 11/85 to 2/86 is clearly below previous values for electric and steam readings.

The previous discussion introduced considerable doubt into the accuracy of estimating Rec Center energy consumption savings attributable to energy conservation measures. Therefore, discussions concerning energy consumption savings are focused on the period beginning 8/16/85 until the present. The cumulative savings that can be attributed to specific turn-off or fine-tuning measures are listed in Table 2-5. Documentation for these measures is provided by daily inspections at the Rec Center and is detailed in the April 1986 Interim report (Claridge et al. 1986).

**2.1.6. Motivation for the Rec Center BEACON**

The need for a Rec Center BEACON system evolved from concern by the Rec Center administration over the inability to predict energy costs from year to year. This concern was solidified when all non-general fund buildings were given notice that they would be fully responsible for all utilities consumed beginning 7/86. Prior to this, the Rec Center had only made substantial contributions toward their utility bills (Bryant, 1985). Since the budget for a particular year must be assembled in advance, not knowing the upcoming utility expenses posed a problem. Historical records were only of limited assistance in predicting future costs. The original concept for the BEACON system was to develop an internal utility bill forecasting procedure that would permit the Rec Center administration to forecast and compare the monthly consumption figures supplied by Facilities Management.

The first attempts to establish the BEACON system using monthly utility consumption information failed. The discrepancies between predicted and metered consumption were unacceptable even for comparative purposes. Therefore, daily measurements were begun August 15, 1985, and continued until the present. The daily inspection of the building's energy consuming sub-systems, disaggregation of the energy distribution network, interviews with building maintenance personnel, and participation of the Rec Center

**Table 2-5: Recent improvements in energy consuming sub-systems.**

August 29, 1985 - The shower heat-reclaim from the ice rink condensor is fine-tuned, supply temperature reduced 140 to 115F.
August 29, 1985 - The shower heat-reclaim from the steam condensate heat exchanger is reactivated.
September 16, 1985 - 20,000 gallon per day leak pool is fixed, normal consumption returns to 700 to 2000 gallons per day.
November 7, 1985 - A main valve in the ice rink brine circulation loop is found half-closed. Ice setpoint raised from 10 to 17F afterward.
November 30, 1985 - Gutter heat tapes re-scheduled for periods during snow storms only, previously found to be operational 24 hours-per-day, fall through spring.
December 3, 1985 - Cross-wiring of locker-room lights corrected. Lights, previously on 24 hours, now off at night.
December 12, 1985 - 1000 W incandescents in the main gym are shut off at the panel, previously 28 kw of lights in use.
April 5, 1986 - Ice resurfacing machine changed over to cold water for refill of resurfacing water. Previously, 2,000 gallons of 140F water consumed each day.
April 24, 1986 - Steam condensate patch from neighboring buildings disconnected. Rec Center had been paying for condensate not used.

staff finally produced significant operational savings in energy usage.

## 2.2. Artificial Intelligence

The debate concerning Artificial Intelligence, its definition, abilities and application is continually evolving. The following quotes demonstrate the polarity of different views:

> "Artificial Intelligence (AI) is the part of computer science concerned with designing intelligent computer systems, that is, systems that exhibit the characteristics we associate with intelligence in human behavior..."(Barr and Feigenbaum, 1981, p. 3)

> "Artificial intelligence is a widely misused term implying the artificial creation of human style

intelligence, usually in computer systems. In that human intelligence is capable of inductive and deductive reasoning based on prior experience, "artificial intelligence" does not exist, and is unlikely to become a reality in the near future. Most computer artificial intelligence software products are, in fact, expert systems...An expert system provides a method of representing the expertise of one of more individuals as a series of rules which, if rigorously followed, will reach conclusions based on available data."
(Osborne, 1986, p. 1)

This thesis utilizes AI in the form of an expert system.

**2.2.1. Background**

AI has its roots in three parallel fields. First, the mathematical logic development by Frege, Whitehead, Russell and Tarske made possible the algorithms for representing logic. Second, the early work of the cyberneticists who attempted to represent the human nervous system with complex electronic components. Third, the availability of computing machines pioneered by Turing, von Neumann and others (Barr and Feigenbaum, 1981).

Alan Turing, the WWII British scientist and agreed upon father of AI, actually argued that logical operators, the heart of AI, should be the fundamental instructions for the early computers. His influence was drowned out by American scientists who insisted on numerical operators that produced the large calculating machines of the 1950s and 1960s (Harmon and King, 1985).

The earliest products of the AI field are embodied in the programs that were written to solve puzzles, play chess and translate text that appeared soon after the computing machines were available (Barr and Feigenbaum, 1981).

The field of AI can be subdivided into three areas: natural language processing, robotics, and knowledge base systems (Harmon and King, 1985). Each of these fields represent significant directions of AI research and (recently) commercialization. Common to all of the fields are the techniques that AI has developed. The most important of these are: problem solving, representing knowledge and search.

This brief introduction to AI is intended to serve as a primer to the non-AI reader in order to establish a framework for the work that is being presented. Many articles and textbooks do this material far greater justice than is done here. Some comprehensive references on AI are Barr and Feigenbaum (1981;1982), Cohen and Feigenbaum (1982), and Nilsson (1980). An excellent treatment of cognitive psychology, a closely related field, can be found in Anderson (1983). Harmon and King (1985) is an excellent introductory text to expert systems.

Basically, AI consists of advanced programming techniques, a culmination of decades of work. Expert systems, or knowledge based systems, are one field of application for these advanced programming techniques. Expert systems are computer programs that solve problems difficult enough to require human expertise by using a previously assembled knowledge base and inference procedures (Barr and Feigenbaum, 1982). AI, in the form of knowledge base systems, is gaining rapid acceptance in such diverse fields as geology, chemistry, medicine and diesel electric locomotive maintenance (Harmon and King, 1985). The building systems field will see rapid implementation of knowledge based systems in the very near future.

### 2.2.2. Representing Knowledge

> "In AI, a representation of knowledge is a combination of data structures and interpretive procedures that, if used in the right way in a program, will lead to 'knowledgeable' behavior."
> (Barr and Feigenbaum, 1981, p. 144).

Knowledge representation is an attempt to computerize intelligent, human interactions. This requires an understanding of the types of knowledge typically used by humans in day-to-day interactions. These types of knowledge include (Barr and Feigenbaum, 1981): objects, events, performance and meta-knowledge. Objects represent facts about specific things around us. Objects are usually represented in categories, classes and groups of similar descriptions. For example, 'people have legs', or 'fish have fins' are examples of objects and descriptors. Events represent actions in a timed sequence. Events are also used to represent cause-and-effect relationships. An example of an event would be 'the building consumed electricity'.

Performance is the knowledge required to know 'how' to perform a specific action; a skill (Barr and Feigenbaum, 1981). Performance knowledge and object knowledge are similar except that performance knowledge embodies the 'how' (and sometimes the 'what'), object knowledge contains the 'what' only.

Meta-knowledge is "knowledge about what we know" (Barr and Feigenbaum, 1981, p. 144). Meta-knowledge, can also be viewed as self-knowledge, knowledge about what the individual (or system) knows. Meta-knowledge includes global knowledge, knowledge about strengths, feelings, emotions, etc.

In order to assemble a system that will acquire and use knowledge one must know something about the intended use of the assembled knowledge system. The three stages in the life of a knowledge base system include the acquiring of the knowledge, the retrieval of the knowledge and the ability to reason with the facts so attained (Barr and Feigenbaum, 1981). The acquiring of knowledge by an AI system usually involves classification of the knowledge into an existing data base, coding of the knowledge for efficient retrieval, and the ability of the newly acquired information to interact with previously acquired information.

Retrieving the knowledge in an efficient fashion is of equal importance to the acquisition of the knowledge. The linking and grouping together of revelant facts constitutes a significant function of an AI system.

Reasoning is the ability of a system to "deduce and verify a multitude of new facts beyond those it has been told explicitly" (Barr and Feigenbaum, 1981, p. 146). For example, if a system has been told that 'a hand has five fingers' and 'people have two hands', a system that reasons would be able to synthesize the conclusion that a person with two hands should have ten fingers. Different types of reasoning include: formal reasoning, procedural reasoning, reasoning by analogy, generalization and abstraction and meta-level reasoning (Barr and Feigenbaum, 1981).

The representation of different reasoning processes is described by the science of experimental epistemology, "the study of the nature of knowledge" (Barr and Feigenbaum, 1981). The methods that have been developed include: formal logic, procedural representation, semantic nets, production system, frames and special-purpose representation techniques.

Formal logic, having its roots in the mathematical logic developments of the 19th century, has many representational schemes. Formal logic schemes are a form of declarative knowledge representation. Two important developments include propositional calculus and predicate calculus. Propositional calculus represents concepts using a combination of variables and logical connectives in a statement form (Kruppenbacher, 1984). Propositional statements are complete representations, they do not decompose into their components. In this regard propositional calculus is not as useful as other forms of logic representation.

Predicate calculus is another formal logic procedure that provides a more detailed capability of representing logic. Predicate calculus can be further divided into its components. This allows for logical reasoning, and proof-of-reasoning using the components of the statement themselves (Kruppenbacher, 1984, ref. Glorioso and Colon Osorio, 1980). Predicates are statements about objects or individuals either by themselves or in relation to others (Barr and Feigenbaum, 1981). For example, the statement 'the queen of hearts is red' contains two predicates; 'the queen of hearts' is the first and 'is red' is the second. The complete statement is therefore two predicates. In propositional calculus, this would have been only one propositional statement that would not have lent itself to decomposition (Barr and Feigenbaum, 1981).

Procedural representation schemes consist of a number of small programs that know how to do a specific thing. These small procedures usually apply to specific "well-defined situations" (Barr and Feigenbaum, 1981). Procedural representation is used in all AI systems to direct the operation of the how the logic in the system is represented. In this repect, procedural representational schemes are fundamendal to all AI systems (Barr and Feigenbaum, 1981).

Semantic nets, developed by Quillian, are psychological models of human memory (Barr and Feigenbaum, 1981). Like formal logic schemes, semantic networks are also a declarative scheme. Semantic nets contain objects (nodes) and interconnections between these objects (links). The nodes can be physical objects, or descriptions (descriptors) of physical objects. The links are the relations between the objects and the descriptors. Links can also be definitional or show membership to a larger class of objects (Harmon and King, 1985).

Production systems, developed by Newell and Simon, are rules that have condition-action pairs (Barr and Feigenbaum, 1981). Production systems are fundamental to the development of expert systems (ie., IF 'condition' THEN 'action').

Frames are a recent knowledge representation development that incorporate both declarative and procedural schemes. A frame, representing a certain situation, constructs a description of the situation using information previously assembled in the data base. Frames contain 'slots' which can link frames to other frames, contain descriptive information and/or procedures (Barr and Feigenbaum, 1981) that help to represent the situation being considered.

Special-purpose representational techniques, as one would expect, include schemes that are not easily classified by the above or contain multiple characteristics from many schemes. Some special-purpose techniques include direct representation techniques used in vision systems, speech understanding programs and natural language programs (Barr and Feigenbaum, 1981).

**2.2.3. Search**

One thing that all AI systems share in common is that they have been created to solve difficult problems and, ultimately, they do so with some form of data base. This section is a brief review of the efficient methods that have been developed to explore a data base while processing information towards a predefined goal. This process is known succinctly as "search".

Search is the process of exploring a network or graph, contained within a data base, while in route to a goal (Barr and Feigenbaum, 1981). Search systems contain a data base, operators and a strategy for controlling the process (Barr and Feigenbaum, 1981).

Search is fundamental to all AI systems. AI systems commonly contain sizable data bases. These data bases can differ from those used in numerical analysis because the information contained tends to be lists of expressions, links between lists, sentences, etc.; all of which require significant space to store, and process. Therefore, researchers in the AI field have developed highly efficient methods that explore these search spaces and reduce the time required to do so.

Search systems require an understanding of two basic ideas the search space, and the control strategy. The search space is the data base that contains the network or diagram that is being explored. A search space, represented as a graph, contains the information being sought within the nodes of the graph and the operators connecting the nodes (Barr and Feigenbaum, 1981). Some examples of graph structures include directed networks (or graphs), tree structures, inverted tree structures, (Barr and Feigenbaum, 1981) and tangled tree structures (Harmon and King, 1985).

Search systems also require strategies for moving through the networks contained within the data base. The strategies employed are control strategies and search strategies. There are many control strategies. Two commonly used strategies are forward reasoning and backward reasoning. Forward reasoning is a bottom-up, data driven procedure that searches through the data towards a goal. Backward reasoning is a top-down, goal directed procedure that starts from the goal and moves through the data (Barr and Feigenbaum, 1981). Both control strategies contain various search strategies to speed-up the search process.

Search strategies are the methods used to move through the network once the control strategy has been chosen. Many search strategies exist. Among the most common are: exhaustive search strategies - including breadth first and depth-first; limited depth-first; heuristic strategies - including ordered depth-first, $A^*$, parallel search, AND/OR and game tree search. A complete review of control strategies and search strategies is beyond the scope of this introductory section. Some comprehensive references on search strategies are Barr and Feigenbaum (1981) and Nilsson (1980).

### 2.2.4. Artificial Intelligence Development Areas

Current AI research has evolved into the three fields of natural language developments, robotics, and expert systems (Harmon and King, 1985). Natural language developments include systems that attempt to read, speak and understand languages like English, French, Chinese, etc. The long term objective of such a field has been summarized by Barr and Feigenbaum as follows: (1981, p. 225)

> "If computers could understand what people mean when people type (or speak) English sentences, the systems would be easier to use and would fit more naturally into people's lives."

Programs, now available, are capable of performing such functions with limited sets of words. The fluent interpretation of language, typical of everyday use, still remains a challenge. Other accomplishments include the cross-interpretation of statements from one language to another, English language "front-ends" to larger mainframe processors, voice recognition and speech (again, using limited word sets).

Robotics, including vision, is the second major field of AI development. The field of robotics, in general, involves the tasks of duplicating the physical actions of people, and more. Advancements in robotics include efficient systems for modelling the "states of the world", important to vision systems (Nilsson, 1980, p. 5). Other advancements of importance include monitoring systems, tactile sensory perception and control mechanisms.

Expert systems, represent the third field of current AI research. Expert systems, or knowledge based systems, are computer programs "that use symbolic knowledge to simulate the behavior of human experts" (Harmon and King, 1985, p. 5). Expert systems, in many ways, appear to be one of the "fruits" of AI. They are focused systems that solve real-world problems using techniques developed over two decades of AI research. Expert system research includes: expert system development toolkits, large problem solvers, narrow problem solvers, intelligent workstations, intelligent instruments, and intelligent tutoring systems (Harmon and King, 1985).

**2.2.5. Expert Systems**

Expert systems are computer programs that solve difficult problems at the same level of expertise as the best experts in a particular field of study (Harmon and King, 1985, ref. Feigenbaum). Most expert systems have a preassembled knowledge base, and a processor that controls the interaction with the knowledge base.

The knowledge base is assembled from interviews with experts in the field of application using facts and heuristics that concern the problem at hand.

> "Facts constitute a body of information that is widely shared, publically available...heuristics are mostly private, little-discussed rules of judgement (...good guessing)" (Harmon and King, 1985, ref. Feigenbaum).

Expert system development work is proceeding at a rapid pace in many fields. Some references on expert systems are (Hayes-Roth, et al., 1983), (Buchanan and Shortliff, 1984) and an excellent introductory text by Harmon and King (1985). The remaining expert system material in this work is focused on expert system applications involving buildings.

### 2.2.6. Intelligent Buildings

"Intelligent buildings" describes buildings that possess, to some degree, integrated communication, control and management systems that assist with the functions occuring within the building. The systems encompassed within an intelligent building include: voice communication, data communication, radio, television, satellite, environmental controls, fire and security systems.

The historical trend for the development of these disparate systems has relied on independent professions. Standardization practices, involving shared systems, have been slow to develop. Recent advances in microcomputer technologies together with de-regulations in the telecommunications industry have forced many independent manufacturers to consider standardizing these functions (Gouin, 1985).

Integrated, shared networks, now being proposed, will offer building occupants diverse services from "dial-up" grocery shopping during a lunch break to remote multi-sensing security systems. The recent trend is to replace (or abandon) existing systems with a single network throughout the building that will offer integrated services, literally, at the same data port. The systems being proposed offer significant savings (25 percent of an average worker's day) and will carry a significant price tag (Golman (1983), cited in Gouin, 1985, p. 26).

The standardization and need for integrated systems is still under discussion. The terminology for such systems has still not been agreed upon. Systems that combine two or more "intelligent" functions have names ranging from "telecommunications-enhanced real estate" to "future-proof buildings" (Ingraham, 1986). Two important aspects pointed out by Ingraham (1986) are that most manufacturers agree that "managing wire" in a building is critical to the success of intelligent systems, and that compatibility of different manufacturer's systems is still, for the most part, needed.

Intelligent buildings will require significant capitalization, both during the initial installation and during each successive remodel that occurs within a building. Costs for various intelligent environmental control systems range from $10,000 per panel (1 to 2 panels per building) to $20,000 per panel (Ingraham, 1986). Completely integrated systems, including telephone, data communications, fire, and security start at these prices and go up. Clearly, present day, intelligent buildings might be more aptly named "intelligent (affluent) buildings".

**2.3. Knowledge Based Systems and Buildings**

Expert systems, also referred to as knowledge based systems, have recently entered the building industry. The potential for the application of Knowledge Based Systems (KBS) to the building industry is currently being debated. The following discussion is intended to review the state-of-the-art in a rapidly changing field.

One outline of application areas of Knowledge Based Systems and buildings has been proposed by Wright (1985). He viewed the application in the context of the "whole building process" (Wright, 1985, p. 170). This whole building process begins with the owner's need for the building and continues throughout the life of the building until demolition.

Wright (1985) points out that engineering standards are the "paper equivalents" of expert systems. Such standards are the agreed upon "collective wisdom" concerning a particular design standard. Wright's work at the National Bureau of Standards involves the "hi-rise" expert system for the preliminary structural design of high rise buildings (Maher, 1985, cited in Wright, 1985), and the Standards Analysis, Synthesis and Expression work (Fenves, in preparation, cited in Wright, 1985).

Schmitt (1985) and others at Carnegie-Mellon are also investigating expert systems and the architectural design process. Schmitt also categorizes the knowledge base applications as being applied to the planning/design process or the building performance and management process. KBEDES1 and KBEDES2 are some of the first prototype system that offer knowledge base capabilities. KBEDES1 has an expert front-end that recommends a given form for the chosen location and orientation. KBEDES1 also incorporates a graphical post-processor that displays the choice of the expert system front-end. The energy simulation for KBEDES1 is performed by EEDO, a version of Lawrence Berkeley Lab's CIRA program.

KBEDES2, inspired by KBEDES1, is a prototype tool that contains both a generative expert system and a diagnostic expert system. The generative expert system suggest an appropriate design from the user's design criteria with a primary knowledge base extracted from the "Small Office Design Handbook" (Burt, et al., 1985). The diagnostic expert system contains additional, detailed rules about small office buildings, for which the tool has been tested.

KBEDES2 is significant because the authors chose to use the Graphical Kernal System (GKS), (Enderle, 1984) and utilizes commercially available data base handling software (Lotus, 1985; Ashton-Tate, 1984).

Greenberg (1984), a pioneer in computer graphics development at Cornell, has also investigated advanced architectural design methods. The design systems developed at Cornell are different than other commercially available systems because they are formulated around the methods that architects use to design buildings. The major difference is that the Cornell systems allow for the rapid sketch, 3-D extension, evaluation and resketch. Most commercially available systems are drafting oriented and do not exactly allow for fast sketch, analysis and resketch capabilities.

Greenberg's systems offer other special characteristics, including a walk through the space being designed. Wall surfaces can be "textured", and digitized photos of actual surroundings can be mapped into a window location.

The impact of the Cornell work is significant. Greenberg fully expects architects to be designing with visual representations of a space in a few years. Clearly, the algorithms for such enormous computational efforts are available today. Hardware will be one of the few remaining limitations, since certain of the Cornell pictures can take hours to generate on very expensive equipment.

Other efforts (Deringer, 1986; Leah, 1986; Reed and Persily, 1986; Lawrie, 1986; Selkowitz, 1986) are considering expert system analysis for topics as diverse as building air infiltration to the construction of concrete buildings. Leah (1986) has developed an on-line HVAC diagnostic system for analyzing problems in air handling units. Deringer (1986) and Selkowitz (1986) are involved with "whole building" design workstations, similar to the combined work of Greenberg (1984) and Schmitt (1986). Reed and Persily (1986) are working with expert system analysis of building air infiltration. Reed, and others at the National Bureau of Standards are also involved with concrete design code analysis, a continuation of the work performed by Noland (1976). Noland's poineering work involved a predecessor to expert systems, the application of decision tables to concrete design.

Clearly, expert system work in the building industry is a rapidly evolving field. Experimental work is being carried out at a number of institutions involving the prototyping and development work. Commercially available products should appear within a few years.

### 2.3.1. The Building Process

The building process, set forth by Wright (1985), is reviewed here as a context for the expert system work being presented.

Wright's building process divides the life of a building into eight distinct stages:

> "1. Programming: formulating requirements and criteria for the building such as the amount of space required for each activity an the extremes of weather to be designed for.
>
> 2. Conceptual Design: selecting the schemes fo each subsystem such as the shape of the building and types of HVAC equipment. Conceptual design identifies the design variables.
>
> 3. Preliminary Design: selecting initial values for each design variable to provide bases for detailed simulation and detailed design

4. Detailed Design: selecting final values for each design variable and preparing plans and specifications for procurement and construction.

5. Acceptance: review and acceptance of design by cognizant regulatory authorities; testing and approving compliance of materials, components and installation with plans and specifications.

6. Construction: (construction), preparation, materials storage, handling and placement, fabricating and finishing.

7. Operation: operating and controlling building systems under normal (ordinary functional and evironmental changes) and extraordinary (e.g., a fire emergency) conditions.

8. Diagnosis and Retrofit: assessing and remedying causes of operational malfunctions."

Each of these eight stages represent significant opportunity for developing knowledge based systems. The expert system, developed in this thesis, spans the operation, diagnosis and retrofit divisions. Previous expert system work in these areas is sparse and concentrates on specific applications. A few examples: Developments at Johnson Controls (Leah, 1986a), and the mentor system developed at Honeywell (Bulman, 1986) have concentrated on expert system diagnosis of specific components. One exceptional work by Stokes and Miller (1986) uses skeletal tree pattern recognition and various statistical techniques to characterize residential load shapes from disaggregated hourly load data. This innovative work by Stokes and Miller (1986a) represents significant progress in energy load shape recognition. Although the work in progress by Stokes (1986b) now involves the automated recognition of such patterns using an expert system no attempt has been made to alter the usage habits of the occupants to save energy. The sole purpose of the system designed by Stokes appears to be for predicting electrical demand for electrical utility suppliers. Aside from the above works, very few systems have been developed an action plan that will identify and alter inefficient building operation.

**2.3.2. KBS and Building Operation**

Effective building operation and maintenance procedures have been well defined and documented. Some of the better procedures include: the maintenance procedures reported by American Institute of Plant Engineers (1985), procedures used by the General Services Administration (1981), and procedures documented by the United States Department of Agriculture (1981).

Well defined operational and maintenance procedures must be orderly in nature to provide servicing and replacement of equipment while minimizing the inconvenience to the facility user. Specifically, the operation and maintenance of a building (in particular, an institutional building) should include the following:

1. Preprogrammed maintenance schedules: Each major piece of equipment should be serviced periodically - preventative maintenance.

2. Corrective maintenance schedules: When a system fails a standard procedure for producing a work order, responding to the work order, part selection, and tracking should be implemented in such a fashion as to reduce redundant jobs and increase service efficiency.

3. Safety maintenance: All systems should protect the user from dangerous conditions. Systems that have inherently dangerous parts or areas should have controled access.

4. Emergency maintenance: A procedure for rapid response in the case of emergency; including, fire, security, freeze protection,

etc.

5. Maintenance training programs: Effective maintenance requires training and retraining of personnel. Increasingly complex systems (especially those that utilize microprocessors) require high-level training of personnel. Appropriate training programs also provide for institutional memory, the combined shared knowledge of expert maintenance personnel that remains with the institution in the form of log books, maintenance procedures, notes, etc.

Knowledge base systems (KBS) can also lend assistance to troubleshooting and training as well as institutional memory. KBS can perform a host of operations; however, the advantage that they offer is the speed of assembly of the computer software, ease of update and the ability to computerize facts as well as heuristics (rules-of-thumb). The CATS expert system, developed by General Electric for diesel-electric locomotives, embodies all of the characteristics of an effective expert system that could be used for building operation and maintenance (Dietz, 1986). The important characteristics of such a system would be:

1. Diagnostic capabilites: The system would diagnose faults directly from sensor information (when available) or track and compare daily energy costs from log book readings. The system would suggest recommended repair procedures for a problem that is identified.

2. On-line training capabilites: The system can fetch video taped sessions of the recommended repair procedure.

3. User friendly: The system would require no special programming skills of the user. Screens would be easy to use, with

on-line help information much like the commercially available spreadsheet programs (Lotus, 1985).

4. Easy to install: The system would be easy to install in a building, being flexible enough to accomodate complex buildings yet simple to apply to any building.

5. Easy to maintain: Once in place the system would require a minimum amount of time to operate, thereby reducing the time commitment of the user.

6. Easy to update: The system would be easy to update and modify by the building maintenance personnel. No special computer language training would be required.

Clearly, such a system would provide a valuable service for building administrators and for maintenance personnel. Administrators would be able to plan future energy consumption budgets as well as project maintenance schedules and replacement costs. Building maintenance personnel could concentrate their work on appliances that require tuning, as indicated by the knowledge base system, and perform the necessary preventative maintenance, listed out on a daily schedule.

Institutional memory is an important ingredient of the knowledge base. The experience with the pilot building indicates that the methodical analysis of an institution's programs tends to improve the performance of the programs being studied. For example, procedures employed to enhance institutional memory at the Jet Propulsion Laboratory (JPL) have been very effective in passing knowledge from one generation of designers to the next (Gaertner, et al., 1986). The introduction of computer aided design (CAD) at JPL introduced many designers and engineers who were unfamiliar with the practices and standards that had been established at JPL over some thirty years. The methods used, which are equally applicable to building operation and maintenance, rely on formal training sessions, mentor/protege learning and "old pro" sessions. "Old pro" sessions are where specialists are called back after retirement to teach new employees special skills that the "old pro" has (Gaertner, et al., 1986, p. 42).

The Building Energy Analysis Consultant (BEACON) system is an attempt to show proof-of-concept for such a system. As a proof-of-concept system, it does not necessarily contain all of the capabilities described above, but is intended to be able to grow into a comprehensive system with the features described. This system is composed of two major compononents, the statistical normalizers and the computerized consultant. The remainder of this thesis describes the methodology used to assemble the BEACON, presents a pilot application to the University of Colorado Recreation Center, and discusses the results.

# CHAPTER 3

## A BUILDING ENERGY ANALYSIS CONSULTANT (BEACON)

This chapter develops the Building Energy Analysis CONsultant (BEACON) system. The focus of this chapter is to: trace what the intended purpose of the system is, describe what kind of system has been developed, review the statistics chosen (a complete explanation is included in the appendix), develop the consumption predictors, develop the computerized consultant (the expert system portion of the system) and explain the respective purposed of each of the modules (the consumption predictors and the computerized consultant). This chapter is also intended to be a general introduction to the system. Specific applications are contained in Chapter 4.

### 3.1. Diagnostic Expert Systems for Buildings

Diagnostic expert systems for buildings must be constructed with the final application as a goal. This goal needs to be defined in terms of whether the system will be applicable to a class of buildings, a site independent system; or whether the system will be applicable to a specific building, a site specific system (Brothers, 1986).

### 3.1.1. Site Independent Expert Systems

Site independent expert systems would be systems that provide analysis of generic components commonly found in a class of buildings. These systems would be of value to the design and diagnostic professionals who require rapid analysis of systems that can be described in a generic sense. Some applications of site independent expert systems include: air-distribution diagnostic systems, comfort diagnostics, boiler diagnostics, chiller diagnostics, visual environment diagnostics, etc.

### 3.1.2. Site Specific Expert Systems

Site specific expert systems would be systems that are designed to analyze the energy consumption, building operation and maintenance for a specific building or complex. Some applications of site specific expert systems include: system that would analyze a standard building energy audit form (COEC, 1983), compare energy usage categories with standards typical of the building type under consideration and make recommendations concerning which systems in the building have above normal consumption; a system that would receive information from the previous system and make recommendations as to possible remedies including information about the building owner's budget, the intended building function, etc.; a system that predicts energy consumption from daily log book readings, identifies abnormal consumption and then makes recommendations concerning which energy consuming systems might be causing the abnormal consumption.

### 3.2. A Site Specific BEACON System for the Rec Center.

The BEACON system developed for the Rec Center is a site specific system. Certain portions of the system might be applicable to other buildings but the system itself is designed to be applicable to the Rec Center only.

#### 3.2.1. Criteria for Candidate Buildings

Based on the experience at the Rec Center, candidate buildings can be roughly defined as those buildings that have annual utility bills that are substantial enough to justify the expense of a BEACON system. The approxomate cost of the BEACON system developed for the Rec Center required about one man-year plus a desktop microcomputer and software.

Our experience at the Rec Center has shown the BEACON system capable of saving 15 percent of energy costs. This would mean that candidate buildings that are similar to the Rec Center (or a group of buildings) would need an annual energy bill in excess of $125,000 in order to achieve a 1 year payback. However, certain refinements to the method will, undoubtedly, reduce the cost of the application.

Other important characteristics of candidate buildings that make them particularly attractive to a BEACON type analysis are:

1. Complex energy consuming subsystems.
2. Seemingly unpredictable year-to-year energy bills.
3. No installed computerized control systems.
4. Excessive maintenance expenditures.
5. Excessive turn over of maintenance personnel.
6. Many influencing parameters.
7. Interrelatedness of energy consuming subsystems.

8. Existing administrative microcomputer and software.
9. Sub-metering of utilities.

Fundamentally, most buildings can benefit from a BEACON system. However, since most administrators are interested in cost effective measures there will be buildings in which the cost savings would not justify a BEACON system. Buildings that are not good candidates for a BEACON type analysis would have some of the following characteristics:

1. Overly aggregated energy consuming sub-systems.
2. Less than $20,000 per year utility bills.
3. Well defined, low-cost maintenance program.
4. Tenant occupied and controlled buildings.
5. Repeatable year-to-year energy bills.

In summary, a BEACON system is most effective in buildings with substantial utility bills that have good maintenance programs in place, yet, still seem to be out-of-control. In contrast, buildings with low to moderate utility bills that are well maintained with very predictable year-to-year utility bills are less likely to have hidden operational cost savings of the type that a BEACON system can uncover.

### 3.2.2. The Role for Statistics

Statistics can play an important role in understanding what is normal consumption and what is abnormal. The primary role for statistics in an automated energy analysis system is to act as a preprocessor for the knowledge base portion of the analysis. Measured consumption needs to be compared to statistically normal consumption to indicate those days when consumption is above or below the norm. Therefore, at the heart of a BEACON system is a simple mathematical model that indicates statistically normal consumption. Typically, statistical analysis maintains the ability to indicate chance events that are caused by unknown influences (Kreysig, 1970). These chance events are important to a BEACON analysis because they are the focus of the information that is passed from the statistical analysis to the knowledge base analysis. Coupling statistical inference with knowledge base inference and daily observations is the computational mechanism the BEACON system uses to unravel complete energy consuming sub-systems.

Although statistical inference is defined as the ability to infer characteristics upon a larger population from a sample population, the context is extended here in an attempt to pinpoint how a decision is made concerning abnormal energy consuming behavior (Kreysig, 1970). Therefore, statistical inference will be extended to include conclusions that can be inferred from statistical calculations performed on daily measurements that use, previous normal consumptions records.

### 3.2.3. The Role for the Knowledge Base

In the same regard, knowledge base inferences are then conclusions made by searching through a knowledge base representative of operational characteristics of an energy consuming sub-system. The information contained in the knowledge base is composed of a compact list of IF-THEN statements assembled by interviewing maintenance personnel, inspecting as-built drawings, and from daily observations.

The role for the knowledge base, expert system analysis now becomes easier to define. If the expert system were forced to perform all the normal knowledge base search operations and the statistical calculations needed at each decision point, the analysis would become painfully slow. Use of a simple statistical preprocessor streamlines the work load for the expert system. The expert system need only scan an array of precalculated values to determine normal, above normal, or below normal consumption.

The primary role for the BEACON Computerized CONsultant (CCON) portion of the analysis is then to scan a precalculated array of consumption indices and draw conclusions about the above, below, or normal consumption values using facts and heuristics imbedded in the knowledge base.

In view of this the BEACON system was constructed around two primary modules; the Predictors for Consumption (PCON) module, and the Computerized CONsultant (CCON) module. The PCON's role is to digest the daily readings, compare these readings with normal consumption readings and pass on a set of indices to the CCON. The CCON merges the PCON indices with the CCON knowledge base (KB) and generates a list of conclusions concerning the daily energy consumption. If abnormal consumption is noted, the CCON asks a number of questions before reaching conclusions about the probable cause. This list of conclusion and/or graphs of the daily energy consumption are the final product of the BEACON system.

### 3.3. Choice of a Statistical Method

#### 3.3.1. General

With the advent of desktop microcomputers, statistical analysis, previously available only on large mainframes, has become readily available (Norusis, 1983, 1985), (Lotus, 1985) and (SPSS, 1986). The criteria used to choose a statistical analysis method to demonstrate proof-of-concept included: the speed of the analysis, whether the analysis package could easily read the existing data base (Lotus, 1985), graphic capabilities, ease of file passing to the available expert system toolkit (Teknowledge, 1985), and finally, simplicity. In order to show proof-of-concept, multiple linearized regression was chosen (Lotus, 1985). A complete discussion of the regression methods is included in the appendix.

#### 3.3.2. Choosing a Time Frame

The choice of a time frame for the analysis of the energy consumption of a building depends, in part, on the accuracy required, level of effort, and historical records. Typical time frames for energy analysis are annual, monthly, weekly, daily and hourly. Annual and monthly energy consumptions can usually be obtained from local utility companies. Weekly, daily and hourly energy consumption will usually need to be recorded on-site at a particular facility. Weekly and daily consumption figures can easily be read on-site by building personnel incurring a moderate cost and manpower commitment. Hourly and/or instantaneous consumption measurements usually will require analogue or digital data acquisition systems.

**Table 3-1: Comparative Data Requirements**

| Item | variables | cycles/yr | variables/yr | data(16b/v) |
|---|---|---|---|---|
| Annual | 5 + 5 = 10 | 1 | 10+1 | 176 |
| Monthly | 10 | 12 | 120+12 | 2,112 |
| Weekly | 10 | 52 | 520+52 | 9,152 |
| Daily | 10 | 365 | 3,650+365 | 64,240 |
| Hourly | 10 | 8,760 | 87,600+8,760 | 1,541,760 |

As an illustration, consider the tracking of 5 consumption indices and 5 independent parameters. The data requirements for such an example are shown in Table 3-1. The storage capacity required to store the 5 consumption variables and the 5 independent parameters in a data file (using 16 bytes per variable and one variable as a separator) increases dramatically from annual to hourly. Experience at the Rec Center indicates that daily measurements take about one hour per day (Claridge et al., 1986). In consideration of the above daily information is the smallest time step that can be considered before the costs of maintaining the data exceeds the cost of a fully automated system (assumed total cost, apx.$40,000).

As another example, the electrical consumption for the Rec Center is shown in Figures 3-1 through 3-4 for monthly, daily and hourly consumptions respectively. The significance of certain events within these figures is discussed in the appendix. When considering an appropriate time step for regression analysis, hourly information yields the most accurate information followed in

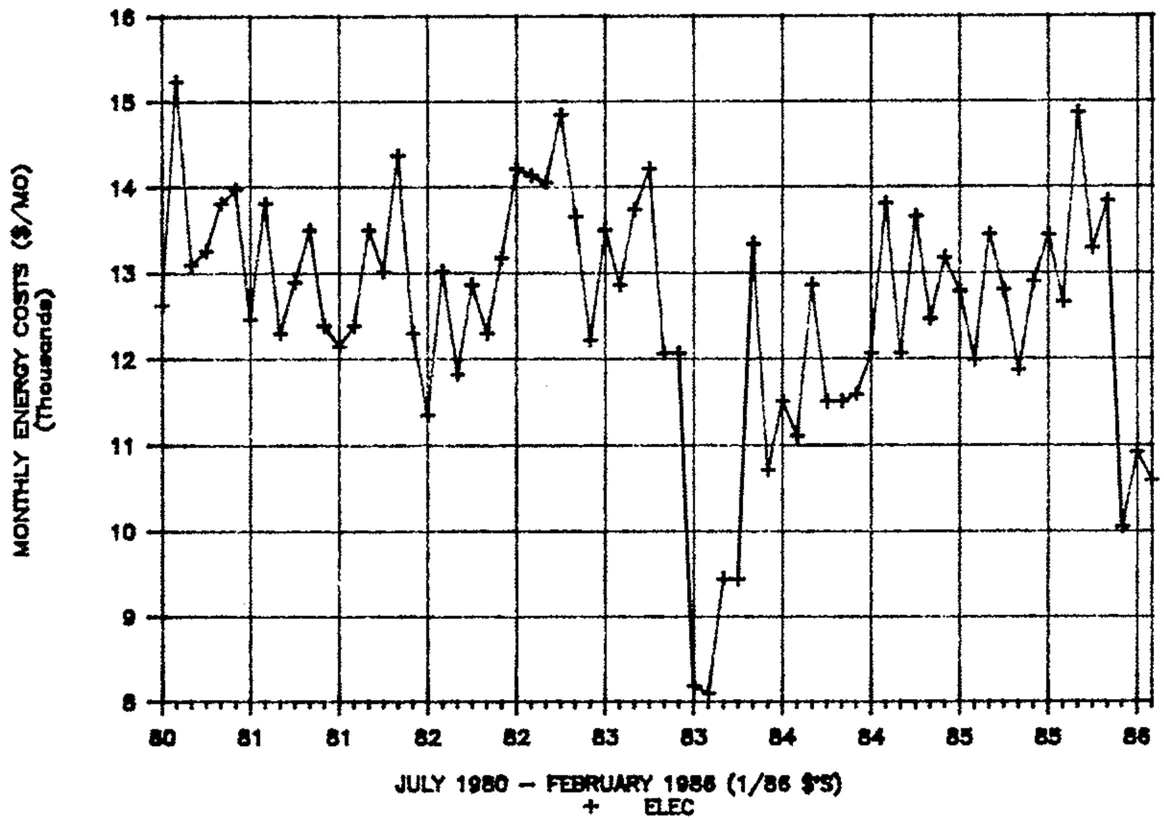



Fig. 3-1: Rec Center Monthly Electrical Use

importance by daily and monthly information. However, again, the experience at the Rec Center indicates that, when forced to use only existing meters, daily information can be sufficiently accurate to predicte energy usage to within 10 to 20 percent for an institutional building.

Since a BEACON system is directed at operational energy conservation measures, operating personnel are therefore an important component of the team. Experience at the Rec Center has shown that monthly consumption figures can be valuable for administrative cost tracking; daily consumption figures, presented once a week, are the most useful for indicating operational problems (Claridge et al., 1986). The daily electrical usage is shown in Figure 3-2. Each day the kwh meter is read, typically in the afternoon. The reading represents an accumulation of the energy that has passed through the meter from one reading to the next. Differences in the time-of-day between each reading are normalized to midnight. All meters are then read at the same time, as well as the independent parameters and normalized in the same operation. The method used to normalize the readings is documented in the appendix.

The accuracy of the daily predictions, when compared to the measured daily consumption, varied with each of the different meters. Electric, steam and compressor runtimes were the most accurate. Pool steam usage, pool water usage and building water usage were the least accurate.

### 3.4. Consumption Predictors (PCONs)

The Predictors of Consumption (PCONs) are a simple method of predicting energy consumption. PCONs are regression equations

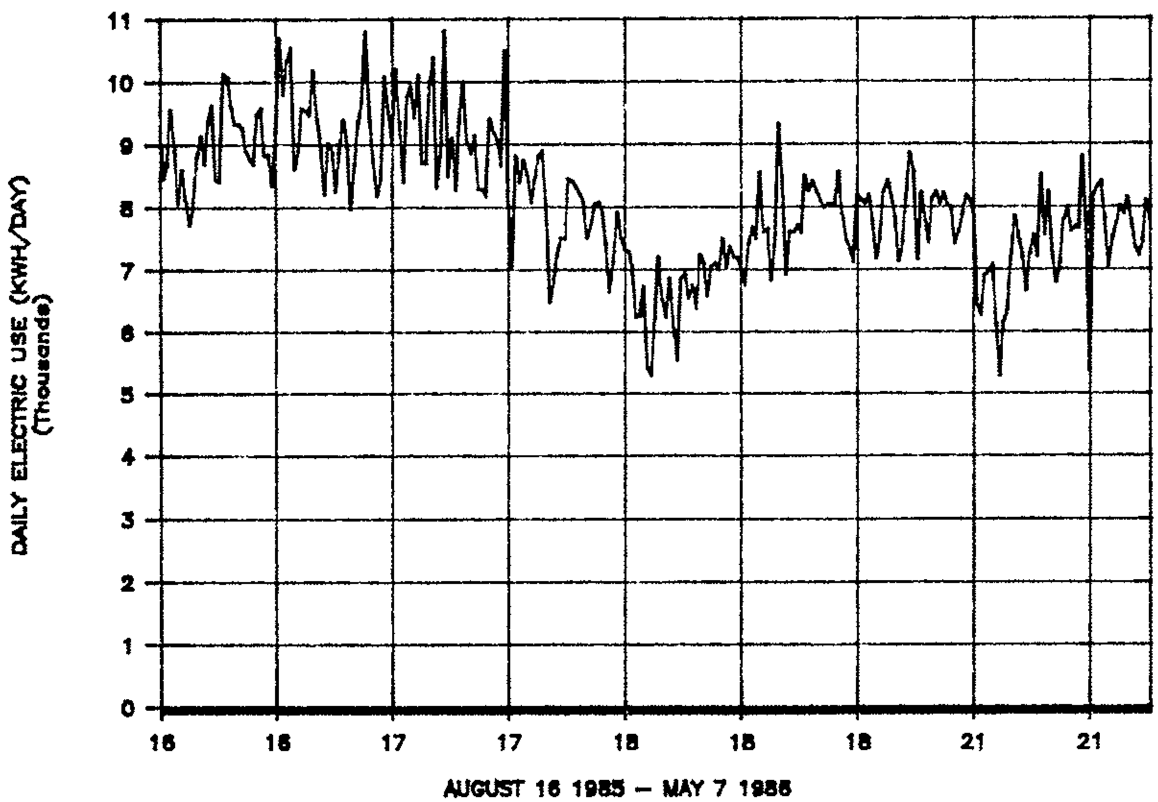



Fig. 3-2: Rec Center Daily Electrical Use

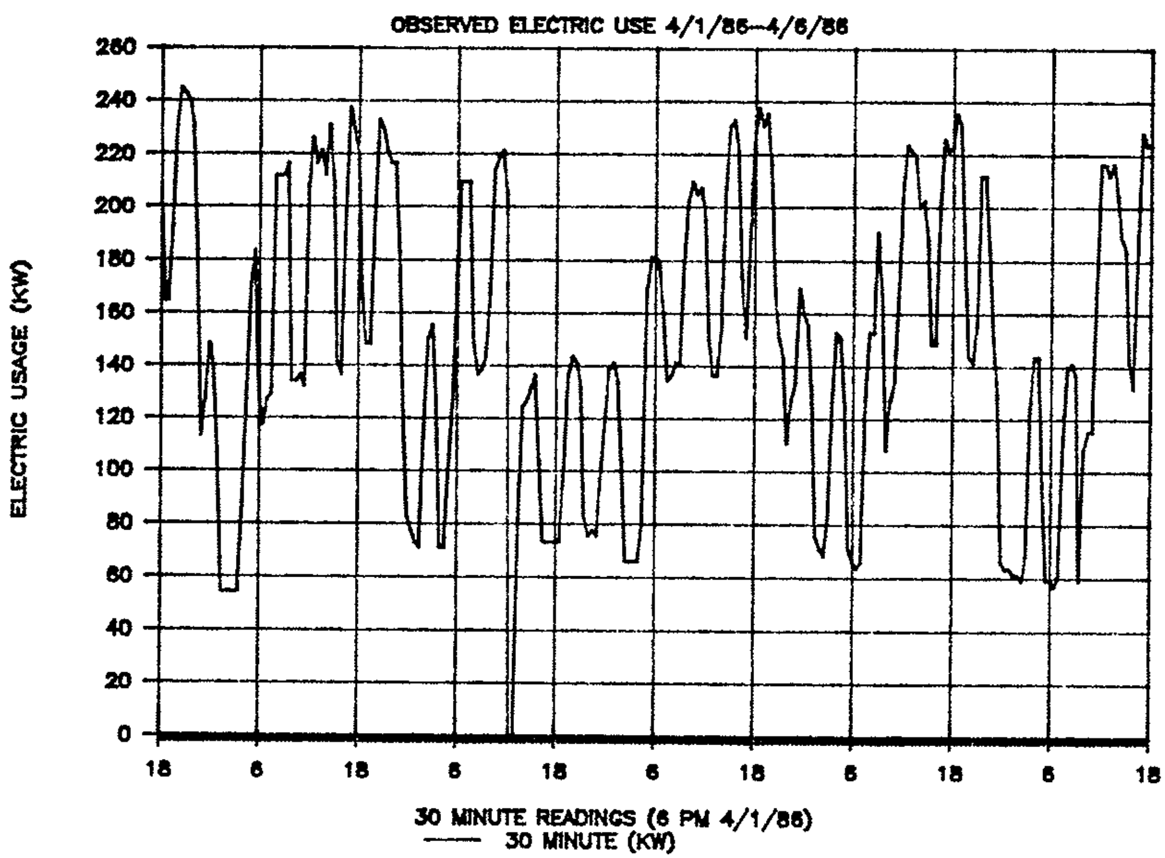



Fig. 3-3: Rec Center Hourly (30min.) Ele. Use.

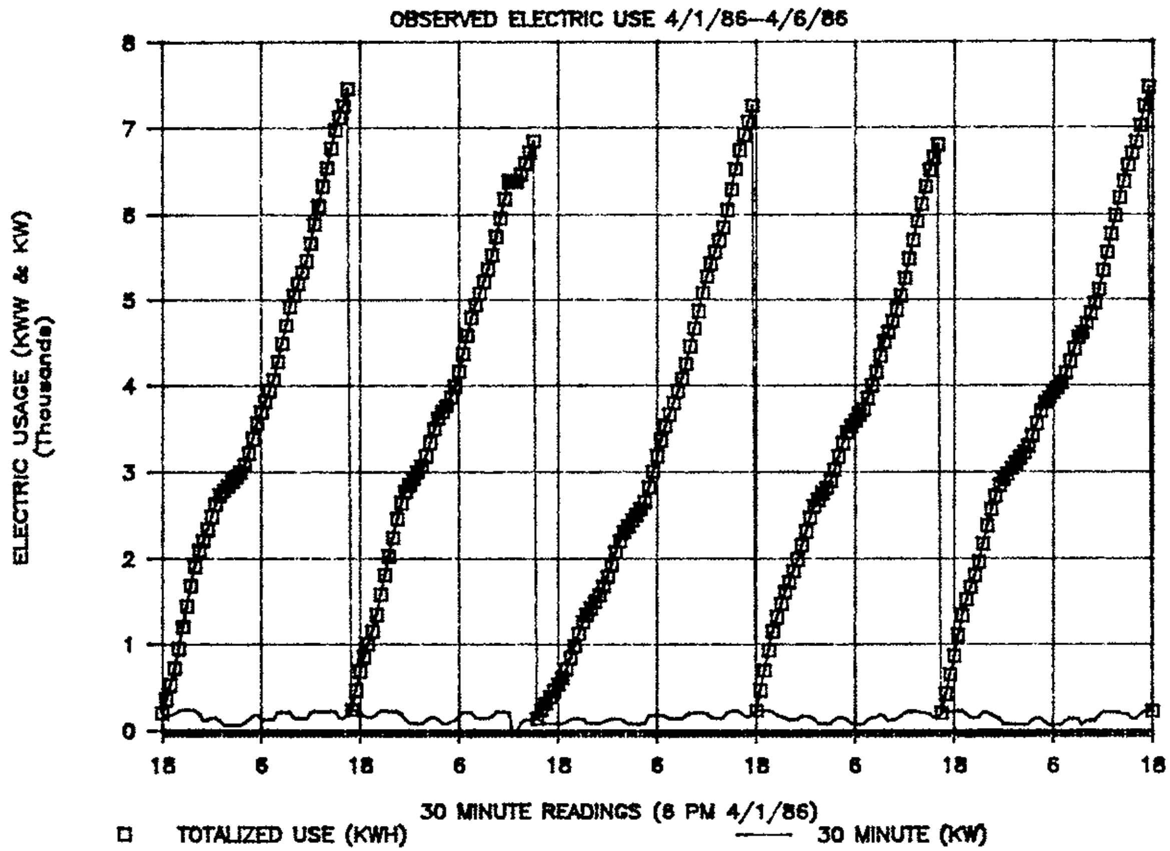



Fig. 3-4: Hourly and Daily Electrical Use

that best represent how key parameters relate to energy consumption measurements. The PCONs chosen to show proof-of-concept are multivariate regressors. The influencing parameters are divided into three categories: Environmental Parameters (EPs), Operational Parameters (OPs) and System parameters (SPs). Each group is explained further in the following sections.

