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DETERMINING LONG-TERM PERFORMANCE OF COOL STORAGE SYSTEMS FROM SHORT-TERM TESTS

ASHRAE Research Project 1004

LITERATURE REVIEW, PRELIMINARY METHODOLOGY DESCRIPTION AND FINAL SITE SELECTION

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ABSTRACT

This preliminary report contains the literature review, a preliminary description of the methodologies that have been chosen for the project and final site selection recommendations for ASHRAE Research Project RP 1004 -- "Determining Long-term Performance of Cool Storage Systems From Short-term Tests".

The literature review covers the relevant literature concerning: (1) different inverse analysis methods, including: building simulation models, regression models, multicollinearity and function forms, (2) methods for predicting long-term performance from short-term measurements, (3) analytical models for chillers, fans and pumps, including a discussion of component-based models versus overall systems models, (4) in-situ testing of chillers, fans and pumps, (5) methods for determining the long-term performance of cool storage systems, including field performance testing, methods for determining annual load frequency distribution, characterization of cool storage system performance, and annual performance projections, and (6) methods for determining the uncertainty associated with measurement and analysis, including: measurement uncertainty, bias and random errors, propagation errors, and regression errors. A preliminary description of the methodologies is included that describes the methods that have been chosen from the literature to perform an in-situ analysis of pumps, HVAC systems, chillers and cool storage facilities. Information for 14 cool storage sites is also presented including recommendations for 3 sites which have been selected for further study.

This report completes Task 1a (Literature Review), and Task 1b (Preliminary Report), and presents our recommendations for approaching Task 2a (Method to estimate long-term building loads from short-term data), Task 2b (Development of analytical methods for Thermal Energy Storage Systems - TES), Task 2c (Development of initial list of TES sites and submit to PMSC), Task 3c (Uncertainty analysis), and Task 3d (Development of long-term TES performance methodology).

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1.0 INTRODUCTION

This is the second interim report on ASHRAE Research Project RP1004: Determining Long-Term Performance of Cool Storage Systems from Short-Term Tests. This report is an expanded version of the preliminary report submitted in November 1997 to the Project Monitoring Sub-Committee (PMSC). This report contains a review of the published literature, an evaluation of available procedures and models, and recommendations for the analysis methodology.

The report covers the following areas:

- Section 2 - Determining the long-term performance of cool storage systems
- Section 3 - Determining HVAC system (or building) loads from short-term data,
- Section 4 - Models for chillers, fans and pumps,
- Section 5 - Uncertainty analysis, including a general preliminary analysis.

An annotated reference list has also been provided for each of the above sections.

Information is provided on the proposed field testing sites including system descriptions, current data channels being monitored, and samples of data collected (shown as time series plots, scatter plots and 3-D plots). Detailed information has also been provided for the three sites that have been chosen for further study.

1.1 Background

Facility owners, public utilities, and energy service companies continue to invest in energy efficiency projects. In order to ensure the prudence of these investments, regulators, investors and owners are requiring detailed, costly evaluations that entail field measurement of equipment performance. Many energy performance contracts mandate such performance evaluations.

Therefore, there is a need for methods to evaluate and verify the energy and cost savings resulting from energy efficiency projects. These methods are needed because there is significant uncertainty regarding how well such cool storage projects perform relative to their design predictions. This has been especially true with non-steady state systems including HVAC applications, and particularly those that incorporate cool storage.

Many cool storage systems are completely or partially dependent upon field assembly of components that cannot be pre-rated or tested prior to assembly. For these systems, field testing is the only way to ensure that the installed systems meet the specified performance requirements. At present, there are no widely accepted standard methods or protocols to conduct these evaluations of entire cool storage systems in place (in-situ) . Investigators must therefore develop custom measurement plans and analysis procedures for each project, increasing evaluation costs and diminishing quality assurance.

The current research is intended to provide reliable and low-cost methods to evaluate the long-term performance of cool storage systems. These methods will simplify the evaluation of cool storage system performance and enhance the application of cool storage technology. They will also provide a basis for the development of evaluation methodologies for other technologies.

This research builds upon previous work by ASHRAE and other organizations, including:

- DOE National Energy Measurement and Verification Protocol (NEMVP).
- DOE Federal Energy Management Program (FEMP) M&V Guideline.
- ASHRAE Guideline 14P: Measurement of Energy and Demand Savings.
- ARI Standard 900P: Thermal Storage Equipment Used for Cooling.
- ASHRAE Standard 150P: Method of Testing the Performance of Cool Storage Systems.
- ASHRAE Research Project RP827: Methodology Development to Measure In-Situ Chiller, Fan and Pump Performance.

The relationship of each of these previous efforts to the current research is briefly discussed below.

The DOE National Energy Measurement and Verification Protocol (NEMVP) and the FEMP M&V Guideline provide guidance for structuring energy-saving projects and related savings verification efforts. These documents do not address specific methods for determining energy savings. ASHRAE Guideline 14P, currently under development, will provide these methods. However, the scope of Guideline 14P does not include detailed methodologies for testing particular systems such as cool storage systems.

Methods of testing cool energy storage systems in the laboratory and in the field are currently being developed by ARI and ASHRAE, respectively. ARI is developing Standard 900P, a method for rating and evaluating cool energy storage devices and generators. ASHRAE Standard 150P has gone through public review and may be approved for publication by late 1998. It provides a standardized field testing method to determine the performance of cool storage systems. Though these proposed Standards are relevant to long term performance evaluation, and their test apparatus applicable, their scopes do not include prediction of long term performance, calculation of cooling load shifted, or determination of the degree of design load performance when design conditions are not available at the time of testing.

ASHRAE Research Project RP827 (Phelan et al. 1996, 1997a, 1997b, 1997c) proposed field monitoring protocols for pumps, fans and chillers. This research also provided an analysis methodology for characterizing the equipment performance as installed, and predicting its long-term energy use. The authors of 827-RP have indicated that additional work is required "to develop simple methods for estimating individual load frequency distributions" to enable long term performance to be predicted from short term monitored data.

The current work will build on the performance measurement method as prescribed by the public review draft of ASHRAE Standard 150P and the analysis method defined in ASHRAE 827-RP, developing a standardized testing method for immediate and widespread application of cool energy storage system performance evaluations.

1.2 Objectives

The objective of this research is to develop a generalized methodology for determining the long term performance of cool storage systems. The following items are needed to support this objective:

- Develop simple methods for estimating building load frequency distributions and load shapes,
- Define and demonstrate an in-situ field monitoring protocol for cool storage systems,
- Evaluate the applicability of analytical models to characterize the actual performance of the cool storage systems,
- Develop and validate a procedure for using the analytical models to predict the long-term energy and demand savings resulting from the installation of the cool storage system,
- Evaluate the sensitivity of the analysis results to the uncertainty of the measurement approach and instrumentation employed,
- Compare alternative methods in terms of their cost, reliability, and uncertainty
- Recommend standardized formats for reporting experimental test and analysis results

1.3 Scope

In order to define the boundaries of this project, we have, with the concurrence of the PMSC, limited the scope of this project as follows:

1. To existing cool storage systems, as opposed to projects where a cool storage system is being evaluated as an alternative.

2. Only savings associated with electric (as against gas or oil) energy and demand will be considered.

3. Though there are numerous types of cool storage systems and modes of operation, we shall limit ourselves to the study of three cool storage systems only, the selection of which is to be approved by the PMSC.

4. The cool storage systems at the test sites selected should be representative of reasonably well engineered and well operated systems though they need not be "excellent" or "optimal" ones. The scope of this project is not to diagnose system operation or to suggest optimal cool storage operation and control strategies, but to study a cool storage system as it is currently operated.

5. The outcome of this research should not be a pre-packaged or "black-box" type of software package but should be a well documented and defensible monitoring and analysis methodology or algorithm that can be widely used by ASHRAE members.

1.4 Approach

Our goal for this project is to develop a test and analysis methodology that ASHRAE practitioners can use to project the annual performance of cool storage systems based on limited short-term testing. An additional goal is to demonstrate the test methods specified in the proposed ASHRAE Standard 150P, *Method of Testing the Performance of Cool Storage Systems* (ASHRAE 1997a).

Our approach to achieving these goals will be influenced by the results of each succeeding task, and by our interactions with the Project Monitoring Subcommittee (PMSC). However, we have developed some general concepts that will guide us in performing this research. For example, there are a number of questions to be resolved by this research. These include:

(a) Building load frequency distributions:
- What monitoring period is required to obtain sufficient load data to accurately predict a building's annual load frequency distribution?
- How is the load frequency distribution affected by the characteristics of the HVAC system?

(b) Amount of load shifted:
- How would a reasonable "base case" or comparison system best be defined?
- How can the performance of the "base-case" chiller(s) be determined from the measured performance of the storage system chiller(s)?

(c) Long-term performance:
- How much data over what range of loads is required to adequately establish a cool storage system's "performance map"?
- What level of detail is required for a cool storage system model to accurately predict long-term performance from short-term data?

We will attempt to address each of these questions in the course of performing this research. We anticipate that the methods for determining building load frequency distributions, and the development of techniques for determining the level of demand shift and annual performance of cool storage systems, can best be developed by applying and extending work reported in the existing literature. These issues are discussed further in the appropriate sections of this report.

We intend to produce a practical, accurate methodology that can be applied in the field by practitioners with some expertise in field testing, analysis, and statistics. We anticipate that the procedure will include the following elements:

- Monitoring protocols defining necessary data points, the length of the monitoring period, and required distribution of loads during the monitoring period, as well as specific test procedures and/or simplified HVAC and building models.

- Information requirements for determining the annual distribution of loads, such as minimum amount and type of monitored data, as well as climatological data, building type, HVAC system characteristics, and other parameters.

- A methodology for determining the degree of load shifted, including recommendations for defining a reasonable "base case" or comparison system. This methodology should maximize the accuracy of the results while minimizing the amount of system "redesign" required. It should provide methods for estimating auxiliary energy consumption. It should also allow determination of the performance of the "base-case" chiller(s) from the measured performance of the existing cool storage system chiller(s), even when the systems may be operating under very different sets of conditions (i.e., different evaporator and condenser temperatures).

- A methodology for estimating cool storage long-term performance, including annual energy consumption and monthly peak demand. This methodology will include a procedure for defining a cool storage system's "annual performance map" based on short-term data. It will also include methods for combining the cool storage system performance data with the load frequency distribution to determine long-term performance.

- Recommendations for specifying an acceptable level of uncertainty in performance estimates.

In addition, we expect to gain valuable experience in the implementation of the Standard 150P test methods, which will be documented in the final report for the use of other ASHRAE practitioners.

1.5 Practical considerations

To summarize, the outcome of this research will be a "tool" which will consist of recommendations of when (i.e., time of year) and how (i.e., what types of metering equipment and associated accuracy) to perform monitoring of the cooling system, including suggestions of how to analyze the data in the framework of analytical models that will be proposed, and how to use these models to predict the impact of the cool storage system. The following considerations will be kept in mind during the development of the tool:

- The tool should be readily implemented by commissioning and practicing ASHRAE engineers (though what level of expertise in monitoring and data analysis is required is open to discussion).

- The tool should be cost-effective , i.e., the total cost of the entire evaluation (i.e., measurement equipment, testing and analysis time) should be in the range of 5% of the total cost of the cool storage system.

- The tool should provide acceptable accuracy in terms of cool storage savings in energy and demand. A preliminary range of accuracy would be in the $\pm 10\%$ range as measured against the total performance of the cool storage system. (Note that this evaluation would be feasible in this project since we propose to gather year-long data from each of the three cool storage sites we will be monitoring).

- The time of the year and the duration of in-situ short-term monitoring are important issues in terms of user perspective. Intuitively, the best time of the year to perform such tests would be either in summer (when the cooling loads and electric demand rates are highest) or during the swing seasons (when the wider range of cooling loads experienced by the system will allow better model characterization). Also, the duration could be anywhere from 1 week to 6 weeks, or even performing tests, say 1-2 weeks long, over different seasons of the year in order to capture a wider variety in system operation behavior. An allied important issue in this research would be to determine how the tool accuracy changes with such choices.

2.0 DETERMINATION OF THE LONG-TERM PERFORMANCE OF COOL STORAGE SYSTEMS

2.0 Background.

A methodology to determine the long-term performance of cool storage systems should include the following steps:

- Identify and specify required information, including:
  - a. Schedules of building operation, system operation, and utility rates
  - b. Desired level of uncertainty
  - c. Definition of base-case system for comparison
- Carry-out field performance testing. This step requires definition of the following:
  - a. Data points to be monitored
  - b. Appropriate monitoring period
  - c. System design data and operating schedules
  - d. Data collection procedures
- Determine the annual load frequency distribution.
- Characterize the performance of the cool storage system during the monitoring period.
- Estimate the annual performance of the cool storage system with the annual load distribution.
- Characterize the performance of a comparison cool storage system.
- Estimate the annual performance of the comparison cool storage system with the annual load distribution. Determine energy and demand savings, and other performance measures, for each of the applicable utility periods
- Evaluate uncertainty

The methodology should also be modular in nature. It should allow the user to select among various options for each of the steps, to specifically suit the user's needs. The following sections discuss the steps, and the options that have been identified for each step. Figure 2-1 illustrates the general steps, with possible alternative paths.

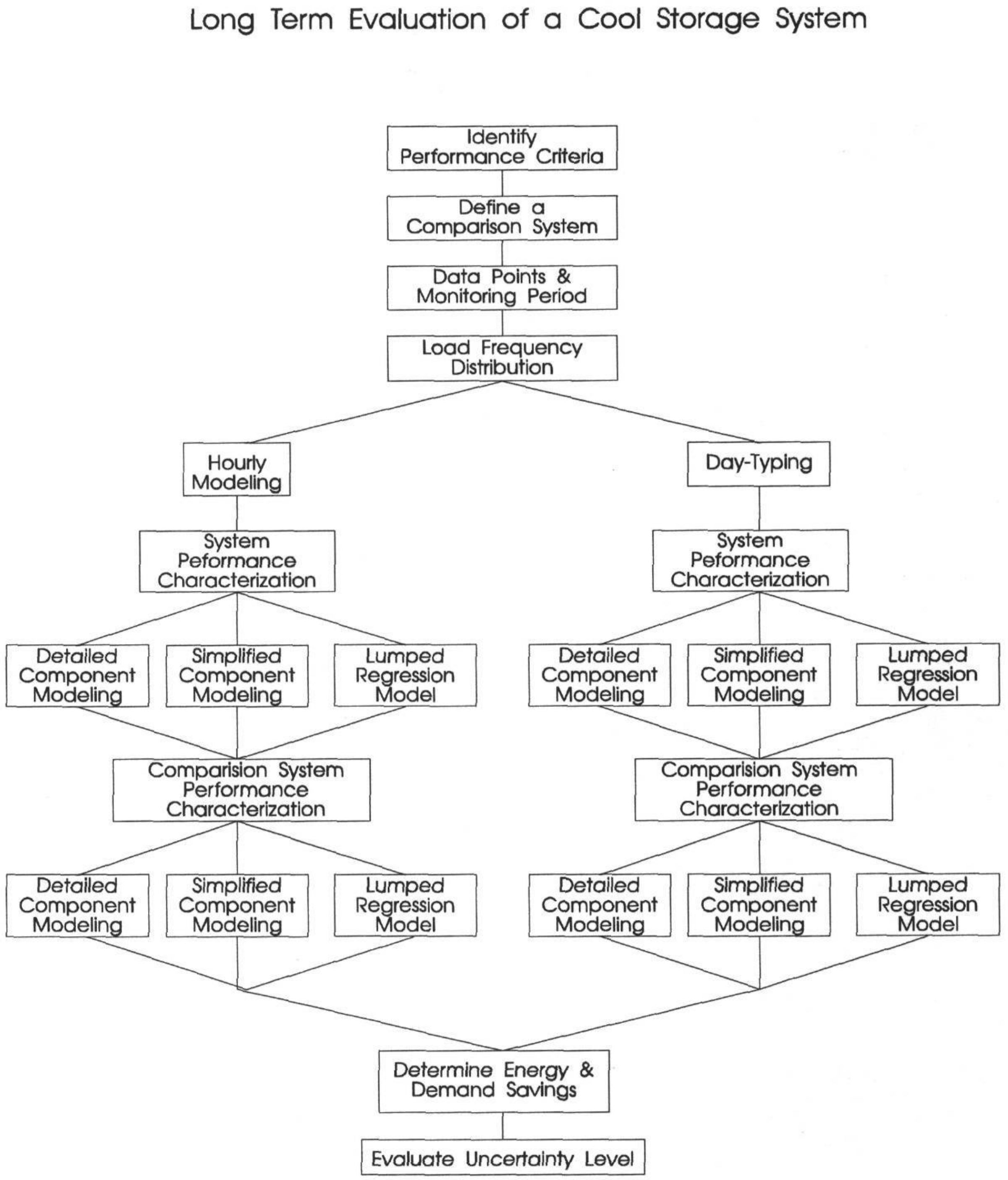

Figure 2.1: General Methodology.

2.1 Required Information

There are a number of definitions and specifications that affect the details of the testing procedure, that will vary depending on the specific installation and the rationale for testing. Since this information cannot be prescribed as part of the generalized methodology to apply to all systems, it must be stipulated before testing begins by the party interested in determining the cool storage system performance. The required information is discussed below:

2.1.1 Desired Level of Uncertainty

The RP1004 test methodology will offer a number of options for testing and analysis, providing for more or less uncertainty in the test results, with a corresponding range of implementation cost. Users will choose testing options based on the desired level of uncertainty, which will be determined by how the test results are to be used and on the budget available for testing.

2.1.2 Definition of Comparison System

The primary goals of the proposed RP1004 methodology are to determine energy savings and demand shift. Therefore, it will be important to define the “base-case” cool storage system to which the cool storage system performance will be compared.

Our intention is for the RP1004 methodology is for it to provide guidance for defining the comparison system, but it would be impossible to provide prescriptive methods that would apply to every case. Ultimately, the basis for defining the base case that determines "savings" and "demand shift" will need to be specified up front by the party that is interested in determining these quantities.

The comparison system is relatively simple to define when:

1. the storage system uses a chiller that is clearly of the same type that would have been used in a non-storage system, and

2. there is some operation of the cool storage chiller at "conventional" chilling temperatures. The practitioner can then determine the chiller performance for conventional operation, and apply this performance to the annual loads.

The problem is more difficult in cases where:

1. The storage cooling plant is of a different type than the most likely non-storage alternative. For example, chiller vs. DX, air-cooled vs. water-cooled, multiple chiller types or sizes. The base-case definition should specify how the comparison system’s performance characteristics are to be determined.

2. There is no obvious choice for the system type that "would-have-been" installed in place of the storage system. The base-case definition should stipulate the comparison system type.

3. The storage system has been designed with a "total system" approach, incorporating design features such as a large chilled water temperature range, cold air distribution, an innovative pumping configuration, or a nonstandard condenser flow rate. The base-case definition must specify to what extent auxiliary energy savings stemming from these features are credited to the cool storage system, or whether they might also have been achieved with a non-storage system.

4. Actual performance falls short of the design intent or the manufacturers' equipment ratings. The base-case definition must address whether the comparison system should also be assumed to have fallen short.

In the literature we reviewed Akbari and Sezgen (1992) provided a methodology for comparing measured cool storage performance with modeled nonstorage system performance. EPRI (1988) provided recommendations for defining a simulated nonstorage system for performance comparison. Merten et al. (1989) described measured performance of six cool storage systems monitored during 1987, and seven systems monitored during 1988, and also describe a method for determining the appropriate efficiency for the simulated nonstorage comparison system.

Liu et al. (1994) used an average kW/ton vs. percent full load performance curve, based on field data from 30 centrifugal chillers, to determine base-case system performance for comparison with cool storage field data collected by Merten et al. (1989). Sohn (1989, 1991a, 1991b) described the results of field monitoring of three ice storage systems, and a comparison with nonstorage system performance. Abbas et al. (1995) and Abbas et al. (1996) presented results of field monitoring at seven cool storage sites.

Some users may wish to compare the performance of a monitored cool storage system with more than one comparison system. For example, Akbari and Sezgen (1992) used three approaches to chiller sizing in defining comparison systems. Dorgan and Dorgan (1995) and Dorgan et al. (1995) compared measured cool storage system performance with multiple non-storage options. The Dorgans also simulated the performance of monitored cool storage systems using revised operating strategies and modified designs. Users of the RP1004 methodology can perform such multiple comparisons by appropriate definition of the comparison system(s).

2.2 Field Performance Testing

Our review of the literature indicates that ARI (n.d.) described a laboratory test method for the purpose of rating cool storage devices at a specific test condition. NAESCO (1993) outlined a basic method of determining cool storage system energy and demand savings. ASHRAE Standard 150P (ASHRAE 1997a) included instrumentation requirements, methods for verifying instrument accuracy, and information required prior to testing.

EPRI (1988) provided recommendations for monitoring cool storage systems. Gillespie (1997) described instrumentation selection, installation, and uncertainty issues for monitoring a cool storage system. Hensel et al. (1991) determined flow to and from a chilled water storage tank by correlating pitot-tube measurements with a mass balance based on orifice-plate measurements at other locations in the system. Bahnfleth (1998) used measurements of the thermocline transit time to determine the flow rate in a chilled water storage tank. Dorgan and Dorgan (1995) and Dorgan et al. (1995) described methods for data verification and post-processing.

2.2.1 Data Points to be Monitored

Our review indicates that a complete performance evaluation requires measurement of the electric demand and energy use of the chiller(s) and auxiliaries, and the thermal energy (cooling) supplied to or from storage, chiller(s), and load. The following data points should be monitored:

Auxiliaries:
- Total electric power for all pumps and cooling towers

For each chiller:
- Return temperature
- Supply temperature
- Entering condenser water temperature
- Leaving condenser water temperature (nice to have but not required)
- Chilled water flow rate
- Condenser water flow (nice to have but not required)
- Electric power to the chiller

Building cooling load:
- Return temperature
- Supply temperature
- Chilled water flow rate
- Ambient dry-bulb
- Ambient humidity
- Whole-building electric power
- Motor control center electricity use (nice to have but not required)

Storage device:
- Entering temperature
- Leaving temperature
- Flow into storage
- Flow out of storage
- Ambient dry-bulb surrounding the storage device (nice to have but not required)

Quantities shown in parentheses are not required, but would provide additional information for validating measured data.

We will investigate the use of subsets of the data for predicting performance, for cases where it is not possible to monitor all the recommended points, and will evaluate the effect on the uncertainty in the result.

Instrumentation requirements will be defined according to the recommendations of ASHRAE

Standard 150P (ASHRAE 1997a).

2.2.2 Appropriate Monitoring Period

The monitoring period must be short enough that it will be practical to apply. However, it must be long enough, and occur at an appropriate time of year, to capture sufficient variation in loads to accurately predict long-term performance. As discussed in Section 4, a minimum of two weeks of data collection will probably be required. A longer monitoring period, or multiple periods to capture seasonal variation, will increase the analysis effort (compared to one period) and reduce the uncertainty in the result. The length and appropriate season of the data collection period will also be evaluated as part of testing the proposed methodology.

2.2.3 System Design Data and Operating Schedules

Certain information about the system is required for developing load frequency distributions, for characterizing system operation, and for evaluating system performance.

Users of the methodology must understand the system design intent in order to model and evaluate the system's operation. Users must also gather equipment nameplate data and performance ratings, and system design parameters, in order to properly select instrumentation. Development of appropriate system models will also rely on system design data, as well as on measured data.

Knowledge of the building operating schedules will be used in selecting monitoring periods and in developing load frequency distributions. System operating schedules will be used to develop system models. System operating schedules and utility rate schedules will be used to determine the appropriate "on-peak" and "off-peak" periods for the load and performance analyses. These schedules will also help determine the appropriate hour for defining the beginning and end of each 24-hour analysis period.

2.2.3 Data Collection Procedures

The specific data to be collected will be determined by the selected approach for characterizing the system performance. The test methods will be in accordance with the requirements of ASHRAE Standard 150P (ASHRAE 1997a) where applicable.

2.3 Determine the Annual Load Frequency Distribution

There are a number of possible approaches to defining the annual load frequency distribution, including hourly modeling, day-typing, and other methods.

Any method for defining the load frequency distribution should provide a means of associating the loads with the pertinent on-peak or off-peak utility periods. Three methods are presented in the following sections, including: hourly modeling, daytyping and other methods.

2.3.1 Hourly Modeling

The hourly modeling approach uses short-term measured load data to determine model parameters that describe the variation in loads based on outdoor temperature, humidity, internal loads, and other statistically significant variables. Given annual hourly data for the driving variables, these model parameters are used to estimate the load for each of 8,760 hours in a year.

Determination of load frequency distributions by hourly modeling is discussed in detail in Section 4 of this report.

2.3.2 Day-typing

The day-typing approach characterizes loads on a daily profile, rather than an hourly basis. The combination of load conditions over a 24-hour period is considered one multi-dimensional "point".

This approach is based on the fact that the performance of a cool storage system in a given hour depends on what has occurred in previous hours. A cool storage system's performance is largely determined by the load profile over the complete storage cycle (Dorgan and Elleson 1993, ARI 1994, Elleson 1997). Characterizing loads and system performance on a daily profile basis helps reduce the complexity of the analysis by reducing the number of points that must be considered.

In the review of the literature Bou Saada and Haberl (1995a, 1995b) described the use of weather daytyping for characterizing building energy usage. Baughman et al. (1993) developed a "characteristic days method" for evaluating cool storage system performance. Daily cooling coil loads (kBtu/day) were found to be correlated with the peak daily temperature. A set of fifteen days was selected to represent the range of variation of cooling coil loads over the year. Performance of a cool storage system was estimated for each of these days using a computer model. Each month of the year was characterized according to the number of each of the characteristic day-types occurring in the month. (Presumably weather data for a typical year was used to perform this characterization.) The storage system demand and energy use for each month was determined from the maximum demand and total energy use of the day-types in the month.

The RP1004 day-typing methodology will be based on the method of Baughman et al. (1993), and on similar unpublished work by Elleson. We anticipate that the method will be comprised of the following steps:

1. Group the measured loads into 24-hour profiles. We believe that a period from 6 a.m. to 6 a.m. will be appropriate, because for most cool storage systems, storage will typically be at the fully charged condition at the beginning and end of the period. We will also investigate whether some other period might be preferable.
2. Determine the number of day-types required to adequately reflect the full range of loads and system performance. This number will be highly system-specific. Some cool storage systems operate similarly over the entire range of loads, and relatively few day-types will be required.

Other systems may vary widely in performance depending on peak temperature, time of year, weekend or weekday, and other factors. In such cases, a large number of day-types would be needed to fully characterize the annual system performance. Note that the primary objective of the day-typing is not to characterize the loads, but to characterize the system's response to the loads.

3. Classify the measured 24-hour load day-type profiles according to the day-types defined in the previous step. Note that the monitoring period(s) should include days representing all or most of the required day-types. It may be necessary in some cases to develop a model to define day-types that are not represented in the measured data.
4. For each day-type, determine the coefficients that best describe the magnitude and shape of the 24-hour load profile.
5. Determine the annual load frequency distribution by assigning each day of the year to one of the day-types.

The annual system performance is determined by modeling the system against the load profile for each day-type, as described in Section 2.5.

2.3.3 Other Methods

Other methods that have been used for determining load frequency distributions include load duration curves and degree-day or degree-hour methods.

A load duration curve describes the number of hours of occurrence of each level of load. This approach is appropriate for simplified modeling of equipment whose operation is coupled directly to the load. However, more detailed information is needed if equipment operation is dependent on other factors such as outdoor temperature. The load duration curve also does not allow for analysis of equipment such as storage systems whose operation depends on the time of day and on previous hours' operation as well as the current load.

Elovitz (1990) used a spreadsheet-based method to estimate savings of several proposed cool storage systems, using a degree-hour method based on bin data to estimate cooling ton-hours per day. This method did not account for variations in the load profile from day to day. The method also made a number of assumptions that would significantly increase the uncertainty in the final result. This degree-hour method is actually an over-simplified approach to load prediction by regression against outdoor temperature.

2.4 Characterize the Performance of the Cool Storage System During the Monitoring Period.

We have identified three modeling approaches for characterizing cool storage system performance:

- Detailed component models of each piece of equipment and their interactions
- Simplified component models for each mode of system operation
- Simplified lumped regression or "black-box" models for each mode of system operation

The modeling approaches described below involve selecting appropriate model parameters to characterize the cool storage system operation and its performance in response to building loads or outside temperatures. These approaches are similar to the calibrated simulation approach of ASHRAE Guideline 14P (ASHRAE n.d.).

Each of the three modeling approaches can be used in conjunction with either the hourly or day-type methods of characterizing the annual load frequency distribution.

Each modeling approach takes into account differences in system operation during the defined on-peak and off-peak periods. The methods described include: detailed component modeling, simplified component models and lumped regression models.

2.4.1 Detailed Component Modeling

The detailed component modeling approach simulates the detailed performance of each individual chiller, pump, heat rejection device, and storage device, in response to the appropriate temperatures, flow rates (or other significant variable), for each time step. Simulation of these components is discussed in Section 3 of the report.

A detailed storage device model should capture the heat transfer and fluid dynamic processes in the storage tank. Several authors have described models for simulation of cool storage devices. Jekel (1991), Jekel et al. (1993), Vick et al. (1996a, 1996b), Neto and Krarti (1997a, 1997b), and Drees and Braun (1995) have developed models for internal melt ice-on-coil systems.

Silver et al. (1989) modeled an external melt ice-on-coil system. Strand et al. (1994) and Pederson et al. (n.d.) described the development of models for internal melt, encapsulated ice, and ice harvester systems, and their implementation in the BLAST program. Gretarsson et al. (1994) developed a model for stratified thermal storage. Zurigat (1989) surveyed stratified thermal storage tank models and compared several of the models against experimental data.

The detailed component model approach also requires a characterization of the cool storage system operating strategy. Braun (1992), Drees and Braun (1996), Ruchti et al. (1996), and Kawashima et al. (1996) discussed conventional and optimized cool storage operation and control strategies. We will use these references, and recent unpublished work by Elleson, to incorporate appropriate modeling of operating strategies.

A detailed cool storage system model that would allow a user to simulate any cool storage system does not currently exist. Because of the wide variety of storage devices, system configurations, and operating strategies, such a model would be too complex for the average ASHRAE practitioner to use in the field. Section 2.4.2 provides a functional description of such a model, outlining the capabilities that would be required. Development of such a detailed model is beyond the scope of the current work.

We expect that the RP1004 methodology will allow the user to choose a model that is appropriate for the specific system to be tested. The following section gives an example of a detailed model.

2.4.2 Example Functional Description for a Detailed Cool Storage System Model

System Configuration

The user shall supply the cooling system model with information to characterize the configuration of the system. In particular, the model must be able to simulate the following configurations:

- Internal melt ice-on-coil
- External melt ice-on-coil
- Encapsulated ice
- Stratified chilled water storage
- Chiller in series with storage, located upstream or downstream of storage
- Chiller in parallel with storage
- Multiple chillers, with any combination of series, parallel, series-parallel arrangements
- Storage, chiller, or load loops separated by heat exchanger(s)
- Storage, chiller, or load loops separated by primary-secondary pumping
- Storage, chiller, and load in one primary loop
- Constant flow or variable flow to load
- Chiller loop or storage loop flow rates vary depending on operating mode
- Optional bypass around storage
- Optional bypass around load
- Water, glycol or other heat transfer fluids, specified separately for load, chiller, storage

Chiller Model

Each chiller in a given system would be modeled by a separate instance of the chiller model. If a chiller has dramatically different performance in direct cooling mode and charging mode it might be represented by two separate models. Two or more identical chillers that always operate with equal capacities could be simulated by a single model.

Input Parameters

- Chilled water temperature entering chiller
- Flow rate entering chiller
- Chiller setpoint
- Chiller demand limit
- Mode of operation
- Outdoor dry-bulb and wet-bulb temperatures
- Condenser water temperature entering chiller

Output Parameters

- Chilled water temperature leaving chiller
- Chiller demand

Configuration Data

- Performance curves defining the capacity and demand of the chiller as a function of demand limit, heat rejection temperature, chilled water entering temperature, condenser water entering temperature, chilled water leaving temperature and chilled water and condenser water flow rates.

Cooling Tower (or Other Heat Rejection Device)

Input Parameters
- Temperature from chiller
- Flow rate from chiller
- Condenser water temperature setpoint

Mode of operation
- Outdoor dry-bulb and wet-bulb temperatures
- Control strategy

Output Parameters
- Temperature to chiller
- Tower airflow or fan speed
- Pump demand
- Tower fan demand

Configuration Data
- Performance curves defining the temperature to the chiller as a function of chiller heat rejection, temperature from the chiller, tower airflow or fan speed, outdoor dry-bulb and wet-bulb temperatures
- Performance curves defining the pump demand as a function of condenser water flow.
- Performance curves defining the tower demand as a function of tower airflow or fan speed.

Cool Storage Model

Input Parameters
- Current storage inventory
- Storage inventory history
- Temperature entering storage
- Flow rate entering storage
- Current load

Output Parameters
- Temperature leaving storage
- New inventory

Configuration Data
- Performance curves defining the temperature leaving storage as a function of current storage inventory, storage inventory history, temperature entering storage, and flow rate entering storage

The inventory must be given in terms of usable storage capacity, which is dependent on the temperature and rate at which the cooling must be delivered. The discharge model should address the temperature and discharge rate available from storage.

Distribution System Model

Input Parameters

- Current operating mode
- Heat exchanger entering temperatures

Output Parameters

- Pump demand
- Heat exchanger leaving temperatures

Configuration Data

- Assignment of what pumps operate in each operating mode.
- Performance curves defining the demand of each pump as a function of pressure and flow.
- Configuration of heat exchangers in the system, in each operating mode.
- Performance curves defining the temperature leaving each heat exchanger as a function of entering temperatures and flow rates.

Cool Storage Control Strategy Definitions

For each time interval, the routine will determine the appropriate cool storage control strategy and associated limits. The standard control strategies are:

- Charging
- Charging and meeting load
- Discharging, chiller priority
- Discharging, storage priority
- Discharging, proportional loading

For each control strategy, the following limits must be specified:

- Chiller demand limit
- Is chiller demand limit based on chiller demand or total facility demand?
- Storage discharge rate limit

The values of these limits may change with time.

Cooling Plant Control Strategy Definitions

A control strategy for sequencing multiple chillers must also be selected. There are many possible approaches to sequencing and loading multiple chillers. A tentative structure for defining the cooling plant control strategy is given below.

The model should allow the user to define the following control parameters for each chiller:

- Priority order
- High load point, the capacity level at which the next priority chiller starts
- Demand limit
- Low load point, the capacity level at which the chiller shuts down

In addition, the model should be able to simulate:

- Chillers that share the load in proportion to their capacities, such as parallel-connected chillers,
- Chillers that meet the load sequentially, such as series-connected chillers
- Combinations thereof

A typical control scheme would be as follows: The first priority chiller meets the load first. When the load on the first chiller reaches its high load point, the second chiller is started. When the load on the second chiller reaches its high load point, the third chiller is started, and so on. When the load on the last-priority chiller that is running falls below its low-load point, it is shut down, etc.

More than one chiller may be assigned the same priority, in which case the chillers would start and stop at the same times, and would be loaded equally.

The model should also have the capability for the user to develop a custom control strategy definition to model a particular system.

2.4.3 Simplified Component Model

The simplified component model simulates the system in terms of four generalized components:

- building loads,
- chiller,
- storage, and
- auxiliaries (pumps and cooling tower fans).

The simulation of equipment performance and operating conditions is not as precise as the detailed component model. This approach demands less effort in the initial formulation of the model, as well as in the determination of appropriate model parameters for a given system. This approach will be used for demonstrating the RP1004 methodology.

The simulation of building loads is discussed in Section 4. The simulation of chillers, pumps, and cooling towers is addressed on Section 3.

For simulation of the cool storage device, we propose to investigate an effectiveness model based on the work of Jekel (1991) and Jekel et al. (1993). These investigators used a heat transfer effectiveness concept to describe the performance of an internal melt ice-on-coil storage tank.

For a heat exchanger, the effectiveness is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate. For both the charging and discharging periods of an ice storage tank, the maximum possible heat transfer rate is obtained when the outlet brine temperature from the tank is equal to the phase-change temperature, T_f (32°F for water). The minimum flow-rate-specific heat product for an ice storage tank is that of the brine.

Therefore, the effectiveness for a storage tank is defined as

$$\varepsilon = \frac{(T_{b,in} - T_{b,out})}{(T_{b,in} - T_f)} \tag{2.1}$$

where $T_{b,in}$ = brine inlet temperature
and $T_{b,out}$ = brine outlet temperature (Jekel, et al. 1993)

This effectiveness model was developed for characterizing an ice storage device. The same concept can be applied to a chilled water storage tank, where the effectiveness would be defined as

$$\varepsilon = \frac{(T_{in} - T_{out})}{(T_{in} - \overline{T}_{in})} \tag{2.2}$$

where T_{in} = inlet water temperature

T_{out} = outlet water temperature

and $\overline{T}_{in}$ = integrated average temperature supplied to the tank over the previous cycle.

During discharge mode, $\overline{T}_{in}$ is the average temperature supplied to the tank over the previous charge cycle. During charge mode, $\overline{T}_{in}$ is the average temperature supplied to the tank over the previous discharge cycle.

The effectiveness is therefore a function of flow rate through the tank, the current state of charge of the tank, and whether the tank is in charging or discharging mode.

2.4.4 Lumped Regression or Black-Box Model

The lumped regression or "black-box" model is based on empirical or semi-empirical correlations of the system's responses to load conditions. The system model, developed by regression, Artificial Neural Network (ANN), or other techniques, returns the cooling system demand and energy use as a function of outside temperature, day of week, time of year, and possibly other parameters. This modeling approach could be used with hourly loads, or with loads expressed by daytypes.

2.5 Estimate the Annual Performance of the Cool Storage System

The annual system performance is determined by combining the cool storage system model with the load frequency distribution. The specific steps differ according to whether the load frequency distribution is based on hourly loads or day-types.

For an *hourly load distribution*, the component model or lumped regression model is run with hourly loads for the year.

For a *day-typed load distribution*, the cool storage system performance will first be determined for each of the characteristic day-types. If the measured data are not sufficient to determine performance for each day-type, a component model or regression model will then be used to fully characterize the performance. The monthly and annual performance are determined by multiplying the performance for each day-type by the number of occurrences of that day-type.

For *either type of load frequency distribution*, the demand and energy usage are broken down according to on-peak and off-peak periods.

2.6 Characterize the Performance of the Comparison System

To characterize the performance of the comparison system, a component model or regression model must be developed. The system to be modeled and the method of determining performance parameters will be guided by the definitions provided by the user, as discussed in Section 2.1.

For the component model, appropriate equipment definitions and operating schedules will be required. For the regression model, characterizing the comparison system performance may be difficult since there are no measured data. In the simplest case, the comparison system is the same as the existing system but with no storage component. In this case, the comparison system performance can be determined by adjusting measured performance to account for different operating schedules. Similarly, if the comparison system differs from the existing system only in the chiller capacity, the measured performance can be scaled to account for the adjusted capacity.

The methodology will provide guidance for defining appropriate model parameters and accounting for differences in operating strategies.

2.7 Estimate the Annual Performance of the Comparison System

The annual performance of the comparison system is determined by the same method as that of the cool storage system.

For an *hourly load distribution*, the component model or lumped regression model is run with hourly loads for the year.

For a *day-typed load distribution*, the comparison system performance is determined for each of the characteristic day-types. The monthly and annual performance are determined by multiplying the performance for each day-type by the number of occurrences of that day-type.

As for *the actual system performance*, the demand and energy usage for the comparison system are broken down according to on-peak and off-peak periods.

