LBNL 42238
CD-472

Early Results and Field Tests of an Information Monitoring and Diagnostic System for Commercial Buildings

Phase 2 Project Report

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September 1998

The research reported here was funded, in part, by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Research and Standards of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Early Results and Fields Tests of an Information Monitoring and Diagnostic System for Commercial Buildings: Phase 2 Project Report

Large commercial buildings generally do not operate at optimal levels of energy efficiency. Performance monitoring projects have shown whole-building energy savings of 20% or more through improved operation and maintenance (O&M) practices. The opportunity for O&M savings is related to many problems, such as the lack of initial commissioning and the lack of feedback available from controls systems on the performance of building systems and components. Even greater energy savings can be achieved with aggressive retrofits.

This report discusses **Phase 2** of a multi-year, multi-institutional project to develop and demonstrate an **Information Monitoring and Diagnostics System** (IMDS). The first phase of the project was a detailed scoping study which included identifying both a group of innovative property managers for collaboration and their most important O&M problems. The key problem we identified is that **building operators lack good information on major building systems.** Phase 1 concluded that information tools currently in use in these buildings limit building managers' ability to assess their O&M practices in a comprehensive manner. We found systemic problems associated with the lack of feedback available from current Energy Management and Control Systems (EMCS). Today's EMCSs are designed for control, with extremely limited capabilities in sensing, archiving, data analysis, diagnostics, and data visualization.

Based on Phase 1 we defined the following objectives for the remainder of the project:

- To save 15% of the energy used in a large commercial building by applying sophisticated monitoring and data visualization techniques, with generalized rules to identify and correct problems in various building system, and
- To develop diagnostic tools and data sets which create a specification for a diagnostics system.

Phase 2 has involved recruiting a building operator and a site for the initial IMDS demonstration, specifying the exact equipment, and installing the system. We collected historical energy use data and developed a baseline model to evaluate changes in energy use that we think will result from use of the IMDS. The system is designed to address common O&M problems and the needs of office building owners and property managers. The IMDS includes 90 points of whole-building, cooling plant, and related data, plus a set of standard diagnostics plots to evaluate key performance metrics and curves. Unique features of the project are (1) sophisticated building operators and engineers as users, (2) permanent installation, (3) high-quality sensing, (4) high-frequency data archives, and (5) top-down design (i.e., whole building, system, and component data). The system does not provide control functions. This report reviews the early results from the IMDS demonstration; key accomplishments and findings are as follows:

- **Working With and Understanding Technology Innovators -** We successfully recruited one of California's key third-party property mangers who is a technical innovator, following Participant Action Research (PAR) concepts. The prototype IMDS is installed in a 100,000 sqft office building in San Francisco, which houses the company's main office. This innovative manager is responsible for over 5,000,000 sqft of commercial property in

California. He has been extremely enthusiastic about the IMDS and the initial response has been excellent.

- **Information Monitoring and Diagnostic System Description –** The IMDS monitors 57 physical and 28 calculated points that cover whole-building electricity use, cooling system measurements, weather, and additional points. The purpose of the system is to offer sophisticated data analysis and visualization tools, plus standard plots and methods to evaluate energy savings opportunities and energy performance data. The data are collected and stored each minute, and available to remote researchers in real-time using the Internet. A partial implementation of the system is available to the public over the web. A detailed analysis of sensor accuracy is included in the report to demonstrate the robustness of laboratory quality measurements installed to minimize uncertainties regarding measured results. Chiller efficiency is accurate to 0.01 kW/ton, or about 1% of typical part-load efficiency.

- **Building Performance and IMDS Findings –** Several years of historical energy data and more recent half-hour data have been compiled and analyzed to develop a baseline against which to evaluate any energy savings that result from the use of the IMDS. The building uses about 90 kBtu/sqft-yr (electricity plus steam, in site units), which is typical for its size, type, and vintage. Seven key findings from the first few days of monitoring demonstrate the presence of typical problems in building operations. Chiller problems include a start-up peak that could have caused a major chiller failure, and back flow that reduces chiller efficiency and brings on the second chiller prematurely. Cooling tower problems include cycling and underutilization of the tower capacity**.** Pumping problems include flow levels both above (on the evaporator side) and below (on the condenser side) optimal conditions, and a high pressure drop on the condenser side. Several additional opportunities for operational improvements have been identified.

- **Automation of Diagnostics –** A critical part of the project is the research on automation of diagnostics, which is important given the large data sets and complex system performance. It is difficult for operations staff to review such extensive data. Progress on a fuzzy logic diagnostics system includes a framework to mimic expert search patterns the standard plots to identify key energy performance maps.

- **Economic and Market Perspectives –**The prototype IMDS cost is about $1/sqft, which includes the hardware, software, ISDN line, and installation. With a goal of about $0.30/sqft savings, we expect a payback time about 3 years. We expect the first cost to be reduced as the technology matures. Furthermore, the non-energy benefits often seen as the primary drivers for such technology, may well exceed the energy savings. One of the main non-energy benefits is improvement in operations that will lengthen equipment life. Comfort improvements and reduced maintenance costs are also expected, and will be tracked in Phase 3. Full-scale implementation of such technology in large Californian office buildings could result in 3 GWh/yr of savings (in electricity), worth about $300 M/yr statewide, plus additional peak demand savings. We will continue to present these results to interested potential service providers such as utilities, Energy Service Companies, and equipment manufacturers. The IMDS should help ensure that building energy performance objectives, defined during design and retrofit activities, are met or updated. We expect that many of the measurement techniques, data archival systems, remote access, and analysis can be incorporated directly into EMCS technology over time.

Phase 3, beginning in late summer of 1998, will include a detailed analysis of the use of the IMDS at the pilot site, including a review of the costs and benefits, plus further analysis of each of the areas described.

ACKNOWLEDGEMENTS

The research team for the project is grateful to the large number of contributors who assisted in the project to date, with special thanks to Lisa Gartland (LBNL) with her help in procuring the IMDS and working with the diagnostic plots. Many thanks to Philip Haves (LBNL) for his careful review of the entire report. We are happy to have Fred Smothers and Glen Starkey (Jones Lang Wootton) as the newest members of the team and our "innovators." We appreciate the ongoing feedback and support from Carl Blumstein, Karl Brown, and Jim Cole from the California Institute for Energy Efficiency (CIEE). Valuable feedback was also provided by Mark Bailey and Dennis Clough (US Department of Energy). This work was supported by CIEE and the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. CIEE is a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor.

SECTION 1.   PROJECT OVERVIEW

Introduction

Buildings generally do not perform as well in practice as anticipated during the design stage. There are many reasons for this, including improper equipment selection and installation errors, the lack of rigorous commissioning, improper maintenance, and poor feedback on ongoing performance, including energy performance. Literature on related building case studies suggest that virtually all buildings have some sort of O&M problems, and the vast majority of buildings are not carefully commissioned (Claridge et al. 1994; Piette et al. 1994; Piette et al. 1996). Similar case studies indicate that careful review of hourly end-use and whole-building energy performance data can result in savings equivalent to about 15 percent of annual operating costs (Herzog and Lavine 1992; Claridge et al. 1994). These savings are much greater (up to 50 percent) in some cases (Liu et al. 1997).

This report summarizes results from the development and early field testing of an Information Monitoring and Diagnostic System (IMDS). The project was conceived to develop and introduce state-of-the-art information technology in buildings in order to enhance substantially building energy performance by continuously improving operations and maintenance (O&M). The research is being conducted by an interdisciplinary team to assess the current state of technology, develop a performance monitoring and diagnosis capability, and test it in real buildings. The system is being designed to improve operations in large Class A commercial office buildings. Class A buildings are the most prestigious buildings in a particular market, with above-average rents, high-quality finishes, state-of-the-art systems, exceptional accessibility, and a definite market presence. Large property management companies usually manage these buildings. There are potential “innovators and early adopters” among these companies, who have been identified for demonstration of the IMDS. Another reason to focus on large office buildings (more than 30,000 square feet) is that they are the largest segment of the sector, accounting for 22% of the total electricity use in commercial buildings (California Energy Commission, 1998). This is equivalent to over 21 BkWh/year (site electricity use in 1996).

Project Phases

This report summarizes results from the project’s second phase. **Phase 1,** reported in Sebald and Piette (1997), included a detailed scoping study, market assessment, and technology evaluation. The Phase 1 market assessment activities included in-depth interviews with six technical managers who are responsible for building operations, and had been identified as among the most sophisticated in California. These interviews included a review of their perceptions of operations and maintenance problems with all major building systems, including controls. The interviews were based on an extensive, 50-page questionnaire designed to tabulate O&M problems and characterize building owners’ and operators’ experiences with diagnostic and control technologies. We sought to identify their most important O&M problems.

Instead of generating these kinds of seemingly straightforward results, the underlying problem turned out to be more complex. The difficulty with identifying common O&M problems is that reports of these problems tend to be anecdotal rather than statistically based. Instead of identifying a detailed set of problems, we found a more critical and diverse set of problems that need to be addressed by a successful diagnostic system. The key problem we identified is that **building operators lack good information on major building systems.** Information tools currently in use in these buildings severely limit building managers' ability to assess their own O&M practices in a comprehensive manner. Rather, there are systemic problems associated with the lack of feedback available from current Energy Management and Control Systems (EMCS). Today's EMCS are designed for control, with extremely limited capabilities in sensing, archiving, data analysis, diagnostics, and data visualization. This technology is slowly improving and evolving to include greater capabilities for performance monitoring (as discussed in Section 6).

Phase 2 has involved recruiting a building for the initial demonstration, specifying the equipment specific to the site, and installing the system. We have also collected historical energy use data and developed a baseline model to evaluate changes in energy use that we think will result from use of the IMDS. We also report on the technology innovation aspects of the project and early findings from the IMDS. The purpose of the project is to deploy and evaluate the IMDS. The overall objectives are: (1) To save 15% of the energy used in a large commercial building by applying sophisticated monitoring and data visualization techniques with generalized rules to identify and correct problems in various building system, and (2) To develop diagnostic tools and data sets which create a specification for a diagnostics system. We will not have achieved these objectives in Phase 2, but will address these objectives in Phase 3. Phase 2 has, however, included the full-scale deployment of the IMDS designed in Phase 1. This report includes a comprehensive review of the system and sensors. We have also completed additional evaluation the technology innovation process. We have documented an initial set of building performance issues discovered using only a few days of data from the IMDS.

The IMDS differs from previously developed systems in several important ways. First, it is specifically targeted toward sophisticated building operators and engineers. Most related research efforts or techniques are targeted toward a remote expert user (Liu et al. 1997; Honeywell 1998). The system under development can be used by a remote user, but we are specifically interested in gaining direct feedback on the IMDS from today's best operating engineers who have a strong influence on the commercial building market. Second, the proposed system will be installed permanently. Many related approaches that are known for ease of use are built around short-term rather than continuous monitoring systems (Waterbury et al. 1994). Third, the monitoring system is based on high-quality sensors that are more accurate and reliable than sensors found in most commercial building systems. Fourth, the proposed system continuously archives data each minute. Most current systems do so every 15 minutes or longer, lacking the ability to catch problems such as equipment short cycling (Liu et al. 1997; Waterbury et al. 1994, Gillespie, 1997). Fifth, the diagnostic system has a top-down design that logically flows from the general whole-building analysis to system and component diagnostics. This is in contrast to bottom-up approaches that attempt to detect performance failures associated with specific individual devices (Hyvarinen & Karki 1996).

Phase 3, scheduled to begin in late summer of 1998, will encompass tracking the energy savings and other benefits that results from operating the system (further described in Section 7). Phase 3 will also include developing a preliminary functional specification to document rules and algorithms to describe the most important faults detected with the diagnostic system.

Report Organization

This report has six remaining sections organized as follows. The next section (**Section 2**) discusses how we selected the pilot site within the context of technology innovation theory. We discuss these theories and present models of information flows and decision-making processes.

Section 3 provides an overview of the IMDS scope, plus hardware and software used. This section includes a discussion of the accuracy of each sensor (57 points) and calculated point (27 points). **Section 4** describes the pilot site building characteristics and historical energy use compiled to serve as a baseline for future energy savings analysis. It also includes a series of findings and graphical IMDS output from the first few days of the system's operation. These graphics identify our preliminary analysis of where there appears to be significant energy savings from operational improvements. **Section 5** outlines the research progress toward automation of the diagnostics using fuzzy logic detectors. **Section 6** discusses the costs and benefits of the IMDS, statewide savings potential, and relation of the IMDS to other research activities and new technologies. **Section 7** outlines our plans for future work and includes a summary of major findings. **Section 8** lists the references. A series of appendices were developed to accompany the report, which are listed in the table of contents.

SECTION 2. PILOT SITE SELECTION AND TECHNOLOGY INNOVATION FINDINGS

Introduction

The method to select a building operator and site for use in our pilot study was based on two theories of innovation adoption. The selection process included analysis of both the individuals who operate the buildings and the features in the buildings themselves, though the selection of the individuals was the more important. The two theories used are as follows. First, in any population, some individuals are likely to try out new ideas first. These individuals are termed innovators and they share many common characteristics including personality and values. Second, these individuals are easily identified by their peers. These theories and their application to the building selection process are further discussed below.

We are interested in utilizing the skills and experiences these innovators have in the operation of commercial buildings. Their expertise in their business environment and corporate culture mean that the project is most likely to include features that are relevant to their peers. We have used the skills and interests of the operators to select the topics to be developed and the features to be used in the IMDS. In Phase 1, we learned that the innovators had little confidence in existing control systems. Furthermore, because they had poor quality information they were reluctant to make decisions to change the existing systems. Lack of good information from control systems is part of a problem that expectations regarding building performance and energy savings from direct-digital controls were never met. Most DDC systems have been operated to mimic older pneumatic systems. The proprietary "black-box" nature of the controls software has also been problematic for building operators who want to make changes to their systems. Poorly maintained and low-quality sensors have created difficulties in basic control for comfort. Similarly, building operators have not been able to use the control system to find and remedy building performance problems and identify energy inefficiencies. In other words, building operators realized that their peers and competitors could not prove that a particular building system was efficient or inefficient except in crude ways. This lack of competitive pressure is one of key elements that has led them to be complacent about energy efficiency.

Innovation theory has repeatedly confirmed that only a portion of a population tries out new ideas or products. (Rogers, 1983). Others, described as early adopters or mature adopters, wait to learn from the opinion of the innovators before proceeding with trying a new technology. Some of the population (late adopters and laggards) may not even be aware of new technologies until they are driven from the field by their more aware competitors. Innovation theory defines the characteristics of these adopters by their "ideal types". This categorization is show in **Figure 2–1.** Innovators tend to be able to cope with a high degree of uncertainty, are risk takers, and are more cosmopolitan. They are easily identified by their peers as more venturesome.

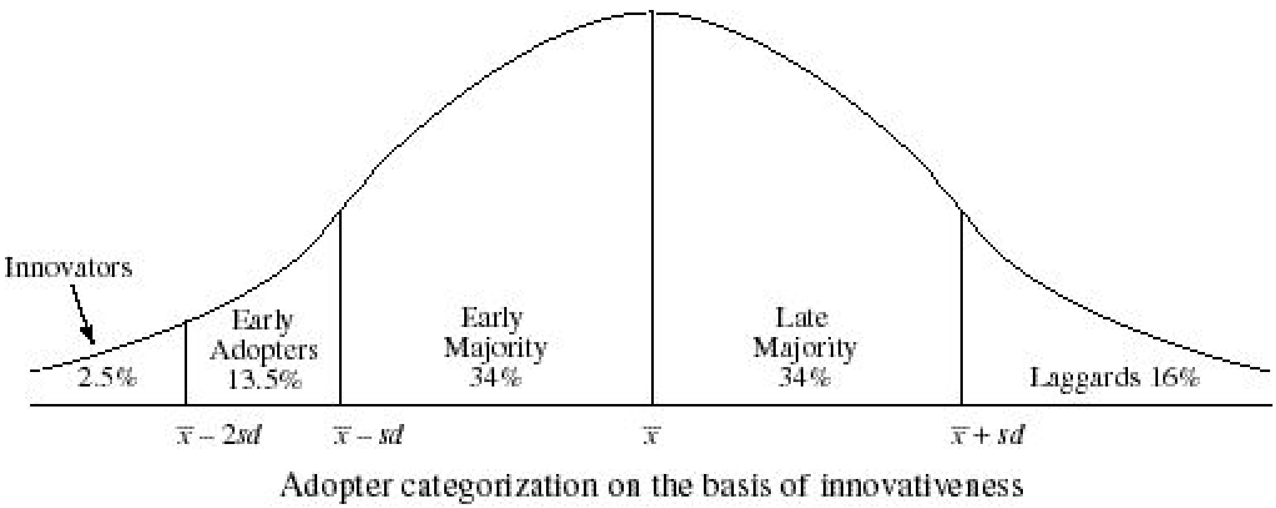

Figure 2–1. Technology Adoption Categories

Innovators have a higher tolerance for new designs and systems that do not immediately work perfectly. They will stay through the development stage that discourages their less innovative followers. Frequently, others wait for their decision before acting. Solutions that have been tested and found worthy by the innovators are acted upon quickly by their less innovative peers.

Phase 1 Research: Identifying a Group of Innovators and Key Energy Issues

The initial identification of innovators was conducted during the Phase 1 scoping effort, which took place in 1994 to 1997 (Sebald and Piette, 1997). This activity is summarized in this section. A general description of the innovators using the "ideal type" description was sent to seven local offices of the Building Owners and Managers Association in California (BOMA). BOMA is the largest organization for owners and managers. The organization represents the membership with strong regional offices. (BOMA is an organization that local building owners and managers in every regional area in California used to negotiate their membership's energy purchases in a deregulated environment.) The staff at these BOMA offices were asked to meet with their technical committees and ask the committees to select their ten most innovative operators. The staff workers at the local BOMA offices and technical committees at the BOMA offices had difficulty selecting the most innovative operators since they did not want their members to know who they picked. After some discussion, they agreed to provide specific names if the list was kept confidential. The companies selected by BOMA were all third party property management companies. The core business of these companies is the management of buildings. They operate buildings as their primary business, providing the marketing, legal and technical management of buildings for tenant-occupied, leased space.

As the lists were compiled it became immediately apparent that there was general concurrence of the technical committees regarding the selection of companies that included innovators. Several companies were selected by more than one BOMA office. In discussion with the BOMA staff of San Francisco and Los Angeles, it became clear that the innovators were well known to those who were familiar with the industry.

The first contact with the companies was made through the local BOMA offices. The BOMA staff sent each company a letter requesting them to respond regarding their interest in the research project. Responses were collected from approximately 35 of the companies. Telephone interviews were conducted to make certain that we had geographical distribution. This was important because we were interested in ascertaining what the company management thought about technology and did not want to get responses from companies whose responses reflected local biases only. Some regulatory environments have stricter requirements and those locations naturally have stronger organizational responses to those regulations.

To determine which individuals at the selected companies would be interviewed, we asked the respondent to identify the person or persons within the company who made technology decisions. In each case, we were referred to one person. Thus, we discovered that these professional property management companies centered their technology decision-making in one person.

The "innovative" technical managers share many characteristics of personality and values. All of them are products of their experience, that is, they did not go through a formal education process for their job. Their experience is practical and they are pragmatic individuals. Only one of the managers interviewed had a university degree. The typical career path for the decision-maker begins as a young operations engineer or in the industry that served building managers. These individuals distinguished themselves as more curious and more tenacious, becoming well versed in the technical details of building systems and components. Questions began to be referred to them by their peers and chiefs, and the research they undertook to answer these questions enhanced their own knowledge. To take advantage of their technical expertise, they were promoted to senior positions earlier than their peers. Later they were promoted to chief engineer at one of their company's largest properties. When the company marketing and property management began to call on their expertise for other properties in the portfolio, each was promoted to the level of a corporate advisor to all of their building operators. Job responsibilities include hiring of engineers, representation of technical issues to the building owners, and responsibility for technical decisions for all properties.

We selected professional management companies because their core business was the management and operation of real estate. Unlike businesses that are owner-occupied and operated, third-party property managers have to respond to a variety of needs and markets. Generally, the portfolios of the companies they work for are quite large. They may have as many as 400 buildings under their direct management with as many as a thousand different tenants.

Three operators in Los Angeles and three operators in San Francisco were selected for interviews because we wanted to have a selection of buildings and operators to choose from. The IMDS technology is robust, but may not be suited to all types of buildings. In particular, we wanted to be sure that we had a building that was not going to change ownership. We wanted a building that they would operate for as many years as possible. We also had focused on larger buildings with central cooling plants rather than packaged units. Cooling plants are easier to monitor (given the centralized location of equipment) and would be more cost-effective for a demonstration project. Each of the technical managers interviewed had been in their positions for more than ten years. These subjects participated in a detailed interview based on a 58-page questionnaire. The questionnaire covered issues such as the size of building portfolios, whom they sought advice from, their opinion of control systems and their personal opinions about the direction of new technology. (See Sebald and Piette, 1997, for a discussion of the questionnaire. Appendix A3 contains the questionnaire).

The results of the questionnaire influenced the research plan to accommodate the interests of the interviewees. Managers told us that they were not confident in the sensors supplied by their control vendors and were reluctant to make change in operating methods and techniques in the absence of better information. We also learned the interviewees placed a high value on real-world experience. While they were likely to learn from an academic experiment, they were unlikely to act unless they had tried out the technology themselves or had a recommendation from a trusted peer.

In order to maintain their interest and cooperation we proposed a research partnership that followed the model of Participant Action Research (PAR, Denzin and Lincoln). PAR is a method of research that involves the active participation of the research subject. PAR has two objectives. The first aim is to produce knowledge and action directly useful to a group of people through research, adult education, and sociopolitical action. The second is to empower people at a second and deeper level through the process of constructing and using their own knowledge. They have been informed of the goals of the research and have been asked to provide some self reporting. This methodology allows the research team to get closer to the "truth" of the culture, business environment, and values of the subjects. Our goal is to develop an in-depth understanding of how these decision-makers select or reject technologies. It has also been a goal of the project to actively engage the participants in developing the features of the IMDS system.

Phase 2 Research on Choosing the Innovator for the Pilot Site

In Phase 2 of the research, we re-interviewed some of the subjects from our initial interviews to determine the best site for the IMDS pilot demonstration. Each of the candidates was asked to submit a possible building for review. We met with the on-site property managers and building engineers and toured several candidate properties. IMDS sensor and communication cost estimates were developed for several of the best candidate sites based on the size of the building, number of chillers, and other such factors.

We determined that all of the properties submitted by the technical managers were technically acceptable to the researchers. We asked the technical managers to estimate the labor (in-house or contracted) costs to install the IMDS using an engineering manual that showed a prototypical building. The technical managers were responsible for obtaining permission from their ownership, asset managers and on-site staff to participate in the demonstration. They also needed to identify the source of funds for the IMDS installation. They were told that they could install the equipment with on-site staff or subcontract labor, but that all associated costs of installation, wiring and connections was their responsibility. We asked the managers to self report their decision-making process and to submit to a series of interviews that would explain the process of getting technology adopted in their companies.