The position of the PCONs in the full BEACON system is shown in Figure 3-5. There are two primary paths of information for the PCON processor, the daily information and the background information. The daily information consists of daily meter readings, daily (influencing) parameter readings and daily observations; all of which are kept in a log book. The background information consists of information that is assembled once, with possible revisions occuring infrequently. Typical background information for the PCON processor includes the pre-assembled PCONs, the meter constants and building configuration information. During a typical consultation session, the PCON processor receives the daily meter readings and parameter readings. The processor normalizes these readings for the time-of-day, and converts the readings into engineering units. The measured energy consumption is then compared to the consumption that is typical for similar conditions (according to historical daily readings). This comparative index is then passed through the PCON-to-CCON translator and onto the CCON. The output from the PCON can be either printed output, or graphic output.

The PCONs used are simple algebraic equations that yield a reference or normalized consumption value for the specific

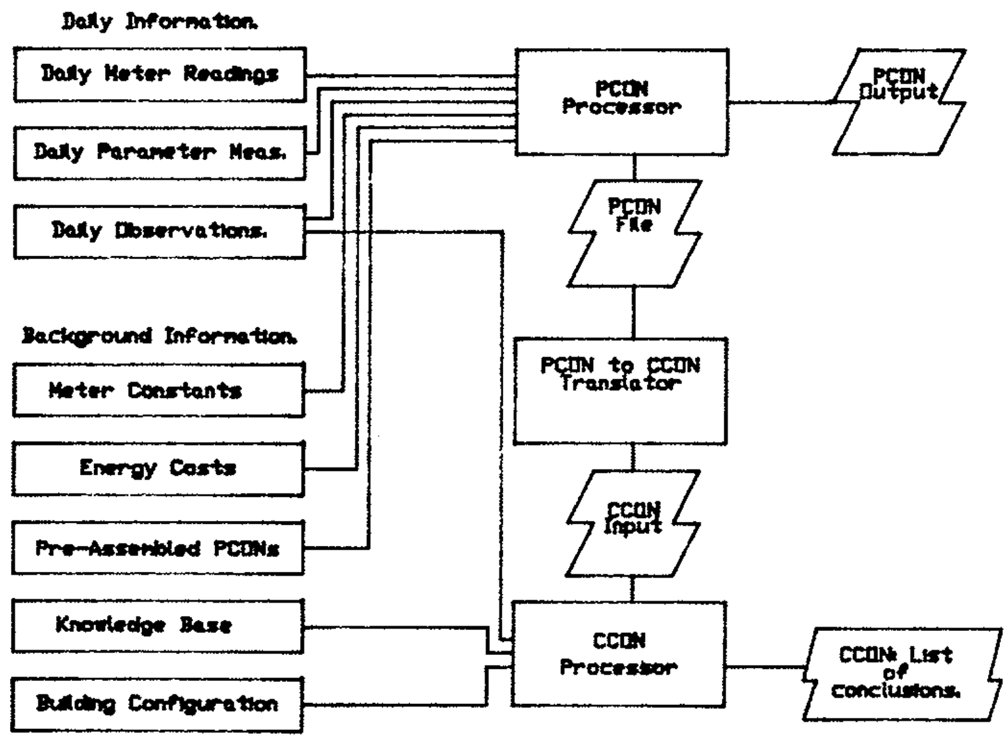



Fig. 3-5 Control Chart for the BEACON Processors

parameters associated with each daily observation. These normalized consumption reference values are then compared with the measured consumption. Abnormal consumption that occurs can then be attributed to one of four causes: 1) an equipment malfunction, 2) an operational problem, 3) a problem within the analysis process, or 4) an unknown problem. Likewise, under-consumption becomes equally important and can usually be grouped into one of the same four categories used for abnormal consumption.

The choice of PCONs, as well as the EPs, OPs and SPs involves engineering judgement, interviews with current building energy experts, daily inspections, and a thorough understanding of the pilot building (Claridge et al., 1986). The appropriateness and accuracy of the resultant PCONs is highly dependent on these factors.

### 3.4.1. Influencing Parameters

The term, influencing parameter, represents any measurable (daily) parameter that significantly influences energy consumption. These influencing parameter are used as the statistical independent variables in the consumption predictors.

Influencing parameters are grouped into three primary groups for convenience. These groups are: Environmental Parameters, Operational Parameters and System Parameters.

#### 3.4.1.1. Environmental Parameters (EPs)

Environmental Parameters (EPs) are those influences on energy consumption that are environmentally related. Wind, ambient temperature, solar flux and cold city water supply temperature are four parameters that can be easily recorded on site. Each EP needs to be recorded over the same period that the energy consumption is recorded. In other words, hourly environmental parameters with hourly metered data, daily environmental parameters with daily metered data, etc.

On site observations are the most reliable data. Observations taken near the building can also provide useful information. The application of linearized regression to the effect of each of the parameters will measure how strongly tied to each of the parameters a particular building is.

#### 3.4.1.2. Operational Parameters (OPs)

Operational Parameters (OPs) are viewed as those influences that are occupant related. OPs typically account for occupant, or staff interaction with the building equipment. Some examples of OPs include: the scheduled operating hours, the attendance in a building, and janitorial schedules. Certain OPs also include system-like parameters that are varied often enough to be primarily occupant related versus system related; for example covering or uncovering the pool. Operational Parameters such as opening and closing doors (sliding patio doors in a pool enclosure) can be very closly related to EPs, but are viewed as OPs since people are involved. Only OPs that are statistically significant are considered important.

#### 3.4.1.3. System Parameters (SPs)

System Parameters (SPs) are the operational characteristics of the energy consuming subsystems. Operational characteristics are both the manufacturer defined characteristics and the setpoints for the various subsystems. SPs differ from OPs in that they are primarily setpoint, on/off, or operating status items. SPs are most often set once and do not change on a daily basis. Some examples of SPs include domestic hot-water setpoints, space thermostat setpoints, and general equipment on/off schedules. SPs are usually inspected and noted only when a change occurs.

### 3.4.2. Defining Normal Consumption

Normal consumption for a building is defined as consumption that falls within a predictable "band". First-level band-width should be established by actual abnormal events (e.g., a steam leak, or lights being left on all night). In lieu of this, one standard error of the Y estimate can be used as a normal band-width of the consumption predicted by the PCONs. The PCONs are constructed using statistically significnat EPs, OPs and SPs that have been identified for a building. Each PCON represents a physical meter or pair of meters. For example should a building have a main meter and a sub-meter, a PCON can be constructed for the sub-meter and for the residual portion left over when the sub-meter is subtracted from the main meter. Disaggregation can, of course, improve the accuracy of an PCON, but is not required for a PCON to be effective.

Abnormal consumption, defined as consumption that is outside of the normal consumption range for a particular day, can easily be attributed to one of four causes as mentioned earlier: an equipment malfunction, an operational problem, a problem with analysis, or an unknown problem.

### 3.4.3. Identifying Consumption Signatures

An ongoing study of abnormal consumptions together with daily visits to the building and interviews with the building staff allows for signature events to be correlated with specific actions and/or system characteristics. A signature event is a specific event that causes abnormal consumption. Signature events can be user caused or equipment related. This is the primary value of the entire BEACON system; the systematic identification of operational and system abnormalities permits corrected operation leading to energy savings. The automation of this systematic identification is the value of the Computerized Consultant (CCON) portion of the BEACON system. The front end portion of the BEACON system, consisting of the PCONs and a building expert's opinion, functions without the CCON portion. Indeed the fine tuning of the CCON relies on the presence of such a preliminary operating system and a building expert.

There are four levels of significance for the four types of causes that the BEACON system can identify. These are: non-significant events, significant events, significant trends, and error identification. An event is defined as an over or under-consumption that has been identified by the PCONs.

**3.4.3.1. Non-Significant Events**

Non-significant events are events that occur because a specific action that is not related to the OPs, EPs, or SPs has caused the event. This specific action must be identifiable. An example of a non-significant event that shows up as an over-consumption might be a social function that requires that the building be open longer than usually scheduled. Non-significant events may or may not occur on a regular basis; therefore, the close examination and incorporation into the CCON may or may not be warranted.

**3.4.3.2. Significant Events**

Significant events are isolated events that occur because an operational, system or other malfunction has occurred within the energy consumption network. Significant events must be identified and traced to a component, operator, or group of components, operational characteristic, etc. Significant events are anticipated to occur on a sufficiently regular basis to warrant close examination of each event. Their inclusion in the CCON strengthens the capabilities of the CCON. An example of a significant event would be a sizeable leak in a hot water pipe that, eventually, is discovered and fixed.

**3.4.3.3. Significant Trends**

Significant trends are downward (or upward), parallel shifts in a PCON related to an identified event. Significant trends differ from non-significant trends in that their identification ultimately leads to action and a remedy. An example of a significant trend would be an energy savings associated with the lowering of the setpoint temperature of the domestic hot water in a building. The PCONs must be readjusted for significant trends, otherwise, the CCON repeatly issues the same warning and the effectiveness of the system is reduced.

This identification of significant trends is essentially the same process, used since the 50's by industrial engineers to monitor manufacturing processes. This procedure has been referred to as statistical process control (Mazzeo, 1984).

### 3.4.3.4. Non-significant Trends

Non-significant trends are shifts that can be traced to an energy consuming sub-system, or occupants that can be identified but not remedied. An example of a non-significant trend can often be the installation of office equipment that increases electric usage and cooling load, without remedy. A non-significant trend is usually not of concern to the CCON, although the PCONs may need to be adjusted for the trend.

### 3.4.3.5. Error Identification

Error identification is the identification of an error in the analysis. Typically, these include: data base problems, the misreading of meters, missing information, and unknowns. One common example is a meter that is mis-read. This occurs often with dial-type meters. It tends to show up in the data base as an unknown overconsumption followed immediately by an underconsumption, then normal consumption.

## 3.5. The Computerized Consultant (CCON)

The Computerized Consultant (CCON) is the final processor in the BEACON system. The CCON's position in the BEACON system can be seen in Figure 3-5. The CCON, in a similar fashion to that of the PCON, utilizes both daily and background information. The daily information consists of daily observations entered directly into the CCON and the translated output from the PCON. The translated output from the PCON is the measured versus predicted consumption indices. The CCON also relies on a preassembled knowledge base. This knowledge base consists of IF-THEN rules that are processed by the CCON inference engine. The network of rules is the method by which the CCON processes information concerning the building's energy consumption. The rules represent: (1) facts about the interrelationships of the energy consuming sub-systems acquired from building plans; (2) rules-of-thumb acquired from the existing building experts; (3) facts (including rules-of-thumb) gained from daily observations.

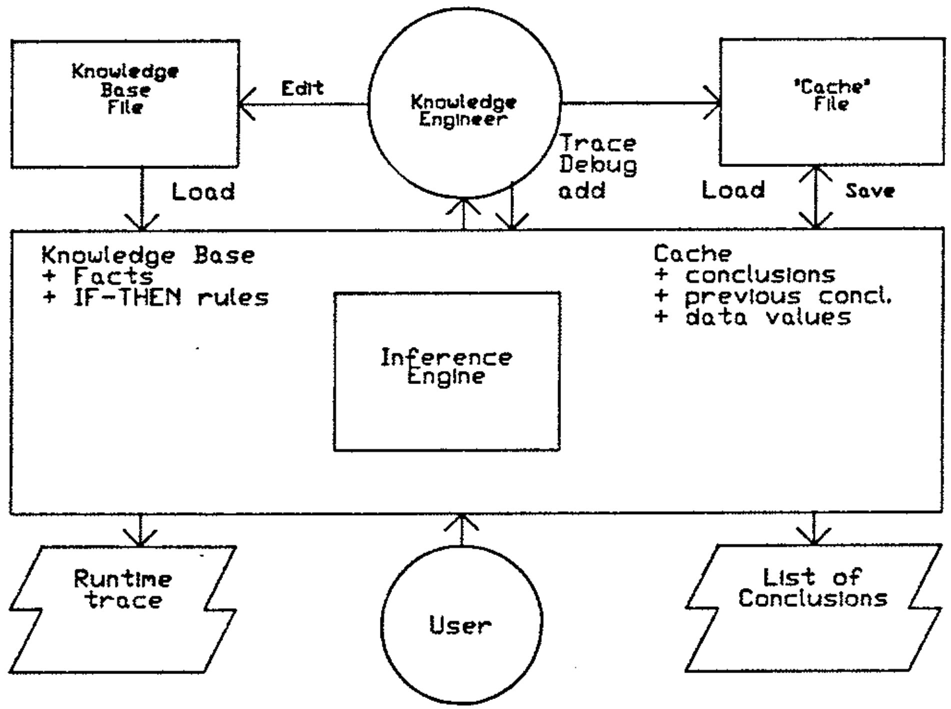
Once a week the user enters the daily readings for the previous week. These readings are processed by the PCON and translated into comparisons of measured versus predicted indices. These indices are then passed to the CCON. The CCON takes this set of indices and compares them with the knowledge base to see if it can determine what has caused the significant abnormal consumption. The results from a typical session include: printed output from the PCON, graphics output from the PCON, and a list of possible causes of overconsumption from the CCON.

**3.5.1. Choosing the Knowledge Base Framework**

The CCON is an expert system that consists of two primary components; the inference engine and the knowledge base. The inference engine is that portion of the expert system toolkit that controls the interaction with the knowledge base and the expert, handles queries for explanation by the user and serves as a general interface with the user.

The knowledge base is a sentence-like structure of IF-THEN rules that have been assembled before-hand by the knowledge engineer. A knowledge engineer is a term that describes a person who extracts knowledge from experts and assembles it into machine readible form the the expert system. The assembly of the knowledge into the CCON expert system depends on the expert system toolkit. The following discussion is presented in a generic fashion in order to avoid specialized jargon associated with a particular expert system toolkit.

Figure 3-6 illustrates the general relationships of the knowledge base and inference engine. The expert or knowledge engineer interacts with the system by translating the available knowledge into the language of the knowledge base. This language consists of an ordered list of rules which are processed by the inference engine during a consultation with the user. The individual rules are simple IF-THEN statements concerning explicit facts about an energy consuming sub-system within a building. The knowledge engineer assembles the knowledge base using an editor and saves the knowledge base in a file that is accessed by the inference engine. During a typical session the user interacts with the inference engine. The inference engine loads the current knowledge base which consists of rules assembled by the knowledge engineer and facts concerning the current consumption patterns. The inference engine then proceeds with the consultation matching rules and facts and




Adapted from Teknowledge (1985, p. 1-3)

Fig. 3-6 Relationship of Knowledge Base and Inference Engine asks the user for any additional information. The results of a typical session are a list of possible reasons for abnormal consumption.

### 3.5.2. Assembling the Knowledge Base (KB)

The CCON knowledge base is assembled from three primary components: facts about the energy consuming sub-systems acquired from building plans, rules-of-thumb acquired from the existing building experts, and facts (including rules-of-thumb) gained from daily observations. The assembly of the knowledge base consists of translating these three domains of knowledge into IF-THEN rules; converting the IF-THEN rules into a decision matrix or rule table; and mapping the decision matrix into a decision tree to facilitate the coding into the expert system language.

The next three sections describe the three types of knowledge that were used to construct the BEACON system: knowledge gained from a review of plans of the building's energy consuming subsystems, knowledge gained from daily observations, and knowledge from the available experts .

#### 3.5.2.1. Knowledge from Drawings

The knowledge gained from a review of the plans of a building is the cornerstone for the acquisition of information concerning a building's energy consuming sub-systems. Knowledge from plans establishes how many systems are in a building, how systems are interconnected, the control of systems and the location of the systems in the building. This information is used to assemble the end-use distribution network as shown in Figure 3-8. The end-use distribution (EUD) network provides important information regarding

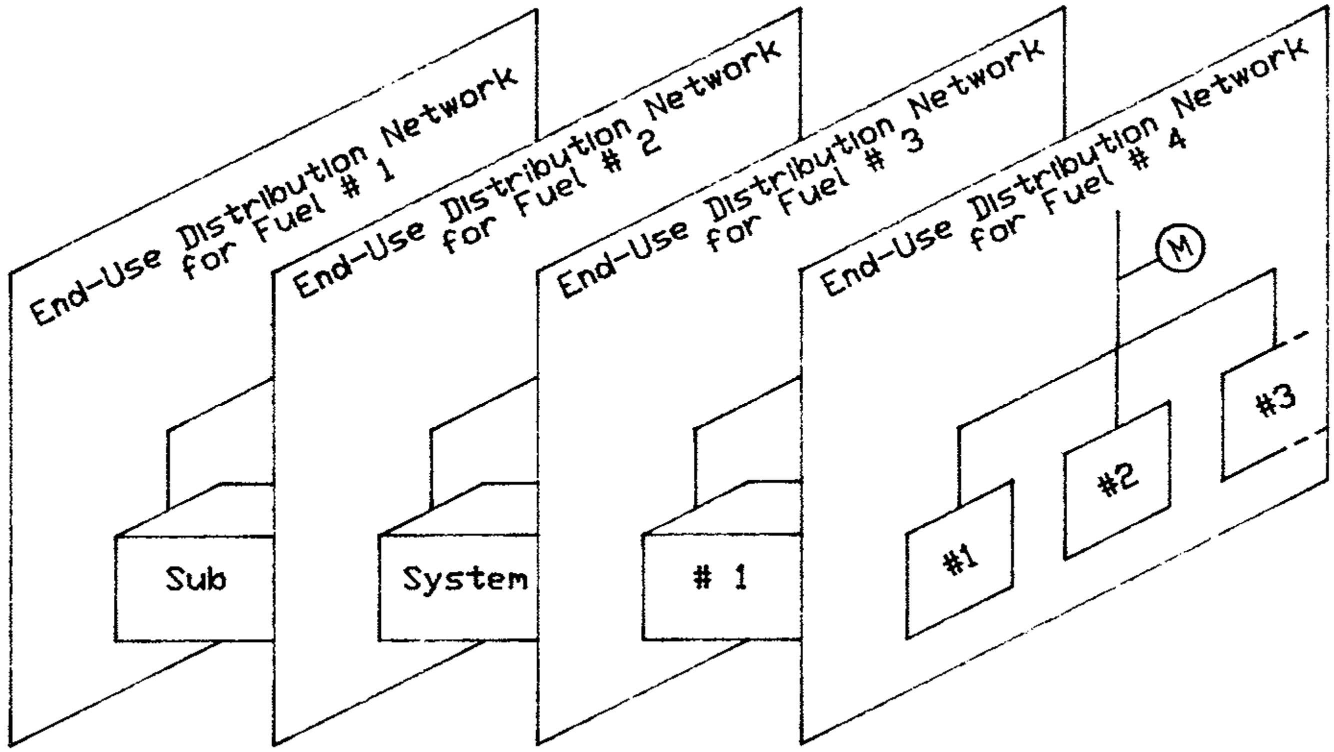



Fig. 3-7: Interrelationships of EUD Networks

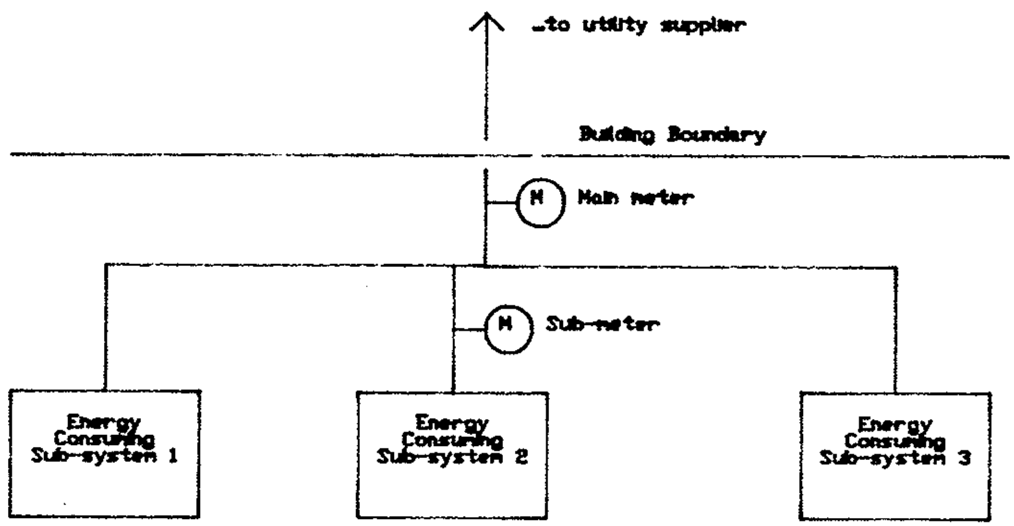



Fig. 3-8: End-Use Distribution Network

the number and type of sub-systems, within a building, that are using a specific type of fuel. The network also provides information about the location of meters and (possible) sub-meters. As illustrated in Figure 3-7, fuel consumed by sub-system 2 could be directly read by the sub-meter; fuel consumed by sub-systems 1 and 3 could be measured by subtraction.

The end-use distribution networks also provide a tool for understanding the interrelationships of energy consuming sub-systems that consume more than one type of fuel. This is shown in Figure 3-8. In this figure sub-systems 2 and 3 consume both fuel types 1 and 2 whereas sub-system 1 only consumes fuel 1. It would be expected that an abnormal consumption from sub-system 2 should show up on meter 2 and meter 3. Likewise, an abnormal consumption in sub-system 3 would show up in meters 1 and 3. These interrelationships are similar, in form, to "tangled tree" networks seen in knowledge representation schemes (Harmon and King, 1985).

This physical interrelationship provided by the EUD networks is the foundation for establishing the IF-THEN rules needed for the knowledge base. The final interrelationships used in the IF-THEN rules are a combination of the physical interrelatedness and the statistical interrelationship established from observations. For example, in the case of the Rec Center, the hockey players consistently use 2 to 3 towels after each practice. Statistically, this meant there should be a physical connection between the ice rink (hockey) usage and the natural gas (laundry), yet no such interconnection exists. This relationship was resolved by inserting a rule into the CCON to watch for excess hockey use.

### 3.5.2.2. Knowledge from Observations

The knowledge gained from daily observations, together with the corresponding measured daily energy consumption provides a second source of information for the knowledge base. A daily log is kept, together with the daily meter readings, that provides information about user effects and equipment malfunctions.

These observations serve as test cases to establish reasons for abnormal consumption of a particular fuel. Usually, over a period of months user malfunctions and equipment malfunctions will occur. Once identified these abnormal consumptions, can be entered into the knowledge base. The knowledge abse can also be supplemented with other (forced) abnormal consumptions. Forced abnormal consumptions are experimental events that are planned in advance to measure the impact of a particular malfunction, a test.

For example, one observed "user-effect" event might be leaving an air-conditioner on in an office over the weekend (when it should have been turned off). Likewise, a forced abnormal consumption might be resetting the domestic hot water temperature from 110F to 140F over a one week period to observe increases in fuel consumption associated with the action.

### 3.5.2.3. Knowledge from Experts

Finally, the knowledge from the available experts is sought. The type of expertise required to construct a knowledge base is usually found in maintenance personnel responsible for the operation and trouble shooting of the energy consuming sub-systems. Since this type of knowledge is obtained after the EUD networks have been established and after certain abnormal consumption events have been observed, the knowledge engineer now has insight into what types of questions need to be asked and which part of the network the associated answer will effect.

Knowledge from experts is obtained from formal interviews and from informal contacts, usually during the daily observations. Formal interviews focus on the individual energy consuming subsystems. The topic of the interviews consists of the diagramming of specific problem-solution sets. An example of a problem-solution set could be as follows: (1)The interviewer is attempting to establish how the expert would discover and then fix a leaking pressure relief valve on a domestic water heating system. (2) Questions are asked concerning the obvious signs of such an event. (3) The maintenance expert details the usual observations (i,e. water on the floor, tracing the water to the valve, adjusting the valve, etc.) (4) The knowledge engineer then translates the verbal description of the problem-solution set into a network of IF-THEN rules. (5) The rules are reviewed by the knowledge engineer and the maintenance expert. (6) the rules are inserted into the knowledge base and tested.

### 3.5.3. Flow Diagram for the BEACON, PCON and CCON

Figure 3-9 is a flow diagram for the operation of the BEACON system. This flow diagram assumes: all necessary background information has been assembled, PCONs have been calculated for all appropriate points, and that the appropriate knowledge base is available. Basically, the user enters the daily meter and parameter readings into the spreadsheet (PCON). The spreadsheet normalizes the readings, checks for certain errors, calculates daily energy consumption and compares this consumption with the consumption

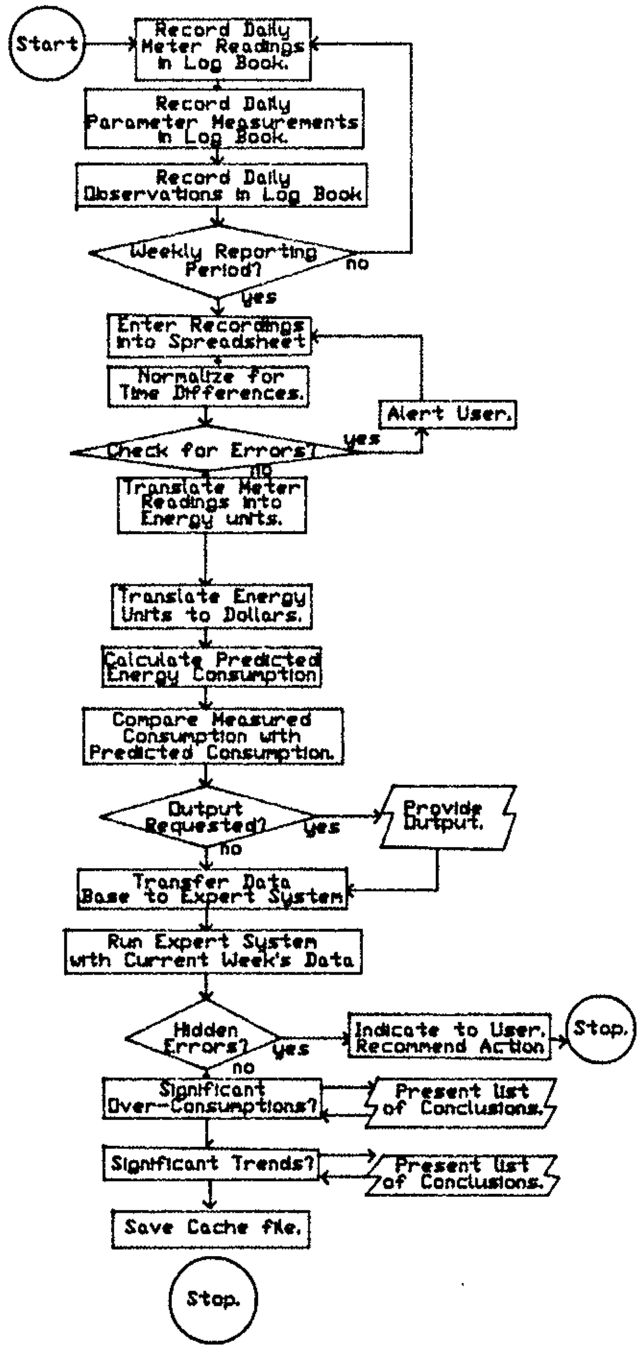



Fig. 3-9 Control Diagram for BEACON

predicted by the PCONs. A listing of parameters and comparison consumption is passed from the spreadsheet to the expert system (CCON). The expert system then takes (any) abnormal consumptions and searches for possible reasons contained within the IF-THEN rules of the knowledge base. The output from a typical analysis consists of printouts and graphs from the spreadsheet and a list of possible reasons from the CCON. This procedure is usually run once-per-week with the information from the preceding week.

**CHAPTER 4**

# APPLICATION OF THE BEACON SYSTEM

This chapter describes the application of the BEACON system to the University of Colorado Student Recreation Center. The various components of the general BEACON are described in terms to their application to the Rec Center. The instruments used to measure the different influencing parameters are described in the appendix. An example analysis for the week July 13 through July 20, 1986 is presented to demonstrate the use of the system.

## 4.1. The Rec Center PCONs

The Predictors for Consumption (PCONs) used in the Rec Center case study are simple algebraic, multivariate regression equations. The PCONs are selected according to a backward elimination procedure. This procedure searches all independent parameters and selects those with t-ratios that equal or exceed unity. These are then rearranged and further eliminated until the highest $R^2$ value results.

The Rec Center PCONs, in some cases, represent linearized regression equations. Visual inspection of scatter plots is used to determine if linear regression is suitable. The appropriate degree of the polynomial expression is then chosen to match the curve being represented. This linearized regression is then extended to include other variables of significance. This process is explained further in the appendix.

The PCONs chosen to represent the Rec Center are shown in the matrix of Figure 4-1. Seven PCONs were chosen to represent the four principal fuels being consumed: steam, electricity, natural gas, and water. Steam metering consists of a main meter (PCON1), and a sub-meter on the pool. PCON2 is the statistical predictor for the pool meter; PCON1 is the statistical predictor for all other steam consumed by the building. In a similar fashion, PCON4 is the statistical predictor that tracks the ice rink compressor runtimes; PCON3 is the residual electrical consumption that represents all other electricity consumed at the Rec Center. PCON5 is the statistical predictor for the natural gas consumed (primarily by the laundry and emergency generator). PCON6 is the water consumed by the pool. PCON7 represents the statistical predictor for all other water consumed on site. Each of the seven PCONs has the influencing parameters indicated. For example, the highest $R^2$ for PCON1 (other steam) results from a linearized regressor for outside air and linear regressors for cold water supply temperature and attendance.

**4.1.1. Evaluating Influencing Parameters**

In order to assume that the independent regressors are, indeed, independent, intercorrelations should be reviewed. One method suggested by Coulter (1986) is to compare linear relations with $R^2$ values obtained by regressing the variables against each other. Such as analysis is presented in Table 4-1. Independent variables that indicate significant dependencies are: the hours of operation and attendance ($R^2$ = 0.649), and the outside air

| | PCON1 Other Steam | PCON2 Pool Steam | PCON3 Other Electric | PCON4 Ice Rink Compressors | PCON5 Natural Gas | PCON6 Pool Water | PCON7 Other Water |
|---|---|---|---|---|---|---|---|
| EP1 - Average Wind | X | | | | | X | |
| EP2 - Outside Air | X | | X | X | | X | X |
| EP3 - Cold Water | X | X | | X | | X | X |
| EP4 - Solar Radiation | SOLAR RADIATION NOT INCLUDED AS OF 6/15/86 | | | | | | |
| OP2 - Oper. Hours | X | X | X | | X | X | X |
| OP3 - Ice Resurface | X | | X | X | X | | X |
| OP8 - Attendance | X | X | X | | X | X | X |
| OP9 - Backwash | | | | | | X | |
| SP1 - Generator | | | | | X | | |
| SP2 - Ice Temp. | | | X | X | | | X |

Fig. 4-1: Rec Center PCON Matrix

temperature compared to the cold water supply temperature ($R^2$ = 0.354). Since the hours-of-operation and the attendance have an intercorrelation greater than 50 percent the variables are combined by cross-multiplying. All other dependencies shown have intercorrelations less than 50 percent and are therefore assumed independent. This 50 percent level was chosen because statistically it is saying that 50 percent of the variables fall outside the standard error deviation from the predicted variable. Otherwise, the choice of the 50 percent level is arbitrary.

| | EP1 - Wind | DP3 - Ice Resurface | SP1 - Generator | DP8 - Attendance | DP9 - Backwash | SP2 - Ice Temperature | EP2 - Outside Air | EP3 - Cold Water | DP1 - Day-of-Week | DP2 - Oper. Hours | EP4 - Sunlight |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EP1 - Wind | 1.0 | 0.008 | 0.000 | 0.000 | 0.005 | 0.008 | 0.164 | 0.000 | 0.002 | 0.000 | 0.049 |
| DP3 - Ice Resurface | | 1.0 | 0.001 | 0.177 | 0.001 | 0.015 | 0.097 | 0.209 | 0.000 | 0.148 | 0.032 |
| SP1 - Generator | | | 1.0 | 0.021 | 0.001 | 0.017 | 0.012 | 0.029 | 0.002 | 0.022 | 0.011 |
| DP8 - Attendance | | | | 1.0 | 0.021 | 0.020 | 0.006 | 0.001 | 0.118 | 0.649 | 0.002 |
| DP9 - Backwash | | | | | 1.0 | 0.009 | 0.003 | 0.006 | 0.004 | 0.018 | 0.000 |
| SP2 - Ice Temp | | | | | | 1.0 | 0.087 | 0.069 | 0.000 | 0.019 | 0.090 |
| EP2 - O/A | | | | | | | 1.0 | 0.354 | 0.000 | 0.004 | 0.187 |
| EP3 - Cold Water | | | | | | | | 1.0 | 0.000 | 0.000 | 0.051 |
| DP1 - Day-of-Week | | | | | | | | | 1.0 | 0.081 | 0.000 |
| DP2 - Oper. Hours | | | | | | | | | | 1.0 | 0.001 |
| EP4 - Sunlight | | | | | | | | | | | 1.0 |

Table 4-1: Intercorrelation Among Independent Variables

#### 4.1.2. The Rec Center Environmental Parameters (EPs)

Environmental conditions that influence energy consumption are called Environmental Parameters (EPs). The environmental parameters (EPs) found to have significant t-ratios with the seven PCONs for the Rec Center are shown in Table 4-2. These EPs have been recorded on site since August 15, 1985. The most influential EP is the average ambient temperature (EP2); followed by the city water temperature (EP3), wind (EP1) and solar radiation (EP4). Intercorrelations among EPs is strongest for the average ambient temperature (EP2) and city water temperature (EP3) ($R^2 = 0.354$); followed by average ambient temperature (EP2) and solar radiation (EP4) ($R^2 = 0.187$); and finally, average ambient temperature and wind (EP1) ($R^2 = 0.164$). The low intercorrelation between sunlight and average ambient temperature corresponds with results published by Brotherton (1986). His analysis of Weather Year for Energy Calculations (WYEC) regressions of hourly temperature against insolation showed $R^2$ of 0.16, 0.26, and 0.17 for Washington, D. C., Los Angeles, and Albuquerque, respectively.

**Table 4-2: Environmental Parameters (EPs)**

1. Wind, average daily, mph (EP1)
2. Ambient Temperature, average daily, F (EP2)
3. City Water Temperature, sampled daily, F (EP3)
4. Solar Radiation, daily totals, Btu/sqft (EP4)

#### 4.1.3. The Rec Center Operational Parameters (OPs)

Operational parameters are those influences that are occupant related and vary daily. The Operational Parameters (OPs) selected for the Rec Center are shown in Table 4-3. OPs differ somewhat from EPs in that certain OPs change infrequently, and therefore do not require a position in the daily data base. The OPs that were found to require a daily record are shown in Table 4-4. All other OPs are noted during daily inspection or input to the CCON as required.

Certain of the OPs exhibited linear intercorrelations. The strongest relationship existed between the operating hours (OP2) and the attendance (OP8) with an $R^2$ of 0.649. Next, but of considerably less significance is the intercorrelation of the Zamboni runtime (OP3) and the attendance ($R^2$ of 0.177). Two other slight dependencies occur between Zamboni runtime (OP3) and operating hours (OP2) ($R^2$ of 0.148); and the day-of-the-week and attendance ($R^2$ of 0.118). The relationship between the operating hours and the attendance is strong enough to warrant modification. Therefore, in the regressions used for the PCONs, OP2 and OP8 are combined through multiplication to an OP2xOP8 variable. This is further described in the appendix. The OPs listed in Table 4-4 are number according to their position in Table 4-3.

**Table 4-3: Operational Parameters (OPs)**

1. Day of the week (OP1)
2. Scheduled operating hours (OP2)
3. Zamboni runtime (OP3)
4. Zamboni hot water usage (OP4)
5. Zamboni snow melt (OP5)
6. Ice Rink curtains (OP6)
7. Ice thickness (OP7)
8. Attendance (OP8)
9. Pool backwash (OP9)
10. Pool covers (OP10)
11. Janitor schedule (OP11)
12. Security lighting (OP12)

**Table 4-4: Daily Recorded Operational Parameters (OPs)**

1. Day of the Week (OP1)
2. Scheduled Operating Hours (OP2)
3. Zamboni Runtime (OP3)
8. Attendance (OP8)
9. Pool Backwash (OP9)

### 4.1.4. The Rec Center System Parameters (SPs)

System characteristics that define the installed equipment are called system parameters (e.g., AHU damper settings, thermostat setpoints, etc.). The System Parameters (SPs) chosen for the Rec Center are shown in Table 4-5. The SPs that are recorded daily and entered into the spreadsheet are shown in Table 4-6. All other SPs are noted daily but are recorded when a change occurs. This infrequent information is used by the CCON in a similar fashion to the information from the infrequent OPs and EPs. Examples of important, infrequent SPs are the gutter heat tape status (40 kw load) and the tennis lights (60 kw load). Monitoring the gutter heat tapes involves checking the status of the panel; monitoring the tennis court lites involves hourly recordings by the security guard stationed nearby. In the case of the gutter heat tapes, the heat tapes are manually turned on when ice begins to form in the gutters and turned off when the gutters are clear. They may be on for a week, and off for a month, etc., thereby requiring only an infrequent notation in the log book.

**Table 4-5: System Parameters (SPs)**

1. Emergency generator usage (SP1)
2. Ice rink setpoint temperature (SP2)
3. Domestic hot water setpoints (SP3,SP4,SP5)
4. Outside air sensor (SP6)
5. Outside reset schedule (SP7)
6. Exhaust reset schedule (SP8)
7. Office refrigeration status (SP9)
8. Gutter heat tapes (SP10)
9. Tennis court lights (SP11)
10. Loading ramp heater (SP12)
11. Pool setpoint (SP13)
12. Pool chlorine setpoint (SP14)
13. Gym incandescent lighting (SP15)
14. Steam condensate cooler (SP16)
15. Building steam traps (SP17)

**Table 4-6: Daily Recorded System Parameters (SPs)**

1. Emergency Generator usage (SP1)
2. Ice rink setpoint temperature (SP2)

## 4.2. The Rec Center CCON

The Rec Center CCON uses the M.1 expert system shell from Teknowledge (1985). Control diagrams for operation of the Rec Center's CCON are shown in Figures 3-5 and 3-9. The user enters information from the daily log book into the spreadsheet. The spreadsheet then calculates comparative energy calculations using previously calculated PCONs and information from daily meter readings. These comparative figures are then passed to the translator which assembles the "cache" files required by M.1. M.1 is then activated by calling up the knowledge base and cache files for the days being analyzed. Output from the entire BEACON systpem consists of listings and graphs from the spreadsheet and a list of possible reasons for over-consumption from the CCON.

**4.2.1. Interrelationships Among Sub-Systems.**

The five principal categories for the description of the type of energy consuming load are those described by the Colorado's Office of Energy Conservation Institutional Buildings Grants Program, Energy Audit Workbook (COEC, 1982). They are: non-electrical baseload, non-electrical space heating, electrical lighting, electrical special systems and electrical heating, ventilation and air conditioning (HVAC).

The interrelationships amoung the Rec Center PCONs can be seen in Table 4-7. Table 4-1 shows any statistical intercorrelation among the independent regressors. Table 4-7 shows the physical connections between the different energy consuming subsystems. The PCON equations are shown in Table 4-8. $R^2$ and standard error of the Y estimate for each PCON are listed below the actual PCONs at the bottom of Table 4-8. The effectiveness of the PCONs can be seen in the $R^2$ values. PCON1, 3, 4, 5, and 7 exhibit acceptable fits. PCON2

**Table 4-7: Rec Center PCON End-Use Distribution Network**

| End-Use Category | PCON1 | PCON2 | PCON3 | PCON4 | PCON5 | PCON6 | PCON7 |
|---|---|---|---|---|---|---|---|
| 1.a Baseload - showers | X | | | | | | X |
| 1.b Baseload - D.H.W. | X | | | | | | X |
| 1.c Baseload - pool | | X | | | | X | |
| 1.d Baseload - laundry | X | | | | X | | X |
| 1.e Baseload - ice resurface | X | | X | X | X | | X |
| 1.f Baseload - generator | | | | | X | | |
| 1.g.Baseload - other | | | | | | | |
| 2.a Space heat - H.V.A.C. | X | | | | | | X |
| 2.b Space heat - radiation | X | | | | | | X |
| 2.c Space heat - ice rinkt | X | | | | | | X |
| 2.d Space heat - pool | X | | | | | | X |
| 2.e Space heat - lobby | X | | | | | | X |
| 2.f Space heat - other | | | | | | | |
| 3.a Electric light - interior | | | X | | | | |
| 3.b Electric light - exterior | | | X | | | | |
| 3.c Electric light - emergency | | | X | | X | | |
| 3.d Electric light - security | | | X | | | | |
| 3.e Electric light - other | | | | | | | |
| 4.a Electric special - rink | X | | X | X | X | | X |
| 4.b Electric special - gutters | | | X | | | | |
| 4.c Electric special - laundry | | | X | | X | | X |
| 4.d Electric special - pool | | | X | | | X | |
| 4.e Electric special - hair dryers | | | X | | | | |
| 4.f Electric special - recepticles | | | X | | | | |
| 4.g Electric special - other | | | | | | | |
| 5.a Electric H.V.A.C. - penthouse | | | X | | | | X |
| 5.b Electric H.V.A.C. - lobby | | | X | | | | X |
| 5.c Electric H.V.A.C. - pool | | | X | | | | X |
| 5.d Electric H.V.A.C. - radiation pumps | | | X | | | | X |
| 5.e Electric H.V.A.C. - snow melt | | | X | | | | X |
| 5.f Electric H.V.A.C. - other | | | | | | | |

PCON1 - Other Steam(lbs/day)
PCON2 - Pool Steam(lbs/day)
PCON3 - Other electric(kwh/day)
PCON4 - Ice rink(kwh/day)
PCON5 - Natural gas(cf/day)
PCON6 - Pool water(gal/day)
PCON7 - Other water(gal/day)

**Table 4-8: Rec Center - Consumption Predictors**

| | | |
|---|---|---|
| PCON1(lbs-steam) "other steam" | $= 81552.179 - 1640.571(EP2) - 2.321(EP2)^3 - 0.001(EP2)^5 + 24.308(OP3) + 0.017(OP8*OP2)$ | $+ 79.407(EP2)^2 + 0.028(EP2)^4 - 481.567(EP3) - 341.500(EP1)$ |
| PCON2(lbs-steam) "pool steam" | $= 1344.790 - 0.010(OP8) - 10.000(EP2) + 53.950(OP2)$ | $- 23.790(OP9) + 4.080(EP3)$ |
| PCON3(kwh) "other electric" | $= 5545.469 + 78.231(OP2) + 3.349(OP3) + 0.224(OP8)$ | $+ 9.521(EP2) - 63.000(SP2)$ |
| PCON4(kwh) "ice rink" | $= 1021.320 + 7.140(OP3) + 5.000(EP2)$ | $- 49.270(SP2) + 19.170(EP3)$ |
| PCON5(cf) "natural gas" | $= 0.000 + 0.190(OP8) + 13.990(OP2)$ | $+ 6.642(SP1) + 1.870(OP3)$ |
| PCON6(gal) "pool water" | $= -204.551 + 176.550(OP9) + 5.860(EP2) - 30.960(EP1)$ | $+ 0.147(OP8) + 9.800(EP3) + 15.190(OP2)$ |
| PCON7(gal) "other water" | $= 8286.350 + 4.070(OP8) - 55.420(EP2) + 227.060(SP2)$ | $- 89.350(EP3) + 267.310(OP2) + 65.790(OP3)$ |

PCON1 - Other steam(lbs/day, $R^2 = 0.98$, $SE_{Yest} = 3451.48$ lbs.)
PCON2 - Pool steam(lbs/day, $R^2 = 0.12$, $SE_{Yest} = 727.57$ lbs.)
PCON3 - Other electric(kwh/day, $R^2 = 0.75$, $SE_{Yest} = 438.12$ kwh)
PCON4 - Ice rink(kwh/day, $R^2 = 0.85$, $SE_{Yest} = 119.22$ kwh)
PCON5 - Natural gas(cf/day, $R^2 = 0.74$, $SE_{Yest} = 186.11$ cf.)
PCON6 - Pool water(gal/day, $R^2 = 0.46$, $SE_{Yest} = 553.14$ gal.)
PCON7 - Other water(gal/day, $R^2 = 0.85$, $SE_{Yest} = 2609.73$ gal.)
EP1 - Wind, average daily (mph)
EP2 - Ambient Temperature, average daily (F)
EP3 - City Water Temperature, sampled daily (F)
EP4 - Solar Radiation, daily totals (Btu/sqft-day)
OP1 - Day of the Week
OP2 - Scheduled Operating Hours (Hours/day)
OP3 - Zamboni Runtime (Minutes/day)
OP8 - Attendance (Persons/day)
OP9 - Pool Backwash (Minutes)
SP1 - Emergency Generator usage (Minutes)
SP2 - Ice rink setpoint temperature (F)

and 6 can be improved. PCON2 and 6 are both related to the heating and the filling of the pools. The consumption of steam and water by the pool is strongly influenced by the pool staff. The low $R^2$ values for the pool steam and pool water indicate the need for further investigation of pool influences.

Overall, the PCONs for the Rec Center can predict the daily energy consumption to within 12 percent. At the current (8/86) cost indices this represents a margin of $62.44 per day or about $22,000 per year.

This chart of interrelationships is important because it is one of the networks used by the CCON to trace possible causes of an abnormal consumption in energy. For example, an abnormal consumption in "other electric" - PCON3, can be attributed to one of fifteen possible sub-systems. Likewise, an abnormal consumption in natural gas can be traced to one of two possible sub-systems. Establishing this chart for a particular building is one of the first steps in setting up the BEACON system.

**4.2.2. Determining Abnormal consumptions**

Abnormal consumptions by the energy consuming sub-systems and their statistical signatures are a fundamental component used to construct the knowledge base for the CCON. These events can be determined by many different methods, for example: possible over-consumptions by sub-systems can be calculated, actual over-consumptions by sub-systems, together with statistically significant signatures can be observed by daily inspections, significant over-consumptions can be forced upon a sub-system and the statistical signature observed during the test.

**Table 4-9: Observed Significant Abnormal Consumptions**

-----General-----

1 Rec Center open extra hours.
2 Janitors coming in early.
3 Administrators and/or students staying late.
4 Building closed during heating season 12/24,12/25,12/31,1/1,11/28
5 Building closed during cooling season .
6 Building closed during swing season 3/28,

-----Ice Rink-----

1 Zamboni ice resurfacing using hot water 10/28,12/5,1/22,4/20, 5/21,
2 Hockey double header 11/15,1/15-17,.
3 Ice skating performance session 12/10,4/19,4/20,,.
4 Ice rink setpoint temperature too cold.
5 Ice rink valving closed off on brine loop 11/7,.
6 Ice rink compressor(s) disabled (under-consumption) 4/21,.
7 Ice rink freon low.
8 Ice rink compressor down.
9 Ice rink krack unit down.
10 Hot water used to melt Zamboni ice 10/10,11/11,.
11 Ice too soft, edges melting.
12 Ice rink room too hot, exhaust off 12/18,,.
13 Ice rink curtains being left open.
14 Ice rink brine leak.
15 Ice rink brine pump(s) broken.
16 Ice thickness exceeds 2 inches.

-----Lighting -----

1 Tennis lights on too long.
2 Interior lites left on all night 12/24,12/25,.
3 Interior lites cross-wired to emergency lites 12/3,.
4 Incandescents being used in gym 11/13,.
5 Lites left on in mechanical rooms 9/30,10/18,10/30,11/3,11/11, 11/15,11/26,12/24,12/27,1/2,1/12,1/14,1/20,2/3,2/4,2/6,2/26, 2/28,3/3,3/7,3/12,3/19,3/20,4/6,5/15,.
6 Emergency lites off in gym and rink 12/1,12/12,1/26,.
7 Spectator lites on in pool room 1/3,2/2,3/4,.

-----Misc. Elec-----

1 Electrical gutter heat tapes on 12/4,12/8-12/15,1/6-1/7,2/11-2/12 2/13-2/14,2/24-2/25,4/4-4/5,.
2 Electrical power outage.
3 Administration office A/C left on at night.

-----laundry-----

1 Extra laundry usage.
2 Hockey double header.

**Observed Significant Abnormal Consumptions (cont.)**

----DHW related----

1 DHW. system setpoint too hot (set to 120 1/17)
2 DHW. system leaking 1/24-1/28,.
3 DHW heat reclaim from steam pit down.
4 DHW heat reclaim from ice rink down 12/7, fixed 1/23.
5 Shower water too cold 2/10,2/19,3/11,.
6 Shower water too hot.

----Pool related problems----

1 Pool deck doors open when O/A <70F.
2 Pool backwashed incorrectly.
3 Pool leaking water 9/9.
4 Pool covers left off at night 9/28,.
5 Pool water loss due to power outage 4/3-4/4,.
6 Pool shut down for cleaning 5/21,
7 Pool filled after cleaning.
8 Pool float valve sticking.
9 Pool room overly-humid 2/5,.
10 Pool balcony carpets wet 11/9,
11 Pool meet being held, 12/6-9.

----Misc heating and cooling----

1 Radiation loop on above 55F 2/26,4/6,4/10,4/11,4/12,4/14,4/21, 4/24,4/25,4/28.
2 Fans running at night to prevent coil freeze-up.
3 Loading ramp snow melt left on 10/11,11/18,12/8,.
4 Water in steam pit room on floor.
5 Administration Office uncomfortable 3/31, (AC on 4/2).
6 Cold air coming down on administrators desk.