2.8 Determine Energy and Demand Savings, and Other Performance Measures

The methodology developed under this project emphasizes the determination of the annual energy usage and peak energy demand of a cool storage system. The methodology also provides for determining the energy savings and demand shifted relative to a comparison system. These performance indices, as well as some additional measures, are discussed in the following sections.

2.8.1 Energy Performance

A common metric for comparing system energy performance is cooling system energy input divided by heat absorbed from the load, commonly expressed in kWh/ton-hour. ASHRAE Standard 150P (ASHRAE 1997a) defined this ratio, calculated over one or more complete storage cycles, as the cycle specific energy consumption. Merten et al. (1989) called this term the system energy use, and used it to compare several cool storage systems and the corresponding non-storage comparison systems. Dorgan and Dorgan (1995) and Dorgan et al. (1995) used a similar approach to compare cool storage systems and non-storage comparison systems.

The cycle specific energy consumption is useful for comparing cool storage systems to each other, as well as to nonstorage systems. The RP1004 methodology will address determination of this performance parameter to ensure that systems are compared on an equivalent basis. The methodology will also provide for calculation of kWh savings, disaggregated according to on-peak and off-peak periods, to allow calculation of utility bill savings.

2.8.2 Peak Demand

The peak energy demand of a cooling system can be characterized by the ratio of the peak demand to the peak cooling load, which can be expressed in terms of KW/ton. Dorgan and Dorgan (1995) and Dorgan et al. (1995) referred to this ratio as the demand efficiency. The RP1004 methodology will address the calculation of this parameter.

2.8.3 Demand Shift

The peak demand shift achieved by a cool storage system is an important performance parameter. The demand shift is a measure of the reduction in demand relative to a comparison system meeting the same loads.

The time of day when the shift in demand is of greatest interest is referred to as the on-peak period. This period is the time during which the cool storage system is designed to reduce demand, and is often, but not always, coincident with the on-peak period as defined by the applicable electric utility rate schedule.

There are several possible approaches to calculating the demand shift. The methods differ in whether they consider whole-building demand or cooling system demand only. Methods that consider cooling system demand only differ in whether they evaluate the maximum demand, or the demand at the time of the maximum cooling load.

Abbas et al. (1995) compared the measured monthly whole-building peak demand of buildings retrofitted with cool storage to whole-building demand measured prior to the retrofits. This approach is appropriate for buildings where cool storage is added to an existing system, where prior years' data are available, and where cooling loads have not changed from the prior years. However, it is not applicable to systems whose cooling loads have increased or decreased, or to systems that are originally designed and constructed to use cool storage.

Merten et al. (1989) and Akbari and Sezgen (1992) estimated the demand shift achieved by cool storage systems by comparing the maximum whole-building demand for buildings with cool storage to the maximum whole-building demand with simulated comparison cooling systems. The measured whole-building demand was divided into cooling and non-cooling components. The total demand for the comparison system was calculated by adding the measured non-cooling demand to the simulated comparison system cooling demand. The on-peak demand reduction was calculated for each month by subtracting the maximum on-peak demand with cool storage from the maximum total on-peak demand with the nonstorage system. Because the maximum non-cooling demand is not necessarily coincident with the maximum cooling demand, the demand shift calculated in this way is not the same as the cooling system demand shift.

Dorgan and Dorgan (1995) and Dorgan et al. (1995) compared the measured monthly cooling system peak demand (chiller plus auxiliaries) to the peak demand of simulated cooling systems without storage.

Annex E of ASHRAE Standard 150P Public Review Draft (ASHRAE 1997a) suggests two simplified methods of assessing demand shift. Both of these methods estimate the comparison system demand associated with the maximum on-peak cooling load. The demand shift is calculated by comparing this comparison system demand: (1) with the maximum measured cool storage system demand, or (2) with the cool storage system demand associated with the maximum on-peak cooling load.

The RP1004 methodology for determining demand shift should be widely applicable to any cool storage system tested under the method. It should allow comparison of different systems, and it should be relatively easy for the practitioner to implement.

We recommend evaluating demand shift based on cooling system demand rather than whole-building demand, primarily because of ease of implementation. This approach is simpler because measurement of whole-building power, and disaggregation of power into cooling and non-cooling demand, is not required.

We recommend determining demand shift using the demand associated with the maximum cooling load, for the cool storage system and for the comparison system. This approach provides a valid evaluation of the performance of a given system, and it is applicable with simplified analysis methods that do not involve hour-by-hour evaluation of system operation.

2.8.4 Other Performance Indices

In some cases, a system owner or other party may be interested in determining other performance parameters such as maximum usable storage capacity, storage tank figure of merit, or storage utilization factor. Testing to determine these or other parameters could be performed concurrently with the RP1004 test methodology, if the need for this information is made clear in the planning stages.

Several authors have addressed the use of other indices to describe cool storage system performance. Tran et al. (1989) described the use of the Figure of Merit to characterize the measured thermal performance of six chilled water storage systems. Bahnfleth (1998) introduced the half-cycle Figure of Merit for evaluating chilled water storage systems. Rosen et al. (1988) discussed the use of exergy analysis, rather than energy analysis, for the evaluation of sensible thermal energy storage systems. Rosen (1992) also developed several definitions of energy and exergy efficiency for sensible thermal energy storage, for the overall storage process and for charging, storing, and discharging periods.

2.9 Evaluate Uncertainty

Ideally, the evaluation of uncertainty begins with the initial selection of instrumentation and analysis methods, and is an integral part of the ongoing analysis. The uncertainty in the final results should also be determined and reported along with the results. As Section 5 shows, a rigorous uncertainty analysis for this performance evaluation methodology is very complex, and will likely be beyond the capabilities of most ASHRAE users of the methodology. It is therefore necessary to develop simplified methods for estimating uncertainty, or generalized guidelines that would allow users to determine "uncertainty bands" in which their results fall.

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Zurigat, Y.H., K.J. Maloney and A.J. Ghajar. 1989. Comparison study of one-dimensional models for stratified thermal storage tanks. ASME Journal of Solar Energy Engineering. v 111 n 3 Aug 1989, p 204-210
Surveys stratified cool storage tank models and compares six of the models against experimental data, primarily with respect to mixing introduced during charge and discharge cycles.

3.0 ANALYTICAL MODELS FOR CHILLERS, FANS AND PUMPS

3.1 Background and Objectives

Task 1a and 2b of our proposal involve a literature review and a description of the proposed analytical models. Section 4 of this document pertains to a literature review and proposed methodology of predicting long-term building loads from short-term data. This section limits itself to the equipment associated with the cooling system that supplies cooling to the HVAC system.

We have suggested, in our proposal, to evaluate two different analytical approaches:

(a) a component based approach that involves developing and characterizing individual components of the system (such as the building, storage tank, chiller, cooling pumps and circulating fans) in terms of climatic variables and other appropriate parameters. The performance of the cooling system under different operating modes is then predicted by assembling these components appropriately and performing a chronological hour-by-hour simulation during the entire season or the entire year;

(b) a lumped model approach where macro-models of the entire cooling system will be developed for each operating mode, and a modified bin-method (ASHRAE, 1997b) type of analysis over the pre-specified day-types (typically weekdays and weekends) will be used to determine the seasonal or annual energy and demand savings as a result of the TES system.

This section will limit itself to approach (a) described above, while a separate section will concern itself with analytical approach (b). The objective of this section is to review existing literature of appropriate component models and in-situ measurements for chillers, fans, pumps and TES systems which we deem appropriate to our research, and state the types of models which we shall evaluate with the monitored data collected in the framework of this research. An annotated bibliography of the references cited in this section has also been included at the end of this section.

Much of the literature on testing of HVAC equipment is based on stand-alone testing of a single component in a dedicated test facility with laboratory-grade measurements and limited specific objectives. Accurate evaluation of energy efficiency improvements/alternatives of installed equipment requires their in-situ field performance. Unfortunately, manufacturers' data and laboratory performance measurements are inadequate because there is often considerable differences between the two.

Field testing can have many different objectives, as well as involve widely varying equipment configurations and limits on measurement techniques and accuracy. Further, the mathematical models based on which the monitored data will be analyzed in order to characterize the equipment in-situ performance are different than those used for design purposes. They are typically macro-models consisting of a relatively few model parameters whose coefficients need to be identified from the monitored data, usually by regression analysis. This approach falls under "inverse modeling" approach described in the ASHRAE Handbook of Fundamentals (1997b).

The effort in performing a literature review on cooling pumps, fans and chillers and in proposing analytical models and in-situ monitoring protocols of such equipment is considerably reduced since the ASHRAE-funded research (RP-827) has recently been completed. The results from this research are well documented in Phelan et al. (1994, 1996, 1997 a, b c) and we shall use many of their conclusions and recommendations in the framework of this research. An overview of the methods, specifically as they relate to this research, is briefly presented below.

3.2 General approach of the component based model

3.2.1 Overall system model

Typically, a TES system consists of several air handler units in the building (and their associated terminal distribution systems) which supply the required cooling (and heating) energy to meet the building loads, several pumps, as well as several chillers. In the framework of this research, we shall assume these to be lumped into one piece of equipment of each type as shown in Fig.3.0. Following Braun (1992), the total electrical power consumed in order to provide the necessary cooling energy to the building is given by:

$$E_{total} = E_{ahu} + E_{bldg\ pump} + E_{chiller} + E_{chiller\ pump} + E_{storage\ pump} \qquad (3.1)$$

where E_{ahu} is the power consumed by the air handlers in the building,
$E_{bldg\ pump}$ is the power consumed by the pump(s) to circulate chilled water in the building,
$E_{chiller}$ is the power consumed by the chiller(s),
$E_{chiller\ pump}$ is the power consumption of the cooling plant consisting of the condenser water pump to the cooling tower (and the fan in the cooling tower fan which we assume to be operated under constant air flow rate) , and the pump used to circulate chilled water in the primary loop of the evaporator (which is often different than $E_{bldg\ pump}$), and
$E_{storage\ pump}$ is the pump(s) used by the TES.

The *component-based method* involves taking in-situ measurements of each of these equipment individually and identifying the empirical coefficients of the appropriate performance models by regressing the models against the monitored data. Subsequently, depending on how the entire system comprising of the building, chiller and TES is operated, the appropriate individual component model equations are simultaneously solved to predict the power (or the hourly energy) used by the individual equipment, and consequently that of the entire cooling system. These equations would then directly allow the analyst to determine the seasonal or annual energy and demand in that building for a given set of conditions. If similar equations have been developed for the baseline (i.e., non-TES system) and TES cases, then the energy and/or demand reductions can be accurately assessed for normalized conditions.

3.2.2 Approach used in RP-827

The approach adopted in RP-827 is directly pertinent to this research because it concentrates on in-situ measurements. A brief description of RP-827 is therefore pertinent to understanding the proposed methodologies. In 1994, ASHRAE undertook research project RP-827, entitled

"Methodology Development to Measure In-Situ Chiller, Fan, and Pump Performance." The overall objective of this research was to develop and evaluate methods for performing in-situ testing of mechanical equipment to determine annual energy use characteristics. More specifically, a set of short-term, in-situ test methods were developed to provide performance information that could be used in long-term energy calculations. For fans and pumps, six different test methods were evaluated, such as single point measurements, single point measurements along with manufacturers performance curves, multiple point tests with loads imposed either artificially at the pump or at the building zone level, and passive monitoring methods. The methods generally result in statistical relationships that express power consumption as functions of part-load ratio and, in the case of chillers, system operating temperatures.

The development of these methods was based on the literature survey of laboratory and field testing methods described by Phelan et al. (1994). The RP-827 methods were guided by the following philosophy:

(a) There will not be a single best method for all situations. In some situations, limited resources for testing and evaluation may allow only a single field measurement. In other cases, a mechanical system can be monitored for a full day, but the methods cannot intrude on normal system operations. In yet other situations, false loads can be readily imposed on the systems outside of normal operating schedules. Therefore, a set of test procedures was developed, each having different minimum measurement requirements.

(b) There are many existing standards for experimental measurements and laboratory testing of mechanical equipment performance. The RP-827 in-situ methods drew on the existing component testing procedures as much as possible, extending the methods to account for the effects of system installation, operation, and control.

(c) The evaluation of annual energy consumption and peak demand characteristics for installed HVAC equipment requires knowledge of the operating load on the system, both at design conditions and throughout the year. However, measurement and characterization of building loads were outside the scope of RP-827. (This aspect of building load prediction from short-term tests is explicitly addressed in the framework of the current RP-1004 research). Therefore, use of the RP-827 test methods require the user to provide the building load distribution, often presented as the number of hours of occurrence of a particular load range.

(d) Annual energy consumption of mechanical equipment is significantly affected by the system control strategy. Therefore, any effort to measure equipment performance for energy characteristics must include the control system within the measurement environment. In particular, any methods of artificially loading the equipment to obtain a rich data set must be applied *outside* the equipment control envelope.

(e) The prediction of annual energy use from in-situ measurements involves several distinct uncertainties. Any in-situ test methods should be accompanied by comprehensive methods of uncertainty analysis accounting for all relevant sources of error.

Given the considerations outlined above, a set of in-situ test methods has been developed for chillers, fans, and pumps by Phelan et al., (1996, 1997 a, b). In all cases, a relationship between power consumption and "load", which varies with each equipment type, was developed for the equipment and system using a combination of direct measurements, statistical regression analysis, manufacturer's data, and engineering principles. Details of the protocols for individual measurements, including guidelines for placement of instrumentation and accuracy of instrumentation, were based on accepted industry standards for stand-alone equipment testing.

In general, each RP-827 testing guideline specified the following test characteristics:

(1) physical characteristic to be measured (power, flow, pressure, etc.)

(2) number of data points required

(3) accuracy of measurements

(4) reference to existing applicable measurement standards

(5) methods of artificial loading (as required)

(6) calculation equations and uncertainty analysis.

Several of the methods involved measurements under a range of load conditions. In some methods, the measurements are taken during times of natural load changes while in others, the load variations are imposed by the user. In such cases, the loads were imposed to represent variations as they would normally occur.

The methods developed under RP-827 were evaluated using long-term measured data on fans, pumps, and chillers. Most of the energy consumption estimates were determined by applying the test methods to equipment monitored under the Texas LoanSTAR program (Haberl et al., 1996). Additional evaluation was also performed using other field data, as necessary. The suitability of the test methods was evaluated by comparing predicted long-term energy consumption with measured energy use.

3.3 Electric power consumed by building air handling units

The theoretical aspects of calculating fan performance are well understood and documented. Fan capacity and efficiency are calculated from measurements of static pressure, velocity pressure, air flow rate, fan speed, and power input. The necessary instrumentation is shown schematically in Figure 3.1. Measurement techniques and calculations are detailed in the ASHRAE, AMCA, and ASME standards described by Phelan et al. (1997a). This research proposes to base the measurement protocols on the RP-827 recommendations as needed.

In order to model electricity used by air-handling units, we need to distinguish between three building air distribution system types and their control (Phelan et al., 1997a):

(a) constant air volume (CV) systems;

(b) variable air volume (VAV) systems with no fan speed control (i.e., fan operates at constant speed and flow modulation is achieved by means of dampers); and

(c) variable air volume systems (VAV) with fan speed control (i.e., fan speed is varied along with damper position to regulate flow; this being more energy efficient than (b) above).

In CV systems, E_{ahu} is essentially constant during the period during which the building HVAC system is operated. There may be minor variations in power consumption as the density of the air varies with changes in the air temperature. Hence a one-time measurement during the occupied period of the building (and, perhaps, one during the unoccupied period in case the AHU is shut down) is adequate.

In both cases (b) and (c), E_{ahu} is a function of the building loads, or more specifically the amount of air supplied to the building $m_{air, bldg}$. Phelan et al., (1997a) have studied the predictive ability of linear and quadratic models between E_{ahu} and $m_{air,bldg}$ and concluded that though quadratic models are superior in terms of predicting energy use, the linear model seems to be the better overall predictor of both energy and demand (i.e., maximum monthly power consumed by the fan). This is a noteworthy conclusion given that a third order polynomial is warranted analytically as well as from monitored field data presented by previous authors (for example, Englander and Norford, 1992 and Lorenzetti and Norford, 1993). Therefore, we propose to evaluate the linear, quadratic and the third order polynomial functional forms for E_{ahu} and investigate the predictive ability of these models with both $m_{air,bldg}$ and Q_{bldg} as the regressor variables. If models based on the latter variable perform well, then one need not measure $m_{air,bldg}$ during the in-situ measurement protocol. We realize that in a VAV system, there is a one-to-one correlation between these two variables only until the minimum threshold flow rate to the building is reached, and so appropriate corrections need to be included in a model with Q_{bldg} as the regressor variable.

3.4 Power consumed by pump(s)

3.4.1 General considerations

The theoretical aspects of calculating pump performance are well understood and documented. Pump capacity and efficiency are calculated from measurements of pump head, flow rate, and pump electrical power input. The type of instrumentation needed is shown schematically in Figure 3.2 These calculations and measurement techniques are detailed in the Standards promulgated by ASME and the Hydraulics Institute, as described by Phelan et al., (1997a). Recommendations on how to perform pump performance measurements have also been made by Phelan et al., (1997a).

In the same manner as fans, we need to distinguish the operation of circulating pumps in buildings and in cooling equipment depending on how they are modulated during part-load operation for the following types of pumps:

(a) constant flow pump with a three way bypass valve to control the amount of heat transfer in the cooling coils;

(b) variable flow pump with a two-way valve to throttle the flow; and

(c) variable flow pump with a variable speed drive.

3.4.2 Power consumed by the building pump(s)

In constant flow systems, $E_{\text{bldg pump}}$ is essentially constant during the period in which the building HVAC system is operated (assuming there are no major pressure variations in the pumping system). Hence a one-time measurement during the occupied period of the building (and, perhaps, one during the unoccupied period) is adequate for those cases where the building pump energy needs to be measured.

However, in both cases (b) and (c), $E_{\text{bldg pump}}$ is a function of the building loads or more specifically of the fluid flow rate $m_{\text{water,bldg}}$.Phelan et al., (1997a) have studied the predictive ability of linear and quadratic models between $E_{\text{bldg pump}}$ and $m_{\text{water,bldg}}$ and concluded that quadratic models are superior to linear models. Therefore, we propose to evaluate both linear and quadratic functional forms for $E_{\text{bldg,pump}}$ and investigate the predictive ability of these models with both $m_{\text{water,bldg}}$ and Q_{bldg} as the regressor variables.

3.4.3 Power consumed by the chiller pump(s)

Normally, there are two separate pumps used by chillers: the condenser pump used to circulate the water to the cooling tower, and the pump which circulates water through the evaporator. In most cases there are two pumps on the evaporator circuit (Hartman, 1996): one for the primary circuit which maintains a constant chilled-water flow through the chiller, and one for the secondary chilled-water flow to the building which is modulated depending on the load. In this section, we deal specifically with the primary loop pump, while the secondary loop pump can (if present) be combined with the building pump addressed in Section 3.4.2.

As discussed by Eppelheimer (1996), controlling head pressure in water-cooled chillers has long been achieved by varying the condenser flow rate. However, flow rate through the evaporators is normally not varied. Though several people have suggested ways and means of modifying the present day controls in order to achieve variable evaporator flow and hence better energy efficiency, the current generation of chillers can be assumed to have constant flow through the evaporator.

3.4.4 Power consumed by the TES pump(s)

The flow rate to the TES, whether during charging or during discharging, may or may not be constant depending on the specific design. Further, not all TES systems use a separate pump for storage. Such factors need to be explicitly recognized during data collection and model identification.

3.4.5 Aggregated model for all auxiliary equipment

Submetering each and every pump (or fan) and then developing appropriate individual models may be too complex for practical applications. Since the net electricity used by the various pumps is usually small compared to that of the chiller, it would be more practical to only monitor the combined electricity used by all pumps and develop one aggregated model for all the auxiliary equipment. Models as discussed above can be evaluated with gathered data to identify the most appropriate model. This is the approach which we advocate in this research project given the overall project objectives that RP 1004 deliver a useful methodology that is also cost effective..

3.5 Power consumed by chiller(s)

3.5.1 Description of different models

The theoretical aspects of calculating chiller performance are well understood and documented. Chiller capacity and efficiency are calculated from measurements of water flow, temperature difference, and power input (see for example, Liu et al., 1994, Hydeman, 1997, Phelan et al., 1997b). Typical measurement locations are shown schematically in Figure 3.3. Calculations can also be checked by a heat balance performed on the entire system. These calculations and ARI and other ASHRAE measurement techniques are detailed in Phelan et al., (1997b).

There are basically two types of in-situ models to describe chiller performance: polynomial models and thermodynamic-type models. These are described below:

3.5.1.1 Polynomial models

This type of model assumes a polynomial function to correlate chiller (or evaporator) thermal cooling capacity or load Q_{evap} and the electrical power consumed by the chiller (or compressor) E_{comp} with the relevant number of influential physical parameters. For example, based on the functional form of the DOE-2 building simulation software (LBL, 1980) models for part-load performance of energy equipment and plant, E_{comp} can be modeled as the following tri-quadratic polynomial model:

$$\begin{aligned} P_{comp} &= a + b.Q_{evap} + c.T_{cond}^{in} + d.T_{evap}^{out} + e.Q_{evap}{}^{2} + f.T_{cond}^{in}{}^{2} + g.T_{evap}^{out}{}^{2} \\ &\quad + h.Q_{evap}.T_{cond}^{in} + i.T_{evap}^{out}.Q_{evap} + j.T_{cond}^{in}.T_{evap}^{out} + k.Q_{evap}.T_{cond}^{in}.T_{evap}^{out} \end{aligned} \tag{3.2}$$

In this model, there are 11 model parameters to identify. However, since all of them are unlikely to be statistically significant, a step-wise regression to the sample data set yields the optimal set of parameters to retain in a given model (Haberl et al. 1997).

Braun (1992) has used a bi-quadratic model with two regressor variables containing six empirical coefficients, namely cooling load on the chiller (Q_{evap}) and the difference between the ambient wet-bulb temperature T_{wb} and the fluid temperature leaving the evaporator (or the supply temperature to the building) T_{evap}^{out}:

$$E_{comp} = a_0 + a_1 . Q_{evap} + a_2 Q_{evap} {}^\wedge 2 + a_3 (T_{wb} - T_{evap}^{out}) + a_4 (T_{wb} - T_{evap}^{out}) {}^\wedge 2 + a_5 Q_{evap}(T_{wb} - T_{evap}^{out}) \qquad (3.3)$$

The model coefficients a_0 to a_5 are determined by regressing data obtained from actual monitoring. We propose to evaluate slight variants of this model, for example, using the inlet temperature to the condenser or the temperature of the water leaving the cooling tower rather than T_{wb} so as to be consistent with the chiller thermodynamic model described below. This is an important criterion in that models for the different components should be formulated in terms of as few physical and climatic parameters as possible in order to minimize the number of channels that need to be monitored during the in-situ testing. Several other authors (for example Hydeman, 1997) have also proposed slightly different variants of such polynomial models. Therefore, we propose to evaluate these generic models with the monitored data collected in the framework of this research using similar variable sets.

3.5.1.2 Thermodynamic models

In contrast to polynomial models, which have no physical basis (merely a convenient statistical one), thermodynamic models are based on fundamental thermodynamic considerations for a chiller. Such models are preferred because they generally have fewer model parameters that appear in a functional form with a scientific basis. Furthermore, their mathematical formulation can be traced to actual physical principles that govern the performance of a chiller. Hence the model coefficients tend to be more robust, leading to sounder model predictions. Currently there is only one such thermodynamic model, which has appeared in two forms, described below.

3.5.1.2a Complete Gordon-Ng model

The complete chiller model proposed by Gordon and Ng (1994,1995) and by Gordon et al. (1995) is a simple, analytical, universal model for the chiller performance based on thermodynamic considerations and linearization of heat losses. These thermodynamic models were also recommended by ASHRAE's RP-827 project (Phelan et al., 1997b). The model predicts the dependence of chiller COP (defined as the ratio of chiller (or evaporator) thermal cooling capacity Q_{evap} divided by the electrical power consumed by the chiller (or compressor) E_{comp}) with certain key (and easily measurable) parameters such as the fluid (water or refrigerant) return temperature from the condenser T_{cond}^{in}, the fluid temperature leaving the evaporator (or the chilled water supply temperature to the building) T_{evap}^{out} , and the thermal cooling capacity of the evaporator. The complete Gordon-Ng model is a three-parameter model which takes the following form for model parameter identification by regression:

$$\left(\frac{1}{COP} + 1 - \frac{T_{cond}^{in}}{T_{evap}^{out}}\right) Q_{evap} = -A_0 + A_1 T_{cond}^{in} - A_2 \frac{T_{cond}^{in}}{T_{evap}^{out}} \qquad (3.4)$$

from which the three parameters are identified by multiple linear regression.

3.5.1.2b Simple Gordon-Ng model

Uniform and systematic procedures for in-situ field measurements of centrifugal chillers were also developed/proposed by Phelan et al. (1997b) under the ASHRAE RP-827 project in order to use the Gordon-Ng chiller model to evaluate annual electrical energy consumption and peak demand loads. They found that many chiller systems, in which in-situ tests are being performed during one season of the year, do not exhibit the required variation in T_{cond}^{in} and T_{evap}^{out} to support a model such as given by eq.(3.4). Under such conditions a simpler two-parameter model was advocated, namely:

$$\frac{1}{\mathrm{COP}} = -c_0 + \frac{c_1}{Q_{evap}} \qquad (3.5)$$

3.6 In-situ testing of chillers

Phelan et al. (1997b) found that the simple Gordon-Ng model identified from in-situ data does an excellent job of predicting the total electricity consumed by the chiller (a difference of only 0.54% is reported on a seasonal basis) while the prediction in maximum demand is poorer but acceptable (with a difference of 4.3% from the measured maximum). Haberl et al. (1997) have also presented results of an analysis involving predicting electricity use and demand of a chiller during different summer months of the year using chiller parameters identified from in-situ chiller measurements. Since the results of Haberl's study are also directly relevant to the objectives of this research, it is instructive to review the procedures and the conclusions of both the Phelan et al.,(1997b) and Haberl et al., (1997) studies.

Haberl et al. (1997) used hourly monitored data during the entire cooling season to determine predictive accuracy of three chiller modeling approaches, namely: (1) the complete Gordon and Ng model (Gordon and Ng, 1994, 1995), (2) the simplified Gordon and Ng model (which was advocated by Phelan et al. (1997b) in the framework of the ASHRAE RP-827 in-situ chiller measurement project), and (3) the quadratic functional form used by DOE-2 to model part-load equipment and plant performance (eq. 3.2). The comparison was made by identifying chiller model parameters from monitored hourly data of chiller under passive conditions, (i.e, normal operation from two different periods): (a) from the first 10 days of May, and (b) from two days each of May, June, July, August and September, in order to illustrate the corresponding differences in prediction accuracy which may result from the choice of the time of the year during which the in-situ test is performed.

The study Haberl et al., (1997) applied the above three models to monitored data from the same Texas site used by Phelan et al. in the ASHRAE RP 827 project in order to predict chiller power during a complete summer period. The site is Victoria High School located in Victoria, Texas. At this site two water-cooled centrifugal chillers supply cooling to approximately 257,000 square feet of conditioned space. All HVAC equipment operate only during occupied hours (i.e.

from 6:00 a.m. till 8:00 p.m.). The HVAC system is manually shut down during unoccupied periods and weekends. Haberl's analysis was based on monitored data from one chiller only.

Monitoring equipment was installed as part of the Texas LoanSTAR program (Haberl et al., 1996) which included monitoring the following points at an hourly time scale:

(a) evaporator thermal load, Q_{evap}

(b) compressor electric power, E_{comp}

(c) supply and return chilled water flows (although only the supply temperature T_{evap}^{out} is actually needed by the models)

(d) cooling water supply and return temperatures (athough only the inlet temperature to the condenser T_{cond}^{in} is actually needed by the models)

(e) other quantities such as electricity used by the pumps and the flow rate to the evaporator were also measured, but did not appear in the chiller model.

The procedure used to compare the three in-situ chiller models consisted of identifying the model parameters from a relatively short data period (akin to an in-situ performance test) and determining the accuracy of the model in predicting hourly E_{comp} values during an entire summer, (specifically May to September 1996). Since model parameters of building energy related equipment are usually better identified from regressor data, an earlier premise was that the in-situ test procedure would yield more representative model parameters if the monitoring time scale of one hour were reduced so that initial transients could provide the needed variability in temperatures not seen in steady-state operation. Thus, one minute data was gathered during two days in summer for model parameter identification.

The one minute data was not compatible with the resolution of the digital measuring instrument and so 5 minute averaging of the data was performed as described by Figueroa (1997). However, it was found that the model identified from one day's data gave a bias in predicting P_{comp} when applied to data from the other test data. Since the Gordon-Ng model is applicable to steady-state performance, it is clear from this one published result that the model parameters should not be identified from a start-up transient test (which contain dynamic conditions) in an effort to obtain a larger scatter in the range of variation of the regressor variables (namely, T_{evap}^{out}, T_{cond}^{in} and Q_{evap}). Accordingly, Haberl et al. concluded that it was better to use part of the hourly monitored data (i.e., that part that did not contain start-up transients) to study the predictive accuracy of the corresponding model over the entire summer period.

In a effort to systematically study the prediction accuracy of the three chiller models whose parameters have been identified from in-situ data, Haberl et al. (1997) considered two different periods containing the same number of hourly data: (a) data taken from one season only (first 10 days of May 1996), and (b) data taken from several months (2 days each from the 5 months, namely May, June, July, August and September). Although it was obvious that in-situ test (b) would provide a wider range of variation in the regressor variables than would 5 days in May alone the degree of variability had not been determined. Furthermore, Haberl et al. sought to determine which representative model parameters could be identified from the short term data. The general conclusions of the Haberl et al. study were as follows:

(a) the simple Gordon-Ng model (eq. 3.5) allows an accurate prediction of monthly chiller electricity use and demand irrespective of the time of the year from which in-situ tests are performed in order to determine model parameters. The prediction accuracy for monthly energy use is less than 3% while that for demand is less than 3.5%. Both these findings are in general agreement with those of Phelan et al. (1997b).

(b) the tri-quadratic model (eq. 3.2) is very accurate only when the model parameters are identified from monitored data that cover the full range of variation of climatic and load variation which the chiller is likely to experience; otherwise it can be very unstable with short data sets and can give grossly misleading predictions -- a finding that is very pertinent to this project.

(c) the complete Gordon-Ng model (eq. 3.4) had little to recommend it in predictive accuracy for the chiller that was studied for the ASHRAE RP 827 project. For water cooled chillers, the variation in the water entering the chiller may not be enough to support such a model. Hence only in climates and for chillers which are operated and controlled in such a way that they experience large variations in T_{evap}^{out} and T_{cond}^{in} during the year is there a merit in considering such a model.

(d) it is very important to realize that the Gordon-Ng model is strictly applicable for steady-state operation of the chiller and should not be used to predict COP or power use during start up or shut-down periods (which may be of the order of one hour or more in many cases). Note that the model was originally developed and validated from steady-state data gathered from laboratory tests by Gordon and Ng (1994, 1995). Though Gordon et al., (1995) have applied the model to chiller data in the field as a case study, there seems to be a need for energy and chiller equipment professionals to better understand and appreciate the fine nuances of analyzing in-situ chiller performance data in the framework of the various chiller models.

Therefore, we propose to passively analyze monitored chiller data from the case study sites in same way as described in the Haberl et al. (1997) paper for the RP 827 site of Victoria, TX, in order to assure ourselves of the generality of these conclusions.

3.7 Summary of Analytical Models for Chillers, Fans and Pumps

This document reviewed existing literature on in-situ test methods for fans, pumps and chillers so that appropriate performance models can be identified to be used for long-term performance prediction. Since the ASHRAE project RP-827 was recently completed, we propose to largely use their recommendations. However, there are some alternate models for fans, pumps and chillers which have been described in this document which we shall also evaluate with monitored data gathered in the framework of this research project.

3.8 Annotated Bibliography

ARI, 1992. Standard 550, Standard for Centrifugal and rotary screw water-chiller packages, Arlington, VA: Air Conditioning and Refrigeration Institute.
This standard establishes definitions and nomenclature for centrifugal and rotary screw chillers. It also defines the standard full and part load rating conditions for these types of chillers so that published ratings will have a consistent basis. In addition to the test methods, equations are presented for calculation of allowable deviation tolerances from rated conditions under both full- and part-load.

ASHRAE, 1997. "ASHRAE Standard 150P: Method of Testing the Performance of Cool Storage Systems", working draft submitted for Public Review, American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA, February.
This is a draft ASHRAE standard which proposes a testing method for evaluating the in-situ performance of cool storage systems. The draft covers definition of terms; instrumentation required, instrumentation accuracy and instrumentation field calibration and verification; test procedures and conditions; the equations to be used in order to determine the required performance, and how to report the test results. An uncertainty analysis methodology is also proposed based on propagation of errors formulas.

ASHRAE, 1997. Fundamentals Handbook, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, GA.
This handbook, revised every 4 years by ASHRAE, covers basic principles and includes data for the entire technology of the HVAC&R industry. Each of the chapters is revised by a concerned technical committee which strives to provide new information, delete obsolete materials, clarify existing information and even reorganize chapters as needed. Of particular interest to this project is the material contained in Chapter 30 which covers inverse analysis methods.

Braun, J.E., 1992. "A Comparison of Chiller-Priority, Storage-Priority, and Optimal Control of an Ice-Storage System", ASHRAE Transactions: Symposia paper An-92-8-1.
This paper describes the results of a simulation study comparing four different control strategies for a partial ice-storage system at an office building in Wisconsin in terms of energy and demand costs. Individual models for each of the components of the cooling plant are assembled together and a programming algorithm used to simulate the optimal performance of the entire system under each of the four different control strategies.

Dorgan, C.E. and Elleson, J.S., 1993. Design Guide for Cool Thermal Storage, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.
This is a design and reference guide for current cool thermal storage systems. It is a valuable first-level reference which discusses fundamentals, compares different technologies and describes a rational procedure for designing cool storage systems.

Englander, S.L. and Norford, L.K., 1992. "Saving Fan Energy in VAV Systems- Part 1: Analysis of a Variable-Speed-Drive Retrofit", ASHRAE Transactions, paper 3543.
This research paper reports a case study of a large commercial building where energy savings

resulted when the fan control of a VAV system was changed from an inlet vane control to variable speed drive. Fan motor performance is examined using an analysis of motor input power as a function of airflow. An alternative energy saving method of reducing supply duct static pressure is also examined.

Eppelheimer, D.M., 1996. "Variable Flow- The Quest for System Energy Efficiency", ASHRAE Trans: Symposia, SA-96-12-1, p. 673.
This paper discusses the engineering problems associated with varying the flow of water through the evaporators of chillers. The types of controls and the fail-safe features which are required are mentioned. The paper challenges the need for varying evaporator flow for purposes of increasing system energy efficiency.

Figueroa, I.E., 1997. "A Thermodynamic Model of Water Cooled Centrifugal Chillers", M.S. thesis, Mechanical Engineering Department, Texas A&M University-Kingsville, Texas.
This Master of Science thesis evaluates the applicability of the Gordon-Ng models (both the complete and the simplified models) to the same water cooled centrifugal chiller in Texas that was used by ASHRAE research project RP 827. Monitored chiller performance data during start-up tests were used to identify model coefficients by regression, and the models were then used to predict future power consumption of the chiller.

Gordon, J.M. and Ng, K.C., 1994. "Thermodynamic modeling of reciprocating chillers", Journal of Applied Physics, 75(6), p.2769, March.
The first of three journal papers which proposed a simple model for chillers that bears the authors' name. The model is based on thermodynamic considerations of reciprocating chillers and correlates COP to the cooling rate. The model is validated with real performance data for 30 chillers that span the range of cooling rates from 30 to 1300 kW.

Gordon, J.M. and Ng, K.C., 1995. "Predictive and diagnostic aspects of a universal thermodynamic model for chillers", International Journal of Heat Mass Transfer, 38(5), p.807.
This second journal paper extends the simple reciprocating chiller model proposed by the authors in the first paper to all refrigeration devices. The accuracy of the model is illustrated for reciprocating, centrifugal and absorption chillers as well as other less conventional cooling devices such as thermoacoustic and thermoelectric chillers. Real performance data is again used to validate the model.

Gordon, J.M., Ng, K.C., and Chua, H.T., 1995. "Centrifugal chillers: thermodynamic modeling and a diagnostic case study", International Journal of Refrigeration, 18(4), p.253.
This journal paper illustrates, by means of a case study, how the simple Gordon-Ng model can be used to diagnose the performance of an operating commercial centrifugal chiller. Chiller performance data, measured both prior to and after chiller maintenance, analyzed in the framework of these models is used to illustrate the diagnostic ability of the chiller model.

Haberl, J.S. Reddy, T.A., Figuero, I.E. and Medina, M. 1997. Overview of LoanStar Chiller Monitoring and Analysis of In-situ Chiller Diagnostics Using ASHRAE RP-827 Test Method, paper presented at Cool Sense National Integrated Chiller Retrofit Forum, Presidio, San

Francisco, September.
This conference paper first presents hourly performance plots of several chiller sites monitored under the Texas LoanSTAR program for a complete summer (May until September 1996). Scatter plots of chiller performance i.e. kW/ton (or the inverse of COP) versus cooling energy are used to illustrate how such plots can be useful for deciding whether the chiller has been sized properly. The second half of this paper presents the results of an analysis where three different models between compressor electric power and cooling rate are evaluated in terms of their usefulness in modeling in-situ field test data. The prediction accuracy of these three models identified from 10 days of in-situ test data are then used to predict the performance during different months of the year, is also discussed.

Haberl, J.S., Reddy, T.A., Claridge, D.E., Turner, W.D., O'Neal, D.L., and Heffington, W.M., 1996. Measuring Energy-Saving Retrofits: Experiences from the Texas LoanSTAR Program", Oak Ridge National Laboratory report ORNL/Sub/93-SP090/1.
This report of 200 pages outlines and discusses the procedures developed in the Texas LoanSTAR program for acquiring and analyzing data to measure savings from energy conservation retrofits when budgets are a constraint. The selection, calibration and installation of monitoring equipment; data retrieval, screening and storage protocols; data analysis, modeling and savings determination; as well as savings reporting formats are documented.

Hartman, T.B., 1996. "Design Issues of Variable Chilled -Water Flow through Chillers", ASHRAE Transactions: Symposia, paper SA-96-12-2, p. 679.
This research paper suggests an alternative to the typical variable flow chilled water systems with a primary circuit that maintains a constant chilled water flow through the chiller while the secondary chilled water circuit and pumps provide variable flow to the loads as needed. The author proposes a single variable-flow circuit and shows how it should be designed and operated so as to provide safe, stable and reliable chiller operation over the entire operating range.

Hydeman, M. 1997, "Water- Cooled Chiller Performance Evaluation Tool Version 2.0", PG&E Energy Center, San Francisco, CA.
This PG&E water-cooled chiller performance evaluation tool is a spreadsheet program that develops chiller performance curves from manufacturer's data. It also simulates the performance (power draw and COP) of the chiller with variations in load profiles and operating conditions.

LBL, 1980. DOE-2 User's Guide, Version 2.1, Lawrence Berkeley Laboratory and Los Alamos National Laboratory, Report no. LBL-8689 Rev.2, DOE-2 User Coordination Office, LBL, Berkeley, CA.
This manual describes how to use the DOE-2 software program used to simulate the hourly energy performance of buildings. This program is based on detailed computational models for building loads and HVAC&R equipment developed in large part with funding from the Department of Energy. It is unofficially considered to be the most-widely used program of its kind by the professional community, and is regarded as the benchmark program to use for design and evaluation of new buildings. It consists of the DOE2.1a manual and updates for DOE2.1b, c, d and e which have been published since the 1980 release of the DOE2.1a manual.