We were aware from the initial interviews that these technology managers acted as gatekeepers for new technology. A gatekeeper is defined as a person who stands at the boundary of an organization and can withhold or shape information as it flows into their business system (Allen, 1981). In each case, we were able to pass through the "gate" of the technical manager gatekeeper. This means that technology used in the pilot study is sufficiently interesting for the managers to consider for use in their buildings despite the fact that we made no promises for its ability to save money or make their buildings more efficient. We believe that the managers proceeded on their desire to understand what was new and innovative in their industry.

We first approached the Embarcadero Center in San Francisco, managed by Jose Gomez who is their technical manager. We informed the technical manager that they were our first choice for the pilot site. The technical manager took the project to his management staff within 24 hours. Although we "passed through the gate" of the technical manager, the pilot study was rejected by the financial management because they wished to avoid the distraction during an impending sale of the building. We were not informed about the reason for the rejection in the initial discussions, although rumors within in the industry suggested the possibility of the building being up for sale. The rumors were subsequently confirmed by the technical manager. The technical manager for the second choice building –Fred Smothers, at the Hong Kong Bank Building (160 Sansome Street)– was notified of our interest in his site. He obtained approval from the management and ownership of the building within three days. We proceeded with the start of engineering October 24, 1997. Installation was completed May 1, 1998. Our findings on the technology innovation process are described in the next section**.**

Phase 2 Research Findings on Technology Innovation Process

The technical managers that are on our short list of innovators are the leaders of their industry. The most important issue facing these managers today is their response to the deregulation of the power industry. The BOMA local offices selected their leaders to study the issues and suggest a direction for their membership. They selected the same people that we included on our short list of innovative managers. We believe that these managers lead their industry on other issues also. They tend to have large, prestigious portfolios of buildings. They also have the organizational slack and technical expertise to experiment with new technologies prior to wide spread use. Although we believe that we have identified the individuals who lead the industry, how they decide which technologies are to be pursued and which are to be avoided was unknown to us.

Literature on diffusion of innovations suggests that the innovators and early adopters of innovations differ significantly from the bulk of users that adopt a new innovation (Rogers and Shoemaker, 1971). Literature on the adoption process of innovations also suggests that the type of innovation impacts the decision adoption (Damanpour, 1991). Innovations can be broken down into many categories including such items as cost, features, and newness to the innovators. Our original organizational research indicated that the managers were able to shepherd small, incremental innovations through the organizations they managed with some ease. However, complex and large-scale experiments were rarely (if ever) conducted. Our research interest poses the hypothesis that that the two types of adoption processes, that is, for radical and routine innovations are not the same. Identifying these two types of processes will lead to a better understanding of the adoption of technical innovations to this market segment. This research will provide a model of the two innovation processes and suggest possible ways that future innovations can be packaged to enhance their review and possible adoption. Below we present a model of the two innovation processes and suggest possible ways that future innovations can be packaged to enhance their review and possible adoption.

In Phase 2 of the project we explored our hypothesis that the process the technical mangers used to review routine and radical innovations is different. The definitions of radical and routine innovations were defined at the onset of the questionnaire by providing the managers with this text**.** The definitions were constructed from a variety of sources (Damanpour, 1988, Dewar and Dutton, 1986, and Nord and Tucker, 1987). The definitions used follow the guide of earlier research studies. The definition was presented to the technical managers to help them separate out the two types of innovations:

> *"This study is a part of a larger technology study on the adoption of innovations within property management companies. In order to tailor this research project and potential future projects to our industry's needs, we are asking you to provide us with information about the process you use to review and select new technologies.*
>
> *"We are studying two types of technologies:*
>
> *Category 1 Innovations: The first type of technology is identified as routine. Routine technology innovations are those that while new to your organization do not require a substantial expenditure or include significant structural or skill changes to your workforce.*
>
> *You will be asked questions about routine innovations you have considered in the past.*
>
> *Category 2 Innovations: The second type of technology is defined as radical. It is new to your organization and provides a product or service that does something you formerly could not do with existing technologies. It is likely to involve more substantial expenditures and be more complex to understand. If it were implemented throughout your company, it could require changes to your company's structure or the skills of your workforce.*
>
> *You will be asked to provide information about the review and possible adoption of a radical innovation. We will introduce the innovation to you. As a part of our review procedure, we will need to work with you over time to understand the adoption process.*
>
> *You will be able to see the results of the study."*

Managers were asked to list one or more technical innovations they had explored in the routine category that they had recently reviewed (within the last year or so) and describe their adoption process. We will present the radical adoption processes in the Phase Three report.

One of the most compelling findings of the innovation process research is how powerful the technical managers are in making technology decisions for the buildings they are responsible, and how little they rely on the input of others. All of the managers determined that their company would try the IMDS system without further consultation with colleagues, professional engineers or review of published literature. In response to the question, "Who decided to adopt the innovation?" all of the managers responded, "I do." The managers were also asked to list some innovations that their company had adopted which they did not recommend. That is, we asked them to list a technology that they had reviewed and rejected, this technology was subsequently adopted by their company over their negative report. None of the managers could recall a single incidence of this occurring. While the gatekeeper cannot force an owner or asset manager adopt a new technology, technologies that they do not deem worthy are never adopted.

Routine Innovations

The routine innovations selected by the managers included light fixtures, motion sensors, new chillers and a variety of small tools to perform diagnostic studies that are used by their engineers. Size and cost of the innovation did not seem to concern these managers. Changes, upgrades, replacement in kind and replacement for obsolescence were all listed as routine innovations. The addition of new features (even if complex) to an existing product did not constitute a radical change to these managers. The ability to project an expected cost into the future, or budget for an upgrade or change out, was a factor in categorizing some of the innovations as routine.

Knowledge about the source of routine innovations was difficult for the managers to pinpoint. Several referred to the idea that “it was in the atmosphere.” By this they meant that they heard of the new technology nearly contemporaneously from several sources. A model of routine change showing the sources of the information for such change is provided in **Figure 2–2.** One simplification of the figure is that some of the communication is two-way to allow technical managers to carry on a dialog about potential changes. By contrast, information from a magazine and not verifiable with a trusted peer, vendor or engineer is one way communication. The most frequently cited sources of information are vendors, trusted peers and their own chief engineers and former chief engineers**.**

Much less common is the route of information flowing through new construction (probably it just occurs less frequently). They obtain new information when they acquire a new building that has new technology. Many technical managers claim they are never asked during the design stage about which products they prefer and systems they prefer. Information flows through competitive forces and managers feel that they need to keep up on new technology because their competitors will inform the building owners of innovations and they will be asked to respond with their input. The technical managers read no-cost trade magazines, such as *Buildings*[1] and *Engineered Systems*[2], but ascribe little value to them. However, new buildings frequently provide new information, but the source of information is much lower quality if the engineering staff including the new chief do not “move with the building.” Finally, the managers on rare occasions are requested to provide an upgrade or new innovation by the owner or asset manager of the building.

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[1] Stamats Communication Inc., Cedar Rapids, Iowa.

[2] Business News Publishing Company, Troy, Michigan, www.esmagazine.com

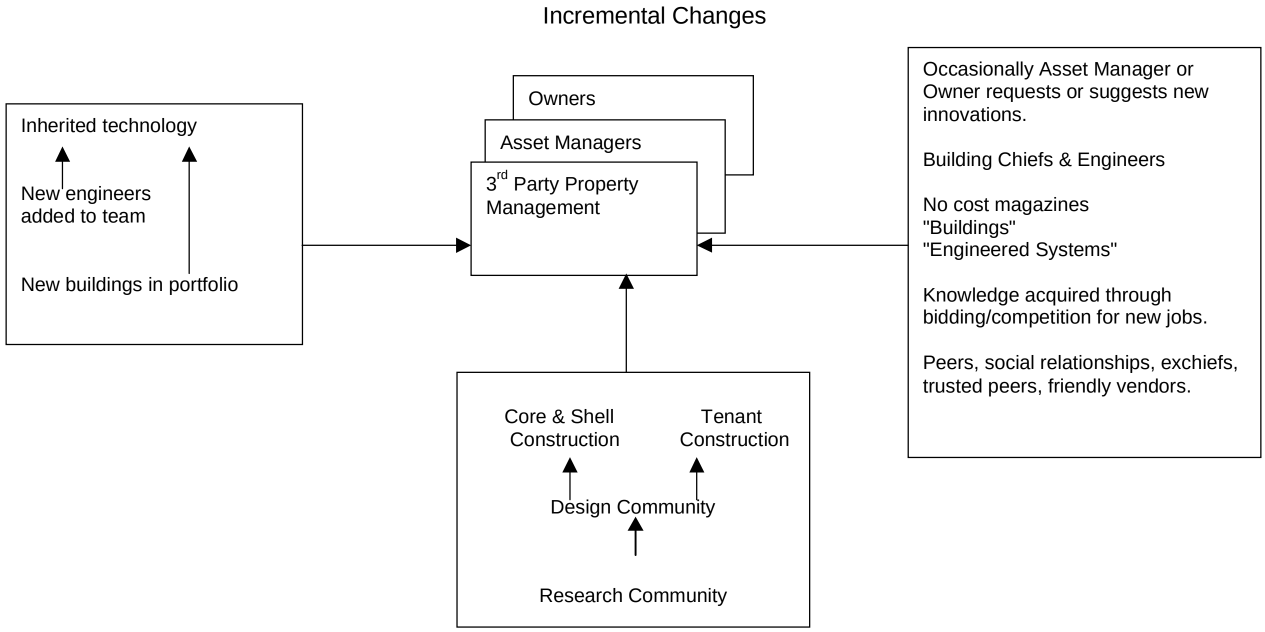


Figure 2–2. Routine Innovations and Incremental Changes

Radical Innovations

Radical innovations occur less frequently in the working environment of these technical managers. Special needs such as data centers or high security areas by an owner are the most frequently cited causes of radical changes after a building is in operation. The managers also report that they learn about new technologies from new construction projects. These technical managers "blame" design engineers for the finicky products (electronic systems appear to be especially annoying) and this seems to be one source of their reluctance to seek design professionals assistance at other times.

The model on the following page outlines sources of information that lead to radical changes (**Figure 2–3**). The model shows how methods used for learning about and evaluating routine innovations continue to exist in radical innovations, but with links weighted to handle the special circumstances of radical changes.

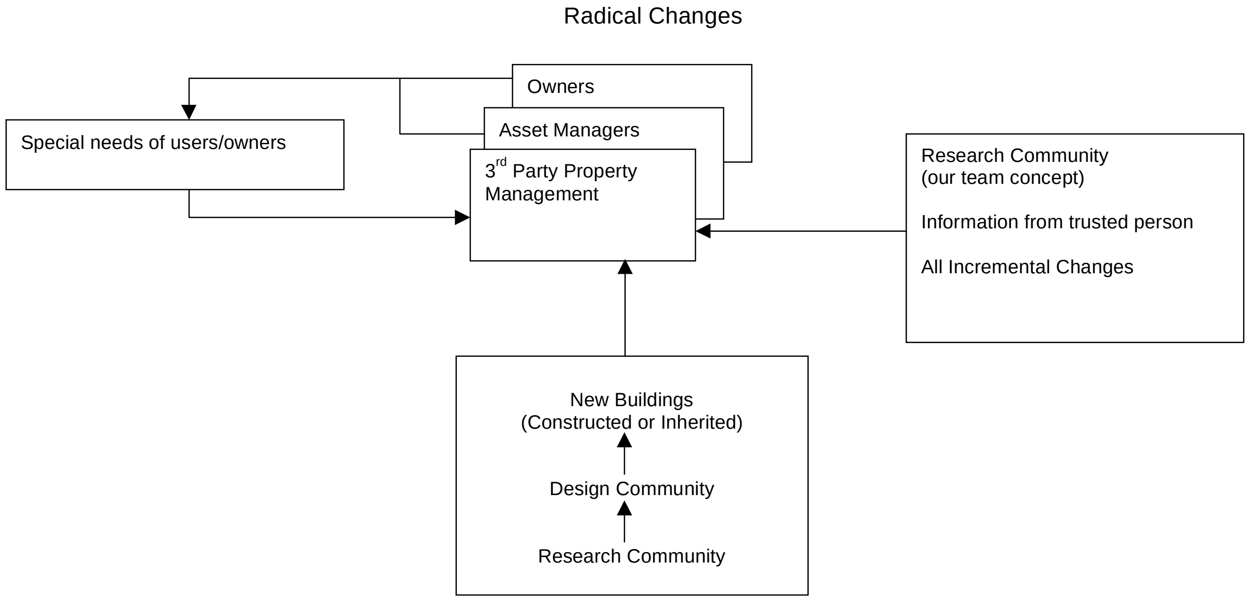


Figure 2–3. Sources of Radical Changes

Exploring radical innovations has revealed several interesting issues. As we previously learned in Phase 1 of the research, the managers strongly prefer "knowledge through experience". But knowledge through personal experience may be difficult (or impossible) to acquire when an innovation is novel or its radicalness puts it beyond economic feasibility. Our interviews with the managers revealed a mode of thinking that, while not unique to this population (scientists use this thinking pattern too), is helpful in understanding how they think and make decisions. This way of looking at their environment is termed "Inference based upon belief" (Silver, 1998).

Inference based upon belief is based in two underlying "proofs" of the sagacity and wisdom of the new concept. The first is the decision maker must believe that the person they are listening is credible. The second is that the person has no reason to lie. The model for radical changes shows how such changes are likely to be introduced into the environment. In each case, the manager can acquire the knowledge serendipitously by forces outside his control. For example, he can acquire the knowledge by bringing a building into his portfolio when his company assumes management, or from an owner with a special need asks for a new technology. The only route that provides direct linkage between a radical new idea and the people who directly manage the projects is the research model on radical changes that we have constructed. These managers have never been asked to participate in research studies until this project.

Phase 3 will demonstrate whether we are a trusted source of information and can further infuse the IMDS technology into third party property management companies. The technical managers will be interviewed to determine if they believe we have this unique experience and if we can be relied upon to faithfully report the results without bias. An expected consequence of selecting just one building for a pilot study is that the companies and individuals not chosen have not been as helpful since the announcement that they were not selected. The introduction of the results from the IMDS study appears to be of sufficient interest to the innovative users that we are able to obtain interview access again. The managers of the innovative companies are curious to see the new IMDS technology and to know what their peers think of the technology.

IMDS Installation Issues

The hardware, software, and installation cost for the IMDS are discussed in Section 6. We provide some comments about the installation process in this section because of their relevance to the pilot site selection. We experienced several problems with the pilot installation, which will require a remedy in future demonstrations. First, while the organization of the building staff is not a problem as there is only one engineer, the organizational slack was difficult to predict since the chief engineer had to respond to other building needs during this time and was unable to work continuously on the project.

We ceased interviewing the technical manager and engineer about the IMDS on May 1, 1998 because we did not want them to start using the system until we had acquired two months of baseline data. The baseline data will be used to develop simple estimates of energy and other savings from with IMDS as the “before IMDS” case. Additional historical data have also been collected (see Section 4). Interviews regarding the use of the IMDS will proceed in August, 1998, after two months of baseline IMDS have been collected.

Conclusions on Technology Innovation

The IMDS technology was developed in response to the concerns the technical managers reported in Phase 1 of the project. The technical manager’s review of the information is expected to reveal that the technology needs to be altered and adjusted to accommodate the business reality they work with. Phase 2 includes our understanding today of the innovation adoption process used by a technical manger in a third party property management company. We find that the technical managers rely primarily on firsthand, verifiable information from trusted sources. Very little outside persuasion is necessary and making the decision to adopt the technology is not a time-consuming process. In Phase 3, we will provide a more complete model for the manager’s decision process for both radical and routine innovations.

SECTION 3. IMDS DESCRIPTION AND ACCURACY

IMDS System Overview

The IMDS demonstration is oriented toward deploying the basic infrastructure for an advanced information system, including field tests of initial applications. This demonstration will allow the controls industry to examine the value of such systems that greatly exceed today's current EMCS technology. Such a system is the starting point for more advanced, automated diagnostics, such as those based on fuzzy logic or neural networks. The system is a distributed data collection and analysis system. The primary elements of the system are:

- A monitoring and data acquisition system that measures 57 physical and 28 calculated points
- A PC that stores the data and houses the data visualization systems (Electric Eye)
- An ISDN line connecting the system to the remote researchers
- A web server that is a real-time analysis tool demonstrating a small fraction of the larger set of data visualization capabilities
- A set of standard graphics used for working with the building operations staff to identify building energy performance problems

Key elements of the system are shown in **Figure 3–1.** The data are stored on a simple flat-file system, with remote data archives at LBNL and Supersymmetry appended each day. We are testing the first PC version of the graphics software, which was previously only available for use with high-end graphics workstations. Data from each sensor are archived in the PC server at the demonstration building. The data acquisition and graphical analysis software are located on the PC, allowing the on-site operator and chief engineer direct access to the data. The IMDS generates nine standard plots available for viewing, plus it offers a series of more sophisticated browsing and statistical analysis tools. These more sophisticated tools will likely be of greater use to the remote researchers. Researchers in several locations will have access to the data, plus the identical analysis software, allowing them to analyze the building performance and test the automated diagnostic systems. The PC server will offer a subset of the real-time analysis graphics from the demonstration site to the public over the World Wide Web. The purpose of these graphs are to demonstrate the technology to interested organizations and potential future service providers such as Energy Service Companies, utilities, and control companies.

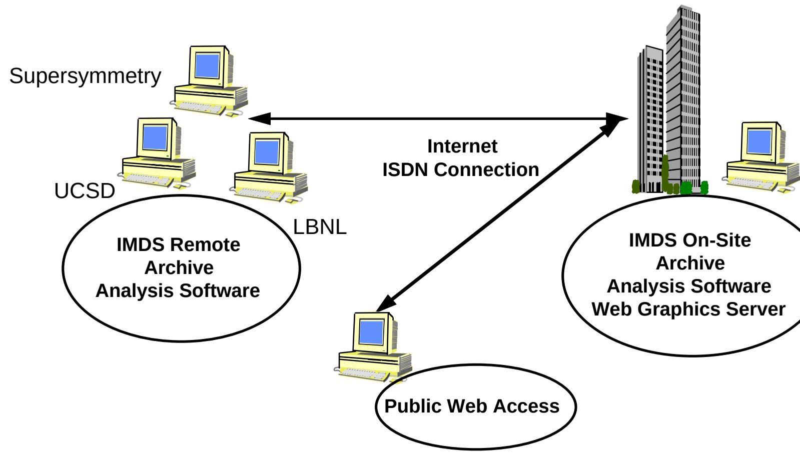


Figure 3–1. Components of the Information and Monitoring Diagnostics System

Four types of physical measurements are taken by the IMDS: temperature (including wet-bulb), power, flow speed, and pressure. The installed system consists of 57 physical and 28 calculated points for a total of 85 points of minute data. The sensors include high-grade thermistors, power meters, magnetic flow meters, and aspirated psychrometers. A summary of the monitoring scope is listed in **Table 3–1**. Further details on the sensors and sensor accuracy are presented below.

Table 3–1. Systems and Sensors in the IMDS

System to be Evaluated	Measurement	Number of Physical Points
Whole Building	Power	1
Two Chillers	Differential Pressure (water) Water Temperatures Flows (water) Power (to chillers)	4 8 5 2
4 Pumps	Differential Pressure (water) Power	4 4
One Cooling Tower	Dry Bulb Temperature Wet Bulb Temperature Water Temperatures Power	2 2 6 2
One Air Handler	Dry Bulb Temperatures Power Static Pressure	5 2 4
Local Micro-Climate	Dry Bulb Temperature Wet Bulb Temperature	1 1
Miscellaneous (lights & plug)	Power	4
Total		57

The IMDS is designed to be a permanently installed and continuously active system. This is necessary because buildings continuously change. For example, some problems reoccur, such as those from modifications to schedules to handle special events. These modifications often lead to equipment being left on when not needed. The diagnostic system is designed to operate in parallel with any existing EMCS, rather than expanding or modifying the EMCS. The IMDS is therefore not constrained by EMCS data collection capabilities, which can be problematic with 50 points of one-minute data. This technology may, however, be incorporated in future EMCS.

Figure 3–2 compares an IMDS and an EMCS. EMCS typically focus on scheduling and controlling building HVAC systems including air temperatures and flows and monitoring zone conditions. By contrast, the IMDS measures energy, weather and water-side variables (temperatures, pressures and flows). As mentioned, sensors commonly used in buildings are typically not adequate due to durability (frequent failures or falling out of calibration) and accuracy problems (e.g. measuring flows accurately is crucial, but typical systems either do not measure flow or do so with inadequate accuracy).

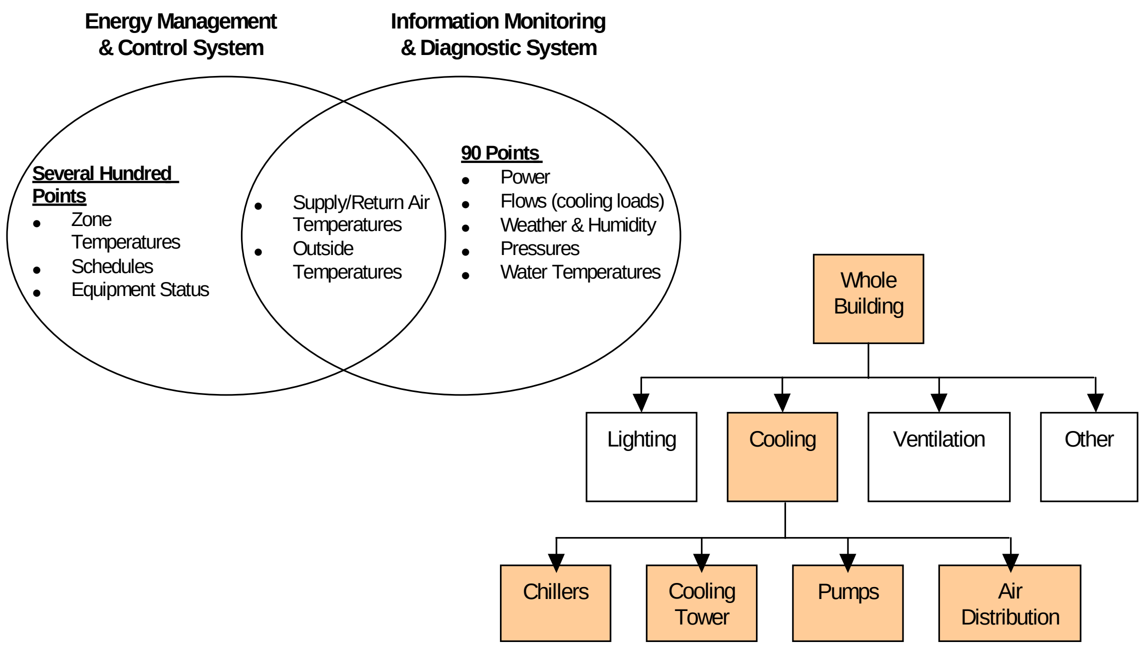


Figure 3–2. Comparison of EMCS and IMDS

The rationale for the scope of the monitoring system is as follows. First, the selection of whole-building diagnostics is the starting point of the proposed diagnostic system. Whole-building data contain the basic yardsticks by which a building operator can get an overall set of metrics to evaluate building performance. The rationale for the selection of the cooling system is related to the benefits of working with it relative to the difficulties related to other candidates for the diagnostics, such as lighting or ventilation systems. Great improvements in cooling plant efficiency measurements can be gained with magnetic flow meters and high-quality thermistors. Chillers are the largest single energy-using component in large office buildings, and are thus a logical item to examine. Evaluating the entire cooling plant will allow us to understand the overall system performance, which is more important than examining a component in isolation from the system. Plus, cooling is the second largest major end-use in commercial buildings (lighting is the first).