----Water consumption----

1 Grounds watering.
2 Tennis courts washed (usually on thursdays).
3 Excessive water due to Zamboni.

NOTE: The influences of these events and the signatures on the various rules can be found in the appendix.

Abnormal consumptions for the Rec Center were taken from those events that were observed by daily inspections. A list of these abnormal consumptions is given in Table 4-9.

### 4.2.3. Assembling the Knowledge Base

The abnormal consumptions by the sub-systems, as shown in Table 4-9, were recorded in a daily log book. For example, under the Ice Rink heading "Zamboni ice resurfacing using hot water" the operators were personally observed to be using hot water for the resurfacing on the dates indicated. The entries shown were then compared to abnormal consumptions for those days to pick up the signatures. These signatures were then entered into the M.1 knowledge base. The "rules" from these are included in the appendix to this report.

The M.1 CCON reads the information from the PCON as an internal M.1 file called a "cache". The cache file used for the sample analysis is shown in the appendix. The CCON then proceeds to determine a (multiple) answer for the goal "abnormal-consumption". In accordance to the procedures of M.1 the CCON looks at the first rule and tries to satisfy the requirements of that rule before proceeding to the next. For a complete analysis of the operating procedure the reader is referred to the M.1 reference (Teknowledge, 1985).

The CCON finishes the analysis when all rules have been considered. The various values for the "abnormal-consumption" goal are then assembled and displayed to the user. The M.1 CCON is a powerful tool because of the ease of the assembly of the rules that form the knowledge base. If a new rule can be determined from daily consumption records, that rule is assembled with an editor and inserted into the stack of rules. In this respect, only the use of a standard editor and a working knowledge of the knowledge base semantics is required. No re-programming is required to expand the knowledge base, only the insertion of the new rule. The complete knowledge base is contained in the appendix along with detail documentation concerning each rule.

### 4.3. BEACON experience at the Rec Center

#### 4.3.1. Sample Analysis

This section contains results from an actual analysis for the week July 13 through July 20, 1986. The following Table 4-10 is a table of the combined conclusions of the log files. The complete log files are included in the appendix in Tables 8-14 through 8-21.

Figures 4-2 through 4-6 are plots of the comparative consumption for 6/1/86 through 7/26/86. In Figure 4-2 the measured consumption is indicated by the "squares", predicted consumption is indicated by the "pluses" and the comparative consumption is indicated by the "diamonds". The x-axis are the dates of the analysis, 1 would be June 1st, 8 for June 8, etc. The y-axis for Figure 4-2 is in thousands of pounds of steam.

Figure 4-3 contains the comparative consumption for other steam, shown as a dollar amount. Figure 4-4 is the comparative consumption for the ice rink compressors, also shown in dollars. Figure 4-4 also contains the ice setpoint temperature.

Figure 4-5 is the comparative consumption for the other electric, in dollars. Figure 4-6 is the comparative consumption for the other water for the same period, also in dollars.

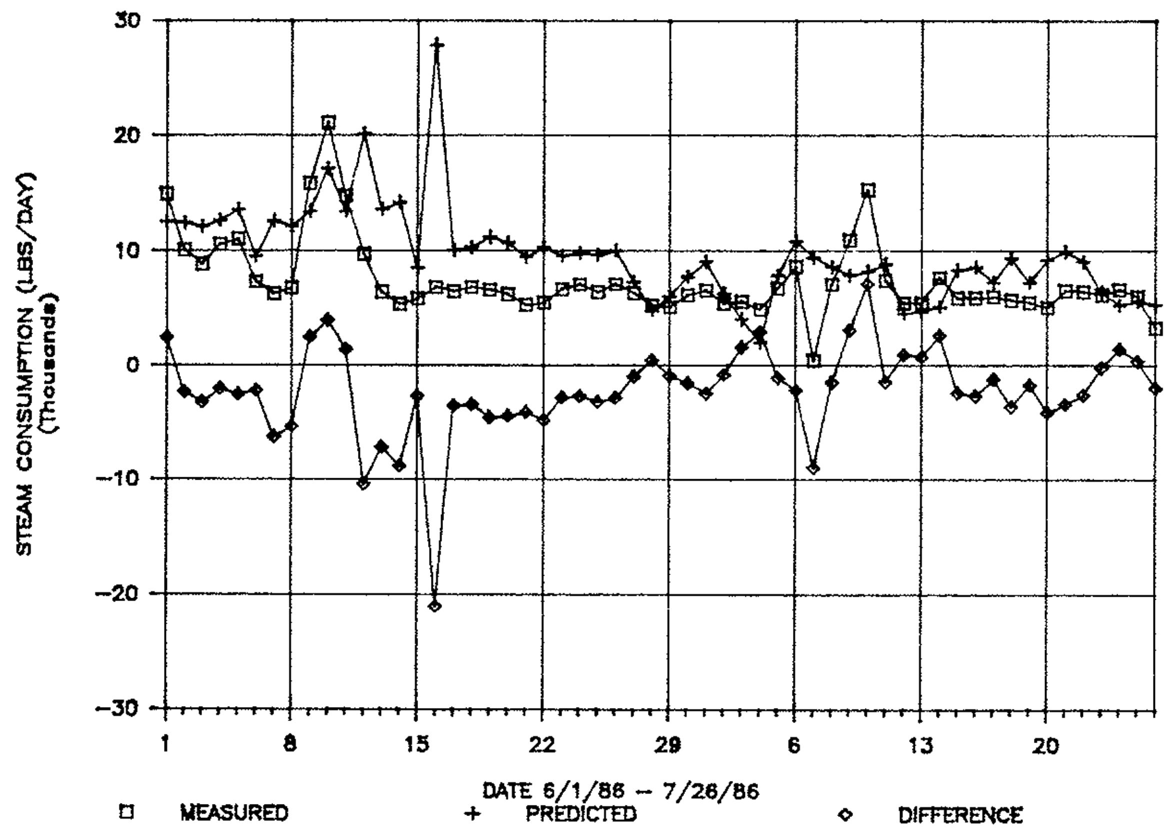



Fig. 4-2: BEACON Sample Analysis (Other Steam 1)

First, some general comments about these comparative graphs. Figure 4-2 and 4-3 show a significant under-consumption June 16, 1986 of about 20,000 lbs ($140). This can be explained by the outside air temperatures for the corresponding period. The recorded average outside-air temperature for June 16 was 42 F. The temperatures for June 15th and 16th were 76 and 77 respectively. Hence this significant under-consumption represents the effect of the thermal mass of the building. Since the PCON does not directly consider thermal mass effects the consumption was over predicted resulting in a significant under-consumption. In reality, the thermal mass in the Rec Center carried the building through June 16 without requiring heating. A savings of $140 had the building been less massive. A similar event occurred on July 7th.

Second, Figure 4-6 shows significant water consumptions for June 3-4 (82,000 gallons), and June 8-10 (253,000). These represent the filling of the diving pool (June 3-4) and the filling of the competition pool (June 8-10). Although these show up as over consumptions, they are in fact considerable savings since both pools usually require 450,000 gallons to fill. This consumption should have showed up on the pool water PCON6 but the meter was inactive at the time since it was being permanently installed. The events that lead to these consumptions are as follows. The valves to the drains in the bottom of the pools were shut. The competition pool was then drained and cleaned, leaving the water in the diving pool. In the past both pools were ususally drained, cleaned and filled. The author noticed a significant energy consumption in steam and water during the annual pool cleaning months and suggested this change in

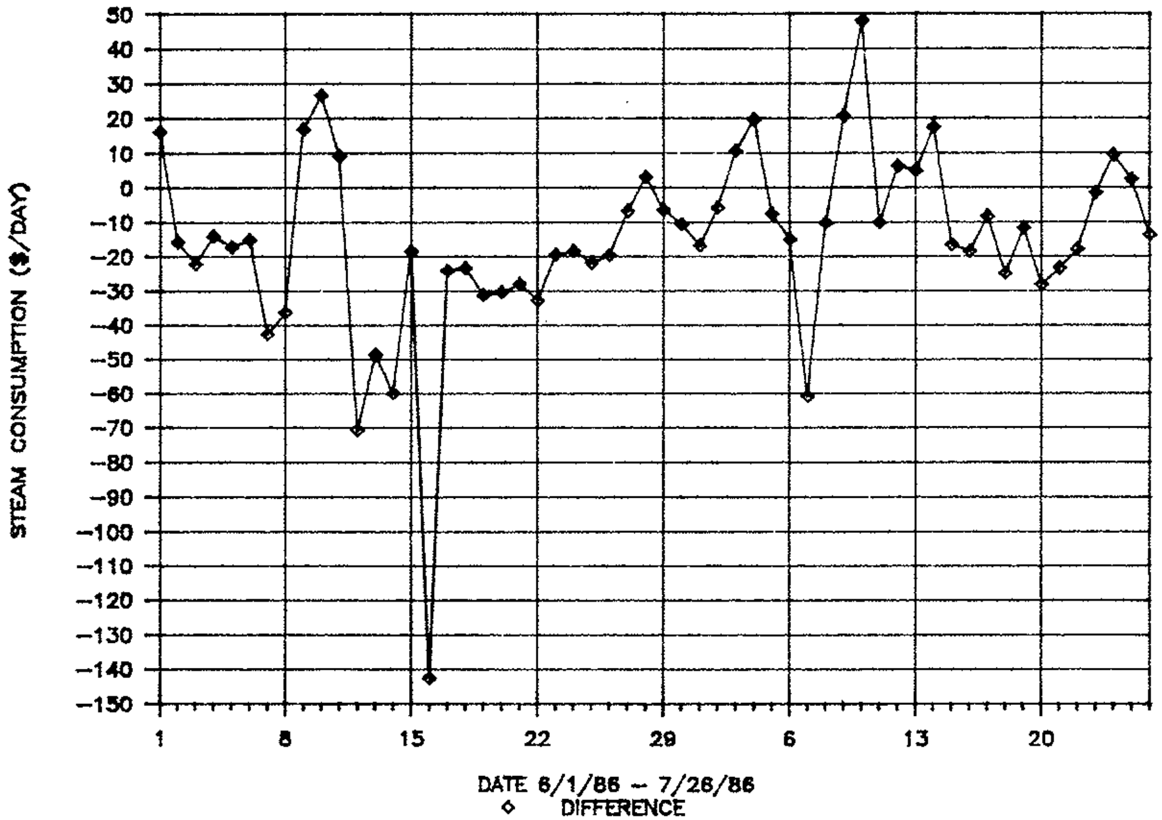



Fig. 4-3: BEACON Sample Analysis (Other Steam 2)

procedure. Once the competition pool was cleaned and rinsed the water from the diving pool was pumped into the competition pool thereby saving water and heating costs. June 3-5 represents the filling of the competition pool. June 9-10 represents the final filling of the diving pool. This savings is expected to increase in the future since the pool staff reported that the pump was unable to draw the water up (15 ft) to the pool deck and into the competition pool. In the future the pump will be placed in the corridor below the pools and the water drawn directly from the associated piping connected to the diving pool.

The week in focus for this analysis is the week of July 13, 1986 through July 20, 1986. This week is chosen because during this week a particular number of events took place that helped to demonstate the effectiveness of the BEACON system and could be traced through interviews with the staff. The events presented in this narrative are those gleaned from interviews with the Rec Center staff.

On Sunday night (July 13) the Zamboni operator noticed that the snow melt pit was not draining. This was evident from the fact that the shaven snow was not melting as usual in the pit. The Zamboni operator mistakenly assumed that the heat reclaim arrangement in the pit was not operational and began to melt the snow with the 140 F hot water hose located at the pit. In actuality, the drain in the pit was clogged, and therefore adding more water to the pit caused the pit to overflow.

Matters were made worse when the Zamboni operator left the hose running in the pit and then left the building for the evening.

In the morning when the Rec Center staff opened the building the errant condition was discovered since the 7,000 gallons that should have gone down the drain now covered the floor of the ice rink and had leaked to the floors below.

Following these events the Rec Center staff lowered the ice rink setpoint temperature to 14.5 degrees since the edges of the ice rink had now melted from the standing water that surrounded them. The staff also turned off the handball court lights in five of the handball courts since the oak flooring was now wet and could not be used until repaired. Later in the week, on July 19, the Rec Center staff contacted Mr. Canfield (Facilities Management) and had the fan runtimes extended through the evening in an attempt to dry out the Rec Center.

In Table 4-10 rules 41 through 61 are used to indicate over of under consumption in general. These rules merely echo the fact that the consumption for a particular PCON is above or below one standard deviation from the norm.

Starting with Figure 4-3 one can trace the effectiveness of the comparative consumption. In Figure 4-3, on July 14, one sees that $17 worth of steam was used to heat the water that was supposed to melt the snow in the pit.

Figure 4-4 shows calculated energy costs to operate the ice rink compressors. The problem occurred here when the staff turned down the rink to 14.5 F. This consumed $149 in excess electricity over a six day period. The rink returned to normal consumption with the return of the setpoint temperature to 16.5 F.

Figure 4-5 shows the effect on the other electric. Since

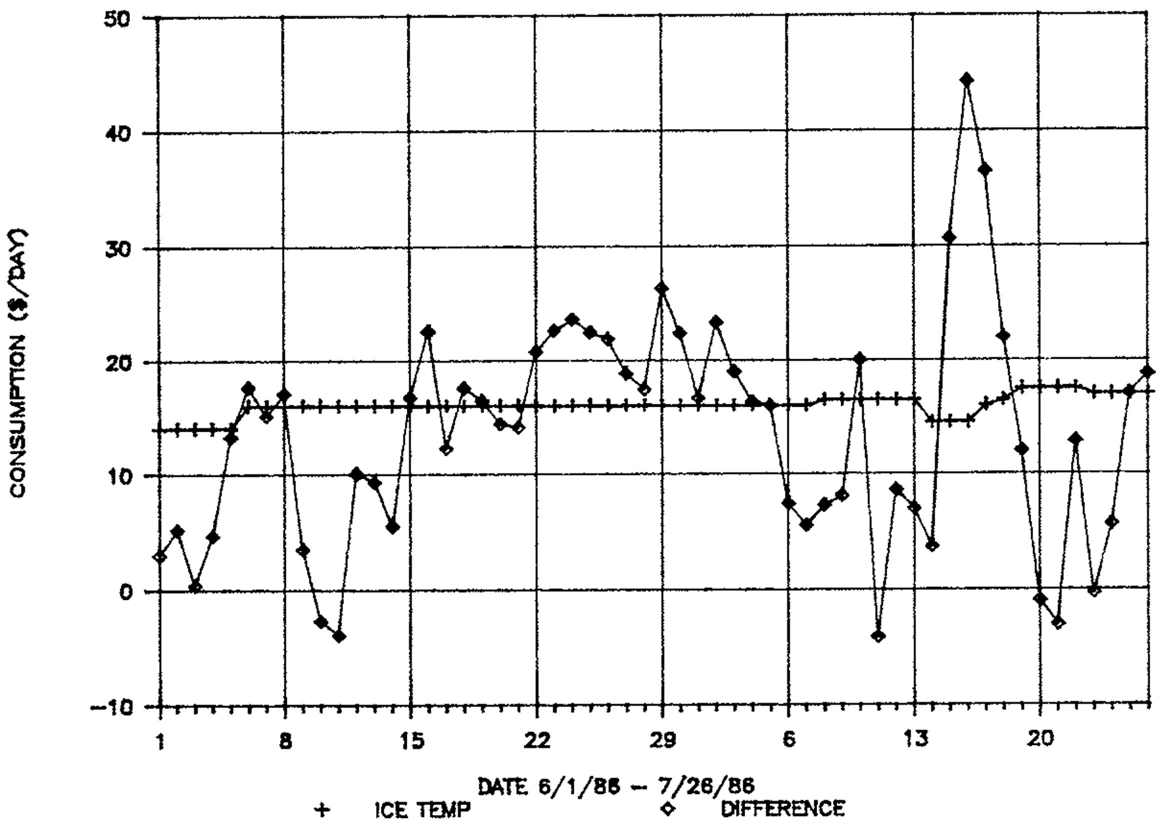



Fig. 4-4: BEACON Sample Analysis (Compressors)

five of the handball courts were now closed, the snow pit event actually saved energy in lighting costs, about $214 from July 14 through July 18. On July 19 the effect of running the fans all evening to remove the stench counter-acted this and returned the building to normal electrical consumption.

The value of the CCON can be seen in Table 4-10. The CCON accurately predicted that hot water had been used in the snow melt pit for both July 13 and July 14. Since the normalization that occurs in the data base tends to average abnormal consumptions over two days, this is expected.

Rule 11, used to look for hot water being used to melt the snow in the snow melt pit, fired because the conditions (excess other steam, excess other water) had been noticed. Rule 11 also asks the user to verify that hot water had been used in the snow melt pit. Rules 58, 47 and 44 are used to indicate abnormal consumptions, in general.

On July 14 rules 58, 55, 48 and 47 indicated general abnormal consumptions, rule 11 indicated, again, that there is or had been trouble with the snow melt pit.

On July 15 rules 58, 55, 48 and 47 again indicated general abnormal consumptions. However, there was not specific evidence to indicate reasons for these causes. One can deduce that the over consumption in the ice rink is being caused by the set point temperature being too low. This condition is accurately pointed out by rule 48.

July 16 has rule 38 firing. Rule 38 concludes that over consumption in the other water category is caused by grounds

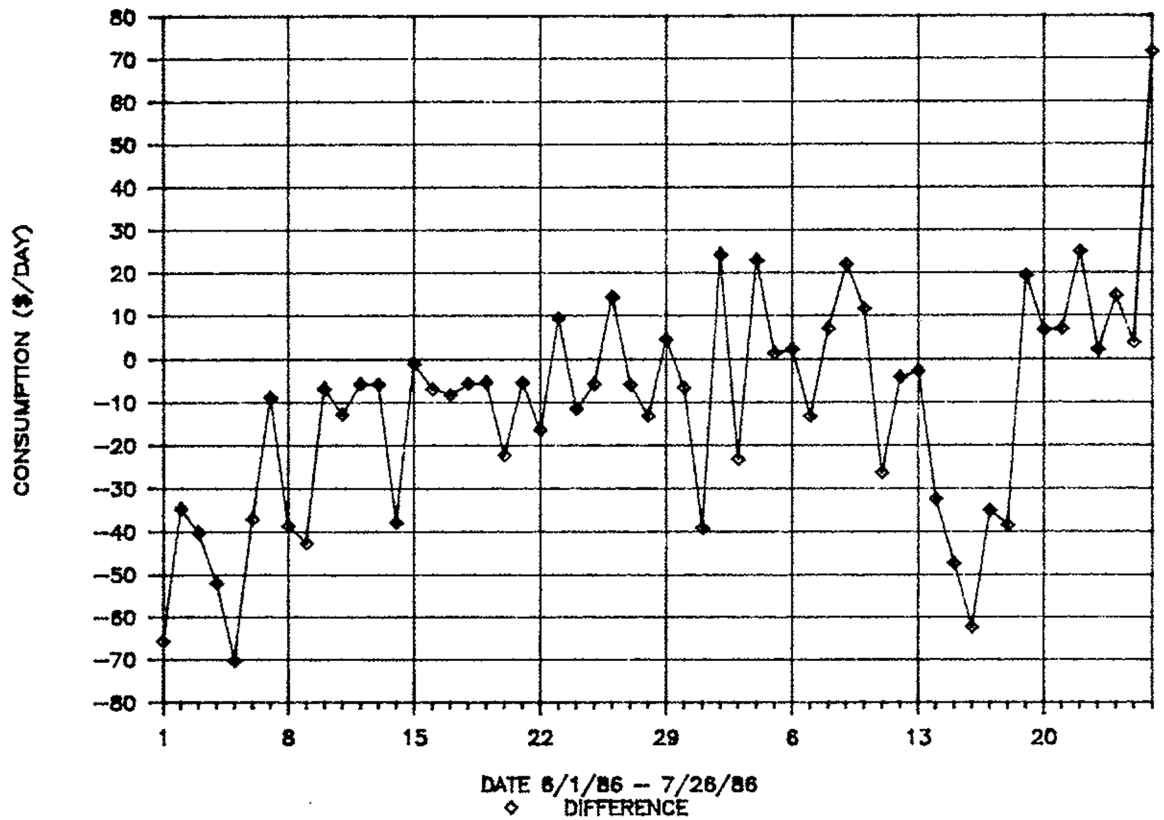



Fig. 4-5: BEACON Sample Analysis (Other Electric)

watering when the outside temperature indicates summertime, ice resurfacing is not excessive and the tennis courts have not been washed lately. The Rec Center staff indicated that the tennis courts are washed every Thursday. Rules 55, 54, 48, 47 and 46 all indicate general abnormal consumption without specific conclusions.

July 17 finally has rule 39 firing. Rule 39 is the indicator for the tennis courts being washed. Rules 55, 47 and 44 also fired indicating general abnormal consumption conditions.

July 18 also has rule 39 firing. Since quite a few thousand gallons of water can be used to wash the tennis courts, the normalizing procedure, again, averages this over two days. Hence the two day indicator. On the 18th rules 55, 44 and 42 also fired indicating that other electric below normal, ice rink consumption was above normal and, unrelatedly, the pool steam was above normal.

July 19 has rule 13 firing. Rule 13 concludes that if the other electric is above the indicated level and the lowest kw measured is above 90 kw (minimum with the lights shut off) then the lights are being left on. Conversations with the staff later indicated that Mr. Canfield (who controls the fans via the Honeywell system) had the fans on and that this was the cause of the electrical over consumption. Both lights being left on and fans being left on have the same signature. Only interviews with the staff can resolve the difference without constant electrical usage monitoring. Further investigation will undoubtedly resolve this. July 20 no rules fired. Only rules 56, 53 and 42 indicate abnormal conditions. In reality, since the rink had been at 14.5 F.

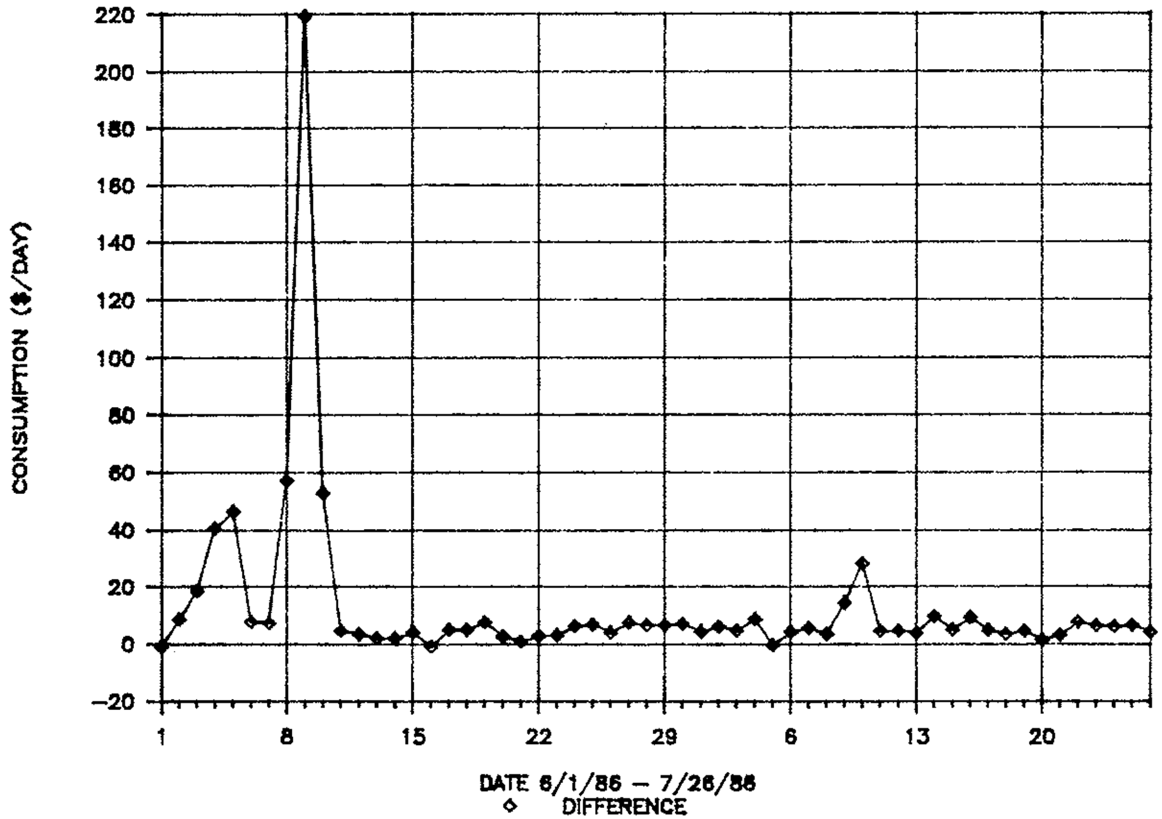



Fig. 4-6: BEACON Sample Analysis (Other Water)

**Table 4-10: BEACON CCON Log Files 7/13-20/86**

```
july13.log
abnormal-consumption = pool-water-below-normal (100%) because rule-58.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = hot-water-for-snow-melt (90%) because rule-11.
july14.log
abnormal-consumption = pool-water-below-normal (100%) because rule-58.
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = ice-setpoint-too-low (100%) because rule-48.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = hot-water-for-snow-melt (90%) because rule-11.
abnormal-consumption = excess-ice-resurfacing (50%) because rule-40.
july15.log
abnormal-consumption = pool-water-below-normal (100%) because rule-58.
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = ice-setpoint-too-low (100%) because rule-48.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
july16.log
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = pool-steam-below-normal (100%) because rule-54.
abnormal-consumption = ice-setpoint-too-low (100%) because rule-48.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = pool-water-above-normal (100%) because rule-46.
abnormal-consumption = natural-gas-above-normal (100%) because rule-45.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = grounds-watering (60%) because rule-38.
july17.log
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = tennis-courts (84%) because rule-39.
july18.log
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = pool-steam-above-normal (100%) because rule-42.
abnormal-consumption = tennis-courts (60%) because rule-39.
july19.log
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = natural-gas-above-normal (100%) because rule-45.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = interior-lites-on-pm (80%) because rule-13.
july20.log
abnormal-consumption = ice-rink-below-normal (100%) because rule-56.
abnormal-consumption = steam-below-normal (100%) because rule-53.
abnormal-consumption = pool-steam-above-normal (100%) because rule-42.
```

for those days indicated, the rink was now coasting since the set point temperature had been brought back up, as indicated.

The performance of the CCON during the week of July 13 through July 20 is acceptable. Certain operational actions were concluded correctly (the snow melt pit hot water usage), others could not be concluded because the information collected in the log book was insufficient. In general, those operational actions and malfunctions that are well predicted need to consume enough energy to show up in the PCONs. Operational actions or malfunctions that do not consume noticeable amounts of energy or are new the the system go unnoticed by the CCON.

### 4.3.2. Fine-Tuning the BEACON system

The installation of the BEACON system at the Rec Center involves dynamically adjusting both the PCONs and the CCON. In the case of the PCONs when significant trends occur the PCON need adjusting. For the CCON, as events are verified and more reliable values can be substituted for calculated or standard deviation indicators.

#### 4.3.2.1. Adjusting the BEACON PCONs

The BEACON PCONs need adjusting when significant trends occur. This occurred at the Rec Center at various times. One example was the ice rink brine valve fix (cf. Table 2-5). The discovery of errant condition and the resultant improvement in the consumption meant that the PCONs were consistently over predicting the energy consumption. To remedy this the PCONs for the ice rink were re-run with the values after the fix. This thereby normalized the consumption to the new values, those occurring after the rink refrigeration system was operating at the reduced level. This same procedure needed to be performed for other PCONs when significant trends occurred. The current application of the BEACON system did not allow for an automatic trend indicator. Therefore, trends needed to be identified visually and the appropriate corrections to the PCONs implemented.

#### 4.3.2.2. Adjusting the BEACON CCON

In a similar fashion to the adjustment of the PCON the CCON periodically needed adjusting. For example, the Zamboni snow melt pit was a known potential problem area. Many observations had been made of the operators using hot water for resurfacing, using hot water to melt excess snow in the pit, etc. Therefore, the initial CCON rules were constructed around calculations and standard deviations. Then, when problem occurred July 13, actual values were available to further fine tune the CCON. In this fashion actual values replace calculated values which replace standard deviations, the initial estimates.

The CCON needs adjusting in this fashion otherwise the conclusions of the CCON will inaccurately reflect assumptions that are out of date. The CCON (listed in the appendix) contains comments and remarks concerning such updates. The reader is referred to those remarks and comments to trace the evolution of the CCON.

# CHAPTER 5

## DISCUSSION

This Chapter presents a discussion of the BEACON system with specific emphasis on the application at the Rec Center. The potential for energy savings is first followed by a discussion of how effective the system has been and finally a discussion of areas for future research.

### 5.1. Potential for Energy Savings

Experience with the Rec Center, has been very rewarding. The process of setting up the system, establishing physical and statistical inter-relations and interviewing the maintenance personnel has yielded a 15 percent savings ($2,500 per month) within the first months of the application. The specific items that led to the savings events are shown in Table 2-5.

In the case of the Rec Center the thorough investigation needed to establish the statistical measurements and assemble the knowledge base uncovered operational inefficiencies, previously overlooked.

The effectiveness of the application of the BEACON to the Rec Center can be seen in Figure 4-7. This figure compares the energy consumption by the Rec Center for 1984/85 and 1985/86. 1984/85 values represent July 1984 through June 1985 and so forth.

In the figure the following symbols are used: squares represent the total monthly steam usage for 1985/86, pluses represent the total electrical consumption for 1985/86, diamonds represent the total energy consumption for 1985/86 (i.e., steam, electric, natural gas, water), the triangles represent the steam consumption for 1984/85, x's represent the electrical consumption for 1984/85 and the inverted triangles represent the total consumption for 1984/85. All values are generated using constant energy costs (6/86).

The savings generated from the application of the BEACON began to show up significantly in November of 1985. The total savings for the building is represented by the shaded area between the total 1984/85 line and the total 1985/86 line. In a similar fashion the electrical and steam savings are illustrated by the shaded areas between the 1984/85 and 1985/86 values for the respective consumptions.

There are some interesting things to note about Figure 4-8. First, the total amount of savings is about $30,000 or 15 percent of the energy consumption. The savings are expected to increase when comparative values become available for July through November. Since the more significant operational problems were found beginning in November (cf. Table 2-5) savings for the application of the BEACON system have not been calculated for July through November. Hence, the expected increase.

Second, electrical savings appear relatively constant throughout the year, steam savings are more significant in the heating month and diminish in the spring. Since, the heating

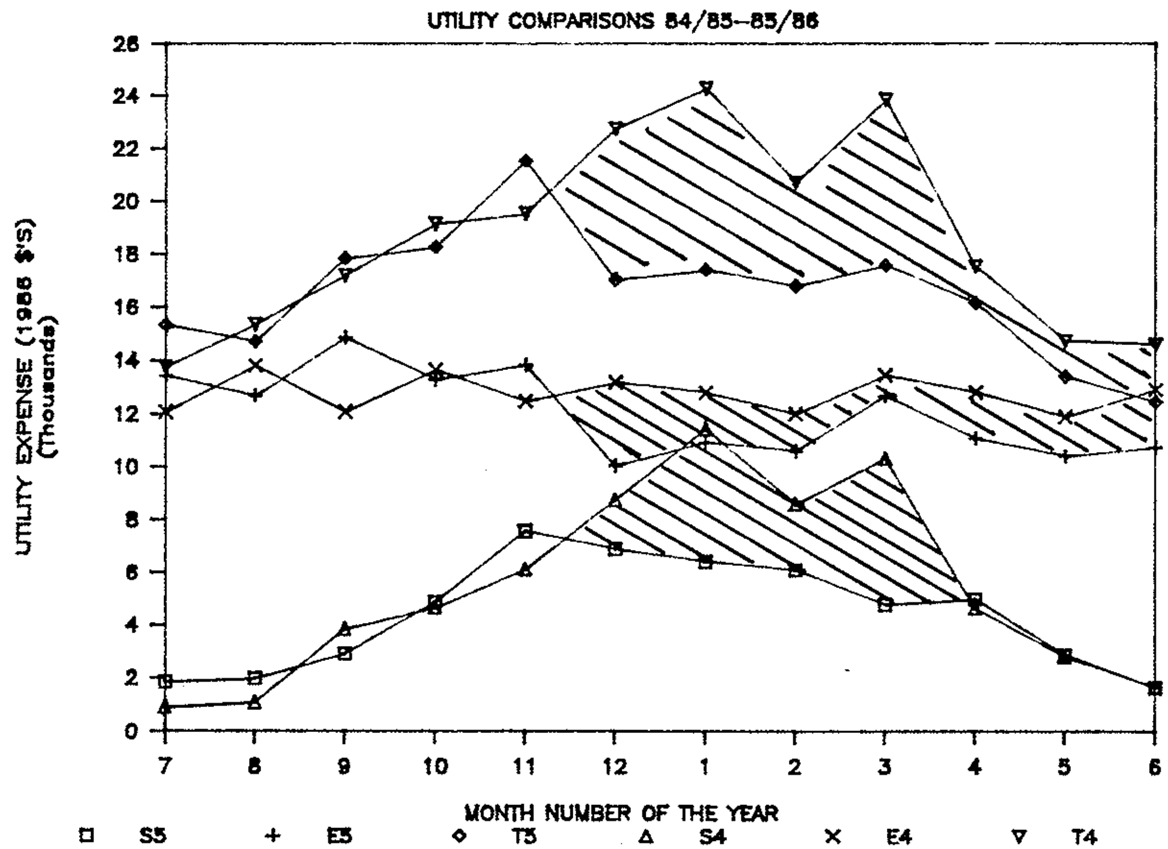



Fig. 5-1: Utility Comparisons 84/85-85/86

requirements for 1984/85 (6,067 F-day (base 65)) and 1985/86 are within 6 percent (5,713 F-day (65)) the steam savings appears to be weather related, versus baseload or domestic water heating related.

### 5.2. Effectiveness of the Expert System

The application of the methodology has yielded mixed results. Certain procedures are spotted with remarkable precision, others go undetected. Bi-monthly reports have been provided for the building administrators that include comparative consumption graphs for each of the meters and a list of conclusions from the expert system that points to possible causes for abnormal consumptions. Once in place the system requires about 8 hours per week from trained maintenance personnel, for the pilot building.

The methodology is somewhat labor intensive, yet maintains significant potential for reducing energy usage. Buildings or complexes with energy consumptions in excess of $200,000 per year can recognize a 1 year payback from the application of the methodology, based on results from the pilot study. The system, once installed, will continue to maintain the building in the "tuned" condition. Again, experience with the pilot building show that operational problems tend to reoccur without constant supervision.

### 5.3. Intended use of the BEACON at the Rec Center

The BEACON systems was developed to help Rec Center administrators reduce energy consumption. Hence, it is intended that the BEACON system be delivered to the Rec Center administration for use at the Rec Center by the Rec Center staff. The BEACON system has shown that it is effective at tracking and identifying certain abnormal energy consuming activities. Therefore, the development and proof-of-concept demonstrates only the first phase of the total development process. The next phase will involve training the Rec Center staff to use the BEACON system, fine-tuning the CCON and adjusting the PCONs as needed.

**5.4. Areas for Future Research**

Many unresolved questions remain concerning the application of the methodology to other buildings. Following is a list of areas for possible research.

1. Refine and streamline the statistical procedures for determining normal and abnormal consumption. The statistical procedures used in the BEACON system, although simple in concept, are labor intensive. Also, a methodology needs to be developed for automatically recalculating the PCONs when significant trends occur and they need to be recalculated. The current system depends on manual interpretation of trends.

2. Refine the methodology in order to produce a site-specific system that can be applied to any building.

3. Develop site-independent systems. The BEACON system, presented here, is a site-specific tool. Almost every aspect of the development relates only to the Rec Center. A site-independent tool would allow for resolution of problems that can be identified from information that could be asked of any site. One such system currently under development attempts to solve stie-independent comfort problems in HVAC systems (Hildebrand, in progress).

4. Extend the application to all systems commonly found in buildings, including plumbing, electric, lighting, safety, fire, etc.

# CHAPTER 6

## CONCLUSIONS

An expert system for building energy consumption analysis has been presented. The system has the potential to reduce energy consumption and improve operational and maintenance procedures. Documented energy savings, attributable to the application of the system, have reduced energy consumption for the pilot building by 15 percent ($30,000), on a building previously studied for energy conservation. The full system, once properly installed, can provide building administrators with a diagnostic tool that can actually keep a building "tuned" and help to further prevent operational problems from reoccuring.

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# APPENDIX

## 8.1. Review of Regression Methods

The work in this thesis necessarily involved the use of "canned" statistical analysis software such as the Lotus 123 package (Lotus, 1985). Since the Lotus software is virtually undocumented, a thorough check of the values presented was necessary for verification purposes. Therefore, a large portion of this section is devoted to verifying the Lotus 123 statistical package used in the thesis. The reader is referred to the references cited for further reading.

Linear regression is the analysis of the linear dependency of one variable upon one or more random variables. The word "regression" is an historical term first used by Galton to describe the tendency of the sons of tall fathers and sons of short fathers to "regress" toward an average height (cited in Kreysig, 1970, p. 285).

Regression techniques have been widely used in the building energy field to establish the parameters that influence energy consumption. The techniques for the application of linear regression are well documented. Recent examples include: parametric curve fit used to represent passive solar performance of various building configurations (Balcomb, 1980); the important, precedence setting work of the Princeton Scorekeeping Method (CEES, 1986); linear regression techniques used to normalize the effects of weather in energy conservation retrofit analysis (Goldman, 1986); the Statistical Package for the Social Sciences (SPSS) linear regression used to analyze measured heat loss and gains in houses used to validate the Variable Base Degree-Day (VBDD) method (Hamzawi, 1984); the use of multiple linear regression, available through the Statistical Analysis System (SAS, 1982) to identify which time varying parameters that effect energy consumption at U.S. Army Armament installations (Leslie, 1986).

The analysis by Leslie (1986) is of particular importance because the parameters identified for each Armament site are then used to forecast energy consumption. This is similar to the approach chosen for the BEACON system with one significant difference, the time scale for the BEACON analysis is daily rather than the monthly scale used in the Armament study.

**8.2. Simple Linear Regression**

Linear regression is a mathematical method for fitting lines to data points that yields predictable results independent of the user. One of the most widely used procedures is the method of least squares developed by Gauss (cited in Kreysig, 1970, p. 287). This method has become the defacto standard among commonly available statistical packages. The following review of the method illustrates how it has been applied to the Rec Center steam consumption. The basics of linear regression are presented followed by the extension of linear regression to piecewise, multiple, linear regression using backward elimination. In this section, the review of the theory is the principal focus. The description of the theory also serves as a verification of the values obtained with the Lotus 123 Version 2 multiple linear regression package (Lotus, 1985). The actual keystroke spreadsheet entries and explanation of the database is presented in the appendix.

Linear regression, using Ordinary Least Squares (OLS), is a simple yet powerful tool for analyzing dependence of one variable on one or more independent variables (Wonnacott, 1985). Typically, the objective of linear regression is to fit a straight line to a set of data points. Many different methods are used to express the basic equations (Kreysig, 1970), (Kerlinger and Pedhazur, 1973), (Norusis, 1983), (Wonnacott, 1985), (Draper and Smith, 1981), (Mosteller and Tukey, 1977). In this treatment of the regression methods used in the PCONs, Kreysig (1970) was found to be of assistance in the derivation of the methods; Wonnacott (1985) was very useful in the wording of the statistical expressions; and finally, methods described in Kerlinger and Pedhazur (1981) were adapted in the example used to verify the Lotus 123 (1985) software.

The review of linear regression and multiple linear regression is adapted from the text of Kerlinger and Pedhazur (1973). The fundamental form of the linear regression equation with one regressor can be expressed as:

$$Y' = a + bX \qquad \text{(VIII.1)}$$

where

$Y'$ are the estimates of the dependent variable,

$a$ is the intercept of the $Y'$ axis by the regression line, b is the regression coefficient for the independent variable,

X is the observed independent variable.

Since, quite often, large numbers of variables are used to obtain the regression line, certain statistical bookkeeping chores help to keep the process orderly. One of these is to track the observed dependent variable, Y, and the observed independent variable X, as their deviations from the mean of all the variables being sampled. To do this the following substitution is used:

$$x = X - \bar{X} \qquad \text{(VIII.2)}$$

and

$$y = Y - \bar{Y}, \qquad \text{(VIII.3)}$$

where

$$\bar{X} = \frac{\sum_{i=1}^{n} X}{N} \qquad \text{(VIII.4)}$$

and

$$\bar{Y} = \frac{\sum_{i=1}^{n} Y}{N} \qquad \text{(VIII.5)}$$

In these equations, Y and X are the observed dependent and independent variables, y and x are then the deviations from the mean of the dependent and independent variables. N is the number of variables in the sample.

We can now express the regression coefficient for the independent variable X as:

$$b = \frac{\sum_{i=1}^{n} xy}{\sum_{i=1}^{n} x^2} \qquad \text{(VIII.6)}$$

and, for the y intercept:

$$a = \bar{Y} - b\bar{X}. \qquad \text{(VIII.7)}$$

The regressor, b, is therefore the sum of squares divided by the sum of the cross products, each of which are given by

$$\sum_{i=1}^{n} xy = \sum_{i=1}^{n} XY - \frac{\sum_{i=1}^{n} X * \sum_{i=1}^{n} Y}{N} \qquad \text{(VIII.8)}$$

and

$$\sum_{i=1}^{n} x^2 = \sum_{i=1}^{n} X^2 - \frac{(\sum_{i=1}^{n} X)^2}{N} \qquad \text{(VIII.9)}$$

One method that is commonly used to determine the goodness of the fit is the coefficient of determination, $r^2$. $r^2$ represents the proportion of the variance of Y that has been "determined" by X (Kerlinger and Pedhazur, 1973, p.15). The variance then is "the average of the squared deviations from the mean of a set of measures" (Kerlinger and Pedhazur, 1973, p. 14). The $r^2$ is given by

$$r^2_{xy} = \frac{\left(\sum_{i=1}^{n} xy\right)^2}{\sum_{i=1}^{n} x^2 * \sum_{i=1}^{n} y^2} \qquad \text{(VIII.10)}$$

So far this analysis has been limited to one independent variable and one dependent variable. The governing equation determines the best linear fit. Often, as was the case for the Rec Center study, more than one independent variable needed to be examined. One efficient way to consider additional dependent variables uses matrix notation. This matrix notation can also be used to describe the previous simple linear regression. In the next section, multiple linear regression is discussed, including an example and the verification of the Lotus 123 (1985) software.

## 8.3. Multiple Linear Regression

### 8.3.1. Description of the Method

Multiple linear regression is easily extended to include many independent variables. The governing equation takes the form

$$Y' = a + b_1X_1 + b_2X_2 + \ldots + b_kX_k \qquad \text{(VIII.11)}$$

where

$Y'$ is the predicted dependent variable,

$a$ is the intercept constant,

$b_1..b_k$ are the regression coefficients for $X_1$ thru $X_k$.

Since we are dealing with k regression coefficients, we need k equations for the solution. Kerlinger and Pedhazur's (1973) notation will, again, be used throughout this development. Three variables are discussed in the following development, the method holds for any number of variables.

The principal set of equations can be written as

$$\begin{aligned} B_1 + r_{12}B_2 + r_{13}\ B_3 &= r_{y1} \\ r_{21}B_1 + B_2 + r_{23}\ B_3 &= r_{y2} \\ r_{31}B_1 + r_{32}B_2 + \ B_3 &= r_{y3}. \end{aligned} \qquad \text{(VIII.12)}$$

This can be rewritten in terms of the component matrices.

$$[R_{ij}][B_j] = [R_{yj}] \qquad \text{(VIII.13)}$$

where

$R_{ij}$ is the matrix of intercorrelations of the independent variables,

$B_j$ are the unknown population regression weights,

$R_{yj}$ are the intercorrelations between the dependent variable Y and the dependent variables $X_1$, $X_2$, and $X_3$.

$r_{ij}$ are the individual elements in the $R_{ij}$ matrix.

The matrix notation then appears as

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} * \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} r_{y1} \\ r_{y2} \\ r_{y3} \end{bmatrix}. \qquad \text{(VIII.14)}$$

Since we are solving for the population regression coefficients, Bj, we invert the intercorrelation matrix of the independent variables and multiply by the matrix or vector of the intercorrelation between the dependent variable and independent variables, thus,

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}^{-1} * \begin{bmatrix} r_{y1} \\ r_{y2} \\ r_{y3} \end{bmatrix}. \qquad \text{(VIII.15)}$$

The estimated regression coefficients, $b_j$, can then be calculated from the now determined population regression coefficients, $B_j$.

$$b_j = \frac{B_j \cdot s_y}{s_j} \qquad \text{(VIII.16)}$$

where

$s_y$ is the standard deviation of the y variable

$s_j$ is the standard deviation of the jth variable.

Finally, the intercept can be calculated from

$$a = \bar{Y} - b_1\bar{X}_1 - b_2\bar{X}_2 - b_3\bar{X}_3. \qquad \text{(VIII.17)}$$

The independent-independent intercorrelation variables, $r_{ij}$, and the dependent-independent intercorrelation variables, $r_{yj}$, are coefficients of correlation in standard score form. A standard score is a standard deviation representation. It represents the deviation from the mean divided by the standard deviation. The standard scores, using equations VIII.18 through VIII.20 have a mean of 0 and a standard deviation of 1. These intercorrelation variables are useful in determining if a dependence exists between assumed independent variables. $r_{ij}$ then represents the sum of the products of these two standard score variables divided by the number of cases, thus

$$r_{ij} = \frac{\sum_{i=1}^{n} z_x z_y}{N} \qquad \text{(VIII.18)}$$

The $z_x$ and $z_y$ are the standard score of the X and Y variables, respectively, N is the number of cases in the sample. The $z_{ij}$ variables are calculated from

$$z_x = \frac{X - \bar{X}}{s_x} = \frac{x}{s_x} \qquad \text{(VIII.19)}$$

and

$$z_y = \frac{Y - \bar{Y}}{s_y} = \frac{y}{s_y}. \qquad \text{(VIII.20)}$$

X and Y are the observed values of the independent and dependent variables, $\bar{X}$ and $\bar{Y}$ are the averages for the set, $s_y$ and $s_x$ are the standard deviations for each variable, respectively and x and y are the deviation scores for each variable. The standard deviation for each independent and dependent variable is found from

$$s_x = \left[ \frac{\sum_{i=1}^{n} x^2}{(N-1)} \right]^{\frac{1}{2}} \qquad \text{(VIII.21)}$$

and

$$s_y = \left[ \frac{\sum_{i=1}^{n} y^2}{(N-1)} \right]^{\frac{1}{2}} \qquad \text{(VIII.22)}$$

where

$$\sum_{i=1}^{n} x^2 = \sum_{i=1}^{n} X^2 - \frac{(\sum_{i=1}^{n} X)^2}{N} \qquad \text{(VIII.23)}$$

and

$$\sum_{i=1}^{n} y^2 = \sum_{i=1}^{n} Y^2 - \frac{(\sum_{i=1}^{n} Y)^2}{N} \qquad \text{(VIII.24)}$$

One needs certain indices to judge whether or not the regression line is fitting the data in an appropriate fashion. One of these indices is the standard error of the estimate. The standard error of the estimate is "an index of the variation or dispersion of the predicted Y measures about the regression" (Kerlinger and Pedhazur, 1973, p. 66). A large standard error of the estimate means a larger dispersion of the estimate of Y based on the X's used as the independent variables. One form of the standard error of the estimate is

$$SE_{est} = \left[\frac{ss_{res}}{N-k-1}\right]^{\frac{1}{2}} \quad (VIII.25)$$

where

$ss_{res}$ is the sum of squares of the residuals, found from

$$ss_{res} = \sum_{i=1}^{n} d^2 \quad (VIII.26)$$

$$d = Y - Y'. \quad (VIII.27)$$

and

Y is the observed dependent variable,

Y' is the estimated dependent variable,

N is the number of cases in the sample,

K is the number of independent variables, and

(N - K - 1) represents the degrees of freedom.

Often, each of the regressors needs to be evaluated. One method of doing so is to consider the standard error of the b coefficients. The formula for this is

$$SE_{bj} = \left[\frac{SE_{est}^{2}}{ss_{x1}(1-R_j^{2})}\right]^{\frac{1}{2}} \quad (VIII.28)$$

$SE_{est}$ is the squared standard error of the estimate,

$ss_{xj}$ is the sum of squares of the xj independent variable,

$R_j^2$ is the "squared multiple correlation between the jth independent variable and the remaining independent variables" (Kerlinger and Pedhazur, 1973, p. 67).

The $R_j^2$ can be found from

$$R_j^2 = 1 - \frac{1}{r^{jj}} \quad \text{(VIII.29)}$$

where

$r^{jj}$ are "the diagonal values of the inverse of the matrix of correlations among the independent variables". (Kerlinger and Pedhazur, 1973, p. 67).

Another valuable indicator of the fit of the regression equation to the observed data is the square of the multiple correlation coefficient, $R^2$, also called the coefficient of determination. R represents the product-moment correlation of the predicted Y's and the observed Ys. An $R^2$ value of unity would indicate a perfect fit, meaning that the regression line exactly predicts all the observed data. Should the data points be randomly scattered, the $R^2$ value would be zero. An $R^2$ of 0.80 would mean that 80 percent of the variance of the observed Y is accounted for by the $X_j$'s in the regression equation. $R^2$ can be calculated from

$$R^2 = \frac{ss_{reg}}{ss_t} \qquad \text{(VIII.30)}$$

It can also be calculated from

$$R^2 = 1 - \frac{ss_{res}}{ss_t} \qquad \text{(VIII.31)}$$

where

$ss_{reg}$ is the regression sum of squares,

$ss_t$ is the total sum of squares, and

$ss_{res}$ is the residual sum of squares.