Liu, K., Guven, H., Beyene, A. and Lowrey, P., 1994. "A Comparison of the Field Performance of Thermal Energy Storage (TES) and Conventional Chiller Systems", Energy, Vol. 19, no.8, p.889

This journal paper presents results of comparing the field performance of four cool energy storage sites to conventional chiller systems located in southern California and in New York. Relative performance over a "mean" day and a "peak" day were used to extrapolate the performance of both systems over monthly and annual time scales.

Lorenzetti, D.M. and Norford, L.K., 1993. "Pressure Reset Control of Variable Air Volume Ventilation Systems", Proceedings of the ASME Solar Engineering Conference, p. 445, April, Washington, D.C.

This conference paper describes a control strategy of a VAV system which involves minimizing the pressure drop across the thermostatically controlled dampers in terminal boxes serving individual thermal zones. One such pressure reset strategy is described. Actual measurements were performed in a building, and fan power versus static pressure data is modeled in order to determine potential savings of such a scheme.

Phelan, J., M.J. Brandemuehl, and M. Krarti. 1994. Literature Review for Methodology Development to Measure In-Situ Chiller, Fan, and Pump Performance. JCEM Report No. JCEM/TR/94-2, University of Colorado at Boulder

Phelan, J., M.J. Brandemuehl, and M. Krarti. 1996. Final Report ASHRAE Project RP-827: Methodology Development to Measure In-Situ Chiller, Fan, and Pump Performance. JCEM Report No. JCEM/TR/96-3, University of Colorado at Boulder.

Phelan, J., M.J. Brandemuehl, and M. Krarti. 1997a. "In-Situ Performance Testing of Fans and Pumps for Energy Analysis." ASHRAE Transactions, V.103, Pt.1. 4040 (RP-827).

Phelan, J., Brandemuehl, M.J. and Krarti, M., 1997b. "In-situ performance testing of chillers for energy analysis", ASHRAE Transactions, 103(1), paper 4040 (RP-827), American Society of Heating and Refrigeration Air-Conditioning Engineers, Atlanta.

The above four publications (two reports and two research papers) were the result of a research project funded by ASHRAE. They describe the work performed in developing and evaluating in-situ methods for HVAC equipment testing, specifically focusing on pumps, fans and chillers. One of the objectives of the project was to do away with the current unique set of measurement protocols for testing and evaluating energy performance of such HVAC equipment, and propose and evaluate a common set of in-situ test methods for energy evaluation. The different types of HVAC systems and how they affect the above in-situ methods are discussed, and recommendations on how to gather data were made accordingly. Methods that described how to analyze the data, what models to use, how to extrapolate the models to predict long-term performance and the uncertainty associated with these predictions were issues that were also addressed.

Phelan, J., M.J. Brandemuehl, and M. Krarti. 1997c. "Review of Laboratory and Field Methods to Measure Fan, Pump, and Chiller Performance", ASHRAE Transactions- Symposia.

This paper reviews the standards and engineering literature for testing fans, pumps, and chillers for HVAC applications, and summarizes the in-situ test methods developed by the authors under ASHRAE research project RP-827.

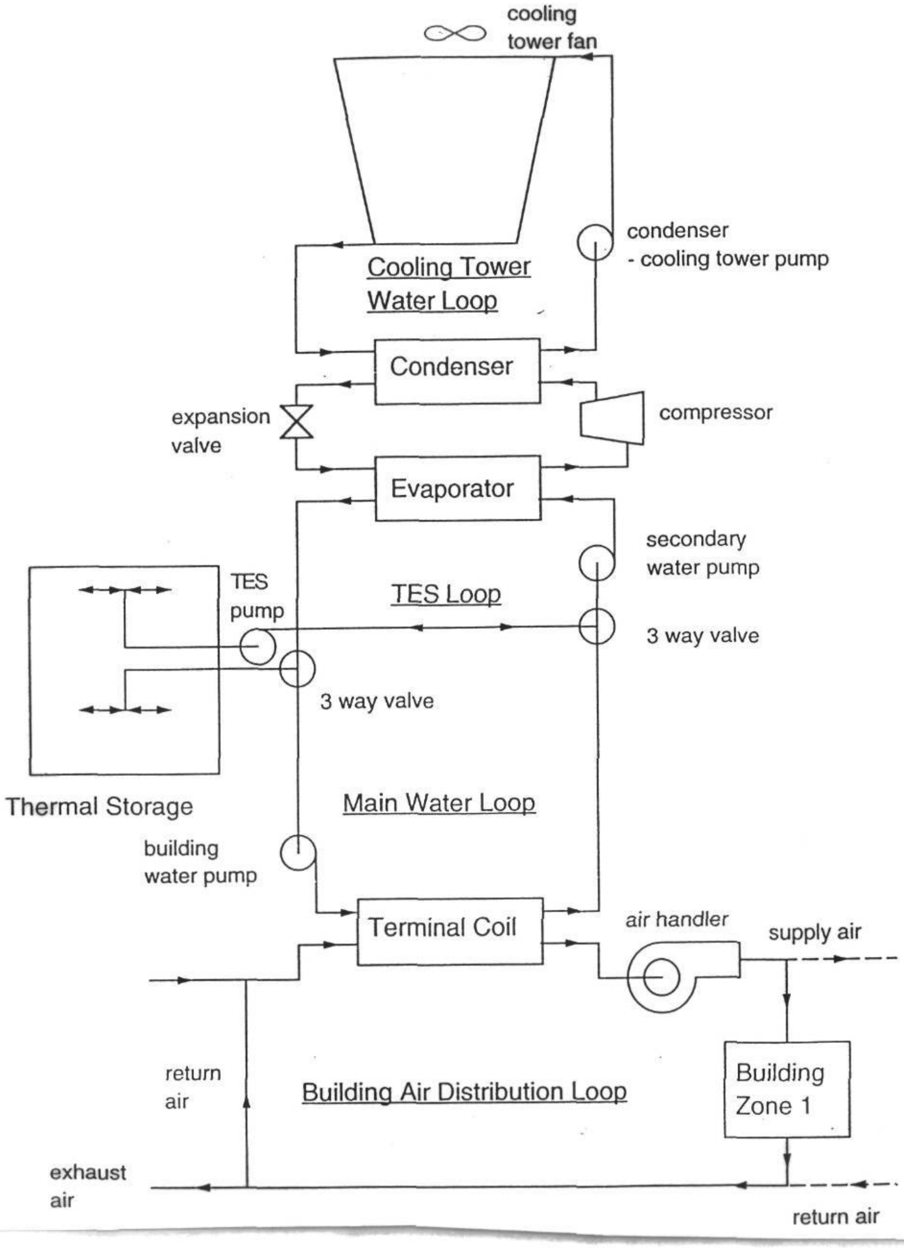

Figure 3.0 Schematic of combined building HVAC system and cool storage system (adapted with modification from Braun 1992).

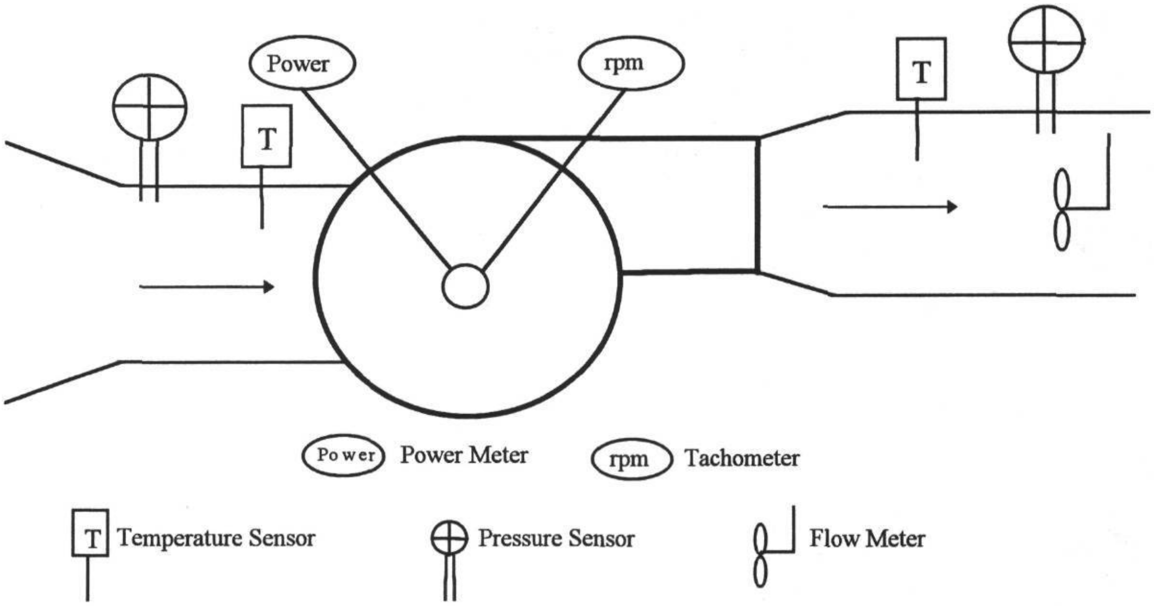

Figure 3.1: Typical Centrifugal Fan with Minimum Required Instrumentation (from Phelan et al., 1997a)

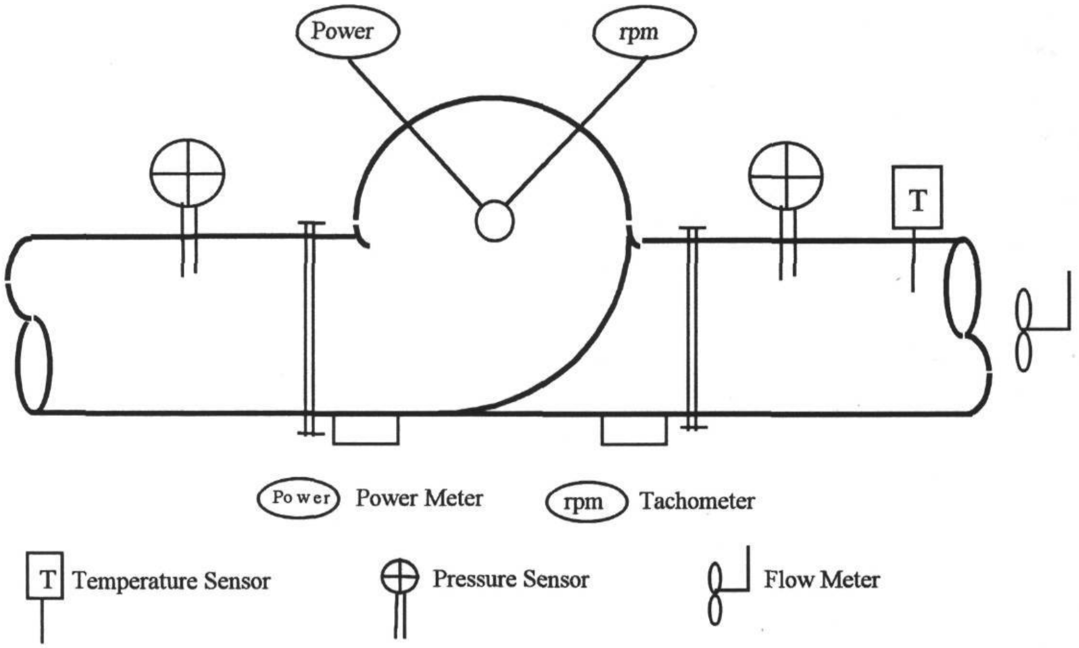

Figure 3.2: Typical Centrifugal Pump with Minimum Required Instrumentation (from Phelan et al., 1997a)

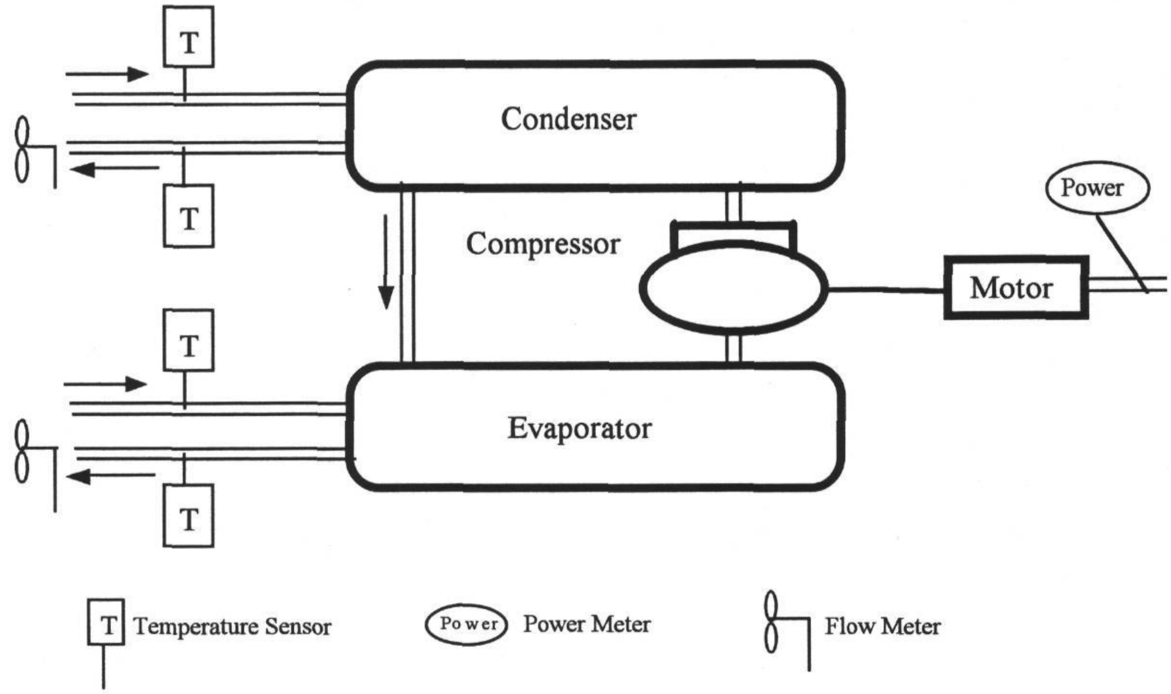

Figure 3.3: Typical Chiller with Minimum Required Instrumentation (from Phelan et al., 1997b)

4.0 DETERMINATION OF HVAC ANNUAL LOADS FROM SHORT-TERM DATA

4.1 Objective and scope

The specific objective of ASHRAE RP-1004 is to propose and validate a short term in-situ measurement protocol along with associated model development and analysis methods which would provide accurate predictions of the long-term performance of a cool storage system in terms of demand and energy savings. We have suggested to evaluate two different analytical approaches: (1) a component-based approach which involves characterizing individual pieces of equipment of the cooling system by simplified models and using a hour-by-hour chronological simulation over the year to determine energy savings due to the TES system, and (2) a lumped parameter approach wherein characteristic day-types based on operating and climatic conditions would be identified and used in conjunction with black-box models of the entire cooling system in order to determine annual TES savings. This section that follows pertains to approach (1) above.

Crucial to approach (1) is the ability to accurately determine the building thermal loads[1]. This has also been explicitly stated in several studies (for example, Kawashima et al., 1995, 1996) where the ability to predict building loads 24 hours in advance is key to deciding on how to optimally operate the cool storage plant. In this project, the objective is not a 24 hour forecast but, rather, the ability to accurately predict the long-term (i.e., seasonal or annual) hourly cooling loads on the HVAC system from building short-term measurements. This issue is complex because of the effect of diurnal and seasonal variations: (1) in the climatic variables that impact building loads (for example, the outdoor dry-bulb temperature, the outdoor humidity and the solar radiation), (2) in the unpredictability of building internal loads, and (3) in the manner in which the building HVAC system is operated. Therefore, the intent of this literature review is to discuss the different attempts at modeling HVAC system loads of actual buildings and to summarize the findings of the relatively few studies which have attempted to predict seasonal or long-term hourly building loads from relatively short measurement periods (which in this study are defined as periods ranging from two weeks to three months)

Another sort of distinction needs to be made in terms of model prediction. Forecasting (or prediction) is the technique used to predict future values using models that are based upon past and present values (Montgomery and Johnson, 1976). There are two types of forecasts: *expost and exante*. In the *expost forecast*, the forecast period is such that observations of both the driving variables and the response variable are known with certainty. Thus expost forecasts can be checked with existing data and provide a means of evaluating the model. An *exante forecast* predicts values of the response variable (i.e., building energy use) when those of the influential or regressor variables are either: (1) known with certainty (*conditional exante forecast*), or (2) not known with certainty (*unconditional exante forecast*). The reader is referred to Montgomery and Johnson (1976) for additional discussions pertaining to the different types of forecasts.

Thus the *unconditional exante forecast* is more demanding than *conditional exante forecasting* since the driving variables need also to be predicted into the future (along with the associated

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[1] Though there is a connotational difference between the two terms, building loads and HVAC loads, we shall use them interchangeably in this report to mean HVAC thermal loads.

uncertainty which it entails). The study by Kawashima et al. (1995) and the study by Seem and Braun (1991) pertain to unconditional exante forecasts. Unfortunately, this is not the objective of this research, rather, we propose to: (1) evaluate our building load prediction model approach by means of *expost forecasts*, and (2) then, use the model for circumstances pertaining to *conditional exante* type of forecasts.

4.2 Background

At the onset, one needs to distinguish between *forward models* and *inverse models* (ASHRAE 1997b) . *Forward modeling* describes the traditional computer simulation programs such as DOE-2 or BLAST that calculate building loads. Forward modeling is most often employed for design purposes, such as: (1) for calculating the energy performance of a prospective building based on its detailed blueprint description and how the building is likely to be operated, or (2) for sizing the HVAC equipment to be installed in the new building. *Inverse modeling* identifies basic building models and model parameters by regressing against measured data of building energy use and other influential variables. Inverse modeling is most appropriate for analyzing existing performance data of building energy use either in the framework of statistical models or macro-models of the building energy flows (Rabl, 1988; ASHRAE, 1997b). We shall limit the scope of this literature review to inverse models only.

The inverse approach to analyzing energy use in buildings is relatively new with the very first appearance in the literature only dating back perhaps 20 years. It arose primarily as a result of the drive to implement energy conservation programs in residential buildings just after the first oil shock in the early 1970s. In one of the earliest methods, data analysts having utility billing data from a residence both prior to and after the retrofit implementation, applied the variable base degree-day (VBDD) concept (ASHRAE, 1997b) to normalize energy use for differences in outdoor-dry-bulb temperature prior to and after the retrofit.

Analysis methods subsequently developed have increased in number and in sophistication as a result of widening objectives and different types of data availability. The amount of monitored data available for analysis has increased substantially in part due to a dramatic increase in data monitoring technology, but more importantly, due to a motivation arising from the increasing awareness that existing means of predicting energy use in a building using forward models were inadequate and sometimes misleading for the purpose of evaluating the effect of an energy conservation program on a specific building or for identifying (and correcting) an improperly operated building.

For example, a study by Greely et al. (1990) of 1,700 buildings in the U.S. indicated that the *estimated* savings in fewer than 16% of the case study buildings came within 20% of the measured savings -- a shocking result. A common theme in this study, as well as others of a similar nature, is the need for better measurement methodologies and more complete data which would restore the faith in the prospective efficiency investments. The development of guidelines on measuring retrofit savings has been ongoing during the last few years, and documents are available (NEMVP, 1996; GPC-14P, 1997). These protocols are, however, not appropriate for the purpose of this research since: (1) the issue of short-term to long-term load predictions is not addressed at all, and (2) useful protocols for cool storage systems are not available..

4.3 Different inverse analysis methods

Different authors have chosen to group the various inverse models for building energy use in different ways. One of the preferred grouping is that of MacDonald and Wasserman (1989) who have suggested the following five groups:

(a) annual total energy and energy intensity comparisons (using metered or utility bills),

(b) linear regression and component models (based on monitored data)

(c) multiple linear regression models,

(d) building simulation models, and

(e) dynamic thermal performance models.

When building or HVAC system loads need to be predicted for the purpose of assessing cool storage performance, the "building loads" model ought to be able to predict hourly heating and cooling HVAC system loads. Thus group (a) above which is primarily at annual or monthly time scales is unsuitable. Also, given the complexity and size of commercial buildings, one would like to keep the in-situ monitoring to a minimum.

Dynamic models (group e above) would require a level of monitoring and analysis which are too complex to the current objectives (as testified, for example, by the PSTAR method suggested by Subbarao (1988) and limited to heat flows in residential building envelopes). Although attempts have been made to extend PSTAR to commercial buildings (Manke et al., 1996), these studies are still limited to smaller size buildings whose loads are primarily determined by the building shell interactions as against the HVAC system effects which are by far the more important determinant of building energy use in large commercial buildings that can afford cool storage systems. Hence such protocols are not useful for cool storage tests. Other attempts, such as the study by Reichmuth and Robison (1990) are more at the conceptual stage rather than field-tested over several buildings. Hence only groups (b), (c) and (d) are appropriate for consideration in the framework of the current research study. We shall briefly discuss the concepts and the status of these three methodologies in the sections that follow.

4.3.1 Building simulation models

The building simulation approach relies on adopting a particular engineering simulation model of energy use in a building and "tuning" or adjusting the inputs of the program so that simulated output and measured values of building energy use match closely. A simulation program thus calibrated, could then serve as a more reliable means of predicting the energy use of the building when operated under different climatic or different pre-specified operating conditions. One can distinguish between two different types of engineering simulation models:

(1) “detailed”, general purpose, fixed schematic models such as DOE-2 (Norford et al., 1989; Bronson et al., 1992; Bou-Saada, 1994), and BLAST (Manke et al., 1996); or

(2) “simplified” fixed schematic HVAC systems models based on the air-side models developed by ASHRAE TC 4.7 (Knebel, 1983) and adopted in slightly different forms by many workers, for example by Katipamula and Claridge (1993) and Liu and Claridge (1995). Typically, the building is divided into two zones: an exterior or perimeter zone and an interior or a core zone. The core zone is assumed to be insulated from the envelope heat losses/gains, while the solar heat gains, infiltration heat loss/gain, the conduction gains/losses from the roof are taken to appear as loads on the external zone only. Given the internal load schedule, the building description, the type of HVAC system and the climatic parameters, the HVAC system loads can be estimated for each hour of the day and for as many days of the year as needed by the simplified systems model. Since there are fewer parameters to vary, the calibration process is much faster. Therefore, these models have a significant advantage over the general purpose models in buildings where the HVAC systems can be adequately modeled.

The detailed calibrated simulation model approach, on the other hand, is more tedious and requires expert knowledge of how the mechanical systems of the building are operated and a certain proficiency in manipulating the particular building energy code. The detailed calibrated simulation approach is typically resorted to under two circumstances: (1) when the analyst would like to model sub-aggregated electric use from monitored whole-building monitored energy use, or (2) when the quality or length of the data period is not adequate to enable proper regression model identification. Both the detailed and the simplified calibrated model approaches have yet to reach a stage of maturity in methodology development where they can be used routinely and with confidence by people other than skilled analysts that developed the models.

Model development using the regression approach is generally less demanding in effort and user-expertise, yields adequate results and permits uncertainty calculations associated with savings to be quantified using accepted statistical procedures. Therefore, we feel that this approach is more pertinent to the objectives of this research given that the entire methodology (experimental protocols and data analysis) should be usable by professionals involved in field testing and commissioning of HVAC&R equipment and systems.

4.3.2 Regression models

Groups (b) and (c) stated earlier are essentially similar, except for the number of regressor variables in the model. Both rely on the ability to formulate energy use in a building as a function of one or more driving forces which impact building energy use. An important aspect in identifying statistical models of baseline energy use is the choice of the functional form and that of the independent (or regressor) variables. Extensive studies in the past (for example, see Fels 1986; Kissock 1993; Katipamula et al. 1994) have clearly indicated that the outdoor dry-bulb temperature is the most important regressor variable, especially at monthly time scales, and even at daily time scales.

Classical linear functions are usually not appropriate for describing energy use in many commercial buildings because of the presence of functional discontinuities, called "change points". These change-points exist due to the presence of control mechanisms which include: (1) thermostats in residences, (2) HVAC operating and control schedules, and (3) economizer cycles in commercial buildings (Reddy et al. 1995). The various types of single variable (SV) models that have been used to model energy use in commercial and residential buildings are described in numerous publications (for example, Kissock, 1993; ASHRAE, 1997b; Reddy et al., 1997), and the reader is referred to these publications for additional details. However, the use of multiple linear regression (MLR) models for modeling building energy use is less known by the professional community, and so we shall provide a brief description of MLR below.

4.3.3 Multiple Linear Regression Models (MLR)

Three basic types of MLR models have been used with some success to model the hourly variation of the heating and cooling energy use in commercial buildings for the purpose of long-term prediction[2] (Reddy et al., 1994):

(a*) Standard multiple linear or change point regression models* where the set of data observations are treated without retaining the time series nature of the data,

(b) *Fourier series models* which retain the time series nature of the building energy use data and capture the diurnal and seasonal cycles according to which buildings are operated (for example, Seem and Braun, 1991; Dhar et al., 1994), and

(c) *ANN or Artificial Neural Network models* (for example, Kreider and Wang, 1991; Cohen and Krarti, 1997) where automated ANN algorithms are used to model the time series trend in a non-linear manner.

How the standard MLR and the ANN fare with respect to the others can be gauged from the ASHRAE Energy Predictor II (Haberl and Thamilseran, 1996) where these and other approaches were used to model the same data set of monitored building energy use and then used to predict energy use into a future time period. Monitored building load data being available during the future time period allowed the various modeling approaches to be evaluated against each other in an absolute manner. Since the standard MLR model approach was only marginally less accurate than the ANN models and being infinitely easier to understand and to use by ASHRAE practitioners, we feel the MLR approach to be more suitable for the HVAC professional community. Therefore, we shall discuss the standard MLR models below.

4.3.4 Standard MLR

The goal of modeling energy use by the MLR approach is to characterize building energy use with a few readily available and reliable input variables. In addition, each independent variable must be

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[2] Note that the building prediction models in the framework of this study cannot be of the transfer function or the ARIMA type of models (Montgomery and Johnson, 1976). Such models are appropriate only when the forecasts can be updated as the prediction interval slides forward in time.

unaffected by the changes in building equipment or building operation intended by the energy retrofit. Environmental variables which meet the above criteria for modeling heating and cooling energy use include outdoor air dry-bulb temperature (T_o) , solar radiation(q_{sol}) and outdoor specific humidity (W_o). In commercial buildings, internally generated loads, such as the heat given off by people, lights and electrical equipment, also impact heating and cooling energy use. Such internal loads are difficult to measure in their entirety given the ambiguous nature of people loads and latent loads. However, we find that the monitored electricity used by internal lights and equipment E_{int} is a good surrogate of the total internal sensible loads (Deng, 1997). For example, when the building is fully occupied, it is also likely to be experiencing high internal electric loads, and vice versa.

The above statement is also true for buildings such as office buildings but may be less so for mixed use buildings (e.g., hotels and hospitals) and buildings such as retail buildings, schools and assembly buildings. As discussed in Section 4.5, we propose an additional term, in the form of a dummy or indicator variable (Draper and Smith 1981) (I_{occup}) to model the differences in HVAC system behavior during occupied and unoccupied periods of the day. For some office buildings, as will be discussed in Section 4.3.6, there seems to be little need to include such a dummy variable, but its inclusion in the general functional form will provide an added flexibility. As for latent loads, we shall assume that their contribution will be implicitly contained in the E_{int} and the dummy variable.

The use of a single variable (SV) 3-P model like the PRISM model (Fels, 1986) has a physical basis only when energy use above a base level is linearly proportional to degree days. This is a good approximation in case of heating energy use in residential buildings in those buildings where the heating load never exceeds the capacity of the heating system. Commercial buildings, in general, have higher internal heat generation with simultaneous heating and cooling energy use and are strongly influenced by HVAC system type and control strategy. This makes energy use in commercial buildings less strongly influenced by T_O alone. Therefore, it is not surprising that blind use of SV models has had mixed success at modeling energy use in commercial buildings (MacDonald and Wasserman, 1989). MLR regression models are a logical extension to SV models provided the choice of the variables to be included and their functional forms are based on the engineering principles on which HVAC systems and other systems in commercial buildings operate and that the variables do not suffer from multicollinearity as defined in the following section.

4.3.5 Multicollinearity

Although physically energy use is dependent on several variables there are strong practical incentives for identifying the simplest model that results in acceptable accuracy. Multivariable models require more metering and are unusable if even one of the variables becomes unavailable. In addition, some of the regressor variables may be linearly correlated. This condition, called multicollinearity, can result in large uncertainty in the estimates of the regression coefficients (i.e., unintended error), and can also lead to poorer model prediction accuracy as compared to a model where the regressors are not linearly correlated (Ruch et al.,1993).

Several authors recommend using Principal Component Analysis (PCA) to overcome multicollinearity effects. Also, PCA analysis was one of the strongest analysis methods in the ASHRAE Predictor Shootout I and II contests (Kreider and Haberl 1994 a, b; Haberl and Thamilseran 1996). In one study analysis of multi-year monitored daily energy use in a grocery store found a clear superiority of PCA over multivariate regression models (Ruch et al., 1993). However, for commercial building energy use in general, this conclusion is unproven. A more general evaluation by Reddy and Claridge (1994) of both analysis techniques using synthetic data from four different geographic locations in the U.S. found that injudicious use of PCA may exacerbate rather than overcome problems associated with multicollinearity (Draper and Smith, 1981 also cautions against indiscriminate use of PCA).

Therefore, when significant collinearity between the predictor variables exists the appropriate statistical approaches that must be used can lead to two additional problems:

(a) though the Principal Component Analysis (PCA) model may provide a good fit to the current data, its usefulness as a reliable predictor of future consumption is suspect; and

(b) the regression coefficients in the PCA model may no longer be proper indicators of the relative physical importance of the regressor parameters.

The results of the above studies suggest that multicollinearity may not be as big a problem as originally thought to overcome problem (a) stated above, primarily because multivariate regression models for most buildings with clean[3] data (such as the Texas LoanSTAR program (Claridge et al., 1991, for example) have high values of R^2 (typically higher than 0.8). However, problem (b) stated above still needs to be overcome (as illustrated by the study by Deng, 1997) and so our proposed analysis methodology will be constructed to circumvent this limitation.

4.3.6 Functional form

Engineering equations describing the air-side performance of HVAC components and systems are well known (see for example, Knebel, 1983). Additionally, studies by Kissock (1993), Reddy et al., (1994) and Katipamula et al., (1994) which were especially aimed at investigating the functional basis of energy use in HVAC systems with monitoring data analysis in mind, indicate that no single empirical model is appropriate for all energy types and HVAC systems. This is a very important finding that will guide our model development. Specifically, it says that energy use in commercial buildings is a complex function of climatic conditions, internal loads, building characteristics (such as the loss coefficient and heat capacity), HVAC system characteristics (air flow rate, outdoor air fraction, economizer operation and control options like deck settings and scheduling,...), and HVAC type (whether CV or VAV, for example). Some of these parameters are difficult to estimate or measure in an actual building and hence, they are not good candidates for regressor variables. Further, some of the variables vary little during the short in-situ monitoring period (or even during a season) and though their effect on energy use may be

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[3] "Clean" data refers to experimental data without excessive (a small amount cannot usually be avoided) missing values, erratic spikes and known biases obtained from instrumentation, loggers and data retrieval routines that have been verified and cross-checked for quality control.

important, MLR would suggest that they not be retained in the final set of regressor variables, their effect being implicitly lumped into the constant parameter of the regression model.

The functional basis of air-side heating and cooling use in various HVAC system types has been addressed by Reddy et al. (1994) and subsequently applied to monitored data in commercial buildings Katipamula et al. (1994). Since none of the quadratic and cross-product terms of the engineering equations are usually picked up by the MLR models, we are left with models for energy use which are strictly linear.

In addition to T_O, internal electric equipment and lights load E_{int}, solar loads q_{sol} and latent effects via the outdoor dew point temperature T_{dp} are candidate regressor variables. In commercial buildings, a major portion of the latent load is due to fresh air ventilation. However, this load appears only when the outdoor air dew point temperature exceeds the cold deck temperature. Hence the term $(T_{dp} - T_s)^+$ (where the + sign indicates that the term is to be set to zero if negative, and T_s is the mean surface temperature of the cooling coil, typically about 11 - 13°C) is a more realistic descriptor of the latent loads than is T_{dp} alone. Consequently, the use of $(T_{dp} - T_s)^+$ as a regressor in the model is a simplification which seems to yield good accuracy (Katipamula et al., 1994).

Thus a MLR regression model with an engineering basis has the following structure:

$$Q_{bldg} = \beta_0 + \beta_1(T_o - \beta_3)^- + \beta_2(T_o - \beta_3)^+ + \beta_4(T_{dp} - \beta_6)^- + \beta_5(T_{dp} - \beta_6)^+ + \beta_7 q_{sol} + \beta_8 E_{int} \qquad (4.1)$$

Because of the above discussion $\beta_4 = 0$. Introducing indicator variable terminology (Draper and Smith, 1981), the above equation becomes identical to Katipamula et al., (1994) :

$$Q_{bldg} = a + b\,T_o + c\,I + d\,I\,T_o + e\,T_{dp}^{+} + f\,q_{sol} + gE_{int} \qquad (4.2a)$$

where the indicator variable (I) is introduced to handle the change in slope of the energy use due to T_O. The variable I is set equal to 1 for T_o values to the right of the change point (i.e., for high T_o range) and set equal to 0 for low T_o values. As for the SV segmented models (i.e., 3-P and 4-P models), a search method is used in order to determine the change point which minimizes the total sum of squares (Fels 1986; Kissock 1993). How the above model is able to remove the effects of patterned residuals (an indication of improper model structure as discussed in most statistical textbooks, for example, Draper and Smith, 1981) is illustrated by Fig. 4.0a with daily monitored cooling data from a Texas LoanSTAR building under VAV operation (Katipamula et al., 1994). In this figure the simple 2-P SV model is clearly inadequate, while the model given by eqs. (4.2a, 4.2b) seems to result in a more or less random residual pattern indicating a more appropriate regression model.

Another finding from the Katipamula et al. study was that though the model given by eq.(4.2a) was appropriate for VAV operation, a simpler model as given below is adequate when the building is operated under CV operation:

$$Q_{bldg} = a + b\,T_o + e\,T_{dp}^{+} + f\,q_{sol} + g\,E_{int} \qquad (4.2b)$$

Note that instead of using $(T_{dp} - T_s)^+$ one could equally use the absolute humidity potential $(w_0 - w_s)^+$ where w_0 is the outdoor absolute humidity and w_s is typically about 0.009 kg/kg (which is the absolute humidity level above the dewpoint of the cooling coil). A final aspect to be kept in mind is that, contrary to cooling energy use, latent loads have not been observed on the heating coil of the HVAC systems that were studied and hence the term T^{+}_{dp} should be omitted from the regressor variable set when regressing heating energy use.

Most of the MLR analysis performed as part of the Texas LoanSTAR buildings which are buildings with conservative amounts of glazing, have found the solar term to be statistically insignificant. This is due to the strong correlation between solar radiation and outdoor temperature which results in the latter variable picking up some or all of the contribution of the latter. Thus, we could further simplify the model by dropping the solar term and assuming the solar contribution to be implicitly present in the outdoor temperature contribution (this is also the basis of the ASHRAE modified bin method in Knebel, 1983).

The MLR model suggested by Katipamula et al. (1994) has been found to be very accurate for daily time scales, and slightly less so for hourly time scales. As discussed in Section 4.3.4 above, this is because changes in the way the building is operated during the daytime and the nighttime for example, lead to different relative effects of the various regressors on energy use, which cannot be accurately modeled by one single hourly model. Breaking up the energy use data in hourly bins corresponding to each hour of the day and then identifying 24 individual hourly models lead to appreciably greater accuracy (Katipamula et al., 1994).

Unfortunately, this is probably too tedious for the current project, and a method which seems to yield comparable accuracy, is to divide the day into as many periods as there are *observable* operating modes. For example, dividing the day into two periods, one corresponding to occupied periods and one to unoccupied periods seems to be an acceptable compromise for buildings operated in more or less two operating modes. Usually not more than two or three such modes are necessary for modeling hourly building energy use. Obviously, it is advisable to determine the number of operating models of a building from monitored data, rather than from hypothetical considerations.

4.4 Short-term to long-term predictions

Although there are no absolute rules for determining the minimum acceptable length of the pre-retrofit period for the regression model to accurately predict long-term HVAC system loads, a full year of energy consumption data is likely to encompass the entire range of variation of both climatic conditions and the different operating modes of the building and of the HVAC system. However, in many cases a full year of data are not available and one is constrained to develop models using less than a full year of data. The problem in such cases is exactly similar to the one faced in in-situ monitoring of the building for the purpose of long-term prediction of building loads. The accuracy with which temperature-dependent regression models of energy use identified from short data sets (i.e., data sets of less than one year) are able to predict annual energy use has been investigated with monitored data by Kissock et al., (1993) for 2-P SV models and by Katipamula et al., (1995) for standard MLR models. Further investigation has also been performed with synthetic energy use data generated from engineering models (Reddy et al., 1998). The study by Kissock et al. (1993) was limited to three LoanSTAR buildings with constant air volume (CV) systems, and that by Katipamula et al. (1995) where buildings under both CV and VAV operation were selected, found certain general characteristics of how, when and to what extent regression models based on short data-sets incorrectly predict annual energy use in the climate of central Texas.

The same type of general conclusions were reached by all these studies, which are discussed below:

(a) As expected, longer data sets provide a better estimate of annual energy use than shorter data sets. In the sample of buildings chosen, the average annual cooling prediction error of short data sets decreased from 7.3% to 3.0% and the average annual heating prediction error decreased from 27.5% to 12.9% as the length of data sets increased from one month to five months.

(b) More important than the length of the data set, however, was the season during which it occurred. When 2P models are used, cooling models identified from months with above-average temperatures (i.e., temperatures above the annual average) tend to over-predict annual energy and underpredict energy use if identified from months with below-average temperatures. The converse seems to hold for heating models.

Tests with synthetic data found that these observations are applicable for other types of models (say 4P models) as well (Reddy et al., 1998). The best predictors of both cooling and heating annual energy use are models from data-sets with mean temperatures close to the annual mean temperature and with the range of variation of daily temperature values in the data set encompassing as much as the annual variation as possible. One month data sets in spring and fall, when the above condition applies, are frequently better predictors of annual energy than five month data sets from a portion of winter and the summer.

Figure 4.0b taken from Reddy et al. (1998) illustrates this feature using synthetic cooling energy use data from a heavily scheduled building. The figure shows the monthly range of temperature variation as well as how well the seasonal cooling energy use data were fit by 4P models. The error in using the seasonal models for annual prediction was expressed as a percentage bias which was also indicated in Figure 4.0b. Though the seasonal models fit the data very well (as shown by the R^2 and CV-RMSE values in Figure 4.0b), only the October-December model was satisfactory for predicting annual energy use as evidenced by its low bias error.

Note that judging a model's predictive ability only from the goodness-of-fit criteria can be erroneous. This is illustrated by the fact that though CV-RMSE is poorer for the model identified from Oct.-Dec. data than that of the April-June and July-Sept. seasonal models. Unfortunately, the annual predictive bias is much smaller for the Oct.-Dec. period. Therefore, the low predictive error of the regression model identified during the Oct.-Dec period may not be too surprising since the variation of outdoor temperature during this period covers most of the annual temperature range (Fig. 4.0b). The best way to avoid the problem of improper long-term prediction is to insure that the outdoor temperature spread in the data set from which the regression model is to be identified captures most of the annual outdoor temperature variation of that location (this is an application of the concept of "proper experimental design" in statistics, (see Montgomery, 1991).

To conclude, the important inferences drawn from the various studies on this issue of short-term to long-term load predictions are that:

(a) only if the monitoring, (in our case, the in-situ tests) are performed during the swing seasons can one expect to have good long-term load predictions where these swing seasons contain data that represents the annual variation, and

(b) there is no way of adjusting regression models to accurately predict annual energy use once improperly identified from short data sets.