The components selected for the analysis are chillers and cooling towers. Both of these components were targets of complaints from building managers about poor sizing. Chillers are often oversized, requiring more power per ton than optimal because they are less efficient at low partial load. Cooling towers are often undersized. Larger towers allow the chiller to operate at cooler condensing temperatures. The diagnostic system will explore major failure modes for these components. Air handler measurements were included to allow for a complete calculation of system efficiency (kW/ton).

Data Visualization Software

The project team chose Electric Eye as the data visualization software for use in the IMDS because of its power and flexibility. The system can: load up to 8 points of one-minute data for a 12-month period, or 4,204,800 values. It offers point and click commands with zoom and screen capture. The calendar and time features allow the user to select days from a calendar with several time-aggregation options (minute, five-minute, hourly, etc.). Additional features include:

- *Scroll vs. Slide Mode*—View one or more time series in scroll or slide mode. In scroll mode, view one day at a time. In slide mode, view a day, a week, or other time period to form patterns and erroneous profiles and to track operation.
- *3-D plots*—View carpet plots for data point vs. time of day vs. day, or create xyz plot. Motion function allows for individual rotation and review of data points.
- *Statistics*—Use in 2-D or 3-D plots. Get slopes, efficiencies, kWh demand and costs.
- *Section*—Look at planes in 3-D plots for easier understanding of daily profiles, operation, & trends. See how temperature, power demand, equipment startup, and seasonal variations affect operation.
- *Equations*—Trend data to form special equations or matrix. Fit linear, quadratic, and hyperbolic functions to 2-D plots.

The IMDS is based on the Linux version of Electric Eye that runs on an on-site PC. The research team is also using the original, more powerful version of Electric Eye, which runs on a graphical workstation. The following features are currently only supported in the SGI version and will be incorporated into the Linux version at a later date: 1) input curves and spreadsheets or other benchmark data, 2) input pictures and video linked to data, and 3) evaluate rate and tariff schedules, perform psychometric analysis, and evaluate fan and pump curves. The inability of the current PC version to import data has presented a minor problem in Phase 2. The system is unable to read the benchmark plot data sets generated from DOE-2 as shown in Appendix B. We choose to use the PC version because the migration of Electric Eye from the SGI to the PC demonstrates the evolution of the computer technology. We hope to use the forthcoming Windows™ based Electric Eye system in the future, moving away from Linux, which is less user friendly and more foreign to building operators

The web-based performance analysis tools are described in Appendix A. We provide a brief review of several aspects of the system because they help demonstrate the scope and purpose of the IMDS. **Figure 3–3** shows the layout of the cooling plant. Real-time snapshots of the last minute’s data are displayed to provide an overview of the efficiency, operational parameters such as the system and component efficiency, temperatures, pressures, and flow rates.

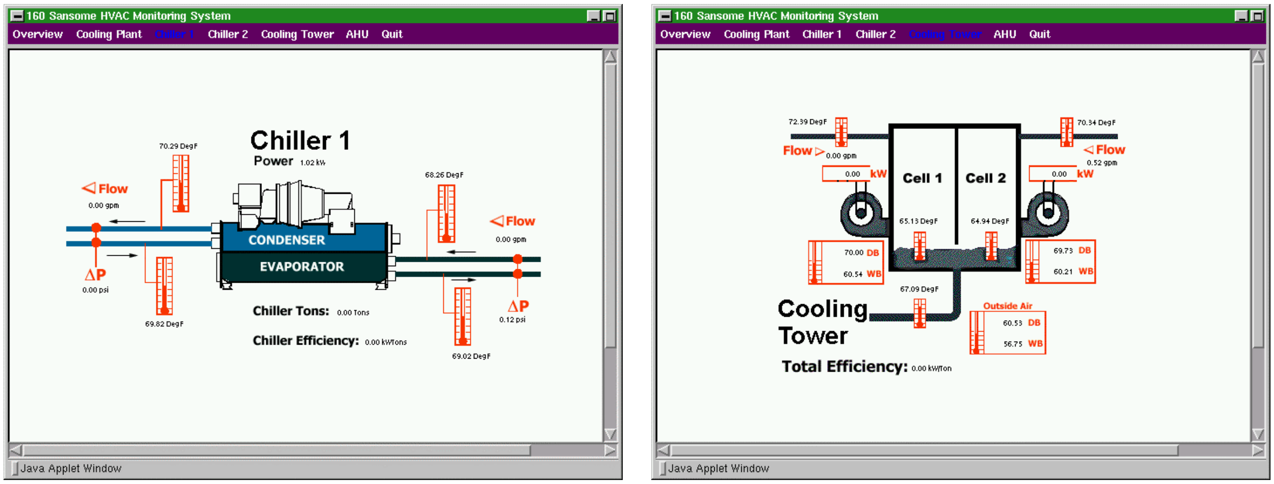


Figure 3–3. Real-Time Cooling Plant Schematics

Failure Modes to be Evaluated with the IMDS

The Phase 1 research included an analysis of performance metrics and benchmark data to characterize the fundamental principles of the selected building, system, and components. We developed a series of standard graphics that will allow the metrics to be displayed in a manner that assists in the diagnosis. These graphs (shown and described in Appendix B, and available at http://www.lbl.gov/EA/IIT/Diag/plots.html) were analyzed to determine benchmark signatures for good performance such as where measured values should fall on a given analysis plot, or what the curve shape should look like if the system or component is performing properly. We developed a series of measurements and sensing requirements to evaluate the systems and components. We also listed common modes of failure that one can diagnose with the given metrics and graphics based on case study data and related literature. The discussion of failure modes is not an entirely exhaustive list of failures, but covers common and critical modes of failure. The graphs also serve as a tutorial to orient the building operator on how best to understand the system or component's energy performance. A list of the nine plots and associated diagnostics are listed in **Table 3–2**. The whole-building data are fairly straightforward, but we provide some additional discussion on the cooling system and component data.

Cooling System Diagnostics. The entire cooling system efficiency can be evaluated using the efficiency versus load analysis (kW/ton vs. cooling tons). The total cooling system performance in kW/ton is affected by the kW/ton for each component. The shape of the efficiency versus percent load curve is dominated by the chiller, so the entire cooling system kW/ton curve tends to look like the chiller curve. Chillers should ideally operate near their rated efficiency (purchase point). Various problems (oversizing, improper scheduling, control problems, etc.) exhibit signatures on these plots.

Chiller and Cooling Tower Diagnostics. The chiller monitoring will capture key parameters in the chiller operation such as water flows and temperatures, pressure drop, and power. These data will allow determination of chiller efficiency (**Figure 3–3**) and loads. We will also measure the pressure drop across the chiller heat exchangers to determine the extent of fouling. The cooling tower monitoring will also include water temperatures and flows, plus local outdoor weather data and cooling tower fan power. A temperature measurement station including an aspirated psychrometer has been installed on the top of the building as far away from the cooling towers as possible. Data from this psychrometer will be used to evaluate "nano-climate" effects at the building scale, which are smaller than well-known city-wide micro-climates. Cooling tower intake conditions will be compared with outdoor air conditions to evaluate re-circulation of cooling tower exhaust.

Table 3–2. Standard Plots and Failure Modes

Building Component	Standard Diagnostic Plots	Example Failure Modes, Problems & Opportunities
Whole building	• 2D – Outside Temperature/ Power (24 plots for each hour of the day) • 2D – Power/ Outside Temperature • 3D – Day/Time/Power	• Sudden changes in consumption • Weather impacts on consumption • Higher consumption than similar buildings • Opportunities for alternative electricity rates – load shapes, • Load management strategies, • Unusual nighttime loads or start-up peaks
Cooling System	• 2D – Cooling System Load (tons)-kW/ton • 3D – Day/Time/Cooling System kW	• Comparison to other similar systems • Changes in consumption or efficiency of cooling system due to such things as improper pump operation, tube fouling, component malfunction, or tower set points. • Scheduling problems such as excessive time on or short cycling
Chillers	(1) 2D – Chiller Load (tons)-kW/ton	• Degradation in efficiency of the chillers away from manufacturer's specs. • Efficiency improvements from changes in operational parameters, i.e. part-loading, and condenser and chilled water temperatures • Efficiency degradation due to refrigerant charge, tube fouling, etc. • Full load or part load performance and chiller oversizing or undersizing
Cooling Towers	(2) 3D – Day/Time/Cooling Tower kW(excluding condenser pumps) (3) 2D – Approach (CWS-WB)/Cooling Tower Tons* (4) 2D – Corrected Cooling Tower Tons/Condenser Flow	• Degradation of tower efficiency due to fouling, excess flow, too few cells running, or recirculation of saturated air leaving tower • Cooling system excess energy use due to tower undersizing • Scheduling problems due to tower not modulating or not interlocked to condenser pumps, temperature control problems

*CWS – condenser water supply and WB – wet bulb

The classic example of chiller diagnostics is depicted in **Figure 3–4**. Here, efficiency (kW/ton) is plotted versus load (tons). Chillers should ideally operate near their rated efficiency (purchase point). Various problems (oversizing, improper scheduling, control problems etc.) exhibit signatures on this type of plot.

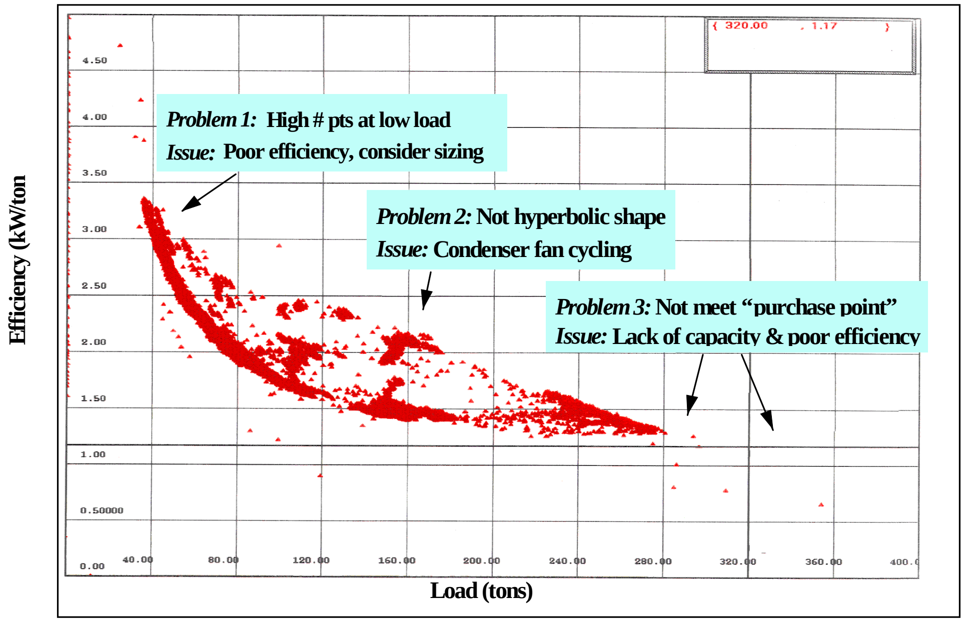


Figure 3–4. Chiller Efficiency versus Load and Sample Problems Diagnosed

Sensors and Data Accuracy

In selecting sensors for installation at our pilot demonstration building, we chose to use high-precision sensors. This section describes the sensors and their accuracy. Over $40,000 was spent on sensors and sensor calibration (not including installation costs) to ensure the reliability of the data obtained from the building.

Using high-quality equipment provides several important assurances. By starting with high-accuracy, we will be able to determine how much accuracy is necessary to uncover problems during Phase 3. If lower-quality (and lower-cost) sensors would have done the job just as well, we may choose to use fewer sensors and lower-quality equipment in future projects. See the Phase 1 report (Sebald and Piette, 1997) and Appendices for additional discussion of these issues.

First, some terminology on measurement issues. **Accuracy** is defined as the *maximum* amount by which a result differs from the true value (Beckwith, 1982). Use of high-quality sensors ensures that our measurements are as accurate as possible. Measurement **error** is the *actual* difference, and its exact value is unknown. Error lies within a range of values, which we call **uncertainty**. Since accuracy is the maximum difference between the measured and actual value, the uncertainty is generally expressed as ± accuracy.

Accuracy for each sensor has been provided by the manufacturer. The accuracy of the data may differ from the rated accuracy of the equipment for several reasons. Any sensor may be accurate when purchased, but several factors figure into maintaining sensor accuracy over time. These factors include sensor placement, calibration, signal conversion, and sensor durability and maintenance. Loading error (the effect of the measurement process itself) and other environmental variations may complicate issues further. Further discussion of these issues is mentioned in the sensor descriptions below, and we intend to examine these issues further in the next phase of the project.

Signal Conversion. Accuracy is effectively maintained during the analog to digital (A/D) conversion, which has a 16-bit resolution. Resolution is the smallest increment of input signal that a measurement system is capable of displaying. With low-resolution systems, accuracy may be lost when the input analog signal is converted to a digital signal which is recorded. Line losses have been considered as a potential source of error and found to be negligible.

Precision. The IMDS instrumentation also has a high degree of precision. Precision is the degree of agreement between repeated results. High precision is important when analyzing data for trends and changes. The sensors used require far less maintenance and less frequent calibration to maintain precision and accuracy.

Sensor Installation and Placement. For most sensors, placement was not a problem; however, placement of the outside air weather station has proven problematic (see Temperature section below).

Calibration. Most sensors did not require complicated calibration procedures. Temperature sensors were calibrated offsite, resulting in an increased degree of accuracy (see Temperature section below). During the commissioning process, additional calibration issues were addressed, such as zeroing of power meters.

Maintenance. By purchasing high-quality sensors, the reliability of the sensor remains relatively constant over time. The IMDS sensors require less maintenance and calibration than their conventional counterparts, a fact that may result in lower life-cycle costs of the equipment.

Physical Points

Four types of physical measurements are taken by the IMDS: temperature, power, flow speed, and pressure. The sections below discuss the sensors used, their rated accuracy, and other issues affecting the reliability of the data obtained from them. Sensor accuracy is summarized in **Table 3–3**.

Table 3–3. Sensor Accuracy Summary

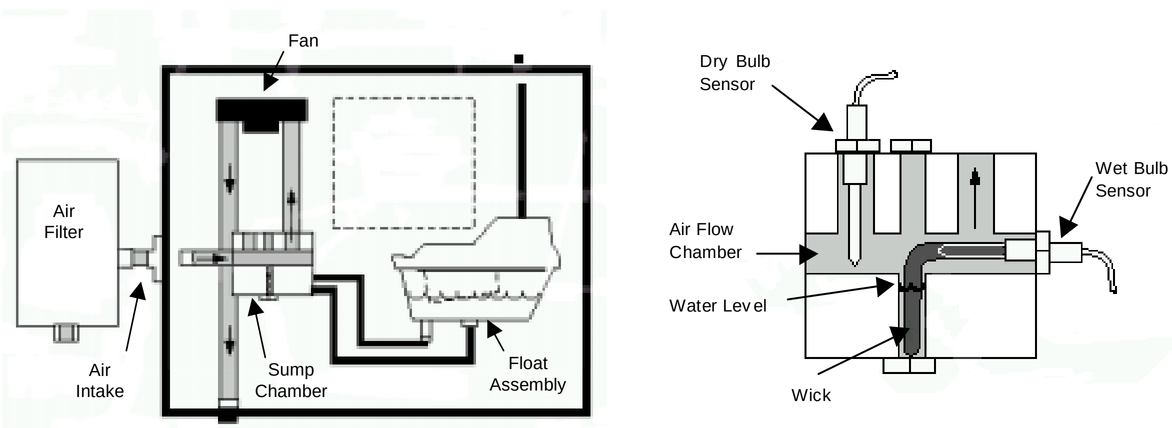
Point	Accuracy
Temperature	.008 deg F
Flow	0.50% (See table below)
Chiller Power	1.20%
Cooling Tower Power	3.20%
AHU Fan Power	1.20%
Static/Differential Pressure	.025 inches
Differential Pressure	.0625 psid
Pump Power	0.20%
Main Power	1.50%
Lighting & Plug Power	1.00%

Temperature. Temperature is measured with precision interchangeable thermistors that provide highly accurate and stable temperature readings. The thermistors use couple glass hermetic encapsulation with 100-percent resistance shift screening. The components have tight interchangeability, providing precise measurements without calibration of circuitry to match individual components. The thermistors are designed to eliminate the typical problem of sensor drift, a common problem in maintaining sensor accuracy over time.

The manufacturer-rated accuracy of the thermistors is 0.09 degrees Fahrenheit; however, they have been calibrated to an accuracy of 0.008 degrees Fahrenheit, for the full range of values, with high-end calibration equipment and a NIST traceable procedure (Mangum, 1990). The calibration equipment includes triple point of water and gallium melting point temperature reference cells.

Thermistors for the cooling tower and outside air wet bulb/dry bulb temperatures are enclosed in an enthalpy wet bulb (EWB) unit, a self-contained aspirated enclosure, shown in **Figure 3–5**. The EWB enclosure contains wet and dry bulb wells, a pressure-compensated float valve assembly, and a fan, which draws air over the thermistors. The wick is bathed continuously by distilled water (stored in a reservoir above the sensor) as moisture evaporates. The unit is designed to be reliable and low-maintenance.

Placement of the outdoor weather station has proven to be problematic. We originally placed the station next to the existing sensor, near the supply air intake. Our initial analysis showed a nighttime temperature peak, an unlikely condition. This was due to warm reverse air when the system is off. The sensor was moved away from the supply fan to an outside location where it is affected less by the air handlers or the cooling tower. A protective shield will be installed shortly which will protect the sensor from solar gain. This is described in Appendix C.



Enclosure

Sump Chamber Detail

Figure 3–5. Enthalpy Wet Bulb Enclosure (or Psychrometer)

Power. With the exception of pump power, power measurements are dependent on a power transducer and two to three current transformers. Pump power is measured by a single direct-connect power transducer. The power transducers used on the cooling system powers (pumps, chillers, fans) are three phase/three wire sensors with an accuracy of 0.2% of readings, including combined effects of voltage, current, load and power factors. These power transducers are used with 600V class solid-core current transformers as noted in the table below. Main power, lighting, and plug power meters use digital power transducers. These sample voltage and current waveforms at high speed with digital signal processing to assure true RMS output accurate to 0.5 percent. These power meters utilize 600V class split-core current transformers with accuracy noted in **Table 3–4**.

Table 3–4. Power Accuracy

	Power Transducer	Current Transformer Accuracy	Combined Accuracy
Main – Whole Building (3 CT's)	0.50%	1.00%	1.50%
Light & Plug Risers (3 CT's)	0.50%	0.50%	1.00%
Pumps (0 CT's)	0.20%	n/a	0.20%
Chillers (2 CT's)	0.20%	1.00%	1.20%
Cooling Tower Fan (2 CT's)	0.20%	3.00%	3.20%
AHU Fan (2 CT's)	0.20%	1.00%	1.20%

Flow. Magnetic flow meters are more reliable than conventional flow meters such as paddle wheel or pitot tube flow meters (Houghton, 1996). Although the full-bore magnetic flow meters used in the IMDS are more expensive then conventional flow meters, they require less maintenance, resulting in lower life-cycle costs (Sebald and Piette, 1997). This is largely due to the absence of moving parts.

A common problem with the installation of flow meters is that a bend in the pipe near the flow meters will cause inaccurate readings. Fortunately, a sufficiently long section pipe was available for each of the five flow meters installed. The flow meters have a variable percentage error, which is ±0.5% at high flows and increases as flow decreases. The accuracy is 0.5% for velocities greater than or equal to 1.5 feet/second[3]. Thus the accuracy is 0.5% for all flow values greater than the flow speeds given the 0.5% column in **Table 3–5** below, which shows the relationship between the accuracy of the magnetic flow sensors and flow rates. For slower velocities, the error, in percent, is given by 0.82/velocity.

In our partial load scenario (further described below), the only flows with error greater than ±0.5% are the condenser water flows, which have an error of ±0.6% at 200gpm. This does not have a significant effect on the condenser load (tons) error calculations.

Example:

A flow speed of 24gpm is equal to .17ft/second in an 8-inch pipe (Condenser Flow and Chilled Water Main Flow). The sensor error when the flow is 24gpm, about 10% of full load, is thus equal to .82/.17 = 5%.

Table 3–5. Flows (gpm) Required for Given Accuracy

			Accuracy:	**0.5%**	**1%**	**1.5%**	**5%**	**20%**
Flow System	**Pipe Size**	**Full Ld**	**Part Ld**	**Flow**	**Flow**	**Flow**	**Flow**	**Flow**
Condenser Flow (gpm)	8"	500	250	**262**	121	81	24	6
Chilled Water Main Flow (gpm)	8"	860	530	**262**	121	81	24	6
Chiller 1 Chilled Water Flow (gpm)	6"	460	275	**145**	68	46	14	4
Chilled Water 2nd Flr Flow (gpm)	3"	60	40	**37**	17	11	3	1

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[3] To determine the velocity at a given flow, convert the flow measurement from gallons per minute (gpm) to ft^3/s, and divide by the surface area of the pipe cross-section. The resulting relationship is *velocity=(0.003)(gpm)/d^2*, where *d* is the diameter of the pipe, in feet.

Pressure. Differential and static pressure are measured with high-output, low-differential pressure transducers. Each contains a fast-response capacitance sensor and an isolation system which responds quickly to pressure changes while providing precision linear analog output proportional to pressure. Both static pressure and differential pressure sensors are accurate to ±0.25% full scale, with a non-repeatability of ±0.05% full scale. A full-scale reading is the maximum reading the measurement system is capable of for the particular scale being used, therefore:

percent accuracy based on full scale = *(V_max/min - V_actual)/V_fs*, while

percent accuracy based on reading = *(V_max/min - V_actual)/V_actual*

where V_fs is the full-scale reading. The full-scale reading for pump differential pressure is 25psid, so the sensor accuracy is 0.0625psid. Static differential pressure sensors are rated for 0–10 inches, giving us a sensor accuracy of 0.025 inches.