By definition, the total sum of squares, the regression sum of squares, and the residual sum of squares are related through

$$ss_t = ss_{reg} + ss_{res}. \qquad \text{(VIII.32)}$$

It is also helpful to know that

$$ss_t = \sum_{i=1}^{n} y^2 \qquad \text{(VIII.33)}$$

and, from before

$$ss_{res} = \sum_{i=1}^{n} d^2 \qquad \text{(VIII.34)}$$

where

$$d = Y - Y'. \qquad \text{(VIII.35)}$$

This allows for the following, after substitution

$$R^2 = 1 - \frac{\sum_{i=1}^{n} d^2}{\sum_{i=1}^{n} Y^2 - \frac{(\sum_{i=1}^{n} Y)^2}{N}} \qquad \text{(VIII.36)}$$

The importance of each regressor can be evaluated by considering the t-ratio of each regressor. The t-ratio is a method of determining which variables are significant and which are not. Although a complete explanation of the t-ratio is quite lengthy (Kerlinger and Pedhazur, 1973, p. 68) the application to the choice of regressors is easy to understand. The t-ratio compares the size of the coefficient for each regressor to the size of the standard error for that coefficient. A t-ratio of less than one indicates that the error for the coefficient is greater than the value of the coefficient itself and therefore a variable with a ratio of less than unity is introducing more error into the expression than is influencing the expression. One picks a lower limit (unity in this case) for the t-ratio and should discard all regressors displaying a value below that limit. The t-ratios can be expressed as

$$t_j = \frac{b_j}{SE_{bj}} \qquad \text{(VIII.37)}$$

where

$b_j$ is the regression coefficient for the jth independent variable,

$SE_{bj}$ is the standard error of the jth regressor, and for this expression the degrees of freedom are N - k - 1, (Kerlinger and Pedhazur, 1973).

**8.3.2. Choosing regressors**

When faced with a large number of independent regressors one needs a systematic method of eliminating those regressors that do not contribute significantly to the overall prediction. Aside from extrastatistical judgement, there are many procedures in common use (Draper and Smith, 1981). Two that are often available in statistical software packages are a stepwise procedure and backward elimination. The stepwise regression procedure begins with the most important regressor, determined from the t-ratio, and introduces additional variables in the order of their t-ratio. Once the highest $R^2$ has been reached, the procedure halts.

Backward elimination considers all variables first, then eliminates those variables that do not meet an established criteria. The remainder are then rearranged and can be eliminated, one-at-a-time until until the highest $R^2$ value results.

**8.3.3. Relationships Among Regressors**

Often, independent regressors exhibit interdependencies or intercorrelations. These relationships show up in the independent-independent intercorrelation matrix. When this occurs the structuring of the set of independent variables needs to be reformed. Either one or more of the variables can be removed from the analysis, or the variables can be combined into a single variable (Little, 1986; Coulter, 1986). The effects of interdependencies are shown in the following example. In the PCON analysis, all independent variables were checked against each other. Intercorrelations greater than 50 percent were used to indicate interdependencies. Variables that exhibited interdependencies were combined.

**8.3.4. Analysis of Residuals**

Another useful tool in the analysis of dependency upon one or more independent variables is the analysis of the residual

(Draper and Smith, 1981). The residual is defined as the difference between the predicted and the observed values for the dependent variable

$$e_i = Y_i - Y' \text{ for } i = 1, 2, 3 \ldots N \qquad \text{(VIII.38)}$$

where

$Y_i$ is the observed dependent variable,

$Y'$ is the predicted dependent variable.

$e_i$ represents the individual pairs for N cases.

The foundation of regression analysis is closely centered around errors that are independent, normally distributed and have a mean centered around the regression line. Any residual that does not display these characteristics indicates that the current regression expression does not adequately describe the behavior of the dependent variable. Satisfactory residuals should display a plots that are randomly distributed about the mean. The mean of these plots represents zero deviation from the estimated value of the regression expression.

A commonly used method for analysis of residuals involves plotting the residuals and visually observing any trends that exist. Residuals can be analyzed using an overall or histogram type plot, in regards to a time sequence, in comparison to the observed Y values, or in comparison to any of the independent variables.

Residuals can be used to determine if the analysis should be reformed. Some typical trends that can be pointed out are: residuals that indicate a curvilinear or non-linear relationship, residuals that indicate an inappropriate intercept, or residuals that display an increasing variance indicating that the estimated values "fit" one range of the data but not another (a candidate for weighted least squares).

Statistical methods have been developed to help analyze residuals. The residual analysis used in the PCONs is basically a graphic analysis of the residuals. Methods presented in Draper and Smith (1981) and Kerlinger and Pedhazur (1973) are reasonably lengthy. The reader is referred to those references for further reading.

**8.3.5. Multiple Linear Regression Example.**

An example of the multiple linear regression used throughout the PCON analysis is presented in this section. This example serves a number of important purposes. First, the Lotus 123 (1985) software is undocumented. So, this example serves as a verification of the values obtained with the Lotus 123, version 2, software (1985). Second, the information obtained from a 123 analysis consists of only the final results. Values for the intercorrelation matrix are unavailable and can only be obtained by tracing through the entire method. Finally, there are many different methods used to analyze regression coefficients. This example is the extracted from the method described by Kerlinger and Pedhazur (1973). This example spans 80 pages in that text, yet it was the most concise explanation of matrix representation of multiple linear regression found.

The observed data represents Rec Center data for the period December 15, 1985 to January 16, 1985. These values are shown in Tables 8-1 through 8-5. The example is limited to three independent variables. The dependent variable is the measured kilowatt-hour consumption at the Rec Center taken at daily intervals. The $X_1$ variable is the daily doorcount of persons entering the Rec Center. The $X_2$ variable is the recorded average daily outside temperature. The $X_3$ variable is the hours of operation for that day as listed in the schedule.

**Table 8-1: Observed Variables**

| MO | DA | YR | Y | $X_1$ | $X_2$ | $X_3$ |
|---|---|---|---|---|---|---|
| 12 | 15 | 85 | 5658 | 984 | 32 | 12 |
| 12 | 16 | 85 | 6380 | 1638 | 42 | 15 |
| 12 | 17 | 85 | 5921 | 1660 | 40 | 15 |
| 12 | 18 | 85 | 5860 | 1567 | 37 | 15 |
| 12 | 19 | 85 | 5698 | 1487 | 37 | 15 |
| 12 | 20 | 85 | 5566 | 1105 | 39 | 15 |
| 12 | 21 | 85 | 4616 | 642 | 48 | 9 |
| 12 | 22 | 85 | 4528 | 514 | 45 | 9 |
| 12 | 23 | 85 | 5272 | 713 | 44 | 9 |
| 12 | 24 | 85 | 4165 | 0 | 35 | 0 |
| 12 | 25 | 85 | 4157 | 0 | 40 | 0 |
| 12 | 26 | 85 | 4869 | 678 | 40 | 9 |
| 12 | 27 | 85 | 5604 | 760 | 26 | 9 |
| 12 | 28 | 85 | 5051 | 667 | 34 | 9 |
| 12 | 29 | 85 | 4837 | 610 | 38 | 9 |
| 12 | 30 | 85 | 5169 | 826 | 34 | 9 |
| 12 | 31 | 85 | 4588 | 0 | 32 | 0 |
| 1 | 1 | 86 | 4123 | 0 | 46 | 0 |
| 1 | 2 | 86 | 5105 | 1219 | 41 | 12 |
| 1 | 3 | 86 | 5262 | 1188 | 42 | 12 |
| 1 | 4 | 86 | 4754 | 835 | 27 | 10 |
| 1 | 5 | 86 | 5367 | 832 | 36 | 10 |
| 1 | 6 | 86 | 4756 | 1202 | 38 | 12 |
| 1 | 7 | 86 | 5682 | 1413 | 32 | 12 |
| 1 | 8 | 86 | 5551 | 1372 | 37 | 12 |
| 1 | 9 | 86 | 4927 | 1310 | 45 | 12 |
| 1 | 10 | 86 | 5377 | 1269 | 44 | 12 |
| 1 | 11 | 86 | 5258 | 935 | 54 | 10 |
| 1 | 12 | 86 | 5049 | 790 | 41 | 10 |
| 1 | 13 | 86 | 5361 | 1488 | 48 | 12 |
| 1 | 14 | 86 | 5055 | 1539 | 45 | 12 |
| SUM = | | | 159566 | 29243 | 1219 | 307 |
| MEAN = | | | 5147.29 | 943.32 | 39.32 | 9.90 |
| SUM2 = | | | 2.5E+10 | 8.6E+08 | 1485961 | 94249 |

Y is the measured daily KWH reading for the Rec Center less the electricity consumed by the compressors.
$X_1$ is the daily attendance measured by doorcounts (persons).
$X_2$ is the average daily temperature (F), recorded on site.
$X_3$ is the schedules hours of operation for each day.

**Table 8-2: $Y^2$, $X_1^2$, $X_3^2$, $X_1-\bar{X}_1$ Values.**

| MO | DA | YR | $Y^2$ | $X_1^2$ | $X_2^2$ | $X_3^2$ | $X_1-\bar{X}_1$ |
|---|---|---|---|---|---|---|---|
| 12 | 15 | 85 | 32012964 | 968256 | 1024 | 144 | 40.68 |
| 12 | 16 | 85 | 40704400 | 2683044 | 1764 | 225 | 694.68 |
| 12 | 17 | 85 | 35058241 | 2755600 | 1600 | 225 | 716.68 |
| 12 | 18 | 85 | 34339600 | 2455489 | 1369 | 225 | 623.68 |
| 12 | 19 | 85 | 32467204 | 2211169 | 1369 | 225 | 543.68 |
| 12 | 20 | 85 | 30980356 | 1221025 | 1521 | 225 | 161.68 |
| 12 | 21 | 85 | 21307456 | 412164 | 2304 | 81 | -301.32 |
| 12 | 22 | 85 | 20502784 | 264196 | 2025 | 81 | -429.32 |
| 12 | 23 | 85 | 27793984 | 508369 | 1936 | 81 | -230.32 |
| 12 | 24 | 85 | 17347225 | 0 | 1225 | 0 | -943.32 |
| 12 | 25 | 85 | 17280649 | 0 | 1600 | 0 | -943.32 |
| 12 | 26 | 85 | 23707161 | 459684 | 1600 | 81 | -265.32 |
| 12 | 27 | 85 | 31404816 | 577600 | 676 | 81 | -183.32 |
| 12 | 28 | 85 | 25512601 | 444889 | 1156 | 81 | -276.32 |
| 12 | 29 | 85 | 23396569 | 372100 | 1444 | 81 | -333.32 |
| 12 | 30 | 85 | 26718561 | 682276 | 1156 | 81 | -117.32 |
| 12 | 31 | 85 | 21049744 | 0 | 1024 | 0 | -943.32 |
| 1 | 1 | 86 | 16999129 | 0 | 2116 | 0 | -943.32 |
| 1 | 2 | 86 | 26061025 | 1485961 | 1681 | 144 | 275.68 |
| 1 | 3 | 86 | 27688644 | 1411344 | 1764 | 144 | 244.68 |
| 1 | 4 | 86 | 22600516 | 697225 | 729 | 100 | -108.32 |
| 1 | 5 | 86 | 28804689 | 692224 | 1296 | 100 | -111.32 |
| 1 | 6 | 86 | 22619536 | 1444804 | 1444 | 144 | 258.68 |
| 1 | 7 | 86 | 32285124 | 1996569 | 1024 | 144 | 469.68 |
| 1 | 8 | 86 | 30813601 | 1882384 | 1369 | 144 | 428.68 |
| 1 | 9 | 86 | 24275329 | 1716100 | 2025 | 144 | 366.68 |
| 1 | 10 | 86 | 28912129 | 1610361 | 1936 | 144 | 325.68 |
| 1 | 11 | 86 | 27646564 | 874225 | 2916 | 100 | -8.32 |
| 1 | 12 | 86 | 25492401 | 624100 | 1681 | 100 | -153.32 |
| 1 | 13 | 86 | 28740321 | 2214144 | 2304 | 144 | 544.68 |
| 1 | 14 | 86 | 25553025 | 2368521 | 2025 | 144 | 595.68 |
| SUM = | | | 830076348 | 35033823 | 49103 | 3613 | -1.5E-12 |

**Table 8-3: $X_2-\bar{X}_2$, $X_3-\bar{X}_3$, $Y-\bar{Y}$, $Z_1*Z_2$, $Z_1*Z_3$, $Z_2*Z_3$ Values**

| MO | DA | YR | $X_2-\bar{X}_2$, | $X_3-\bar{X}_3$, | $Y-\bar{Y}$, | $Z_1*Z_2$, | $Z_1*Z_3$, | $Z_2*Z_3$ |
|---|---|---|---|---|---|---|---|---|
| 12 | 15 | 85 | -7.32 | 2.10 | 510.71 | 0.081637 | -1.17316 | 0.479893 |
| 12 | 16 | 85 | 2.68 | 5.10 | 1232.71 | 1.394173 | 0.428954 | 1.166510 |
| 12 | 17 | 85 | 0.68 | 5.10 | 773.71 | 1.438326 | 0.108530 | 1.166510 |
| 12 | 18 | 85 | -2.32 | 5.10 | 712.71 | 1.251681 | -0.37210 | 1.166510 |
| 12 | 19 | 85 | -2.32 | 5.10 | 550.71 | 1.091126 | -0.37210 | 1.166510 |
| 12 | 20 | 85 | -0.32 | 5.10 | 418.71 | 0.324476 | -0.05168 | 1.166510 |
| 12 | 21 | 85 | 8.68 | -0.90 | -531.29 | -0.60473 | 1.390227 | -0.20672 |
| 12 | 22 | 85 | 5.68 | -0.90 | -619.29 | -0.86162 | 0.909591 | -0.20672 |
| 12 | 23 | 85 | 4.68 | -0.90 | 124.71 | -0.46224 | 0.749379 | -0.20672 |
| 12 | 24 | 85 | -4.32 | -9.90 | -982.29 | -1.89318 | -0.69252 | -2.26657 |
| 12 | 25 | 85 | 0.68 | -9.90 | -990.29 | -1.89318 | 0.108530 | -2.26657 |
| 12 | 26 | 85 | 0.68 | -0.90 | -278.29 | -0.53248 | 0.108530 | -0.20672 |
| 12 | 27 | 85 | -13.32 | -0.90 | 456.71 | -0.36791 | -2.13443 | -0.20672 |
| 12 | 28 | 85 | -5.32 | -0.90 | -96.29 | -0.55456 | -0.85274 | -0.20672 |
| 12 | 29 | 85 | -1.32 | -0.90 | -310.29 | -0.66895 | -0.21189 | -0.20672 |
| 12 | 30 | 85 | -5.32 | -0.90 | 21.71 | -0.23545 | -0.85274 | -0.20672 |
| 12 | 31 | 85 | -7.32 | -9.90 | -559.29 | -1.89318 | -1.17316 | -2.26657 |
| 1 | 1 | 86 | 6.68 | -9.90 | -1024.29 | -1.89318 | 1.069803 | -2.26657 |
| 1 | 2 | 86 | 1.68 | 2.10 | -42.29 | 0.553267 | 0.268742 | 0.479893 |
| 1 | 3 | 86 | 2.68 | 2.10 | 114.71 | 0.491052 | 0.428954 | 0.479893 |
| 1 | 4 | 86 | -12.32 | 0.10 | -393.29 | -0.21739 | -1.97422 | 0.022148 |
| 1 | 5 | 86 | -3.32 | 0.10 | 219.71 | -0.22341 | -0.53231 | 0.022148 |
| 1 | 6 | 86 | -1.32 | 2.10 | -391.29 | 0.519149 | -0.21189 | 0.479893 |
| 1 | 7 | 86 | -7.32 | 2.10 | 534.71 | 0.942613 | -1.17316 | 0.479893 |
| 1 | 8 | 86 | -2.32 | 2.10 | 403.71 | 0.860328 | -0.37210 | 0.479893 |
| 1 | 9 | 86 | 5.68 | 2.10 | -220.29 | 0.735898 | 0.909591 | 0.479893 |
| 1 | 10 | 86 | 4.68 | 2.10 | 229.71 | 0.653614 | 0.749379 | 0.479893 |
| 1 | 11 | 86 | 14.68 | 0.10 | 110.71 | -0.01670 | 2.351500 | 0.022148 |
| 1 | 12 | 86 | 1.68 | 0.10 | -98.29 | -0.30770 | 0.268742 | 0.022148 |
| 1 | 13 | 86 | 8.68 | 2.10 | 213.71 | 1.093133 | 1.390227 | 0.479893 |
| 1 | 14 | 86 | 5.68 | 2.10 | -92.29 | 1.195487 | 0.909591 | 0.479893 |
| SUM = | | | 6.4E-14 | 2.5E-14 | 0.00 | 3.6590 | 27.8691 | 2.2722 |

**Table 8-4: $ZY*ZX_1$, $ZY*ZX_2$, $ZY*ZX_3$, $X_1*Y$ Values**

| MO | DA | YR | $ZY*ZX_1$ | $ZY*ZX_2$ | $ZY*ZX_3$ | $X_1*Y$ |
|---|---|---|---|---|---|---|
| 12 | 15 | 85 | 0.08 | -1.11 | 0.45 | 20774.35 |
| 12 | 16 | 85 | 3.18 | 0.98 | 2.66 | 856335.5 |
| 12 | 17 | 85 | 2.06 | 0.16 | 1.67 | 554500.2 |
| 12 | 18 | 85 | 1.65 | -0.49 | 1.54 | 444500.9 |
| 12 | 19 | 85 | 1.11 | -0.38 | 1.19 | 299408.4 |
| 12 | 20 | 85 | 0.25 | -0.04 | 0.90 | 67695.90 |
| 12 | 21 | 85 | 0.60 | -1.37 | 0.20 | 160089.7 |
| 12 | 22 | 85 | 0.99 | -1.04 | 0.24 | 265875.3 |
| 12 | 23 | 85 | -0.11 | 0.17 | -0.05 | -28723.4 |
| 12 | 24 | 85 | 3.44 | 1.26 | 4.12 | 926616.6 |
| 12 | 25 | 85 | 3.47 | -0.20 | 4.16 | 934163.2 |
| 12 | 26 | 85 | 0.27 | -0.06 | 0.11 | 73836.70 |
| 12 | 27 | 85 | -0.31 | -1.81 | -0.17 | -83725.1 |
| 12 | 28 | 85 | 0.10 | 0.15 | 0.04 | 26607.19 |
| 12 | 29 | 85 | 0.38 | 0.12 | 0.12 | 103426.7 |
| 12 | 30 | 85 | -0.01 | -0.03 | -0.01 | -2547.03 |
| 12 | 31 | 85 | 1.96 | 1.22 | 2.35 | 527591.1 |
| 1 | 1 | 86 | 3.59 | -2.03 | 4.30 | 966236.1 |
| 1 | 2 | 86 | -0.04 | -0.02 | -0.04 | -11658.4 |
| 1 | 3 | 86 | 0.10 | 0.09 | 0.10 | 28066.86 |
| 1 | 4 | 86 | 0.16 | 1.44 | -0.02 | 42602.22 |
| 1 | 5 | 86 | -0.09 | -0.22 | 0.01 | -24458.6 |
| 1 | 6 | 86 | -0.38 | 0.15 | -0.35 | -101217. |
| 1 | 7 | 86 | 0.93 | -1.16 | 0.48 | 251141.0 |
| 1 | 8 | 86 | 0.64 | -0.28 | 0.36 | 173061.2 |
| 1 | 9 | 86 | -0.30 | -0.37 | -0.20 | -80775.4 |
| 1 | 10 | 86 | 0.28 | 0.32 | 0.20 | 74811.25 |
| 1 | 11 | 86 | -0.00 | 0.48 | 0.00 | -921.390 |
| 1 | 12 | 86 | 0.06 | -0.05 | -0.00 | 15070.12 |
| 1 | 13 | 86 | 0.43 | 0.55 | 0.19 | 116402.8 |
| 1 | 14 | 86 | -0.20 | -0.16 | -0.08 | -54975.2 |
| SUM | | | 24.3113 | -3.7187 | 24.4862 | 6539811. |

**Table 8-5: $X_2$*Y, $X_3$*Y, Y(123), $(Y\text{-}YEST)^2$, Y(CALC) Values**

| MO | DA | YR | $X_2$*Y | $X_3$*Y | Y(123) | $(Y\text{-}YEST)^2$ | Y(CALC) |
|---|---|---|---|---|---|---|---|
| 12 | 15 | 85 | -3739.71 | 1070.842 | 5406 | 63543 | 5400 |
| 12 | 16 | 85 | 3300.48 | 6282.842 | 5700 | 462851 | 5690 |
| 12 | 17 | 85 | 24.12 | 3943.423 | 5747 | 30247 | 5735 |
| 12 | 18 | 85 | -1655.32 | 3632.520 | 5755 | 10938 | 5743 |
| 12 | 19 | 85 | -1279.06 | 2806.842 | 5716 | 308 | 5705 |
| 12 | 20 | 85 | -135.06 | 2134.068 | 5489 | 5971 | 5487 |
| 12 | 21 | 85 | -4610.22 | 479.8751 | 4794 | 31607 | 4806 |
| 12 | 22 | 85 | -3515.97 | 559.3590 | 4785 | 65881 | 4797 |
| 12 | 23 | 85 | 583.31 | -112.640 | 4902 | 136847 | 4910 |
| 12 | 24 | 85 | 4246.02 | 9727.842 | 4261 | 9125 | 4273 |
| 12 | 25 | 85 | -670.84 | 9807.068 | 4169 | 154 | 4185 |
| 12 | 26 | 85 | -188.51 | 251.3590 | 4958 | 7838 | 4963 |
| 12 | 27 | 85 | -6084.55 | -412.511 | 5254 | 122806 | 5247 |
| 12 | 28 | 85 | 512.51 | 86.97190 | 5061 | 108 | 5063 |
| 12 | 29 | 85 | 410.38 | 280.2622 | 4960 | 15153 | 4965 |
| 12 | 30 | 85 | -115.55 | -19.6087 | 5141 | 804 | 5139 |
| 12 | 31 | 85 | 4095.44 | 5538.778 | 4315 | 74419 | 4325 |
| 1 | 1 | 86 | -6839.61 | 10143.77 | 4060 | 3964 | 4080 |
| 1 | 2 | 86 | -70.93 | -88.6732 | 5359 | 64516 | 5356 |
| 1 | 3 | 86 | 307.12 | 240.5202 | 5325 | 4010 | 5323 |
| 1 | 4 | 86 | 4846.35 | -38.0603 | 5323 | 323467 | 5316 |
| 1 | 5 | 86 | -730.00 | 21.26222 | 5157 | 44011 | 5157 |
| 1 | 6 | 86 | 517.51 | -820.447 | 5405 | 421469 | 5400 |
| 1 | 7 | 86 | -3915.45 | 1121.165 | 5620 | 3879 | 5605 |
| 1 | 8 | 86 | -937.64 | 846.4880 | 5508 | 1836 | 5499 |
| 1 | 9 | 86 | -1250.68 | -461.899 | 5331 | 163576 | 5329 |
| 1 | 10 | 86 | 1074.44 | 481.6493 | 5329 | 2281 | 5327 |
| 1 | 11 | 86 | 1624.93 | 10.71383 | 4880 | 142527 | 4892 |
| 1 | 12 | 86 | -164.87 | -9.51196 | 5045 | 15 | 5050 |
| 1 | 13 | 86 | 1854.44 | 448.1009 | 5365 | 20 | 5362 |
| 1 | 14 | 86 | -523.97 | -193.511 | 5446 | 152543 | 5439 |
| SUM | | | -12530.9 | 57758.87 | | 2366714.98 | |

The preceeding tables present the values needed to complete the primary equations. Following this the matrix of intercorrelations of the independent and dependent variables can be found.

$$[R_{ij}][B_j] = [R_{yj}] \tag{VIII.39}$$

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} * \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} r_{y1} \\ r_{y2} \\ r_{y3} \end{bmatrix}. \tag{VIII.40}$$

Substituting the values from the tables yields

$$[R_{ij}] * [B_j] = [R_{yj}]$$

$$\begin{bmatrix} 1 & 0.118032 & 0.899002 \\ 0.118032 & 1 & 0.073298 \\ 0.899002 & 0.073298 & 1 \end{bmatrix} * \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} 0.7842 \\ -0.1200 \\ 0.7899 \end{bmatrix} \tag{VIII.41}$$

One now solves for the sum of the products of these two standard score variables divided by the number of cases, again

$$r_{ij} = \frac{\sum_{i=1}^{n} (z_x)(z_y)}{N} \tag{VIII.42}$$

which yields

$$r_{12} = 0.118032$$

$$r_{13} = 0.899002$$

$$r_{23} = 0.073298$$

$$r_{y1} = 0.784236$$

$$r_{y2} = -0.11995$$

$$r_{y3} = 0.78987$$

where

$z_x$ and $z_y$ are the standard score variables,

$r_{ij}$ are the independent-independent intercorrelation variables, and

$r_{yj}$ are the dependent-independent intercorrelation variables.

Knotice that the indepedent-independent correlation coefficients and the independent-dependent correlation coefficients are strongly influenced by the standard score, $z_i$ variables. These in turn are determined, in part by the standard deviations for each. Applying each separately, yields

$$z_x = \frac{X - \bar{X}}{s_x} = \frac{x}{s_x} \qquad \text{(VIII.43)}$$

$$z_y = \frac{Y - \bar{Y}}{s_y} = \frac{y}{s_y} \qquad \text{(VIII.44)}$$

where

$$s_x = \left[ \frac{\sum_{i=1}^{n} x^2}{(N-1)} \right]^{\frac{1}{2}} \qquad \text{(VIII.45)}$$

$$s_y = \left[ \frac{\sum_{i=1}^{n} y^2}{(N-1)} \right]^{\frac{1}{2}} \qquad \text{(VIII.46)}$$

which results in

$s_1 =$ 498.2717
$s_2 =$ 6.241725
$s_3 =$ 4.369247
$s_y =$ 539.8709

where

$s_y$ is the standard deviation of the y variable, and
$s_j$ is the standard deviation of the jth variable.

The sum of squares of each dependent and independent variable occurs often enough to note

$$\sum_{i=1}^{n} x^2 = \sum_{i=1}^{n} X^2 - \frac{(\sum_{i=1}^{n} X)^2}{N} \qquad \text{(VIII.47)}$$

and

$$\sum_{i=1}^{n} y^2 = \sum_{i=1}^{n} Y^2 - \frac{(\sum_{i=1}^{n} Y)^2}{N} \qquad \text{(VIII.48)}$$

$\Sigma x1^2 =$ 7448240.

$\Sigma x2^2 =$ 1168.774

$\Sigma x3^2 =$ 572.7096

$\Sigma y^2 =$ 8743820.

When we invert the intercorrelation matrix the result is

[Rij]-1

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}^{-1}$$

or

[Rij]-1

$$\begin{bmatrix} 5.2892609054 & -0.27725 & -4.73473 \\ -0.277256915 & 1.019935 & 0.174495 \\ -4.734734024 & 0.174495 & 5.243745 \end{bmatrix}$$

The beta values can now be determined by multiplying the inverted matrix by the correlation coeffients for the independent and dependent variables, thus

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}^{-1} * \begin{bmatrix} r_{y1} \\ r_{y2} \\ r_{y3} \end{bmatrix} . \qquad \text{(VIII.49)}$$

This yields

$$B_1 = 0.441427$$

$$B_2 = -0.20195$$

$$B_3 = 0.407837$$

The regression coefficients can now be determined by

$$b_j = \frac{B_j s_y}{s_j} \qquad \text{(VIII.50)}$$

This results in

$$[b_j]$$

$$b_1 = 0.478280$$

$$b_2 = -17.4677$$

$$b_3 = 50.39301$$

Finally, the intercept coefficient can be found using

$$a = \bar{Y} - b_1\bar{X_1} - b_2\bar{X_2} - b_3\bar{X_3}, \qquad \text{(VIII.51)}$$

which yields

$$a = 4883.94$$

The final expression can now be assembled

$$Y' = a + b_1X_1 + b_2X_2 + \ldots + b_kX_k \qquad \text{(VIII.52)}$$

$$Y' = 4883.94 + 0.478280(X_1) + -17.4677(X_2) + 50.39301(X_3).$$

For the standard error of the estimate

$$SE_{est} = \left[\frac{ss_{res}}{(N-k-1)}\right]^{\frac{1}{2}} \qquad \text{(VIII.53)}$$

which is

$$SE_{est} = 296.0677$$

In a similar fashion, the standard errors of the independent variables are

$SE_{x1} =$ 0.249494

$SE_{x2} =$ 8.746052

$SE_{x3} =$ 28.32987

What remains is the $R^2$ variables which are

$$R_j^2 = 1 - \frac{1}{r^{jj}} \tag{VIII.54}$$

$$R_{1.23} = 0.810937$$

$$R_{2.13} = 0.019545$$

$$R_{3.12} = 0.809296.$$

The multiple $R^2$ value is then

$$R^2 = 1 - \frac{ss_{res}}{ss_t} \tag{VIII.55}$$

$$R^2 = 0.725570$$

Finally, the t-ratios can be calculated

$$t_j = \frac{b_j}{SE_{bj}} \tag{VIII.56}$$

which are

$$t_1 = 1.92$$

$$t_2 = 2.0$$

$$t_3 = 1.78.$$

Notice that each of the t-ratios has satisfied the original criteria of values greater than unity.

Using the Lotus 123 Version 2 software (1985) the following values were generated:

$a = 4898.436$

$SE_{est} = 296.0677$

$R^2 = 0.729327$

$b_1 = 0.498348$

$b_2 = -18.2260$

$b_3 = 50.02884$

$SEb_1 = 0.295981$

$SEb_2 = 8.771261$

$SEb_3 = 33.59838$

$t_1 = 1.68$

$t_2 = 2.08$

$t_3 = 1.49$

**8.3.6. Discussion**

Regression analysis should almost always be accompanied by plots of the information being considered. Visual verification is highly recommended by Kerlinger and Pedhazur (1973), and others, in order to determine if the information being considered is being fitted properly. Lotus 123 V.2 (1985) provides this capability with ease. Figures 8-1 through 8-12 are typical of the plots needed for each regression analysis in order to visually verify the regression fit.

Figure 8-1 demonstrates the verification of the calculated values (as represented in the previous section) and values obtained with the Lotus 123 V.2. The figure shows the measured Kwh for the period 12/15/85 through 1/14/86 as compared to the predicted Kwh from calculated values (pluses) and from Lotus 123 V.2 (squares).

Figure 8-2 is a plot of the measured Kwh against the measured attendance or doorcount. The days of zero attendance are Christmas eve day, Christmas day, New Year's Eve day and New Year's day. The attendance ($r^2$ value of 81 percent) indicates a strong influence upon the electical consumption.

Figure 8-3 illustrates the weak correlation between electrical consumption and outside temperatures in the range of 26 to 54 F.

The influence of operating hours on electrical consumption is shown in Figure 8-4. The building seems to consume a baseload of 4,000 kwh per day when unoccupied; 6,000 kwh then fully scheduled at 15 hours per day. The lack of information between 0 and 9 hours means that the building is open a minimum of 9 hours per day; otherwise the building is closed.

Inspection of the intercorrelation matrix (equation VIII.14) shows that there is a strong relationship between independent variables 1 and 3, as indicated by an $r_{13}$ of 0.89. This matrix also shows no relationship between independent variables $X_1$ to $X_2$ and $X_2$ to $X_3$.

When there is a strong relationship, typically an $R^2$ above 0.6 to 0.70, the assumption of independent variables is violated. Hence, one of two measures needs to be considered; remove one of the variables from the regression, or combine the variables. (Little, 1986). One way to combine the variables is to represent them with a