These findings and the strategy suggested are, however, unacceptable for the current project since one does not have the luxury of monitoring for several years and waiting until the climatic conditions are favorable to perform the in-situ tests. Further, we wished to evaluate what we consider to be a cost-effective option. Therefore, we deemed that practical considerations dictate that in-situ tests (even if they entail non-intrusive monitoring left at the site with automated data collection and retrieval) should not last more than 3 months, and it would be preferred if they could be limited to 2-3 weeks at the most.

Finally, we reiterate that the objective of this research is to estimate the *annual* energy and demand savings from a TES system. Though the long-term building load predictions are likely to be more accurate from models identified from short-term tests performed during the shoulder months, this may not necessarily be the best for characterizing the TES performance. It may be better from the overall TES system point of view to monitor during the peak summer season with a limited range of loads rather than the shoulder seasons where the building loads are relatively low but with greater variability. Therefore, we propose to evaluate a slightly different in-situ testing and monitoring strategy as described below.

4.5 Proposed methodology

Let us briefly summarize our thinking which was described in the previous sections. One possible approach to predicting long-term building loads from short-term data is to use a simplified calibrated HVAC systems models. However, as discussed earlier, this requires specialized skills beyond those of most energy professionals. Further, HVAC systems have set points (such as the cold or hot deck reset temperatures) which can be season dependent, or the building may be operated differently during different seasons of the year which a short-term monitoring protocol will fail to adequately capture unless the analyst acquires such information by other means (say, from the EMCS system or from the building energy manager). Hence, we propose to use a standard MLR model in this research.

Further, the regression model approach, even when a MLR model or a Fourier series model are adopted, is adequate when say 14 days or even 1 month of monitored data are available. Therefore, we are proposing a Short-term Monitoring - Long-term Prediction method (SMLP) by using 14 days (two weeks) of monitored hourly data (which can be provided by an non-intrusive or passive in-situ monitoring protocol) supplemented with year-long utility bills of the building. This combination should provide the necessary detailed short-term (i.e., hourly) data as well as the long-term data to meet the objective of this research phase. The short-term data is likely to provide the large variation in internal loads (along with the necessary insight to separate the different operating modes of the building) necessary for proper identification of the regression coefficient associated with this variable, while the utility bills will provide the necessary variability in energy use, outdoor temperature and outdoor humidity levels over an annual cycle to be able to identify the associated model coefficients in a robust fashion.

As a final note, it is important to realize that the SMLP method, or any method based on short-term measurements to predict long-term building energy use, explicitly relies on building operation being consistent within the day-types chosen. As will be discussed in Section 5, there are two sources of prediction error in the internal electric loads of the building: (1) the year-to-year variability as equipment is added/removed/replaced from the building, and (2) the fact that the short term period (say the 14 day period chosen) for monitoring the diurnal variation in E_{int} may be unrepresentative of the year-long variation. The former source of uncertainty will not be addressed in this research, while the latter will be included in the uncertainty analysis.

4.5.1 Selection of monitoring periods

In order to evaluate and refine the SMLP method, year-long monitored hourly building energy use data is preferred. We will then select different two-week periods (and "assume" that the required in-situ monitored data was gathered during that period) in order to evaluate how well the two-week selection process affects the prediction accuracy of long-term building loads. This will give insights into: (1) time of the year when the in-situ monitoring is likely to yield a regression model that is most accurate in its long-term predictions, and (2) the extent to which the accuracy of the building load predictions become poorer when periods other than this optimal period are chosen for the in-situ monitoring period. Given that there are several permutations possible, we have to narrow down the search by selecting time periods based on the criteria suggested from past studies (described earlier in Section 4.4), namely that building load prediction accuracy will be best when models are identified from data periods during which the outdoor dry-bulb temperature (which is usually the single most influential driver of building energy use) is closest to the annual mean and has a large day-to-day variability.

An intuitively appealing and simple approach to select such a 14-day period is to do so graphically. For example, one could generate a time series plot of a 14-day moving average of outdoor temperature along with plus one and minus one standard deviation bans. Such a plot, which is very easy to generate using a spreadsheet program, is shown in Figure 4.1 using yearlong daily outdoor dry-bulb temperature from College Station (handling 8670 hourly data is beyond the current generation of spreadsheet programs, and hence the reason for selecting daily values). From here we can identify that a possible "worst" two week period is during the middle of July when mean values are farthest from the annual average and the day-to-day variability is least (reflected by the one standard deviation bands being narrowest). The "best" two week period is not so clearly determined: beginning of April or end of October are likely candidates. We plan to evaluate, using monitored data gathered in the framework of this project, the relative impacts of selecting such periods on the annual and seasonal prediction accuracy of regression models for building loads.

Further, such plots could also provide some insight into how the length of the period selected for testing is likely to affect the analysis. The basic premise is that looking at how close the average of these periods is to the annual average and the relative amount of variability of daily data within the different time scale would provide some sort of relative indication as to how much better one period is as compared to another. One could generate moving average plots as shown in Figure 4.1 with the different time scales of sliding window one wishes to compare. Though there is more variability in the mean values of the 3-day averaging, the standard deviation is larger for 13-day-averaging. How this tradeoff affects the model prediction accuracy is unclear (though intuitively one would prefer the longer period). In order not to stray away from the basic intent of this research project, we do not propose to study such affects in the framework of this research.

4.5.2 Modeling variants

The SMLP approach is based on the condition that two weeks of monitored data (entailing chilled water energy use, internal lights and equipment loads, outdoor dry-bulb temperature and outdoor humidity) and 12 monthly utility bills are available for model identification. We have identified four different variants by which the SMLP approach could be implemented statistically to identify the regression model coefficients.

Variant 1: Regression of hourly and monthly values simultaneously

The 12 utility bill data are first converted into monthly mean hourly values. They are then collated to the two weeks of hourly data for building energy use data in order to form one data set. The corresponding outdoor dry-bulb temperature and specific humidity potential data (T and W) are determined from the available hourly climatic data and added to the energy use data set. Finally the monitored hourly values of E_{int} and the I_{occup} columns are added in. Note that while I_{occup} is binary (either 0 or 1) for hourly data, it appears as a fraction on a monthly basis which represents the number of hours during the month that the building is occupied.

The functional form for regression is

$$Q_{bldg} = \mathrm{a} + \mathrm{bT} + \mathrm{c}(\mathrm{w} - 0.009)^{+} + \mathrm{d}\,E_{\mathrm{int}} + e.I_{occup} \qquad (4.3)$$

where, Q_{bldg} is the predicted hourly building energy consumption
T is the outdoor dry bulb temperature,

$(w - 0.009)^+$ is the adjusted specific humidity difference (set to be zero if negative),

Variant 2: Weighted regression of hourly and monthly values simultaneously

Here also the monthly utility bills and weather variables are processed into hourly mean values by dividing them by the total number of hours for each month, as in Variant 1. These 12 hourly-mean monthly values are grouped with the data set of the two-week hourly values. Since the hourly-mean monthly and in-situ hourly values are deduced from different time scales, one needs to distinguish between both during regression by performing a weighted regression (Draper and Smith, 1982). The monthly-mean values can be seen as being an average of (24 x k) where k is the number of days in the month. Recall from basic statistics that the sampling distribution of a population varies as the square root of the sample size. Thus the logical manner of regressing the mixed time scale data is to weight the hourly-mean monthly values by $(24 \times k)^{1/2}$ and the hourly values by 1.

Variant 3: Addition of individual hourly and monthly regression coefficients

Here, the two weeks of hourly data for energy consumption and weather conditions are used to develop an hourly MLR model. The hourly model is used with the hourly climatic data throughout the year to generate year-long hourly predictions. These are then summed into monthly total predictions. The residuals resulting from the difference between the predicted monthly values (aggregated from predicted hourly values) and the monthly utility bills are again regressed against monthly weather conditions and internal loads (monthly values for internal loads might not be available in a real application). The complete model is formed by adding the individual monthly and hourly coefficients of each of the regressor terms.

Variant 4: Two-stage regression model

In order to minimize the confounding effects of collinearity discussed in Section 4.3.5, a two-stage approach has been shown to be advantageous in other building related studies (Deng, 1997). This variant involves using the monthly mean hourly data to identify the coefficients associated with weather variables only, and then using the model residuals at an hourly time scale to identify the occupant and building related diurnal schedules. For instance, a model such as

$$Q_{bldg,k} = a + bT_k + c(w_k - 0.009)^+ \qquad (4.4a)$$

with k = 1,........12 (indicating the 12 months)

is first identified from monthly mean data. Then an hourly model is developed using the coefficients **b** and **c** found by the monthly mean hourly model, and two weeks of hourly energy consumption data (for instance, CW or HW), internal loads (E_{nt}), and an occupancy indicator variable I_{occup}, in the following fashion:

$$Q_i - b.\,T_i - c.(w_i - 0.009)^+ = d + e.E_{int,i} + f.I_{occup} \qquad (4.4b)$$

This method retains the simplicity in model identification of variants 1 and 2 while offering the possibility of identifying more physically-meaningful model coefficient values.

4.5.3 Proposed variant

The four variants were first evaluated with monitored data from the Fine Arts Building of the University of Arlington monitored by ESL under the LoanSTAR project. It was found that variants (2) and (4) were distinctly better than the other two in terms of ease in model identification effort and in subsequent model prediction accuracy. However, the coefficients of the regressor term of variant (2) were not physical. For example, chilled water use should increase when internal loads increase. A negative regression coefficient was found when variant (2) was used. This was not the case when variant (4) was used. Hence, a preliminary indication would be that variant (4) has the potential of providing a better physical interpretation of the regression coefficients. This conclusion, however, needs further evaluation which will be done during the course of this research project.

To summarize, the proposed SMLP approach is likely to yield better predictions than the previously developed techniques due to the following reasons. The short-term data is likely to provide the large variation in internal loads (along with the necessary insight to separate the different operating modes of the building) necessary for proper identification of the regression coefficient associated with this variable, while the utility bills will provide the necessary variability in energy use, outdoor temperature and outdoor humidity levels to be able to identify the associated model coefficients in a robust fashion. A more complete evaluation along with documented analysis results of all four methods is being performed as part of an ongoing Ph.D. thesis work at Texas A&M University, the results of which will be incorporated into this work as they become available.

4.6 Evaluation of proposed methodology

The results of an evaluation of the SMLP method using variant (4) is presented in this section. The same data set of the Engineering Center analyzed in the Great ASHRAE Energy Predictor Shootout II (Haberl and Thamilseran 1996) was selected because this would provides an absolute means of evaluating the SMLP method as against other sophisticated modeling techniques proposed by researchers world-wide.

The Engineering Center is an institutional building located in College Station, Texas. It comprises 32,440 m^2 of classes, laboratories, computer rooms, offices, and an unconditioned underground parking garage. It is a heavy structure building with precast concrete walls. The building is occupied on weekdays from 7:30am to 6:30pm and on weekends from 7:30am to 5:30pm. Computer facilities operate 24 hours a day. The building is primarily served with 12 dual-duct air handlers operating 24 hours a day. Chilled and hot water for cooling and heating are supplied to the building by the campus physical plants.

The best two weeks of hourly data of the Engineering Center were chosen according to the visual display provided by Figure 4.1. Because the data stream started only from May, the period from

May 7th till May 20th was selected as representative of the "best" two-week period.

The monthly utility bills were "created" by aggregating hourly values available for the Engineering Center. Average monthly weather conditions were also calculating from hourly values. The monthly chilled water use (CW) and the corresponding weather conditions are shown in Table 4.1. Some monthly values could not be used due to large gaps of missing hourly values for those months, and for some months, only a few days were missing. The number of days for each month for which we had clean and complete data are given in Table 2.1 along with monthly mean values of the CW energy use and the climatic regressor variables. The ACW variable which represents CW use on an average day of the month has been determined by only considering the actual number of days per month when data was available.

The following MLR monthly mean hourly models were fit to the data by ordinary least squares regression:

$$ACW = 1.2113 + 0.0632\,T_{db} \qquad \text{with } R^2 = 0.7997 \qquad (4.5)$$

and

$$ACW = 6.6408 - 0.0335\,T_{db} + 27.99(w_{db} - 0.009)^{+} \qquad \text{with } R^2 = 0.9019$$

The first model was chosen since the negative coefficient of the outdoor dry bulb temperature in the second model is doubtful and misleading, even though a better correlation was obtained.

The hourly MLR model was developed as follows. An hourly variable (CW_i - $0.0632.T_i$) was calculated and regressed against the internal electric loads (E_{int}) and the occupancy indicator variable (I_{occup}) which was assigned the following values from how the internal load schedule varied at the Engineering Center:

I_{occup} = 0 for Weekdays, 7:00am - 7:00pm; 1 otherwise
0 for Weekends, Holidays, Semester Breaks, 7:00am - 6:00pm; 1 otherwise.

The following MLR hourly model was finally obtained:

$$CW_i - 0.0632.T_i = 1.2581 + 0.00036.E_{int,i}) + 0.02079.I_{occup,i}) \qquad (4.6)$$

This hourly model was used to predict CW use during days when monitored CW data was intentionally removed by the organizers of the ASHRAE Energy Predictor Shootout II to evaluate the accuracy of the models developed by the contestants. Time series plots of the removed data in the Shootout competition, predicted with the SMLP method and measured, are shown in Figs. 4.1(a and b) for different periods of the year. Generally the model seems to be satisfactory, though large differences do appear. Some of the differences between model predicted and observed values could be due to the fact that the building is operated differently that it was during the 14-day period used for model identification. There is often no definite way to determine this, and it is in such cases, that performing an evaluation with synthetically generated data (i.e., using a building energy simulation program) can provide certain insights which actual field data cannot.

A comparison of the accuracy of the SMLP model's prediction with other models is shown in Table 4.2. It is clear that the SMLP is only slightly poorer than the top contestants (i.e, E1 through E5). The SMLP prediction error on an hourly time scale had a CV (%) of 8.84 and an MBE (%) of 2.709. It is worth mentioning that the top contestants used more sophisticated and involved methods such as neural networks, MLR models for each hour of the day, and inverse binning method (method E5, Haberl and Thamilseran 1995). All these methods made use of the approximately full year of hourly data set to identify a model while the SMLP Method utilized only two weeks of hourly data, supplemented by monthly utility bills and weather conditions (that can be obtained in a real situation from the national weather service or from normalized weather conditions). Hence, not only are the predicted hourly values accurate for the SMLP approach, but the results compare very favorably with other much more sophisticated approaches.

Because the overall objective of this research is to determine energy and demand savings from the TES system, we should be able to consider differential time-of-day and time-of-year rates for electricity in our analysis. In order to do so, we need to evaluate the SMLP method by its ability to predict building loads on a time-of-day and on a seasonal basis. A preliminary analysis of this capability has also been carried out with the Predictor Shootout II data and our "best" model. We have divided the year into summer (from June 15th till September 15th) and non-summer months.

Further, we have considered four different daily periods:

1. all hours of the day

2. occupied on-peak hours (noon till 6:00 p.m.)

3. occupied off-peak hours (6:00 a.m. till noon)

4. non-occupied off-peak hours (6:00 p.m. till 6:00 a.m.)

How well the SMLP model does with such disaggregation is summarized in Table 4.3. One notes that though the CV-RMSE values are close to 10%, the relative MBE is generally small, less than 10% for summer months and close to zero for the non-summer months. These numbers will be used while performing a preliminary uncertainty analysis as described in Section 5. A pictorial representation of the predictive ability of the SMLP method is given in Figure 4.3 in terms of load duration curves. The monitored data has been sorted in descending order and this is plotted both with the concurrent (i.e., unsorted) values of the model predictions as well as with the sorted values of the model predictions. Such an illustration provides a better illustration for the purposes to which the model predictions will be used during the analysis than does the hour-hour comparison shown in Figure 4.1.

4.7 Future Work

The above findings are limited to the specific case when the SMLP model used non-intrusive data from the "best" two weeks of the year. We are currently evaluating the prediction accuracy of this method, with other two-week periods. Specifically, we propose to repeat such analyses using the "worst" two weeks as well as a "mediocre" two week period with the same Great Energy Predictor Shootout II data.

Further, we propose to select 2-3 more buildings monitored under the Texas Loan STAR program, or similarly appropriate buildings and repeat the above analyses. We shall select buildings of different types (offices, classes, hospitals, dormitories), different HVAC types (CV, VAV), and different climates (i.e., Texas and Minnesota). Actual monitored data presents a challenge in evaluating the proposed prediction method since the operation of the building might (and does) change (without us being cognizant of the fact) from year to year, or even, from season to season. Another problem arises from the availability of clean hourly data covering at least one complete year, and preferably two years (one for model identification, and the other year for evaluating the model prediction accuracy). Since the conclusions of our study would be directly impacted by such considerations, we shall give adequate care to selecting the proper buildings and "clean" data periods for further analysis.

Finally, there are two additional factors which we propose to explicitly consider. Some buildings are already being monitored by the electric utility and 15 minute demand data may be available to supplement the in-situ measurements. In such cases, a more accurate building load model could be identified than resorting to utility bills. Secondly, the presence of a TES system will affect the proposed building load model identification scheme since the billing data will also implicitly contain the performance of the TES system. How to separate the effect of the TES system from that of the building loads and the chiller needs to be investigated further.

4.8 Annotated Bibliography

ASHRAE, 1997. Fundamentals Handbook, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, GA.
This handbook, revised every 4 years by ASHRAE, covers basic principles and includes data for the entire technology of the HVAC&R industry. Each of the chapters is revised by a concerned technical committee which strives to provide new information, delete obsolete materials, clarify existing information and even reorganize chapters as needed.

Bou Saada, T. and J. Haberl. 1995a. A weather daytyping procedure for disaggregating hourly end-use loads in an electrically heated and cooled building from whole-building hourly data. Proceedings of the 30th Intersociety Energy Conversion Engineering Conference, July 31 - August 4 1995, Orlando, FL, pp. 323-330.
This paper presents a weather day-typing procedure capable of disaggregating whole-building electricity signal into end-use loads. Representative days were used to designate the non-weather dependent base load for occupied and non-occupied hours which were then sorted into three additional weather types: one for cooling, one for heating and one for non-heating/non-cooling. Results of applying this methodology to a case study building in Washington, D.C. were also presented.

Bou Saada, T. and J. Haberl. 1995b. An improved procedure for developing calibrated hourly simulation models. Proceedings of the 30th Intersociety Energy Conversion Engineering

Conference, July 31 - August 4 1995, Orlando, FL, pp. 323-330.
This paper investigates techniques for improving the calibration of DOE-2 simulation results to monitored building data. Several new methods were suggested that include new graphical procedures and the use of statistical goodness-of-fit parameters. A case study building of four zones with electric heating and cooling was used to demonstrate the techniques with hourly measured whole-building electricity data.

Bou-Saada, T., 1994. An Improved Procedure for Developing a Calibrated Hourly Simulation Model of an Electrically Heated and Cooled Commercial Building", Master of Science thesis, Mechanical Engineering Department, Texas A&M University, College Station, TX.

This Master of Science thesis investigated several techniques for improving the calibration of detailed building simulation software to measured data. The use of architectural rendering software allowing better visual verification of size and placement of the building's exterior surfaces and shading surfaces was illustrated. The thesis also illustrated the combined use of statistical and visual data display techniques for achieving better calibration. The use of solar beam and diffuse data synthesized from on-site global horizontal solar measurements were also shown to improve the calibration.

Bronson, D., Hinchey, S., Haberl, J., O'Neal, D., and Claridge, D., 1992. "A Procedure for Calibrating the DOE-2 Simulation Program to Non-Weather Dependent Measured Loads," ASHRAE Transactions, v. 98, pt. 1, AN-92-1-5.
This paper describes a procedure to calibrate DOE-2 building simulation program to non-weather dependent (or scheduled) loads. The procedure relies on special purpose 3-D graphics of differences in the hourly monitored and simulated data as an aid in the calibration process. Four different types of day-typing routines were used to demonstrate the effectiveness of the procedure.

Claridge, D., Haberl, J., Turner, W., O'Neal, D., Heffington, W.M, Tombari, C. and Jaeger, S. 1991. "Improving Energy Conservation Retrofits with Measured Savings," ASHRAE Journal, October.
This ASHRAE Journal paper is one of the first articles that describes the general philosophy and approach taken to verify retrofit energy savings in the Texas LoanSTAR revolving-loan program. The process of how state, county and local government building agencies in Texas could apply for energy conservation loans, and how the Monitoring and Analysis (MAP) quality-assurance program, sub-contracted to Texas A&M University, has been structured in order to monitor, verify and report actual retrofit savings is described.

Cohen, D.A. and Krarti, M., 1997. "Neural Network Modeling of Measured Data to Predict Building Energy System Retrofit Savings", Proceedings of the 1997 ASME International Solar Energy Conference, p.27, Washington, D.C., April.
This conference paper describes a study that used neural networks for predicting the energy and demand savings resulting from energy conservation measure retrofits in commercial buildings. An example based on simulated synthetic data is used to illustrate proof of concept for the method. Subsequently, another example is given using measured end-use data from another building.

Deng, S., 1997. Development and Application of a Procedure to Estimate Overall Building and Ventilation Parameters from Monitored Commercial Building Energy Use", Master of Science thesis, Mechanical Engineering Department, Texas A&M University, College Station, TX.

This thesis proposes a multi-stage scheme to identify a buildings over all physical parameters from monitored data. The scheme is validated by using synthetic data generated from a detailed computer simulation programs as "monitored" data. The explanation of how the parameters were identified is for identifying the energy delivery efficiency of HVAC systems. Results from the application to several buildings with monitored data is discussed.

Dhar, A., Reddy, T.A. and Claridge, D.E., 1994. "Improved Fourier Series Approach to Model Hourly Energy Use in Commercial Buildings", Proceedings of the 1994 ASME/JSME/JSES International Solar Energy Conference, p.455, Washington, D.C.

This conference paper proposes a Fourier Series functional form to model hourly building energy use data (electric, heating or cooling thermal loads) using climatic variables and time of day and day of year. The validity of this approach is illustrated with year-long monitored hourly data from 5 commercial buildings in Texas. The consistency with which certain frequencies appeared in the diurnal scheduling of buildings and their physical interpretation were also discussed.

Draper, N., and Smith, H., 1981. Applied Regression Analysis, 2nd Edition, John Wiley & Sons, New York.

This is a classic highly-acclaimed textbook which deals with the fundamentals of regression analysis emphasizing an understanding of concepts and the application of methods. Both linear and non-linear regression models are covered. Written at an undergraduate level for students of statistics, the book is very formal in its statistical treatment.

Fels, M. (Ed.), 1986. "Special Issue Devoted to Measuring Energy Savings, The Princeton Scorekeeping Method (PRISM)", Energy and Buildings, Vol. 9, Nos. 1 and 2.

This is a special issue of the Energy and Buildings Journal devoted solely to measurement of energy savings from billed data. The 17 papers written by various authors include a description of the PRISM method, its application to single-family and multi-family houses, its applicability to homes heated by oil, wood and electricity (heat pumps) and the reliability of PRISM results. One of the papers is of particular interest to this project since it addresses the predictive accuracy of a PRISM model identified from less than one complete year of utility bills.

GPC 14P, 1997. "ASHRAE Guideline for Measuring Savings from Energy Conservation Projects", draft document, August.

This guideline provides three methods for measuring savings from energy conservation retrofits: component isolation, main-meter before-after measurements and calibrated simulation. Such methods can be used to measure and verify the payments that should be made to energy service companies, utilities and others who provide Energy Conservation Retrofit Measures (ECRMs).It includes using data from specific components, main meters, or simulated data, and encompasses all forms of energy (electricity, gas, oil, district heating/cooling, etc.) in residential, commercial and industrial buildings. Sampling methodologies, metering standards and major industrial process

loads are excluded.

Greely, K.M., Harris, J.P. and Hatcher, A.M., 1990. "Measured Energy Savings and Cost Effectiveness of Conservation Retrofits in Commercial Buildings", Proceedings of the ACEEE 1990 Summer Study on Energy Efficiency in Buildings, Washington D.C., pp. 3.95 - 3.108.
This paper summarizes a study performed to assess the differences between predicted and measured savings from energy retrofit programs. The study covered over 1,700 buildings where retrofits were performed, and it was found that only one in six came within 20% of measured results. The different methods used to predict savings were evaluated, and the authors concluded that the lack of an accepted and accurate method of predicting/determining retrofit savings was a major reason for this discrepancy.

Haberl, J.S. and Thamilseran, S., 1996. " The Great Energy Predictor Shootout II: Measuring Retrofit Savings- Overview and Discussion of Results", ASHRAE Trans, 102(2).
This seminal paper summarizes the comparative prediction accuracy of several models of hourly building energy use data. This second shootout competition, open to anyone who wished to participate, involved the following steps: (1) each contestant was supplied with an identical baseline data set consisting of hourly energy use data and climatic variables for a certain period of the year for one building, (2) the contestants then developed models (regression, artificial neural networks, etc.) based on this baseline data, and (3) the judges then used these models to predict energy use into the future for which they alone had monitored data, and ranked the entries based on their predictive accuracy. This second shootout differed from the first predictor shootout (Kreider and Haberl 1994 a, b) because it attempted to compare the retrofit savings ability of the contestants models, and is therefore more relevant to this project.

Katipamula, S., and Claridge, D., 1993. "Use of Simplified Systems Model to Measure Retrofit Energy Savings," Trans. of the ASME Journal of Solar Energy Engineering, Vol.115, pp.57-68,May.
This paper was the first to suggest the use of simplified HVAC system models (based on the ASHRAE TC4.7 Simplified Energy Analysis Procedure- SEAP) for calibrating simulations against monitored building energy use data. The paper deals specifically with hourly data being available as against utility bill data. Though the paper only addressed the case of determining savings when the baseline period was inadequately monitored or not monitored at all, the approach adopted for model calibrations has been subsequently found to be very convenient and relatively easy to implement, as testified by allied papers by several authors. The authors illustrate the use of this approach with monitored data from a building where the dual-duct constant air volume system was retrofitted to a VAV system.

Katipamula, S., Reddy, T.A. and Claridge, D.E., 1994. "Development and Application of Regression Models to Predict Cooling Energy Consumption in Large Commercial Buildings", ASME/JSME/JSES International Solar Energy Conference Proceedings, (Eds. D.E.Klett, R.E.Hogan and T.Tanaka), p.307, San Francisco, March.
This ASME conference paper presents the results of using multiple linear regression to model cooling thermal energy use in five large commercial building in Texas. The functional forms of the regression models are based on engineering considerations as against a pure curve fitting

approach. Data from both CV and VAV systems was used, and the accuracy of the models was evaluated with both hourly and daily monitored data. The extent to which such models fare better than the simple linear model is also illustrated and discussed.

Katipamula, S., Reddy, T.A. and Claridge, D.E., 1995. "Bias in Predicting Annual Energy Use in Commercial Buildings with Regression Models Developed from Short Data Sets", Proceedings of the ASME International Solar Energy Conference, pp.99-110, San Francisco, April
This paper presents the results of a study whose objective was to approximately quantify the bias error in the annual or seasonal energy use predicted by regression models which have been identified from short-term monitored data over one month only. Multiple regression models were used to study the bias error in five buildings where year-long monitored data was available. How the bias error changes when different months of the year are selected for model identification is also addressed. This study was an extension of a previous work by Kissock et al. (1993) wherein only simple linear models were considered.

Kawashima, M., Dorgan, C.E. and Mitchell, J.W., 1995. "Hourly Thermal Load Prediction for the Next 24 Hours by ARIMA, EWMA, LR, and an Artificial Neural Network", ASHRAE Transactions, V.101, Pt.1, paper no. 3849.
This paper reports the findings of a research project which compared the relative accuracy of four different methods to predict hourly thermal loads of buildings 24 hours in advance. Of the ARIMA, EWMA, LR and artificial network models studied, the neural networks were found to be most accurate. Contrary to many studies of this type which assume that climatic variables are explicitly known for the prediction period, this study considered the issue of predicting the climatic variables into the next 24 hour period as well.

Kawashima, M., Dorgan, C.E. and Mitchell, J.W., 1996. "Optimizing System Control with Load Prediction by Neural Networks for an Ice-Storage System:, ASHRAE Transactions: Symposia paper AT-96-21-4, pp. 1169-1178.
This paper describes the performance of a partial ice storage system that has a controller which predicts the future loads by a neural network model. This study, which is a simulation study, considered two different control strategies, namely the conventional chiller priority strategy and one based on the ability to predict future building loads for optimal control, and found the latter to be much more effective in reducing energy use. Not surprisingly, the study found that the accuracy of the prediction algorithm is key to the success of the latter control strategy.

Kissock, J.K., Reddy, T.A., Fletcher, D. and Claridge, D.E., 1993. "The Effect of Short Data Periods on the Annual Prediction Accuracy of Temperature-Dependent Regression Models of Commercial Building Energy Use", Proceedings of the ASME International Solar Energy Conference, pp.455-463, Washington D.C., April.
This paper examines how simple linear, temperature-dependent regression models of energy use based on periods of less than one year fared in terms of their accuracy in predicting the annual energy use. Heating and cooling energy use data in three large commercial buildings in Texas were analyzed considering three scenarios, namely when the baseline data covered only 1-month or only 3-months or only 6-months. The effect of the selection of these periods in terms of the season of the year was also studied. Several characteristics of the data-sets and models which

influenced their predictive ability were also identified.

Kissock, J.K., 1993. "A Methodology To Measure Retrofit Energy Savings In Commercial Buildings", Ph.D. dissertation, Mechanical Engineering Department, Texas A&M University, December.
This doctoral dissertation proposes and illustrates a methodology to determine retrofit energy savings in commercial buildings when pre-retrofit and post-retrofit monitored data are available. The methodology which uses 1-P, 2-P, 3-P, and 4-P change-point models with outdoor temperature as the only regressor variable is applicable to both weather independent and weather dependent data. The effect of short baseline data sets on model predictions, and how to determine prediction uncertainty bands when the model residuals were correlated was also addressed. The EModel software package capable of performing data analysis, modeling and retrofit savings determination is also presented.

Knebel, D.E., 1983. Simplified Energy Analysis using the Modified Bin Method, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, GA.
This report, which has been developed under the guidance of ASHRAE TC 4.7, describes the basis of the modified bin method. It starts with a brief background and description of the existing energy analysis methods, and then points out the limitations of the original bin method which the modified bin method is supposed to overcome. Detailed algorithms along with all relevant equations, detailed illustrative example as well FORTRAN code listing of the simulation modules for a variety of all-air HVAC systems makes this report a one-of-a-kind, valuable guide and reference.

Kreider, J.F. and Wang, X.A., 1991. "Artificial Neural Networks Demonstrated for Automated Generation of Energy Use Predictors for Commercial Buildings", ASHRAE Trans., 97(1).
The first of a series of papers on artificial neural network from Univ. of Colorado at Boulder, this paper givens a good introduction to the application, construction and operation of neural networks. It then applies the technique to monitored hourly building energy use data and compares it to more conventional regression based techniques. The advantages of neural networks to building energy use modeling are also pointed out. The paper also points to the previous methods investigated including: multiple non-linear regression and singular valued decomposition.

Liu, M. and Claridge, D.E., 1995. "Application of Calibrated HVAC System Models to Identify Component Malfunction and to Optimize the Operation and Control Schedules", Proceedings of the ASME/JSME/JSES International Solar Energy Conference Proceedings,, Vol.1, p.209, Maui.
This paper applies and extends the simplified HVAC system calibration methodology proposed by Katipamula and Claridge (1993) to diagnosis of HVAC component malfunction and to optimization of the operation and control of the reset schedules of the HVAC system. The procedures to achieve the above are described, and case studies involving actual buildings for both the above applications are provided.

MacDonald, J. and Wasserman, D., 1989. Investigation of Metered Data Analysis Methods for Commercial and Related Buildings, ORNL/CON-279, Oak Ridge National Laboratory, Oak

Ridge, TN.
This well-written ORNL report covers an in-depth review and evaluation of data analysis techniques for evaluating the baseline energy use and potential energy efficiency improvements in commercial and related buildings that use metered energy data. The current analysis methods, ranging from annual to sub-hourly data, are classified and discussed. The authors also describe the types of features which the development of new methods should address.

Manke, J.M., Hittle, D.C. and Hancock, C.E., 1996. "Calibrating Building Energy Analysis Models using Short-Term Data", Proceedings of the 1996 International ASME Solar Energy Conference, p.369, San Antonio, TX.
This paper presents the results of a project whose objective was to develop and demonstrate an inexpensive, short-term performance test for building energy systems. A protocol for short-term energy monitoring tests was developed, as well as a systematic approach to reconcile differences between the simulated (using the BLAST program) and measured energy use data. The approach is illustrated for a relatively small commercial building located in Sacramento, CA. It also recommends the use of "effective" simulation input parameter values to obtain the optimum simulation results. The fact that such effective parameters (sometimes 10x larger than observed) gives better results than observed parameters (such as wall area and U-value) indicates one of the pitfalls of calibrating simulation programs to limited measurements from an actual building.

Montgomery, D.C. and Johnson, L.A., 1976. Forecasting and Time Series Analysis. McGraw-Hill, NY.

This is a very well written undergraduate text-book on time series analysis. The statistical basis, model identification, model prediction and prediction uncertainty issues of various time series analysis methods which include moving averages, exponential smoothing, and transfer function (ARIMA) methods are covered in a clear and very readable manner.

Montgomery, D.C., 1991. Design and Analysis of Experiments, Third Edition, John Wiley and Sons, New York.
In this book, the title may be misleading in that the book does not deal with data analysis or uncertainty or regression. However, it does a very good job of addressing allied and more efficient sampling methods other than the widely used random sampling technique to determine statistical properties of a population from sampled sub-sets. This too is a well-written textbook which has been written for a second undergraduate statistics course for engineering and science students as well as for practitioners of statistical methods. The book treats the subject comprehensively and contains numerous illustrative examples.

NEMVP, 1996. "USDOE North-America Energy Monitoring and Verification Protocol", US Department of Energy, Washington D.C.
This document, the result of a concerted effort by Federal and State agencies as well as financial and energy efficiency experts, proposes different options for measuring energy savings from energy conservation retrofits depending on the particular situation of how to quantify the performance of energy conservation measures and to determine savings. It is a complementary document to the GPC-14 Guideline being developed by ASHRAE but lacks the mathematical and

scientific rigor provided by the latter. In contrast to the GPC-14P document which focuses on the relationship of the measurement to the equipment being verified, this document discusses the variety of monitoring and verification options as they relate to actual contracts for energy services. Both the verification of the conditions for baseline model development as well as verification of the quantity of energy savings are addressed.

Norford, L.K., Socolow, R.H., Hsieh, E.S. and Spadaro, G.V., 1989. "Two-to-one Discrepancy between Measured and Predicted Performance of a Low-Energy Office Building: Insights from a Reconciliation based on the DOE-2 Model", Energy and Buildings, vol.21, p.121
This is probably the first paper to present a procedure for calibrating DOE-2 computer models to two companion buildings is presented. The procedure uses both the design-stage building description and measurements of building energy use on hourly, daily, monthly, and yearly time scales. The factors critical to the calibration process are identified and discussed. Guidance as to the types of instrumentation and the level and amount of data necessary for proper building characterization is also provided.

Rabl, A., 1988. "Parameter Estimation in Buildings: Methods for Dynamic Analysis of Measured Energy Use", ASME Journal of Solar Energy Engineering, Vol. 110, p. 52.
This is an excellent paper which classifies the various types of dynamic inverse model formulations applicable to building shell interactions, lays down the basic mathematical approach to each, and draws attention to the common underlying features of all these methods. A review of past work on building inverse work is also provided. A case study example of how such models capture monitored data behavior from a commercial building in New Jersey is also presented.

Reddy, T.A. and Claridge, D.E., 1994. "Using Synthetic Data to Evaluate Multiple Regression and Principal Component Analysis for Statistical Modeling of Daily Building Energy Consumption", Energy and Buildings, vol. 114, p.35.

This paper presents a comparison of multiple regression and principal component analysis for the statistical modeling of daily building energy use. The paper shows that the collinearity between regressor variables of a multiple regression model result in unstable model coefficients which adversely affect the predictive accuracy of the model. It also shows that building energy use is affected by both outdoor temperature and humidity which are correlated variables. This paper starts with an introduction of such issues, and then evaluates a technique, called "principal components" or PCA which supposedly can minimize the effect of such confounding effects on model identification and prediction. How PCA and standard multiple regression compare with each other is studied based on synthetic sequences of building energy use data. It is concluded that indiscriminate use of PCA can exacerbate rather than alleviate the effects due to collinear regressor variables for the particular buildings studied.

Reddy, T.A., Katipamula, S., Kissock, J.K. and Claridge, D.E., 1995. "The Functional Basis of Steady-State Thermal Energy Use in Air-Side HVAC Equipment", ASME Journal of Solar Energy Engineering, vol.117, pp.31-39, February.
The purpose of this paper was to derive closed-form steady-state functional relations for air-side cooling and heating thermal energy use for four of the most widespread HVAC system types, namely terminal reheat and dual-duct systems under constant air volume and VAV operation.

Expressions were derived for hourly energy use as a function of climatic variables, building characteristics, and system parameters. The effects of economizer cycle and cold or hot deck reset schedules were also treated. How such functions were used for proper regression modeling and sensitivity analyses was also pointed out.

Reddy, T.A., Kissock, J.K and Ruch, D.K., 1998. "Uncertainty in Baseline Regression Modeling and in Determination of Retrofit Savings", paper submitted to the ASME Journal of Solar Energy Engineering.
This is an overview paper which summarizes the various sources of uncertainty in retrofit energy savings from regression models based on continuous monitoring of building energy use. Statistical equations for uncertainty when the regression models have improper residual behavior were also given.

Reddy, T.A., Kissock, J.K., Katipamula, S., Ruch, D.K. and Claridge, D.E., 1994. An Overview of Measured Energy Retrofit Savings Methodologies Developed in the Texas LoanSTAR Program", Energy Systems Laboratory report ESL-TR-94/03-04, Texas A&M University, College Station, TX.
This report summarizes the experiences and lessons learned in baseline model development in the framework of the Texas LoanSTAR program. How retrofit savings were measured when monitored data was available is first presented. Subsequently, the equations and the salient points to be kept in mind when modeling monthly, daily or hourly data with simple regression, multiple regression, Fourier series or calibrated simplified HVAC models were presented. The question of when should one adopt one technique over the other was also pointed out. Results obtained in using these approaches to the Texas LoanSTAR buildings are also presented.

Reddy, T.A., Saman, N.F., Claridge, D.E., Haberl, J.S., Turner, W.D. and Chalifoux, A., 1997. "Baselining Methodology for Facility-Level Monthly Energy Use- Part 1: Theoretical Aspects", ASHRAE Transactions, V.103, Pt.2, paper no BN-97-16-4 (4089).
This paper discusses the various issues involved in a proper baselining methodology used to verify savings due to retrofits or due to energy efficiency measures when monthly utility bills are available. The various parameters which need to be explicitly considered and whose effects should be removed in order to determine savings were also discussed. The various single variable change point regression models used were also summarized. The noteworthy feature of this paper is the proposal of uncertainty bands in the model predictions which can serve as a means of identifying changes in energy use either at a month-to-month or at an annual level. A companion paper presents the results of applying this baselining methodology to eight U.S. army bases.

Reichmuth, H. and Robison, D., 1992. "Innovations in Short-Term Measurement- Economical Alternatives to Long-term Monitoring", Proceedings of the ACEEE 1992 Summer Study on Energy Efficiency in Buildings, pp. 10.211 -10.219, Washington, D.C.
This conference paper reviews a collection of short-term measurement tests and techniques that are available to characterize building energy use. The authors' have relied on their experience from the monitoring and modeling efforts in Pacific Power's in-house commercial monitoring program as well as that from Energy Edge and CHEUS programs. They identified a number of key determinants, and argued that if these can be determined or measured properly, then the need

for continuous long-term measurement can be minimized. An illustrative example is also provided.