Calculated Points

Calculated point accuracy is derived from physical point accuracy by means of simple error propagation formulas. To compare the accuracy at different HVAC and cooling loads, we developed two scenarios, based on expected values at full load and partial load. The assumptions for the values of the physical points used in a calculation are given in **Table 3–6**.

Calculated point accuracy for each scenario is included in **Table 3–7**. Points calculated from flow values, such as chiller loads (tons), have a percentage error that is greater at lower flows. For calculated points not dependent on flows, the percentage accuracy is for the full range. Small differences between the scenarios are accounted for by rounding error.

There are two simple error propagation rules used to determine the uncertainty of the calculated points.

$$\text{For } z = \mathrm{a}x \pm \mathrm{b}y \pm \ldots,\ s_z = \mathrm{a}s_x + \mathrm{b}s_y + \ldots \text{ and For } z = x * y * \ldots,\ s_z = z\left(\frac{s_x}{x} + \frac{s_y}{y} + \ldots\right)$$

where z is a function of x, y, … and s_x is the uncertainty in x.

These formulas make no assumptions about the interaction between the errors of input values. The calculated error s_z is the maximum combined error, given s_x and s_y (Beckwith, 1982).

Note that these formulas result in more conservative error estimates than the commonly used error propagation formulas given below. These formulas are valid for errors in means of large samples. The formulas assume that z is a function of independent random variables, and thus the error in z is not likely to be as high as the maximum.

$$\text{For } z = \mathrm{a}x \pm \mathrm{b}y \pm \ldots,\ s_z = \sqrt{(\mathrm{a}s_x)^2 + (\mathrm{b}s_y)^2 + \ldots} \text{ and}$$

$$\text{For } z = x * y * \ldots,\ s_z = z\sqrt{\left(\frac{s_x}{x}\right)^2 + \left(\frac{s_y}{y}\right)^2 + \ldots}$$

Example:

CHW1_dt = CHWR1_Temp-CHWS1_Temp

Since the uncertainty for both temperatures is ±0.008 deg F, $\text{error} = .008 + .008 = .016$ deg F.

Example:

Total Tons = Chiller 1 Tons + Chiller 2 Tons, which have uncertainties of 0.03% and 0.13% respectively, when Chiller 1 Tons = 208 and Chiller 2 Tons = 83. Note that the uncertainty of Chiller 2 is greater than Chiller 1, as Chiller 2 flow is calculated; whereas Chiller 1 flow is measured directly. The error calculation for Total Tons is:

$$\text{error} = (0.0003)(208) + (0.0013)(83) = .17 \text{ tons}$$

Since Total Tons = 208 + 83 = 292, we can express this error as .17/292 = 0.06%

Example:

Tower Efficiency = CT_Fans_Pwr/Tot_Tons

The associated uncertainties are ±2.26% and ±0.03%, so we have

$$\text{error} = z(\frac{0.0226x}{x} + \frac{0.0003y}{y}) = z(0.0226 + 0.0003) = .0229z$$

Thus the tower efficiency error is 2.29%.

Table 3–6. Physical Point Values Assumed for Scenarios

Physical Point Values Assumed Point Description	Point Name	Full Load	Part Load	Accuracy
Chiller 1 Chilled Water Flow	CHWR1_Flw	500gpm	275gpm	0.50%
Chiller 1 Condenser Water Flow	CWR1_Flw	500gpm	200gpm	0.50% *
Chiller 2 Condenser Water Flow	CWR2_Flw	500gpm	200gpm	0.50% *
Chilled Water Main Flow	CHWR_Main_Flw	800gpm	340gpm	0.50%
Chilled Water 2nd Flr Coil Flow	L2_CHWR_Flw	100gpm	40gpm	0.50%
Return Air Static Pressure	RA_Stat_Pres	5in	5in	0.30%
Supply Air Static Pressure	SA_Stat_Pres	2in	2in	0.30%
Chiller 1 Power	Ch1_Pwr	160kW	100kW	1.20%
Chiller 2 Power	Ch2_Pwr	75kW	75kW	1.20%
Cooling Tower Fan 1 Power	CT1_Pwr	15kW	7kW	3.20%
Cooling Tower Fan 2 Power	CT2_Pwr	15kW	7kW	3.20%
Supply Air Fan Power	SA_Pwr	60kW	30kW	1.20%
Return Air Fan Power	RA_Pwr	80kW	40kW	1.20%
Chilled Water Pump 1 Power	CHWP1_Pwr	10kW	5kW	0.20%
Condenser Water Pump 1 Power	CWP1_Pwr	10kW	5kW	0.20%
Chilled Water Pump 2 Power	CHWP2_Pwr	10kW	5kW	0.20%
Condenser Water Pump 2 Power	CWP2_Pwr	10kW	5kW	0.20%
Whole Building Power	io05.mainpwr	500kW	250kW	1.50%
Plug Load Riser 1 Power	io05.plgr1pwr	20kW	10kW	1.00%
Plug Load Riser 2 Power	io05.plgr2pwr	40kW	20kW	1.00%
Lighting Riser 1 Power	io05.lgtr1pwr	50kW	25kW	1.00%
Lighting Riser 2 Power	io05.lgtr2pwr	50kW	25kW	1.00%

* Accuracy for Condenser flows at part load is 0.6%

Scenarios do not necessarily represent typical operating conditions. Actual data is recorded to 3 decimal places.

Table 3–7. Calculated Point Accuracy

Point Description	Units	Point Name	Full Load Scenario Value	Full Load Scenario Accuracy	Full Load Scenario % of value	Partial Load Scenario Value	Partial Load Scenario Accuracy	Partial Load Scenario % of value
CHILLER ONE								
Chilled Water Temp Difference	Deg F	CHW1_dt	10.0	.016		5.0	.016	
Condenser Water Temp Difference	Deg F	CW1_dt	5.0	.016		2.0	.016	
Chilled Water Load	Tons	Ch1_Tons	208	.057	0.03%	57.3	.020	0.03%
Condenser Load	Tons	Ch1CW_Tons	104.2	.036	0.03%	16.7	.010	0.06%
Condenser Water Efficiency	kW/ton	Ch1CW_kWpton	1.5	.019	1.23%	6.0	.076	1.26%
Chilled Water Efficiency	kW/ton	Ch1_kWpton	0.8	.009	1.23%	1.7	.022	1.23%
CHILLER TWO								
Chilled Water Temp Difference	Deg F	CHW2_dt	10.0	.016		5.0	.016	
Condenser Water Temp Difference	Deg F	CW2_dt	5.0	.016		2.0	.016	
Condenser Load	Tons	Ch2CW_Tons	104.2	.036	0.03%	16.7	.010	0.06%
Chilled Water Load	Tons	Ch2_Tons	83.3	.110	0.13%	21.9	.031	0.14%
Chilled Water Flow (Chiller 2)	gpm	Ch2_Flw	200.0	6.000	3.00%	105.0	3.275	3.12%
Condenser Water Efficiency	kW/ton	Ch2_CWkWpton	0.9	.011	1.23%	4.6	.046	1.26%
Chilled Water Efficiency	kW/ton	Ch2_kWpton	0.9	.012	1.33%	4.6	.049	1.34%
COOLING TOWER								
Tower Approach Temperature	Deg F	CT_Approach		.016			.016	
Total Tower Fan Power	kW	CT_Fans_Pwr	30.0	.960	3.20%	14.0	.448	3.20%
Tower Fan Efficiency	kW/ton	CT_Eff	0.1	.003	3.26%	0.2	.006	3.26%
AHU								
Total Conditioned Air Fan Power	kW	AHU_Fan_Pwr	140.0	1.680	1.20%	70.0	.840	1.20%
Mixed Air Temperature Average	Deg F	MA_AveDB_Temp		.008			.008	
Total System Static Pressure	in WC	Tot_System_Stat	7.0	.050	0.71%	7.0	.050	0.71%
Conditioned Air Fan Efficiency	kW/ton	Fan_Eff	0.5	.006	1.26%	0.9	.011	1.26%
PUMPS								
Total Pump Power	kW	Pump_Pwr	40.0	.080	0.20%	20.0	.040	0.20%
Pump Efficiency	kW/ton	Pump_Eff	0.1	.000	0.26%	0.3	.001	0.26%
SYSTEM								
Total System Cooling Load	Tons	Tot_Tons	291.7	.167	0.06%	79.2	.051	0.06%
Total System Condenser Load	Tons	Tot_CWTons	208.3	.071	0.03%	33.3	.019	0.06%
Total Cooling System Power	kW	Cooling_Pwr	445.0	5.540	1.24%	304.0	3.488	1.23%
Total Cooling System Flow	gpm	CHW_Flw	700.0	3.500	0.50%	380.0	1.900	0.50%
Total Cooling System Efficiency	kW/ton	Cooling_Eff	1.5	.020	1.30%	3.8	.046	1.29%
Building Watts per Square Foot	wsf	main_pwr_wsf	5.1	.077	1.50%	2.6	.038	1.50%
Cooling Load Watts per Square Foot	wsf	cooling_wsf	4.5	.057	1.24%	3.1	.036	1.23%
Plug Load Riser Power	kW	Plug_Riser_Pwr	60.0	.600	1.00%	30.0	.300	1.00%
Plug Load Watts per Square Foot	wsf	plug_wsf	0.6	.006	1.00%	0.3	.003	1.00%
Lighting Load Riser Power	kW	Light_Riser_Pwr	100.0	1.000	1.00%	50.0	.500	1.00%
Lighting Load Watts per Square Foot	wsf	light_wsf	1.0	.010	1.00%	0.5	.005	1.00%

Comparison of IMDS and Existing EMCS Data

One of the important issues in this research is the comparison of EMCS data with the IMDS data. During Phase 1 we reported that building operators and engineers claimed to have O&M problems related to the lack of information on major building systems (Sebald and Piette, 1997). They reported problems in keeping sensors properly calibrated. Thus, the information directly available from the EMCS was considered questionable. Temperature, humidity, and flow sensors were all reported as problematic, with the most concern over humidity and flow sensors.

Unfortunately the comparison between data quality from the IMDS and EMCS system is limited since there are only three points of overlap between the two systems: outside air temperature, return air temperature, and supply air temperature. This overlap is sparser than that on typical EMCS for this size of buildings. The EMCS in the building is a 15-year old system controlled by a 286 PC, which is somewhat outdated for this size and type of building. EMCS data, for example, at UC Berkeley's Soda Hall included chilled water supply and return temperatures, which would have been useful to compare at this site (Piette et al., 1997). It is striking, however, that the building operator did not have direct measurements of these values for his use in controlling the building. We expect that the information from the IMDS will be useful for improving the operating strategies to reduce energy use (See Section 4).

In order to compare the new IMDS sensors with the existing EMCS, we trended EMCS data and plotted both data sets using Electric Eye. The steps to retrieve the trend logs are as follows:

1. Suspend trend log.
2. Copy binary file from floppy disk to hard disk.
3. Translate file to ASCII format.
4. Copy ASCII file to floppy disk.
5. Resume trend log.

Using the data retrieved requires transferring files from the floppy to the system where the data will be viewed and analyzed. The data format is not in a logical format and requires some processing before it can be used. An example of an EMCS trend file is shown below:

```
H,HKB,SE1,OAT,    57.7    FRI MAY 08 1998 15:37:30
H,HKB,SE1,SAT,    62.5    FRI MAY 08 1998 15:37:30
H,HKB,SE1,RAT,    72.5    FRI MAY 08 1998 15:37:30
H,HKB,SE1,DPR,    99.1    FRI MAY 08 1998 15:37:30
H,HKB,ZON,Z11,    72.7    FRI MAY 08 1998 15:37:30
H,HKB,SE1,OAT,    57.4    FRI MAY 08 1998 15:38:30
```

It is difficult to analyze data in this format. The file size is also unnecessarily large as there are five lines for each minute of data and information is needlessly repeated. In our case, we developed "awk" scripts on UNIX to arrange the data in a spreadsheet format that we could import into Electric Eye, which looks like:

```
date,time,oat,sat,rat,dpr,z11
5-08-98,15:38:30,57.7,62.5,72.5,72.7,57.4
5-08-98,15:39:29,57.4,62.5,72.5,72.7,57.7
5-08-98,15:40:29,57.4,62.5,72.5,72.6,57.4
```

The overall trends of the EMCS and IMDS data sets are similar; however, there are cases where temperature readings differ by several degrees. Such differences appear to be due to differences in sensor placement rather than sensor accuracy. The following discussion outlines the specific nature of these differences.

Outside Air Temperature

This is an important data point as the EMCS uses this sensor to determine when to turn on the chillers. Placement of this sensor has been problematic. Our sensor was originally placed 18 inches from the EMCS sensor, which is located at the Northeast corner of the building, near the supply fan intake. This was useful for comparison with the existing sensor, but initial analysis of the data collected showed a problem with the location. A significant temperature drop was observed when the fans were turned on, while peak temperatures were observed at nighttime when warm reverse air left the building. **Figure 3–6** shows this happening on weekdays, while weekend temperatures more closely resemble typical outdoor air temperatures.

While the general trend in both outdoor air sensors is similar, they differ by as much as three degrees F, suggesting that not only has the EMCS sensor been placed in a poor location but that it is probably calibrated poorly. The EMCS sensor consistently reads higher temperatures.

A new location for the outdoor air sensor was chosen on the outside of the building, where it is affected less by airflow. Solar gain proved to be a problem in the afternoon hours, resulting in measured peak temperatures 10 to 20 degrees above the peak temperature recorded by a nearby National Weather Service station. A protective shelter was installed to prevent solar gain. While the sensor still experiences some solar influence, it is the best location available.

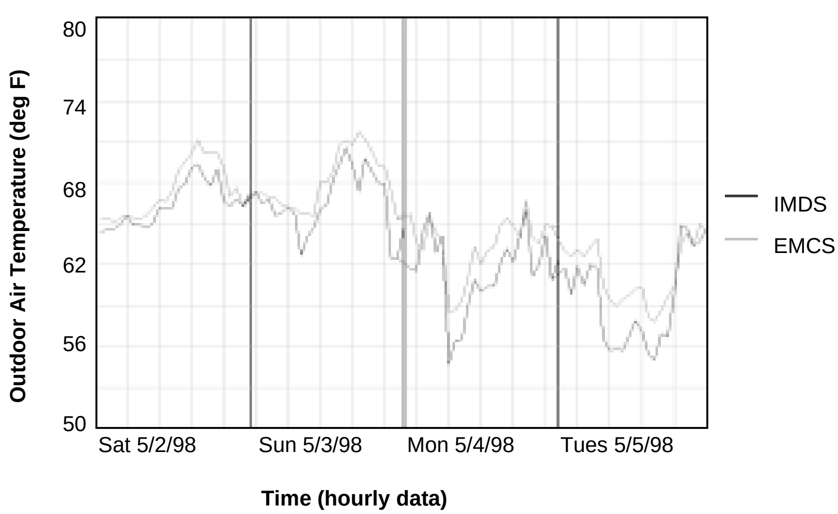

Figure 3–6. Outside Air Temperature from IMDS and EMCS.

Return Air Temperature

The IMDS return air sensor shows the most drastic difference from the EMCS (**Figure 3–7**). While the EMCS data reflects very little change in temperature, our sensor shows daily fluctuations. The EMCS sensor is located on the fan side of the silencers; whereas the IMDS sensor is located by the dampers. The difference in the data appears to be a result of the difference in the location of the sensor. The IMDS temperature appears to be strongly influence by diurnal outdoor temperature fluctuations because it is near the outside surface of the dampers. It is also worth noting that this data is most comparable and relevant when the fans are in use, and less reliable during times with no ventilation.

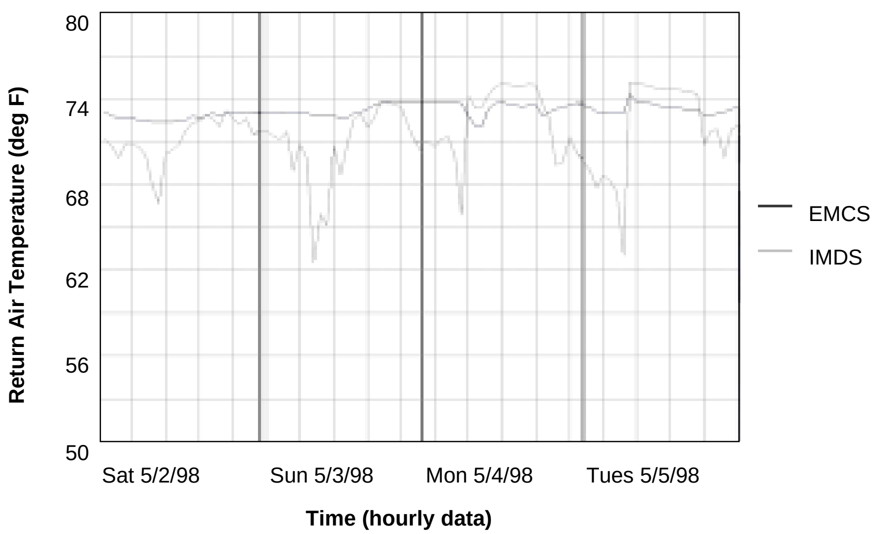

Figure 3–7. Return Air Temperature from IMDS and EMCS.

Supply Air Temperature

The supply air sensors for the EMCS and the IMDS are located near the supply air down shaft. In this case, the two sensors show nearly the same trend (**Figure 3–8**). At nighttime, when the temperature rises due to warm air leaving the building, the IMDS sensor reads about a degree warmer. Daytime readings from the two sensors are nearly identical. Nighttime and weekend readings differ by one to two degrees.

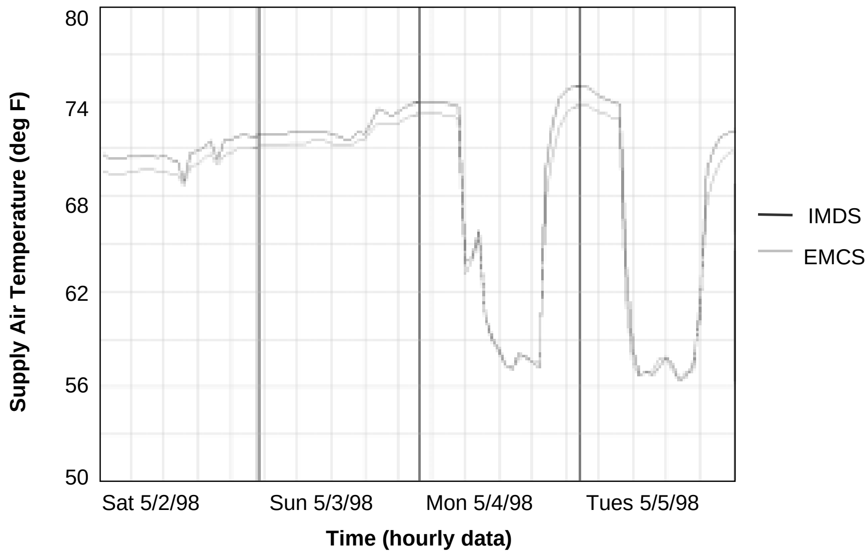

Figure 3–8. Supply Air Temperature from IMDS and EMCS.

SECTION 4. BUILDING PERFORMANCE AND FINDINGS FROM THE IMDS

Section 4 begins with a brief description of the building. This is followed by a discussion of historical energy use data and the development of a baseline model against which to evaluate future changes in energy use that result from findings from use of the IMDS. The last section discusses the findings from the IMDS during the first few weeks of use, which includes a discussion of energy savings opportunities identified by the research team**. We note that these are preliminary findings, subject to change upon further inspection of the IMDS data**.

Pilot Site Characteristics and Historical Baseline Data

As mentioned, the building selected for the demonstration is a 100,000 sqft office building at 160 Sansome Street in San Francisco, also known as the Hong Kong Bank Building. The building is about 30 years old, with two 200-ton chillers that are also 30 years old. Additional facts about the building characteristics and operating patterns are described in **Table 4–1** below in reference to changes in energy use over time.

Table 4–1. Building Characteristics and Features

Building Size	100,000 sqft
Chillers	Two @ 225 tons each (centrifugal), 0.8 kW/ton at full load
Cooling Towers	Two-cells, 20 hp each
Air Handlers	100hp Supply Fan w/VFD; 75hp Return Fan w/VFD; both at 100,000cfm
Space Heating	Purchased steam
Controls	286 PC pnuematic system with limited automation of central plant; some occupancy sensors
HVAC Distribution	Combination of CV and VAV systems
Lighting	Combination of T-12 and T-8 lamps

In order to understand the current energy use and potential savings it is necessary to obtain historical energy use data. We also collected other whole-building energy use intensities to compare this building with others of its type. The historical data are needed to develop a baseline to evaluate changes in energy use that may result from the use of the IMDS. The data collected for the baseline analysis include:

Whole-Building Energy Use Comparison Data

- Described below

Energy Use Data

- Utility bills (energy and costs) for electricity (plus monthly peak demand) and steam use between 1991 and 1997
- One year of half-hourly electricity data

Weather Data (for Regression and Climate Analysis)

- Average daily temperatures for the city of San Francisco (Kissock, 1998)
- Hourly weather data

IMDS Data

- Minute data for the entire suite of 90 points from May, 1998 to August 1, 1998

The data collected and presented are limited to energy use data at the request of the property manager. We do not include energy costs or rates.

Whole-Building Energy Use Comparison Data

Figure 4–1 shows that the site annual energy use intensity (EUI) is fairly typical compared with related benchmarks. The building used 90 kBtu/sqft-yr in 1996, which consisted of 64 kBtu/sqft-yr for electricity and 24 kBtu/sqft-yr for purchased steam. The first of the comparison data sets is the EUI for a 100,000 sqft large office building from a Northern California simulation prototype developed from energy analysis of 74 similar buildings (labeled **CEC No.Cal**, Akbari et al. 1993). The second EUI is the west-coast large office building average from the US Department of Energy's Commercial Building Energy Consumption Survey (labeled **CBECS-West**, CBECS, EIA 1995). The third, and most similar, is the average EUI for San Francisco office buildings from BOMA (labeled **BOMA-SF,** Energy User News 1995).