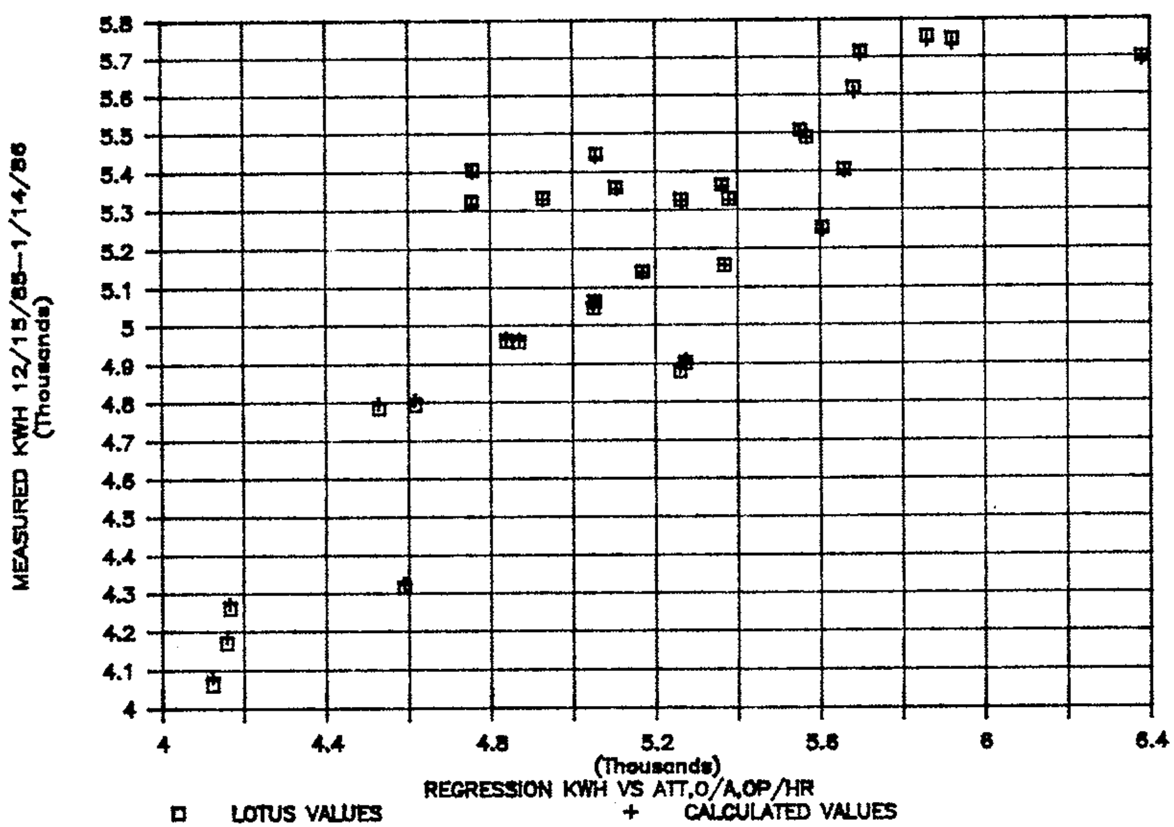


Fig. 8-1: kWh vs Attendance, O/A, Op/Hr

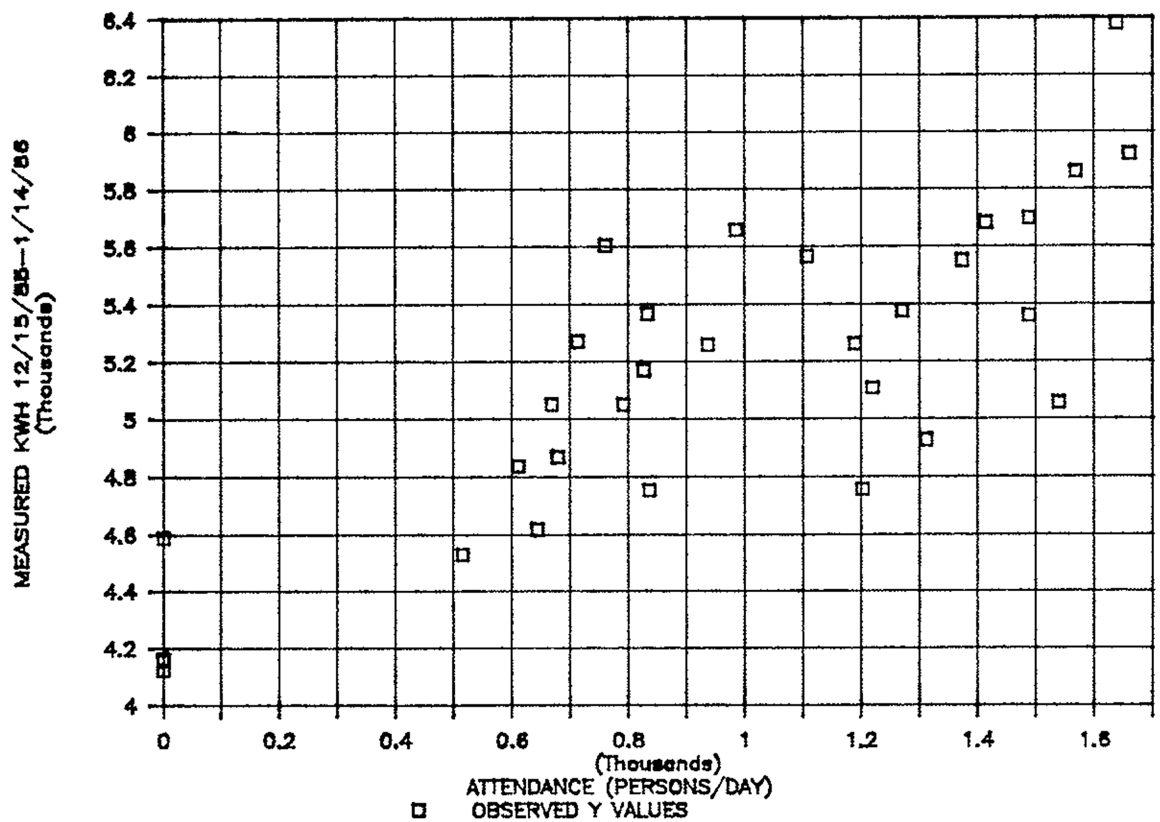


Fig. 8-2: kWh Versus Attendance

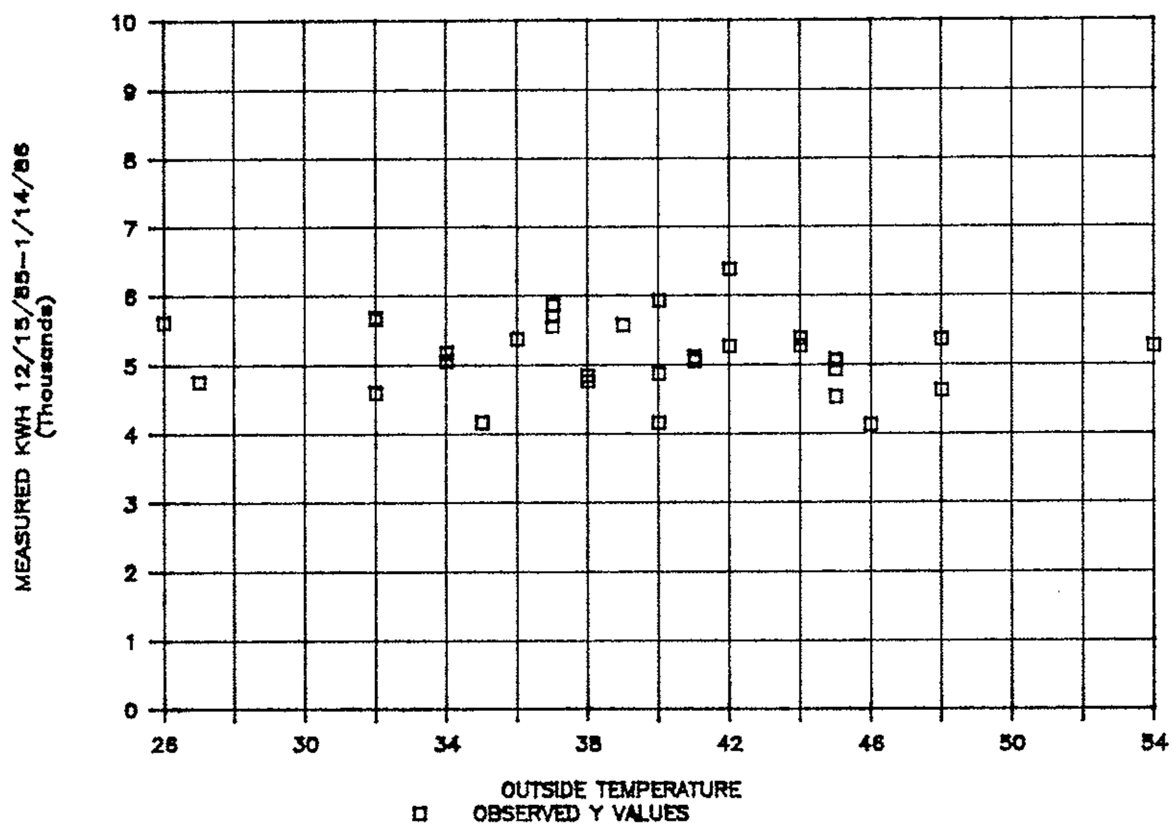


Fig. 8-3: kWh Versus Outside Air

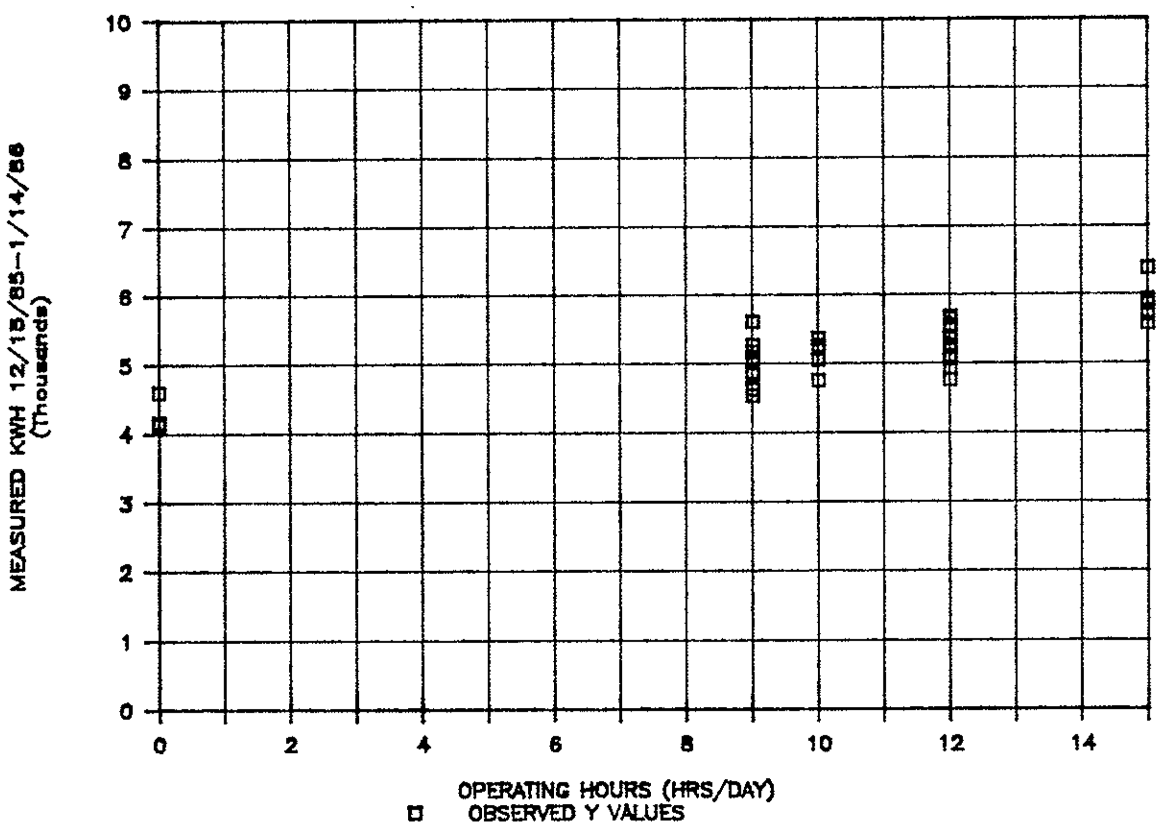


Fig. 8-4: kWh Versus Operating Hours

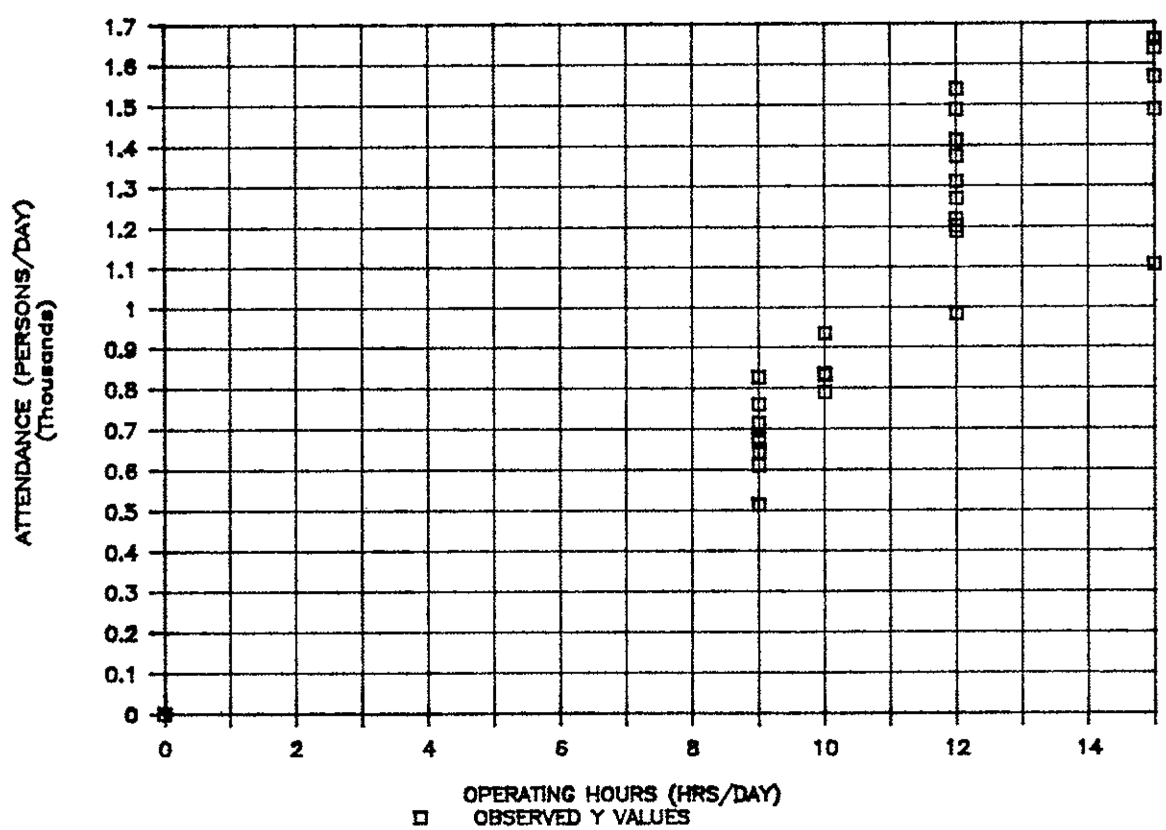


Fig. 8-5: Attendance Versus Operating Hours

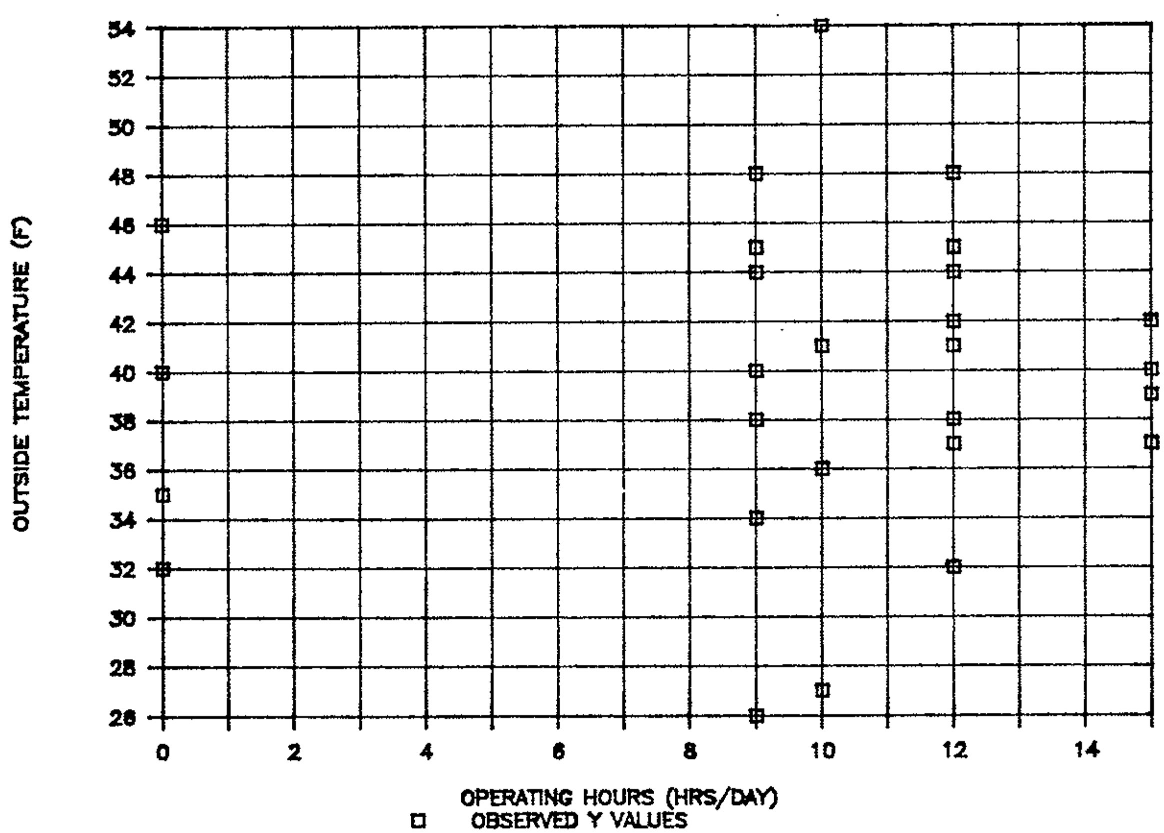


Fig. 8-6: Outside Air Versus Operating Hours

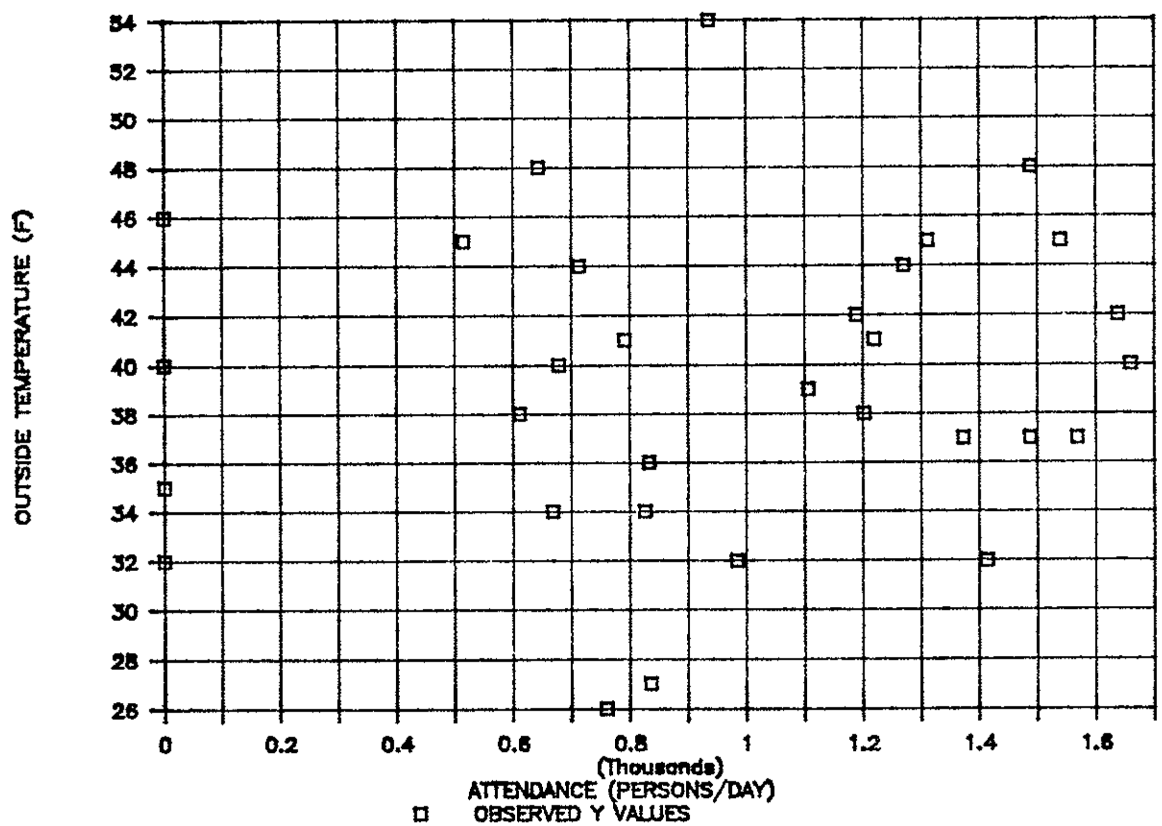


Fig. 8-7: Outside Air Versus Attendance

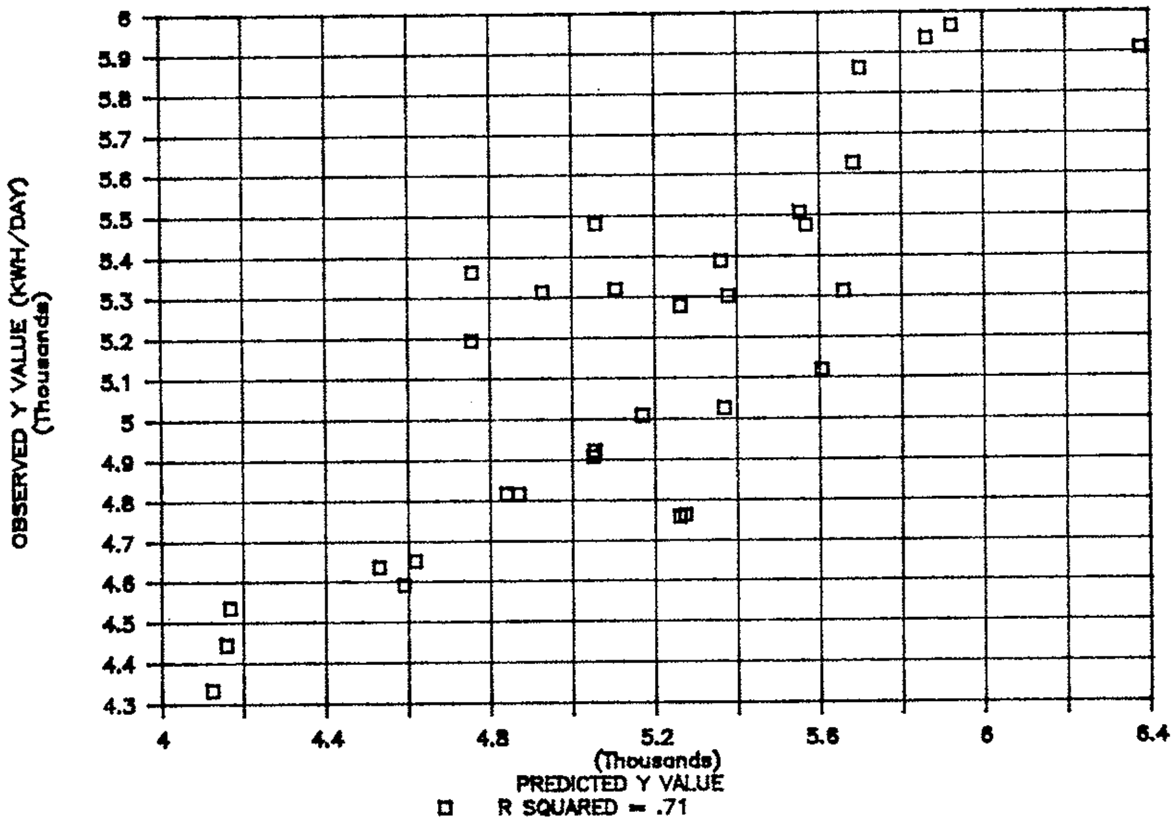


Fig. 8-8: kWh Versus Att-Op/Hr, O/A

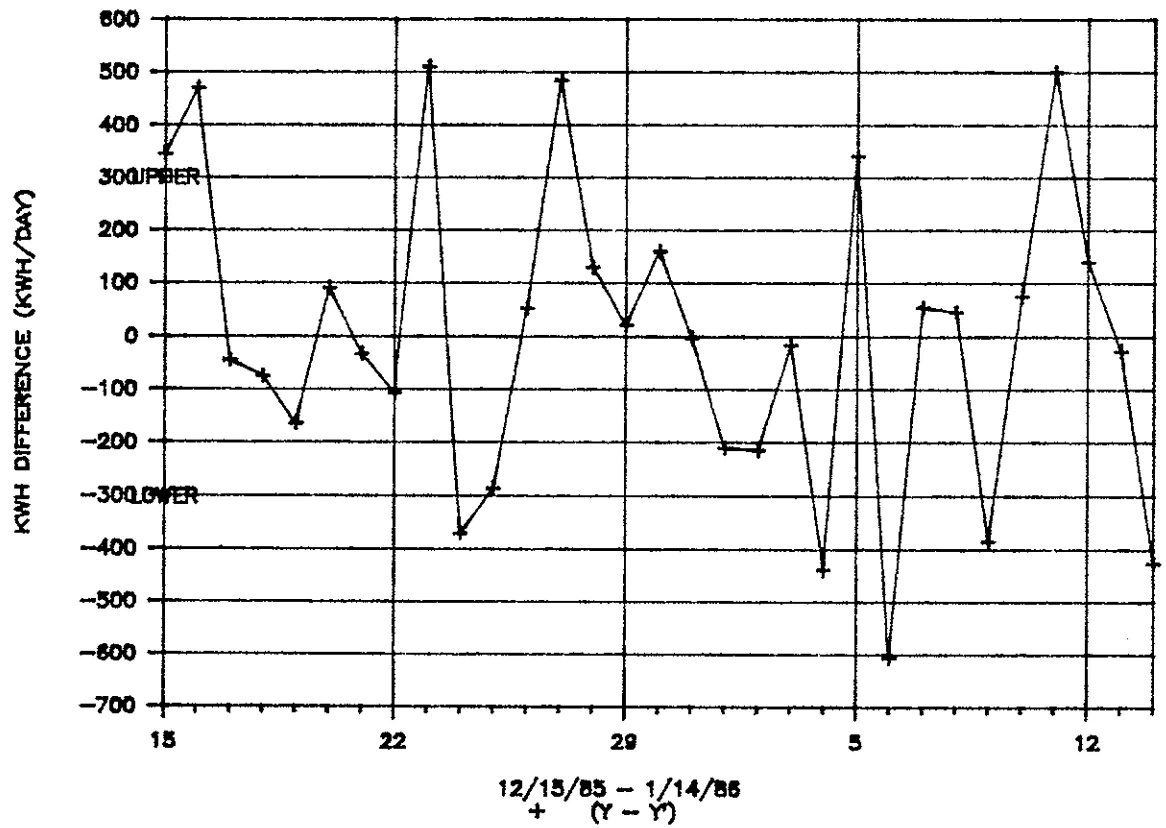


Fig. 8-9: Residual (Y - Y') Versus Time

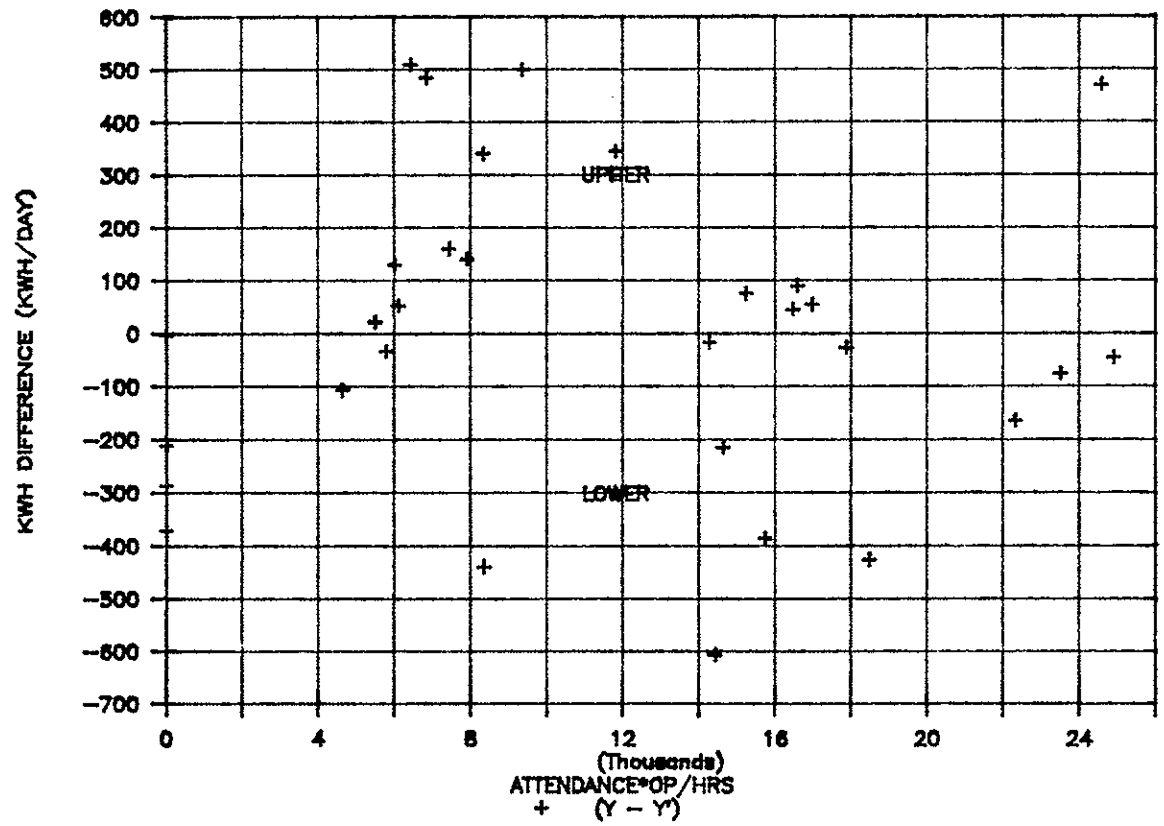


Fig. 8-10: Residual (Y - Y') Versus $X_1 {*} X_3$

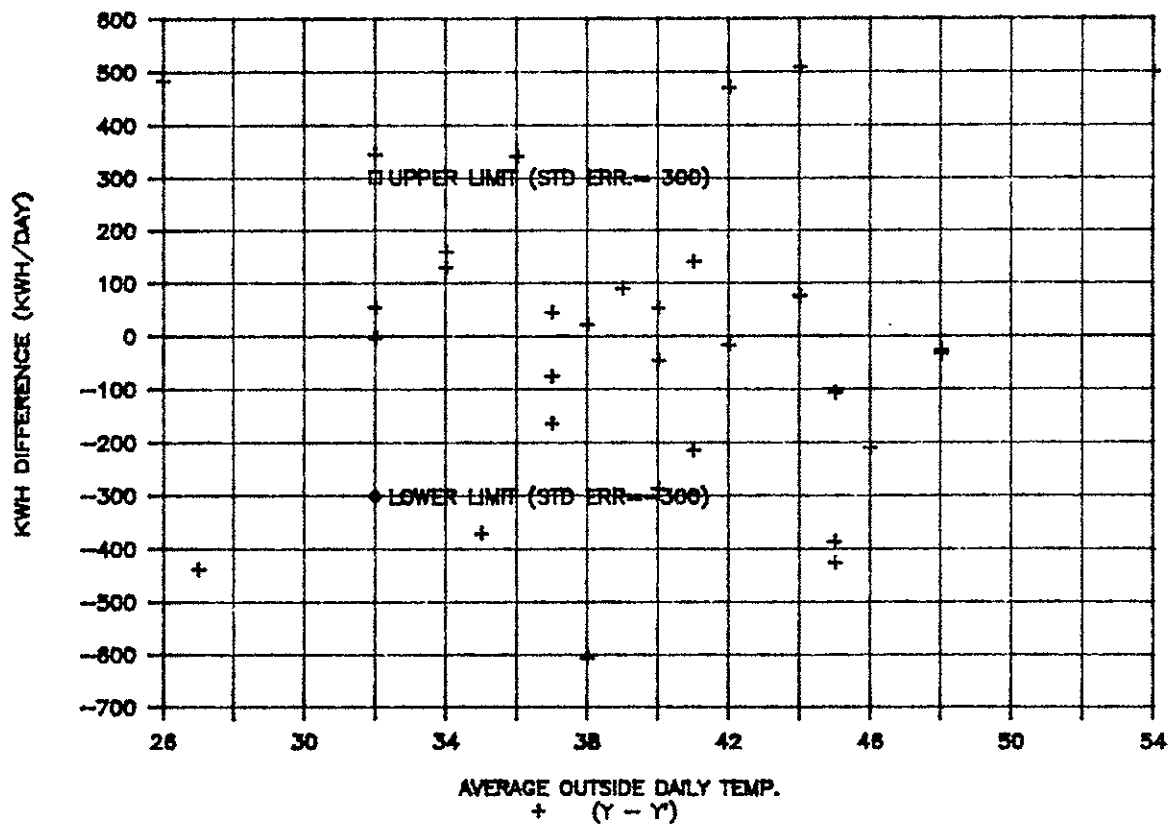


Fig. 8-11: Residual (Y - Y') Versus $X_2$

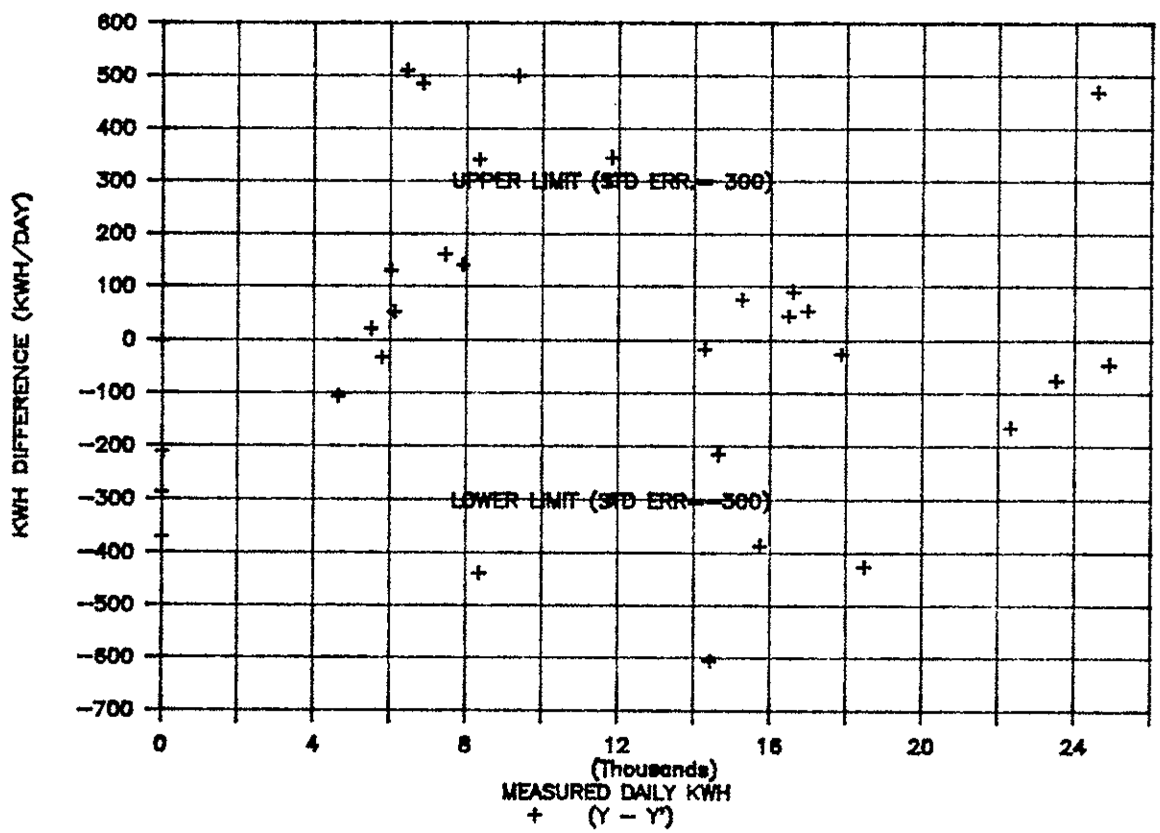


Fig. 8-12: Residual (Y - Y') Versus Y

third variable that is the product of the two variables. The relationship of the two variables is shown in Figure 8-5. Likewise Figures 8-6 and 8-7 indicate the lack of relationship between the outside air temperature and operating hours and outside air and attendance, respectively.

The new predictions, generated by the combining the $X_1$ and $X_3$ regressors are shown in Figure 8-8. This new prediction equation has the following characteristics

$$Y' = 5179.45 + 0.06(Att*Ophr) - 18.38(O/A) \qquad \text{(VIII.57)}$$

where

Att*Ophr is the daily attendance times the daily scheduled operating hours,

O/A is the average daily temperature (F).

The following were obtained from running a similar analysis with the Lotus regression analysis (Lotus, 1985).

Standard Error of the Y estimate = 300.92

R Squared = 0.71

Degrees of freedom = 28

Std. Error of $X_1*X_3$ = 0.0075

Std. Error of $X_2$ = -2.0772

t ratio of $X_1*X_3$ = 8.19

t ratio of $X_2$ = -2.077

The combined regression equation exhibits a similar $R^2$ coefficient to that of the original regression equation. The important improvement is in the t-ratios of the independent variables; by comparison the t-ratios for the original regression were

$$t(X_1) = 1.68$$

$$t(X_2) = 2.08$$

$$t(X_3) = 1.49.$$

Clearly, the combined $X_1*X_3$ coefficient yields a significantly higher t-ratio. Larger t-ratios indicate a greater statistical significance within the regression equation.

The residuals from the combined regression analysis are shown in Figures 8-9 through 8-12. In all of these figures the upper and lower bounds represent the standard error of Y'. These are typical of the types of residual analysis that was performed on the regression equations used at the Rec Center. Figure 8-9 is the residuals plotted against time. Figure 8-10 is the residuals plotted against the combined $X_1*X_3$ variable. Figure 8-11 is the residuals plotted against the average daily temperature. Finally, Figure 8-12 is the residuals plotted against the observed Y variable, the daily Kwh measurements. According to the methods outlined in Kerlinger and Pedhazur (1973) as well as Draper and Smith (1981), these residual plots do not appear to indicate any remaining dependencies. Should this not be the case, and the residuals indicate a remaining linear or non-linear dependency the regression would need to be reshaped to eliminate these non-random indicators that show up in the residuals.

This completes the discussion about the primary method used to construct the statistical predictors used in the BEACON system. The remainder of this section discusses other statistical methods that show promise in improving the accuracy of the methodology, and a discussion of the choice of time step upon which the methodology is based.

### 8.4. Improving the Model.

A statistical model of a data set is appropriate if the data matches the criteria for which the model was developed. In the case of multiple linear regression two important criterial must be satisfied. First, the data set should be exhibiting linear trends. Second, the independent variables must be, in fact, independent. Should these criteria not be fully satisfied, the model loses accuracy and/or becomes inappropriate for the data being analyzed. In the case of the analysis performed at the Rec Center a linearized multiple regression was used to model the steam consumption of the building.

Multiple linear regression can easily be extended to fit a set of data points by linearization. In the next section, the methods used to linearize the independent variables are discussed. Following this section is a discussion of other methods considered, but not used in this analysis. Canonical correlation is discussed as an improvement of the numerical model used to represent the interrelated dependencies observed at the Rec Center. Time series analysis is also discussed as the next step in developing a dynamic, or moving model. There are many other methods, such as Kalman Filters, that also hold promise in improving the accuracy and workability of the model.

This section is intended to be a brief introduction to each of these methods. For additional information concerning linearization techniques, Wonnacott and Wonnacott (1985) contains a good explanation; Draper and Smith (1981) also contain an extensive section devoted to this topic. One very good source for the treatment of linear, quadratic, cubic, bi-linear and bi-quadratic curve fitting can be found in the DOE-2.1A Engineers Manual (York and Cappiello, 1981); the FORTRAN code for these curve fits is, of course, readily available in the subroutines of DOE2 (LBL, 1986). Kerlinger and Pedhazur (1973) has a good introductory section on Canonical correlation as well as numerous references to additional literature. Further reading about time series analysis can be found in Box and Jenkins (1976), as well as Glass et al. (1975). Two good texts on Kalman filtering theory are Ryumgarrt and Soong (1985) and Balakrishnan (1984).

### 8.4.1. Linearized Regression

When the grouping of the data points suggests a non-linear function such as $X^2$, Sqrt(X), or 1/X, one simple method is to linearize the independent variables and then proceed with the linear analysis of the linearized variables (Wonnacott and Wonnacott, 1985). For example, if one were faced with a particular function that was described by the following second degree equation

$$Y' = a + b_1X + b_2X^2 \qquad \text{(VIII.58)}$$

this equation can easily be linearized by substituting

$$X_1 = X \qquad \text{(VIII.59)}$$

and

$$X_2 = X^2 \qquad \text{(VIII.60)}$$

which would yield

$$Y' = a + b_1 X_1 + b_2 X_2 \qquad \text{(VIII.61)}$$

This can now be solved as a linear regression model. The redefining of the independent variables is a powerful extension of linear regression techniques. In a similar fashion, general polynomials, reciprocals, cyclic equations, etc. can be represented.

Non-linearity can also be removed by exponentials, and log variables (Wonnacott and Wonnacott, 1985). The exponential

$$P = Ae^{bX} \qquad \text{(VIII.62)}$$

can be fit this into the standard linear regression model by taking the logs of the different variables; thus

$$\log P = \log A + bX \qquad \text{(VIII.63)}$$

The substitution would then be

$$Y = \log P \qquad \text{(VIII.64)}$$

$$a = \log A \qquad \text{(VIII.65)}$$

with b and X being described as usual. This can easily be accomplished with a spreadsheet analysis such as 123 (1985).

Linearization of the steam consumption, as a function of the outside air temperature, improved the regression fit. This curve fit will be used as an example to demonstate the extension of multiple linear regression to multiple linearized regression.

The steam consumption at the Rec Center is highly influenced by the outdoor air temperature. Figure 8-13 shows the effect of a first degree polynomial regression fit. The equation generated by the regression is

$$Y' = 59052 - 685.06(\text{Outside Temp F}) \qquad \text{(VIII.66)}$$

The $R^2$ for this simple linear expression is

$$R^2 = 0.85 \qquad \text{(VIII.67)}$$

Figure 8-14 shows the fifth degree polynomial curve fit represented in (VII.50).

$$Y' = 65601 - 2823\ X_1 + 159.94\ X_1^{\ 2} - 4.51\ X_1^{\ 3} + 0.05\ X_1^{\ 4} - 0.0008\ X_1^{\ 5} \qquad \text{(VII.68)}$$

The coefficient of determination, $R^2$, for the fifth degree fit is

$$R^2 = 0.88 \qquad \text{(VIII.69)}$$

a 3 percent improvement of the fit. More importantly, the curve clearly follows the underlying trends that have been observed that identify certain characteristics of the building. First, in the summer (temperatures above 55F) the building steam consumption flattens. Second, the building steam consumption has a "hip" at 35 degrees because of control characteristics of the air handling units. The fifth degree fit picks-up these important observed non-linear characteristics. Obviously, the first degree fit does not.

This polynomial expression is handled rather efficiently with the 123 (1985) software. The improvement to the accuracy of the model is clearly demonstrated. The PCONs are listed in Table 3-14, shown earlier.

**8.4.2. Canonical Correlation**

Canonical correlation is the extension of multiple regression analysis that considers k dependent and n - k independent variables for an analysis involving n cases. Canonical correlation forms "linear composites" of the dependent and independent variables by utilizing least squares analysis (Kerlinger, 1973, p. 342). Canonical correlation seeks out the maximum correlation possible between two sets of variables; such as the set of k dependent and n-k independent variables. Multiple regression can be performed with canonical correlations of k = 1 dependent variable and N independent variables.

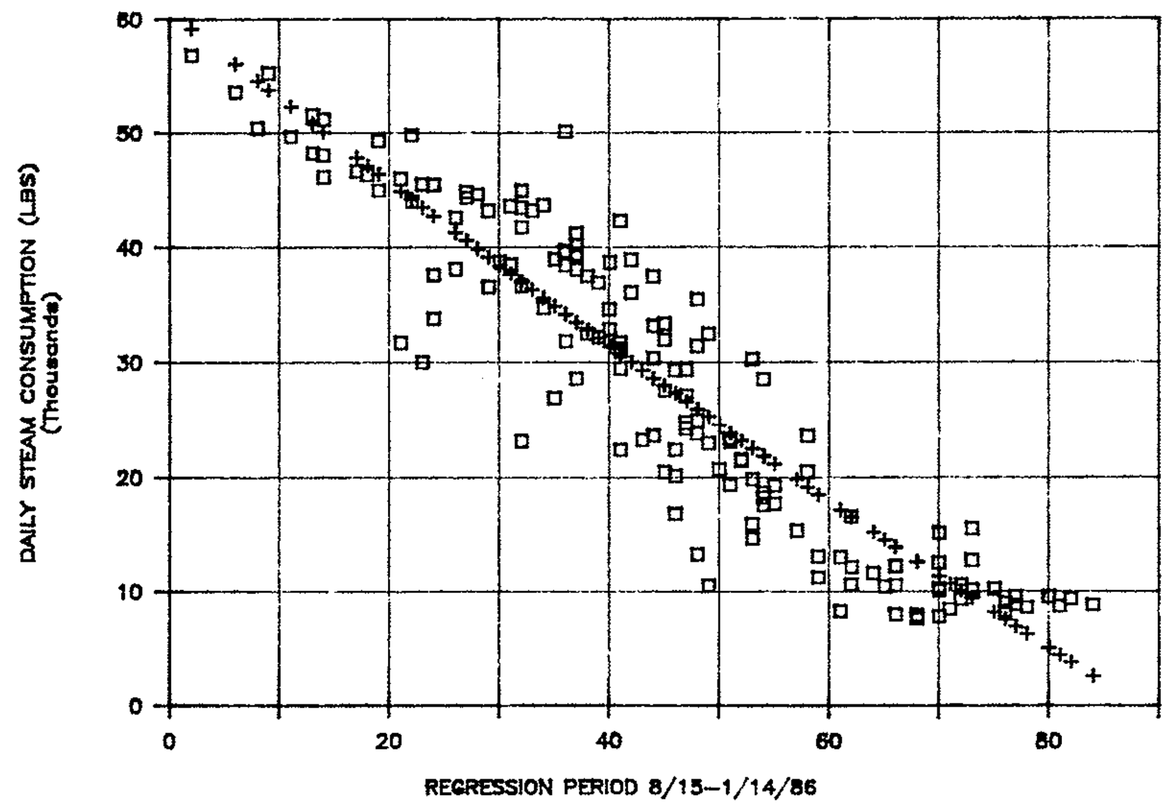


Fig. 8-13: First Degree Regression of Steam Consumption

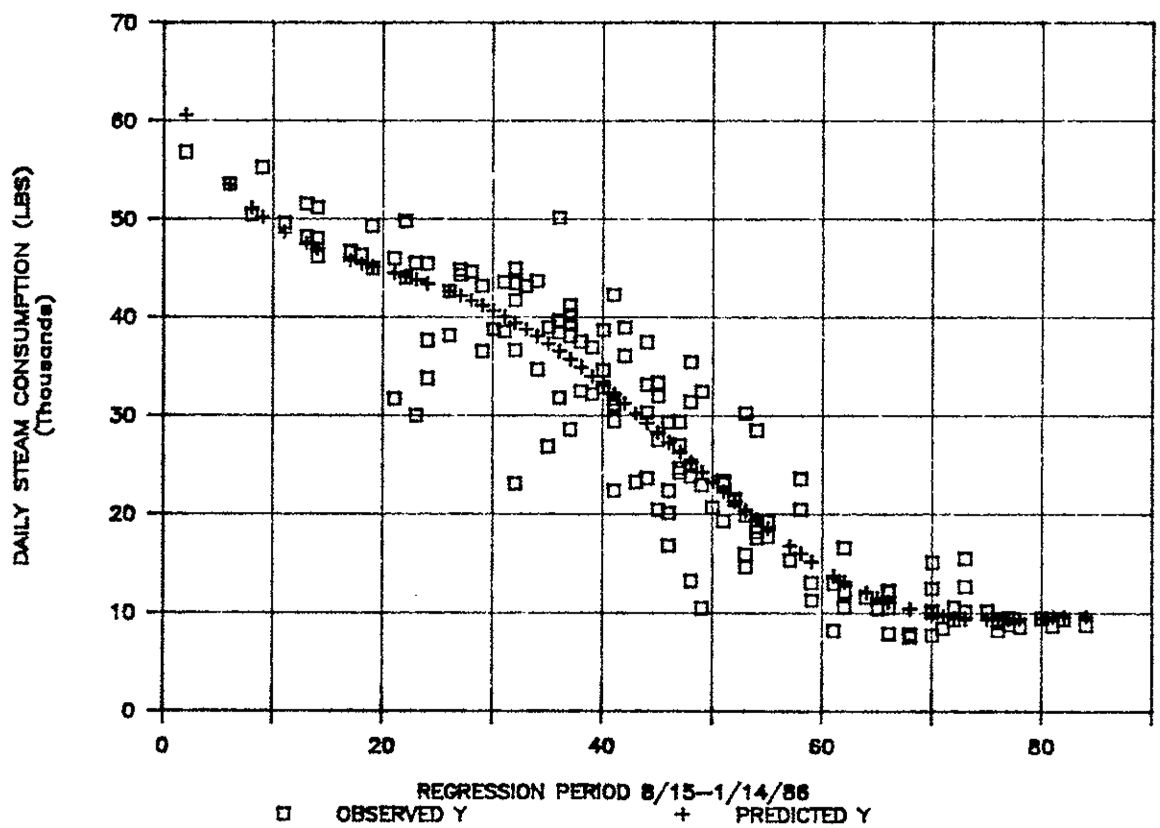


Fig. 8-14: Fifth Degree Regression of Steam Consumption

Canonical processing of the matrix produces a "double least squares solution" (Kerlinger and Pedhazur, 1973, p. 343). One linear composite is formed on the left side and one is formed on the right side of the matrix; the correlation between these linear composites is the canonical correlation. The canonical correlation coefficient $R_c$ is the indicator of the correlation between the two composites. The square of the canonical correlation coefficient, $R_c^2$, is similar to the multiple correlation coefficient used in linear regression. Canonical correlation also yields "weights" which are similar to the regression weights obtained from multiple regression analysis (Kerlinger and Pedhazur, 1973, p. 344).

A brief example of canonical correlation follows. For a complete explanation of the method Kerlinger and Pedhazur (1973) is highly recommended. Begin with the canonical correlation matrix

$$R = \begin{bmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{bmatrix} \qquad \text{(VIII.70)}$$

where

$R_{xx}$ are the correlations among the k independent variables,

$R_{yy}$ are the correlations among the n - k dependent variables,

$R_{xy}$ are the correlations among the dependent and independent variables, and

$R_{yx}$ is the transpose of $R_{xy}$.

Next calculate

$$[R_{yy}^{-1}][R_{yx}][R_{xx}^{-1}][R_{xy}] \qquad \text{(VIII.71)}$$

Next, one chooses as a solution to equation III.70 a matrix of the form

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \qquad \text{(VIII.72)}$$

by substituting

$$\begin{bmatrix} (a - X) & b \\ c & (d - X) \end{bmatrix} = 0 \qquad \text{(VIII.73)}$$

The canonical correlation coefficients are then the roots to the quadratic equation that accompanies the solution to equation VIII.73.

Canonical correlation is a very powerful analysis method. The main advantage of the method is the speed (assuming the necessary computing facilities exist) with which all intercorrelations can be considered. Also, canonical correlation considers the intercorrelation of the dependent variables, something that can only be considered by multiple linear regression with great difficulty.

**8.4.3. Time Series Analysis**

One difficulty in applying regression analysis is accomodating significant trends or when a change occurs the regression model needs to be reworked. Canonical correlations are seen as one method that can speed the reworking of the group of regression equations, but they do not offer a systematic methodology of extending the entire prediction process to one that is capable of rapidly adjusting to dynamic changes. Time series analysis was found to be a good candidate for the extension of the method to handle such capabilities. The next is a brief introduction to time series analysis. Additional information concerning time series analysis can be found in Box and Jenkins (1976).

Time series analysis is a forecasting method used in economic, process control and other industrial applications where important future trends can be predicted by statistical analysis of discrete historical data. Time series analysis also can be used to combine the forecasting of dynamic or non-stationary processes where the shifting of trends tend to obscure the process. Time series analysis can be coupled with feedback and feedforward control schemes similar to those used in direct digital control systems (Box and Jenkins, 1976).

Time series analysis is capable of analyzing non-stationary processes that are referred to as autoregressive-integrated moving average processes (ARIMA processes). Autoregressive refers to a stochastic or probability model that is composed of "finite, linear aggregate of previous values of the process" (Box and Jenkins, 1976, p. 9). Since the model is based on "previous values of itself" the model is termed "auto"regressive.

A moving average process is another modelling process that employs a finite number of weights to model a non-stationary model. A mixed process employs both autoregressive and moving average models. The process is then integregated or summed in order to better analyze those effects that are hidden by dynamic events.

These parts of the analysis have been referred to as "filters" (Box and Jenkins, 1976), a term that is easier to grasp than the obscure functional titles of the actual computational mechanisms. ARIMA processes then can be said to employ sets of these filters that produce the forecasting model required. Typically, these filters include a "moving average filter", a "stationary autoregressive filter", and a "nonstationary summation filter" (Box and Jenkins, 1976, p. 12).

The time series model approach usually begins with an estimation of the process by fitting a model to observed data. This is followed by diagnostic checking of the parameters that have been developed. Once satisfactory parameters have been developed, forecasting and dynamic tuning of the model then follow. The principal advantage to adapting the regression techniques, developed in the previous sections, to those of time series analysis, would be in the ability to apply proven dynamic modeling techniques that have well outlined procedures for detecting such things as shifts in the forecast, trends and noise. The linearized regression methods used in this thesis fall short in this capability.

**8.5. The BEACON System**

This section contains the BEACON PCON and CCON components. Each component is explained in the respective sections. The BEACON system was developed using an IBM/PC XT with 2 Mbytes of ram, 20 Mbyte disk and assorted plotters and printers. This treatment assumes that the reader is already familiar with the use of the IBM/PC, PC/DOS and the usual software programs associated with its use.

### 8.5.1. BEACON spreadsheet PCON

The BEACON spreadsheet PCON is the consumption predictor for the entire system. This section explains the data base required for the pilot building and contains the necessary instructions to operate the existing system. The user is expected to be familiar with the operation of the Lotus 123 software (Lotus 1985).

#### 8.5.1.1. Spreadsheet Printout

The next section contains a printout of the Lotus 123 BEACON PCON spreadsheet analysis for the month of July. The entire data base is too large to include in this volume (96 tables, 1.3 Mbytes). However, the author feels that a one month printout will provide the necessary information to understand how the PCON spreadsheet analysis works. The section following this contains the explanation of each cell contained in this analysis.

**Table 8-6: PCON Spreadsheet Printout-1**

PCON spreadsheet analysis file:RECCT09.WK1

| A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| TODAY'S | | | TIME | DAY | TIMELIN | ELAPS | SCHED | NORMAL | TOTAL | POOL |
| MO | DA | YR | OF | OF | VALUE | TIME | OPER | MIDNIG | STEAM | STEAM |
| 8 | 4 | 86 | READ | WEEK | (DAYS) | (HRS) | (HRS) | FRACTI | GALLON | LBS |
| MO | DA | YR | (SAT=0) | | 31629.341 | <-TODAY'S | | | METERED | ------- |
| 7 | 1 | 86 | 19.0 | 3 | 31594.792 | 25.5 | 15.5 | 0.227 | 4434390 | 823903 |
| 7 | 2 | 86 | 17.0 | 4 | 31595.708 | 22.0 | 14.5 | 0.292 | 4435060 | 824535 |
| 7 | 3 | 86 | 17.0 | 5 | 31596.708 | 24.0 | 15.5 | 0.292 | 4435850 | 825177 |
| 7 | 4 | 86 | 17.0 | 6 | 31597.708 | 24.0 | 0.0 | 0.292 | 4436560 | 825832 |
| 7 | 5 | 86 | 17.0 | 0 | 31598.708 | 24.0 | 10.0 | 0.292 | 4437170 | 826504 |
| 7 | 6 | 86 | 17.0 | 1 | 31599.708 | 24.0 | 10.0 | 0.269 | 4438820 | 827169 |
| 7 | 7 | 86 | 19.0 | 2 | 31600.792 | 26.0 | 14.5 | 0.227 | 4438735 | 827901 |
| 7 | 8 | 86 | 17.0 | 3 | 31601.708 | 22.0 | 15.5 | 0.292 | 4439590 | 828523 |
| 7 | 9 | 86 | 17.0 | 4 | 31602.708 | 24.0 | 14.5 | 0.304 | 4440666 | 829623 |
| 7 | 10 | 86 | 16.0 | 5 | 31603.667 | 23.0 | 15.5 | 0.336 | 4442975 | 830229 |
| 7 | 11 | 86 | 15.8 | 6 | 31604.660 | 23.8 | 14.5 | 0.318 | 4444214 | 832123 |
| 7 | 12 | 86 | 17.5 | 0 | 31605.729 | 25.7 | 10.0 | 0.262 | 4445095 | 833063 |
| 7 | 13 | 86 | 18.3 | 1 | 31606.763 | 24.8 | 10.0 | 0.261 | 4445782 | 834018 |
| 7 | 14 | 86 | 16.2 | 2 | 31607.674 | 21.9 | 14.5 | 0.324 | 4446840 | 834848 |
| 7 | 15 | 86 | 16.3 | 3 | 31608.679 | 24.1 | 15.5 | 0.339 | 4447680 | 835649 |
| 7 | 16 | 86 | 15.0 | 4 | 31609.625 | 22.7 | 14.5 | 0.353 | 4448434 | 836380 |
| 7 | 17 | 86 | 16.5 | 5 | 31610.688 | 25.5 | 15.5 | 0.337 | 4449333 | 837129 |
| 7 | 18 | 86 | 14.8 | 6 | 31611.615 | 22.2 | 14.5 | 0.327 | 4450345 | 840104 |
| 7 | 19 | 86 | 19.0 | 0 | 31612.792 | 28.3 | 10.0 | 0.217 | 4451420 | 842062 |
| 7 | 20 | 86 | 18.0 | 1 | 31613.750 | 23.0 | 10.0 | 0.271 | 4452248 | 844424 |
| 7 | 21 | 86 | 16.2 | 2 | 31614.674 | 22.2 | 14.5 | 0.284 | 4453488 | 848418 |
| 7 | 22 | 86 | 19.8 | 3 | 31615.823 | 27.6 | 15.5 | 0.194 | 4454774 | 851422 |
| 7 | 23 | 86 | 17.7 | 4 | 31616.736 | 21.9 | 14.5 | 0.264 | 4455740 | 853583 |
| 7 | 24 | 86 | 17.7 | 5 | 31617.736 | 24.0 | 15.5 | 0.283 | 4456770 | 855982 |
| 7 | 25 | 86 | 16.0 | 6 | 31618.667 | 22.3 | 14.5 | 0.308 | 4457950 | 857593 |
| 7 | 26 | 86 | 18.0 | 0 | 31619.750 | 26.0 | 10.0 | 0.247 | 4459050 | 859618 |
| 7 | 27 | 86 | 18.3 | 1 | 31620.760 | 24.3 | 10.0 | 0.237 | 4459920 | 862024 |
| 7 | 28 | 86 | 18.5 | 2 | 31621.771 | 24.2 | 14.5 | 0.243 | 4461405 | 864664 |
| 7 | 29 | 86 | 17.2 | 3 | 31622.715 | 22.7 | 15.5 | 0.283 | 4462325 | 866171 |
| 7 | 30 | 86 | 17.3 | 4 | 31623.722 | 24.2 | 14.5 | 0.257 | 4463520 | 868360 |
| 7 | 31 | 86 | 19.3 | 5 | 31624.802 | 25.9 | 15.5 | 0.209 | 4464740 | 871781 |

**Table 8-7: PCON Spreadsheet Printout-2**

PCON spreadsheet analysis file:RECCT09.WK1

| A B C | L | M | N | O | P | Q | R | S |
|---|---|---|---|---|---|---|---|---|
| TODAY'S | ELEC | N/GAS | COMPRES | | | POOL | MAIN WAT | |
| MO DA YR | USAGE | USAGE | W | C | E | WATER | #1 | #2 |
| 8 4 86 | KWH | CCF | | | | GALLONS | | |
| MO DA YR | ------------------>>> | | | | | | <<<<<---- | |
| 7 1 86 | 5576.0 | 6592.0 | 71499.4 | 74428.5 | 73478.0 | 5313551 | 327038 | 49375220 |
| 7 2 86 | 5581.0 | 6598.5 | 71511.2 | 74445.1 | 73492.9 | 5314283 | 330806 | 49390190 |
| 7 3 86 | 5586.0 | 6604.0 | 71523.5 | 74462.9 | 73509.5 | 5316812 | 334045 | 49408380 |
| 7 4 86 | 5590.0 | 6607.5 | 71535.5 | 74479.3 | 73523.8 | 5317742 | 337587 | 49416320 |
| 7 5 86 | 5594.5 | 6611.0 | 71547.4 | 74495.9 | 73536.9 | 5318221 | 342033 | 49420340 |
| 7 6 86 | 5599.0 | 6612.0 | 71558.8 | 74511.7 | 73548.8 | 5321130 | 346511 | 49428690 |
| 7 7 86 | 5604.0 | 6618.5 | 71570.8 | 74528.3 | 73563.5 | 5321500 | 350790 | 49446450 |
| 7 8 86 | 5608.5 | 6624.5 | 71581.0 | 74542.9 | 73576.4 | 5322167 | 354965 | 49458470 |
| 7 9 86 | 5613.5 | 6632.5 | 71592.0 | 74558.1 | 73589.3 | 5324236 | 358803 | 49474920 |
| 710 86 | 5618.5 | 6637.5 | 71603.8 | 74574.6 | 73603.1 | 5324878 | 358271 | 49516440 |
| 711 86 | 5623.0 | 6645.5 | 71614.4 | 74589.4 | 73616.0 | 5325543 | 363102 | 49533521 |
| 712 86 | 5627.5 | 6650.5 | 71625.7 | 74605.2 | 73629.8 | 5326295 | 367996 | 49542265 |
| 713 86 | 5632.0 | 6652.5 | 71636.8 | 74620.8 | 73643.4 | 5326733 | 372996 | 49547895 |
| 714 86 | 5636.0 | 6656.0 | 71647.6 | 74636.1 | 73656.5 | 5327079 | 376280 | 49564461 |
| 715 86 | 5641.0 | 6665.3 | 71661.1 | 74655.5 | 73673.2 | 5327546 | 380175 | 49579140 |
| 716 86 | 5645.2 | 6673.0 | 71674.9 | 74675.8 | 73692.6 | 5332017 | 384374 | 49596440 |
| 717 86 | 5650.5 | 6679.5 | 71689.2 | 74696.4 | 73711.9 | 5332700 | 388786 | 49612582 |
| 718 86 | 5654.5 | 6685.5 | 71700.5 | 74712.8 | 73727.2 | 5333550 | 392425 | 49625800 |
| 719 86 | 5660.0 | 6693.0 | 71713.8 | 74731.3 | 73742.3 | 5334442 | 397723 | 49637335 |
| 720 86 | 5664.0 | 6696.5 | 71722.6 | 74743.5 | 73752.5 | 5335066 | 401590 | 49643251 |
| 721 86 | 5668.0 | 6701.3 | 71731.2 | 74755.0 | 73761.6 | 5335650 | 405460 | 49653230 |
| 722 86 | 5674.0 | 6712.8 | 71744.1 | 74772.9 | 73776.9 | 5336340 | 409785 | 49674130 |
| 723 86 | 5678.0 | 6718.5 | 71753.8 | 74784.7 | 73786.7 | 5337090 | 413000 | 49687590 |
| 724 86 | 5683.0 | 6725.0 | 71764.2 | 74799.3 | 73799.5 | 5337630 | 416364 | 49701470 |
| 725 86 | 5687.0 | 6731.0 | 71774.4 | 74813.6 | 73811.2 | 5340330 | 419640 | 49715520 |
| 726 86 | 5693.0 | 6736.5 | 71787.1 | 74831.5 | 73827.7 | 5340885 | 424341 | 49725672 |
| 727 86 | 5697.5 | 6739.5 | 71797.3 | 74845.8 | 73839.2 | 5341400 | 429019 | 49731250 |
| 728 86 | 5702.0 | 6746.3 | 71808.7 | 74861.7 | 73851.3 | 5342060 | 431898 | 49748520 |
| 729 86 | 5707.0 | 6754.0 | 71818.7 | 74875.7 | 73863.4 | 5342760 | 435610 | 49760040 |
| 730 86 | 5711.9 | 6761.5 | 71830.3 | 74892.0 | 73876.1 | 5345280 | 439220 | 49776820 |
| 731 86 | 5717.5 | 6768.0 | 71834.6 | 74910.6 | 73888.5 | 5346030 | 443296 | 49792455 |