Ruch, D., Chen, L., Haberl, J., and Claridge, D.E., 1993. "A Change-point Principal Component Analysis (CP/PCA) Method for Predicting Energy Usage in Commercial Buildings: The PCA Model", ASME J. Solar Energy Eng., 115(2), p.77.
This paper suggested that the principal component analysis (PCA) method be used to remove some of the drawbacks in predictive accuracy which a multiple regression model with correlated variables is likely to suffer from. A discussion of the PCA method as well as its applicability to building energy use data are discussed. Results of applying the PCA method to monitored data from a commercial building are described and its advantage over the standard regression methods are highlighted.

Seem, J.E. and Braun, J.E., 1991. "Adaptive Methods for Real-Time Forecasting of Building Electrical Demand", ASHRAE Trans., vol.97(1), p.710.

This paper presents an adaptive algorithm for forecasting the electrical demand of a building for cooling purposes. The algorithm uses a cerebellar model articulation controller (CMAC) model that is able to handle non-linear behavior to model the deterministic part of the time series, while an autoregressive model with three parameters is used to capture the stochastic behavior. According to the authors, the algorithm is simple enough to implement and its computational and memory requirements are modest. Electrical data gathered from a grocery store and a restaurant are used to demonstrate the accuracy and robustness of the algorithm.

Subbarao, K., 1988. "PSTAR-Primary and Secondary Terms Analysis and Renormalization: A Unified Approach to Building Energy Simulations and Short-term Monitoring," SERI/TR-254-3175, Solar Energy Research Institute, Golden, Colorado.
This SERI report details the final results of a project whose goal was to develop, field test, and transfer to industry a technique for assessing the energy performance of a residential building through short-term tests. This report, the culmination of many years of research by the author, is probably the best document describing the PSTAR method which is the state-of-art method for inverse parameter identification in envelope driven buildings. The methodology involves performing hourly simulations from a detailed audit description of the residence, and then "renormalizing" the important heat flows by analyzing the residuals between modeled and measured performance. The experimental protocol called STEM involves performing intrusive tests during 2 days and 2 nights. The applications of such a methodology are presented, as well as several case study illustrative examples.

Thamilseran, S. and Haberl, J.S., 1995. "A Bin Method for Calculating Energy Conservation Retrofit Savings in Commercial Buildings". Proceedings of the ASME/JSME/JSES International Solar Energy Conference Proceedings,, Vol.1, p.111, Maui.
This conference paper suggests a novel inverse bin method for developing a baseline model to building energy use data. The approach is based on the ASHRAE bin method which is a widely used simplified design (or "forward") method to determine annual or seasonal energy use in buildings. The methodology uses hourly monitored data grouped into 5^0F bins to identify a regression model to serve as the baseline model. According to the authors, this approach is

especially useful when the baseline data is noisy in which case a standard regression model can yield misleading results. Monitored data of several buildings from the Texas LoanSTAR program are used to illustrate this approach.

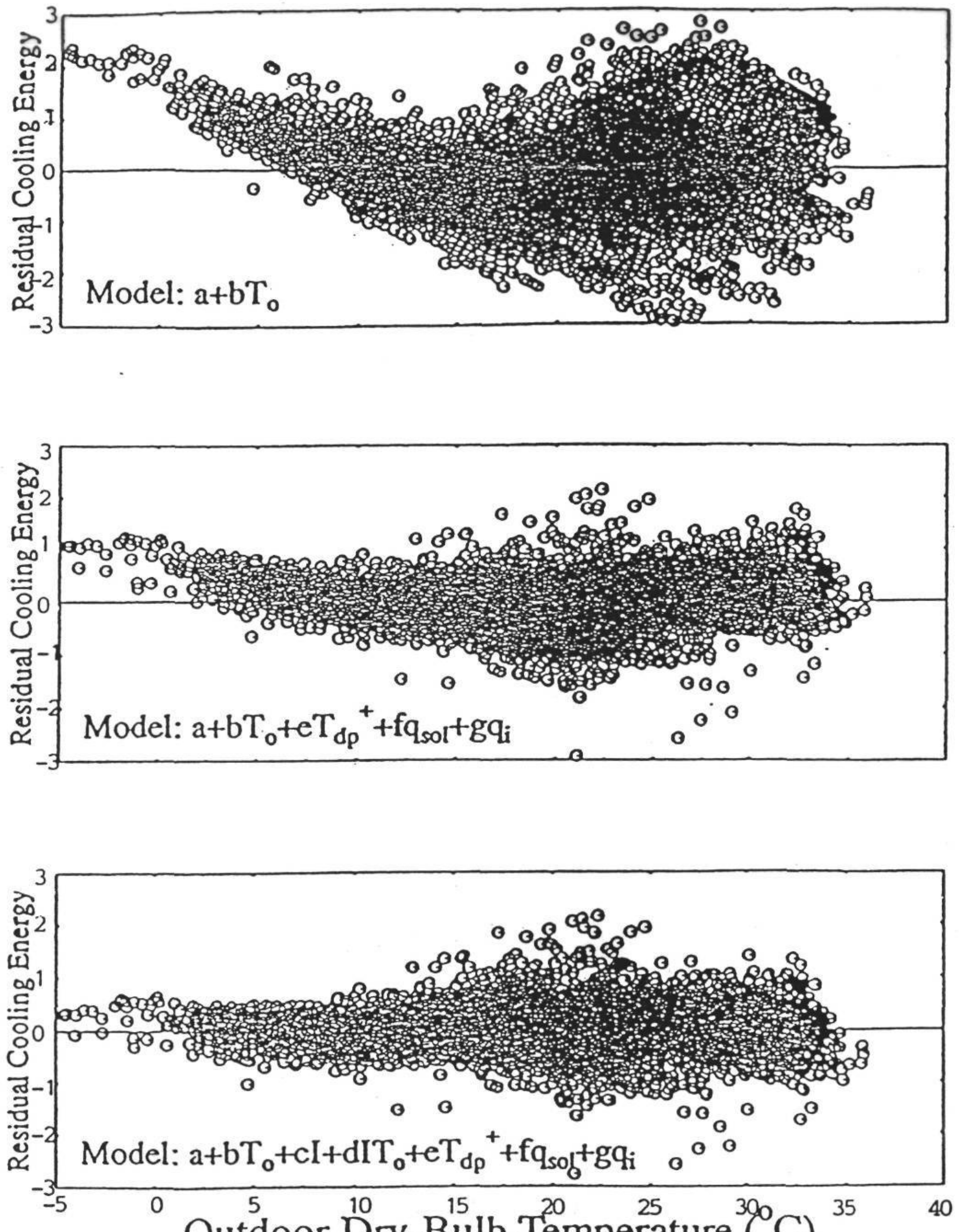
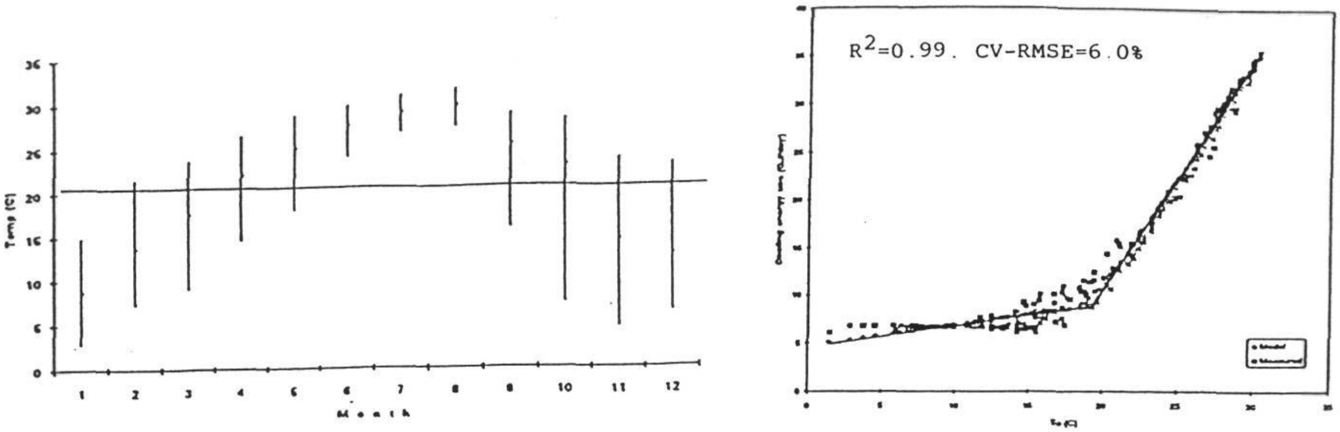
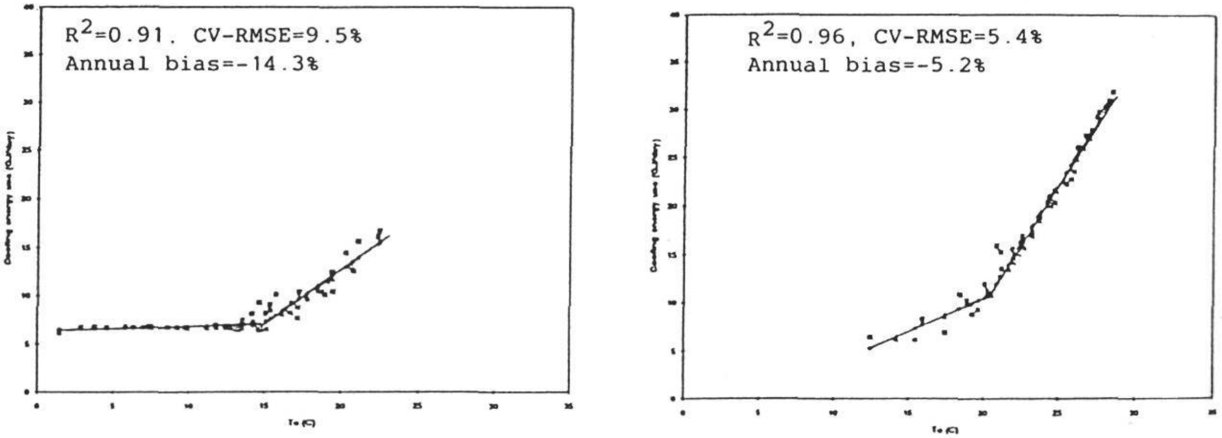


Figure 4.0a. Plots of hourly cooling energy use residuals when different functional forms are used for regression (Katipamula et al. 1994)



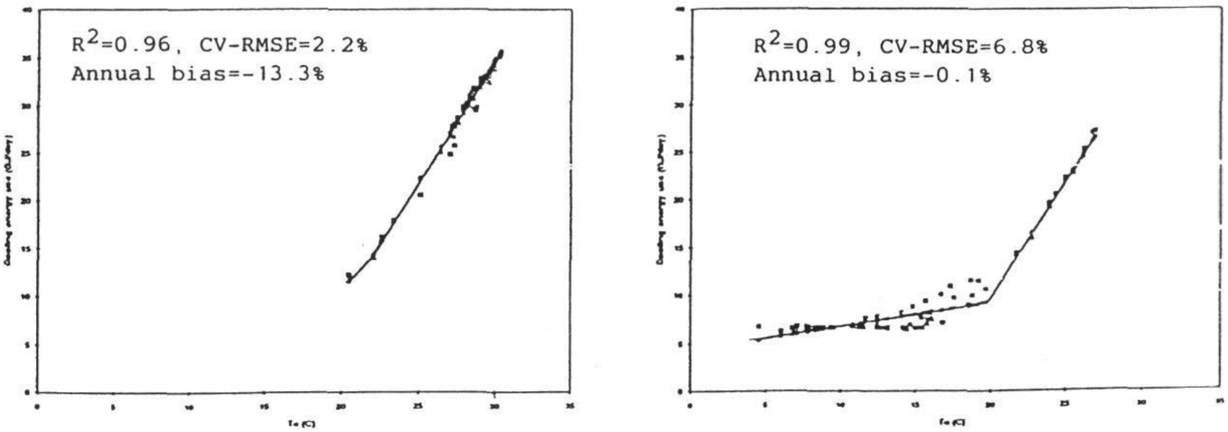
(a) Range of variation of daily T_0 values

(b) Whole year



(c) January to March

(d) April to June



(e) July to September

(f) October to December

Figure 4.0b. Plots illustrating how regression models identified from short data sets compared with one identified from a whole year (from Reddy et al., 1998).

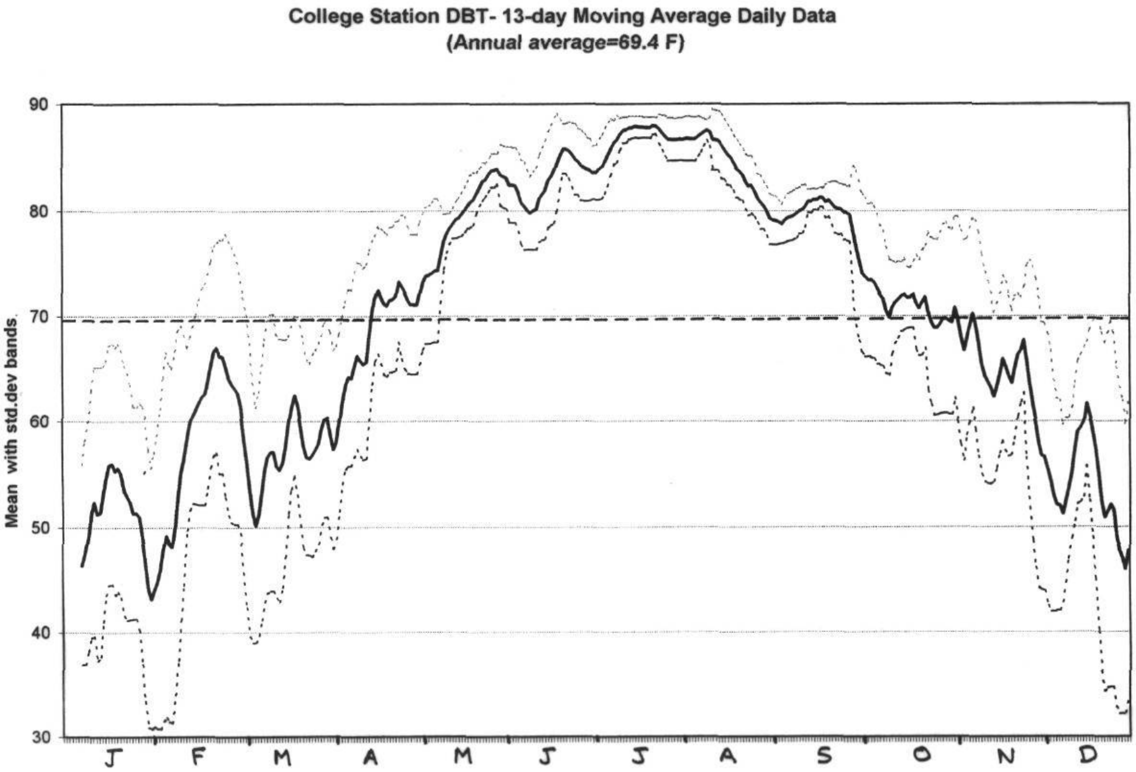


Figure 4.1. Time series plot of the 13-day moving average and plus minus one standard deviation uncertainty bands of daily outdoor dry bulb temperatures at College Station (for the year 1996).

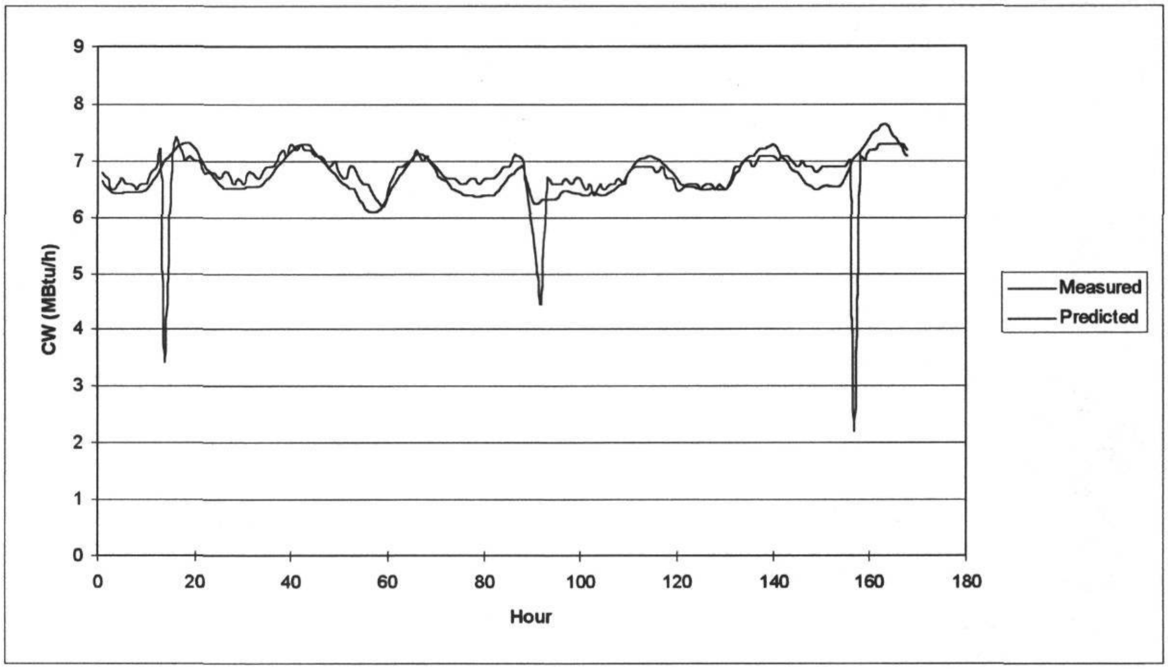


Figure 4.2a. Time series plot of the chilled water use (CW) of the Engineering Center for the week of May 15- 21 1990.

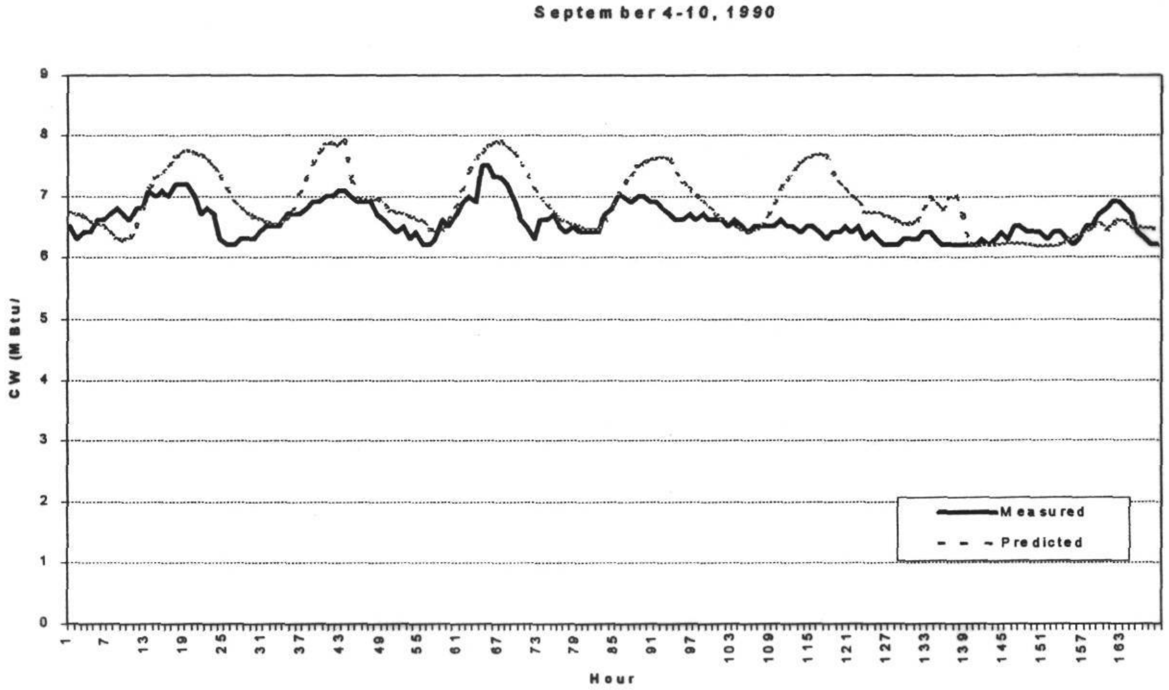
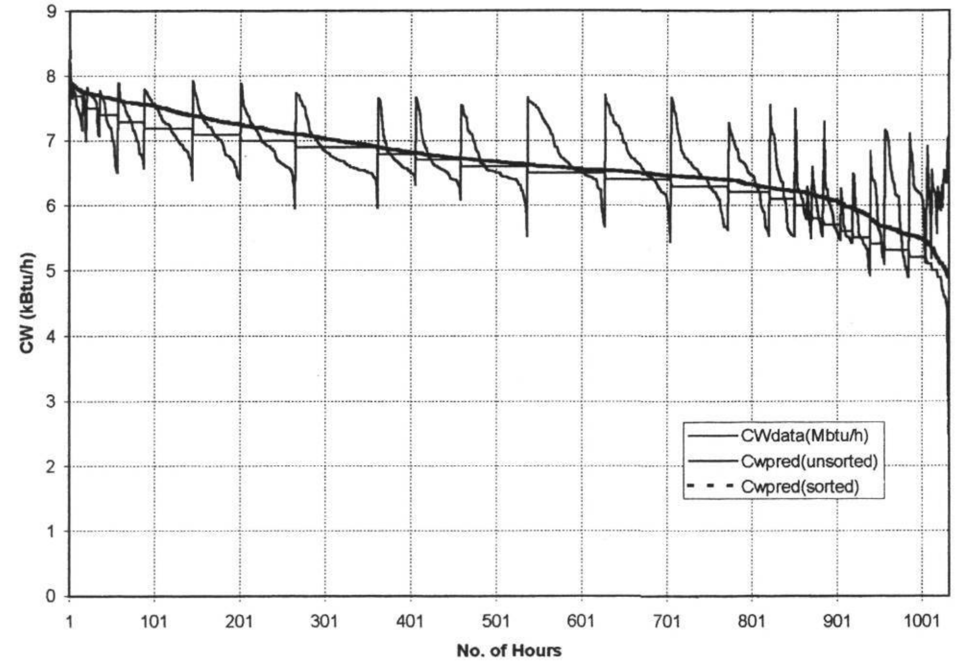
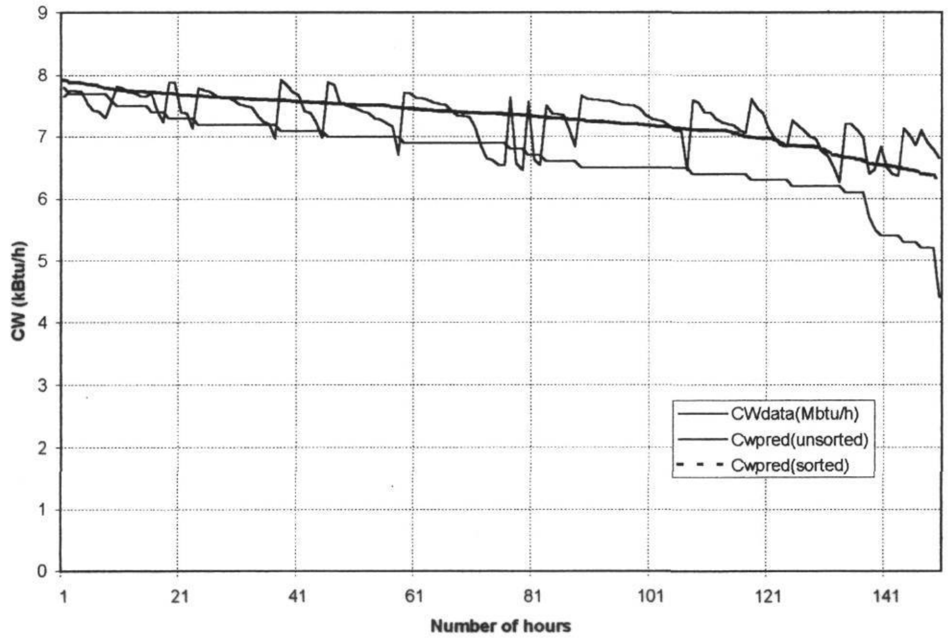


Figure 4.2 b. Time series plot of the chilled water use (CW) of the Engineering Center for the week of September 4-10, 1990



Load Duration Curves of Measured and Predicted Chilled Water Use and Concurrent Predicted Values (Shootout Bldg)- All Hours of the Year



Load Duration Curves of Measured & Predicted Chilled Water and Concurrent Model Predictions: (Shoot-out Bldg)- Occupied On-Peak Hours (Noon:6:00 pm) of Summer Data (15th June - 15th Sept)

Figure 4.3 Prediction accuracy of the proposed SMLP method in terms of load duration curves for the ASHRAE Predictor shootout data. (a) on an annual basis, (b) for the occupied peak hours

Table 4.1. Available data for the Engineering Center.

Month	Days	CW (MBtu) (MBtu)	Temp (F)	(w-0.009)+ (lb/lb dryair	ACW (MBtu/day)
Jan-90	31	3537.5	54.26	0.0008	114.11
Feb-90	28	3418.2	58.88	0.0015	122.08
Apr-90	22	2975.7	63.92	0.0029	135.26
May-90	22	3493.04	82.41	0.0139	158.77
Jun-90	30	5111.9	87.60	0.0158	170.40
Jul-90	31	4847.6	85.10	0.0134	156.37
Aug-90	31	4857	87.88	0.0134	156.68
Sep-90	17	2650.7	83.43	0.0129	155.92
Nov-90	21	2301.8	67.25	0.0025	109.61

Table 4.2. Comparison of the accuracy of the models of the top contestants in the Predictor Shootout II competition and the SMLP for the chilled water use (CW) of the Engineering Center. For the entire data period (E1 to E5 stand for the competition entries, Haberl and Thamilseran 1996).

	E1	E2	E3	E4	E5	SMLP
CV (%)	7.13	8.26	8.88	7.03	9.45	8.84
Relative MBE (%)+	-0.89	-3.03	-3.42	-1.34	-1.69	2.709

+ Relative MBE is the mean bias error divided by the long-term average hourly CW use

Table 4.3 Summary of the statistical criteria allowing a comparison of the predictive accuracy of the SMLP method as applied to the Engineering Center of the Predictor Shootout II data for various subsets of the entire data set

		Summer (6/15 – 9/15)				Non-summer			
		No. of hours	Average kBtu/h	CV-RMSE (%)	Rel. MBE (%)	No. of hours	Average kBtu/h	CV-RMSE	Rel. MBE (%)
1	Whole data period	1032	6.51	8.82	2.6	-	-	-	-
2	All hours	600	6.54	9.84	5.2	432	6.47	7.79	-0.93
3	Occupied on-peak	150	6.71	11.42	8.6	108	6.76	7.43	0.15
4	Occupied off-peak	150	6.45	6.95	12.4	108	6.23	10.67	-0.96
5	Non-occupied off peak	300	6.51	9.42	5.4	216	5.95	8.20	-0.50

5.0 PROPOSED METHODOLOGIES FOR PERFORMING UNCERTAINTY ANALYSIS

5.1 Objectives

The need for an uncertainty analysis and its methodology is well documented in the literature, and there are several textbooks and reports that treat this subject with varying levels of detail (for example, Coleman and Steele 1989; ASHRAE 1990). A proper uncertainty analysis can be very complex and cumbersome especially if the potential user strives to be very meticulous. Fortunately, there are three good references in the ASHRAE literature which we draw attention to: ASHRAE Guideline 2-1986 (ASHRAE, 1990), ASHRAE RP-827 (Phelan et al.,1997) and Appendix B of ASHRAE Standard 150P on cool storage performance testing (ASHRAE, 1997). The last reference is especially pertinent to this research given that it applies to thermal energy storage (TES) systems and that it contains a simplified and fairly complete treatment of the various sources of uncertainty and simplified ways to deal with them is provided.

The objective of this section is to outline our proposed approach to deal with the issue of uncertainty in the framework of the current research. We shall start with a brief discussion of the concept of uncertainty, present the causes of uncertainty in what we think is a novel outlook, outline how we propose to deal with: (1) measurement errors in equations, (2) errors related to the use regression models, (3) errors arising from both measurement errors *and* the use of regression models, and (4) errors in time series data. Finally, the results of a preliminary uncertainty analysis will be presented.

At this stage we would like to draw attention to another source of error which may overwhelm the types of uncertainties associated with the data and with the use of regression models delineated above. This has to do with implicit global assumptions made to the adopted approach. For example, the economic variables (like inflation rates, discount rates, and even the unit cost of electricity and demand charged by the electric utilities) have an enormous, inherent uncertainty associated with the future. Further, buildings are dynamic in nature, i.e., they exhibit large variability over time in how they are operated and in their installed equipment (such as computers, for example). Quantifying such sources of uncertainty is beyond the scope of this project.

Therefore, we shall neglect such sources of year-to-year variability, and propose a methodology for determining savings in energy use and in demand which a cooling system with a TES system is likely to achieve over one without a TES system assuming similar behavioral patterns in building operation and in internal load variability over the year. Since the savings determination is a difference between the two types of systems, the effect in neglecting the above sources of variability is somewhat attenuated (though by exactly how much can be only a guess-estimate). Note, therefore, that short-term in-situ testing may be inadequate to provide exact information about how the building is going to be operated over the year. This factor will be explicitly considered in this research.

5.2 Introduction

The concept of *uncertainty* is better understood in terms of *confidence limits.* Confidence limits define the range of values which can be expected to include the true value with a stated probability of obtaining that value (ASHRAE, 1990). Thus, a statement that the 95% confidence limits are 5.1 to 8.2 implies that the true value will be contained between the interval bounded by 5.1 and 8.2 in 19 out of 20 predictions, or more loosely, that we are 95% confident that the true value lies between 5.1 and 8.2.

For a given set of n observations with normal or gaussian error distribution, the total variance (var) about the mean predicted value ($\bar{X}'$) provides a direct indication of the confidence limits. Thus the "true" mean value $\bar{X}$ of the random variable is bounded by:

$$\text{bounds of } \bar{X} = \bar{X}' \pm (t_{\alpha/2,n-1} . \text{var}) = \bar{X}' \pm \frac{(t_{\alpha/2,n-1} . \sigma)}{\sqrt{n}} \qquad (5.1)$$

where $t_{\alpha/2,n-1}$ is the t-statistic with probability of $(1 - \alpha / 2)$ and (n-1) degrees of freedom (tabulated in most statistical textbooks), and σ^2 is the estimated variance.

There are three separate sources of uncertainty or error (terms which we shall use interchangeably though others like Phelan et al., 1997 distinguish between them) when dealing with analysis of observed data such as that encountered in the framework of this research: (1) measurement errors, and (2) prediction errors where a regression model is fit to data with no measurement error in the independent variables, and (3) prediction errors where a regression model is fit to data and the independent variables of the regression model have measurement uncertainties. A clear conceptual understanding of when these arise is provided below.

Consider a model such as: $y = a_0 + a_1 . x_1 + a_2 . x_2$ where the x's are the independent variables and a's are model coefficients. An uncertainty in the variable y can arise from three sources:

(a) in case the coefficients a_0 , a_1 and a_2 are known with zero uncertainty (i.e., either they are constants or are values which one can look up from tables such as steam tables, for example). The uncertainty in the derived variable y is then only due to the measurement uncertainties present in the x's. How to determine the uncertainty in y for such models or equations is given by the "propagation of errors" formulae which most engineers are familiar with (and which is presented in Section 5.3). An example of this type of uncertainty is when charging capacity of the TES system is deduced from measurements of mass flow rate and inlet and outlet temperature differences.

(b) when the x's are assumed to have no error in themselves but the coefficients a_0, a_1 and a_2 have some inherent error (as a result of identifying them from regression to measured data). Under such a case we have prediction errors in the y variable since any regression model cannot explain the entire variation in the regressor variable (this source of error, called model prediction error, is addressed in Section 4). An example of this source of uncertainty is when a simple regression model is used to predict building loads from outdoor temperature (T). If the measurement error in the outdoor temperature (T) is assumed to be so small as to be negligible, then the uncertainty in predicting building loads falls in this category.

(c) when both the x's and the coefficients a's have uncertainties, the former (x) due to measurement errors and the latter (a) because a regression model is identified from monitored data. The standard practice in classical regression analyses is to assume no measurement error in the regressor variables. Such an assumption is perhaps misleading for this research since we may then be placing too much confidence in our predictions, i.e., underestimating the uncertainty. An example of this source of uncertainty is when a polynomial model is used to predict pump electricity consumption from measured values of fluid flow rate (which inherently have non-negligible measurement errors). Although the statistical complexity is substantially enhanced when dealing with this case, we shall address this issue in the current research.

Finally, we shall try, at a later stage during this research project, to simplify some of these overly complex formulae so as to be more usable by the ASHRAE community. This simplification will, however, not be attempted in this document but later in the project on as monitored data becomes available and the validity of the simplifications can be tested.

5.3 Measurement uncertainty

5.3.1 Bias and random errors

Both measurement and model uncertainties consist of two types of error: a *systematic* or *biased error* (b) and a *random* or "white noise" error (ε). The term *precision* is often used to denote the *random error.* A set of measurements with *small bias errors* is said to have *high accuracy*, while a set of measurements with *small random errors* is said to have *high precision* (ASHRAE,1990).

Since bias and random errors are usually uncorrelated, we can express measurement variance as:

$$\sigma^2_{meas}(b_{m,}\varepsilon_m) = \sigma^2(b_m) + \sigma^2(\varepsilon_m) \qquad (5.2)$$

The error sources of monitoring equipment can be further divided into: (1) calibration errors, (2) data acquisition errors, and (3) data reduction errors. The interested reader can refer to ANSI/ASME standard (1990) for a more complete discussion of error sources. *Bias errors* include: (1) those which are known and can be calibrated out by adjusting the data points after the measurements are made, (2) those which are negligible and are ignored, and (3) those which are estimated and are included in the uncertainty analysis.

Unfortunately, it is usually very cumbersome to perform an uncertainty analysis with data having known biases. The normal approach is to remove known biases from the data prior to data analysis and only treat random errors. However, it is argued by Coleman and Steele (1989) that such a simplified treatment should be avoided, and they present pertinent formulae to treat both precision and bias errors in a rigorous fashion. This is what will be used in the framework of this research.

5.3.2. Propagation of random errors

The treatment of random errors in measurement and their propagation is in most cases treated by the well-known Kline and McClintock (1953) method, which will be described below. The uncertainty in a measurement or variable x is described by specifying the expected or mean value $\bar{x}$ for the variable followed by the absolute uncertainty Δx at a certain confidence level (usually 90% or 95%). This is written as: $x = \bar{x} \pm \Delta x$. In general, the uncertainty Δy of a function $y = y(x_1, x_2, .., x_n)$ whose independently measured variables are all given with the same confidence level, is obtained by the first order expansion of the Taylor series (ASHRAE, 1997):

$$\Delta y = [(\sum_{i=1}^{n} \frac{\partial y}{\partial x_i} \Delta x_i)^2]^{1/2} \tag{5.3}$$

For some of the basic operations:

addition or subtraction:

$$y = (x_1 \pm x_2),\ \Delta y = (\Delta x_1^2 + \Delta x_2^2)^{1/2} \tag{5.4}$$

multiplication:

$$y = (x_1) * (x_2),\ \Delta y = [(\frac{\Delta x_1}{x_1})^2 + (\frac{\Delta x_2}{x_2})^2]^{1/2} \tag{5.5}$$

division:

$$y = (x_1) / (x_2),\ \Delta y = \frac{\Delta x_1}{\Delta x_2}[(\frac{\Delta x_1}{x_1})^2 + (\frac{\Delta x_2}{x_2})^2]^{1/2} \tag{5.6}$$

For multiplication and division, the fractional error is given by the same expression. Say R = xy/z. Then:

$$\frac{\Delta R}{R} = [\frac{\Delta x^2}{x^2} + \frac{\Delta y^2}{y^2} + \frac{\Delta z^2}{z^2}]^{1/2} \tag{5.7}$$

In many cases, deriving partial derivatives of complex analytical functions is usually a tedious, error-prone mathematical affair. Fortunately, a simple computer routine can be written to perform the task of calculating uncertainties without resorting to analytical methods (Holman and Gajda, 1994). Such a method is based on approximating partial derivatives by finite differences as follows.

Let $y = y(x_1, x_2, ... x_n)$. Then

$$\frac{\delta y}{\delta x_1} = \frac{y(x_1 + \Delta x_1, x_2 \ldots x_n) - y(x_1, x_2 \ldots x_n)}{\Delta x_1} \tag{5.8}$$

$$\frac{\delta y}{\delta x_2} = \frac{y(x_1, x_2 + \Delta x_2 \ldots x_n) - y(x_1, x_2 \ldots x_n)}{\Delta x_2}, \text{ etc...}$$

These approximations can be introduced into any equation to determine the uncertainty in the result. This method is most convenient for complicated functional forms or for sets of simultaneous equations. The types of equations encountered in this research are usually simple equations or polynomials, which we shall use to a large extent.

5.4 Uncertainty due to regression models

5.4.1 Different sources of error

The determination of prediction errors from using regression models is subject to different types of problems. The various sources of error can be classified into three categories (Reddy et al.,1992):

(a) Model mis-specification errors which are due to the fact that the functional form of the regression model is usually an approximation of the true driving function of the response variable. Typical causes are: (1) inclusion of irrelevant regressor variables or non-inclusion of important regressor variables (for example, neglecting humidity effects); (2) assumption of a linear model, when the physical equations suggest non-linear interaction among the regressor variables; and (3) incorrect order of the model, i.e., either a lower order or a higher order model than the physical equations suggest. Engineering insight into the physical behavior of the system helps minimize this type of error.

(b) Model prediction errors which arise due to the fact that a model is never "perfect". Invariably a certain amount of the observed variance in the response variable is unexplained by the model. This variance introduces an uncertainty in prediction. In essence, this uncertainty arises because even though the “exact” functional form of the regression model may be known, the model parameters are random variables as a result of randomness in the regressor and response variables.

(c) Model extrapolation errors which arise when a model is used for prediction outside the region covered by the original data from which the model has been identified. Models identified from short data sets, which do not satisfactorily represent the annual behavior of the system, will be subject to this source of error. Although we cannot quantify this error in statistical terms alone, we can suggest experimental conditions to be satisfied which are likely to lead to more accurate predictive models. The prediction of building loads from short-term in-situ tests will suffer from this type of error.

Both sources (a) and (c) are likely to introduce *bias* and *random* error in the predictions. *If* ordinary least squares (OLS) regression is used for parameter estimation and *if* the model is subsequently used for prediction, *error due to source (b) will be purely random with no bias*. Thus, models identified from short data sets and used to predict seasonal or annual energy use are affected by both (a) and (c) sources of error. The best way to minimize all the above sources of error is to calibrate the instruments properly (so as not to have any bias errors) and increase the number of data observations (or sampling points) and take observations under different operating conditions that cover the entire range of variation of system operation.

It should be noted that no statistical assumptions regarding the errors need be made in obtaining OLS parameter estimates. Information regarding the model residuals or errors is required only when one wishes to specify confidence limits of these parameter estimates (Beck and Arnold, 1977).

Finally, the statistically efficient way of dealing with *improper residual behavior* (i.e., residuals which have *non-constant variance* or show distinct patterns implying a serial correlation) is not to use OLS but to use other regression schemes which will yield unbiased parameter estimates and narrower confidence intervals. This is probably too demanding statistically for most ASHRAE members, and an alternative approach, is to use OLS parameter estimates but to widen the confidence intervals. Papers by Reddy et al., (1994), Ruch et al., (1997) and Reddy et al., (1998) discuss these issues, especially as they pertain to statistical models for building energy use. Such sources of error are usually secondary compared to the model prediction error and make the error analysis much more complex. We propose to evaluate such effects with the data gathered in this research project, and overlook such effects if they are small.