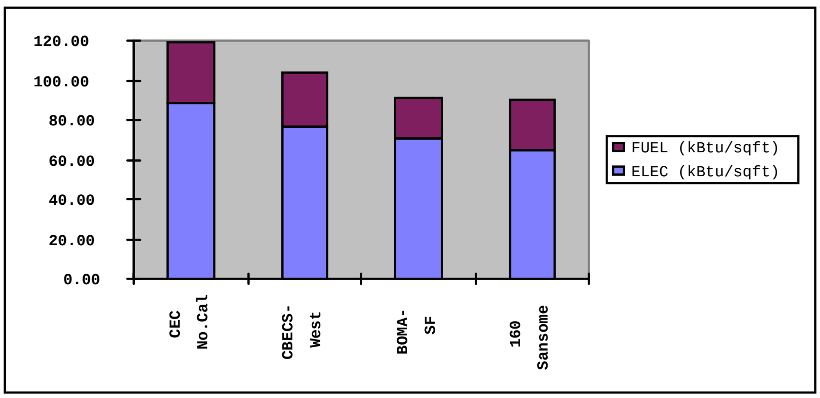

Figure 4–1. Annual Site Energy Use (kBtu/sqft-yr) of Demonstration Site and Comparison Buildings

Energy Use Data

Whole-building energy use has varied from slightly under 80 kBtu-sqft-yr to 90 kBtu/sqft-yr over the last six years (**Figure 4–2**). This variation is related to changes in building occupancy during system upgrades. In 1994, three floors were not in use due to construction and asbestos abatement, resulting in a lower energy use. In 1996, new tenants moved in with a large number of employees and computers, increasing plug and cooling loads. Over the past few years, lighting retrofits **a**nd conversion from constant volume (CV) to variable air volume (VAV) have occurred on about half of the floors. **Table 4–2** outlines some of the changes in occupancy and construction activities in the recent operational history.

Table 4–2. 160 Sansome History

Year	Occupancy*	Construction Floors**	Other Comments
1991	600- 800	2	
1992			
1993			
1994	200	12, 9, 5	Lower occupancy after construction. Relatively cool weather year.
1995	300-400	6	
1996	400	17,18	Large kitchen removed
1997	500-600		

* Occupancy figures are general estimates made by the building operator.
** Construction involved complete gutting of interior and asbestos removal.
Lighting retrofits were also completed, replacing F40/T12 lamps with T8.

Energy consumption declined once again in 1997, due to completed retrofits, increased automation, and the installation of motion sensors and hallway tenant switches**.** Similar trends can be seen in the annual maximum peak demand data (**Figure 4–3**). The recent peak is slightly over 6 W/sqft.

IMDS Use and Findings Logsheet

We have asked the building operator and the on-site technical manager to complete logsheets detailing findings made using the IMDS, shown in the appendix. They have been asked to record information about graphs that find most useful, and to print the graphs for our records. These logsheets will help us to learn the following the types of problems and characteristics of the building's energy use that the operators find most interesting. We want to learn about how they use the IMDS, addressing specific questions such as what time increments are most useful, and what are preferred formats for viewing data. This information will help in both the technology transfer and the automation of diagnostics described in Section 5.

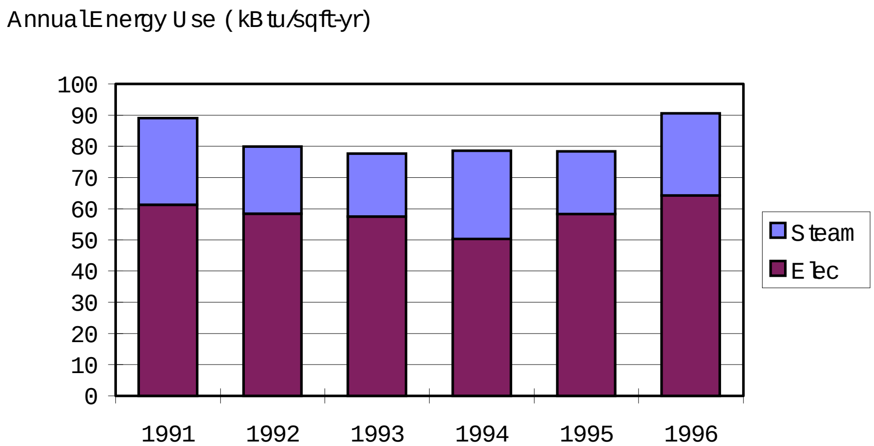

Figure 4–2. Total Annual Energy Use from 1991-1996 (Elec. Plus steam kBtu/sqft-yr)

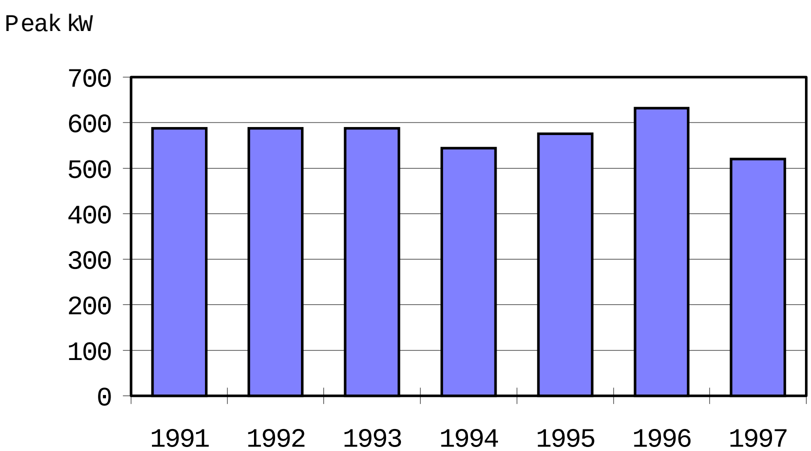

Figure 4–3. Annual Maximum Peak Electricity Usage (kW)

Figures 4–4 and **4–5** show seasonal trends in energy consumption from historical data (not the IMDS). **Figure 4–4** shows six years of data for each month of the year. **Figure 4–5** shows the average monthly energy use over the six-year period. We see very little change in electricity usage over the year. One might expect an increase in electricity use during warmer months from cooling energy. We do, however, see some temperature sensitivity of electricity use at the daily level, as further discussed below. Steam follows the pattern one expects, with increased usage during colder months when more heat is required.

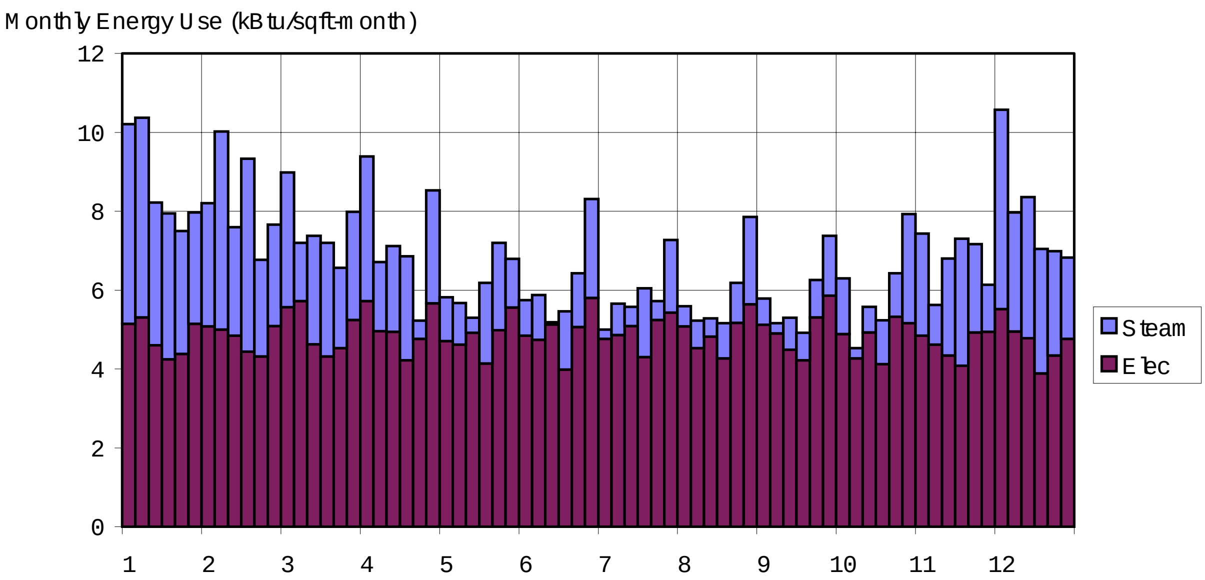

Figure 4–4 Monthly Energy Use (1991-1996).
(The first 6 bars are monthly energy use for 6 Januarys from 1991 through 1996, followed by 6 bars for Februarys, etc.)

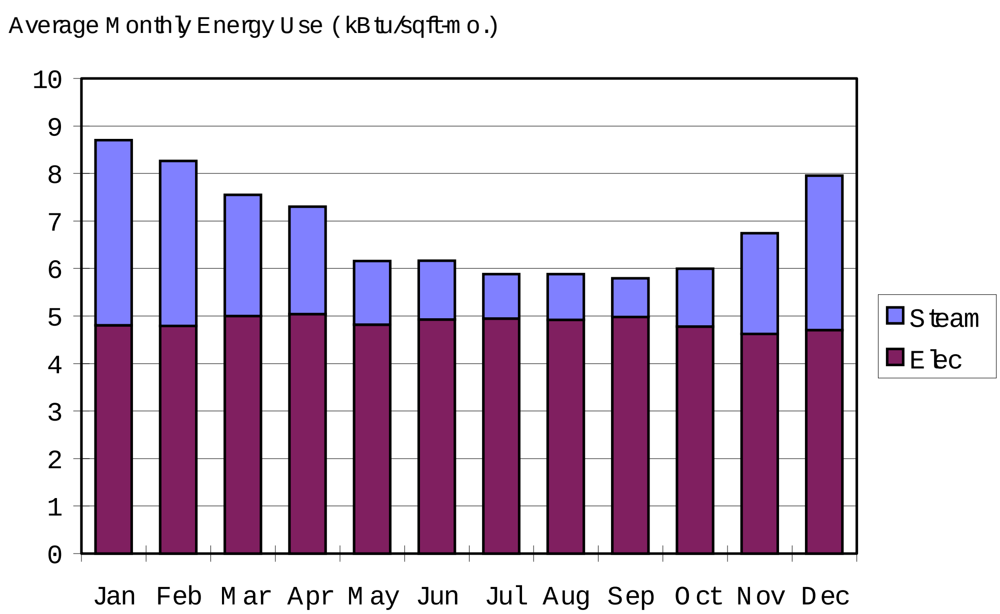

Figure 4–5. Average Monthly Whole-Building Energy Use
(Elec. Plus Steam in kBtu/sqft-yr for 1991-96)

Figure 4–6 shows the hourly electric load profiles for about three months (June 19 through September 30, 1997). The load profiles show that the building is extremely regular in its usage pattern. Nighttime energy use is extremely low. All HVAC systems and most equipment tend to be off at night, with HVAC coming on at about 6AM. Although we do not yet have end-use data, there appear to be four distinctive day-types that can be easily identified. First, weekends and holidays are days with low power similar to nighttime power. (There are few nighttime and weekend occupants; after-hour HVAC services are available at a relatively high price.) Next, there appear to be typical workdays that are those when the chillers are not needed. The next higher load shape represents days when one chiller was used. Finally, the highest power days are those when both chillers are used. These days correspond to the periods with the warmest weather.

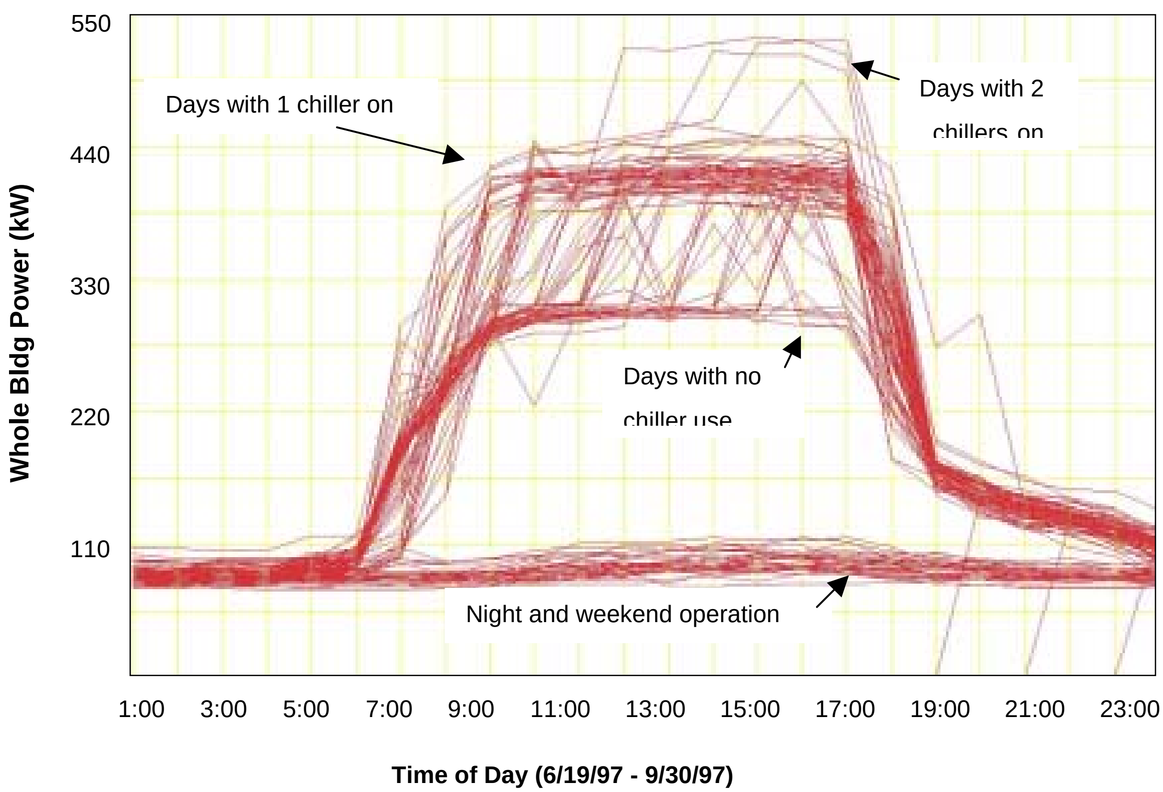

Figure 4–6. Hourly Electric Load Profile for 160 Sansome Street.

The highly regular and well-controlled building systems suggest that basic equipment scheduling will not be where we will find energy savings. Rather, we expect that the IMDS can be used to improve chiller and cooling tower control. We will only explore these changes after we first give the on-site staff time to use the system without our intervention. The current outdated EMCS, unlike most for this type of building, does not provide any information about the chilled water supply temperature or condensing water temperature. We also expect that the overall cooling plant has poor efficiency (high kW/ton). We provide some examples here of the opportunities for improving the cooling tower performance. The cooling towers are blow-through towers with centrifugal fans, which are inherently inefficient. We will consider the savings possible with a variable frequency drive for the tower fans. We will examine the general conditions of the cooling tower, such as the fill water treatment and airflow rate. We will consider alternatives to the current cooling tower operation, such as changing the fill or water treatment, or perhaps increasing the louver area. Another possibility might be to increase the condenser flow by removing obstructions (such as the strainer, globe and balancing valve, and orifice plates, etc.) and possibly running two pumps to one chiller.

Weather Data and Regression Analysis

The relationship between electricity consumption and outside air temperature is a useful characteristic of the building's energy use profile, and will serve as a model for evaluating changes in energy use from use of the IMDS. Daily average outside air temperature data were obtained from a nearby National Weather Service weather station through a public domain web site (Kissock, 1998). We condensed three months of half-hour data into daily averages. A regression of hourly temperature data against energy use is problematic because it is affected by autocorrelation. That is, the temperature in one hour is heavily dependent on the temperature during the previous hour. There is some auto-correlation in daily temperature data as well, but it is not as significant. See Piette et al, 1997 and Ruch et al, 199x for further discussion of this issue.

Two linear regressions, one for weekends and the other for weekdays, were developed using an analysis tool from researchers at Texas A&M known as Emodel (Kissock et al, 1994). (Weekday and weekend energy use are dramatically different, as shown in **Figure 4–6** above.) EModel was designed to integrate data processing, graphing, and modeling of building energy use data to determine baseline energy consumption and calculate retrofit savings, supporting simple linear and change-point regression models. Results are shown in **Figure 4–7**. The upper regression line represents weekday usage and the lower regression line represents weekend usage. The regression statistics are as follows:

Fraction of the variance explained by the model	R^2=0.57
Adjusted R^2	adjR^2=0.57
Measure of deviation from the model	RMSE=299.35
Non-dimensional measure of deviation	CV-RMSE=6.0%
Autocorrelation coefficient of the residuals	p=0.49
Domain = 48 - 78 (deg F)	
Range = 1646 - 6573 (kWh/day)	

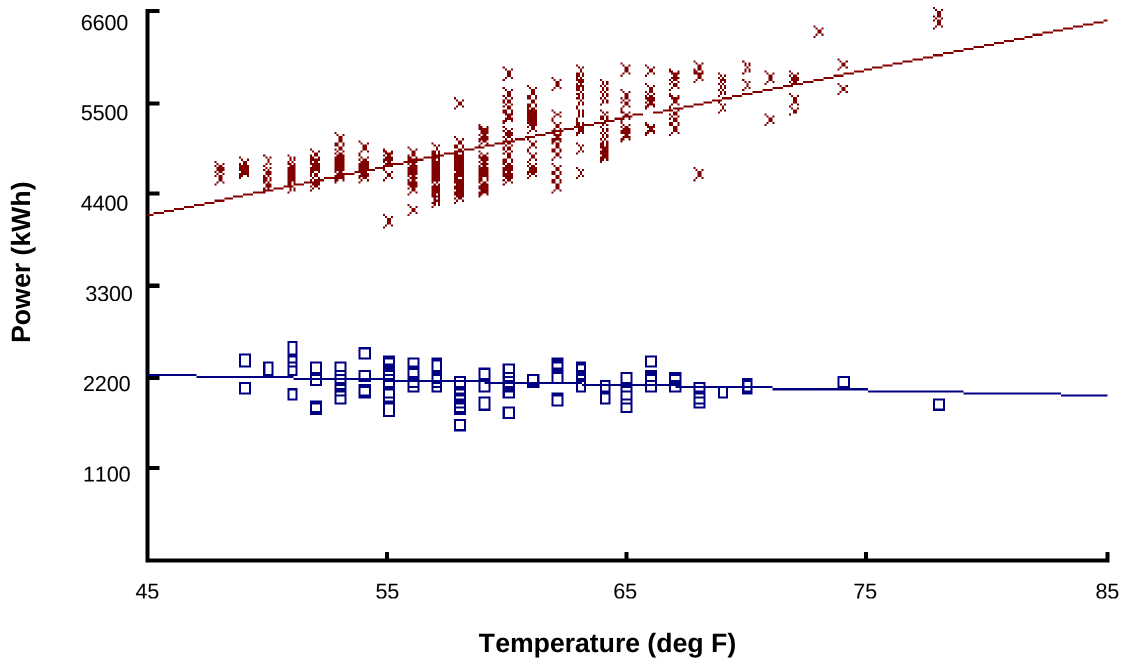

Figure 4–7. Electric Power vs. Outside Air Temperature (7/15/97 – 7/14/98)

An R2=0.57 represents a reasonable correlation between weather and electricity usage. Even more important, however, is the low RMSE and CV-RMSE. We are not concerned with predicting energy use at a given temperature; rather, we are concerned with establishing a baseline model to estimate changes in energy use over time, which are likely to be energy savings from the IMDS. Studies suggest that in this case the RMSE is a better indicator of goodness of fit than R^2. The baseline model will be evaluated further in the Phase 3 effort.

We attempted to determine a long-term historical relationship between weather and energy use by comparing monthly temperature averages to our monthly energy use data. We saw little or no correlation between electricity and monthly temperature averages. (Note there is also little variation in this data – San Francisco monthly temperature averages between 1991 and 1996 ranged approximately between 50 and 65 degrees Fahrenheit.) A heating slope was observed in steam consumption data.

Operational Findings from Initial IMDS Data

In this section we review results from the first few days of data collected in early May 1998. These graphs were developed by the project team and were not initially shared with the on-site staff because we were examining how the staff would use the IMDS on their own. These results will be shared with them later in Phase 3. The graphs are screen shots from Electric Eye, the data visualization software used by the on-site operator.

Whole Building and Major End-Uses. The whole-building and major end-use data provide an overview of major operating trends (**Figure 4–8**). The graph shows whole-building power, total cooling (chillers, pumps, towers, and air handlers), total lighting, and plug loads, all in area normalized units (W/sqft). The remainder is additional miscellaneous loads such as elevators, plus zone fans such as variable-air-volume boxes. This most dramatic pattern is the sharp drop off of power each day at 6:00 PM. This reflects good tracking of tenant schedules and needs. Most of this reduction is due to effective HVAC management. Another interesting observation is that the lighting load does not exceed 1.1 W/sqft, and the plug load is less than 0.7 W/sqft. This is valuable information for design of new buildings or ducting systems where HVAC systems are typically sized to meet combined lighting and plug loads greater than 5 W/sqft.

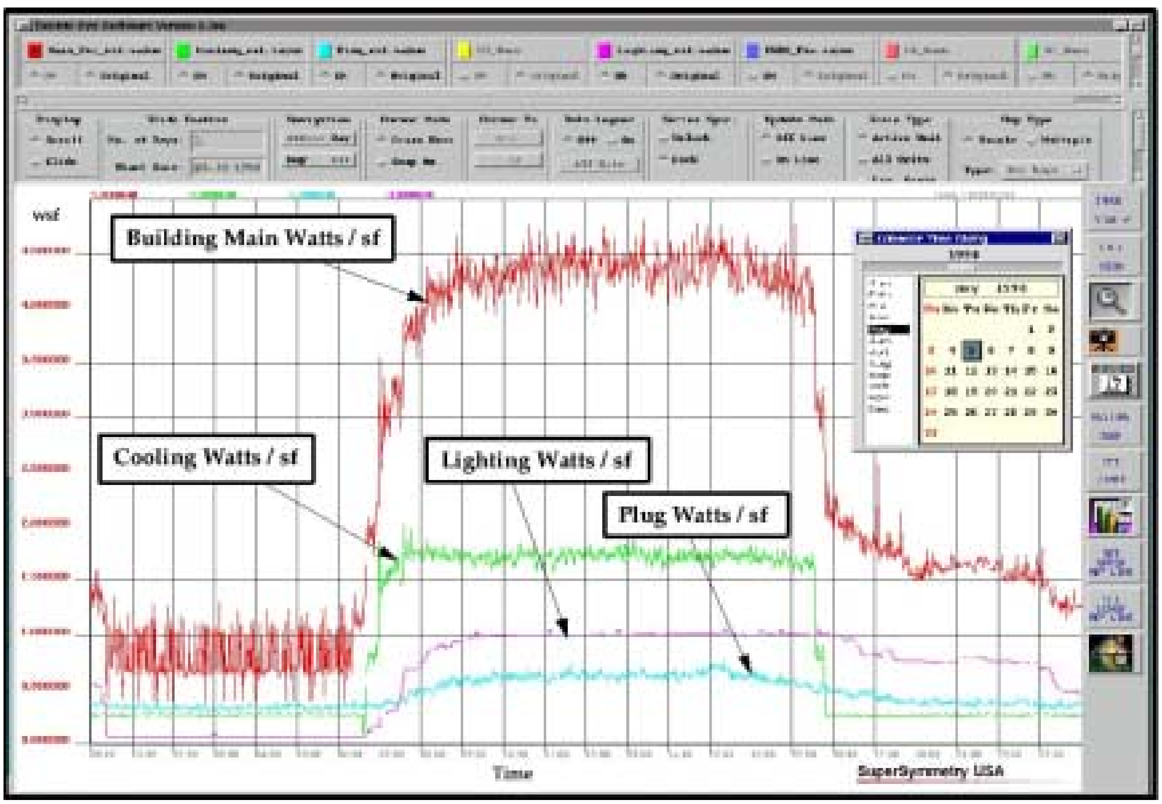

Figure 4–8. Preliminary Whole Building and Major End Use Data

Cooling System. The cooling system is the largest electric load for days that require cooling. Most buildings do not have measurement systems to evaluate the cooling system thermal load or electricity use. The IMDS allows for precise measurements of these loads. During early May the cooling system requires 0.8 W/sqft when the cooling system is operating without the chillers (**Figure 4–9**). This represents about 25% of the total load of the building. When the cooling system is operating with two chillers the load is 1.75 W/sqft accounting for approximately 40% of the whole-building electric load (**Figure 4–10**). In both cases cooling energy is equal or greater than the lighting load.