**Table 8-8: PCON Spreadsheet Printout-3**

PCON spreadsheet analysis file:RECCT09.WK1

| A | B | C | T | U | V | W | X | Y | Z | AA | AB |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TODAY'S | | | WIND | ZAMB | EMER | SUN | TOTAL | POOL | OTHER | ELEC | N/GAS |
| MO | DA | YR | KM/DAY | RUN-HRS | GEN | METER | STEAM | STEAM | STEAM | USE | USE |
| 8 | 4 | 86 | | | RUN-HR | (LANGL | | | | KWH | FT3 |
| MO | DA | YR | ------- | | | | USE | ----------- | ----------- | -------->>>> | |
| 7 | 1 | 86 | 2973.6 | 5447.8 | 646.80 | 81028 | 7169 | 636 | 6533 | 7183 | 5028 |
| 7 | 2 | 86 | 3100.0 | 5448.7 | 647.00 | 87369 | 6052 | 676 | 5377 | 8515 | 663 |
| 7 | 3 | 86 | 3299.5 | 5449.8 | 647.00 | 92234 | 6202 | 646 | 5557 | 7533 | 492 |
| 7 | 4 | 86 | 3531.2 | 5450.4 | 647.00 | 96520 | 5508 | 660 | 4848 | 6633 | 350 |
| 7 | 5 | 86 | 3684.8 | 5450.9 | 647.00 | 99871 | 7389 | 670 | 6719 | 7200 | 277 |
| 7 | 6 | 86 | 3778.9 | 5451.7 | 647.00 | 3025 | 9270 | 668 | 8602 | 7254 | 246 |
| 7 | 7 | 86 | 3919.7 | 5452.8 | 647.00 | 8787 | 1070 | 676 | 393 | 7483 | 611 |
| 7 | 8 | 86 | 3999.1 | 5453.6 | 647.60 | 11523 | 7884 | 801 | 7082 | 7897 | 697 |
| 7 | 9 | 86 | 4117.6 | 5454.8 | 647.60 | 16724 | 11851 | 964 | 10887 | 8101 | 719 |
| 7 | 10 | 86 | 4266.4 | 5455.0 | 647.60 | 19634 | 16360 | 1057 | 15302 | 7982 | 616 |
| 7 | 11 | 86 | 4390.7 | 5456.6 | 647.60 | 24017 | 8927 | 1557 | 7370 | 7074 | 691 |
| 7 | 12 | 86 | 4496.8 | 5457.1 | 647.60 | 29174 | 6316 | 891 | 5424 | 6796 | 393 |
| 7 | 13 | 86 | 4657.6 | 5457.7 | 647.60 | 32636 | 6332 | 921 | 5411 | 6981 | 239 |
| 7 | 14 | 86 | 4817.7 | 5459.0 | 647.60 | 38156 | 8534 | 874 | 7660 | 7328 | 561 |
| 7 | 15 | 86 | 4979.4 | 5460.2 | 648.10 | 43433 | 6660 | 789 | 5871 | 7684 | 889 |
| 7 | 16 | 86 | 4986.8 | 5461.2 | 648.10 | 47003 | 6598 | 747 | 5850 | 7433 | 738 |
| 7 | 17 | 86 | 5249.2 | 5462.0 | 648.10 | 51010 | 7466 | 1487 | 5978 | 7644 | 623 |
| 7 | 18 | 86 | 5378.8 | 5462.9 | 648.10 | 54016 | 8275 | 2613 | 5662 | 7124 | 643 |
| 7 | 19 | 86 | 5577.3 | 5463.6 | 648.10 | 58678 | 7305 | 1830 | 5475 | 7310 | 581 |
| 7 | 20 | 86 | 5668.8 | 5463.9 | 648.10 | 62406 | 7957 | 2929 | 5028 | 6741 | 404 |
| 7 | 21 | 86 | 5742.8 | 5464.7 | 648.10 | 67786 | 10270 | 3766 | 6504 | 7393 | 677 |
| 7 | 22 | 86 | 5859.1 | 5465.5 | 648.70 | 73528 | 8965 | 2570 | 6395 | 8115 | 934 |
| 7 | 23 | 86 | 6001.2 | 5466.0 | 648.70 | 77818 | 8497 | 2375 | 6123 | 7269 | 631 |
| 7 | 24 | 86 | 6134.5 | 5466.7 | 648.70 | 83529 | 8841 | 2223 | 6618 | 7704 | 649 |
| 7 | 25 | 86 | 6285.9 | 5467.1 | 648.70 | 88105 | 9578 | 1777 | 7801 | 7540 | 599 |
| 7 | 26 | 86 | 6451.4 | 5467.7 | 648.70 | 93744 | 7902 | 1997 | 5905 | 8428 | 455 |
| 7 | 27 | 86 | 6625.9 | 5468.2 | 648.70 | 100075 | 8145 | 2437 | 5709 | 7126 | 387 |
| 7 | 28 | 86 | 6771.5 | 5468.9 | 648.70 | 106499 | 10971 | 2380 | 8591 | 7434 | 706 |
| 7 | 29 | 86 | 6934.7 | 5469.7 | 649.20 | 111658 | 8370 | 1760 | 6610 | 8275 | 795 |
| 7 | 30 | 86 | 7081.6 | 5470.6 | 649.20 | 117964 | 9474 | 2450 | 7024 | 7929 | 705 |
| 7 | 31 | 86 | 7195.8 | 5471.4 | 649.20 | 124285 | 8850 | 3134 | 5716 | 7991 | 587 |

**Table 8-9: PCON Spreadsheet Printout-4**

PCON spreadsheet analysis file:RECCT09.WK1

| A | B | C | AC | AD | AE | AF | AG | AH | AI | AJ | AK | AL | AM | AN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TODAY'S | | | COMP | | | | POOL | TOTAL | AVG | ZAM | EME | TOT | BA | ICE |
| MO | DA | YR | RUNTIME (HRS) | | | | WATER | WATER | WIND | USE | GEN | ATT | TI | TMP |
| 8 | 4 | 86 | W | C | E | TOT | USE/G | USE | MPH | M | USE | PER | MIN | F |
| MO | DA | YR | | | | | | | | <<<<<<---------------- | | | | |
| 7 | 1 | 86 | 11.8 | 16.6 | 14.4 | 42.8 | 666 | 18943 | 2.9 | 53 | 752 | 1371 | 0 | 16.0 |
| 7 | 2 | 86 | 12.7 | 18.0 | 16.4 | 47.1 | 1303 | 20729 | 4.0 | 61 | 9 | 1495 | 0 | 16.0 |
| 7 | 3 | 86 | 12.2 | 17.4 | 15.9 | 45.5 | 2063 | 18528 | 5.4 | 57 | 0 | 1272 | 4 | 16.0 |
| 7 | 4 | 86 | 12.0 | 16.5 | 13.9 | 42.4 | 798 | 10602 | 5.4 | 34 | 0 | 0 | 0 | 16.0 |
| 7 | 5 | 86 | 11.8 | 16.4 | 12.7 | 40.9 | 1188 | 9738 | 3.5 | 35 | 0 | 617 | 0 | 16.0 |
| 7 | 6 | 86 | 11.3 | 15.7 | 12.4 | 39.4 | 2160 | 15020 | 2.7 | 52 | 0 | 683 | 0 | 16.0 |
| 7 | 7 | 86 | 11.1 | 15.4 | 13.7 | 40.2 | 422 | 19786 | 3.1 | 59 | 8 | 1258 | 0 | 16.0 |
| 7 | 8 | 86 | 11.1 | 15.7 | 13.7 | 40.5 | 1119 | 18432 | 2.5 | 58 | 28 | 1298 | 4 | 16.5 |
| 7 | 9 | 86 | 11.4 | 15.8 | 13.3 | 40.5 | 1661 | 26845 | 3.3 | 55 | 0 | 1421 | 0 | 16.5 |
| 7 | 10 | 86 | 11.8 | 16.4 | 13.9 | 42.1 | 670 | 35869 | 3.8 | 41 | 0 | 1156 | 0 | 16.5 |
| 7 | 11 | 86 | 10.6 | 14.9 | 13.0 | 38.5 | 681 | 18896 | 3.0 | 73 | 0 | 1079 | 0 | 16.5 |
| 7 | 12 | 86 | 10.6 | 14.9 | 13.0 | 38.4 | 627 | 12084 | 3.0 | 30 | 0 | 519 | 0 | 16.5 |
| 7 | 13 | 86 | 11.0 | 15.5 | 13.4 | 40.0 | 413 | 13017 | 4.2 | 47 | 0 | 599 | 0 | 16.5 |
| 7 | 14 | 86 | 12.4 | 17.6 | 15.1 | 45.1 | 407 | 20704 | 4.4 | 81 | 10 | 723 | 0 | 14.5 |
| 7 | 15 | 86 | 13.8 | 20.0 | 17.9 | 51.7 | 1832 | 19839 | 2.9 | 69 | 20 | 1378 | 8 | 14.5 |
| 7 | 16 | 86 | 14.2 | 20.7 | 19.6 | 54.5 | 3195 | 21461 | 2.5 | 57 | 0 | 1247 | 0 | 14.5 |
| 7 | 17 | 86 | 13.1 | 18.9 | 17.6 | 49.6 | 728 | 18982 | 5.5 | 49 | 0 | 1423 | 0 | 16.0 |
| 7 | 18 | 86 | 11.8 | 16.9 | 15.1 | 43.9 | 856 | 16687 | 3.9 | 50 | 0 | 1059 | 0 | 16.5 |
| 7 | 19 | 86 | 10.9 | 15.1 | 12.4 | 38.3 | 736 | 13448 | 4.0 | 32 | 0 | 652 | 0 | 17.5 |
| 7 | 20 | 86 | 9.2 | 12.7 | 10.4 | 32.3 | 646 | 11404 | 2.4 | 27 | 0 | 712 | 0 | 17.5 |
| 7 | 21 | 86 | 9.9 | 13.5 | 11.0 | 34.4 | 622 | 17262 | 2.3 | 49 | 10 | 1199 | 0 | 17.5 |
| 7 | 22 | 86 | 11.1 | 15.1 | 12.9 | 39.1 | 640 | 21297 | 2.9 | 40 | 26 | 1513 | 0 | 17.5 |
| 7 | 23 | 86 | 10.6 | 13.4 | 11.3 | 35.2 | 747 | 17990 | 3.9 | 35 | 0 | 1175 | 0 | 17.0 |
| 7 | 24 | 86 | 10.5 | 14.8 | 12.7 | 38.1 | 1163 | 17607 | 3.7 | 38 | 0 | 1071 | 0 | 17.0 |
| 7 | 25 | 86 | 11.2 | 15.8 | 13.5 | 40.4 | 2105 | 16985 | 4.1 | 28 | 0 | 1027 | 4 | 17.0 |
| 7 | 26 | 86 | 11.3 | 15.9 | 14.3 | 41.5 | 512 | 12820 | 4.1 | 32 | 0 | 678 | 0 | 17.0 |
| 7 | 27 | 86 | 10.4 | 14.5 | 11.5 | 36.4 | 544 | 12496 | 4.3 | 33 | 0 | 677 | 0 | 17.0 |
| 7 | 28 | 86 | 11.1 | 15.5 | 12.2 | 38.8 | 673 | 19067 | 3.9 | 44 | 7 | 1348 | 0 | 17.0 |
| 7 | 29 | 86 | 10.9 | 15.2 | 12.8 | 38.8 | 1243 | 17301 | 4.3 | 52 | 23 | 1299 | 4 | 17.0 |
| 7 | 30 | 86 | 9.4 | 16.5 | 12.3 | 38.2 | 2001 | 19698 | 3.5 | 51 | 0 | 1472 | 0 | 17.0 |
| 7 | 31 | 86 | 7.0 | 16.5 | 11.6 | 35.0 | 726 | 17251 | 2.7 | 44 | 0 | 1216 | 0 | 16.5 |

**Table 8-10: PCON Spreadsheet Printout-5**

PCON spreadsheet analysis file:RECCT09.WK1

| A | B | C | AO | AP | AQ | AR | AS | AT | AU | AV | AW | AX | AY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TODAY'S | | | AVG | BLDR | COLD | COLD | SUN | SUN | WATR | POOL | SH | NATL | ELEC |
| MO | DA | YR | TMP | HDD | SUPP | SUPP | HORZ | HORZ | USE | WATR | OT | GAS | USE |
| 8 | 4 | 86 | BLDR | 65F | T(C) | T(F) | BTU | MIN | $/D | $/D | $/D | $/D | $/D |
| MO | DA | YR | ---------- | | | | | DEN | $$$--->>> NOTE: COSTS DEPEND | | | | |
| 7 | 1 | 86 | 75 | 0 | 14.1 | 57.4 | 2411 | | $23 | $0.75 | $23 | $19 | $386 |
| 7 | 2 | 86 | 82 | 0 | 14.8 | 58.6 | 2420 | | $26 | $1.46 | $24 | $3 | $458 |
| 7 | 3 | 86 | 85 | 0 | 14.9 | 58.8 | 1799 | | $23 | $2.32 | $21 | $2 | $405 |
| 7 | 4 | 86 | 86 | 0 | 15.9 | 60.6 | 1537 | | $13 | $0.90 | $12 | $1 | $357 |
| 7 | 5 | 86 | 72 | 0 | 15.4 | 59.7 | 1284 | | $12 | $1.33 | $11 | $1 | $387 |
| 7 | 6 | 86 | 67 | 0 | 14.9 | 58.8 | 1207 | | $19 | $2.43 | $16 | $1 | $390 |
| 7 | 7 | 86 | 71 | 0 | 15.2 | 59.4 | 2207 | | $24 | $0.47 | $24 | $2 | $403 |
| 7 | 8 | 86 | 74 | 0 | 15.2 | 59.4 | 1391 | | $23 | $1.26 | $21 | $3 | $425 |
| 7 | 9 | 86 | 75 | 0 | 15.3 | 59.5 | 1750 | | $33 | $1.87 | $31 | $3 | $436 |
| 7 | 10 | 86 | 74 | 0 | 14.6 | 58.3 | 1339 | | $44 | $0.75 | $43 | $2 | $429 |
| 7 | 11 | 86 | 75 | 0 | 14.7 | 58.5 | 1744 | | $23 | $0.77 | $23 | $3 | $381 |
| 7 | 12 | 86 | 82 | 0 | 15.8 | 60.4 | 1694 | | $15 | $0.70 | $14 | $2 | $366 |
| 7 | 13 | 86 | 82 | 0 | 15.6 | 60.1 | 1529 | | $16 | $0.46 | $16 | $1 | $376 |
| 7 | 14 | 86 | 83 | 0 | 15.6 | 60.1 | 2219 | | $26 | $0.46 | $25 | $2 | $394 |
| 7 | 15 | 86 | 75 | 0 | 15.5 | 59.9 | 1829 | | $24 | $2.06 | $22 | $3 | $413 |
| 7 | 16 | 86 | 73 | 0 | 15.6 | 60.1 | 1445 | | $26 | $3.59 | $23 | $3 | $400 |
| 7 | 17 | 86 | 75 | 0 | 15.2 | 59.4 | 1381 | | $23 | $0.82 | $23 | $2 | $411 |
| 7 | 18 | 86 | 69 | 0 | 15.2 | 59.4 | 1348 | | $21 | $0.96 | $20 | $2 | $383 |
| 7 | 19 | 86 | 71 | 0 | 16.4 | 61.5 | 1511 | | $17 | $0.83 | $16 | $2 | $393 |
| 7 | 20 | 86 | 70 | 0 | 0.0 | 58.6 | 1675 | | $14 | $0.73 | $13 | $2 | $363 |
| 7 | 21 | 86 | 70 | 0 | 0.0 | 58.6 | 2127 | | $21 | $0.70 | $21 | $3 | $398 |
| 7 | 22 | 86 | 70 | 0 | 0.0 | 60.2 | 1893 | | $26 | $0.72 | $26 | $4 | $437 |
| 7 | 23 | 86 | 77 | 0 | 0.0 | 60.3 | 1901 | | $22 | $0.84 | $21 | $2 | $391 |
| 7 | 24 | 86 | 79 | 0 | 0.0 | 61.4 | 2107 | | $22 | $1.31 | $20 | $2 | $414 |
| 7 | 25 | 86 | 76 | 0 | 0.0 | 61.5 | 1920 | | $21 | $2.36 | $19 | $2 | $406 |
| 7 | 26 | 86 | 78 | 0 | 0.0 | 61.0 | 2159 | | $16 | $0.57 | $15 | $2 | $453 |
| 7 | 27 | 86 | 76 | 0 | 0.0 | 61.7 | 2408 | | $15 | $0.61 | $15 | $1 | $383 |
| 7 | 28 | 86 | 80 | 0 | 0.0 | 61.4 | 2356 | | $24 | $0.76 | $23 | $3 | $400 |
| 7 | 29 | 86 | 85 | 0 | 0.0 | 61.7 | 2179 | | $21 | $1.40 | $20 | $3 | $445 |
| 7 | 30 | 86 | 79 | 0 | 0.0 | 61.6 | 2355 | | $24 | $2.25 | $22 | $3 | $427 |
| 7 | 31 | 86 | 73 | 0 | 0.0 | 61.7 | 2142 | | $21 | $0.82 | $20 | $2 | $430 |

**Table 8-11: PCON Spreadsheet Printout-6**

PCON spreadsheet analysis file:RECCT09.WK1

| A | B | C | AZ | BA | BB | BC | BD | BE | BF | BG | BH | BI | BJ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TODAY'S | | | STM | POOL | SHOW | COM | ELEC | TOTAL | EST->M1 EST | | M1 | M2 | M3 |
| MO | DA | YR | USE | STM | &OTH | USE | LTS | $/D | EST->VS | | VS | VS | VS |
| 8 | 4 | 86 | $/D | $/D | STM | $/D | &OTH | | EST->SHOW | | SHOW $ | POOL | OTHER |
| MO | DA | YR | ON | F.M. | CHARGE/MONTH SEE SCH | | | | EST->& OTH | | COMPARISTEAM | | ELEC |
| 7 | 1 | 86 | $49 | $4 | $44 | $129 | $258 | $478 | EST-> | 9020 | -2487 | -1015 | -728 |
| 7 | 2 | 86 | $41 | $5 | $36 | $142 | $316 | $527 | EST-> | 6236 | -859 | -861 | 447 |
| 7 | 3 | 86 | $42 | $4 | $38 | $137 | $268 | $472 | EST-> | 4001 | 1555 | -818 | -431 |
| 7 | 4 | 86 | $37 | $4 | $33 | $128 | $229 | $409 | EST-> | 1966 | 2882 | -77 | 425 |
| 7 | 5 | 86 | $50 | $5 | $45 | $123 | $264 | $450 | EST-> | 7842 | -1123 | -732 | 24 |
| 7 | 6 | 86 | $63 | $5 | $58 | $118 | $272 | $472 | EST-> | 10835 | -2233 | -784 | 40 |
| 7 | 7 | 86 | $7 | $5 | $3 | $121 | $282 | $437 | EST-> | 9396 | -9003 | -975 | -247 |
| 7 | 8 | 86 | $53 | $5 | $48 | $122 | $303 | $504 | EST-> | 8588 | -1506 | -774 | 131 |
| 7 | 9 | 86 | $80 | $7 | $74 | $122 | $314 | $552 | EST-> | 7853 | 3035 | -642 | 408 |
| 7 | 10 | 86 | $111 | $7 | $104 | $127 | $303 | $587 | EST-> | 8209 | 7093 | -610 | 216 |
| 7 | 11 | 86 | $60 | $11 | $50 | $116 | $265 | $467 | EST-> | 8856 | -1487 | -47 | -490 |
| 7 | 12 | 86 | $43 | $6 | $37 | $116 | $250 | $425 | EST-> | 4510 | 915 | -415 | -79 |
| 7 | 13 | 86 | $43 | $6 | $37 | $120 | $255 | $435 | EST-> | 4704 | 707 | -382 | -52 |
| 7 | 14 | 86 | $58 | $6 | $52 | $136 | $259 | $480 | EST-> | 5109 | 2551 | -661 | -603 |
| 7 | 15 | 86 | $45 | $5 | $40 | $155 | $258 | $486 | EST-> | 8334 | -2464 | -688 | -880 |
| 7 | 16 | 86 | $45 | $5 | $40 | $164 | $236 | $474 | EST-> | 8585 | -2734 | -887 | -1158 |
| 7 | 17 | 86 | $51 | $10 | $40 | $149 | $262 | $488 | EST-> | 7227 | -1249 | -177 | -652 |
| 7 | 18 | 86 | $56 | $18 | $38 | $132 | $251 | $462 | EST-> | 9342 | -3680 | 945 | -716 |
| 7 | 19 | 86 | $49 | $12 | $37 | $115 | $278 | $462 | EST-> | 7214 | -1739 | 407 | 359 |
| 7 | 20 | 86 | $54 | $20 | $34 | $97 | $265 | $432 | EST-> | 9213 | -4185 | 1513 | 124 |
| 7 | 21 | 86 | $70 | $25 | $44 | $103 | $294 | $491 | EST-> | 9953 | -3448 | 2112 | 128 |
| 7 | 22 | 86 | $61 | $17 | $43 | $118 | $319 | $527 | EST-> | 9034 | -2638 | 854 | 462 |
| 7 | 23 | 86 | $58 | $16 | $41 | $106 | $285 | $473 | EST-> | 6357 | -234 | 778 | 39 |
| 7 | 24 | 86 | $60 | $15 | $45 | $115 | $300 | $499 | EST-> | 5227 | 1391 | 592 | 273 |
| 7 | 25 | 86 | $65 | $12 | $53 | $122 | $284 | $494 | EST-> | 5626 | 2174 | 265 | 68 |
| 7 | 26 | 86 | $53 | $14 | $40 | $125 | $328 | $524 | EST-> | 5275 | 630 | 651 | 1331 |
| 7 | 27 | 86 | $55 | $16 | $39 | $110 | $274 | $455 | EST-> | 5439 | 270 | 1067 | 294 |
| 7 | 28 | 86 | $74 | $16 | $58 | $117 | $283 | $500 | EST-> | 5181 | 3410 | 811 | -37 |
| 7 | 29 | 86 | $57 | $12 | $45 | $117 | $328 | $526 | EST-> | 2872 | 3738 | 285 | 763 |
| 7 | 30 | 86 | $64 | $17 | $48 | $115 | $312 | $518 | EST-> | 5744 | 1280 | 872 | 430 |
| 7 | 31 | 86 | $60 | $21 | $39 | $105 | $325 | $513 | EST-> | 7451 | -1736 | 1439 | 585 |

**Table 8-12: PCON Spreadsheet Printout-7**

PCON spreadsheet analysis file:RECCT09.WK1

| A | B | C | BK | BL | BM | BN | BO | BP | BQ | BR | BS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TODAY'S | | | M4 EST | M5 EST | M6 EST | M7 EST | $$ | $$ | $$ | $$ | $$ |
| MO | DA | YR | VS | VS | VS | VS | M1 EST | M2 ES | M3 EST | M4 EST | M5 EST |
| 8 | 4 | 86 | COMP | N/G | PO WA | OTH WA | VS OST | VS PS | VS OEL | VS CO | VS NG |
| MO | DA | YR | ELEC | CF | GAL | GAL | | | | | |
| 7 | 1 | 86 | 309 | -539 | -480 | 3129 | ($17) | ($7) | ($39) | $17 | ($2.06) |
| 7 | 2 | 86 | 433 | 0 | 140 | 4594 | ($6) | ($6) | $24 | $23 | $0.00 |
| 7 | 3 | 86 | 352 | -74 | 231 | 3488 | $11 | ($6) | ($23) | $19 | ($0.28) |
| 7 | 4 | 86 | 303 | 286 | 75 | 6585 | $20 | ($1) | $23 | $16 | $1.09 |
| 7 | 5 | 86 | 296 | -46 | 252 | -358 | ($8) | ($5) | $1 | $16 | ($0.18) |
| 7 | 6 | 86 | 138 | -121 | 1230 | 3183 | ($15) | ($5) | $2 | $7 | ($0.46) |
| 7 | 7 | 86 | 103 | 5 | -677 | 4191 | ($61) | ($7) | ($13) | $6 | $0.02 |
| 7 | 8 | 86 | 136 | -60 | -748 | 2556 | ($10) | ($5) | $7 | $7 | ($0.23) |
| 7 | 9 | 86 | 151 | 144 | 517 | 11034 | $21 | ($4) | $22 | $8 | $0.55 |
| 7 | 10 | 86 | 372 | 104 | -419 | 21627 | $48 | ($4) | $12 | $20 | $0.40 |
| 7 | 11 | 86 | -77 | 146 | -412 | 3152 | ($10) | ($0) | ($26) | ($4) | $0.56 |
| 7 | 12 | 86 | 160 | 99 | -377 | 3244 | $6 | ($3) | ($4) | $9 | $0.38 |
| 7 | 13 | 86 | 130 | -103 | -563 | 2701 | $5 | ($3) | ($3) | $7 | ($0.39) |
| 7 | 14 | 86 | 69 | 4 | -653 | 6943 | $17 | ($4) | ($32) | $4 | $0.02 |
| 7 | 15 | 86 | 569 | 147 | -748 | 3451 | ($17) | ($5) | ($47) | $31 | $0.56 |
| 7 | 16 | 86 | 822 | 193 | 2061 | 6594 | ($19) | ($6) | ($62) | $44 | $0.74 |
| 7 | 17 | 86 | 677 | 44 | -359 | 3319 | ($8) | ($1) | ($35) | $36 | $0.17 |
| 7 | 18 | 86 | 408 | 147 | -181 | 2335 | ($25) | $6 | ($38) | $22 | $0.56 |
| 7 | 19 | 86 | 223 | 257 | -201 | 3149 | ($12) | $3 | $19 | $12 | $0.98 |
| 7 | 20 | 86 | -18 | 78 | -317 | 907 | ($28) | $10 | $7 | ($1) | $0.30 |
| 7 | 21 | 86 | -57 | 87 | -485 | 2162 | ($23) | $14 | $7 | ($3) | $0.33 |
| 7 | 22 | 86 | 238 | 183 | -522 | 5322 | ($18) | $6 | $25 | $13 | $0.70 |
| 7 | 23 | 86 | -5 | 139 | -361 | 4493 | ($2) | $5 | $2 | ($0) | $0.53 |
| 7 | 24 | 86 | 105 | 158 | 23 | 4341 | $9 | $4 | $15 | $6 | $0.60 |
| 7 | 25 | 86 | 317 | 148 | 312 | 4629 | $15 | $2 | $4 | $17 | $0.57 |
| 7 | 26 | 86 | 348 | 126 | -464 | 2887 | $4 | $4 | $72 | $19 | $0.48 |
| 7 | 27 | 86 | 59 | 58 | -420 | 2505 | $2 | $7 | $16 | $3 | $0.22 |
| 7 | 28 | 86 | 101 | 117 | -487 | 4576 | $23 | $5 | ($2) | $5 | $0.45 |
| 7 | 29 | 86 | 11 | 84 | -656 | 2552 | $25 | $2 | $41 | $1 | $0.32 |
| 7 | 30 | 86 | 15 | 127 | 813 | 4178 | $9 | $6 | $23 | $1 | $0.49 |
| 7 | 31 | 86 | -114 | 56 | -428 | 2735 | ($12) | $10 | $31 | ($6) | $0.21 |

**Table 8-13: PCON Spreadsheet Printout-8**

PCON spreadsheet analysis file:RECCT09.WK1

| A | B | C | BT | BU |
|---|---|---|---|---|
| TODAY'S | | | $$ | $$ |
| MO | DA | YR | M6 EST | M7 EST |
| 8 | 4 | 86 | VS PW | VS OW |
| MO | DA | YR | | |
| 7 | 1 | 86 | ($0.62) | $4.07 |
| 7 | 2 | 86 | $0.18 | $5.97 |
| 7 | 3 | 86 | $0.30 | $4.53 |
| 7 | 4 | 86 | $0.10 | $8.56 |
| 7 | 5 | 86 | $0.33 | ($0.47) |
| 7 | 6 | 86 | $1.60 | $4.14 |
| 7 | 7 | 86 | ($0.88) | $5.45 |
| 7 | 8 | 86 | ($0.97) | $3.32 |
| 7 | 9 | 86 | $0.67 | $14.34 |
| 7 | 10 | 86 | ($0.55) | $28.12 |
| 7 | 11 | 86 | ($0.58) | $4.41 |
| 7 | 12 | 86 | ($0.53) | $4.54 |
| 7 | 13 | 86 | ($0.79) | $3.78 |
| 7 | 14 | 86 | ($0.91) | $9.72 |
| 7 | 15 | 86 | ($1.05) | $4.83 |
| 7 | 16 | 86 | $2.89 | $9.23 |
| 7 | 17 | 86 | ($0.50) | $4.65 |
| 7 | 18 | 86 | ($0.25) | $3.27 |
| 7 | 19 | 86 | ($0.28) | $4.41 |
| 7 | 20 | 86 | ($0.44) | $1.27 |
| 7 | 21 | 86 | ($0.68) | $3.03 |
| 7 | 22 | 86 | ($0.73) | $7.45 |
| 7 | 23 | 86 | ($0.50) | $6.29 |
| 7 | 24 | 86 | $0.03 | $6.08 |
| 7 | 25 | 86 | $0.44 | $6.48 |
| 7 | 26 | 86 | ($0.65) | $4.04 |
| 7 | 27 | 86 | ($0.59) | $3.51 |
| 7 | 28 | 86 | ($0.68) | $6.41 |
| 7 | 29 | 86 | ($0.92) | $3.57 |
| 7 | 30 | 86 | $1.14 | $5.85 |
| 7 | 31 | 86 | ($0.60) | $3.83 |

#### 8.5.1.2. Explanation of Equations

This section is intended to be a brief explanation of the equations contained within the Lotus (1985) spreadsheet used to generate the BEACON SCON analysis. The notation used is compatible with the Lotus 123 format. The equations were transferred directly from the spreadsheet through a "print to file" command.

Each equation contains the location of the cell, the format used in the column, and the width of the column. For example, in the first equation shown the "A341" is the location of the cell, the "(F0)" is the format of the cell (i.e., fixed with no decimal), and the [W3] is the width of the column in which the cell resides. The reader is referred to the Lotus (1985) manual for further a complete explanation.

The equations begin with the first column for the day, July 1, 1986, and proceed across the spreadsheet. This first equation is therefore in row 341, column A. The column numbers can be located at the top of each of the columns.

A341: (F0) [W3] 7

B341: (F0) [W3] 1

C341: (F0) [W3] 86

These equations contain the month, day and year that the information was recorded. These columns contain data that was generated automatically with the spread sheet.

The next equation D341 contains the hour of the day that the reading was taken. This information is entered by the user. The format is in hours and decimal minutes.

D341: (F1) [W5] 19.0

Equation E341 is the calculation of the day of the week. The Lotus spread sheet contains a dateline serial number function. Taking the mod 7 of this number serial number yields the day of the week. For this spreadsheet, 0 is Sunday, 6 is Saturday.

E341: (F0) [W2] @MOD(@DATE(C341,A341,B341),7)

Equation F341 is the dateline serial number of the date and hour of the reading. This value is used later in the calculations to normalize the readings to midnight of each day. For 19 hours on July 1 1986, the dateline serial number would read 31594.792.

F341: (F3) [W10] (@DATE(C341,A341,B341)+(D341/24))

Equation G341 is the elapsed time between the current reading and the previous reading. For July 1st this would be 25.5 hours.

G341: (F1) [W5] (F341-F340)*24

H341 contains the scheduled operating hours for the building, in hours per day. This value was obtained form the published operating schedule of the building.

H341: (F1) [W6] 15.5

Equation I341 is the normalizer to midnight fraction. This value represents the differenct in hours between when the reading was taken and midnight divided by the total number of hours between readings. For July 1 this value was 0.227. This normalizer will be used to assign part of the consumption to July 1st and part to July 2nd.

I341: (F3) [W7] (@DATE(C342,A342,B342)-F341)/(F342-F341)

J341 is the actual meter reading for the main steam meter. This meter reads in gallons.

J341: (F0) [W8] 4434390

K341 is the pool steam meter reading. This meter reads in lbs of steam.

K341: (F0) [W7] 823903

L341 is the electrical kwh reading from the main electrical meter. This is the dial reading. The meter constant is applied in the conversion in AA341.

L341: (F1) [W7] 5576

M341 is the dial reading for the natural gas meter. This dial reads in 100 cubic feet of natural gas.

M341: (F1) [W7] 6592

N341 is the compressor runtime reading for the west compressor. This meter reads in elapsed hours since the compressor was installed.

N341: (F1) [W8] 71499.4

O341 is the compressor runtime reading for the center compressor. This meter reads also reads in elapsed hours since the ceter compressor was installed.

O341: (F1) [W8] 74428.5

P341 is the compressor runtime reading for the east compressor. This also reads in elapsed runtime.

P341: (F1) [W8] 73478.00

Q341 is reading for the gallons of water that have entered the pool. This installation of this meter uncovered the 20,000 gallon per day leak in the surge tank.

Q341: (F0) [W8] 5313551

R341 and S341 are the tandom water meters that service the entire building. Tandom meters have two separate meters for measuring low and high flow rates. Therefore, the meters are added together and the additive rate is compared. Both these meters read in gallons.

R341: (F0) [W8] 327038

S341: (F0) [W9] 49375220

T341 is the kilometers of wind that have passed the site during the interim period since the last reading. These readings are from a contact anemometer located on the roof of the Rec Center.

T341: (F1) [W7] 2973.6

U341 are the runtime hours for the Zamboni ice resurfacing machine. This reading is taken from the runtime meter located on the machine.

U341: (F1) [W7] 5447.8

V341 is the runtime reading from the emergency generator located in the penthouse of the Rec Center. This generator is usually tested every Tuesday at 8 am by Facilities Management.

V341: [W7] 646.8

W341 is the total horizontal insolation recorded at the Rec Center. This reading was taken with a integrating solar meter located on the roof of the Rec Center. The reading represents Langleys.

W341: (F0) [W7] 81028

Equation X341 is the calculation for total amount of steam used by the building. This amount represents the steam that is recorded by the main steam meter. The amount represented by this equation is the normalized amount of steam consumed by the building from midnight, the previous day, to midnight the current day.

X341: (F0) [W8] ((I341*(J342-J341)+J341)-(I340*(J341-J340)+J340))*8.09

The normalizing function (similar for all equations) works in the following fashion:

First, the amount of steam having passed through the meter since the last reading calculated, thus

(J342-J341)

Then, this amount is normalized by only accounting for that part that would have passed through the meter at midnight, as follows

I341*(J342-J341)

This amount is then added to the current day's consumption,

(I341*(J342-J341)+J341)

This procedure is then repeated for the previous day.

(I340*(J341-J340)+J340)

Finally, the two normalized consumptions are then subtracted and multiplied by the meter constant, yielding equation X341, which reads in pounds of steam.

X341: (F0) [W8] ((I341*(J342-J341)+J341)-(I340*(J341-J340)+J340))*8.09

This procedure is used throughout the meter readings used in this analysis. The procedure was chosen because it frees the meter reading of the tedium of reading the meters at the exact time each day. Other procedures can be developed. This procedure does tend to smear one particular day's consumption over two to three days, depending on the amount consumed and the difference between the preceeding and the succeeding days.

Equation Y341 is the normalized consumption for the pool steam usage. The resultant normalized steam consumption is in pounds.

Y341: (F0) [W6] ((I341*(K342-K341)+K341)-(I340*(K341-K340)+K340))

Equation Z341 is the normalized "other" steam consumption. This steam represents the subtracted difference for all steam used in the building besides that used in the pool. This normalized steam consumption is also in pounds of steam.

Z341: (F0) [W6] (X341-Y341)

AA341 is the equation that calculates the normalized electrical consumption for the entire building. This calculation yields kilowatt-hours.

AA341: (F0) [W6] ((I341*(L342-L341)+L341)-(I340*(L341-L340)+L340))*1600

AB341 calculates the normalized natural gas usage for the building in cubic feet of gas consumed.

AB341: (F0) [W7] ((I341*(M342-M341)+M341)-(I340*(M341-M340)+M340))*100

AC341 through AE341 calculates the compressor runtimes for the ice rink refrigeration equipment. These equations yield normalized hours of runtime.

AC341: (F1) [W5] ((I341*(N342-N341)+N341)-(I340*(N341-N340)+N340))

AD341: (F1) [W5] ((I341*(O342-O341)+O341)-(I340*(O341-O340)+O340))

AE341: (F1) [W5] ((I341*(P342-P341)+P341)-(I340*(P341-P340)+P340))

AF341 is then the total hours of runtime logged by all three compressors.

AF341: (F1) [W5] +AC341+AD341+AE341

AG341 is the normalized pool water usage in gallons.

AG341: (F0) [W7] ((I341*(Q342-Q341)+Q341)-(I340*(Q341-Q340)+Q340))

AH341 is the normalized total building water usage, inclusive of the pool water usage. AH341 reads in gallons.

AH341: (F0) [W7] (I341*(R342-R341)+R341)+(I341*(S342-S341)+S341)-
(I340*(R341-R340)+R340)-(I340*(S341-S340)+S340)

AI341 is the normalized average wind speed recorded at the Rec Center in miles per hour, average per day.

AI341: (F1) [W5] ((I341*(T342-T341)+T341)-(I340*(T341-T340)+T340))
/(24*1.6093)

AJ341 is normalized runtime for the Zamboni ice resurface machine, in minutes per day.

AJ341: (F0) [W4] ((I341*(U342-U341)+U341)-(I340*(U341-U340)+U340))*60

AK341 is the normalized runtime for the emergency generator, in minutes per day.

AK341: (F0) [W4] ((I341*(V342-V341)+V341)-(I340*(V341-V340)+V340))*60

AL341 is the recorded door count for each day, in persons per day. This value is not normalized.

AL341: (F0) [W5] 1371

AM341 is the number of minutes that the pool permanent media filters have been backwashed. This value is not normalized.

AM341: (F0) [W3] 0

AN341 is the observed ice rink setpoint temperature, in degrees Fahrenheit.

AN341: (F1) [W5] 16

AO341 is average outside temperature (F), recorded at the Rec Center. This value is the mean of the recorded minimum and maximum temperatures. This value is not normalized.

```
AO341: (F0) [W4] 75
```

AP341 is an equation that calculates heating degree days, should the temperature fall below 65 F. This value, likewise is not normalized.

```
AP341: (F0) [W5] @IF(AO341<65,(65-AO341),0)
```

AQ341 and AR341 are the measured city water temperature, taken at the Rec Center. AQ341 is in degrees C, and AR341 is the conversion to degrees F.

```
AQ341: (F1) [W5] 14.1
AR341: (F1) [W6] (AQ341*9/5)+32
```

AS341 is the equation that calculates the normalized horizontal sunlight from the meter readings at the Rec Center. AS341 has an @IF mechanism to check to see is the meter has "rolled" over. This simple check looks to see if "100010" has been recorded as "10". An ERR condition is signaled to the user to correct this problem.

```
AS341: (F0) [W7] @IF(W342<W341,@ERR,((I341*(W342-W341)+W341)
                 -(I340*(W341-W340)+W340))*0.383)
```

AT341 is the unused total horizontal sunlight from Denver NOAA information. This column can be used as a check of the sunlight recordings. Horizontal sunlight, recorded by NOAA is recorded in minutes of sunshine per day, a somewhat arbitrary unit.

AS341: (F0) [W7] ...unused...

AU341 is the normalized total water use for the building, expressed in dollars per day. All associated dollar values for water, electric, natural gas and steam are the actual rates for each month charged by Facilities Management. The values can fluctuate each month, based on the recharge formula used by Facilities Management. For water usage, on this day the rate was $0.001233.

AU341: (C0) [W5] (AH341*0.001233)

AV341 is the normalized water consumption for the pool, in dollars.

AV341: (C2) [W7] (AG341*0.001233)

AW341 is the normalized "other" water usage for the building, expressed in dollars. This is arrived at by subtracting the pool water consumption from the total building water consumption.

AW341: (C0) [W6] (AU341-AV341)

AX341 is the normalized natural gas consumption for the building expressed in dollars. For July 1, the natural gas recharge rate was $0.382 per CCF.

AX341: (CO) [W4] (AB341*0.382/100)

AY341 is the normalized electrical usage for the total building, expressed in dollars. The recharge rate during the day shown was $0.0538 per kwh.

AY341: (CO) [W6] (AA341*0.0538)

AZ341 is the normalized steam consumption for the total building, expressed in dollars. The recharge rate for July 1 was $6.77 per 1000 pounds of steam.

AZ341: (CO) [W5] (X341*6.77/1000)

BA341 is the normalized pool steam consumption, expressed in dollars. The rate for July 1, which is identical to AZ341, is $6.77 per 1000 pounds of steam.

BA341: (CO) [W5] (Y341*6.77/1000)

BB341 represents the normalized "other" steam consumption for the building, expressed in dollars. This value is the subtractive "other" steam usage after the pool steam has been accounted for.

BB341: (CO) [W5] (AZ341-BA341)

Equation BC341 calculates the equivalent electrical energy used by the ice rink compressors. This value multiplies the total compressor runtime (75 horsepower) times a 0.7457 conversion factor times $0.0538 ($/kwh), yielding dollars per day. Since this is a comparative value, no system inefficiencies are accounted for.

BC341: (CO) [W5] (AF341*0.7457*75*0.0538)

BD341 is therefore the normalized "other" electrical consumption, in dollars. This subtractive electrical consumption accounts for all other electrical consumption in the building, including certain ice rink functions (eg. condensor pumps, circulating pumps, etc.). Again, since these values were used for regression and comparative purposes, no attempt was made to account for electrical system losses other than what showed up in the regression analysis.

BD341: (CO) [W5] (AY341-BC341)

BE341 is the total normalized consumption. Inclusive of total water usage, natural gas consumption, electric consumption and steam consumption.

BE341: (CO) [W6] (AU341+AX341+AY341+AZ341)

BF341 is a marker used to identify the beginning of the prediction portion of the spreadsheet.

BF341: [W5] 'EST->

The equations contained in this portions of the spreadsheet are the prediction equations for the BEACON PCON processor. The following table lists the entire group:

Rec Center - Consumption Predictors

PCON1(lbs-steam) "other steam"

$$PCON1 = 81552.179 - 1640.571(EP2) + 79.407(EP2)^2 - 2.321(EP2)^3 + 0.028(EP2)^4 - 0.001(EP2)^5 - 481.567(EP3) + 24.308(OP3) - 341.500(EP1) + 0.017(OP8*OP2)$$

PCON2(lbs-steam) "pool steam"

$$PCON2 = 1344.790 - 0.010(OP8) - 23.790(OP9) - 10.000(EP2) + 4.080(EP3) + 53.950(OP2)$$

PCON3(kwh) "other electric"

$$PCON3 = 5545.469 + 78.231(OP2) + 9.521(EP2) + 3.349(OP3) - 63.000(SP2) + 0.224(OP8)$$

PCON4(kwh) "ice rink"

$$PCON4 = 1021.320 + 7.140(OP3) - 49.270(SP2) + 5.000(EP2) + 19.170(EP3)$$

PCON5(cf) "natural gas"

$$PCON5 = 0.000 + 0.190(OP8) + 6.642(SP1) + 13.990(OP2) + 1.870(OP3)$$

PCON6(gal) "pool water"

$$PCON6 = -204.551 + 176.550(OP9) + 0.147(OP8) + 5.860(EP2) + 9.800(EP3) - 30.960(EP1) + 15.190(OP2)$$

PCON7(gal) "other water"

$$PCON7 = 8286.350 + 4.070(OP8) - 89.350(EP3) - 55.420(EP2) + 267.310(OP2) + 227.060(SP2) + 65.790(OP3)$$

PCON1 - Other steam(lbs/day, $R^2 = 0.98$, $SE_{Yest} = 3451.48$ lbs.)
PCON2 - Pool steam(lbs/day, $R^2 = 0.12$, $SE_{Yest} = 727.57$ lbs.)
PCON3 - Other electric(kwh/day, $R^2 = 0.75$, $SE_{Yest} = 438.12$ kwh)
PCON4 - Ice rink(kwh/day, $R^2 = 0.85$, $SE_{Yest} = 119.22$ kwh)
PCON5 - Natural gas(cf/day, $R^2 = 0.74$, $SE_{Yest} = 186.11$ cf.)
PCON6 - Pool water(gal/day, $R^2 = 0.46$, $SE_{Yest} = 553.14$ gal.)
PCON7 - Other water(gal/day, $R^2 = 0.85$, $SE_{Yest} = 2609.73$ gal.)
EP1 - Wind, average daily (mph)
EP2 - Ambient Temperature, average daily (F)
EP3 - City Water Temperature, sampled daily (F)
EP4 - Solar Radiation, daily totals (Btu/sqft-day)
OP1 - Day of the Week
OP2 - Scheduled Operating Hours (Hours/day)
OP3 - Zamboni Runtime (Minutes/day)
OP8 - Attendance (Persons/day)
OP9 - Pool Backwash (Minutes)

SP1 - Emergency Generator usage (Minutes)
SP2 - Ice rink setpoint temperature (F)

Equation BG341 is the PCON1 predictor. This equation predicts the steam energy used for "other" steam purposes in pounds of steam per day.

```
BG341: (FO) [W7] (81552.179-1640.6*AO341+79.4*AO341©2
                        -2.3*AO341©3+0.028*AO341©4
                        -0.00012*AO341©5-481.6*AR341
                        +24.3*AJ341-341.5*AI341
                        +0.017*AL341*H341)
```

BH341 is the comparative steam consumption for PCON1. This equation yields a difference in steam consumption between what was predeicted (BG341) and what was measured (Z341) in pounds of steam per day.

```
BH341: (FO) [W7] +Z341-BG341
```

BI341 is the comparative steam consumption for pool steam usage, expressed in pounds of steam per day. Pool steam is the value predicted by PCON2.

```
BI341: (FO) [W7] +Y341-(1344.79-0.01*AL341
          -23.71*AM341-10*AO341
          +4.08*AR341+53.95*H341)
```

BJ341 is the comparative electrical consumption for the "other" electric meter. BJ341 calculates PCON3 in kwh per day.

```
BJ341: (F0) [W6] +AA341-(5545.469+H341*78.231
                 -AO341*9.521+AJ341*3.349
                 -AN341*63+AL341*0.224)
                 -(AF341*0.7457*75)
```

BK341 is the comparative PCON4 predictor. PCON4 predicts the compressor electric for each day in calculated kwh per day.

```
BK341: (F0) [W7] (AF341*0.7457*75)-(1021.32
                 +AJ341*7.14-AN341*49.27
                 +AO341*5+AR341*19.17)
```

BL341 is the comparative PCON5 for natural gas usage, expressed in CF per day.

```
BL341: (F0) [W7] +AB341-(0.19*AL341+6.6417*AK341
                 +13.99*H341+1.87*AJ341)
```

BM341 is the comparative PCON6 for pool water usage in gallons per day.

```
BM341: (F0) [W7] +AG341-(-204.551+176.55*AM341
                 +0.147*AL341+5.86*AO341
                 +9.8*AR341-30.96*AI341+15.19*H341)
```

BN341 is the last comparative equation, PCON7. This equation predicts the "other" water consumption for the building in gallons per day.

BN341: (F0) [W9] +AH341-(8286.35+4.07*AL341
-89.35*AR341-55.42*AO341
+267.31*H341+227.06*AN341
+65.79*AJ341)

BO341 is the comparative PCON1 consumption, expressed in dollars per day.

BO341: (C0) [W6] (BH341*6.77/1000)

BP341 is the comparative PCON2 consumption, expressed in dollars per day.

BP341: (C0) [W6] (BI341*6.77/1000)

BQ341 is the comparative PCON3 consumption, expressed in dollars per day.

BQ341: (C0) [W7] (BJ341*0.0538)

BR341 is the comparative PCON4 consumption, expressed in dollars per day.

BR341: (C0) [W7] (BK341*0.0538)

BS341 is the comparative PCON5 consumption, expresssed in dollars per day.

BS341: (C2) [W7] (BL341*0.382/100)

BT341 is the comparative PCON6 consumption, expressed in dollars per day.

BT341: (C2) [W8] (BM341*0.0013)

Finally, BU341 is the comparative PCON7 consumption, expressed in dollars per day. BU341 represents the final column in the spreadsheet.

BU341: (C2) [W9] (BN341*0.0013)

**8.5.1.3. Instructions for Using BEACON PCON Spreadsheet**

Use of the PCON spreadsheet begins by firing up the Lotus 123 software. The proper file is the loaded into the 123 program using the FILE RETRIEVE filename.wk1 command. The current version of the PCON spreadsheet requires extended memory for the 1.3 Mbyte to load into memory. Once loaded the PCON session begins. The user will need to go to the bottom left-hand side of the spreadsheet to enter the meter readings for the each day.

Assuming that the proper extension of all columns has been made with the COPY command, the first entry made is for the "time of the reading" in hours and decimal minutes. The day-of-the week is calculated as is the timeline and elapsed time values. The next entry is the scheduled operating hours. This values comes from the posted schedule provided by the Rec Center Administration. The next column, the normalizing fraction is then calculated from the previously provided information.

The next value, the first of the metered information, is the total steam reading followed, consecutively by pool steam, electric usage, natural gas usage, west compressor reading, center compressor reading, pool water usage, main water meter number one, main water meter number two, the wind meter reading, the zamboni runtime meter, the emergency generator meter, and finally the sun meter reading.

The next values entered is the total attendence, followed by the backwash time, ice setpoint temperature, average Boulder temperature and city water temperature (degrees F or C).

The final item that needs to be entered is the cost values from Facilities Management. These are inserted into the equations in for water, natural gas, electricity and steam. These cost values are entered once per month. They are also required in the last seven columns, which are a repeat of the first cost columns.

Once the values are entered for each day of the analysis, the user then calculates the values, once, by pressing the F9 key. Should the values be calculating each cycle, the user will need to set WORKSHEET GLOBAL RECALCULATION MANUAL to assure that calculations are done once and not after each entry.

When the spreadsheet has been calculated the appropriate graphs and printouts can be made using the lotus functions. The PCON comparison values are then available for assembly into the cache files. The use of the cache files is discussed in the following BEACON CCON section.