5.4.2 Prediction error of single variate linear models

Let us consider a simple linear model given by $y = a + b\,x$ which has been used to perform a least squares regression to monitored x and y data. This regression equation can be used to predict future values of y provided the x value is within the domain of the original data from which the model was identified. We differentiate between the two types of predictions, as follows:

A mean response is where we would like to predict the mean value of y for a large number of repeated x_0 values. The mean value is directly deduced from the regression equation while the variance is (Draper and Smith, 1982):

$$\mathrm{var}(\hat{y}_0) = MSE.\left[\frac{1}{n} + \frac{(x_0 - \bar{x})^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}\right] \qquad (5.9)$$

where MSE is the mean square error of the model, given by

$$MSE = \sum (y_i - a - b.x_i)^2 / (n-2) \qquad (5.10)$$

in the case of the simple linear model with two parameters.

(b) An individual or specific response where we would like to predict the specific value of y for a specific value x_0. The specific response is directly deduced from the regression equation but its variance is larger than the previous case and is given by (Draper and Smith, 1982):

$$\operatorname{var}(\hat{y}_0) = MSE.[1 + \frac{1}{n} + \frac{(x_0 - \bar{x})^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}] \qquad (5.11)$$

Thus the 95% confidence interval for the individual response at level X_0 is:

$$\hat{\mu}_0 = \hat{y}_0 \pm t_{0.025}.\operatorname{var}(\hat{y}_0) \qquad (5.12)$$

where $t_{0.025}$ is the value of the t-student distribution at an error level of 0.025 or 2.5% (i.e., a two-tailed error distribution is assumed). In eq.(5.12) the confidence intervals for individual responses will be wider than those of the mean response

(c) sum of values is where we would like to determine the error in the sum of n values. For example, we would like to determine the uncertainty in the electric power consumed by a pump during the entire year where the hourly pump consumption is determined by using a regression model. If the sum is made up of n predictions, we could determine the uncertainty in each prediction and then use eq. (5.11) to determine the uncertainty in the sum. It is often simpler to do a bin type of calculation, and the appropriate equations are presented by Phelan et al. (1997).

5.4.3 Prediction error of multi-variate (or polynomial) regression models (Draper and Smith, 1981)

When dealing with multiple regression, it is advantageous to resort to matrix algebra because of the compactness and ease of manipulation it offers. Consider a data set of n readings that include k regressor variables. The corresponding multiple linear regression model is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k + \varepsilon \qquad (5.13)$$

Note that the same model formulation assumption (as well as the subsequent error analysis provided the prediction range is within the range used to identify the model) is equally valid to polynomial models of the following type (Montgomery and Runger, 1994):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_1^2 + ... + \beta_k x_1^k + \varepsilon \qquad (5.14)$$

Let x_{ij} denote the i^{th} observation of parameter j. Then eq.(5.13) can be re-written as a linearized equation:

$$y = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + ... + \beta_k x_{ik} + \varepsilon_i \qquad (5.15)$$

In matrix notation (with **y'** denoting the transpose of **y**), eq.(5.13) can be expressed as follows (with the matrix dimension shown as subscripted brackets):

$$Y_{(n,1)} = X_{(n,p)}\beta_{(p,1)} + \varepsilon_{(n,1)} \tag{5.16}$$

where p is the number of parameters in the model = k+1

and $Y' = [y_1\ y_2 \dots y_n]$, $\beta' = [\beta_0\ \beta_1 \dots \beta_k]$, $\varepsilon' = [\varepsilon_1\ \varepsilon_2\ \dots \varepsilon_n]$

$$\text{and } X = \begin{bmatrix} 1 & x_{11} & .. & x_{1k} \\ 1 & x_{21} & .. & .. \\ .. & .. & .. & .. \\ 1 & x_{n1} & .. & x_{nk} \end{bmatrix} \tag{5.17}$$

The classical least-squares approach used by the majority of analysts is the OLS method where the parameter set β is determined such that the sum of squares function is minimized. This results in the regression coefficients being given by the following equation:

$$b = (X'\hat{X})^{-1} X'Y \tag{5.18}$$

provided matrix **X** is non-singular and where **b** is the least square estimator matrix of β

Pure regression models, even when they fit the data extremely well, should not be blindly used for predictions outside the range of variation of the original data. One has a better chance of doing so with models based on engineering (such as thermodynamic or heat transfer) considerations specially if the model parameters are estimated accurately.

Therefore, it is practically impossible to statistically determine the uncertainty or variance of predictions outside the range of variation of the original data. Hence, the short-term to long-term prediction of building loads, for example, which is part of this research, defies a rigorous uncertainty analysis. The only recourse is to estimate the prediction uncertainty under specific case studies during which year-long monitored data is available, and assume that the error would be approximately the same for other instances as well. (This type of reasoning is what was implicitly performed in the framework of the ASHRAE RP-827 research by Phelan et al., 1997). Also, since we shall be comparing two alternatives, i.e., without (the baseline case) and with the TES system, the large uncertainty in the load profile determination is likely to affect both alternatives equally, thus minimizing its importance to this research.

However, for predictions within the range of variation of the original data, the equations for determining the variance in model predictions are well known.

(a) For the mean response at a specific set of x_0 values, the variance is:

$$\mathrm{var}(\hat{y}_0) = \sigma^2 [\mathbf{X}_0(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'_0] \tag{5.19}$$

where **1** is a column vector of unity.

Confidence limits at a significance level α are:

$$y_0 \pm t(n-k, \alpha/2).\,\mathrm{var}^{1/2}(\hat{y}_0) \tag{5.20}$$

(b) The variance of an individual prediction is:

$$\mathrm{var}(\hat{y}_0) = \sigma^2 [\mathbf{1} + \mathbf{X}_0(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'_0] \tag{5.21}$$

(c) For the sum of m individual responses, the prediction error is given by Theil (1971):

$$\mathrm{var}[\sum_{j=1}^{m}(y_j)] = \sigma^2\{\mathbf{1}'[X_0(X'X)^{-1}X'_0 + \mathbf{I}].\mathbf{1}\} \tag{5.22}$$

where **I** is an identity matrix, i.e., a diagonal matrix of unity. Note that pre and post multiplying of the matrix within the square brackets by an unit vector is akin to summing all the elements of the matrix.

5.4.4 Uncertainty of models identified with error in the regressor variables

How to determine prediction uncertainty of models identified from data where the regressor variables had inherent measurement errors is extremely complex statistically. Most of the standard text-books (for example, Draper and Smith 1981) do no more than cursorily acknowledge this case without providing the appropriate mathematical equations. However, this type of uncertainty has direct bearing on this research; for example, the electric power consumed by a fan or pump is usually a polynomial function of the fluid flow rate, which can only be measured to within 8-10% uncertainty in the field. We have been able to identify a book (Fuller, 1987) which treats this subject thoroughly. Therefore, we propose to ascertain whether the equations in that book are pertinent to the current research and if they are, apply them accordingly.

5.5 Uncertainty in time series data

Time series data used to determine charging or discharging capacity of TES systems needs to be handled differently from the cases described above. A fairly complete discussion is provided in Annex B of the proposed ASHRAE standard 150P (ASHRAE, 1997). We propose to use the procedures described in standard 150P as a starting point for our own research.

5.6 Concluding remarks

This document reviews the various sources of uncertainty which have to be explicitly considered in our research. Appropriate equations of how we propose to determine the uncertainty in our predictions are also presented. We realize that the statistical equations to determine prediction uncertainty of regression models other than the simple one variable regression model are complex and may be beyond the comprehension of most energy professionals. Consequently, as part of this research, we shall forsake some statistical rigor and endeavor to simplify these equations to a level that practicing engineers could use which will include examples that can be used to further explain the use of the equations.

5.7 Annotated Bibliography

ANSI/ASME, 1990. "Measurement Uncertainty: Instruments and Apparatus", ANSI/ASME Standard PTC 19.1-1985, American Society of Mechanical Engineers, New York. NY.
This is a fairly comprehensive standard document that defines, describes and illustrates the various terms and methods used in uncertainty analysis of engineering data. Propagation of errors is well treated but uncertainty from regression models and time series models are discussed very cursorily. Step by step calculation procedures are also provided.

ASHRAE, 1990. "Engineering Analysis of Experimental Data", ASHRAE Guideline 2-1986 (RA90), American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA.
This document from ASHRAE provides guidelines for reporting uncertainty results of experimental data related to HVAC&R. It also provides a very basic treatment of probability, propagation of errors and uncertainty in regression models. Several illustrative examples are given. The document also contains a definition of terms used.

ASHRAE, 1997. "ASHRAE Standard 150P: Method of Testing the Performance of Cool Storage Systems", working draft submitted for Public Review, American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta, GA, February.
This is a draft ASHRAE standard which proposes a testing method for evaluating the in-situ performance of cool storage systems. The draft covers definition of terms; instrumentation required, their accuracy and their field calibration and verification; test procedures and conditions; the equations to be used in order to determine the required performance, and how to report the test results. An uncertainty analysis methodology is also proposed based on propagation of errors formulas.

Beck, J.V. and Arnold, K.J., 1977. Parameter Estimation in Engineering and Science, John Wiley and Sons, New York.
This is classical formal textbook which treats parameter estimation in a comprehensive manner. Though meant for engineers, the treatment contained in the book is too mathematical and statistical for the average ASHRAE HVAC&R engineer.

Coleman, H.W. and Steele, W.G., 1989. Experimentation and Uncertainty Analysis for

Engineers, John Wiley and Sons, New York.
This is an excellent undergraduate text-book for engineering students as well as for practicing engineers. It is very clear in its treatment on how to perform a preliminary uncertainty analysis prior to data gathering as well as a more complete analysis after the data has been gathered. It is one of the only books which treats uncertainty arising from instrument bias errors in a comprehensive manner. However, the book treats uncertainty arising from regression models in a very simplistic manner.

Draper, N., and Smith, H., 1981. Applied Regression Analysis, 2nd Edition, John Wiley & Sons, New York.
This is a classic highly-acclaiming text book which deals with the fundamentals of regression analysis emphasizing an understanding of concepts and the application of methods. Both linear and non-linear regression models are covered. Written at an undergraduate level for statistical students, the book is very formal in its statistical treatment.

Fuller, W.A., 1987. Measurement Error Models, John Wiley, New York.
Perhaps the most comprehensive statistical textbook which addresses regression models with error in the regressor or independent variables. Uncertainty due to different sampling techniques is also covered. The treatment is too mathematical for the average ASHRAE HVAC&R engineer. Examples provided are geared towards agricultural applications.

Holman, J.P. and Gajda, W.J., 1994. Experimental Methods for Engineers, 5th Ed., McGraw-Hill, New York.
This text-book, extensively used by engineering students during lab sessions, has only one chapter on uncertainty and data analysis while devoting the remaining chapters to various types of instruments. The basis of uncertainty and propagation errors are well covered, while uncertainty in regression models is not treated.

Kline, S. and McClintock, F.A., 1953. "Describing Uncertainties in Single-Sample Experiments", Mech. Eng., 75, pp. 2-8.
This research paper is the basis of the widely accepted and used propagation of error equation involving a first-order Taylor Series expansion. Most text-books and documents on uncertainty analysis describe this method.

Montgomery, D. and Runger, G., 1994. Applied Statistics and Probability for Engineers. John Wiley and Sons Inc, New York.
This is a very good undergraduate textbook on statistics and probability which is appropriate for engineers, more so than the Draper & Smith textbook. Both the treatment and the illustrative examples are from the field of engineering and the treatment of the subject matter is less formal.

Montgomery, D.C. and Johnson, L.A., 1976. Forecasting and Time Series Analysis. McGraw-Hill, NY.
This is a very well written undergraduate textbook on time series analysis. The statistical basis, model identification, model prediction and prediction uncertainty issues of various time series analysis methods which include moving averages, exponential smoothing, and transfer function

(ARIMA) methods are covered in a clear and very readable manner.

Phelan, J., M.J. Brandemuehl, and M. Krarti. 1997b. "In-Situ Performance Testing of Fans and Pumps for Energy Analysis." ASHRAE Transactions, V.103, Pt.1. 4040 (RP-827).
This research paper applies the concepts of propagation of errors and regression model prediction uncertainty to perform uncertainty analysis of monitored data collected from field testing of fans, pumps and chillers.

Reddy, T.A., Kissock, J.K. and Claridge, D.E., 1992. "Uncertainty Analysis in Estimating Building Energy Retrofit Savings in the LoanSTAR Program," , Proceedings of the ACEEE 1992 Summer Study on Energy Efficiency in Buildings, Vol.3, pp.225-238, American Council for an Energy Efficient Economy, Pacific Grove, CA, Aug.-Sept.
This research paper classifies the various sources of uncertainty in retrofit energy savings arising from the use of baseline regression models identified from continuous monitoring of building energy use. Basic statistical equations are also given, and an illustrative example is provided.

Reddy, T.A., Kissock, J.K. and Ruch, D.K., 1998, Uncertainty in Baseline Regression Modeling and in Determination of Retrofit Savings", submitted to ASME Journal of Solar Energy Engineering.
This is an overview paper which summarizes the various sources of uncertainty in retrofit energy savings from regression models based on continuous monitoring of building energy use. Statistical equations for uncertainty when the regression models have improper residual behavior are also given.

Ruch, D.K., Kissock, J.K. and Reddy, T.A., 1993. "Model Identification and Prediction Uncertainty of Linear Building Energy Use Models with Autocorrelated Residuals", Solar Engineering 1993,(Eds. A.Kirkpatrick and W.Worek), Proceedings of the ASME International Solar Energy Conference, pp.465-473, Washington D.C., April.
This research paper proposes and validates a statistical equation for uncertainty in retrofit energy savings when the model residuals are auto-correlated. This often arises when the regression models are identified based on hourly or daily data.

Thiel, 1971, Principles of Econometrics, John Wiley, New York.
This is a standard textbook and/or reference book for econometricians written at an advanced level. The treatment is very mathematical and rigorous and inappropriate for general use by the HVAC&R professional.

6.0 CANDIDATE TEST SITES

6.1 Preliminary Selection.

This section of the contains a complete list of sites that were considered candidates for monitoring for the ASHRAE RP 1004 project. In the first column is the agency or university where the system is located followed by the site contact, phone and FAX number. In the next column the design engineering firm and design engineer are then listed with phone and FAX number. This is followed by the chiller capacity, thermal storage capacity, chiller type, chiller manufacturer, storage type, storage manufacturer. Finally, each site was asked whether or not they would be willing to participate in the ASHRAE project and whether or not the plans were available for photocopying.

Table 6.1: Complete list of Thermal Storage sites considered for the RP 1004 project.

Site	Site Contact	Site Phone #	Site Fax #	Design Engineer	Design Phone #	Chiller Capacity	Thermal Capacity	Chiller Type	Chiller Manuf	Storage Type	Storage Manufacturer	Willing to Monitor?	Plan Availability
Del Mar	Mike Snyder	512-886-1642	512-886-1920	ACR Engr	512-440-8333	2 @ 1000	16700 ton-h	centrifugal	Trane,	CHW	CBI	Y	Y
College				Austin, TX	Rajeesh	tons each	(calculated)		Westinghouse				
					Kapileshwari								
Midland County	Bill Decker	915-688-8940	915-688-8903	FEULS	512-331-5181	1 @ 250	8 @ 160	screw	Trane	Ice	Calmac	Y	Y
Courthouse				Austin, TX	David Parr	tons	ton-h each			Internal melt			
Ward Memorial	Maynard Clark	915-943-2511	915-943-3679	Fannin&Fannin	806-745-2533	1 @ 130	1100 ton-h	rotary	Trane	CHW	Scott Manuf.	undecided	Y
Hospital				Lubbock, TX	Jack Roberts	tons	ton-h						
TSTC	Jerry Behrens	956-425-0687	956-425-0688	Gomez-Garza	956-546-0110	450 ton	5560 ton-h	screw	Trane	H2O	Built on-site	N	??
				Brownsville, TX	Pete Garza	500 ton	(calculated)	centrifugal	McQuay		Converted from		
											water treatment plant		
UH Clear Lake	Doug Willenberg	281-283-2250	281-283-2257	Cohn & Daniels		475 ton	6800 ton-h	screw	Vilter	Ice		undecided	Y
				OR Joe Consella	214-337-8300					Exter. melt			
Oppe Elementary	Justin Gordon	409-762-8181	409-765-6248	Building Environmental		1 @ 188	665 ton-h	D/X	York	ice	N/A	N	Y
School				Engineering		1 @ 45							
				Ft. Worth									
Weis Middle	Justin Gordon	409-762-8181	409-765-6248	Building Environmental		2 @ 120	902 ton-h	D/X	York	ice	N/A	N	Y
School				Engineering		1 @ 60							
				Ft. Worth									
Parker Elementary	Justin Gordon	409-762-8181	409-765-6248	Building Environmental		3 @ 100	862 ton-h	D/X	York	ice	N/A	N	Y
School				Engineering		1 @ 60							
				Ft. Worth									
Morgan Elementary	Justin Gordon	409-762-8181	409-765-6248	Building Environmental		3 @ 100	1038 ton-h	D/X	York	ice	N/A	N	Y
School				Engineering		1 @ 70							
				Ft. Worth									
Rosenberg Elementary	Justin Gordon	409-762-8181	409-765-6248	Building Environmental			800 ton-h	D/X	York	N/A	N/A	N	Y
School				Engineering									
				Ft. Worth									
Austin Convention	Rudy Farias	512-404-4300	512-404-4352	Page-Southerland-	512-472-6721	2 @ 600	8260 ton-h	centrifugal	McQuay	Ice	Fafco	Y	Y
Center				Page Austin, TX		tons each				Internal melt			
EPCC Valle Verde	Cecil Lance	915-594-2556	915-594-2551	RBM Engr	915-584-9934	1 @ 300	5475 ton-h	centrifugal	Trane	ice	N/A	Y	Y
						ton							

Site	Site Contact	Site Phone #	Site Fax #	Design Engineer	Design Phone #	Chiller Capacity	Thermal Capacity	Chiller Type	Chiller Manuf	Storage Type	Storage Manufacturer	Willing to Monitor?	Plan Availability
EPCC Trans Mountain	Cecil Lance	915-594-2556	915-594-2551	RBM Engr	915-584-9934	1 @ 200	2280 ton-h	screw	Trane	ice	N/A	Y	Y
						ton							
MHMR 673 Terrel	Ken McDonald	972-563-6452	972-551-0101	ACR Engr	512-440-8333	1 @ 200	7000 ton-h	rotary	Trane	CHW	PDM	Y	Y
				Austin, TX	Rajeesh	ton	supplied by						
					Kapileshwari	1 @ 120	a combination	screw	Multistack	CHW		Y	Y
						ton	of the six						
MHMR 676 Terrel	Ken McDonald	972-563-6452	972-551-0101	ACR Engr	512-440-8333	1 @ 240	chillers in 4	screw	Multistack	CHW	PDM	Y	Y
				Austin, TX	Rajeesh	ton	different						
					Kapileshwari		mechanical						
MHMR 680 Terrel	Ken McDonald	972-563-6452	972-551-0101	ACR Engr	512-440-8333	1 @ 275	rooms	rotary	Trane	CHW	PDM	Y	Y
				Austin, TX	Rajeesh	ton							
					Kapileshwari								
MHMR 686 Terrel	Ken McDonald	972-563-6452	972-551-0101	ACR Engr	512-440-8333	2 @ 425		centrifugal	Carrier	CHW	PDM	Y	Y
				Austin, TX	Rajeesh	ton each							
					Kapileshwari								
USA CERL	Chang Sohn	217-398-5424	217-373-3430	Univ of Illinois/CERL		2@175	1700	screw	York	encap		Y	Y
						ton each	ton-hours			Ice			

The sites in Table 6.1 were evaluated according to the following criteria:

- Over 1000 ton-hours storage capacity
- Provides for diversity in storage technologies
- Load profile is representative of common storage applications
- Available and accessible for testing
- Owner willing to cooperate
- Currently instrumented with all or most of required instrumentation.

The most promising sites are listed in the following table.

Table 6.2 Short List of Sites for RP1004 project.

Site	Storage Medium	Storage Technology	Storage Capacity (ton hours)
Midland County Courthouse	Ice	Ice internal melt	1160 TH
Del Mar College	Chilled Water	Stratified tank	One million gallons (7-10,000 TH)
Austin Convention Center	Ice	Ice internal melt	6000 TH
University of Houston, Clear Lake	Ice	Ice external melt	6,800 TH
CERL	Ice	Encapsulated Ice	1,700 TH

These sites have been further evaluated with site visits in January and February for their suitability for testing, and the final candidates have been selected using the following criteria:

- Over 1000 ton-hours storage capacity
- Provides for diversity in storage technologies
- Load profile is representative of common storage applications
- Available and accessible for testing
- Owner willing to cooperate
- Currently instrumented with all or most of required instrumentation.
- Datalogger
- Storage flow
- Temperature entering storage
- Temperature leaving storage
- Load Btu measurement, or flow and entering/leaving temperatures
- Chiller power
- Auxiliaries power

During the December 1997 PMSC conference call the above sites were discussed and it was recommended that the Midland County Court House be dropped from the list and that the Ward Memorial Hospital be added to the list.

A subsequent review of the existing instrumentation at the Ward Memorial Hospital reveals that there is insufficient thermal metering at the site to be economically upgraded within the budget constraints of this project. Therefore, we are recommending that the proposed list for the duration of the detailed monitoring consist of: the Austin Convention Center in Austin, Texas, the Del Mar College in Corpus Christie, Texas, and the CERL site in Illinois.

Table 6.3 Short List of Sites for RP1004 project.

Site	Storage Medium	Storage Technology	Storage Capacity (ton hours)
Del Mar College	Chilled Water	Stratified tank	One million gallons (7-10,000 TH)
Austin Convention Center	Ice	Ice internal melt	6000 TH
CERL	Ice	Encapsulated Ice	1,700 TH

Additional information about these sites is provided in the next section.

6.2 Final Site Selection.

6.2.1 Austin Convention Center

The TES at the Austin Convention Center (ACC) is an ice-on-coil, full cool storage system that was installed at the time the building was originally constructed. There are two chillers that have a 650 ton capacity in the chilled water mode and a 425 design capacity in the ice mode. The ACC is equipped with 42 ice storage tanks with a total capacity of 6,000 ton-hours. Figure 6.1 is simplified diagram of the TES showing the proposed monitoring points. Table 6.4 is a list of the points to be monitored at the ACC.

Table 6.4: Proposed points to be monitored at the Austin Convention Center.

Thermal Channels	**Electrical Channels**	**Other**
Whole-bldg cooling - Btu	Whole-bldg - kWh	Ambient temp.
Whole-bldg cooling - flow	Chiller #1 - kWh	Ambient humidity
Chiller - Btu	Chiller #2 - kWh	Mech. room temp.
Chiller - flow	Bldg chw pumps - kWh	Condenser return temp.
Cool Storage Btu (charge)	Ice Pumps - kWh	Chiller Evap. supply temp
Cool Storage Btu (discharge)	Condenser pumps - kWh	Cool Storage inlet temp.
Cool Storage flow	Condenser fans - kWh	Cool Storage outlet temp.
		Bldg chw supply temp.
		Bldg chw return temp.

Figure 6.2 and 6.3 are photos from the site showing the cool storage tanks (Figure 6.2a), the ice

storage pumps (Figure 6.2b), the chillers (Figure 6.3a), and the flow meter that measures the flow of the glycol across both chillers (Figure 6.3b).

In general these operating modes are used at the ACC: (1) direct cooling using one or more chillers at 40 F, (2) cooling using the cool storage only, (3) a combination of stored cooling and direct cooling, and (4) charging of the cool storage at 20 F.

The new instrumentation to be added to the site consists of

(1) a charge/discharge Btu meter to the cool storage.
(2) cool storage inlet and outlet temperatures.
(3) electricity for ice pumps, building pumps, condenser pumps & condenser fans,
(4) ambient temperature & humidity near the condensing tower & mechanical room temperature,
(5) temperature of the brine leaving the chillers & condenser water entering the chillers,
(6) temperature of the supply & return chilled water to/from the building.

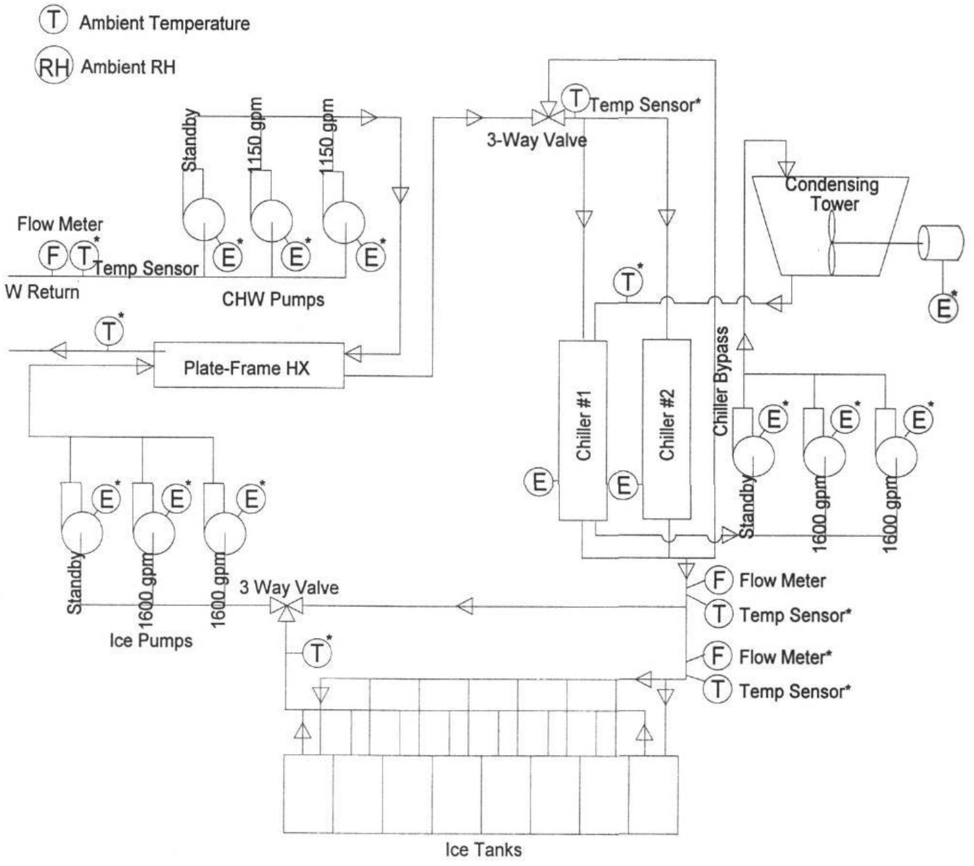


Figure 6.1: Proposed monitoring at the Austin Convention Center. This diagram shows the proposed monitoring at the ACC with the additional metering points indicated with an asterisk (*).

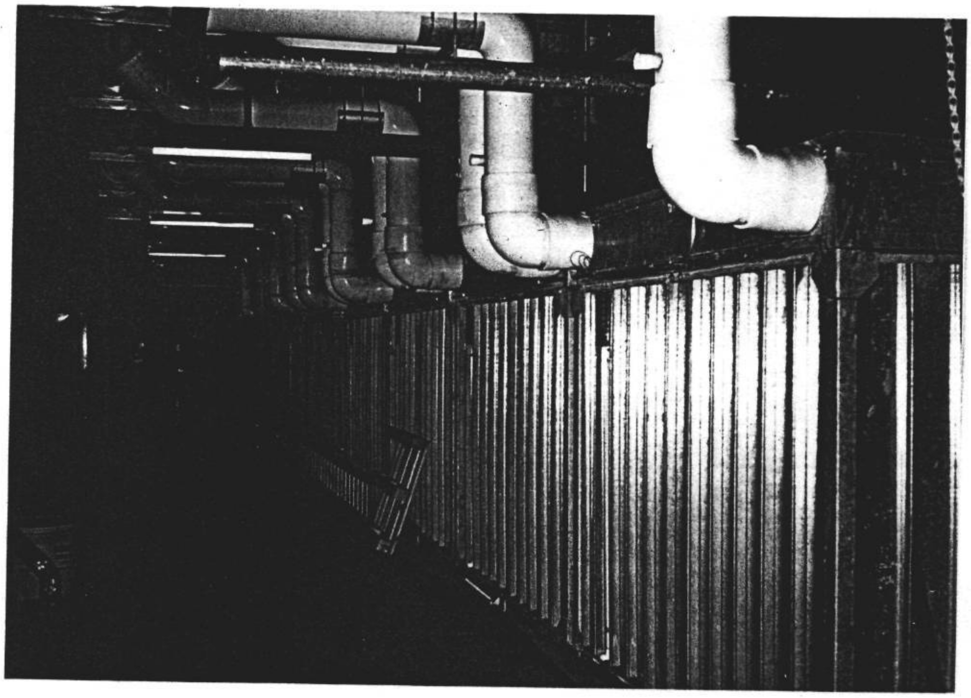


Figure 6.2a: Photo of one row of thermal storage tanks at the ACC. Each tank contains a manual level indicator and temperature sensor. Flow to all tanks is in parallel.

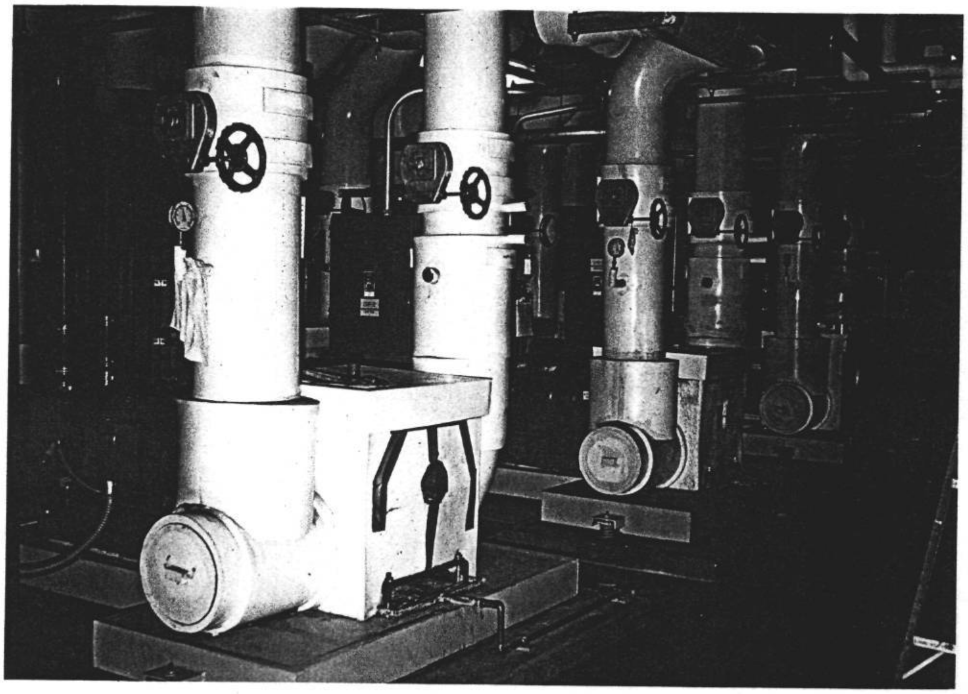


Figure 6.2b: Photo of the three 1,600 GPM chilled ice storage circulating pumps. One pumps operates for each chiller that is on-line with the third pump remaining in reserve.

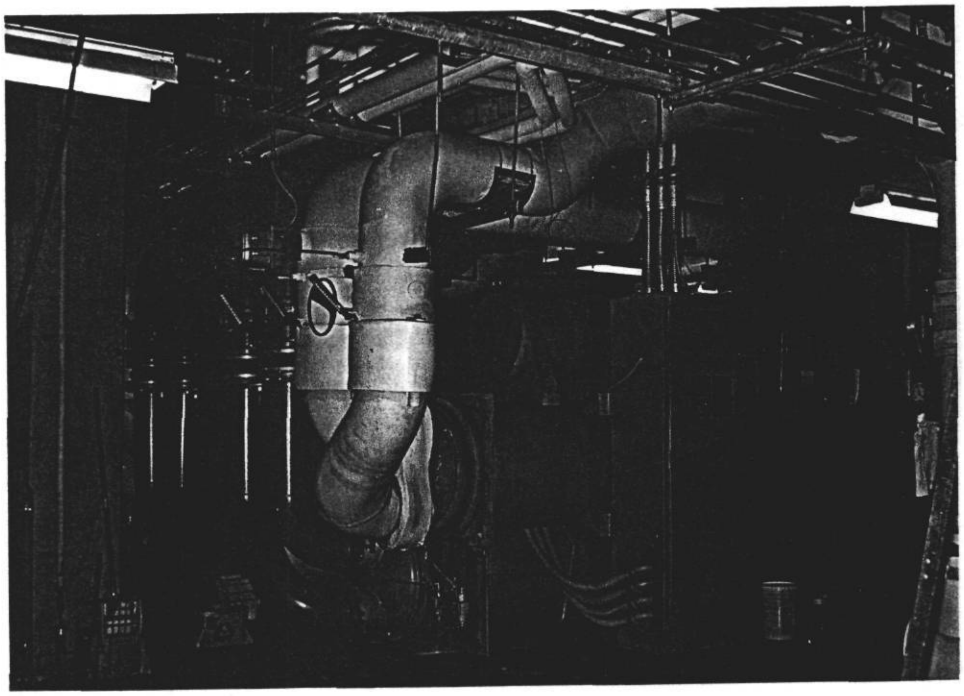


Figure 6.3a: Photo of the two 650 ton chillers at the Austin Convention Center.

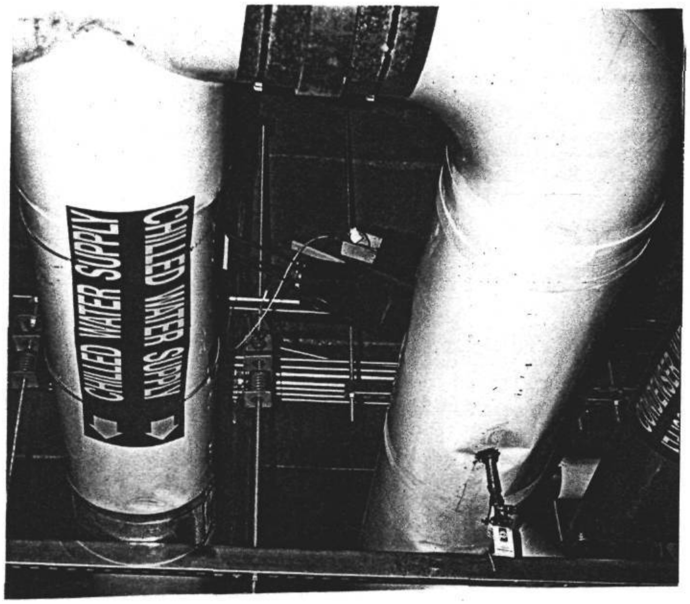


Figure 6.3b: Photo of the flow meter that measures the combined glycol flow (30% solution) across both chillers. Btu measurements are calculated with a Btu meter that measures the flow and temperature drop across the two chillers.

6.2.2 Delmar College

The TES at Delmar College consists of a 1.2 million stratified chilled water storage tank that provides partial cooling to the 681,592 square foot campus located in Corpus Christie, Texas. The TES system was added to the cooling system in 1992 to reduce electricity use during peak utility periods and to provide additional capacity to an overburdened system. The existing cooling system consists of one 800 ton chiller and one 1000 ton chiller. The TES also contains a 300 ton industrial heat pump heat recovery system that provides heating to the building from the heat rejected by the chillers. Table 6.5 is a list of the points to be monitored at Delmar.

Table 6.5: Proposed points to be monitored at Delmar College.

Thermal Channels	**Electrical Channels**	**Other**
Whole-campus cooling - Btu x 3	Whole-campus - kWh	Ambient temp.
Whole-campus cooling - flow x 3	Chiller #1 - kWh	Ambient humidity
Chiller - Btu x 2	Chiller #2 - kWh	Cond. #1 return temp.
Chiller - flow x 2	Chiller #1 pump - kWh	Cond. #2 return temp.
Cool Storage flow (charge)	Chiller #2 pump - kWh	Chiller#1 chw supply temp
Cool Storage flow (discharge)	Cond. pump #1 - kWh	Chiller#2 chw supply temp
Cool Storage Btu (charge/discharge)	Cond. pump #2 - kWh	Cool Storage inlet temp.
	Cond. fan #1 - kWh	Cool Storage outlet temp.
	Cond. fan #2 - kWh	Bldg chw supply temp.
	Heat pump - kWh	Bldg chw return temp.

Figure 6.5 and 6.6 are photos from the site. Photos of Delmar College. Figure 6.5 shows the 1.2 million gallon stratified storage tank at the Delmar. The 10 temperature array for measuring internal temperatures can be clearly seen running up the side of the tank. Figure 6.6a shows one of two cooling towers at Delmar. Each chiller has its own dedicated cooling tower. Figure 6.6b shows the dual flow meters already installed to monitor the bi-directional flow for charging and discharging operations.

In general these operating modes are used at Delmar: (1) one chiller charges the tank, one chiller carries the campus load the charging cycle, (2) two chillers carry the campus load during off-peak periods, (3) one chiller and cooling from storage carry the campus during peak periods. The 300 ton heat-recovery heat pump cools the condenser water from the chillers to produce heating water and is supplemented in the winter months by a boiler.

The new instrumentation to be added to the site consists of :

(1) a charge/discharge Btu meter to the cool storage.
(2) cool storage inlet and outlet temperatures.
(3) electricity for chiller pumps, building pumps, condenser pumps & condenser fans,

(4) ambient temperature & humidity near the condensing tower,
(5) temperature of the chilled leaving the chillers & condenser water entering the chillers,
(6) temperature of the supply & return chilled water to/from the building.

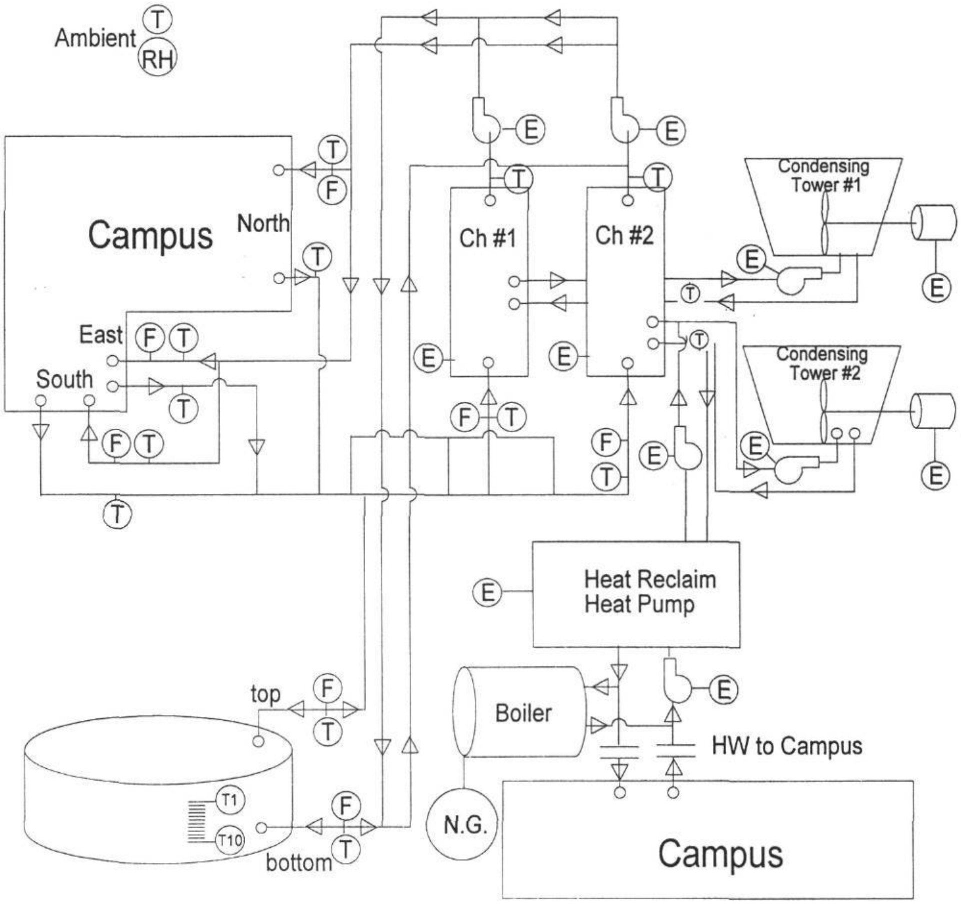


Figure 6.4: Proposed monitoring at Delmar College. This diagram shows the proposed monitoring at Delmar college.