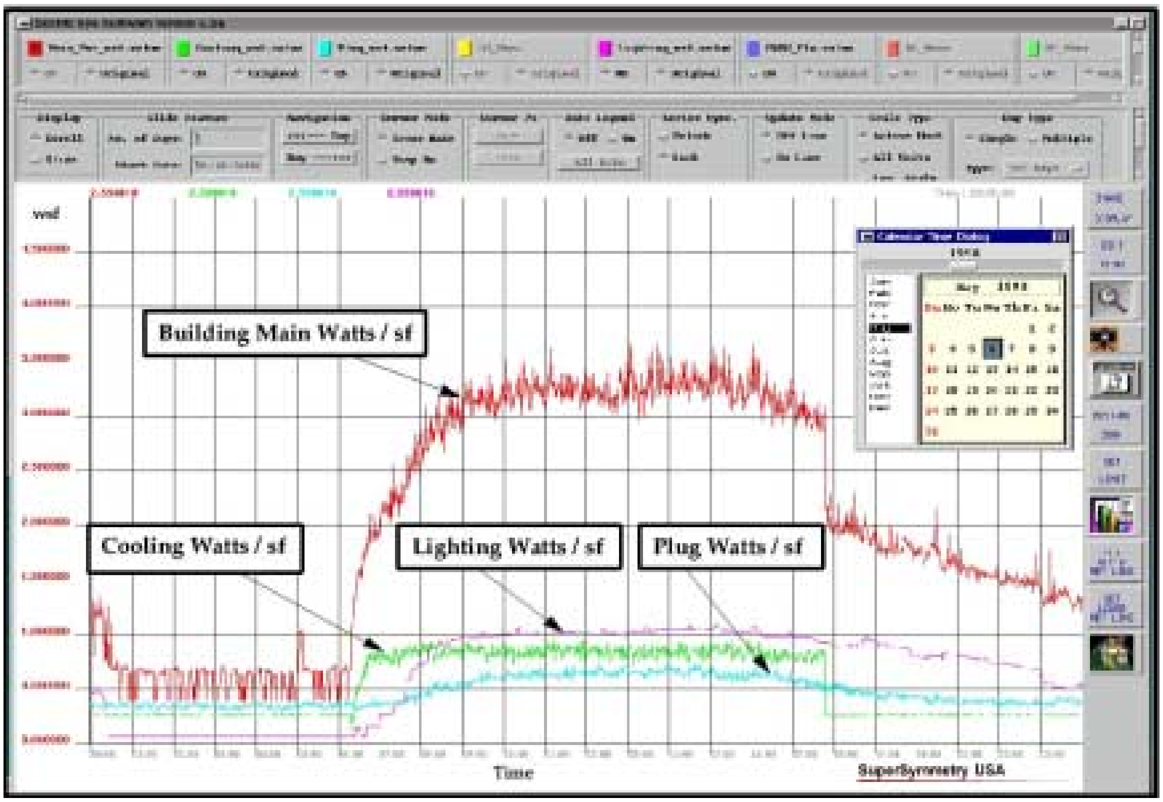

Figure 4–9. Preliminary Cooling System Data – No Chiller Operation

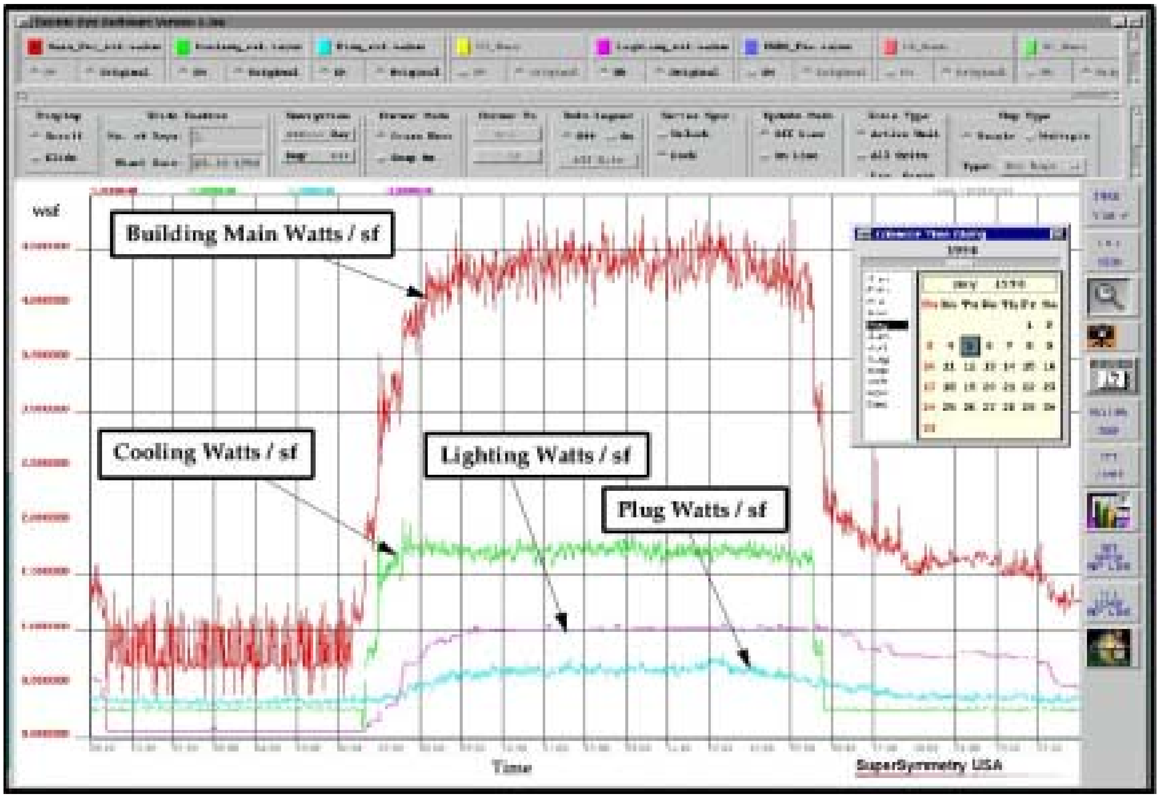

Figure 4–10. Preliminary Cooling System Data – Chillers in Operation

Cooling System and Chillers. The chillers are the heart of the cooling system. Ensuring that they run at peak performance is critical to optimal energy use. The two chillers in the 160 Sansome building are over 20 years old and are rated at 225 tons each. During these few days the chillers meet their specified efficiency. However, the chillers are less efficient when they operate below 100 tons, which is less than 45% of their rated capacity (**Figure 4–11**). During the first few days of monitoring (during May, 1998), the chilled water loads were well below the rated capacity of the chillers, requiring 1 to 2 kW/ton for the majority of the time. A good practice benchmark of 0.45 kW/ton is shown for reference. It is also important to examine the combined plant efficiency. The efficiency of the combined system is twice that of the chiller, or the chiller accounts for about half of the power of the cooling system. The tower, pumps and air handling fans account for the other half. Any efforts to improve efficiency of the whole cooling system will have to include those components of the system. Again a benchmark of 0.6 kW/ton for the total plant efficiency is shown for reference. (Note that the cooling plant efficiency capping at 3.0 is an error due to limits on the individual points, and has been corrected.)

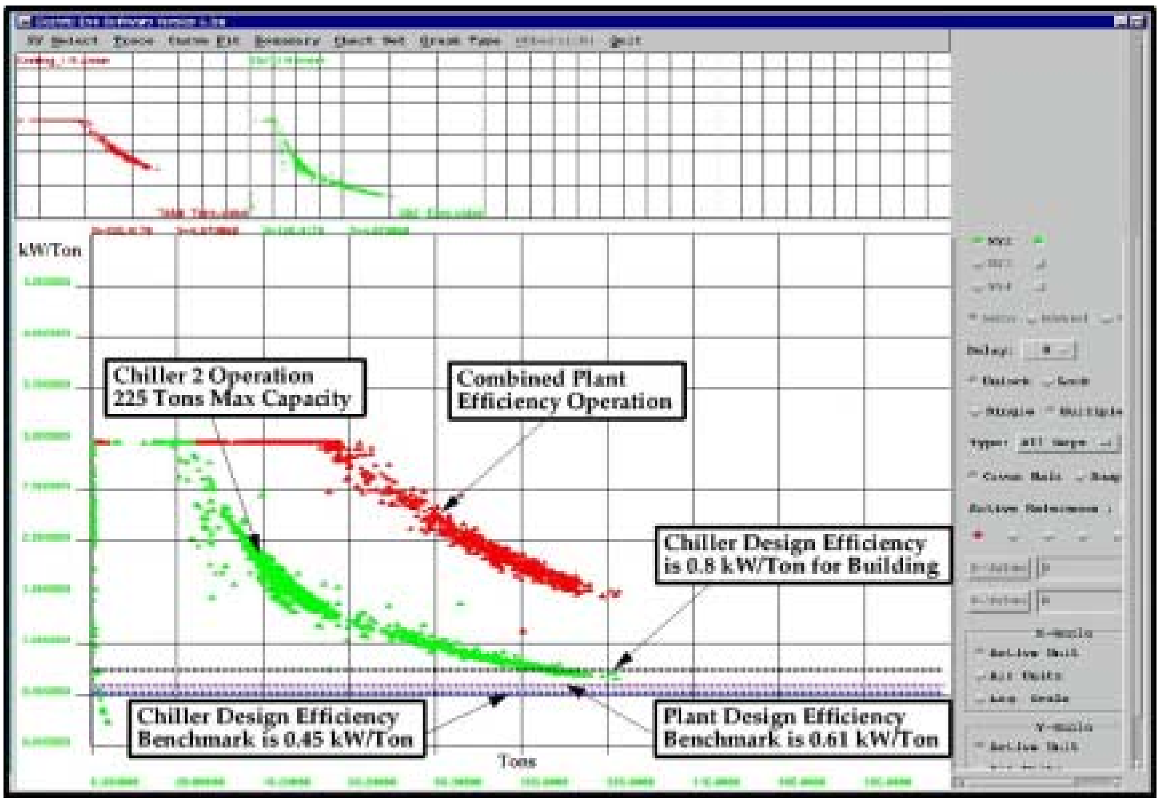

Figure 4–11. Preliminary Cooling System Operation – Graph 1

One dramatic finding from the monitoring was the chiller turn on time. It appears that the chiller was coming on each morning at 7:30am for 15 minutes and then staying off for the rest of the day. This was the result of a recent control programming change. In fact on those days, the chiller should have never have come on at all (**Figure 4–12).** The chiller was coming on without any load, which could have resulted in a major failure. The other problems shown in **Figure 4–12** are further described below.

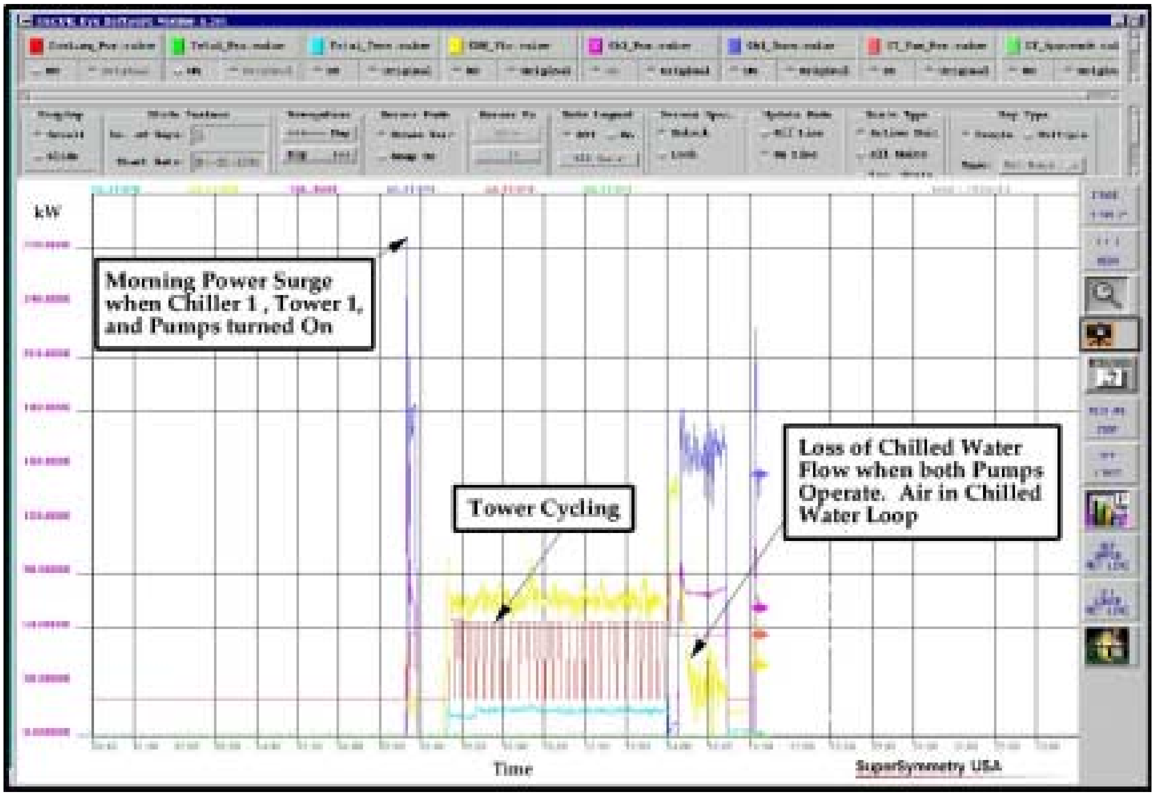

Figure 4–12. Preliminary Cooling System Operation – Graph 2

The IMDS also showed a problem with controlling water flow though the chillers. When chiller 1 was off, the chilled water temperature responded to chiller 2 operation (**Figure 4–13**). This may be the result of chilled water was flowing through chiller 1 and that the back flow preventer or check valve was not operating correctly. This could be corrected by service of the check valve. This problem results in a low temperature boost across the evaporator. The chillers end up working harder (higher kW) for the same amount of cooling (tons), resulting in a poorer efficiency (high kW/ton). This also cuts the capacity of the chillers so the second chiller is brought on-line sooner than needed, which also increases chilled water and condenser water pumping energy.

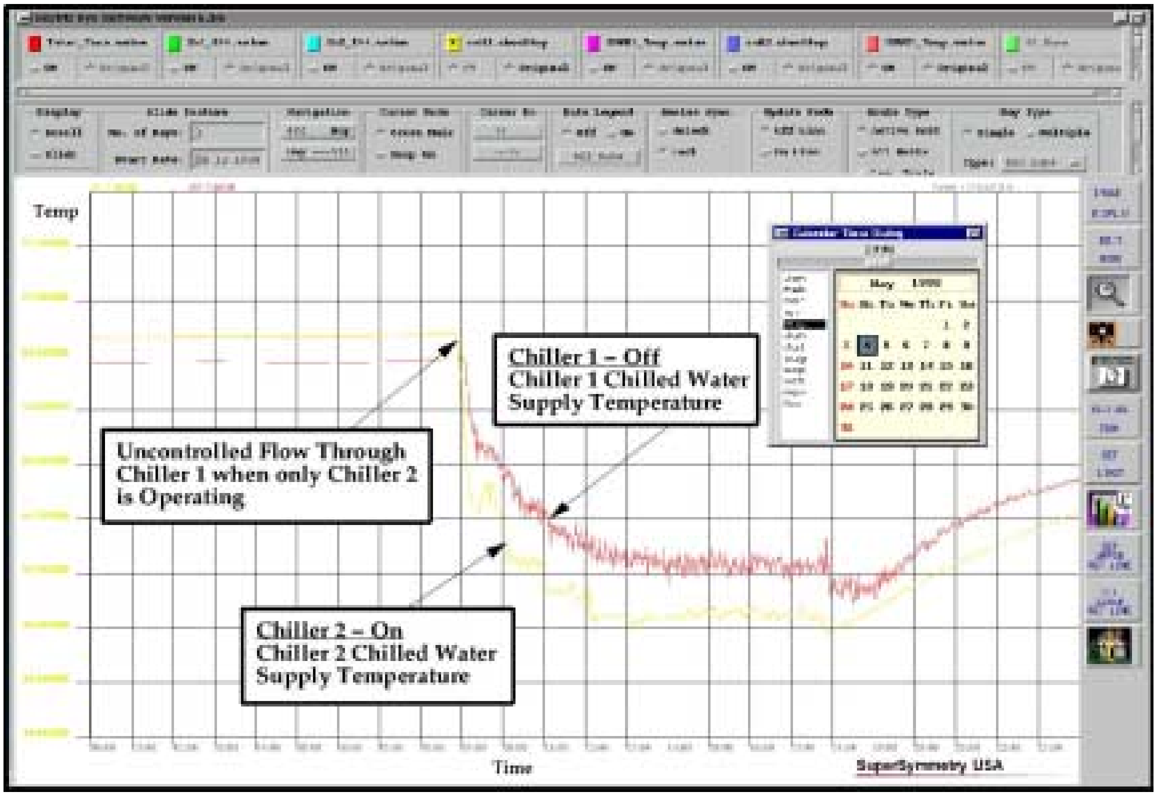

Figure 4–13. Preliminary Cooling System Operation – Graph 3

Cooling Towers. Cooling towers use a small portion of the total energy of a cooling plant. However, their operation can have a large impact on chiller energy use. It is common to operate towers to produce condenser water 10°F warmer than what is optimal. For each degree that the condenser water temperature is too high, there is a 1.2% degradation in chiller efficiency. Therefore the 10° F can be translated into 12% efficiency improvement in the chillers. At 160 Sansome the tower is controlled to supply approximately 75° F condenser water. On the day displayed in **Figure 4–14**, the wet bulb temperature averaged about 55° F, while the tower was supplying 75° F condenser water. The chiller should be able to operate at condenser water temperatures as low as 55 degrees (this should be re-verified with the manufacturer). This can be corrected through changes to the central plant controls.

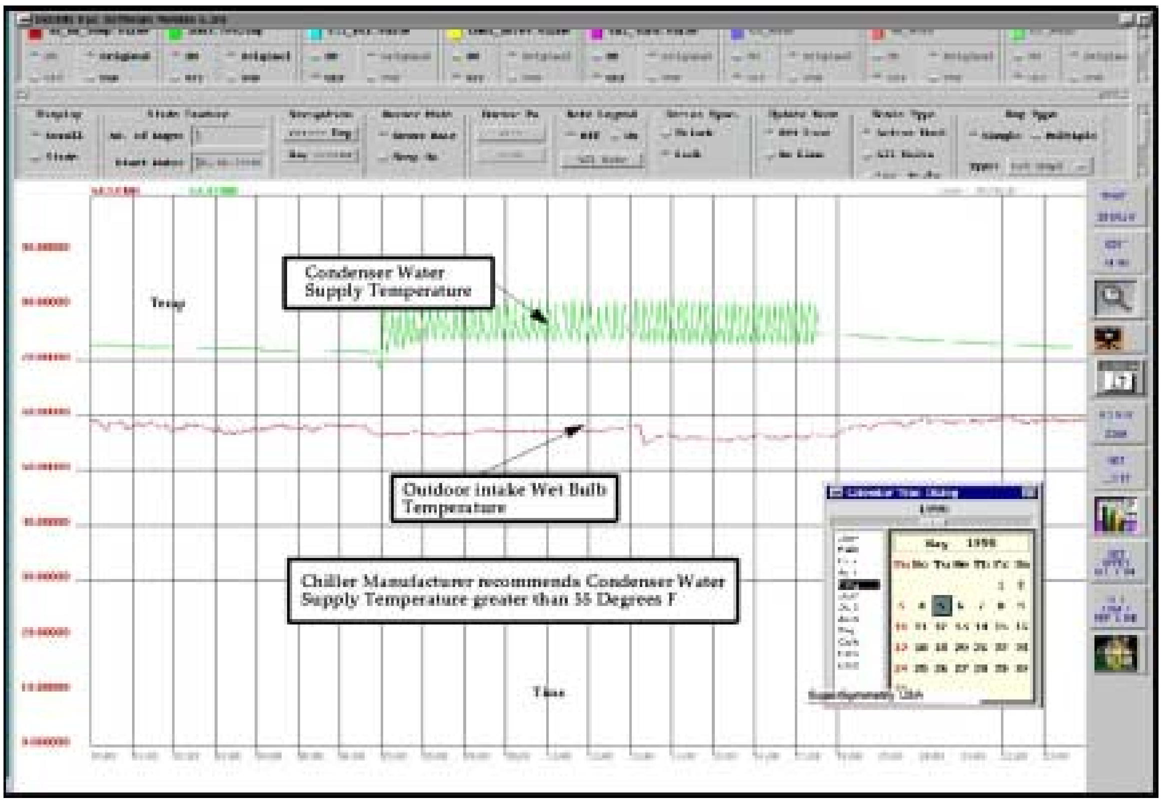

Figure 4–14. Preliminary Cooling Tower Operation – Graph 1

In addition to the high condenser water temperatures, the towers tend to cycle excessively, creating additional wear on the tower fan motors (**Figure 4–15**). One remedy for this problem would be to use variable speed drives on the tower fans. Operators could also adjust control algorithms to increase the on/off temperature band and should definitely use both cells with one chiller to improve the energy efficiency of the cooling plant.