### 8.5.1.4. Instructions for Using BEACON PCON Regressions

This section contains a sample BEACON PCON regression analysis. The user is referred to the Lotus (1985) literature for further analysis of the commands. This section is intended to be a brief overview for users that are already familiar with the software.

The regressions are run using the Lotus 123 (1985) spreadsheet. This analysis is performed by establishing the Y variable in column AMxx and the X variables in column ANxx through BDxx. The first step is to organize the spread sheet so that this can be facilitated. Column AL is the actual data, as observed. Column AM is the regressed predictor for each day (a plot of actual versus regressed can be seen in the following figure. Column AN is the outside temperature. Column AO is the square of the outside temperature. Column AP is the cube of outside air temperature. Column AQ is the outside temperature to the fourth power. Likewise, column AR is the outside temperature to the fifth power. Column AS is the cold water supply temperature. Column AT is the Zamboni ice resurface usage. Column AU is the average wind speed. Column AV is the combined person*hours. Column AV is constructed by multiplying the number of persons in the building by the numbers of hours that the building is open. Since regression analysis assumes, by definition, that the X variables are independent, the dependency between the number of persons and the operating hours was removed by cross multiplying each value and constructing a new variable, as shown in column AV. AX is the backwash time. AY is the setpoint temperature of the ice. AZ is the day-of-the-week. The day-of-the-week is assembled using the Lotus MOD function and the DATE function, as discussed earlier. BA is the use of the emergency generator. BB is the total attendence at the Rec Center for each day. BC is the scheduled operating hours. BD (unused) is the combined variables (persons/hour).

The regression output is shown following the last value of the BD column. This output is the standard output from the Lotus 123 (1985) regressions. Each of these variables is described in detail in the preceeding section on statistics. The Constant is the Y intercept variable. Next is the standard error of the Y estimate (equation VIII.25), followed by the multiple $R^2$ variable (equation VIII.30). The next value is the number of observations used during the regression followed by the degrees of freedom on the analysis. The V7 and V7@2 markers were inserted to help track the effect of the different variables. They refer to variable number seven and variable number seven squared (the outside air temperature). The next value (-17.739) is the value of the first coefficient (V7 - outside air). The Standard error of the coefficient is the standard error of that X variable, mentioned previously as equation VIII.28. The T RATIOS are simply the X Coefficients for each variable divided by the Std Err of each coefficient. The T RATIO is what is used as an indicator to show whether each variable is of value in the regression.

The final equation used to predict the steam consumption consists of the assembly of variables, as shown in the equation for column AM22:. The figure following the tables demonstrates the fit.

**Table 8-14: BEACON PCON Example Regression File**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| TODAY'S | | | STEAM | Y EST | AVG | | | | |
| MO | DA | YR | USE | FIFTH | TMP | | | | |
| 7 | 8 | 86 | 11/1/8 | DEGREE | BLDR | | | | |
| MO | DA | YR | FORWAR | POLY | | | | | |
| Column # | | | --->AL | AM | AN | AO | AP | AQ | AR |
| | | | | | | V7 | V7©2 V7©3 | V7©4 | V7©5 |
| 11 | 1 | 85 | 29415 | 30254 | 41 | 1681 | 68921 | 2825761 | 115856201 |
| 11 | 2 | 85 | 27023 | 24668 | 47 | 2209 | 103823 | 4879681 | 229345007 |
| 11 | 3 | 85 | 23355 | 21388 | 51 | 2601 | 132651 | 6765201 | 345025251 |
| 11 | 4 | 85 | 19269 | 18917 | 55 | 3025 | 166375 | 9150625 | 503284375 |
| 11 | 5 | 85 | 23640 | 27740 | 44 | 1936 | 85184 | 3748096 | 164916224 |
| 11 | 6 | 85 | 32206 | 31397 | 39 | 1521 | 59319 | 2313441 | 90224199 |
| 11 | 7 | 85 | 29325 | 25054 | 47 | 2209 | 103823 | 4879681 | 229345007 |
| 11 | 8 | 85 | 32455 | 24425 | 49 | 2401 | 117649 | 5764801 | 282475249 |
| 11 | 9 | 85 | 38138 | 40659 | 26 | 676 | 17576 | 456976 | 11881376 |
| 11 | 10 | 85 | 46152 | 46473 | 14 | 196 | 2744 | 38416 | 537824 |
| 11 | 11 | 85 | 46333 | 44108 | 18 | 324 | 5832 | 104976 | 1889568 |
| 11 | 12 | 85 | 45978 | 43997 | 21 | 441 | 9261 | 194481 | 4084101 |
| 11 | 13 | 85 | 45492 | 42851 | 23 | 506 | 11391 | 256289 | 5766504 |
| 11 | 14 | 85 | 45456 | 43203 | 24 | 552 | 12978 | 304980 | 7167031 |
| 11 | 15 | 85 | 43175 | 41762 | 29 | 812 | 23149 | 659750 | 18802877 |
| 11 | 16 | 85 | 50127 | 37376 | 36 | 1296 | 46656 | 1679616 | 60466176 |
| 11 | 17 | 85 | 38727 | 39728 | 30 | 900 | 27000 | 810000 | 24300000 |
| 11 | 18 | 85 | 33784 | 42157 | 24 | 576 | 13824 | 331776 | 7962624 |
| 11 | 19 | 85 | 46667 | 46299 | 17 | 289 | 4913 | 83521 | 1419857 |
| 11 | 20 | 85 | 48234 | 48326 | 13 | 169 | 2197 | 28561 | 371293 |
| 11 | 21 | 85 | 49309 | 45805 | 19 | 361 | 6859 | 130321 | 2476099 |
| 11 | 22 | 85 | 49648 | 50340 | 11 | 110 | 1158 | 12155 | 127628 |
| 11 | 23 | 85 | 48055 | 48581 | 14 | 182 | 2460 | 33215 | 448403 |
| 11 | 24 | 85 | 44825 | 41767 | 27 | 729 | 19683 | 531441 | 14348907 |
| 11 | 25 | 85 | 39640 | 36498 | 36 | 1296 | 46656 | 1679616 | 60466176 |
| 11 | 26 | 85 | 36550 | 41810 | 29 | 841 | 24389 | 707281 | 20511149 |
| 11 | 27 | 85 | 38414 | 37175 | 36 | 1260 | 44739 | 1588230 | 56382167 |
| 11 | 28 | 85 | 41718 | 37092 | 32 | 992 | 31256 | 984560 | 31013642 |
| 11 | 29 | 85 | 44967 | 44634 | 19 | 361 | 6859 | 130321 | 2476099 |
| 11 | 30 | 85 | 50413 | 51520 | 8 | 64 | 512 | 4096 | 32768 |
| 12 | 1 | 85 | 56834 | 57281 | 2 | 4 | 8 | 16 | 32 |
| 12 | 2 | 85 | 55235 | 50757 | 9 | 81 | 729 | 6561 | 59049 |
| 12 | 3 | 85 | 43591 | 41086 | 31 | 930 | 28373 | 865365 | 26393634 |
| 12 | 4 | 85 | 39392 | 36785 | 37 | 1369 | 50653 | 1874161 | 69343957 |
| 12 | 5 | 85 | 39322 | 36906 | 37 | 1332 | 48627 | 1774890 | 64783487 |
| 12 | 6 | 85 | 37448 | 30774 | 44 | 1892 | 82313 | 3580610 | 155756538 |
| 12 | 7 | 85 | 37598 | 44397 | 24 | 576 | 13824 | 331776 | 7962624 |
| 12 | 8 | 85 | 38481 | 40352 | 31 | 930 | 28373 | 865365 | 26393634 |
| 12 | 9 | 85 | 43996 | 44727 | 22 | 484 | 10648 | 234256 | 5153632 |
| 12 | 10 | 85 | 51198 | 49387 | 14 | 182 | 2460 | 33215 | 448403 |
| 12 | 11 | 85 | 53587 | 54420 | 6 | 36 | 216 | 1296 | 7776 |
| 12 | 12 | 85 | 51567 | 49844 | 13 | 169 | 2197 | 28561 | 371293 |
| 12 | 13 | 85 | 49788 | 45973 | 22 | 484 | 10648 | 234256 | 5153632 |
| 12 | 14 | 85 | 43177 | 39221 | 33 | 1089 | 35937 | 1185921 | 39135393 |
| 12 | 15 | 85 | 43452 | 40571 | 32 | 992 | 31256 | 984560 | 31013642 |
| 12 | 16 | 85 | 38915 | 33476 | 42 | 1764 | 74088 | 3111696 | 130691232 |

| TODAY'S | | | | COLD | ZAM AVG | PERSON | SUN | BAK | ICE | DAY | EMER | TOT | SCHE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MO | DA | YR | SUPP | USE | WIND | HOURS | HORZ | TI | TMP | OF | GEN | ATT | OPER |
| 7 | 8 | 86 | T(F) | M | MPH | V4*V10 | BTU | MIN | F | WEEK | USE | PER | (HRS |
| MO | DA | YR | | <<<<<<------------------------- | | | | | USE | | | | |
| Column # ---> | | | | AS | AT | AU | AV | AW | AX | AY | AZ | BA | BB |
| | | | | V8 | V2 | V1 | V4*V10 | V11 | V5 | V6 | V9 | V3 | V4 |
| 11 | 1 | 85 | 51.8 | 71 | 2.1 | 40736 | 1485 | 4 | 13.0 | 6 | 0 | 2546 | 16.0 |
| 11 | 2 | 85 | 53.6 | 68 | 2.4 | 21336 | 1203 | 0 | 13.0 | 0 | 0 | 1524 | 14.0 |
| 11 | 3 | 85 | 53.6 | 60 | 2.5 | 18492 | 1452 | 0 | 13.0 | 1 | 0 | 1541 | 12.0 |
| 11 | 4 | 85 | 53.6 | 78 | 3.0 | 58599 | 1214 | 8 | 13.0 | 2 | 14 | 3447 | 17.0 |
| 11 | 5 | 85 | 53.6 | 98 | 4.2 | 57120 | 922 | 0 | 13.0 | 3 | 16 | 3264 | 17.5 |
| 11 | 6 | 85 | 53.6 | 91 | 5.7 | 61710 | 1402 | 0 | 13.0 | 4 | 0 | 3630 | 17.0 |
| 11 | 7 | 85 | 53.6 | 84 | 7.0 | 53865 | 1271 | 0 | 13.0 | 5 | 0 | 3078 | 17.5 |
| 11 | 8 | 85 | 51.8 | 86 | 2.4 | 47776 | 1300 | 0 | 13.0 | 6 | 0 | 2986 | 16.0 |
| 11 | 9 | 85 | 51.8 | 98 | 1.7 | 24010 | 644 | 0 | 13.0 | 0 | 0 | 1715 | 14.0 |
| 11 | 10 | 85 | 50.9 | 90 | 0.0 | 18060 | 644 | 0 | 13.0 | 1 | 0 | 1505 | 12.0 |
| 11 | 11 | 85 | 50.9 | 69 | 0.0 | 55505 | 644 | 4 | 13.0 | 2 | 19 | 3265 | 17.0 |
| 11 | 12 | 85 | 49.1 | 84 | 0.3 | 55160 | 644 | 4 | 13.0 | 3 | 17 | 3152 | 17.5 |
| 11 | 13 | 85 | 50.0 | 83 | 0.9 | 63172 | 1207 | 0 | 14.0 | 4 | 0 | 3716 | 17.0 |
| 11 | 14 | 85 | 49.1 | 99 | 0.9 | 55773 | 644 | 0 | 14.0 | 5 | 0 | 3187 | 17.5 |
| 11 | 15 | 85 | 48.2 | 127 | 1.1 | 45216 | 686 | 0 | 14.0 | 6 | 0 | 2826 | 16.0 |
| 11 | 16 | 85 | 48.2 | 142 | 1.8 | 25326 | 1032 | 0 | 14.0 | 0 | 0 | 1809 | 14.0 |
| 11 | 17 | 85 | 48.2 | 79 | 1.3 | 16452 | 902 | 0 | 14.0 | 1 | 0 | 1371 | 12.0 |
| 11 | 18 | 85 | 48.2 | 48 | 1.3 | 59364 | 860 | 4 | 14.0 | 2 | 12 | 3492 | 17.0 |
| 11 | 19 | 85 | 48.2 | 87 | 1.6 | 54005 | 1259 | 0 | 14.0 | 3 | 18 | 3086 | 17.5 |
| 11 | 20 | 85 | 48.2 | 92 | 1.4 | 73661 | 1373 | 0 | 14.0 | 4 | 0 | 4333 | 17.0 |
| 11 | 21 | 85 | 46.4 | 68 | 1.6 | 54215 | 1036 | 4 | 14.0 | 5 | 0 | 3098 | 17.5 |
| 11 | 22 | 85 | 47.3 | 99 | 1.8 | 48160 | 1251 | 0 | 14.0 | 6 | 0 | 3010 | 16.0 |
| 11 | 23 | 85 | 47.3 | 95 | 0.9 | 25186 | 1307 | 0 | 14.0 | 0 | 0 | 1799 | 14.0 |
| 11 | 24 | 85 | 46.4 | 58 | 2.0 | 16944 | 1282 | 0 | 14.0 | 1 | 0 | 1412 | 12.0 |
| 11 | 25 | 85 | 46.4 | 70 | 3.6 | 45271 | 1362 | 0 | 14.0 | 2 | 5 | 2663 | 17.0 |
| 11 | 26 | 85 | 45.5 | 87 | 3.3 | 44870 | 644 | 0 | 14.0 | 3 | 7 | 2564 | 17.5 |
| 11 | 27 | 85 | 44.6 | 48 | 1.4 | 29189 | 1044 | 8 | 14.0 | 4 | 0 | 1717 | 17.0 |
| 11 | 28 | 85 | 48.2 | 8 | 1.4 | 0 | 1023 | 0 | 14.0 | 5 | 0 | 0 | 0.0 |
| 11 | 29 | 85 | 46.4 | 20 | 1.4 | 13984 | 655 | 0 | 14.0 | 6 | 0 | 874 | 16.0 |
| 11 | 30 | 85 | 45.5 | 41 | 1.2 | 14070 | 719 | 0 | 15.0 | 0 | 0 | 1005 | 14.0 |
| 12 | 1 | 85 | 46.4 | 43 | 0.7 | 9672 | 1181 | 0 | 16.0 | 1 | 0 | 806 | 12.0 |
| 12 | 2 | 85 | 45.5 | 40 | 0.6 | 43248 | 1129 | 0 | 16.0 | 2 | 14 | 2544 | 17.0 |
| 12 | 3 | 85 | 44.6 | 76 | 0.3 | 52045 | 1343 | 0 | 17.0 | 3 | 16 | 2974 | 17.5 |
| 12 | 4 | 85 | 44.6 | 75 | 0.7 | 48467 | 1426 | 0 | 17.0 | 4 | 0 | 2851 | 17.0 |
| 12 | 5 | 85 | 44.6 | 65 | 0.8 | 47268 | 1213 | 8 | 17.0 | 5 | 0 | 2701 | 17.5 |
| 12 | 6 | 85 | 46.4 | 64 | 1.1 | 40224 | 778 | 0 | 17.0 | 6 | 0 | 2514 | 16.0 |
| 12 | 7 | 85 | 44.6 | 68 | 1.2 | 23562 | 1319 | 0 | 17.0 | 0 | 0 | 1683 | 14.0 |
| 12 | 8 | 85 | 45.5 | 63 | 0.8 | 13344 | 881 | 0 | 17.0 | 1 | 0 | 1112 | 12.0 |
| 12 | 9 | 85 | 44.6 | 43 | 1.0 | 34935 | 644 | 4 | 17.0 | 2 | 14 | 2055 | 17.0 |
| 12 | 10 | 85 | 43.7 | 57 | 0.3 | 40618 | 747 | 0 | 18.0 | 3 | 19 | 2321 | 17.5 |
| 12 | 11 | 85 | 43.7 | 56 | 0.4 | 39933 | 1178 | 0 | 18.0 | 4 | 0 | 2349 | 17.0 |
| 12 | 12 | 85 | 42.8 | 47 | 0.9 | 37590 | 1162 | 4 | 19.0 | 5 | 0 | 2148 | 17.5 |
| 12 | 13 | 85 | 42.8 | 59 | 1.4 | 34736 | 1417 | 0 | 18.0 | 6 | 0 | 2171 | 16.0 |
| 12 | 14 | 85 | 43.7 | 45 | 3.2 | 16058 | 1143 | 0 | 18.0 | 0 | 0 | 1147 | 14.0 |
| 12 | 15 | 85 | 42.8 | 44 | 3.3 | 11808 | 1240 | 0 | 18.0 | 1 | 0 | 984 | 12.0 |
| 12 | 16 | 85 | 42.8 | 56 | 4.6 | 24570 | 1299 | 0 | 18.0 | 2 | 13 | 1638 | 15.0 |
| 12 | 17 | 85 | 42.8 | 69 | 5.2 | 24900 | 923 | 0 | 18.0 | 3 | 20 | 1660 | 15.0 |
| 12 | 18 | 85 | 42.8 | 49 | 3.1 | 23505 | 829 | 0 | 18.0 | 4 | 0 | 1567 | 15.0 |

| Column ---> | | | BD V4/V10 |
|---|---|---|---|
| 11 | 1 | 85 | 159 |
| 11 | 2 | 85 | 109 |
| 11 | 3 | 85 | 128 |
| 11 | 4 | 85 | 203 |
| 11 | 5 | 85 | 187 |
| 11 | 6 | 85 | 214 |
| 11 | 7 | 85 | 176 |
| 11 | 8 | 85 | 187 |
| 11 | 9 | 85 | 123 |
| 11 | 10 | 85 | 125 |
| 11 | 11 | 85 | 192 |
| 11 | 12 | 85 | 180 |
| 11 | 13 | 85 | 219 |
| 11 | 14 | 85 | 182 |
| 11 | 15 | 85 | 177 |
| 11 | 16 | 85 | 129 |
| 11 | 17 | 85 | 114 |
| 11 | 18 | 85 | 205 |
| 11 | 19 | 85 | 176 |
| 11 | 20 | 85 | 255 |
| 11 | 21 | 85 | 177 |
| 11 | 22 | 85 | 188 |
| 11 | 23 | 85 | 129 |
| 11 | 24 | 85 | 118 |
| 11 | 25 | 85 | 157 |
| 11 | 26 | 85 | 147 |
| 11 | 27 | 85 | 101 |
| 11 | 28 | 85 | 0 |
| 11 | 29 | 85 | 55 |
| 11 | 30 | 85 | 72 |
| 12 | 1 | 85 | 67 |
| 12 | 2 | 85 | 150 |
| 12 | 3 | 85 | 170 |
| 12 | 4 | 85 | 168 |
| 12 | 5 | 85 | 154 |
| 12 | 6 | 85 | 157 |
| 12 | 7 | 85 | 120 |
| 12 | 8 | 85 | 93 |
| 12 | 9 | 85 | 121 |
| 12 | 10 | 85 | 133 |
| 12 | 11 | 85 | 138 |
| 12 | 12 | 85 | 123 |
| 12 | 13 | 85 | 136 |
| 12 | 14 | 85 | 82 |
| 12 | 15 | 85 | 82 |
| 12 | 16 | 85 | 109 |
| 12 | 17 | 85 | 111 |
| 12 | 18 | 85 | 104 |

REGRESSION FOR V7 V7©2 V7©3 V8 V2 V1 V4*V10

Regression Output:

| | |
|---|---|
| Constant | 74111.099 |
| Std Err of Y Est | 3479.714 |
| R Squared | 0.931 |
| No. of Observations | 240.000 |
| Degrees of Freedom | 232.000 |

| | V7 | V7©2 |
|---|---|---|
| X Coefficient(s) | -17.736 | -17.111 |
| Std Err of Coef. | 165.589 | 4.221 |
| T RATIOS | -0.107 | -4.054 |

| | V7©3 | V8 | V2 | V1 | V4*V10 |
|---|---|---|---|---|---|
| X Coefficient(s) | 0.137 | -499.572 | 24.386 | -345.574 | 0.012 |
| Std Err of Coef. | 0.032 | 66.231 | 10.098 | 167.049 | 0.012 |
| T RATIOS | 4.231 | -7.543 | 2.415 | -2.069 | 1.005 |

**Table 8-15: BEACON PCON Spreadsheet Equations for Example**

These equations correspond to the column numbers listed above the columns in the previous table. These equations are used to generate the graph on in the following figure.

```
AM22: (F0) +$BI$162+$BH$168*AN22+$BI$168*AN22©2+$BJ$168*AN22©3
           +$BK$168*AN22©4+$BL$168*AN22©5+$BM$168*AS22
           +$BN$168*AT22+$BP$168*AU22
AN22: (F0) [W4] 70
AO22: (F0) [W5] +AN22©2
AP22: (F0) [W8] +AN22©3
AQ22: (F0) [W11] +AN22©4
AR22: (F0) +AN22©5
AS22: (F1) [W5] (AI22*9/5)+32
AT22: (F0) [W4] ((G22*(S23-S22)+S22)-(G21*(S22-S21)+S21))*60
AU22: (F1) [W8] ((G22*(R23-R22)+R22)-(G21*(R22-R21)+R21))/(24*1.6093)
AV22: (F0) [W8] +BB22*BC22
AW22: (F0) [W7] 643.96+1.37*AJ22
AX22: (F0) [W5] 0
AY22: (F1) [W5] 12
AZ22: (F0) [W5] 6
BA22: (F0) [W5] ((G22*(T23-T22)+T22)-(G21*(T22-T21)+T21))*60
BB22: (F0) [W5] 1141
BC22: (F1) [W5] 12
BD22: (F0) [W5] +BB22/BC22
```

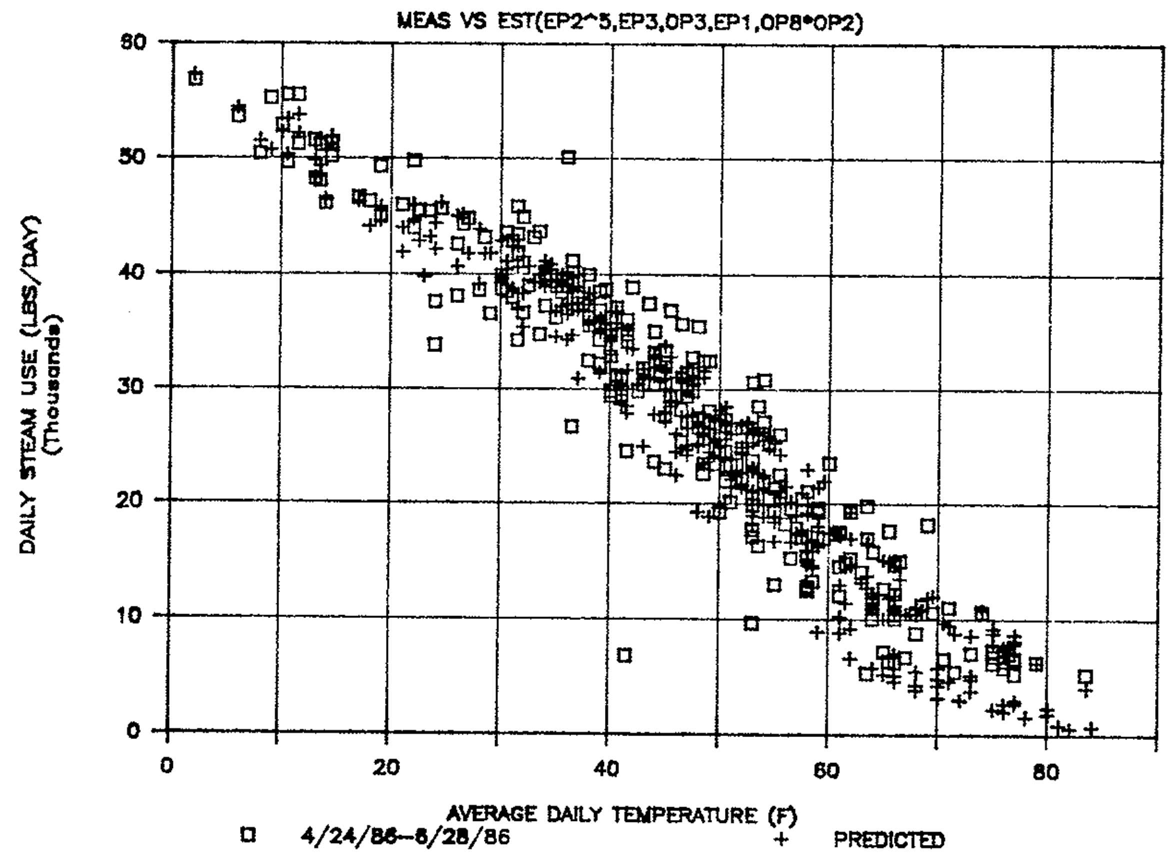


Fig. 8-15: BEACON PCON Example Regression

**8.5.2. BEACON Computerized Consultant CCON**

This section is the Knowledge base for the BEACON CCON. Each of the rules that are in the knowledge base are documented as to how they were established and when. This is the actual source code on which the CCON operates. This knowledge base was created with Wordstar (a word processor) and is loaded into the M.1 program prior to execution.

**8.5.2.1. BEACON Knowledge Base**

```
/*
        Knowledge base for the Rec Center abnormal-consumption
                    7/14/86 Jeff Haberl
               Comments added 11/9/86 J.S.H.

    This knowledge base is composed of observed abnormal-consumption
   events. Period of observation is from 8/15/85 to 5/8/86. PCONs
         were run 1/86 (PCON1 = 7/86) using multivariate
                    linearized regressions.

*/

/*

   The goal of this knowledge base is to find the values for the
                expression 'abnormal-consumption'.
*/
/* -------------------- set ups --------------------------------*/

configuration(prompt) = 'CCON>'.

configuration(banner) =

'                 University of Colorado Rec Center
      Building Energy Analysis CONsultant (BEACON) system.
        Computerized CONsultant (CCON) processor JSH 11/86
->'.

/* -------------------- goals --------------------------------*/

/* This is a test case for a one-day consultation. A cache file
will need to be made for each day to be analyzed.
 */

/* This next expression allows instructs the inference engine to
search for values of "abnormal-consumption"
*/
goal = abnormal-consumption.

/* Since a number of abnormal consuming events can occur in one
day, the goal is multivalued...
*/
multivalued(abnormal-consumption).

/*  ---------------- initial data section --------------------*/

/* This initial data section requires the inference engine to
have these values provided before consultation proceeds...should
this not be the case the M.1 processor will ask the user, using
the questions supplied, to supply the answers.
*/
```

```
/* The following is typical of the "cache" file that must be read
by the CCON to start the analysis.

analysis-day= july-13-1986 cf 100 because'calculated'.
other-steam= 707.0 cf 100 because'calculated'.
pool-steam= -382.0 cf 100 because'calculated'.
other-electric= -52.0 cf 100 because'calculated'.
compressor-electric= 130.0 cf 100 because'calculated'.
natural-gas= -103.0 cf 100 because'calculated'.
pool-water= -563.0 cf 100 because'calculated'.
other-water= 2701.0 cf 100 because'calculated'.
sunlight= 1529.0 cf 100 because'measured'.
cold-water-temp= 60.1 cf 100 because'measured'.
outside-temp= 82.0 cf 100 because'measured'.
ice-setpoint= 16.5 cf 100 because'observed'.
backwash= no cf 100 because'observed'.
attendance= 599.0 cf 100 because'counted'.
ice-resurface= 47.0 cf 100 because'measured'.
wind-speed= 4.2 cf 100 because'measured'.
compressor-west= yes cf 100 because'calculated'.
compressor-center= yes cf 100 because'calculated'.
compressor-east= yes cf 100 because'calculated'.
day-of-week= sunday cf 100 because'calculated'.
*/

initialdata = [analysis-day,
     other-steam,
     pool-steam,
     other-electric,
     compressor-electric,
     natural-gas,
     pool-water,
     ice-setpoint,
     ice-resurface,
     compressor-west,
     compressor-center,
     compressor-east,
     other-water].

/* -----------------questions-----------------------------*/

/* This section provides M.1 with the necessary questions to ask
the user in the event that the cache file is not provided and the
user must be asked for the initialdata values.
*/

/*---------------analysis-day question----------------*/

question(analysis-day) =
'What is the date of the analysis day (ie. april-25-86)'.

question(other-steam) =
'What is the value of the PCON1 - other steam consumption?'.
```

```
legalvals(other-steam) = number.

/*----------------------pool steam question----------------*/

question(pool-steam) =
'What is the value of the PCON2 - pool-steam consumption?'.

legalvals(pool-steam) = number.

/*---------------------other electric question--------------*/

question(other-electric) =
'What is the value of the PCON3 - other-electric consumption?'.

legalvals(other-electric) = number.

/*-------------------compressor electric question------------*/

question(compressor-electric) =
'What is the value of the PCON4 - compressor-electric  consumption?'.

legalvals(compressor-electric) = number.

/*-------------------natural gas question-----------------------*/

question(natural-gas) =
'What is the value of the PCON5 - natural-gas consumption?'.

legalvals(natural-gas) = number.

/*-----------------pool water question-------------------------*/

question(pool-water) =
'What is the value of the PCON6 - pool-water  consumption?'.

legalvals(pool-water) = number.

/*-----------------other water question -----------------------*/

question(other-water) =
'What is the value of the PCON7 - other-water consumption?'.

legalvals(other-water) = number.

/*-------------------sunlight question-------------------------*/

question(sunlight) =
'What is the value of sunlight (ie. 1300.0 Btu/ft2-day)?'.

legalvals(sunlight) = number.

/*-------------------outside temp question---------------------*/
```

```
question(outside-temp) =
'What is the outside air temperature (ie. 59.0 F)?'.

legalvals(outside-temp) = number.

/*--------------------ice setpoint question------------------*/

question(ice-setpoint) =
'What is the ice setpoint temperature (ie. 17.0 F)?'.

legalvals(ice-setpoint) = number.

/*------------------backwash question-----------------------*/

question(backwash) =
'Has there been a backwash of the pool filters (yes,yesterday,no)?'.

legalvals(backwash) =  [yes,yesterday,no].

automaticmenu(backwash).

enumeratedanswers(backwash).

/*--------------------ice-resurface question----------------------*/

question(ice-resurface) =
'How many minutes has the ice-resurface been run today?'.

legalvals(ice-resurface) = number.

/*--------------------wind speed question--------------------*/

question(wind-speed) =
'What is the average daily windspeed (ie. 3.2 mph)?'.

legalvals(wind-speed) = number.

/*--------------------compressor west question---------------*/

question(compressor-west) =
'Has the west compressor logged runtime hours? (yes,no)?'.

legalvals(compressor-west) = [yes,no].

automaticmenu(compressor-west).

enumeratedanswers(compressor-west).

/*-----------------------compressor center question-------------*/

question(compressor-center) =
'Has the center compressor logged runtime hours? (yes,no)?'.

legalvals(compressor-center) = [yes,no].
```

```
automaticmenu(compressor-center).

enumeratedanswers(compressor-center).


/*------------------compressor east question---------------------*/

question(compressor-east) =
'Has the east compressor logged runtime hours? (yes,no)?'.

legalvals(compressor-east) = [yes,no].

automaticmenu(compressor-east).

enumeratedanswers(compressor-east).

/*-----------------day of the week question---------------------*/

question(day-of-week) =
'What is the day of the week for the analysis?'.

legalvals(day-of-week)=
[monday,tuesday,wednesday,thursday,friday,saturday,sunday].

automaticmenu(day-of-week).

enumeratedanswers(day-of-week).


/* ------------------janitor early question --------------------*/

question(janitors-early)=
'Has the janitorial staff been coming in early(yes,no)?'.

legalvals(janitors-early) = [yes,no].

/* ---------------------staff late question---------------------*/

question(staff-late) =
'Has anybody on the staff been staying late (yes,no)?'.

legalvals(staff-late) = [yes,no].

/* ------------------hockey double header----------------------*/

question(hockey-double-header) =
'Has there been a hockey double header within the last few days
(yes,no)?'.

legalvals(hockey-double-header) = [yes,no].

/* -----------------operating hours -----------------------*/
```

```
question(operating-hours) =
'Has the building been open longer than shown on the schedule (yes,
no)?'.

legalvals(operating-hours) = [yes, no].

/* -----------------skating performance ---------------------*/

question(skating-performance) =
'Has there been a skating performance in the past few days (yes,no)?'.

legalvals(skating-performance) = [yes,no].

/*----------------rink maintenance -----------------------------*/

question(rink-maintenance) =
'Has theicerink staff been performing maintenance on the rink
(yes,no)?'.

legalvals(rink-maintenance) = [yes,no].

/* ---------------brine valve question -------------------------*/

question(brine-valving) =
'What is the status of the ice rink brine valving?'.

legalvals(brine-valving) = [open, closed].

automaticmenu(brine-valving).

enumeratedanswers(brine-valving).

/* --------------condition of the ice question-----------------*/

question(ice-condition) =
'What is the condition of the ice (soft,hard)?'.

legalvals(ice-condition) = [soft,hard].

/* ----------------freon level question-----------------------*/

question(freon-level) =
'What is the status of the freon in the compressors (ok,low)?'.

legalvals(freon-level) = [ok,low].

/* ---------------krack status-----------------------------*/

question(krack-status) =

'What is the status of the krack unit (on,off)?'.

legalvals(krack-status) = [on,off].
```

```
/* ---------------ice-resurface snow melt question---------------*/

question(ice-resurface-snow-melt) =
'Is the ice-resurface snow melt pit operational (yes,no)?'.

legalvals(ice-resurface-snow-melt) = [yes,no].

/* ------------------minimum nighttime electric ------------*/

question(night-time-electric) =
'What is the minimum hourly (total building) kw reading (60-150kw)?'.

legalvals(night-time-electric) = number.

/* -----------------lights not turning off question------------*/

question(cant-turn-lights-off) =
'Are there problems with the lights turning off at night (yes,no)?'.

leagalvals(cant-turn-lights-off) = [yes,no].

/* -----------------incandescents turned off in gym-------------*/

question(incandescents-gym) =
'Are the incandescent lights being used in the gym (yes,no)?'.

legalvals(incandescents-gym) = [yes,no].


/* -----------------pool meet question-----------------------*/

question(pool-meet) =
'Has there been a pool meet recently (yes,no)?'.

legalvals(pool-meet) = [yes,no].

/* -----------------pool spectator lights on question -----------*/

question(pool-spectator-lights) =
'Are the pool spectator lights currently in use (yes,no)?'.

legalvals(pool-spectator-lights) = [yes,no].

/* ------------------gutter tape status -----------------------*/

question(gutter-tape-status) =
'Are the gutter heat tapes currently in use (on,off)?'.

legalvals(gutter-tape-status) = [on,off].

/* ------------ question for dhw setpoint ----------------*/

question(dhw-setpoint) =
'What is the current D.H.W. setpoint (highest, ie. 115F)?'.
```

```
legalvals(dhw-setpoint) = number(100,140).

/*-------------------- question for dhw-leaking-------------*/

question(dhw-leaking) =
'Is there a leak in the D.H.W. system (yes,no) ?'.

legalvals(dhw-leaking) = [yes,no].

/*----------------dhw heat reclaim question----------------*/

question(dhw-rink-heat-reclaim) =
'Is the D.H.W. rink, heat-reclaim working (yes,no)?'.

legalvals(dhw-rink-heat-reclaim) = [yes,no].

/*--------------dhw steam heat reclaim---------------------*/

question(dhw-steam-heat-reclaim) =
'Is the D.H.W. steam, heat-reclaim working (yes,no)?'.

legalvals(dhw-steam-heat-reclaim) = [yes,no].

/*----------------pool water amount-----------------------*/

question(pool-water-amount) =
'How much water has the pool consumed (ie. 10000 gallons)?'.
legalvals(pool-water-amount) = real.

/*------------------pool drained question---------------------*/

question(pool-drained) =
'Has the pool been drained purposefully, lately (yes,no)?'.

legalvals(pool-drained) = [yes,no].


/*----------------swim meet question---------------------------*/

question(swim-meet) =
'Has there been a swim meet within the past few days (yes,no)?'.

legalvals(swim-meet) = [yes,no].

/*-------------power outage question----------------------------*/

question(power-outage) =
'Has there been a power outage lately (yes,no)?'.

legalvals(power-outage) = [yes,no,yesterday].

/*-------------pool-filled question------------------------*/
```

```
question(pool-filled) =
'Has the pool been filled lately (yes,no)?'.

legalvals(pool-filled) = [yes,no].

/*----------------tennis light question-----------------------*/
question(tennis-lights) =
'Have the outside tennis courts been used at night (yes,no)?'.

legalvals(tennis-lights) = [yes,no].

/*----------------loading ramp question----------------------*/

question(loading-ramp) =
'Is the loading ramp snow melt on (yes,no)?'.

legalvals(loading-ramp) = [yes,no].

/*----------------administration office ac question--------------*/

question(admin-office-ac) =
'Does the hourly electric show a cyclic profile during the closed
period in the evening at the minimum point when the compressors
are off (yes,no)?'.

legalvals(admin-office-ac) = [yes,no].

/*------------------tennis courts washed------------------------*/

question(tennis-courts-washed) =
'Have the tennis courts been washed lately (yes,no)?'.

legalvals(tennis-courts-washed) = [yes,no].

/* --------------------rules----------------------------------*/

/* This section contains the rules that are processed by M.1
during a consultation. Each of these rules have been created to
represent events that were observed to occur at the Rec Center
during the period of observation. Each rule contains the
necessary documentation as to how the rule was developed and why.

Certainty factors are a measure of the "certainty" with which the
events have occured. The certainty factors chosen reflect the
correlation of the occurance of the event and the occurance of
abnormal-consumption. The following guideline was used to
establish the certainty factors:

50 percent - first order correlation, ability of CCON to predict
abnormal-consumption not yet confirmed.

60 percent - second order correlation, ability of CCON to predict
abnormal-consumption confirmed at least once.
```

70 percent - third order correlation, ability of CCON to predict abnormal-consumption confirmed more than once.

80 percent - third order correlation, ability of CCON to predict abnormal-consumption confirmed on a regular basis.

90 percent - fourth order correlation, ability of CCON to predict abnormal-consumption occurs 9 out of 10 times.

100 percent - fifth order correlation, ability of CCON to predict abnormal-consumption occurs every time, 100 percent.

Also, in lieu of using actual data, one standard deviation (as calculated with the Lotus 123 software), fractions or multiples of the standard deviation were used. These standard deviations are shown below for informative purposes. The use of the standard deviation was arbitrary. In most of the rules actual deviations are used.

```
other-steam= 4225
pool-steam= 726
other-electric= 439
compressor-electric= 119
natural-gas= 186
pool-water= 553
other-water= 2610
*/

/* -------------------- extra hours rule ----------------------*/

/* This rule provides looks for overconsumption in the other
electric category. This abnormal-consumption would be caused by
the interior lights being left on. Leaving the all the interior
lights on  longer than scheduled for the entire Rec Center
consumes 167 kw per hour of electricity. Therefore, it is assumed
that this level of abnormal-consumption indicates that some
portion of the lighting was left on longer than necessary. The
value of 167 kw is calculated by counting fixtures in the Rec
Center. This was done during the 1981 Dow study. This event was
not able to be observed during the trial period.
*/

rule-1:  if other-electric = A
          and A > 167
          and operating-hours = yes
          then abnormal-consumption = extra-hours cf 50.

/* ---------------------- janitors in early rule----------------*/

/* This rule assumes that the janitors arrived early at the
building at least 2 hours early and turned all lights on. The
calculated consumption is therefore 2x167=333 kwh. No
observations of this rule were made.
*/
```

```
rule-2: if other-electric = A
          and A > 333
          and janitors-early = yes
          then abnormal-consumption = janitors-early cf 50.

/* ---------------------- staff staying late ------------------*/

/* This rule assumes that a staff person stayed late 2 hours and
left all lights on in the Rec Center, 333 kwh. No observations
were made of this rule.
*/
rule-3: if other-electric = A
          and A > 333
          and staff-late = yes
          then abnormal-consumption = staff-late cf 50.

/* -----------------ice-resurface hot water ---------------------*/
/* This rule is the most observed of all abnormal-consumptions at
the Rec Center, therefore the high certainty factor. The CCON has
accurately predicted this abnormal-consumption. The days when
this occurred, and were observed were 10/28, 12/5, 1/22, 4/20,
5/21. All values that  are watched are assembled from the average
of the consumption during these days.
*/
rule-4: if other-steam = A
          and A > 364
          and compressor-electric = B
          and B > 192
          and other-water = C
          and C > 1217
          and other-electric = D
          and D > 128
          then abnormal-consumption = ice-resurface-hot-water cf 90.

/*---------------hockey double header --------------------------*/

/* In a similar fashion to the ice-resurface-hot-water over-
consumption predictor, this rule is based on two occurances,
11/15 and 1/15-17. All values are based on the averages for these
days. During a hockey double header, the ice rink staff more
water for the resurfacing and make almost double the number of
resurfaces. The building also has the rink lights left on longer
than normal. There is one problem with the indicators for the
predictions on this one: the abnormal-consumption does not appear
as an abnormal-consumption because the influencing parameters are
accounted for in the predictions. Therefore, the abnormal-
consumption only appears as a modest abnormal-consumption.
However, by watching for the low ice-setpoint consumption and the
excessive zamboni runtime, the CCON can spot this occurance. This
is because hockey double headers need colder ice and more
resurfacing.
*/
rule-5: if other-steam = A
          and A > 0
```

```
          and other-electric = B
          and B > 0
          and compressor-electric = C
          and C > 0
          and ice-resurface = D
          and D > 115
          and ice-setpoint = E
          and E < 17
          and hockey-double-header = yes
          then abnormal-consumption = hockey-double-header cf 80.

/* ----------------ice skating performance----------------------*/
/* In a similar fashion to the hockey double header, the ice
skating performance is very consumptive. Ice skating performances
were observed 12/10 and 4/19-20. All values are derived from
these observations. During an ice skating performance carbon arc
lamps are used to spot-light the performers. These lamps are
damn-near like a direct short across the electric lines and are
connected to a special panel that Norm Berry installed for this
event. Therefore one of the key indicators is a large over-
consumption in the "other-electric" category. Also, but not
completely explained, the ice skating performers seem to prefer
hot water for the resurfacing. Since the zamboni uses apx 200
gallons of hot water, this shows up as excess other-steam
consumption.
*/

rule-6: if other-electric = A
          and A > 412
          and other-steam = B
          and B > 3527
          and compressor-electric = C
          and C > 81
          and ice-resurface = D
          and D > 80
          and ice-setpoint = E
          and E < 16.5
          and skating-performance = yes
          then abnormal-consumption = skating-performance cf 80.

/* ----------------rink maintenance------------------------*/

/* Infrequently during the year the ice rink staff perform
maintenance on the rink. Often this is repairing the leaking
edges. To do this they commonly lower the ice rink temperature
which causes an overconsumption. Also noted was the sometime
diminished use of the zamboni.  Maintenance was observed during
12/31 and 1/1.  This particular problem will cause over-
consumption for the compressors for one day and under-consumption
when the ice is returned to normal...This rule could be improved
by allowing for the CCON to sort through data from a number of
days.
*/
rule-7: if compressor-electric = A
```

```
          and A > 60
          and ice-setpoint  = B
          and B < 15
          and ice-resurface = C
          and C < 50
          and rink-maintenance = yes
          then abnormal-consumption = rink-maintenance cf 80.

/*-----------------brine valving-------------------------*/
/* This rule watches for a condition that was occurring at the
Rec Center from 8/15 to 11/7. This condition was caused by the
half-closing of the main circulation valve by persons unknown.
When this condition occurs the ice must be maintained at
temperatures below 15 F in order for the ice to stay firm... what
happens is that the compressor electric goes up, other electric
goes up, the set point remains below 15 F, the other water
consumption goes up since the condensor on the roof is required
to work overtime shedding heat, which wastes water since
everytime the condensor cycles it loses 200 gallons of water
because the sump reservoir cannot hold all the water that is
stored above it. These values used are the average for the period
8/15 to 11/7.
*/
rule-8: if compressor-electric = B
          and B > 119
          and ice-setpoint = A
          and A < 15
          and brine-valving = closed
          and other-water = C
          and C > 1305
          and ice-condition = soft
     then abnormal-consumption = brine-valving cf 80.


/* ------------------freon level low ---------------------*/

/* In a similar fashion, should the freon contained in the
compressor loop fall below the recommended level a similar over-
consumption will occur. The ice set-point will creep down, the
compressor electric will rise. This condition has not been
observed to occur.
*/
rule-9:   if compressor-electric = A
          and A > 119
          and ice-setpoint = C
          and C < 15
          and freon-level = low
          and ice-condition = soft
          then abnormal-consumption = freon-level-low cf 50.

/* -------------------krack unit down ---------------------*/

/* The krack unit is the sub-cooling unit located in the
penthouse. The purpose of the krack subcooling unit is to lower
```

the temperature of the return freeon from the condensor from about 50 F to 35 F. Without this unit, compressor consumption goes up, and other electric goes down, since the krack unit is not running. No noticable effect usually occurs with the ice quality. However, the unit can be observed in the penthouse. This particular unit will go down and stay down should there be a power fluctuation. The unit will need to be reset by hand and thereby will continue working. This was observed to occur, however, no written record was made during the occurance. Therefore, standard deviations were used for this rule. 1/2 standard deviation was used for compressor electric and 1/2 standard deviation was used for other electric. Since the event has not been officially observed...the certainty factor is 50 percent.
*/

```
rule-10:  if compressor-electric = A
          and A > 59
          and other-electric = B
          and B < 219
          and krack-status = off
          then abnormal-consumption = krack-unit-disabled cf 50.

/* ---------------------hot water used to melt ice-------------*/
```

/* This ridiculous practice by the ice rink staff is where the zamboni driver uses hot water to melt the ice in the snow melt pit...this usually is caused by the recirculation pump being shut off or pit actually being plugged up with debris. This is what happened on July 13th. The ice rink staff placed the hot water hose in the pit...thinking that it was not melting...then left for the evening forgetting to turn off the hot water. This caused extensive flooding to the ice rink area and the level below. The abnormal-consumption for this event is documented in a previous section of the thesis. Originally, the CCON watched for other-steam > 1725 and other-water > 0 ... however in light of the event July 13 these numbers now are revised to the actual over-consumption that occured. One problem exists with the current version of the CCON... since this occurred over a number of days the only day that the CCON accurately predicts the over consumption for is July 14 when the extra hot water usage occurred. Since the hose was left in the pit for about 8 hours the value for the steam consumption was reduced so that even smaller events could be discovered (2 hrs, 1/4x).
*/

```
rule-11:  if other-steam = A
          and A > 637
          and other-water = B
          and B > 1735
          and ice-resurface-snow-melt = no
          then abnormal-consumption = hot-water-for-snow-melt cf 90.

/* -------------------tennis lights left on------------------*/
```

/* This is another event that occurs frequently, too frequently to count. Interestingly enough, there are days when this occurs more frequently: when it is above 55 F and when the wind speed is less than 2 mph, and it is sunny versus cloudy and possibly raining - these are the days when people request to play tennis. Since the lights are all on one circuit, all courts are illuminated (96 kw) even though one or two courts may be in use. Also, people may play from 7 pm to 8 pm but the lights stay until 11 pm or 12 pm when the Rec Center closes. It is assumed, therefore that an occurrence is of two hours in duration or 192 kw.
*/

```
rule-12:  if other-electric = D
          and D > 192
          and outside-temp  = A
          and A > 55
          and wind-speed = B
          and B < 2
          and sunlight = C
          and C > 700
          then abnormal-consumption = tennis-lights-on cf 60.
```

/* --------------------interior lights on ---------------------*/

/* This rule was created to look for the interior lights being left on. On the nights of 12/24 and 12/25 the interior lights were left on. The observed abnormal-consumption for these nights was 86 kwh (12/24) and 184 kwh (12/25) for an average of 135 kwh. In this rule an over consumption of 135 kwh ($7.5) is used as the indicator for leaving the lights on. From the observations of 12/24 and 12/25, leaving the lights on all night in the men's, and women's lockerroom as well as the hallway (observed) consumes as average 17 kwh/hr of lighting. Night time electric refers to the minimum amount of electric as seen on the strip chart recorded attached to the main panel in the electrical vault. When this reads more than 90 kw at the minimum, lights have been left on all night.
*/

```
rule-13:  if other-electric = B
          and B > 135
          and night-time-electric = A
          and A > 90
          then abnormal-consumption = interior-lights-on-pm cf 80.
```

/* -------------------interior lights cross wired-------------*/

/* This problem was found to occur up until 12/3. The interior lights in the men's locker room had been cross wired to the emergency lights. This was causing the lights to stay on all night and actually made it impossible to turn the lights off at night. This problem has not been observed to occur since, however, should these symptoms show up then this is the problem.

```
The value of 135 is the same as someone leaving the lights on all
night...also, should the strip chart recorded be attached then
this problem can be verified.
*/
rule-14:  if other-electric = B
          and B > 135
          and night-time-electric = A
          and A > 90
          and cant-turn-lights-off = yes
      then abnormal-consumption = interior-lights-cross-wired cf 80.

/* -------------------incandescents used in gym---------------*/

/* 1000 watt incandescents were installed in the gym for color
improvement purposes. Their use has been discontinued when the
originial mercury vapor lamps were replaced with high pressure
sodium lamps. Therefore the incandescents have been shut off at
the panel and are no longer in use. The 336 kwh is the 28 kw
times 12 hours of use per day...a normal day of operation.
*/

rule-15:  if other-electric = A
          and A > 336
          and incandescents-gym = yes
          then abnormal-consumption = incandescents-gym-on cf 70.

/* -----------------spectator lights on in pool room----------*/

/* Often, the pool staff allows the spectator lights to be turned
on when there is no need. There are at least 10 of these lamps on
this circuit 10x400=4kw over 12 hours is 48 kwh of usage. It is
alos important to ask if there has been a pool meet, and if the
lights are actually on or not. This was observed to occur 1/3,
2/2, and 3/4.
*/
rule-16:  if other-electric = A
          and A > 0
          and pool-meet = no
          and pool-spectator-lights = yes
       then abnormal-consumption = pool-spectator-lights-on cf 70.

/* ----------------gutter heat tapes -----------------------*/

/* The Rec Center has miles of gutter heat tapes. These heat
tapes are turned on and off in the penthouse at the panel near to
the emergency generator, appropriately marked.  These heat tapes
need to be on only when there is ice in the gutters. The observed
occurances are too numerous to mention them all (see table 3-16).
However, the connected load on the heat tapes is at least 20 kw
(some of the tapes are burned out) and therefore for 24 hours
would be 480 kwh.
*/

rule-17:  if other-electric = A
```

```
          and A > 480
          and gutter-tape-status = on
          then abnormal-consumption = gutter-tapes-on cf 80.

/* ----------------- extra laundry usage ---------------------*/

/* One odd correlation that showed up was the fact that hockey
players tend to use more towels than the average customer. So
when there is an excess amount of natural gas, as shown, and the
zamboni runtime is up, and the other steam is normal or above,
chances are that there has been extra hockey practice and more
towels than normal are being used. The fact that no appreciable
extra other-steam is used is as shown on the days that this
occured, 11/5 1/15-17.
*/
rule-18:  if other-steam = B
          and B > 0
          and natural-gas = C
          and C > 93
          and ice-resurface = A
          and A > 80
          then abnormal-consumption = laundry-use-ice-hockey cf 70.

/* ----------------------extra laundry other------------------*/

/* There also is a correlation between the natural gas being one
standard deviation from the normal and the other steam being at
least 1/4 of a standard deviation above normal, in general. This,
obviously, is due to the use of 140 F water by the laundry.
*/
rule-19: if other-steam = A
          and A > 1056
          and natural-gas = B
          and B > 186
          then abnormal-consumption = laundry-use-other cf 60.

/* -------------------- dhw setpoint too high-----------------*/

/* Periodically, the DHW setpoint should be checked to see that
the setting is not above the 115 mark. Should this occur, extra
steam will be consumed to raise the water to the higher setpoint
than is needed if it had been set at 115 F. On the average, this
amount of steam was estimated to be about 1/4 of a standard
deviation.
*/
rule-20:  if other-steam = B
          and B > 1056
          and dhw-setpoint = A
          and A > 115
          then abnormal-consumption = dhw-setpoint-too-high cf 70.

/* -------------------dhw leaking ---------------------------*/

/* On  1/24 through 1/28 the DHW system had a significant leak.
```

This leak caused, on the average 370 gallons of water to be lost per day, or 277 extra lbs of steam.
*/

```
rule-21:  if other-steam = A
          and A > 277
          and other-water = B
          and B > 370
          and dhw-leaking = yes
          then abnormal-consumption = dhw-leaking cf 80.

/* -------------------- dhw heat reclaim down------------------*/

rule-22:  if other-steam = A
          and A > 1725
          and other-water = B
          and B > 1305
          and dhw-rink-heat-reclaim = no
      then abnormal-consumption = dhw-rink-heat-reclaim-down cf 80.

/* --------------------dhw steam heat reclaim-------------------*/
```

/* The DHW heat reclaim from the ice rink compressors occaisionally breaks down. This was observed 12/7 through 1/23. The in situ effectiveness of the heat reclaim system is calculated to be about 1.8 MMBtu/day or about 1800 lbs of steam per day ($11/day, less than 10 percent of the available heat). On the average this trend can be seen in the data over this period. Also, since the heat reclaim is disabled, there tends to be an excess consumption of other-water during this period in the penthouse condensor. However, in comparison to the normal amount of water used in the condensor this could not be seen in the data. Therefore, the primary indicator is the steam usage.