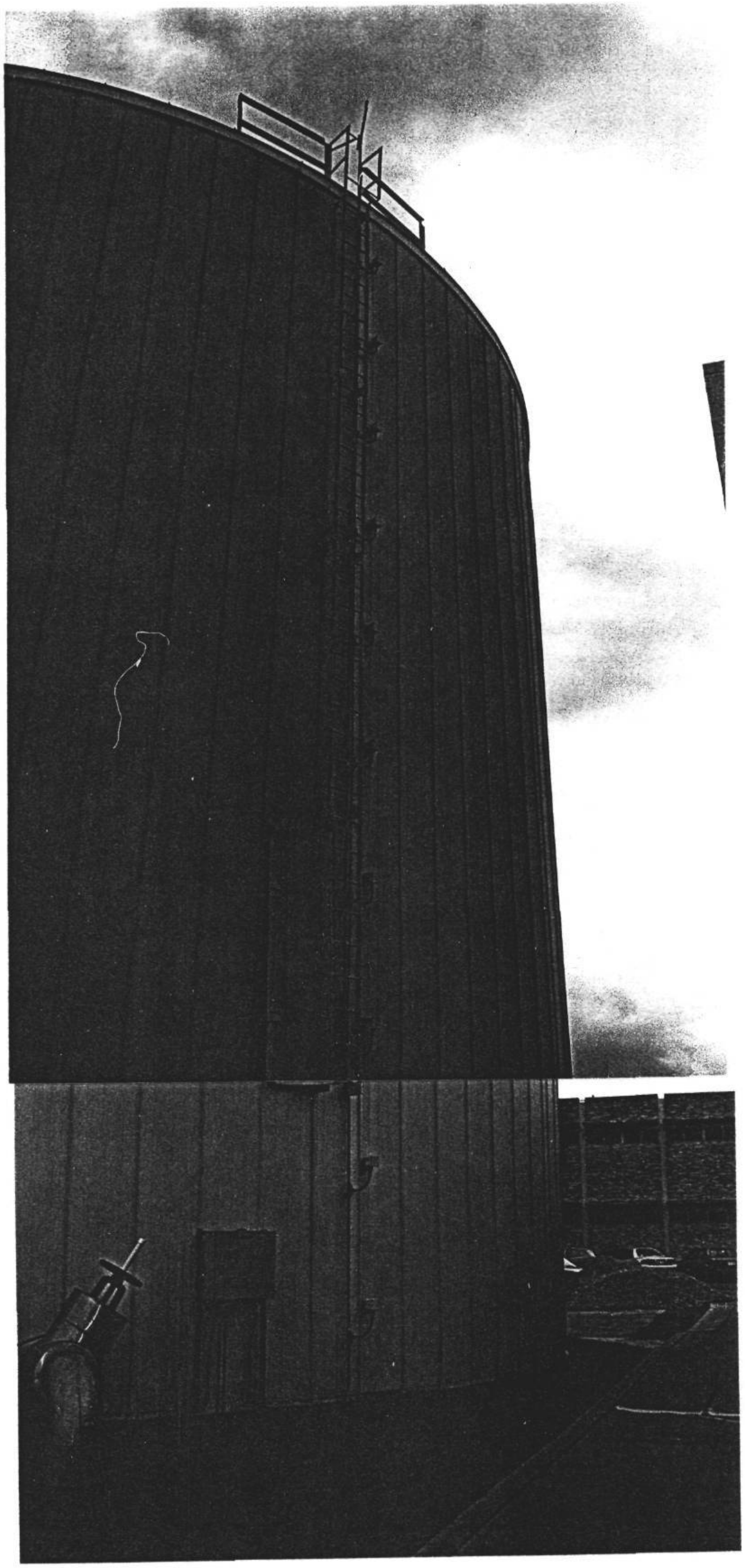


Figure 6.5: Photo of Delmar College. This figure shows the 1.2 million gallon stratified storage tank at the Delmar. The 10 temperature array for measuring internal temperatures can be clearly seen running up the side of the tank.

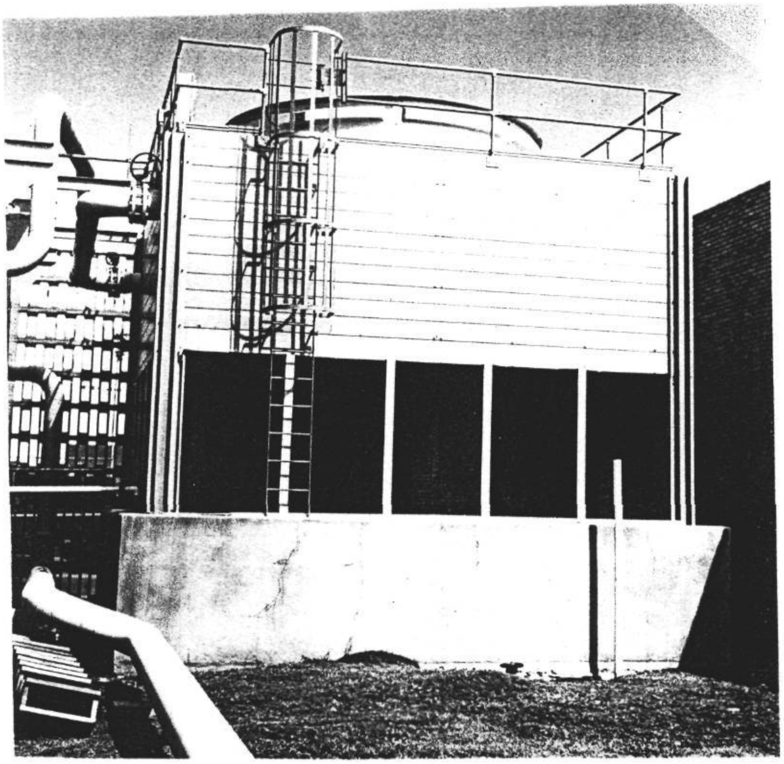


Figure 6.6a: Photo of Delmar College. One of two cooling towers at Delmar. Each chiller has its own dedicated cooling tower.

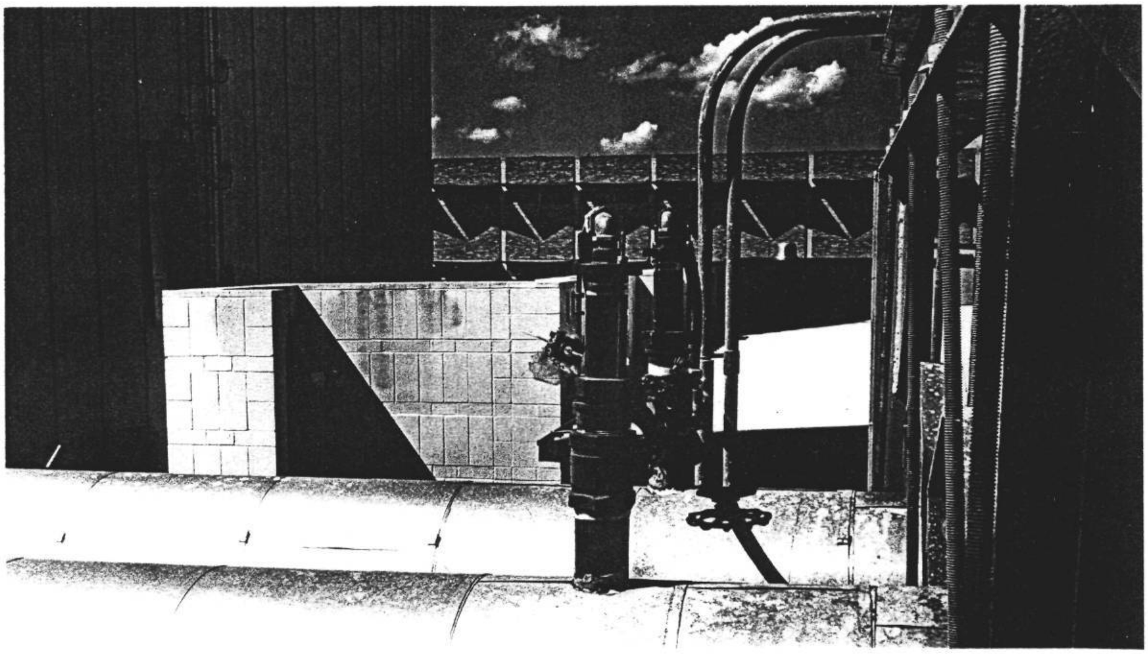


Figure 6.6b: Photo of Delmar College.Dual flow meters already installed to monitor the bi-directional flow for charging and discharging operations.

6.2.3 CERL Site.

The proposed TES at the CERL site will be a site that shares data with the U.S.Army Civil Engineering Research Labs in Champaign, Illinois. The TES system consists of 1,700 ton-hours of encapsulated ice storage which is charged by two 175 ton chillers. Table 6.5 is a list of the points to be monitored at Delmar. Figure 6.7 is a diagram of the sites.

Table 6.6: Proposed points to be monitored at the CERL site.

Thermal Channels	**Electrical Channels**	**Other**
Whole-building cooling - Btu x 3	Whole-bldg - kWh	Ambient temp.
Whole-building cooling - flow x 3	Chiller #1 - kWh	Ambient humidity
Chiller - Btu x 2	Chiller #2 - kWh	Cond. #1 return temp.
Chiller - flow x 2	Chiller #1 pump - kWh	Cond. #2 return temp.
Cool Storage flow (charge)	Chiller #2 pump - kWh	Chiller#1 chw supply temp
Cool Storage flow (discharge)	Cond. pump #1,#2 - kWh	Chiller#2 chw supply temp
Cool Storage Btu (charge/discharge)	Cond. fan #1,#2 - kWh	Cool Storage inlet temp.
	Storage pump - kWh	Cool Storage outlet temp.
	2nd pumps #1,#2 - kWh	Bldg chw supply temp.
		Bldg chw return temp.

Figures 6.8 and 6.9 are photos from the site. Figure 6.8a shows the inventory storage tank and the cooling tower. Figure 6.8b shows the location of one of the flow meters at the CERL site. Figure 6.9a shows one of the chillers at the CERL site. Figure 6.9b shows the existing control system and integrated EMCS/data logger.

The new instrumentation to be added to the site consists of :

(1) electricity for chiller pumps, building pumps, condenser pumps & condenser fans,
(2) ambient temperature & humidity near the condensing tower,

Data monitoring at the site will consist of data loggers and data collected by the York ISN system.

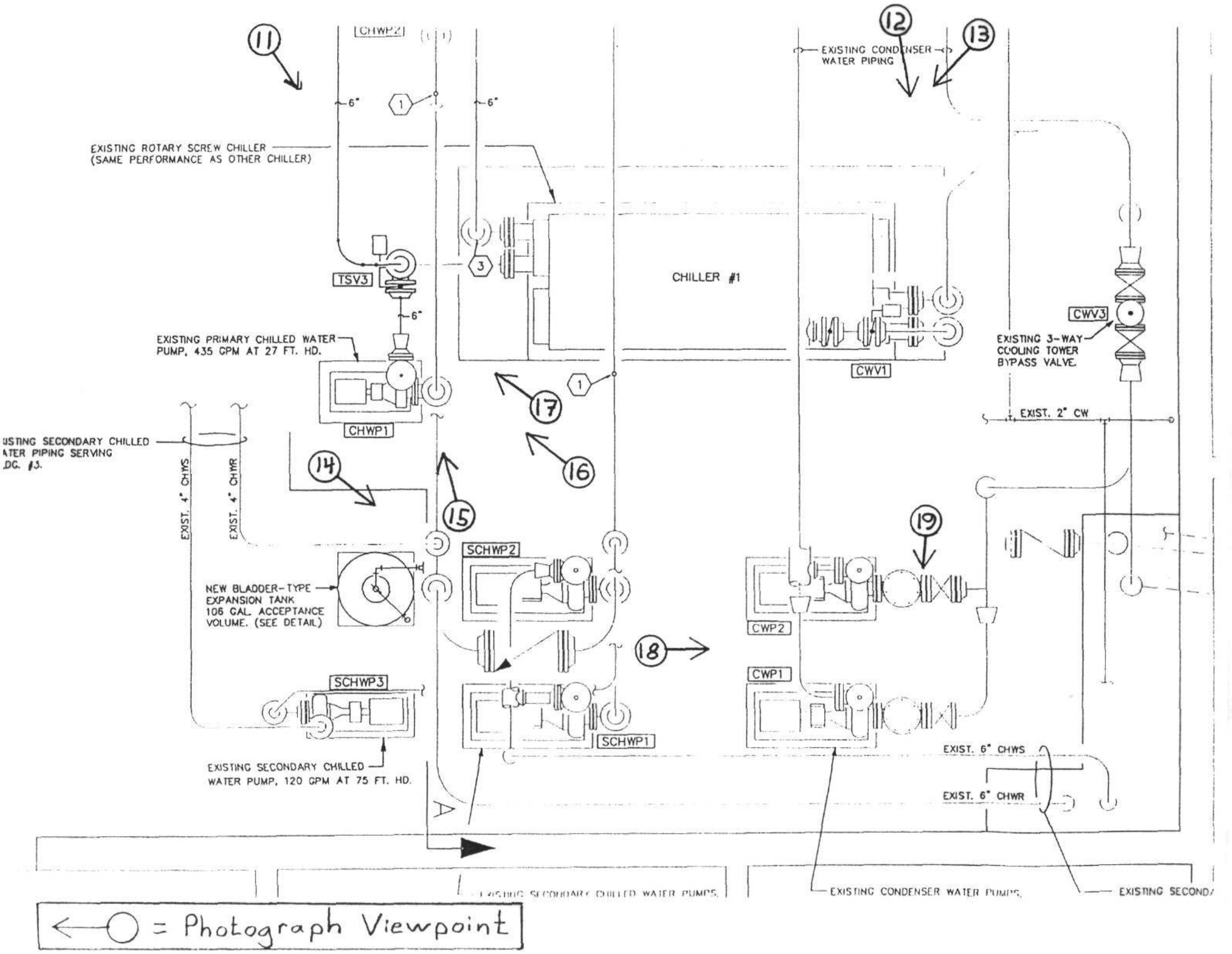


Figure 6.7a: Proposed monitoring at the CERL site.

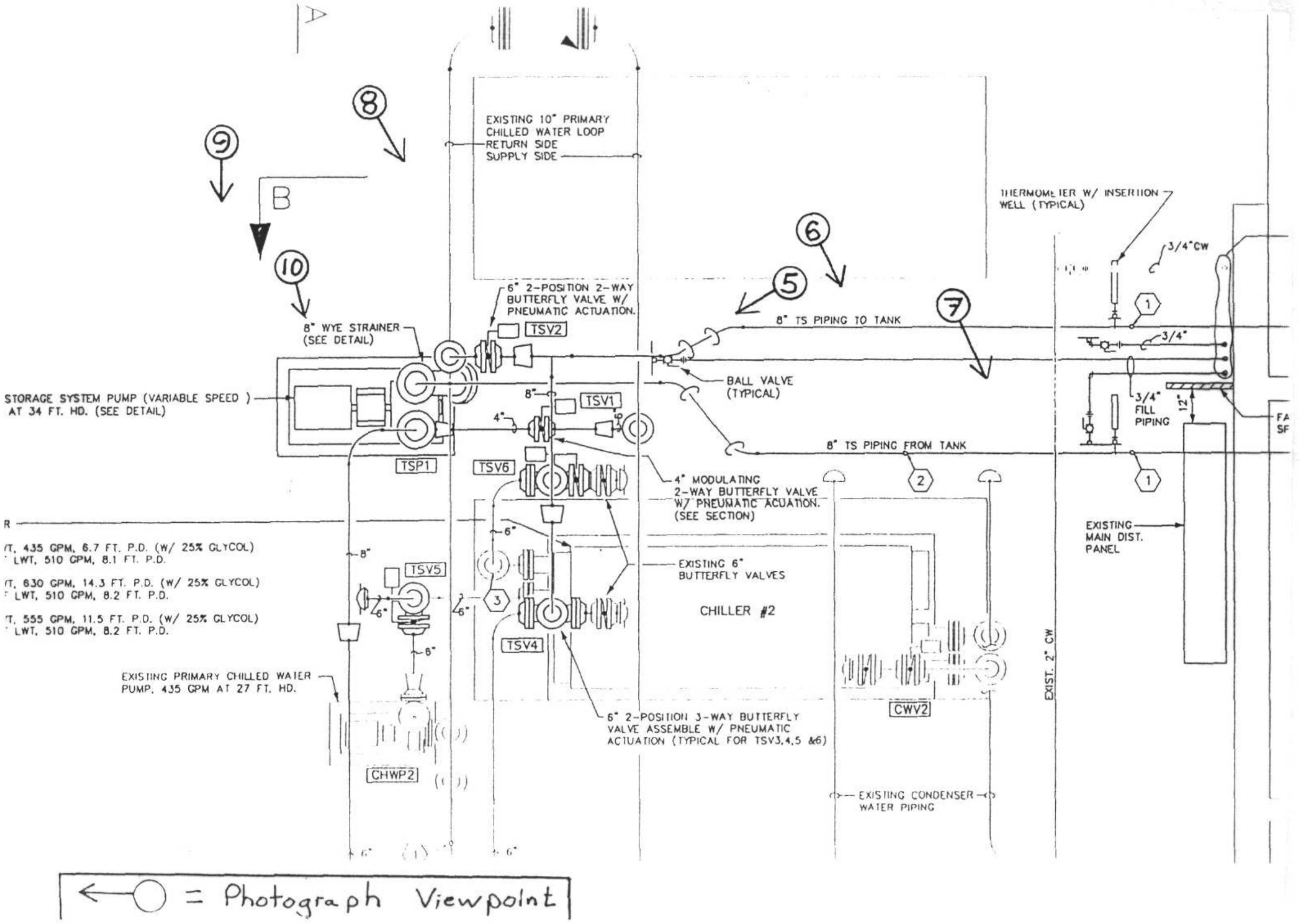


Figure 6.7b: Proposed monitoring at the CERL site.

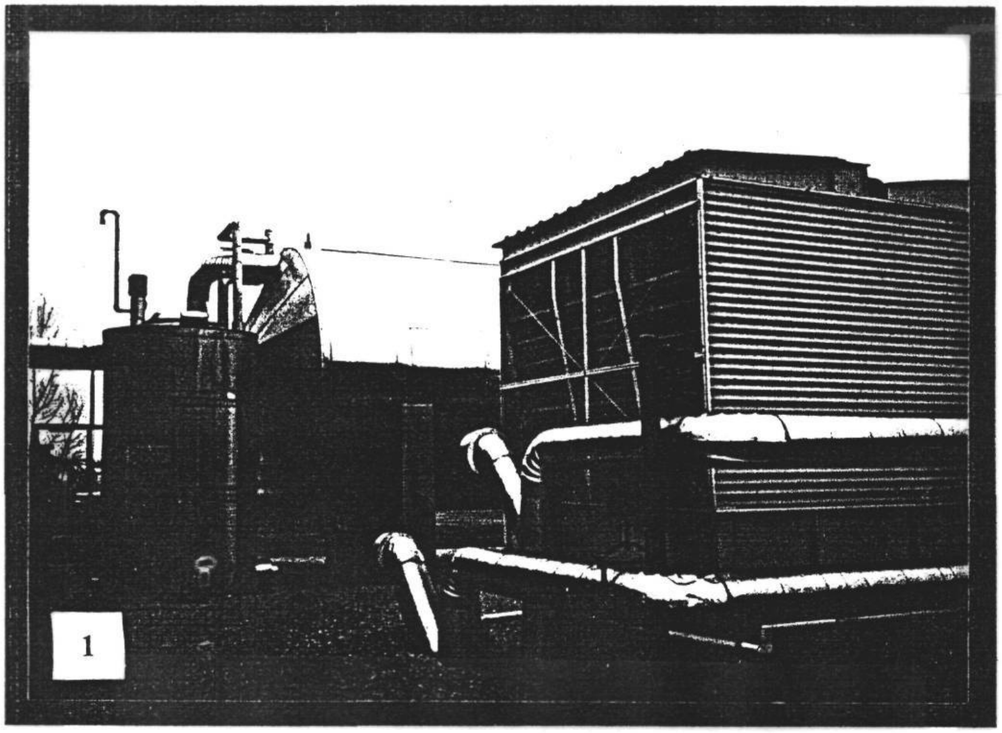


Figure 6.8a: Photos of the CERL site. This photo shows the inventory storage tank and the cooling tower.

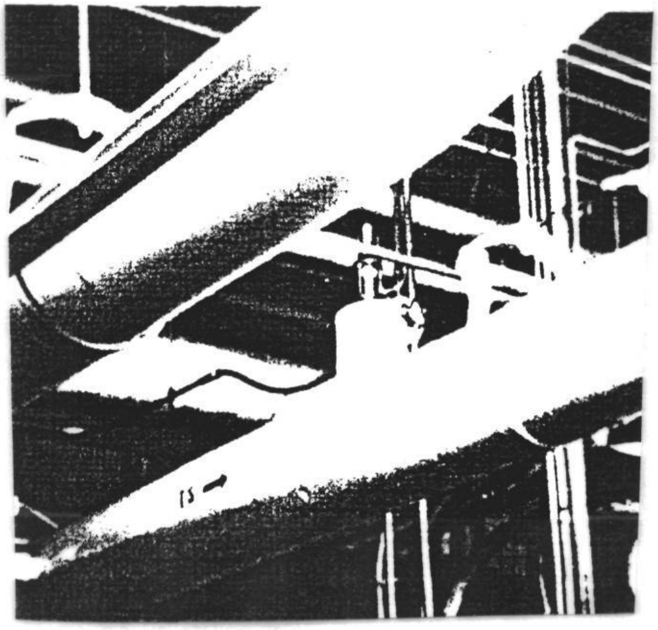


Figure 6.8b: Photos of the CERL site. This photo shows the location of one of the flow meters at the CERL site.

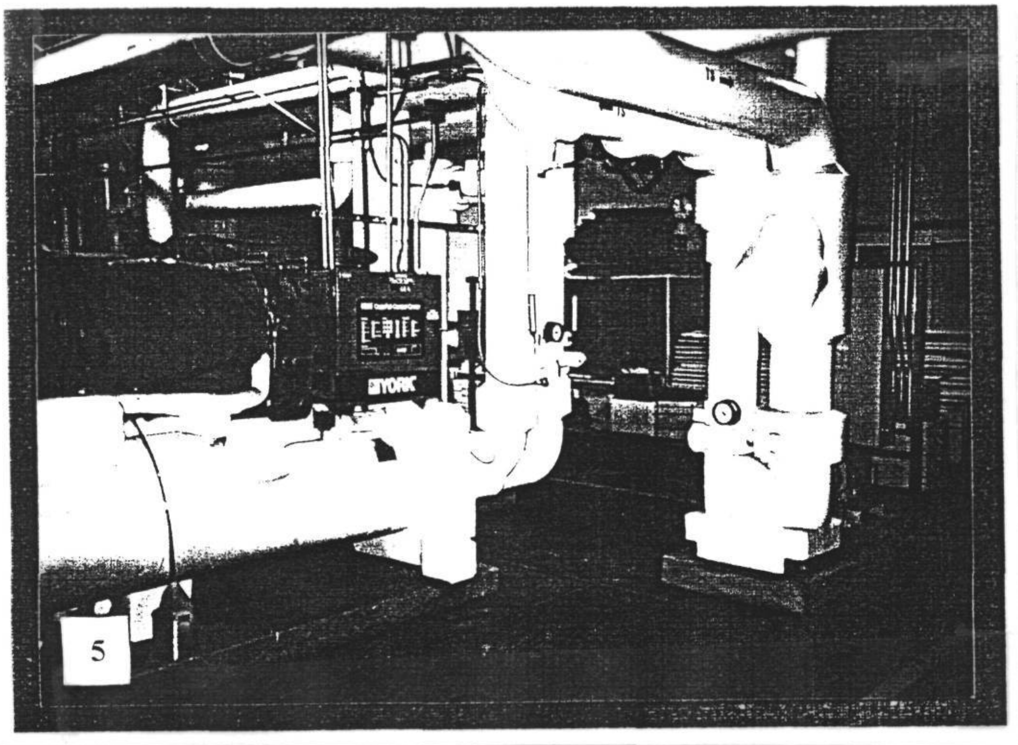


Figure 6.9a: Photos of the CERL site. This photo shows one of the chillers at the CERL site.

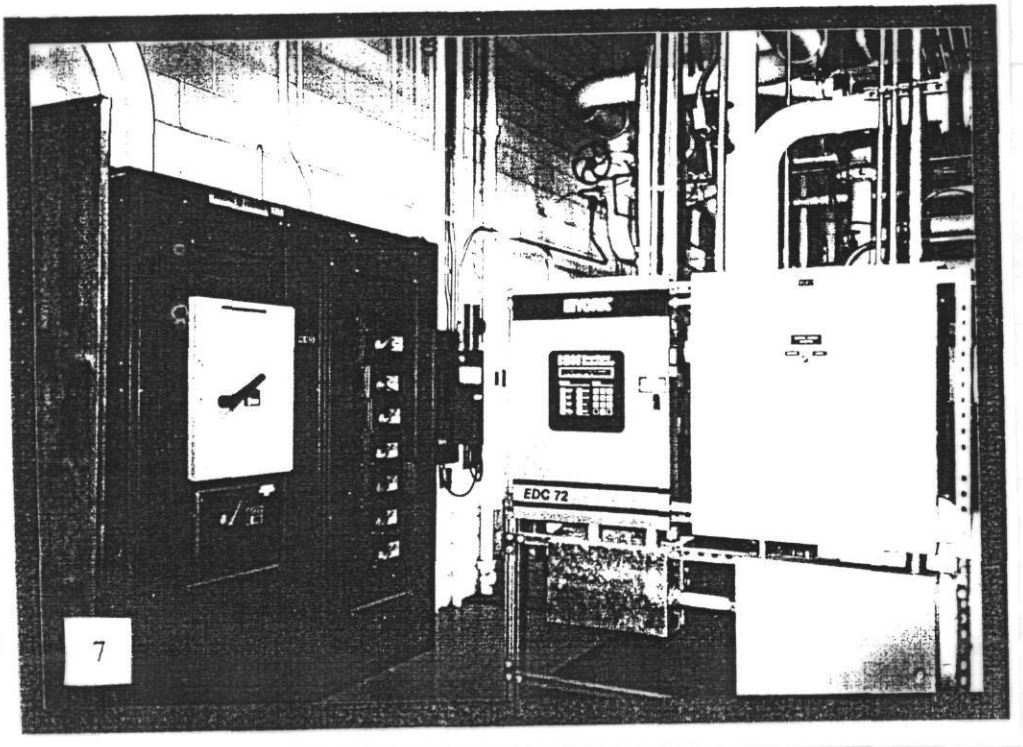


Figure 6.9b: Photos of the CERL site. This photo shows the existing control system and integrated EMCS/data logger.

7.0 NOMENCLATURE

ACW	monthly mean daily value of CW
AHU	air handler unit
b	bias error
COP	coefficient of performance
CV	constant air volume HVAC system, coefficient of variation
CW	chilled water thermal energy use
E	electric power or energy use
I	indicator or dummy variable
I_{occup}	dummy variable (either 0 or 1) indicating whether the building is occupied or not
k	number of regression parameters in the model
MBE	mean bias error
m	mass flow rate
n	number of observation points (months, days, hours,...)
p	number of model parameters (=k+1)
R	model residual
R^2	coefficient of determination
RMSE	root mean square error
SMLP	short-term monitoring for long-term prediction
Q	thermal loads or energy use
T	temperature
TES	thermal energy storage
VAV	variable air volume
W	specific humidity
t	t-statistic
$\overline{X}$	mean value of X
$\hat{X}$	model predicted value of X
α	significance level
ε	random error
σ^2	estimated variance of the model error
var	model prediction uncertainty

Subscripts

bldg	building
comp	compressor
evap	evaporator
db	dry-bulb
dp	dew point
i	subscript denoting hour
int	internal
k	subscript denoting month of year
o	outdoor
sol	solar
wb	wet-bulb

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APPENDIX

Specific information for selected thermal storage monitoring sites.

SITE No.	SITE NUMBER	LOCATION	TYPE OF STORAGE
143	Delmar College	Corpus Christi, TX	Chilled water
144	Midland County Courthouse	Midland, TX	Internal melt - ice
230	Austin Convention Center	Austin, TX	Internal melt - ice
322	University of Houston - Clearlake	Houston, TX	External melt- ice

Site #143

Delmar College
Corpus Christi, TX

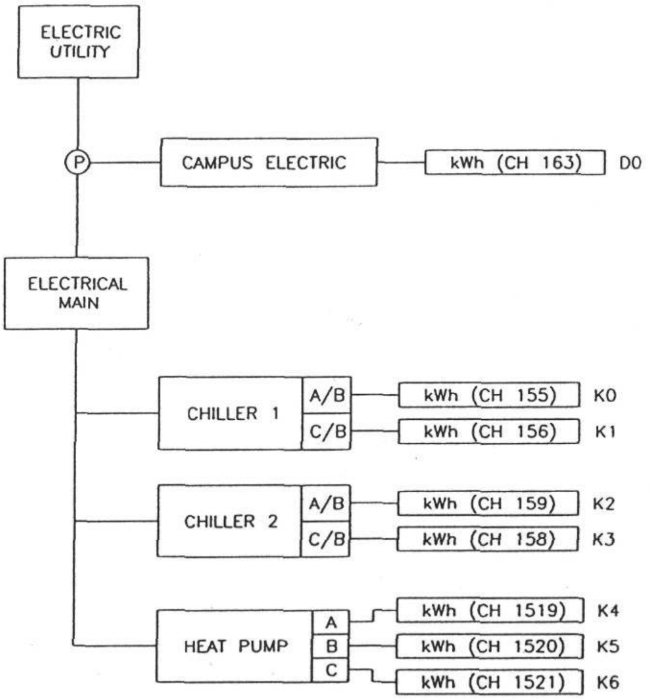
Chilled Water

Date MM/DD/YY ([illegible] DDD)	Time HH:mm	Raw-Data lin pos	coln pos	Arch coln pos	Name of Channel	Archive Units	Arch Format	Conv'n Code	Conv'n Constants	Error Code	Error Constants	Channel Description
09/24/91	00:00	1	0	0	Begin	Del Mar						Beginning date
09/24/91	00:00	1	1	1	Bldg. #	xx	I3	2	0 143	0		Building Number
09/24/91	00:00	1	1	2	Mon-Raw	MM	I3	1		0		Month
09/24/91	00:00	1	2	3	Mon-Raw	DD	I3	1		0		Day
09/24/91	00:00	1	3	4	Mon-Raw	YY	I3	1		0		Year
09/24/91	00:00	1	3	5	Greg-Jul	MMDDYY	I5	24	1 2	0		Gregorian Date to Julian
09/24/91	00:00	1	4	7	Time	HH mm	I5	16	5	0		Time
09/24/91	00:00	1	3	6	Greg-Dec	DDD.frac	F10.4	28		0		Gregorian Date to Jul.Decimal
09/24/91	00:00	1	6	8	Ch1 AB	F9.3	F9.3	1		1	-5 500	Chiller 1 AB (kWh/h)
09/24/91	00:00	1	7	9	Ch1 CB	F9.3	F9.3	1		1	-5 500	Chiller 1 CB (kWh/h)
09/24/91	00:00	1	8	10	Ch2 AB	F9.3	F9.3	1		1	-5 500	Chiller 2 AB (kWh/h)
09/24/91	00:00	1	9	11	Ch2 CB	F9.3	F9.3	1		1	-5 500	Chiller 2 CB (kWh/h)
09/24/91	00:00	1	10	12	Ch1 S T	F9.3	F9.3	1		1	-5 200	Chl 1 Sup Temp (F)
09/24/91	00:00	1	11	13	Ch1 R T	F9.3	F9.3	1		1	-5 200	Chl 1 Ret Temp (F)
09/24/91	00:00	1	12	14	Ch2 S T	F9.3	F9.3	1		1	-5 200	Chl 2 Sup Temp (F)
09/24/91	00:00	1	13	15	Ch2 R T	F9.3	F9.3	1		1	-5 200	Chl 2 Ret Temp (F)
09/24/91	00:00	1	14	16	Campus E	F9.3	F9.3	1		1	0 15000	Campus Elec (kWh/h)
09/24/91	00:00	1	15	17	Campus G	F9.3	F9.3	1		1	0 100000	Campus Gas (MCF)
09/24/91	00:00	1	16	18	ChW1 Btu	F9.3	F9.3	1		1	0 100000	Chl 1 Energy (kBtu)
09/24/91	00:00	1	17	19	ChW1Flow	F9.3	F9.3	1		1	0 100000	Chl 1 Flow (gal)
09/24/91	00:00	1	18	20	ChW2 Btu	F9.3	F9.3	1		1	0 100000	Chl 2 Energy (kBtu)
09/24/91	00:00	1	19	21	ChW2Flow	F9.3	F9.3	1		1	0 100000	Chl 2 Flow (gal)
03/11/99	23:00	1	0	0	End	Del Mar						

DEL MAR COLLEGE
ELECTRICAL MONITORING DIAGRAM

LEGEND

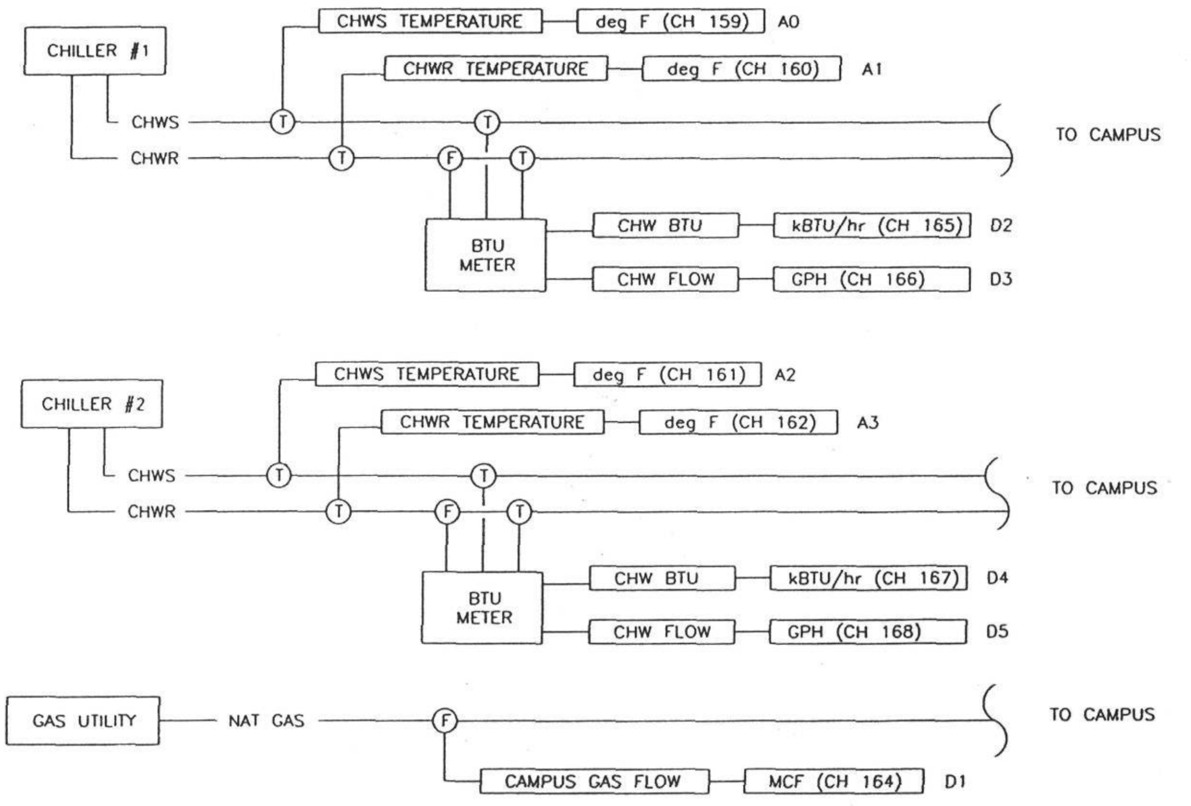
K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL
P=PULSE METER



DEL MAR COLLEGE
THERMAL MONITORING DIAGRAM

LEGEND

K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL
F=FLOW METER
GPH=GALLONS PER HOUR
CHWS=CHILLED WATER SUPPLY
CHWR=CHILLED WATER RETURN