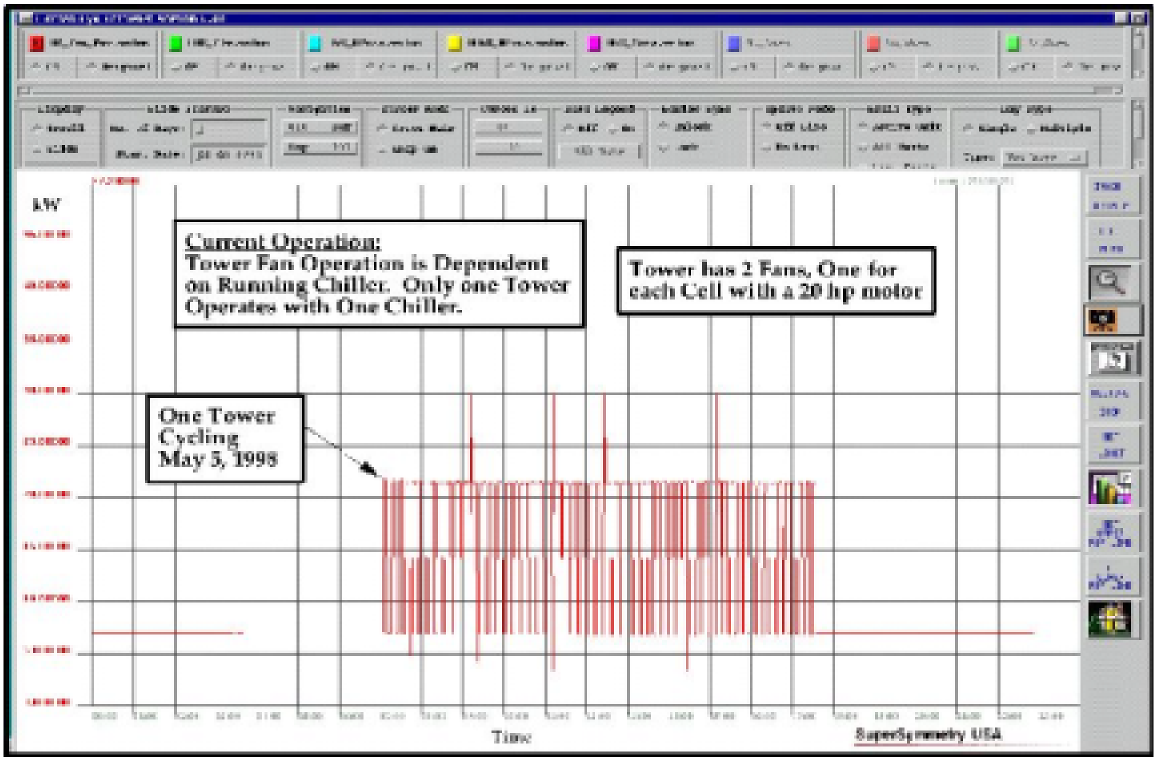

Figure 4–15. Preliminary Cooling Tower Operation – Graph 2

Pumps. Several interesting problems were found with the pumps. On the chilled water system, the chilled water flow exceeded design flow by 15% (**Figure 4–16**). Due to the cube law of pumping, decreasing chilled water flow to the design rate would result in a 34% reduction in pumping energy ($100[1-1/(1.15)^3]$). It would be simple to trim the impellers on the pump to accomplish this. Another problem on the chilled water system was in the pressure drop across the chiller evaporator. The design pressure drop is 5 psi while the measured pressure drop is 8 psi (**Figure 4–17**). The expected pressure drop is 6.6 psi ($5 * (1.15)^2$), indicating a possible problem with the tubes in the evaporator; cleaning should improve this. (Notice the design and measured pressure drop for the water through the condenser is much closer).

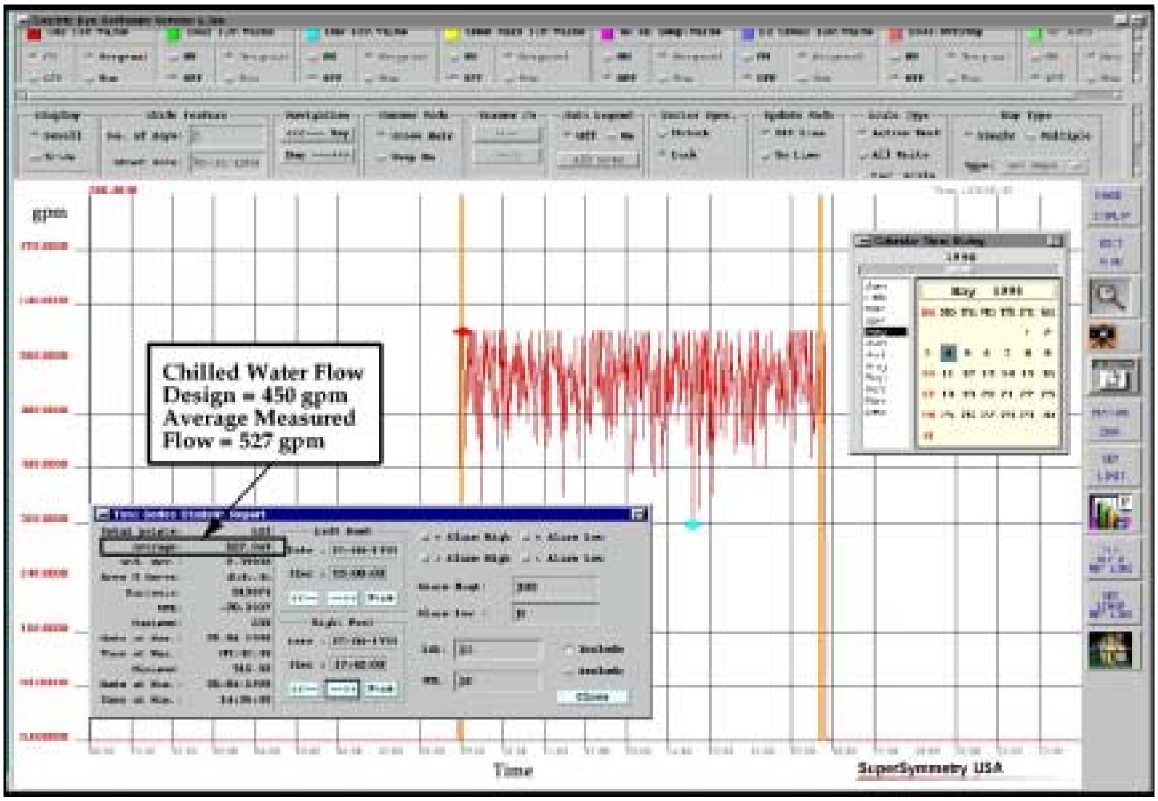

Figure 4–16. Preliminary Pump Operation – Graph 1

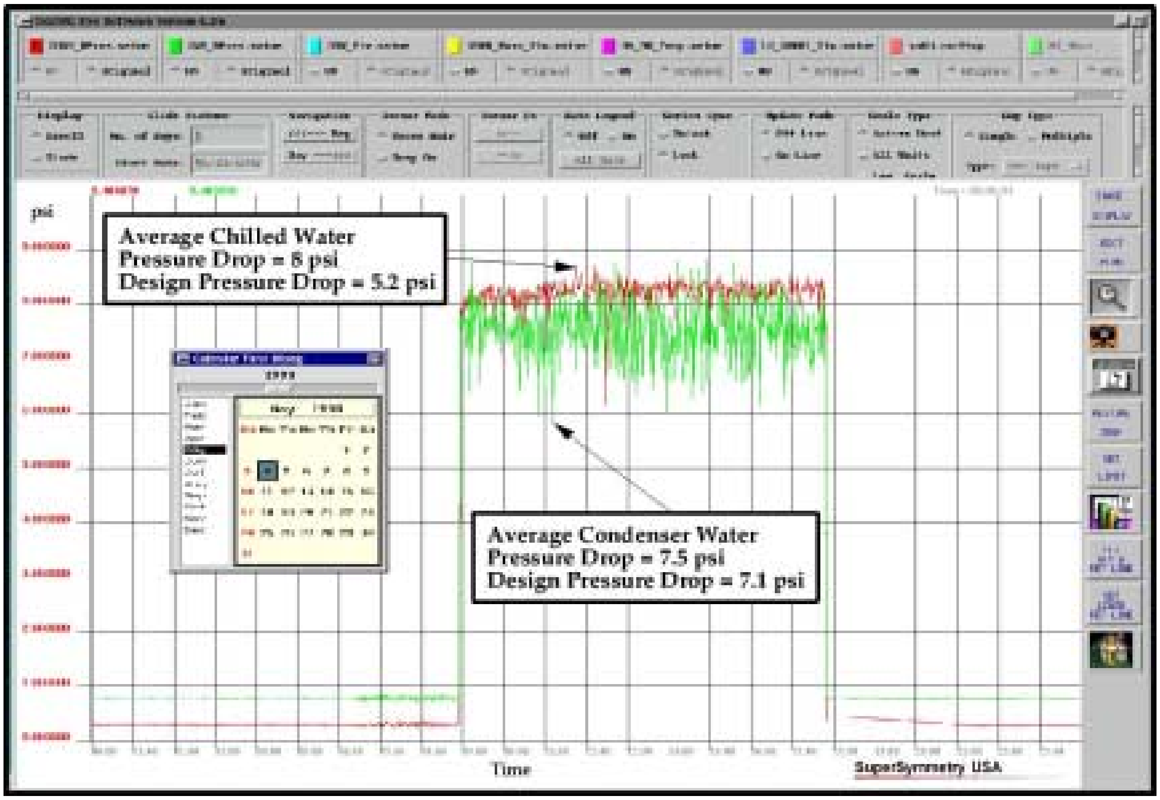

Figure 4–17. Preliminary Pump Operation – Graph 2

A more dramatic problem was found in the condenser water system. In chiller 2 the design flow is 615 gpm. The measured flow was 60% below the design flow (**Figure 4–18**). While increasing the condenser water flow will consume more pumping energy, it will make the chillers operate more efficiently. More flow and better heat exchange in the condenser of the chiller should improve the chiller efficiency and reduce the energy consumed by the chiller.

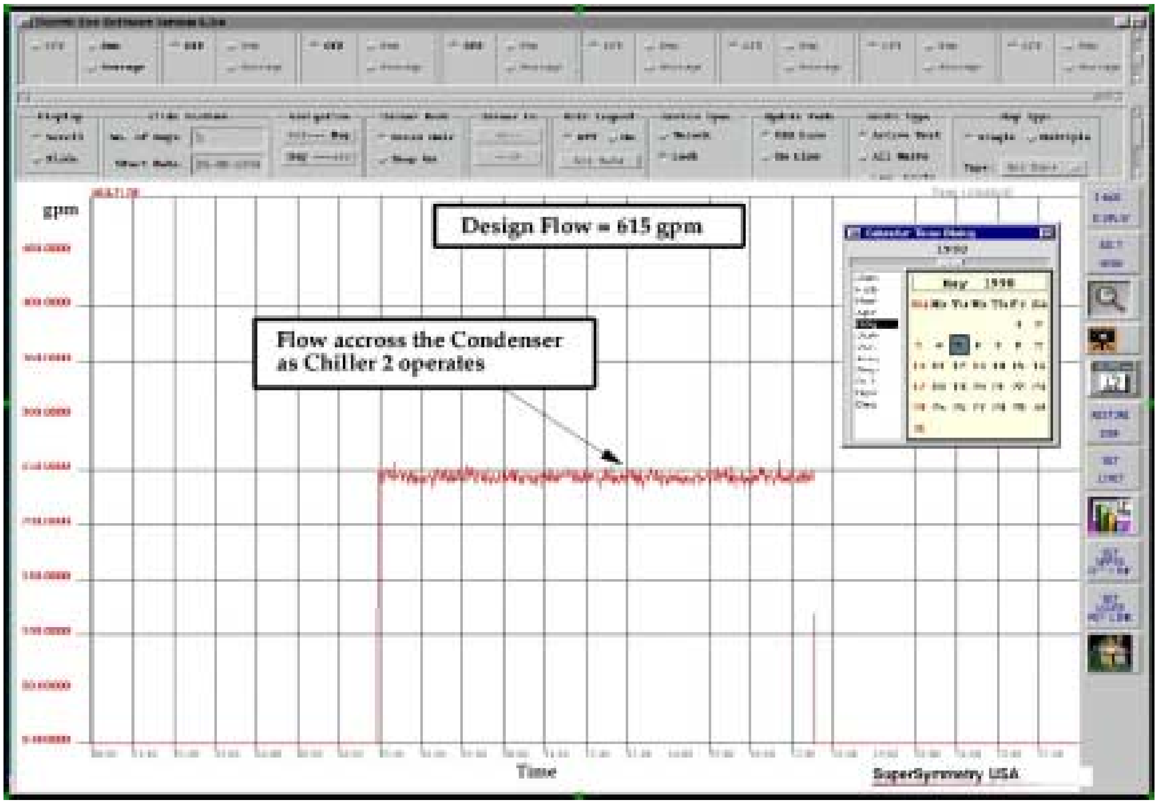

Figure 4–18. Preliminary Pump Operation – Graph 3

One additional comment on the pumps is that air was found in the pipes. Thus, when the second chiller was brought on, the flow actually was reduced. This can be seen in **Figure 4–12**. This problem is under investigation for Phase 3.

Summary of Findings from Initial Use of IMDS. The key findings are summarized below. During Phase 3 we will be developing estimates of the energy and other impacts of these issues. The chiller start-up problem was by far the most severe problem, and was actually identified on the first day of operation of the IMDS. The building operator saw **Figure 4–12** in the first training session and took immediate action to correct the problem. This problem could have caused a major chiller failure. The operator is also aware of the tower cycling, but has not yet corrected the problem.

Chiller Issues

- **Start-up peak due to control sequence modifications**.
  Implications: Could have resulted in major failure of chillers from no load
- **Back flow through one chiller when other chiller off**.
  Implications: Energy waste, chillers used more than needed. causes low delta T through chillers

Cooling Towers Issues

- **Frequent cycling**
  Implications: Premature failure, poor control of condenser water temperature and resulting chiller modulation
- **High condensing water temperature, plus only one tower cell at a time**
  Implications: Higher than optimal chiller energy use

Pumping and Flow Issues

- **Chilled water flow 15% greater than design flow**
  Implications: Higher pumping energy use.
- **High pressure drop on water side of the evaporator**
  Implications: Greater pumping energy.
- **Low condenser flow (60% below design)**
  Implications: Poor energy efficiency

Longer-Term Energy Saving Opportunities – In addition to the lessons from the first few days of data, we have observed several other issues in the building's performance. The availability of high-quality building operations data is useful to identify concepts for additional low-cost modifications and retrofit opportunities. One of the most significant opportunities for the cooling plant is to make better use of the cooling tower system. There appears to be a significant opportunity to use the towers more, and run them during mild weather in place of, or before the chillers. The towers could be used to pre-cool the building, which should result in peak demand savings on warm days. It may be cost effective to add pre-cooling coils or use the chillers as heat exchangers. It also appears that the air-handler silencers are larger than needed. The project team has observed that the fans are very quiet. The silencers increase the fan pressure drop resulting in higher energy costs. Lowering the pressure drop would also reduce the fan heat load, expanding the opportunities for free cooling. Finally, there are additional opportunities for further reductions in the lighting power densities, which will have the added savings from reducing the cooling load.

SECTION 5. AUTOMATION OF DIAGNOSTICS

Overview of Diagnostic Technology and IMDS Design

Phase 1 included an investigation and evaluation of diagnostic methods, tools, and techniques for inclusion in the current project. Our analysis considered issues such as sensor and communications technology, bottom-up versus top-down diagnostics architecture, and the design of temporary versus permanent systems. We also examined the status of techniques from the field of intelligent systems (e.g., artificial intelligence, fuzzy logic, neural networks) and diagnostics used in process control industries.

A diagnostic system comprises the components depicted in **Figure 5–1**. We have installed the system in the building, with the set of sensors, data processing, and standard graphics already specified. We are currently training the building operator to use the system and will be closely monitoring their actions taken as a result of the system, which we expect to result in energy savings. There are difficult tradeoffs between advancing the automation of the diagnostic systems versus designing the system for optimal human-based diagnostics. The current emphasis in this project is to provide reliable and easily interpreted standard performance graphs that the operator can use for “human-based” diagnostics. The project also includes research on automated diagnostics, which include methods to detect faults and identify fault sources.

Automated diagnostic systems generally include model-based (e.g., simple functions, physical, or black-box) fault detection and classifiers (knowledge or association based). The development of automated diagnostics can be justified by the recognition that building systems are becoming more complex over time and are difficult for the average operator to understand (Hyvarinen & Karki 1996). One study found that after a few months of strong enthusiasm, building operators lost interest in standard energy use plots provided by a utility research project that provided detailed energy data to building operators (Behrens & Belfer 1996). Thus, some automation of diagnostics is needed to set alarms that can tell an operator when the diagnostic system has identified a performance problem or deviation from normal operation. When such an alarm is sounded, the operator can than query the standard plots to look at the nature of the problem. We have chosen to work with the most sophisticated operators we can find, and will explore how to automate some of their "expert diagnosis" so that the system could be developed for a broader set of users.

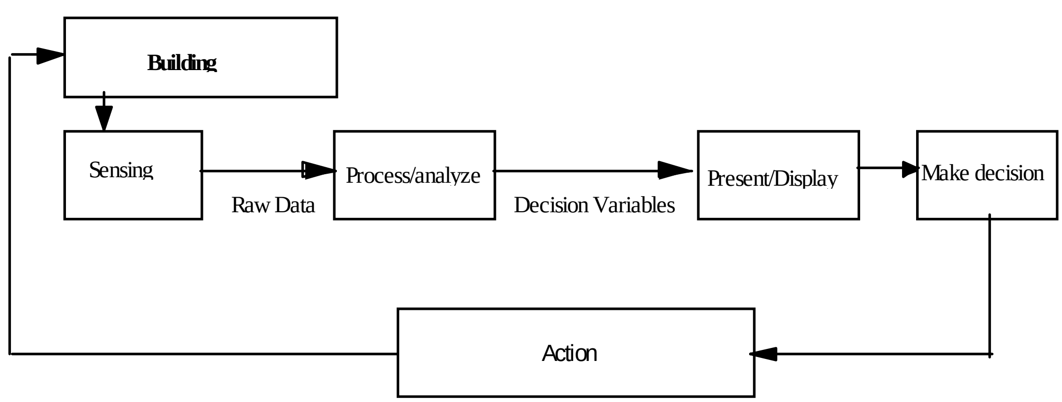

Figure 5–1. Components of a Diagnostic System

The basic architecture for the automated diagnostics has been defined and the approach for constructing the appropriate fuzzy-logic maps has been specified. We have begun to build a prototype of the basic routines needed to implement the system, which will use some of the project's basic plots as test beds. The basic goal is to develop the automation part of the diagnostic system in such a way that:

- Using fuzzy detector it can alert operators to the existence of predetermined failures in such a way that the certainty of the detection and diagnosis is clear to the operator. These predetermined failure modes come either from the team experts or from the operators themselves.
- It is structured to eventually be able to learn from its own experience in such a way that operators can ask the diagnostic system how it came to its conclusion. This also will involve a fuzzy structure since such a structure can both deliver information on certainty and answer questions that are logical to people, such as "why did the problem occur?"

In other words, the system must first take input such as requests for information, plots, or facts (including graphical facts). Second, it must be able to work with less than perfect evidence or data. Ideally it will learn on its own.

Phase 2 Automated Diagnostics Development

The Phase 2 research effort has focused on two issues regarding automation of diagnostics. The first is on tool generation. The second is to exploit experience (albeit limited) associated with the instrumented building.

Tools

Mathematically, we are building what are called detectors. These involve dividing some space into regions, each associated with some condition (e.g. failure or no failure). In its simplest mathematical form, the decision problem is determination of an operator, D, which maps a data space, X, into the set {0,1}:

$$D: X \quad \{0,1\}, \tag{1}$$

Where, for example, 0 implies no failure and 1 implies a specific failure. In complex problems like buildings, one could imagine a set of such functions, {Di}, each detecting a particular failure. In the problems of interest in this project, X represents a space of 90 points measured once per minute over at least a year.

There are many ways to construct the mapping D, some extremely cumbersome to others which are extremely simple. Sometimes, people give specific coordinate systems and looks for patterns in the chiller efficiency versus load (kW/ton vs. ton) plots. Other times human insight is less specific and the diagnosis becomes more difficult. For reasons described above, we have settled on the fuzzy paradigm. Detecting and diagnosing failures therefore is always associated with fitting a fuzzy patch to the data (usually some transformed form of the raw data). The fuzzy patch yields two choices: no failure or a specific failure. These fuzzy patches are either easy or hard depending on two elements. First is the shape of the set of points associated with either failure or no failure. Second is the coordinate system within which the data are viewed. They are found by optimizing some patch shape to fit the problem.

It turns out that Evolutionary programming provides an extremely powerful tool for searching for the best solution in both of the above categories. Details of this approach are given in two papers by Sebald and Chellapilla (1998 Part I and 1998 Part II). A third paper is being developed for an upcoming special issue of the IEEE Proceedings dedicated to Evolutionary Computation. All of the underlying logic and technical details were developed in the three papers.

It is worth highlighting the significance of these results. We are pursuing a real time, automated determination of ideal methods[4] to identify whether a problem has occurred. This is based on using the detector shape with the cleanest way of capturing the desired pattern. Most important of all, we are talking about doing this autonomously. This can be done on-line without human intervention. Human intervention is possible if it makes sense, but not mandatory. Our goal is to develop a system which programs itself. The system under development is intended to mimic pattern searches already known to be useful, such as those developed in the nine standard plots. It should also be useful autonomous, hands off learning by the machine. We have begun to apply these tools to the specific diagnostic graphs listed in **Table 3–2**.

Evolving a Detector for Regions in the Standard Chiller Plot

As a test of the procedures developed in this project, regions in the standard chiller plot shown in **Figure 5–2** were detected via evolved detectors. There are three regions shown in the figure (1) purchase point operation, (2) correct sub capacity performance (the hyperbolic cluster), and (3) improper performance (e.g. due to control problems). This is synthetic data used to illustrate the concept.

Using the techniques outlined in Sebald and Chellapilla (1998 Parts I and II), and a population size of 50 solutions, a perfect solution (all points correctly classified) in 19 generations which requires an extremely small amount of CPU time (and real time). This was accomplished without parsimony constraints. The next step will be to incorporate fuzzy rather than yes/no classification and apply it to real data.