*/

```
rule-23:  if other-steam = A
          and A > 1800
          and dhw-steam-heat-reclaim = no
      then abnormal-consumption = dhw-steam-heat-reclaim-down cf 80.

/* ---------------------pool doors open 50-70F----------------*/
```

/*
This next rule is strictly from observations. When the outside temperature is between 50 to 70 F the doors are sometimes left open to the southside porch. When this occurs there is a significant increase in the pool steam heating consumption. On the average, this tended to use an extra 350 lbs of steam. This trend tends to reverse itself when the outside temperature rises above 70F. It was also observed that people tended to want to go out on the deck when the average wind speed was below 2 mph. When it is windy, it is uncomfortable to be outside on the deck, sunbathing.
*/

```
rule-24:  if pool-steam = C
          and C > 350
          and outside-temp = A
          and A < 70
          and A > 50
          and sunlight = B
          and B > 700
          and wind-speed = C
          and C < 2
          then abnormal-consumption = pool-doors-open cf 70.

/* --------------------pool backwash ----------------------*/
/*
This rule tends to account for most of the extra water
consumption by the pool. The pool staff sometimes is not careful
when they backwash. Also, this tends to be an indicator that the
present method of correlating backwash to the day in which it
occurred needs some improving. The problem with the present
method is that the backwash is recorded as un-normalized data and
the pool water consumption is recorded as normalized. Since the
present normalization procedure tends to smear the informatio
over a couple of days, the backwash information should also be
normalized. The value of 700 gallons of water usage per day is
the observed average water consumption for the pool.
*/
rule-25:  if pool-water = A
          and A > 700
          and backwash = yes
          then abnormal-consumption = pool-backwashed cf 90.

/* --------------------pool leaking-------------------------*/
/*
This rule looks for a leak in the pool. When this occurs the pool
water consumption rapidly rises to over 10000 gallons per day.
Two things that can also cause this are when there is a power
outage and the pool staff does not quickly shut the valve on the
pool drains that leads into the surge tank. Since the over flow
valve for the surge tank is below the level of the pools it will
back siphon about 10 to 18 inches of pool level, about 100,000
gallons out of the pool. The other event is when the pool is
drained for maintenance.
*/
rule-26: if pool-water = A
          and A > 553
          and backwash = no
          and pool-water-amount = X
          and X > 10000
          and pool-drained = no
          and power-outage = no
          then abnormal-consumption = pool-leaking cf 90.

/* ----------------------pool covers off swim meet-------------*/
/*
```

When there is a scheduled pool meet, the pool staff installs the lane dividers and other associated equipment. This equipment interferes with the installation of the pool covers, making it impossible to put the covers on and off. So, pool meets are one event when the pool covers must be left off. When this happens in the winter, an extra amount of pool steam is consumed to heat the pool. One major pool meet where this occurred was 12/6-9. The average extra steam consumption was 1300 lbs and the average extra water consumption was 783 gallons.
*/

```
rule-27: if pool-steam = A
          and A > 1300
          and pool-water = B
          and B > 783
          and backwash = no
          and swim-meet = yes
          then abnormal-consumption = swim-meet-covers-off cf 60.
```

/* ---------------------pool covers off unknown------------------*/
/*
This rule reflects the same information as rule 27 except this rule determines that if there has been no meet than someone is leaving the covers off anyway. This rule also checks to see that the outside temperature is below 55F as this would indicate a night when the net heat flow is away from the pool.
*/

```
rule-28:  if pool-steam = B
          and B > 1300
          and pool-water = C
          and C > 783
          and outside-temp = A
          and A < 55
          and backwash = no
          and swim-meet = no
          then abnormal-consumption = covers-off-at-night cf 60.
```

/*   ---------------pool water loss during power outage----------*/
/*
This another one of the stange McFall Konkel design flaws in the building. The 8 inch drain overflow stem located in the surge tank is apx. 1 foot below the level of the pools. When there is a power outage for some time, the water drains backward through the drains inthe bottom of the pool into the surge tank and down the drain overflow stem. This stem is at the level that it is at because the supply water fill tube is 18 inches below the top of the tank. Back-siphoning could occur if the drain overflow tube were raised above the fill tube. Hence, the only way to fix this problem is to raise both tubes and the air vent that leads to the pump room. When this problem occurs 100,000 gallons can be lost if the pool staff does not act quickly and shut the valves that lead from the pool drains to the surge tank.
*/

```
rule-29: if pool-water = B
          and B > 553
```

```
         and backwash = no
         and pool-water-amount = A
         and A > 10000
         and pool-drained = no
         and pool-filled = no
         and power-outage = yes
         or power-outage = yesterday
      then abnormal-consumption = pool-overflow-power-outage cf 90.

/* -----------------pool shut down for cleaning------------------*/
/*
Each year, usually in the spring, the pool is drained and filled.
For about a period of one week, the pool is cleaned and then
refilled. During this period, the pumps to the pool are shut off
and hence the other-electric goes negative since these are 15 hp
pumps and consume about 268 kwh per day ($13) each. The current
procedure is to shut both pumps off while the either pool is
drained since the draw from a common surge tank.
*/

rule-30: if other-electric = A
         and A < 0
         and pool-water = B
         and B < 0
         and pool-steam = C
         and C < 0
         and pool-drained = yes
         then abnormal-consumption = pool-drained-pumps-off cf 60.

/* ---------------pool filled after cleaning---------------------*/
/*
This is the obvious follow-up to the pool being cleaned. The two
pools contain about 400,000 gallons of water. When they are
filled, only one of the pools at a time should ever be emptied.
This allows for the water from one pool to be pumped to the other
pool. Thus saving 200,000 gallons of water and various steam
heating costs, chemicals, etc. The values used for this are
standard deviations.
*/

rule-31: if pool-water = A
         and A > 553
         and pool-steam = B
         and B > 726
         and pool-water-amount = X
         and X > 10000
         and pool-cleaned = yes
         and pool-filled = yes
         then abnormal-consumption = pool-being-filled cf 90.

/* ---------------pool float sticking ---------------------------*/
/*
One possible problem that can occur in the pool is the sticking
of the automatic pool fill valve in the surge tank. This has not
```

been observed to occur, but it would cause the excess water to be consumed unobserved. This can be checked to see is the float valve is sticking. The 10,000 gallon amount is the limit on the amount of normal water usage for one day. During the course of observations, no abnormal events, aside from the leak, were observed to exceed this amount.
*/

```
rule-32:  if pool-water = A
          and A > 553
          and backwash = no
          and pool-water-amount = X
          and X > 10000
          and pool-drained = no
          and power-outage = no
          then abnormal-consumption = pool-float-sticking cf 70.
```

/*-----------------pool steam traps leaking----------------------*/
/*
When the pool is drained and the pumps are shut down there should be no steam being consumed. In the event that there is it can be assumed that the pneumatic valves that control the pool are leaking.
*/

```
rule-33:  if pool-steam = A
          and A > 0
          and pool-water = B
          and B < 0
          and pool-filled = no
          and pool-drained = yes
          and backwash = no
          then abnormal-consumption = pool-steam-traps-leaking cf 60.
```

/*----------------radiation loop on above 55F -------------------*/
/*
This next problem relates to the fact that the pneumatic outside air temperature does not always know what the temperature is outside. Most often, the building controls are operating as though they are set at 10 lower than the outside temperature really is. In this case, the other-steam consumption jumps up to the indicated level. For estimation purposes, this level has been established at the 1725 because this is the level that is observed when one plots the data base against the outside temperature. The outside temperature at 55 F is supposed to be the temperature at which the steam system shuts down. This problem is rarely seen to occur at temperature above 70 F.
*/

```
rule-34:  if other-steam = B
          and B > 1725
          and outside-temp = A
          and A > 55
          and outside-temp = C
          and C < 70
          then abnormal-consumption = radiation-loop-on cf 70.
```

```
/*----------------fans running to prevent freeze up------------*/
/*
When the temperature is below 37 F all fans in the Rec Center
remain on in the evening hours. The calculated horsepower for all
these fans remaining on is about 58 kw or 465 kwh ($23) during
an evening.
*/
rule-35:  if other-electric = B
          and B > 465
          and outside-temp = A
          and A < 40
          and tennis-lights = no
          then abnormal-consumption = hvac-freeze-protection cf 70.

/*---------------loading ramp snow melt on------------------------*/
/*
The loading ramp snow melt is capable of using 125,000 Btu/hr of
steam energy when in use this amounts to about 3 MMBtu of steam
energy per day ($18) when in use. This item is controlled by a
switch in the penthouse on the wall of the administration air
conditioning unit, marked "snow melt".
*/

rule-36:  if other-steam = A
          and A > 3,000
          and loading-ramp = on
          then abnormal-consumption = loading-ramp-on cf 60.

/*----------------administration office AC left on---------------*/
/*
Often the administration office air conditioning unit is on when
nobody is in the office. This is controlled by a switch in the
directors office marked "occupied/unoccupied". This ac/unit is
capable of consuming 219 kwh over the course of a day. This
usually only happens then the temperature is above 40 F.
*/
rule-37:  if other-electric = A
          and A > 219
          and outside-temp = A
          and A > 40
          and admin-office-ac = yes
          then abnormal-consumption = admin-office-ac-on cf 80.

/*---------------grounds watering---------------------------*/
/*
Ground watering at the Rec Center occurs during the summer
months. Usually, this consumes in excess of 5000 gallons of
water. This option is chosen only when the tennis courts are not
washed, as scheduled, on Thursdays. Also, grounds watering rarely
occurs on days where the temperature is below 50 F. Ice
resurfacing above 80 minutes seems to effect this also.
*/
rule-38:  if other-water = C
          and C > 5000
```

```
          and outside-temp = A
          and A > 50
          and ice-resurface = B
          and B < 80
          and tennis-courts-washed = no
          then abnormal-consumption = grounds-watering cf 60.

/*---------------tennis courts washed ----------------------*/
/*
As one would expect, the tennis courst are washed, on Thursdays.
This consumes at least 5000 gallons of water. It does not occur
when the temperatures are below 50 F, and is also effected by ice
resurfacing. The staff does not wash the courts when it is windy
either.
*/
rule-39:  if other-water = B
          and B > 1305
          and outside-temp = A
          and wind-speed = C
          and C > 2
          and A > 50
          and ice-resurface = D
          and D < 80
          and day-of-week = thursday
          or
          tennis-courts-washed = yes
          then abnormal-consumption = tennis-courts cf 60.

/*---------------water due to excess ice-resurface-----------------*/
/*
The resurfacing of the ice rink causes excess cycling of the
condensor on the roof as well as extra water use by the zamboni
maching. 80 minutes of resurfacing is excessive, 2112 is 1/2
standard deviation.
*/
rule-40:  if ice-resurface = A
          and A > 80
          and other-water = B
          and B > 2112
          and tennis-courts-washed = no
          then abnormal-consumption = excess-ice-resurfacing cf 50.

/*------------rules to state over consumption (general)-----------*/

/* This next section contains rules that state the presence of
abnormal-consumption,in general. These rules are based on the
assumption that one standard deviation above the normal is an
abnormal-consumption. */

rule-41:  if other-steam = A
          and A > 4225
          then abnormal-consumption = steam-above-normal cf 100.

rule-42:  if pool-steam = A
```

```
          and A > 726
          then abnormal-consumption = pool-steam-above-normal cf 100.

rule-43:  if other-electric = A
          and A > 439
          then abnormal-consumption = electric-above-normal cf 100.

rule-44:  if compressor-electric = A
          and A > 119
          then abnormal-consumption = ice-rink-above-normal cf 100.

rule-45:  if natural-gas = A
          and A > 186
          then abnormal-consumption = natural-gas-above-normal cf 100.

rule-46:  if pool-water = A
          and A > 553
          then abnormal-consumption = pool-water-above-normal cf 100.

rule-47:  if other-water = A
          and A > 2610
          then abnormal-consumption = water-above-normal cf 100.

rule-48:  if ice-setpoint = A
          and A < 15
          then abnormal-consumption = ice-setpoint-too-low cf 100.

rule-49:  if ice-resurface = A
          and A > 120
          then abnormal-consumption = ice-resurfacing-too-much cf 100.

rule-50:  if compressor-west= no
          then abnormal-consumption = west-compressor-down cf 100.

rule-51:  if compressor-center= no
          then abnormal-consumption = center-compressor-down cf 100.

rule-52:  if compressor-east= no
          then abnormal-consumption = east-compressor-down cf 100.

rule-53:  if other-steam = A
          and A < -4225.0
          then abnormal-consumption = steam-below-normal cf 100.

rule-54:  if pool-steam = A
          and A < -726.0
          then abnormal-consumption = pool-steam-below-normal cf 100.

rule-55:  if other-electric = A
          and A < -439.0
          then abnormal-consumption = electric-below-normal cf 100.

rule-56:  if compressor-electric = A
          and A < -119.0
```

```
        then abnormal-consumption = ice-rink-below-normal cf 100.

rule-57: if natural-gas = A
         and A < -186.0
         then abnormal-consumption = natural-gas-below-normal cf 100.

rule-58: if pool-water = A
         and A < -553.0
         then abnormal-consumption = pool-water-below-normal cf 100.

rule-59: if other-water = A
         and A < -2610.0
         then abnormal-consumption = water-below-normal cf 100.

rule-60: if ice-setpoint = A
         and A > 20.0
         then abnormal-consumption = ice-setpoint-too-high cf 100.

rule-61: if ice-setpoint = A
         and A < 10.0
         then abnormal-consumption = ice-setpoint-emergency cf 100.
```

**8.5.2.2. BEACON CCON Cache File**

This next table is the PCON to CCON transfer file. The particular version of M.1 used to create the CCON required that the data be in this form for the analysis to begin. This data file represents the comparitive energy consumption for 4/25/86. The units are consistent with the PCON prediction equations. The "cf" is the certainty factor. The first line of the file reads thus; comparitive consumption for other steam was 4,893 lbs above what was predicted. This value has a certainty factor of 100 percent because the value was calculated.

**Table 8-16: PCON-CCON Transfer (cache) file (July 13 1986)**

```
analysis-day= july-13-1986 cf 100 because'calculated'.
other-steam= 707.0 cf 100 because'calculated'.
pool-steam= -382.0 cf 100 because'calculated'.
other-electric= -52.0 cf 100 because'calculated'.
compressor-electric= 130.0 cf 100 because'calculated'.
natural-gas= -103.0 cf 100 because'calculated'.
pool-water= -563.0 cf 100 because'calculated'.
other-water= 2701.0 cf 100 because'calculated'.
sunlight= 1529.0 cf 100 because'measured'.
cold-water-temp= 60.1 cf 100 because'measured'.
outside-temp= 82.0 cf 100 because'measured'.
ice-setpoint= 16.5 cf 100 because'observed'.
backwash= no cf 100 because'observed'.
attendance= 599.0 cf 100 because'counted'.
ice-resurface= 47.0 cf 100 because'measured'.
wind-speed= 4.2 cf 100 because'measured'.
compressor-west= yes cf 100 because'calculated'.
compressor-center= yes cf 100 because'calculated'.
compressor-east= yes cf 100 because'calculated'.
day-of-week= sunday cf 100 because'calculated'.
```

**Table 8-17: PCON-CCON Transfer (cache) file (July 14 1986)**

```
analysis-day=july-14-1986 cf 100 because'calculated'.
other-steam= 2551.0 cf 100 because'calculated'.
pool-steam= -661.0 cf 100 because'calculated'.
other-electric= -603.0 cf 100 because'calculated'.
compressor-electric= 69.0 cf 100 because'calculated'.
natural-gas= 4.0 cf 100 because'calculated'.
pool-water= -653.0 cf 100 because'calculated'.
other-water= 6943.0 cf 100 because'calculated'.
sunlight= 2219.0 cf 100 because'measured'.
cold-water-temp= 60.1 cf 100 because'measured'.
outside-temp= 83.0 cf 100 because'measured'.
ice-setpoint= 14.5 cf 100 because'observed'.
backwash= no cf 100 because'observed'.
attendance= 723.0 cf 100 because'counted'.
ice-resurface= 81.0 cf 100 because'measured'.
wind-speed= 4.4 cf 100 because'measured'.
compressor-west= yes cf 100 because'calculated'.
compressor-center= yes cf 100 because'calculated'.
compressor-east= yes cf 100 because'calculated'.
day-of-week= monday cf 100 because'calculated'.
```

**Table 8-18: PCON-CCON Transfer (cache) file (July 15 1986)**

```
analysis-day=july-15-1986 cf 100 because'calculated'.
other-steam= -2464.0 cf 100 because'calculated'.
pool-steam= -688.0 cf 100 because'calculated'.
other-electric= -880.0 cf 100 because'calculated'.
compressor-electric= 569.0 cf 100 because'calculated'.
natural-gas= 147.0 cf 100 because'calculated'.
pool-water= -748.0 cf 100 because'calculated'.
other-water= 3451.0 cf 100 because'calculated'.
sunlight= 1829.0 cf 100 because'measured'.
cold-water-temp= 59.9 cf 100 because'measured'.
outside-temp= 75.0 cf 100 because'measured'.
ice-setpoint= 14.5 cf 100 because'observed'.
backwash= yes cf 100 because'observed'.
attendance= 1378.0 cf 100 because'counted'.
ice-resurface= 69.0 cf 100 because'measured'.
wind-speed= 2.9 cf 100 because'measured'.
compressor-west= yes cf 100 because'calculated'.
compressor-center= yes cf 100 because'calculated'.
compressor-east= yes cf 100 because'calculated'.
day-of-week= tuesday cf 100 because'calculated'.
```

**Table 8-19: PCON-CCON Transfer (cache) file (July 16 1986)**

```
analysis-day=july-16-1986 cf 100 because'calculated'.
other-steam= -2734.0 cf 100 because'calculated'.
pool-steam= -887.0 cf 100 because'calculated'.
other-electric= -1158.0 cf 100 because'calculated'.
compressor-electric= 822.0 cf 100 because'calculated'.
natural-gas= 193.0 cf 100 because'calculated'.
pool-water= 2061.0 cf 100 because'calculated'.
other-water= 5694.0 cf 100 because'calculated'.
sunlight= 1445.0 cf 100 because'measured'.
cold-water-temp= 60.1 cf 100 because'measured'.
outside-temp= 73.0 cf 100 because'measured'.
ice-setpoint= 14.5 cf 100 because'observed'.
backwash= no cf 100 because'observed'.
attendance= 1247.0 cf 100 because'counted'.
ice-resurface= 57.0 cf 100 because'measured'.
wind-speed= 2.5 cf 100 because'measured'.
compressor-west= yes cf 100 because'calculated'.
compressor-center= yes cf 100 because'calculated'.
compressor-east= yes cf 100 because'calculated'.
day-of-week= wednesday cf 100 because'calculated'.
```

**Table 8-20: PCON-CCON Transfer (cache) file (July 17 1986)**

```
analysis-day=july-17-1986 cf 100 because'calculated'.
other-steam= -1249.0 cf 100 because'calculated'.
pool-steam= -177.0 cf 100 because'calculated'.
other-electric= -652.0 cf 100 because'calculated'.
compressor-electric= 677.0 cf 100 because'calculated'.
natural-gas= 44.0 cf 100 because'calculated'.
pool-water= -359.0 cf 100 because'calculated'.
other-water= 3319.0 cf 100 because'calculated'.
sunlight= 1675.0 cf 100 because'measured'.
cold-water-temp= 59.4 cf 100 because'measured'.
outside-temp= 75.0 cf 100 because'measured'.
ice-setpoint= 16.0 cf 100 because'observed'.
backwash= no cf 100 because'observed'.
attendance= 1423.0 cf 100 because'counted'.
ice-resurface= 49.0 cf 100 because'measured'.
wind-speed= 5.5 cf 100 because'measured'.
compressor-west= yes cf 100 because'calculated'.
compressor-center= yes cf 100 because'calculated'.
compressor-east= yes cf 100 because'calculated'.
day-of-week= thursday cf 100 because'calculated'.
```

**Table 8-21: PCON-CCON Transfer (cache) file (July 18 1986)**

```
analysis-day=july-18-1986 cf 100 because'calculated'.
other-steam= -3680.0 cf 100 because'calculated'.
pool-steam= 945.0 cf 100 because'calculated'.
other-electric= -716.0 cf 100 because'calculated'.
compressor-electric= 408.0 cf 100 because'calculated'.
natural-gas= 147.0 cf 100 because'calculated'.
pool-water= -181.0 cf 100 because'calculated'.
other-water= 2335.0 cf 100 because'calculated'.
sunlight= 1354.0 cf 100 because'measured'.
cold-water-temp= 59.4 cf 100 because'measured'.
outside-temp= 69.0 cf 100 because'measured'.
ice-setpoint= 16.5 cf 100 because'observed'.
backwash= no cf 100 because'observed'.
attendance= 1059.0 cf 100 because'counted'.
ice-resurface= 50.0 cf 100 because'measured'.
wind-speed= 3.9 cf 100 because'measured'.
compressor-west= yes cf 100 because'calculated'.
compressor-center= yes cf 100 because'calculated'.
compressor-east= yes cf 100 because'calculated'.
day-of-week= friday cf 100 because'calculated'.
```

**Table 8-22: PCON-CCON Transfer (cache) file (July 19 1986)**

```
analysis-day=july-19-1986 cf 100 because'calculated'.
other-steam= -1739.0 cf 100 because'calculated'.
pool-steam= 407.0 cf 100 because'calculated'.
other-electric= 359.0 cf 100 because'calculated'.
compressor-electric= 223.0 cf 100 because'calculated'.
natural-gas= 257.0 cf 100 because'calculated'.
pool-water= -201.0 cf 100 because'calculated'.
other-water= 3149.0 cf 100 because'calculated'.
sunlight= 1511.0 cf 100 because'measured'.
cold-water-temp= 61.5 cf 100 because'measured'.
outside-temp= 71.0 cf 100 because'measured'.
ice-setpoint= 17.5 cf 100 because'observed'.
backwash= no cf 100 because'observed'.
attendance= 652.0 cf 100 because'counted'.
ice-resurface= 32.0 cf 100 because'measured'.
wind-speed= 4.0 cf 100 because'measured'.
compressor-west= yes cf 100 because'calculated'.
compressor-center= yes cf 100 because'calculated'.
compressor-east= yes cf 100 because'calculated'.
day-of-week= saturday cf 100 because'calculated'.
```

**Table 8-23: PCON-CCON Transfer (cache) file (July 20 1986)**

```
analysis-day=july-19-1986 cf 100 because'calculated'.
other-steam= -4698.0 cf 100 because'calculated'.
pool-steam= 1513.0 cf 100 because'calculated'.
other-electric= 54.0 cf 100 because'calculated'.
compressor-electric= -169.0 cf 100 because'calculated'.
natural-gas= 39.0 cf 100 because'calculated'.
pool-water= -317.0 cf 100 because'calculated'.
other-water= -481.0 cf 100 because'calculated'.
sunlight= 1675.0 cf 100 because'measured'.
cold-water-temp= 58.6 cf 100 because'measured'.
outside-temp= 70.0 cf 100 because'measured'.
ice-setpoint= 17.5 cf 100 because'observed'.
backwash= no cf 100 because'observed'.
attendance= 712.0 cf 100 because'counted'.
ice-resurface= 48.0 cf 100 because'measured'.
wind-speed= 2.4 cf 100 because'measured'.
compressor-west= yes cf 100 because'calculated'.
compressor-center= yes cf 100 because'calculated'.
compressor-east= yes cf 100 because'calculated'.
day-of-week= sunday cf 100 because'calculated'.
```

**8.5.2.3. BEACON CCON Runtime Log File**

This section contains the "log" file for the BEACON analysis of 7/13/86 through 7/20/86. The user has loaded the "cache" file into the program and begins the M.1 analysis. The expert system then sorts down through the knowledge base attempting to discover which systems are consuming energy abnormally, and what the possible cause might be. In each case the questions and the conclusions are shown. this week on consultation is discussed further in section four of this thesis.

**Table 8-24: BEACON/CCON Log File (July 13 1986)**

```
CCON>restart.
What is the status of the krack unit (on,off)?
>> on.
Is the ice-resurface snow melt pit operational (yes,no)?
>> no.
Is there a leak in the D.H.W. system (yes,no) ?
>> no.
Has the pool been drained purposefully, lately (yes,no)?
>> no.
Have the tennis courts been washed lately (yes,no)?
>> no.
abnormal-consumption = pool-water-below-normal (100%) because rule-58.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = hot-water-for-snow-melt (90%) because rule-11.

CCON>log off.
```

**Table 8-25: BEACON/CCON Log File (July 14 1986)**

```
CCON>restart.
What is the status of the krack unit (on,off)?
>> on.
Is the ice-resurface snow melt pit operational (yes,no)?
>> no.
What is the current D.H.W. setpoint (highest, ie. 115F)?
>> 115.
Is there a leak in the D.H.W. system (yes,no) ?
>> no.
Is the D.H.W. rink, heat-reclaim working (yes,no)?
>> yes.
Is the D.H.W. steam, heat-reclaim working (yes,no)?
>> yes.
Has the pool been drained purposefully, lately (yes,no)?
>> no.
Have the tennis courts been washed lately (yes,no)?
>> no.
abnormal-consumption = pool-water-below-normal (100%) because rule-58.
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = ice-setpoint-too-low (100%) because rule-48.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = hot-water-for-snow-melt (90%) because rule-11.
abnormal-consumption = excess-ice-resurfacing (50%) because rule-40.

CCON>log off.
```

**Table 8-26: BEACON/CCON Log File (July 15 1986)**

```
CCON>restart.
What is the status of the ice rink brine valving?
    1. open
    2. closed
>> open.
What is the status of the freon in the compressors (ok,low)?
>> ok.
What is the status of the krack unit (on,off)?
>> on.
Has the pool been drained purposefully, lately (yes,no)?
>> no.
Have the tennis courts been washed lately (yes,no)?
>> no.
abnormal-consumption = pool-water-below-normal (100%) because rule-58.
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = ice-setpoint-too-low (100%) because rule-48.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.

CCON>log off.
```

**Table 8-27: BEACON/CCON Log File (July 16 1986)**

```
CCON>restart.
What is the status of the ice rink brine valving?
    1.  open
    2.  closed
>> open.
What is the status of the freon in the compressors (ok,low)?
>> ok.
What is the status of the krack unit (on,off)?
>> on.
How much water has the pool consumed (ie. 10000 gallons)?
>>  3195.0.
Have the tennis courts been washed lately (yes,no)?
>> no.
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = pool-steam-below-normal (100%) because rule-54.
abnormal-consumption = ice-setpoint-too-low (100%) because rule-48.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = pool-water-above-normal (100%) because rule-46.
abnormal-consumption = natural-gas-above-normal (100%) because rule-45.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = grounds-watering (60%) because rule-38.

CCON>log off.
```

**Table 8-28: BEACON/CCON Log File (July 17 1986)**

```
CCON>restart.
What is the status of the krack unit (on,off)?
>> on.
Has the pool been drained purposefully, lately (yes,no)?
>> no.
Have the tennis courts been washed lately (yes,no)?
>> yes.
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = tennis-courts (84%) because rule-39.

CCON>log off.
```

**Table 8-29: BEACON/CCON Log File (July 18 1986)**

```
CCON>restart.
What is the status of the krack unit (on,off)?
>> on.
Has the pool been filled lately (yes,no)?
>> no.
Has the pool been drained purposefully, lately (yes,no)?
>> no.
Have the tennis courts been washed lately (yes,no)?
>> yes.
abnormal-consumption = electric-below-normal (100%) because rule-55.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = pool-steam-above-normal (100%) because rule-42.
abnormal-consumption = tennis-courts (60%) because rule-39.

CCON>log off.
```

**Table 8-30: BEACON/CCON Log File (July 19 1986)**

```
CCON>restart.
Has the building been open longer than shown on the schedule
(yes, no)?
>> no.
Has the janitorial staff been coming in early(yes,no)?
>> no.
Has anybody on the staff been staying late (yes,no)?
>> no.
What is the minimum hourly (total building) kw reading (60-150kw)?
>>  134.4.
Are there problems with the lites turning off at night (yes,no)?
>> no.
Are the incandescent lites being used in the gym (yes,no)?
>> no.
Has there been a pool meet recently (yes,no)?
>> no.
Are the pool spectator lites currently in use (yes,no)?
>> no.
Has the pool been filled lately (yes,no)?
>> no.
Has the pool been drained purposefully, lately (yes,no)?
>> no.
Have the tennis courts been washed lately (yes,no)?
>> no.
abnormal-consumption = water-above-normal (100%) because rule-47.
abnormal-consumption = natural-gas-above-normal (100%) because rule-45.
abnormal-consumption = ice-rink-above-normal (100%) because rule-44.
abnormal-consumption = interior-lites-on-pm (80%) because rule-13.

CCON>log off.
```

**Table 8-31: BEACON/CCON Log File (July 20 1986)**

```
CCON>restart.
Has there been a pool meet recently (yes,no)?
>> no.
Are the pool spectator lites currently in use (yes,no)?
>> no.
Has the pool been filled lately (yes,no)?
>> no.
Has the pool been drained purposefully, lately (yes,no)?
>> no.
abnormal-consumption = ice-rink-below-normal (100%) because rule-56.
abnormal-consumption = steam-below-normal (100%) because rule-53.
abnormal-consumption = pool-steam-above-normal (100%) because rule-42.

CCON>log off.
```

**8.5.2.4. Instructions for using BEACON CCON**

The Building Energy Analysis Consultant - Computerized Consultant (BEACON CCON). Is composed of three parts: the RECCEN.KB knowledge base (included in this thesis) and the "filename".CAC cache files on which the M.1 expert system shell operates. Therefore, to operate the CCON the use needs to have the following files and executable codes.

M1.COM - the M.1 expert system shell from Teknowledge

RECCEN.KB - the Rec Center knowledge base.

"filename".CAC - the cache file for each day.

The CCON the produces

"filename".LOG - the log file of the conclusions.

To operate the CCON the following steps are observed:

**Step 1** - Load the M.1 expert system shell by typing the following:

M1 <return>

The M.1 shell will respond with the M.1 banner and await the next instruction.

**Step 2** - Load the RECCEN.KB using the following command:

load reccen.kb. <return>

**Note:** Two important things to note about this instruction: First, all M.1 commands must be in lower case and must be followed by a period. Second, the RECCEN.KB knowledge base must reside in the same directory as M.1.

The M.1 shell will again return the prompt and await further instructions.

**Step 3** - Load the appropriate cache file for the day being analyzed. For example, let's assume that JULY13.CAC is being analyzed, the JULY13.CAC file must first be assembled using a word processing file. Then the file must be moved to the M.1 directory. All this prior to the execution of M.1. Once the user is in M.1 the appropriate files must already be assembled. Should this not be the case the user should "exit" CCON, assemble the .CAC file and repeat the instructions.

Let's assume that all this has been done, the JULY13.CAC file can be loaded into the CCON by typing the following:

loadcache july13.cac. <return>

M.1 will again respond when ready.

**Step 4** - Instruct M.1 to log the information to a log file by the name of "july13.log". This is done with the following command:

log july13.log. <return>

M.1 will again respond when ready.

**Step 5** - Begin the analysis. This is done by issuing a "restart" command. This command tells M.1 to restart the analysis using the already assembled conclusions in the cache. Do not issue a "go" command, as this would clear the working memory and the user would have to enter all the information at the appropriate prompts. The cache file is then a way of streamlining the analysis so that the user does not have to spend time entering the information by hand.

restart. <return>

M.1 will now begin sorting through the knowledge base looking for abnormal consumptions, and try to resolve why any have occurred. At any time the user can ask M.1 why the program is looking for something by issuing a "why." command. The user can also watch the analysis on the screen by issuing a "panels on" command. These commands, and others, are further explained in the M.1 user manuals. The reader is referred to those manuals for further information.

**Step 6** - When the analysis is complete, M.1 will list the conclusions and await further instructions. The user will now need to close the log file with the following command:

log off. <return>

At this point the user can terminate the session with a "exit." command or continue with another day's analysis by going to step 7.

**Step 7 -** The user must now instruct M.1 to reset the cache. This is done with the following command:

reset. <return>

M.1 now cancels the cache and is ready to start over. The user should now repeat step 3 through 7 until completed with the session.

## 8.6. Measuring Influencing Parameters at the Rec Center

This section of the appendix contains information regarding the measuring of influencing parameters at the Rec Center. The specific devices used to collect information are discussed with the intent of documenting the process of developing the BEACON system at the Rec Center.

The weather station at the Rec Center was set up on the roof of the pool directly on top of the intake air cover for the HVAC system. The wind speed recorder and the solar meter were placed on the top of the intake cover, the temperature recorder was placed underneath the north edge of the cover, to shade it from direct sunlight. All instruments were locked in place to prevent volunteers from removing them. The temperature recorded was locked in an environmental case constructed of plywood, painted white with small holes cut in the sides to allow for air flow and thus prevent radiation effects.

EP1 - Average Wind (average mph/day)

The average wind speed was recorded at the Rec Center site beginning August 15, 1985. The wind speed was recorded at the weather station. The wind speed was recorded with a totalizing anemometer manufacturered by Weathermeasure/Weathertronics (1984). Readings were taken once per day at the time when the meters were read. Wind speed on the contact anemometer is recorded in km, an internal conversion in software converted this to average miles-per-hour over for each day. No backup was needed for the wind recordings.

EP2 - Outside Air (average F DB temperature)

The outside air temperature was recorded at the weather station using a spring-wound, two-speed hygrothermograph manufactured by Cole-Parmer (1986). The temperature was recorded on weekly charts and entered in the the SCON data base. Average temperatures were calculated by taking the mean of the minimum and the maximum temperature recorded on the weekly charts. Backup data was provided by Daily Camera temperatures, and temperatures recorded at the Physical Plant and Facilities Management.

EP3 - Cold Water (F)

Cold water temperatures were taken in the pool mechanical room beginning September 15, 1986. Readings previous to this were obtained from the City of Boulder city water department. The hose bib on the city pressure side of the pressure reduction station was opened and the temperature taken once per day with a hand thermometer. The temperature reading was stabilized during each reading until a constant temperature reading was observed for at least 30 seconds. No backup was provided for this reading.

EP4 - Solar Radiation (Btu/Day)

Incident total horizontal radiation was recorded at the

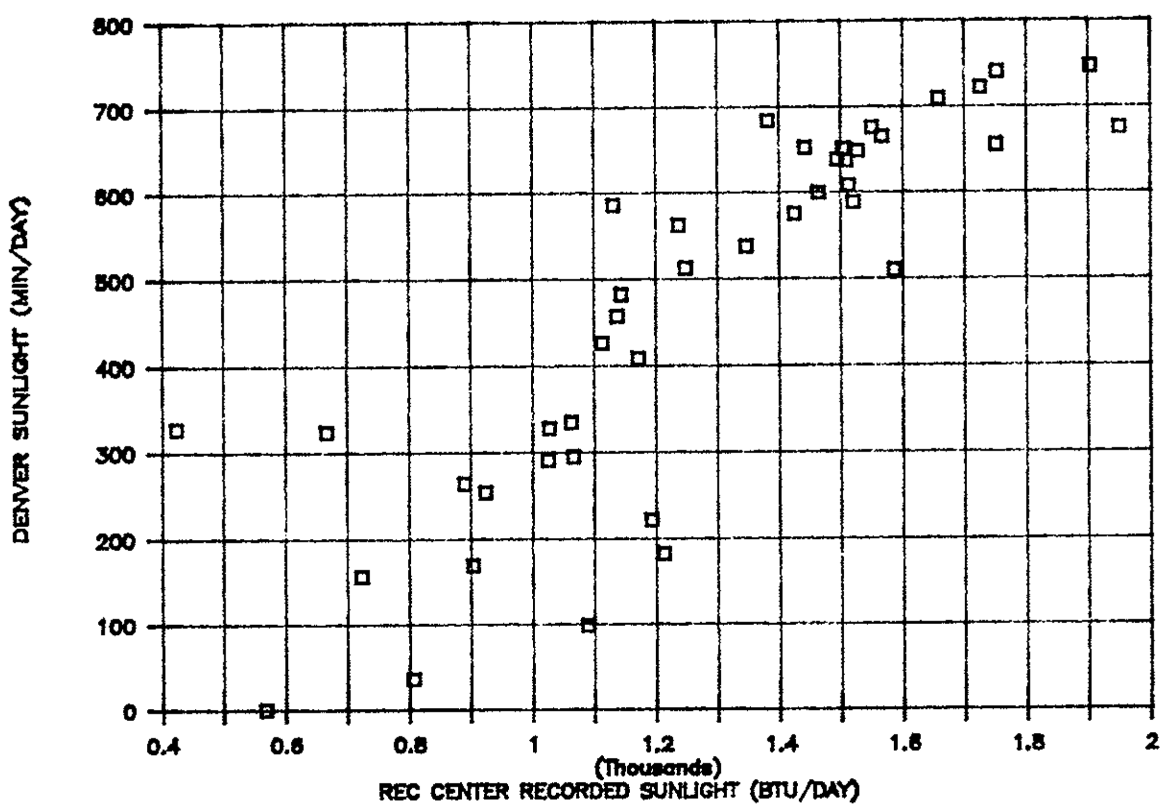


Fig. 8-16: NOAA (Stapleton Airport) vs Rec Center Insolation

weather station with an integrating Sol-A-Meter manufactured by the Matrix (1986) company beginning in February 1986. Readings prior to this were synthesized by regressing against NOAA recorded sunlight for the Denver Stapleton airport (Pautz, 1986). The correlation between the two readings can be seen the the accompanying figure. Backup for the sunlight was provided in this fashion.

OP2 - Operating Hours (hours per day)

The operating hours for the building are the scheduled operating hours available from the Rec Center Administration.

OP3 - Zamboni Runtime (minutes per day)

The Zamboni runtime was read off the runtime meter located on the Zamboni ice resurface machine (Zamboni, 1986). This meter reads in hours and decimal hours, conversions to minutes of runtime is performed in the spreadsheet software. There is no backup for this reading.

OP8 - Attendance (persons per day)

The attendance at the Rec Center is recorded by the security guards at each of entrances. One person is accounted for each time a person passed into the Rec Center. Tallies from the front and the rear doors are added-up on attendance cards. The sum is then entered into the data base. There is no backup for this reading.

OP9 - Backwash (minutes per day)

The pools at the Rec Center contain permanent media filters. These permanent media filters require flushing or backwashing periodically. This operation reverses the flow of water through the filters and flushes the contaminents into the city sewer. Each backwashing wastes about 2,000 gallons of treated pool water. This parameter is then the minutes that the pool personnel have written down on charts next to each of the pumping stations. This reading is noted periodically when a backwash occurs, therefore, it is not necessary to record the information each day. There is no backup for this reading.

SP1 - Generator (minutes per day)

The Rec Center contains a natural gas fired emergency generator located in the penthouse. This generator "fires-up" automatically when the voltage to the building drops below a specified level. The readings for the emergency generator are taken from the runtime gauge on the operator panel. This generator is checked each Tuesday to assure that it is operational by Facilities Management. There is no backup for this meter.

SP2 - Ice Temperature (F)

The ice temperature is the observed set-point ice temperature for the ice rink. This set point temperature is the temperature indicated by a thermocouple directly underneath the east end of the ice rink at the interface to the supporting concrete. This temperature is observed at the time of the compressor readings. There is no backup for this meter.

SCON1 - Other Steam (pounds per day)

This reading is a subtractive steam consumption. This reading consists of the main steam meter reading less the pool steam meter reading. The main steam meter reading is taken in the "steam metering" room located at the east end of the competition pool at the corridor level. The main steam meter reads in gallons/day, conversions to pounds per day are made in the spreadsheet software. This reading represents the pounds per day of condensate that are pumped back to the Physical Plant for reprocessing. The main meter is read once per day.

SCON2 - Pool Steam (pounds per day)

This reading is the actual pounds of steam recorded in the pool mechanical room. This meter is located in between the steam traps from both the competition and the diving pools and the main meter. This meter is read once per day. There is no backup for this reading.

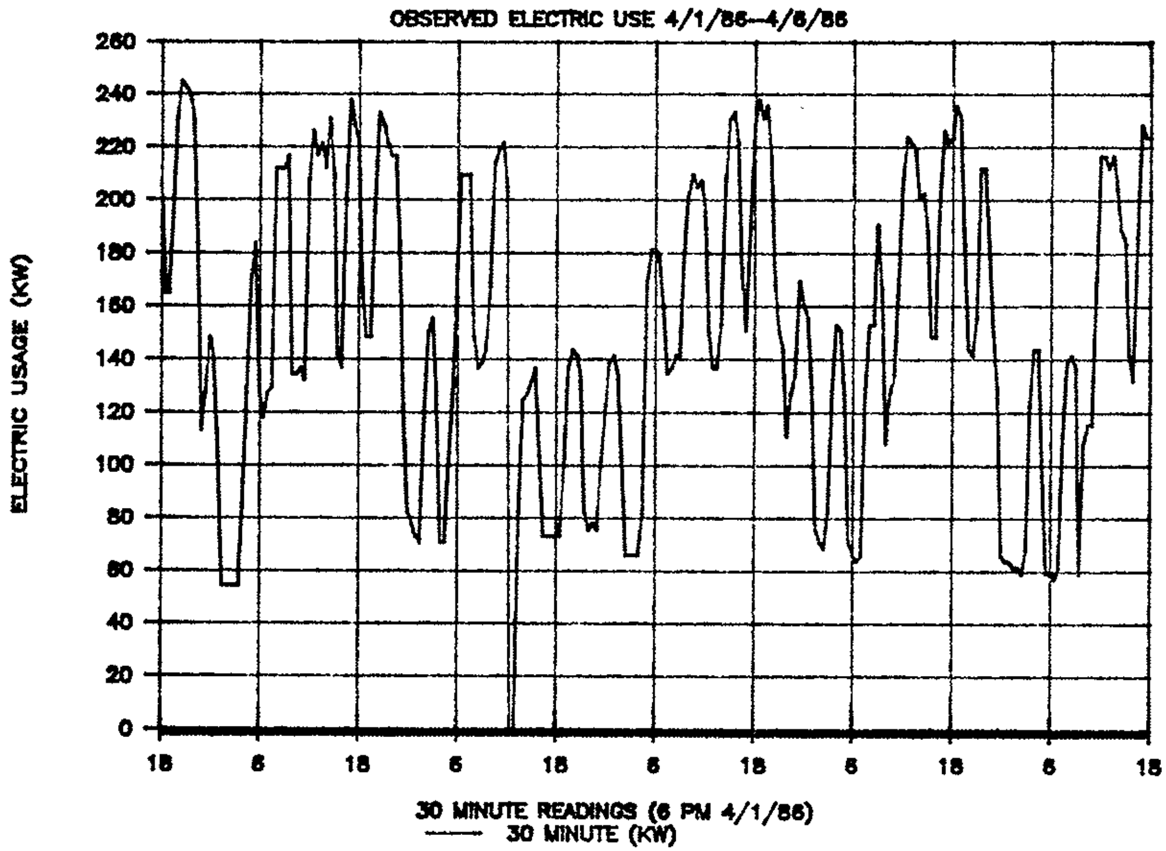


Fig. 8-17: Hourly Strip Chart Recording at the Rec Center

SCON3 - Other Electric (kwh per day)

This reading is the subtractive "other" electric consumed by the building. This reading consists of the electric that is consumed once the ice rink compressor runtime have been subtracted from the main electric panel reading. This reading is taken once per day in the main vault. Electrical demand (unused) is also read. Hourly electrical meter readings are also available. A two element wattage transducer was installed with the appropriate potential transformers and current transformers attached to the main 480 VAC feeder. Hourly readings are not directly used by the BEACON, but were used to establish minimum electrical consumption during the periods when the building was unoccupied. A strip chart recorded is hooked up to the taps from the wattage transducer. A varying milliamp signal can then be recorded on the strip chart. An example of the type of signal recorded is shown in the accompanying figure.

SCON4 - Ice Rink Compressors (kwh per day)

The electrical consumption for the ice rink compressors is calculated from the runtime meters located on the front of the compressor control panel in the ice rink mechanical room. These meter are read once per day. The sum of all three meters is then converted to an electrical consumption within the spreadsheet software. Backup for this meter is provided by duplicate runtime monitoring logged on the Facilities Management Honeywell Delta 1000 computer.

SCON5 - Natural Gas (cubic feet per day)

The natural gas readings were taken at the meter located outside the building at the southeast corner of the main gym. This meter was read once per day. No backup is available for this meter.

SCON6 - Pool Water (gallons per day)

The readings for this meter are taken off the pool water meter installed on the pool supply water line. These readings were started near the end of August. As a result of this meter being hook-up a 20,000 gallon per day leak was discovered in the surge tank drain, September 9th, 1986. Remedial measures were then taken by the pool staff and the pool water consumption returned to normal. The original meter was installed in the surge tank by the author with hose clamps and a fire hose, purchased from the City of Boulder Fire Department. Permanent installation of the meter was accomplished in June 1986. The meter is now located in the pool mechanical room on the west side of the surge tank. This meter reads in gallons. There is no backup for this meter.

SCON7 - Other Water (gallons per day)

This meter is located in the pool mechanical room. This meter is actually a dual meter, both dials must be read and added together. The "other" water meter is a subtractive meter, arrived at by subtracting the pool water consumption from the total building water consumption. There is no backup for this meter.

## Index

This index was generated with the Micropro STARINDX program. Page numbers generated by this program for this thesis were found to be in error. To resolve this the author graphically transcribed page numbers over the indexed page numbers generated with the program. Therefore, the page numbers shown in this index represent approximate locations within the thesis of the actual occurance of the the reference. Attempts to resolve this matter with MicroPro were unsuccessful at this printing.

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