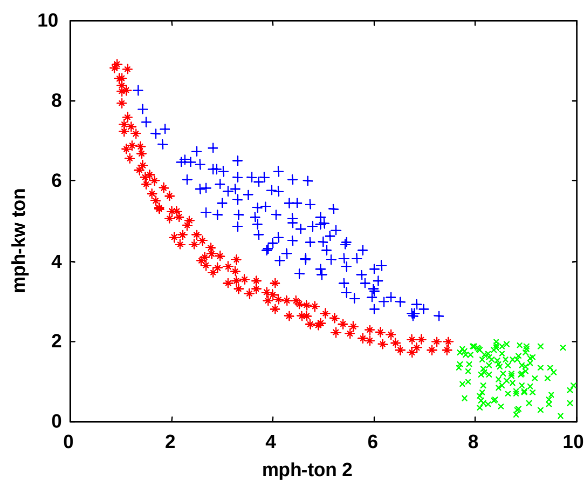

Figure 5–2. Detector Regions in Chiller Efficiency Plot

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[4] i.e. the best coordinate system

Learning from Experience

Another important aspect of the diagnostics problem is whether or not the system can learn from experience with limited or no help from the human operators. We have been working on extensions to the Evolutionary methods to determine a good way to develop a self learning capability. We are aiming toward systems that can learn to diagnose problems from simple information like a statement from the operator that a specific fault has been fixed. We would also like the system to build inferences involving basic detection components already assembled.

The research team of Sebald and Chellapilla has direct access to the IMDS data and is using it to perform analysis of the standard plots. They set up the IMDS software to have the full set of features (see section entitiled, “Data Visualization Software”), and are observing the techniques used by the project team and on-site staff to review the IMDS data. Their interest is to understand how approach the building systems data. From what they have seen, each IMDS users has a different mental model of how things are supposed to work and how one checks operations data. What do you look at first, second etc.?

The collection of information from experts for incorporating into an intelligent detection and diagnosis system can be achieved in two ways. The first is by directly interviewing the expert and gathering first hand information. However, in most cases when using such a direct method, it may not be possible to collect all the desired information. Typically, the expert or operator examines facts and takes decisions on an instinct that he develops from years of experience. As a result, he may not be able to verbalize all the knowledge he has, but can performs detection and diagnosis successfully through a sequence of checks when a problem appears. Further, when efficient visualization software such as the Electric Eye is available, there might be certain charts or data that the operator regularly checks or monitors to ensure proper functioning of the building. Thus, monitoring the expert or operator during these processes of daily checking or monitoring and during detection and diagnosis of problems that he finds and successfully fixes, could be an invaluable source of information that can be incorporated into the visualization software itself or implemented separately in an automated detection and diagnosis system.

The current software does not include the ability to store keystrokes or mouse clicks sequences. Information on how people have used the IMDS would reduce the need for making fault trees. Fault trees require characterizing the influence of single faults (such as a sensor out of calibration and providing erroneous data). Next one must consider the data stream that occurs with double faults (e.g., faulty sensor combined with fouled tubes). One needs a method to evaluate each condition. This requires a tremendous amount of work and can be viewed as a vast space of solutions. Such as space is quantitatively difficult to describe and hard to search. This approach can be considered a “bottom-up” diagnostic system.

By contrast, Sebald and Chellapilla are developing a top-down system designed to be used by the on-site staff and remote expert users. They are obtaining information on top-level building data, such as whole-building and cooling plant data, to evaluate the overall performance. Given this information, combined with other building characteristics and weather data, they are seeking to develop a logical set of analytical procedures to improve energy performance. The strategy to use more cooling tower cooling at 160 Sansome (described in the section entitiled “Operational Findings from Initial IMDS Data”) is an example of an energy-efficiency opportunity that the on-site staff have not considered. This will be explored in more detail during Phase 3.

SECTION 6. ECONOMIC ISSUES AND RELATED TECHNOLOGY

In this section we discuss the potential costs and benefits of the IMDS, along with how the current system compares with emerging innovations in EMCS and related information technology for building energy performance assurance. As discussed in Phase 1, the market for the diagnostic system comprises suppliers and users of the products and services. The users are primarily building owners and property managers. There are many potential scenarios for the delivery of the products and services being explored in this project. Three likely suppliers are utilities, ESCOs, and equipment manufacturers. Our purpose in this project is to de-mystify some of the technology and work with the most innovative managers to help define which aspects of this type of technology are of greatest interest and value. The current project requires a specialized research team to specify, install, and even operate the information technology being presented and reviewed. This will change as new, related, technology enters the marketplace. As discussed Section 2, today we only see such technology used under special circumstances in high-technology and industrial buildings where owners have more stringent information management and monitoring requirements. We know that such technology can be useful in large commercial buildings. We don't know, however, what the best use or optimal design of such technology is for this newer market.

Our long-term goal is to achieve a "transformed market" where IMDS-related technologies are available to improve energy use in commercial buildings. Market transformation research itself is evolving to better characterize what is necessary to understand a given marketplace (Blumstein et al, 1998). Market transformation research requires multi-disciplinary research with elements such as cost-benefit improvements of new technologies, pilot tests, full-scale market transformation initiatives, and evaluations of research gaps concerning the theories of how various markets operate. The IMDS project is a research project, not a large-scale market transformation project. It does, however, contain critical elements to inform a future strategy on information technology market transformation given the innovation research and pilot demonstrations. The research nature of the project must be kept in mind as we examine the potential costs and benefits of the pilot site IMDS and future versions of the IMDS.

Some promising emerging technologies fail to become accepted in the larger marketplace despite early interest by innovative users. Innovation researchers have encountered this phenomenon so frequently that they describe the need for a technology to "cross a chasm" to gain broader market acceptance (Moore, 1991). Technologies that appear promising to the innovator and early adopters must be packaged differently before they are adopted by mainstream users. The next phase of our research includes obtaining information from the innovative users targeted toward determining how the technology can be modified to gain a more widespread adoption by a larger set of users. We are in search of the unique and compelling applications that are of popular appeal to building operators.

Costs and Benefits

Site-Specific Savings

The property managers that we have approached have all expressed a strong interest in participating in this research. The pilot collaboration is structured as follows. The research project's budget covers the cost of the hardware and software at the building site. The property management company covered the cost of the system installation. This arrangement worked fairly well in practice, but required some assistance from the research team in the installation process in order to keep to the tight project schedule, as further discussed below. We have spent approximately $63,000 for the hardware and software, including the ISDN phone line (**Table 6–1**).

Table 6–1. IMDS Costs

System	Cost
Data Acquisition System (Enflex)	**$8,535**
Computer System	**$3,938**
Sensors	
Cooling System	$31,860
Air Handlers	$5,784
Building Power	$3,916
Sensor Total	**$41,560**
Networking (ISP and 1 year of ISDN)	**$8,912.**
Grand Total	**$62,945.**

The cost of the installation of the instruments on the site has been self-reported by the participants at $23,000 to $25,000. The technical managers provided the hours and subcontract labor costs. We have used an industry standard $75 per hour for on-site labor that was provided by the technical manager. We are suspicious that this number does not accurately represent the true costs. We believe the managers at the building may have paid for some of the costs through "bolting the costs" on to other items. We will be investigating the true costs in our Phase 3 reports but our estimate is that the costs are from 30 to 50% higher than the initial self reported figure.

A 50% increase in the system installation cost results in a total cost for hardware, software, and installation of about $1/sqft. As mentioned, one of the primary goals of the project is to demonstrate the economic value of monitoring, diagnostic, and information systems to improve operations in commercial buildings. Such information is useful to identify energy savings from low-cost operational changes. Our target of 15% energy savings translates into about $0.30/sqft-year for a 100,000 sqft building consuming about $2/sqft, or $60,000/year for the pilot building. This would offer a simple payback time of about three years. Our expectation is that the first costs will decrease significantly as this technology becomes more commonplace, and we evaluate the benefit of the high-quality sensors. Since high-quality sensors are a critical element of the diagnostic system design, the Phase 3 activities will include a review of the costs, benefits and relative value of each data point. This will also include evaluating the life-cycle costs (first costs and maintenance costs) of such high-quality high-end sensors versus compared with lower-cost alternatives.

The non-energy benefits of the IMDS are major drivers for the high level of interest in this technology. The "innovators" we are working with recognize the general value of having high quality information about building performance. Perhaps the primary non-energy benefit the IMDS offers is vast improvements in data about the general operating conditions of major building equipment. Field studies have shown that building equipment are often not operated in an optimal fashion. For example, it is common to find cooling towers cycling too frequently (Piette et al., 1996). Another common problem is that equipment is often on when not needed. Both of these examples bring about premature end of life or equipment failures. The IMDS data may also lead to better comfort conditions and tenant satisfaction given the improved ability to evaluate the performance of the cooling plant. These benefits will be difficult to quantify, but will be tracked in our evaluation.

The diagnostic system meters various building systems and components to provide feedback on building performance. The users of the system are building operators and property managers. The project involves working with innovative experts in two ways. First, they are assisting us in developing new technology. Second, we are using them and their peer groups to develop a technology pull strategy by providing feedback on the technology. As mentioned, the suppliers could be electric utilities, other third-party experts such as ESCOs, or control companies. The service would ideally be paid for through savings in the operating budget. It could reduce operating costs and make tenant spaces more comfortable. It also gives the building operations staff a choice of local or remote building diagnosis. The IMDS is prototype that takes advantage emerging information technology, giving customers direct experience in this new field. We hope to extend the IMDS demonstrations to additional buildings, and will be exploring modifications to the current monitoring suite.

Statewide Energy Savings Potential

Commercial buildings currently consume about 86 BkWh/yr (or 86,000 GWh/yr in site units) of electricity in California (CEC 1998). Approximately 17% of this total is used for cooling, with another 10% for ventilation. Thus, cooling and ventilation are responsible for more than one-fourth of the commercial-building electricity use**.**

Large office buildings (those over 30,000 sqft) account for twenty-two percent of total commercial sector electricity use, or 19 BkWh/yr (CEC, 1998). With greater internal gains and less envelope dependence, cooling and ventilation requirements are higher than in other building types, at 20% and 13% of total energy use, or one-third of electricity use when combined. We have described a target savings of 15% of total electricity use. Assuming no savings in other end-uses, this would require reducing cooling and ventilation electricity use by 50%. Such savings are possible, though it is also likely that we will see energy savings in other end-uses from scheduling improvements. Section 4 outlined several areas where we expect to achieve significant energy savings at 160 Sansome Street. The 15% savings in large office building energy use represent nearly 3 BkWh/yr of electricity savings, worth nearly $300 M/yr. Such a target savings level could be achieved if the technology pursued in this project is successfully developed and deployed. We also expect to identify savings in peak electrical demand, and will conduct some analysis of these savings based on a generic rate structure since the on-site manager wants to keep energy costs at 160 Sansome confidential.

Related Emerging Technology

EMCS are limited in their use as performance monitoring tools, as mentioned in Section 1 (see also Sebald and Piette, 1997). There are, however, significant efforts underway to make better use of EMCS data and to improve the technology itself. Several examples of emerging products, protocols, and research activities are described below. This is not a comprehensive survey of the entire field, but is provided for to give an overview of how emerging technology and applications compare with the IMDS.

Accessing and Storing Data

EMCSs typically are capable of providing a wealth of building operation and performance information, although those data have traditionally been difficult to access in a convenient and powerful way. While it is usually possible to manually export a trend-log of point data, the methods for exporting these data, and the data formats typically vary from manufacturer to manufacturer, and model to model (Heinemeier, 1994). Most EMCS require that you archive the data to disk as a separate step of the trend. Newer EMCS will allow you to select the data archival format as a database or spreadsheet file. Even more sophisticated are real-time connections to EMCS that archive data to a database, often using Internet technology.

Atrium. One such example of an emerging application for real-time connections to EMCS is Atrium (Honeywell, 1998). Atrium provides a database platform for application development, to aid in use of energy control system data, as well as providing other data services. Once exported, these data can often be easily imported to spreadsheet programs, although the capability of these programs to handle large amounts of data is limited. Atrium provides an interface to gain information from any EMCS that is compliant with the BACnet standard for EMCS communication. BACnet has been developed by industry consensus within ASHRAE to ensure that control systems provided by different manufacturers are capable of communicating with one another. It is a Data Communication Protocol for Building Automation and Control Networks (ASHRAE, Standard 135-1995). By contrast, most of today’s BMS and EMCS utilize proprietary communications systems and expensive gateways are needed to connect them to other systems.

Atrium has a web-based public application interface, based on a published API (Application Protocol Interface), so that applications developed by any vendor would be interoperable with Atrium. Atrium is currently under development, and is expected to be beta-tested by the end of 1998. Several applications have been developed, or are being currently under development, that make use of Atrium, including several Honeywell-developed applications--Real-Time Pricing Control, Uptime Assurance Browser, Whole-Building Diagnostician (described below), Atrium Browser, and Tenant Billing--as well as third-party applications (such as Enforma, Waterbury et a., 1994). Once Version 1.0 of Atrium is available, any vendor will be able to develop interoperable applications to make use of EMCS-collected data (Honeywell, 1998 and Heinemeier, 1994).

Remote Monitoring and Operations. A similar effort to retrieve EMCS data using the Internet and store it in a database has been explored at LBNL (Olken et al, 1996, Olken et al., 1998). This effort is similar to Atrium in several respects, such as the standard database schema and interest in a BACnet interface. The LBNL effort did not, however, include a BACnet interface because there were few, if any, BACnet EMCS to work with when the project began in 1995. The RBMO project centered around using Common Object Request Broker Architecture (CORBA). CORBA aims to provide a uniform communication infrastructure for building distributed applications. This standard and the use of other Internet networking protocols permits access to a wide variety of low-cost hardware and software over many different media. The aim is to develop a system architecture that will be robust and flexible, allowing a building owner to access data from heterogeneous EMCS. They system collected several hundred points of minute data from two buildings.

State-of-the Art EMCS Data Evaluation Techniques

There are only a few well-documented applications and techniques that are focused on specific procedures to analyze EMCS. We present a few examples to provide an overview of the status of such technology.

Exporting EMCS Data to External Evaluation Tool. Brightbill and Rutt (1988) present an overview of a methodology to perform simple diagnostic techniques to evaluate issues such as leaking controls valves, simultaneous heating and cooling, economizers, and calibration problems. They present general, simplified equations and examples of results from analysis of hourly data. EMCS data are, however, often problematic for such analysis. The authors note: the economizer date should "be used with caution when return air and outside temperatures are within 10° F of each other due to the inaccuracy of each sensor."

Whole-Building Diagnostician. A more formal analysis tool under development examines whole-building energy and air-handler performance (PNNL, http://aggie.pnl.gov:2080/wbd/web). An air handler analysis is performed when the user develops prescribed trend log data to feed into the EMCS and receives a series of graphical reports outlining potential problems with air handlers. The whole-building energy use component trains a neural-net model to predict energy use, then compares predicted energy use to actual, flagging significant differences. The WBD has been designed to operate with Atrium.

Pricing Controller Software. Another example of an application design to work with EMCS data with almost any BMS is the Pricing Controller Software (PCS) for real-time price operations (Blanc et al., 1997). The PCS has been demonstrated at a large hotel to impact four systems: hot water pumps, duct static pressure, supply air temperature, and fan scheduling. Nearly $12,000/yr of energy cost savings has been estimated from one week of monitoring based on a simple extrapolation.

Web-Based EMCS Data. At the Claremont Colleges, in Claremont, California, a web site has been developed which provides a single interface for multiple systems. A few such sites have been custom developed around the US. The Claremont EMCS web site is used primarily for scheduling and control, as well as for diagnostic purposes (Moe, 1998). Maintenance personnel routinely turn to the system to diagnose problems remotely. The system includes current-transformers and most fans and pumps. Historical data analysis has not yet been integrated into the system but is archived and stored in another database. Future plans include adding the historical data as well as graphical schematics to the interface. Some of the data are stored in collapsing trend logs, which collapse the data to smaller time-aggregation intervals after a specific time period has passed. The original data are collapsed to daily averages. This could be useful when data storage is an issue. However, in the Claremont case, they would like to change the system to archive at least one year of hourly data from their EMCS software.

Interoperability and Building Life-Cycle Information Systems

Another related activity is research to develop tools and data systems that provide good decision making in multiple phases of the building life, referred to as Building Life-cycle Information Systems (BLISS) (Hitchcock et al, 1998, Selkowitz et al, 1996). As building systems, controls, technology, and operations become more complex and dynamic, successful projects rely on good decision making in design, construction, commissioning, and operations, informed by appropriate and timely data. Successful deployment of the software technologies explored in this project is a major step toward achieving interoperability among building software programs. That is, information input and output from one program can be used in another without manual re-entry. Software interoperability allows the programs to communicate with one another, to avoid redundant (and possibly error-prone) data entry for each tool, and to ensure more realistic “as-built” inputs. If these tools include a broad range of applications and span the life cycle of the building, they will have the advantage of providing a more seamless optimization of the building systems, from design to operation, with resulting decreased energy consumption and improved operation and maintenance.

The BLISS effort is greatly facilitated by an important industry-based effort to improve the capture and transferability of building information. The International Alliance for Interoperability (IAI) is a worldwide non-profit alliance of the building industry including: architects, engineers, contractors, building owners and facility managers, building project manufacturers, software vendors, information providers, government agencies, research labs, and universities. Its mission is to “integrate the AEC/FM (Architecture, Engineering, Construction and Facility Management) industry by specifying Industry Foundation Classes (IFC’s) as a universal language to improve the communication, productivity, delivery time, cost, and quality throughout the design, construction, operation and maintenance life cycle of buildings” (IAI 1997). The IFC is a standard data model specification designed to support direct sharing of data between software applications. The relationship between building software and IFC’s is analogous to BACnet and EMCS interoperability.

Relation of Emerging Technology to IMDS

Many of the above technologies are being developed because of the recognition that EMCS data are greatly underutilized. There are often, however, significant problems in using many of the existing EMCS to perform the desired analysis. These problems include issues such as sensor placement errors, lack of good calibration, and limited scope of EMCS data. By contrast the IMDS is focused on providing a comprehensive and quantitative handle on building performance, emphasizing the cooling equipment identified for this phase of the research. Our objective is to collect top-level energy data, using high-quality instrumentation to push total system efficiency to the highest economically feasible level. While on the one hand we are trying to ensure that the building operates as intended, we are also trying to exploit the high-quality measurements and human analysis to obtain insights from both remote experts and on-site operators to obtain optimal energy efficiency in the entire building. The IMDS is trying to do this by measuring energy, temperature, flow, pressures, and climatic data with greater precision and frequency than other related systems. This system will compliment many of the emerging systems and approaches described above. IMDS data could help to ensure that building energy performance objectives, defined during design and retrofit activities, are met or updated. We also expect that many of the measurement techniques, data archival systems, remote access, and analysis can be incorporated directly into EMCS technology over time.

SECTION 7. CONCLUSIONS AND FUTURE PLANS

The primary objective of this project is to introduce state-of-the-art building monitoring and diagnostic information systems into Class A buildings for use by sophisticated building operators. This objective is based on our background research, which suggests that the proposed system meets the needs of operators and that they support the system we've designed. The concept is to deploy a permanent system to assist in continuous improvements in O&M to reduce energy use and operating costs. Our overall goal is to work with building owners and property managers in demonstrating the cost effectiveness of the proposed diagnostic system, thereby creating a market demand for such technology. We hope to demonstrate that the system could be cost effective when commercialized by the private sector. The report has presented results from the initial field testing of the IMDS. The system includes high quality sensors, automated communications and data management, and data visualization to diagnose building energy performance problems. In addition, the appendices are the first step toward a specifications for a building monitoring, diagnostics, and data-visualization system that will provide a platform for further commercial development and provide information needed to automate the diagnosis of building performance problems. This system is significantly different from related information technology for commercial buildings. The demonstration project will offer unique results on the technology preferences of innovative Class A building managers.

The system design was developed in response to the concerns the technical managers reported in Phase 1 of the project. The technical manager's review of the information is expected to reveal that the technology needs to be altered and adjusted to accommodate the business reality within which they work. Phase 2 has reported on our understanding of the innovation adoption process used by a technical manger in a third party property management company. We find that the technical managers rely primarily on firsthand, verifiable information from trusted sources. Little outside persuasion is necessary, and making the decision to adopt the technology is not time consuming. In Phase 3, we will provide a more complete model for the manager's decision process for both radical and routine innovations.

The prototype IMDS cost is about $1/sqft, which includes the hardware, software, ISDN line, and installation. With a goal of about $0.30/sqft savings, we expect a payback time about about 3 years. We expect the first cost to be reduced as the technology matures. Furthermore, the non-energy benefits may well exceed the energy savings benefits. One of the main non-energy benefits is improvement in operations that will lengthen equipment life. Comfort improvements and reduced maintenance costs are also expected, and will be tracked in Phase 3. Full-scale implementation of such technology in large Californian office buildings could result in 3 GWh/yr of savings (in electricity), worth about $300 M/yr statewide, plus additional peak demand savings. We will continue to present these results to interested potential service providers such as utilities, Energy Service Companies, and equipment manufacturers.

Future Work: Phase 3

Phase 3, scheduled to begin in late summer of 1998, will encompass tracking the energy savings that result from operating the system. We have developed a log sheet (contained in the appendices) for the on-site staff to report on their use of the IMDS. These forms are currently being used at the site. We will also conduct periodic interviews with the staff to evaluate what they like and dislike about the system.

Our early interviews with third party property managers indicated that the managers were frustrated with conventional control systems and unlikely to change the how they operated their buildings without more believable information. The IMDS system installed in this phase is a response to the needs they had expressed earlier for better quality data presented in a way that facilitated decisionmaking. Now that the IMDS is in a real building and it is being utilized by one of their peers, we have begun informing the larger property management community that the technology exists and is available for review. Our intention is to use access to the technology to gain further entry into the property management industry so that we can finalize our interviews on the process of innovation adoption. That is, while presenting the IMDS technology to the technical managers of other innovative companies, we will complete our adoption process study.

Another primary task within Phase 3 will be the development of a more detailed functional specification documenting rules and algorithms to describe the most important faults detected with the diagnostic system. The specification will include an electronic document to (a) describe rules and variables used for performance assessment and diagnosis, (b) identify degradation and failure modes and conditions associated with each mode, and (c) identify all ranges of variables used to categorize performance. As mentioned above, the demonstration effort will continue to explore methods to automate the diagnostics. The increased intelligence will take two forms: (1) more automated diagnoses and (2) the beginning of a capability of the system to be self-learning (learn from experience).

During Phase 3 we will continue with the efforts to test the hypothesis that the IMDS can save 15% of whole-building energy use by identifying opportunities to improve control, operations and maintenance practices. Now that the system is fully operational we will conduct extensive discussions and tours with on-site and peer building owners and operators, plus potential service providers. The technical tours will include discussions on the development, installation, testing, and demonstration of building performance measurement and diagnostic solutions.

SECTION 8. REFERENCES

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