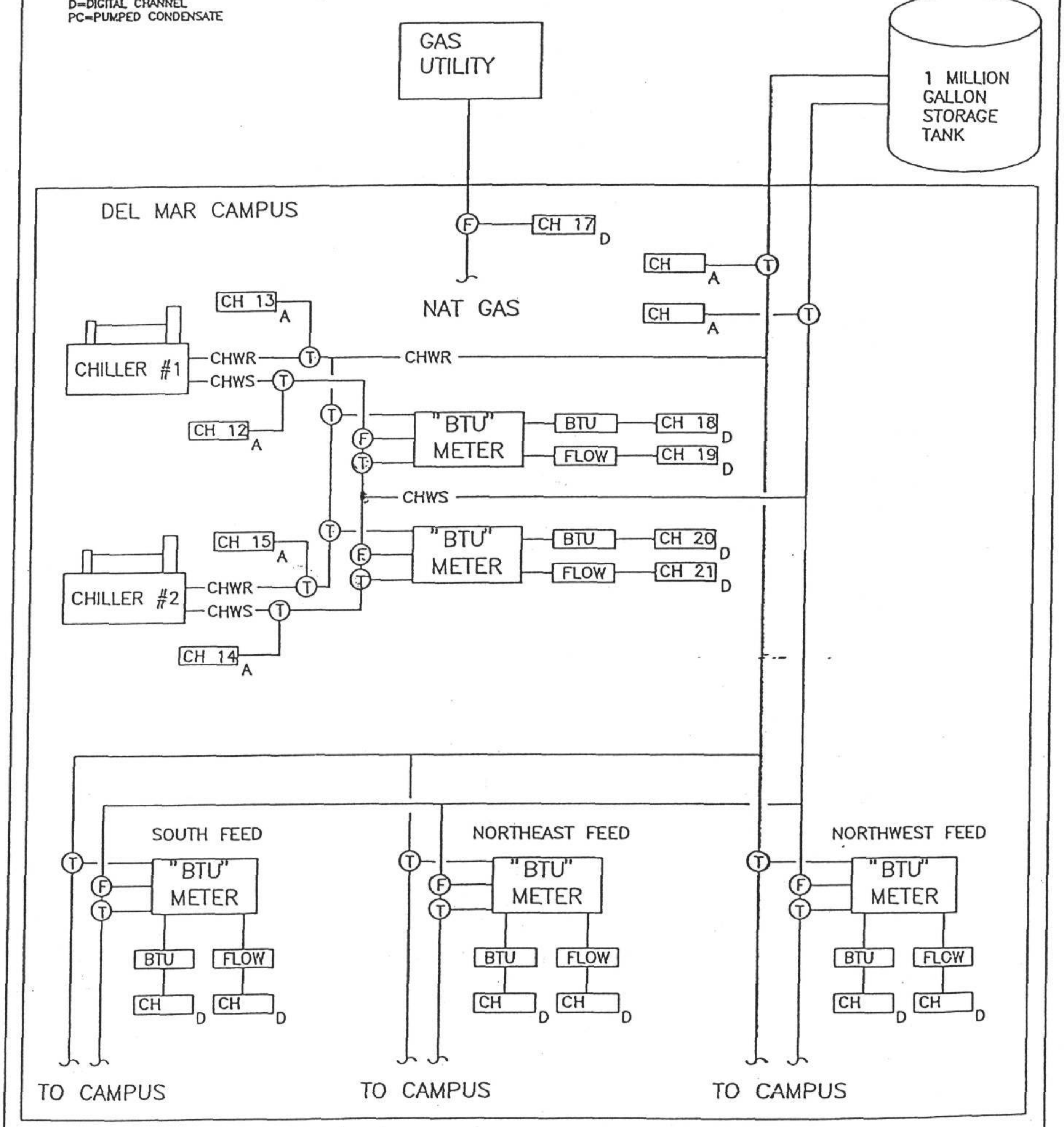


THERMAL MONITORING DIAGRAM

DEL MAR COLLEGE

LEGEND

K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL
PC=PUMPED CONDENSATE



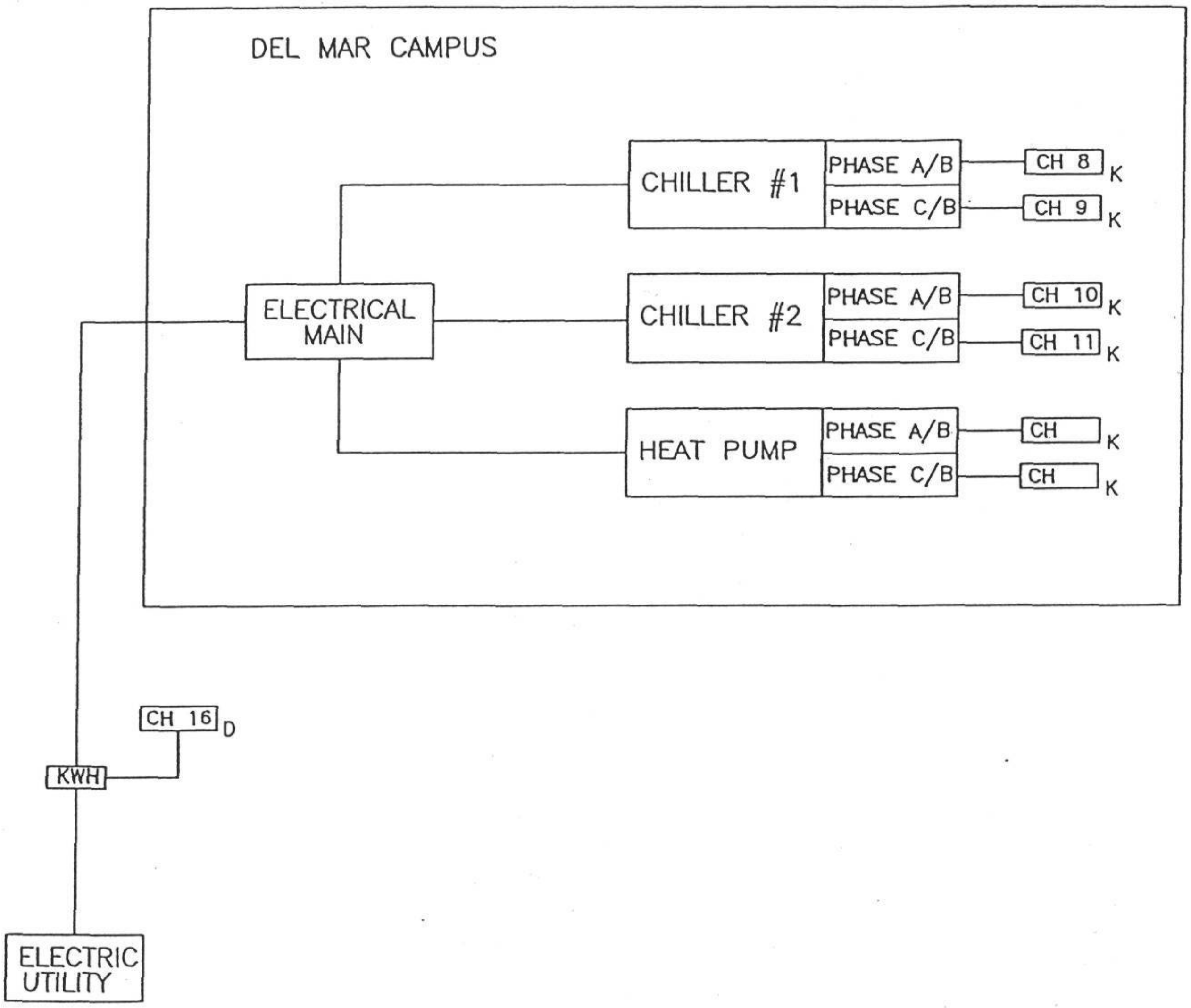
DEL MAR COLLEGE – SITE 143

ELECTRICAL MONITORING DIAGRAM

DEL MAR COLLEGE

LEGEND

K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL



DEL MAR COLLEGE – SITE 143

DELMAR COLLEGE

Building Envelope:
- 681,592 sq. ft.
- 23 buildings, built in in 1940-present
- Conditioned floor area: 636,707 sq. ft.
- walls: variable construction
- windows: N/A
- roof: built-up flat

Building Schedule:
- Monday - Friday 7:30 am to 12:00 pm
- Saturday and Sunday - some buildings partially occupied

Building HVAC and Auxiliary Equipment
- Information for the individual AHUs in each building is not available. Campus has a mixture of single duct, double duct constant volume, variable volume and DX units. All the new buildings have variable volume system with DDC control.
- 1 - 1000 ton Trane Centrifugal Chiller
- 1 - 1000 ton Westinghouse Centrifugal Chiller
- Several DX units, total cooling capacity 300 tons
- 2 hot water boilers, 300 hp each

HVAC Schedule
- 24 hrs/day

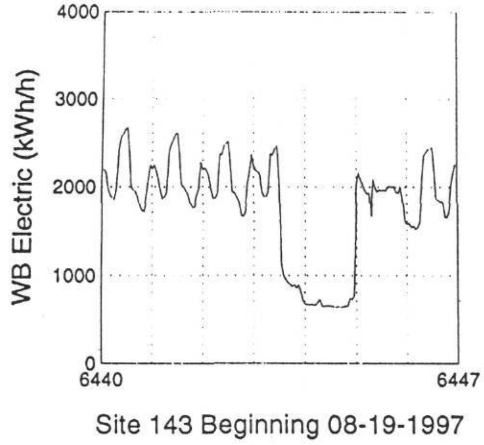
Lighting
- mixture of florescent, incandescent in the classrooms, offices, and corridors
- metal halides, H.P. sodium and L.P. sodium in the Gym, swimming pool, for parking and security lights.

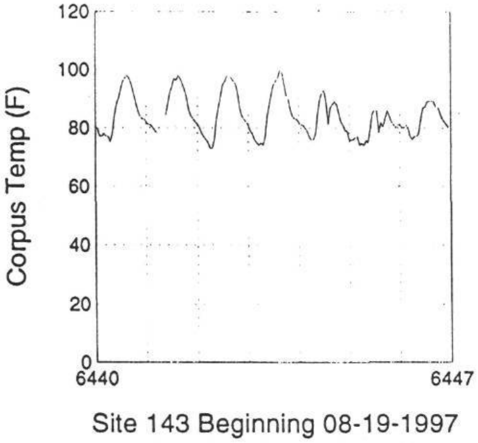
Proposed Maintenance and Operation Measures
- None

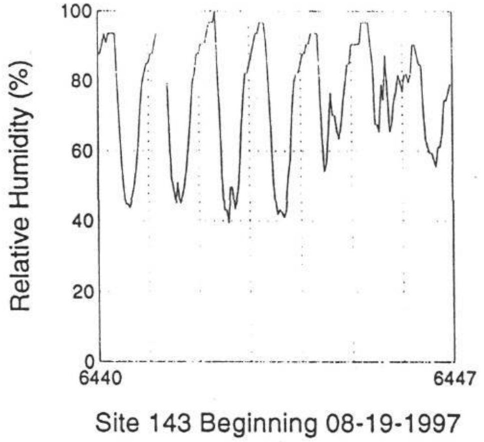
Proposed Retrofits
- thermal energy storage/industrial water source heat pump
- capacitors for power factor improvement
- interior lighting controls
- exterior lighting conversions
- fixture relamping
- Total loan amount $1,157,404 with audit estimated savings of $287,930/yr

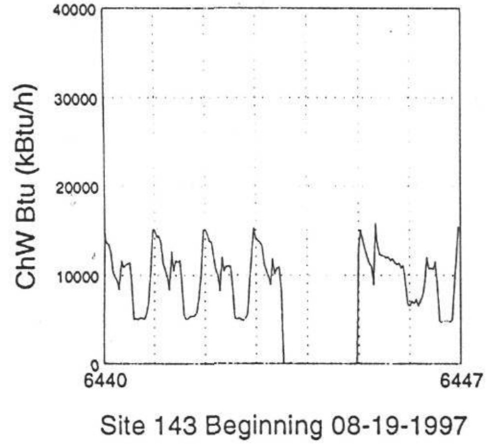
Status of Retrofits
- Capacitors were installed in July 1992.
- Thermal storage system will be completed in November 1993. Heat pump became operational on June 30, 1993.

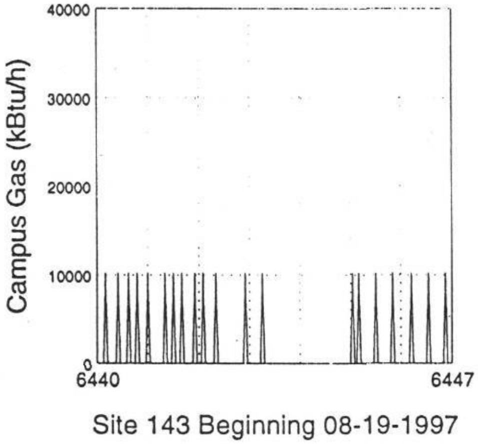
Site 143 Page 1

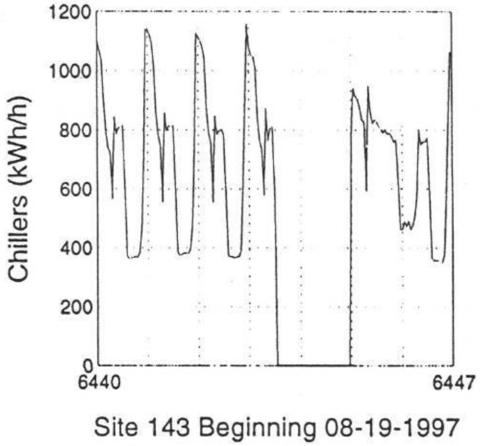


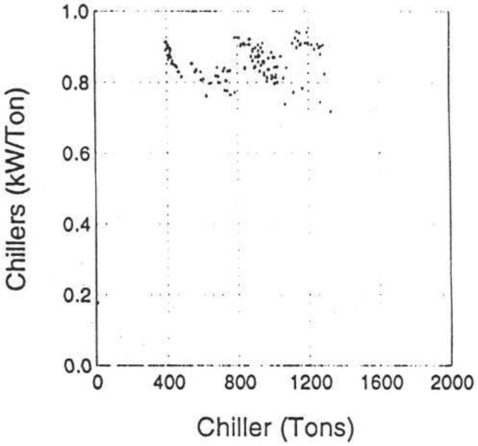


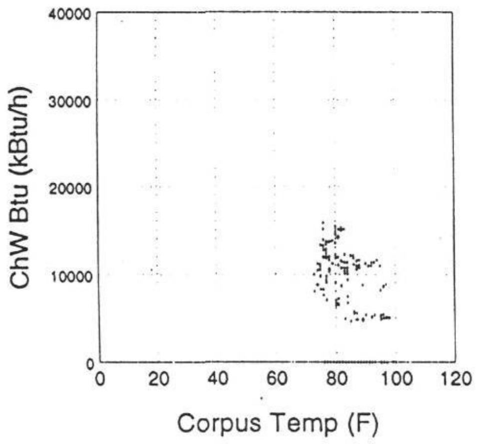


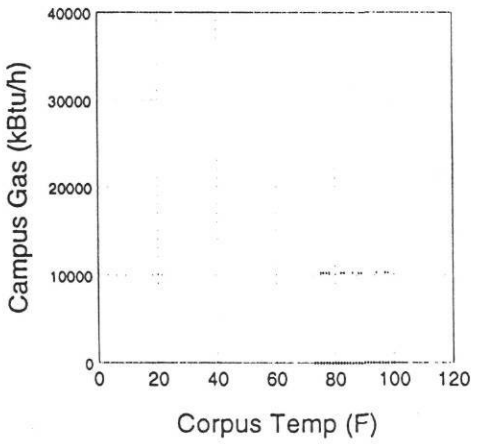


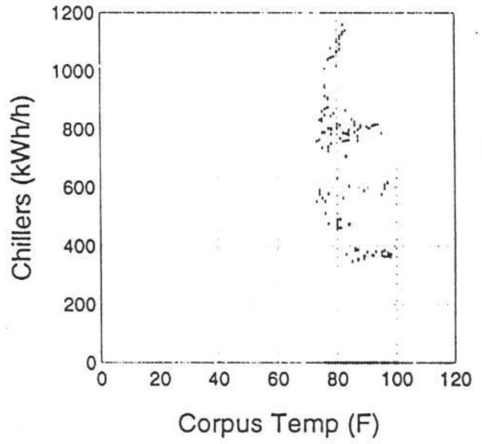


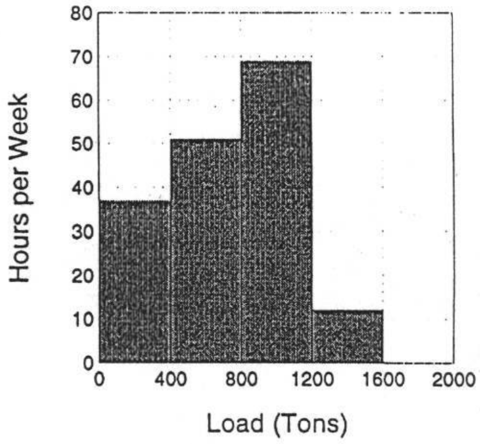




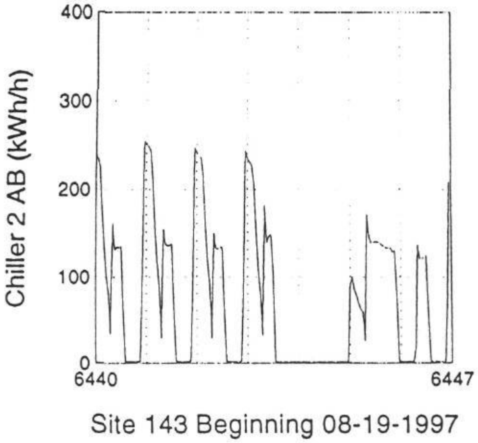


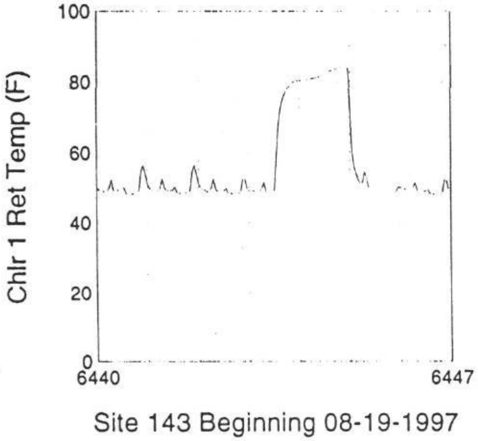


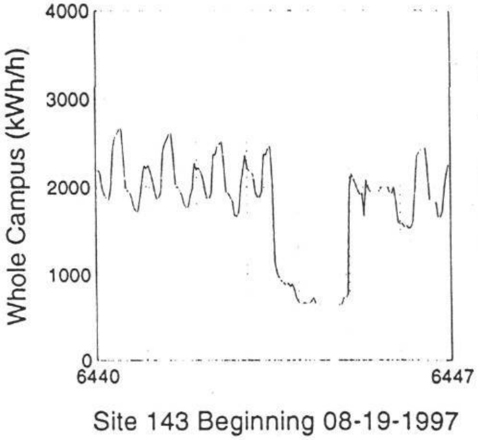


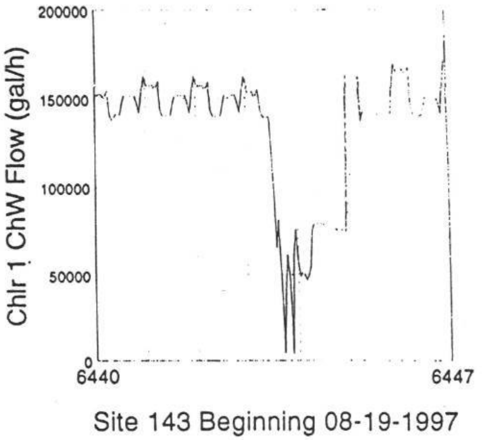


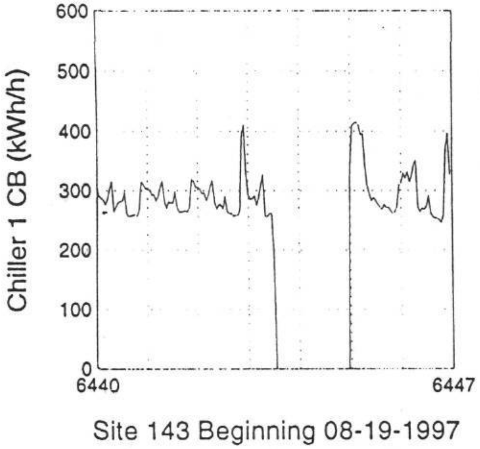
Site 143 Page 2

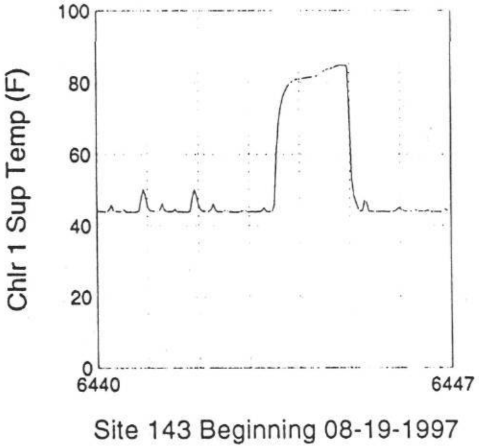


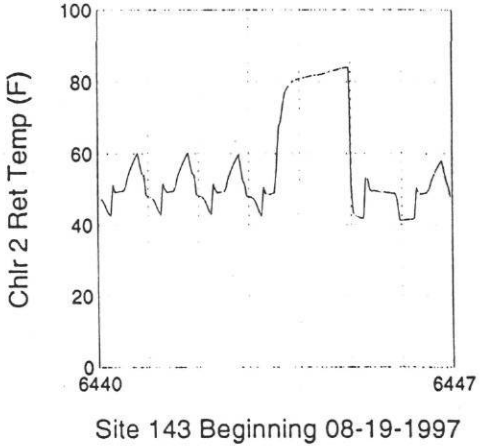


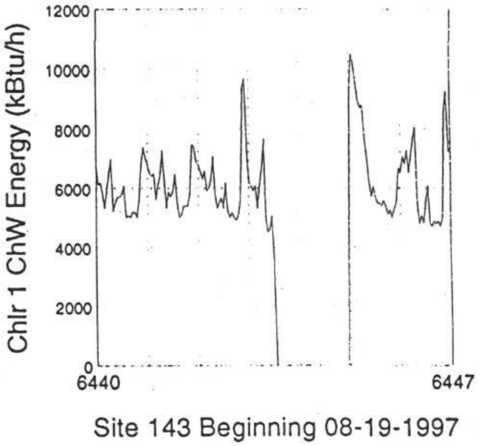


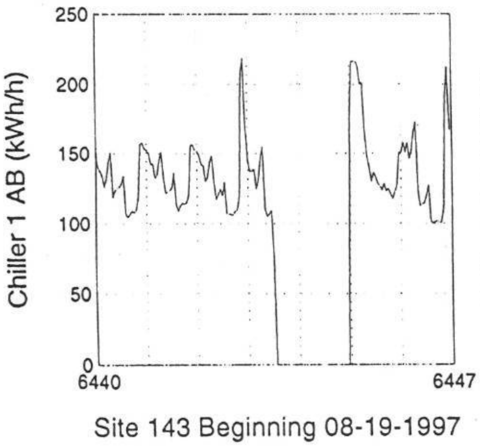


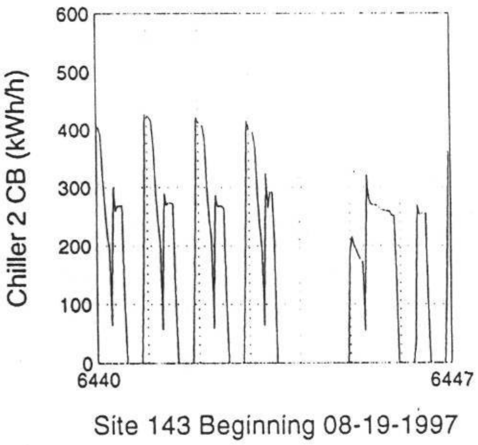


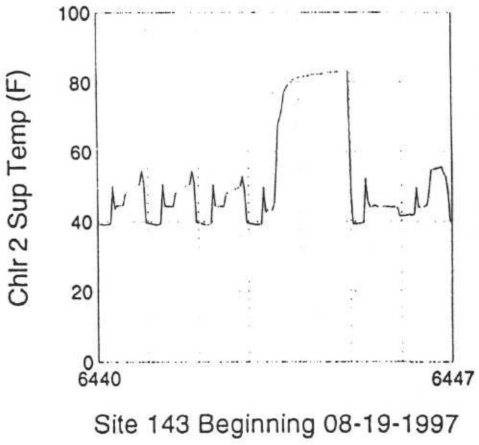


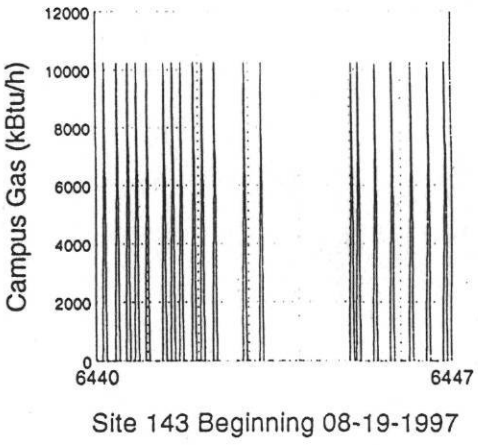




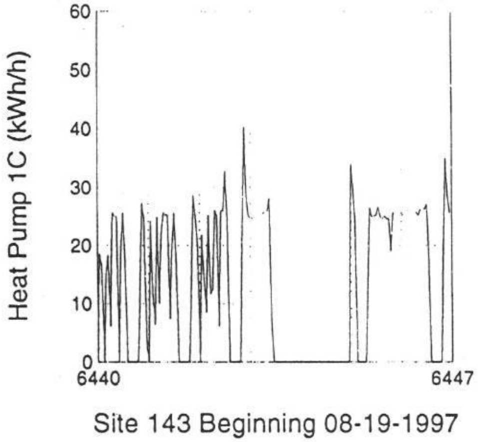


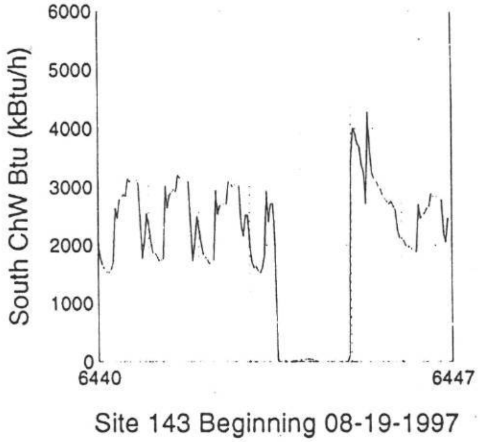


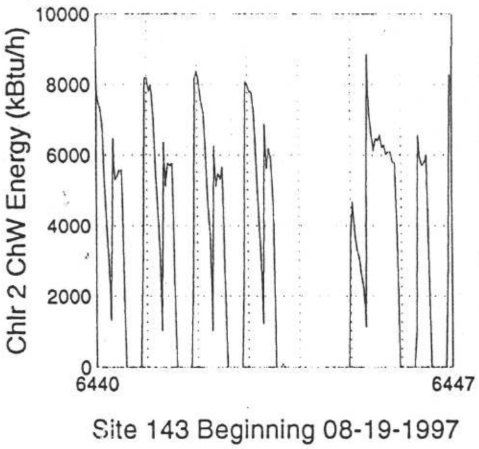


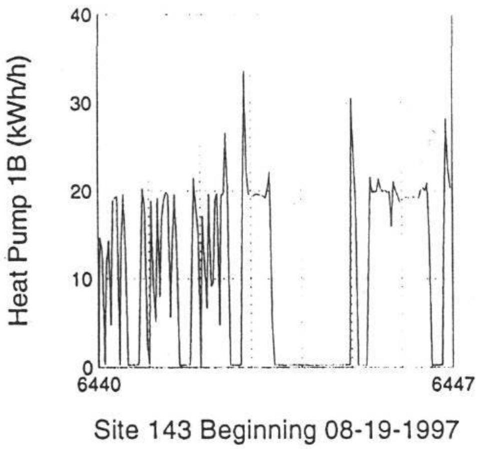


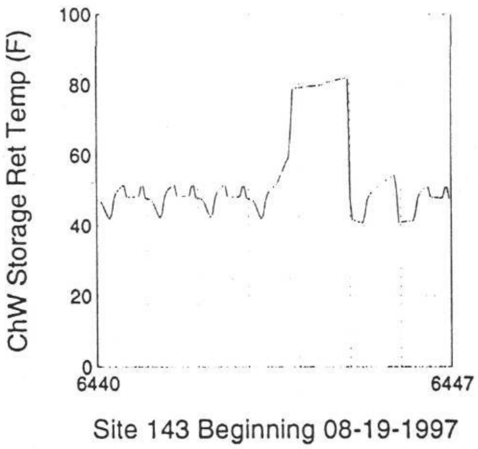
Site 143 Page 3

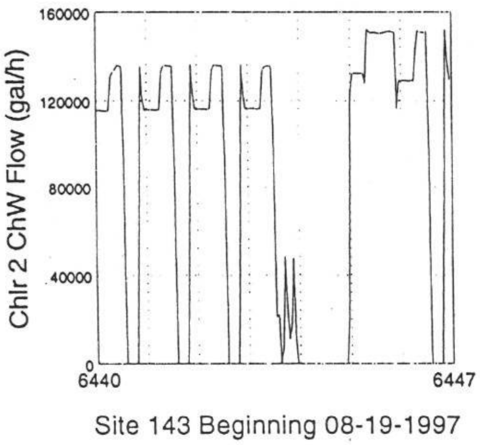


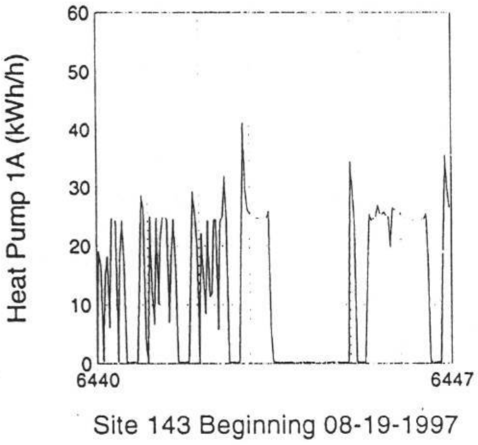


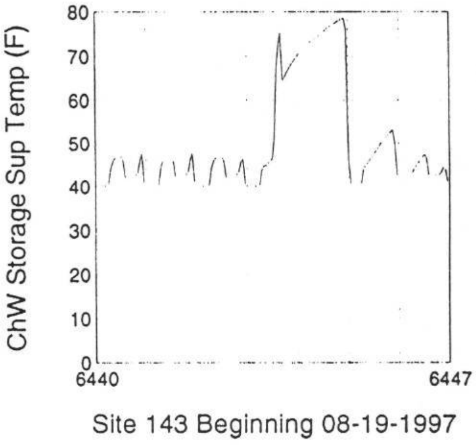


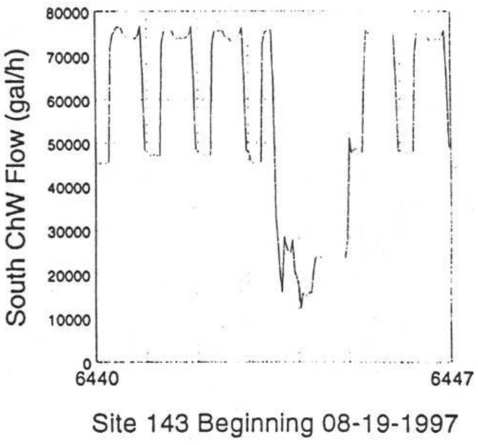












Delmar College

Whole Campus
636,702 square feet

Site Contact	LoanSTAR Metering Contact
Mr. Johnny L. White	Aamer Athar or Namir Saman
Director of Physical Facilities	053 WERC
Delmar College	Texas A&M University
Baldwin & Ayers	College Station, TX 77843-3123
Corpus Cristi, TX 78404	(409) 845–9213
(512) 886–1242	

Summary of Energy Consumption

	Measured Use	% hours reported	Unit Cost	Estimated Cost
Electricity	1446293 kWh	100	$0.02940	$42521
Peak 60 Minute Demand	2845 kW	100	$13.52	$38461
Chilled Water	6886.3 MMBtu	100	$6.000	$41318
Natural Gas	1699.5 MMBtu	100	$3.940	$6696

Peak 60 minute demand was recorded at 1200 Tuesday 06/17/97.
There were 720 hours in this month.

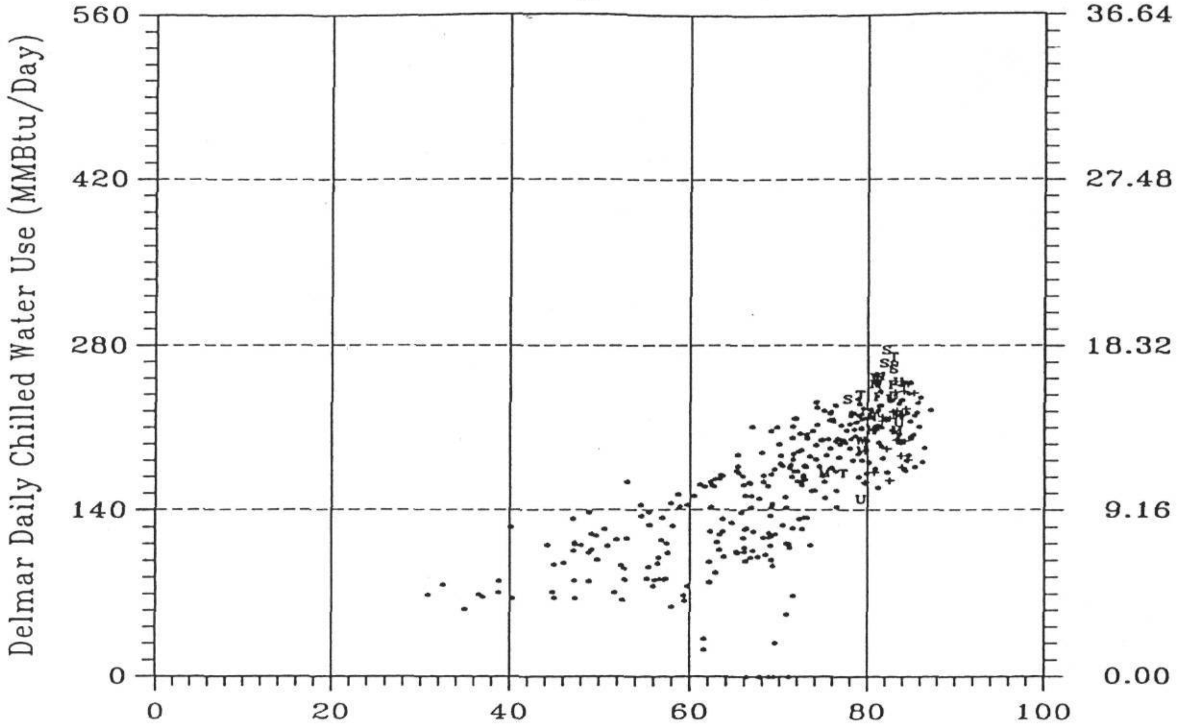
Monthly Retrofit Savings

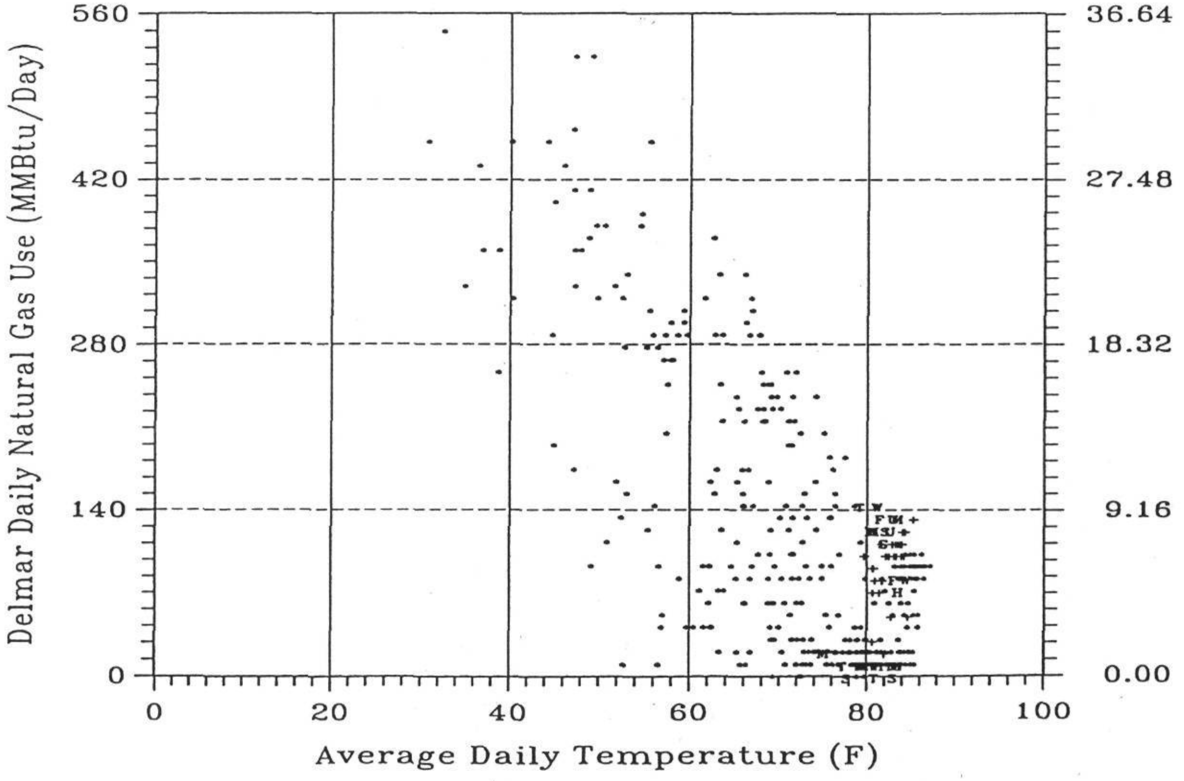
	Measured Savings		Audit Estimated Savings	
Electricity (kWh)	-38202	$-1123	-127565	$-3750
Electricity Demand (kW)	834	$11276	1139	$15399
Cond./H.W./N.G. (MMBtu)	3932	$15492	2079	$8191
Monthly Total		$25645		$19840
Total to Date*	(51 months)	$1468182	(48 months)	$844531

*Measured savings include construction period. Audit estimated savings do not.

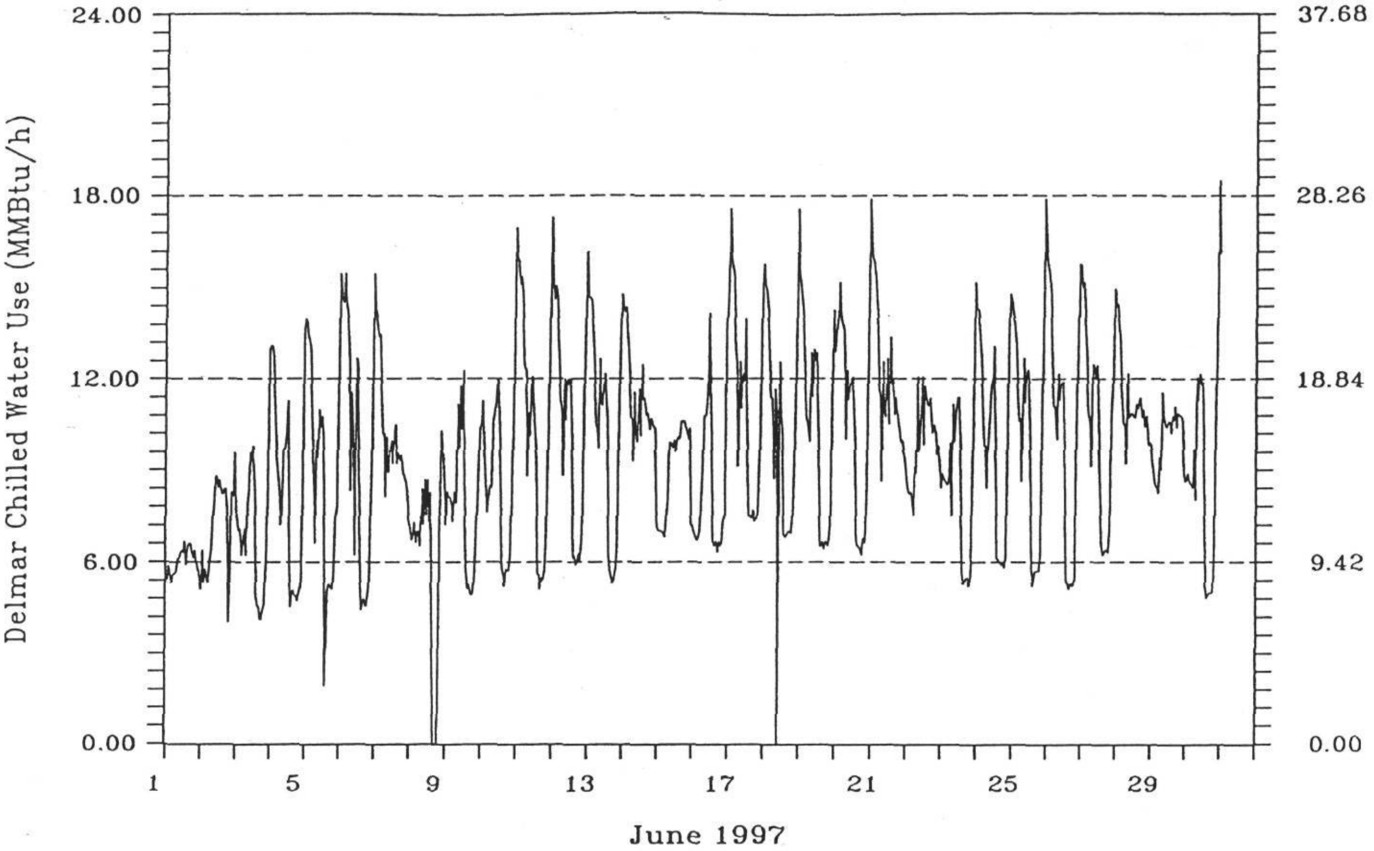
Comments

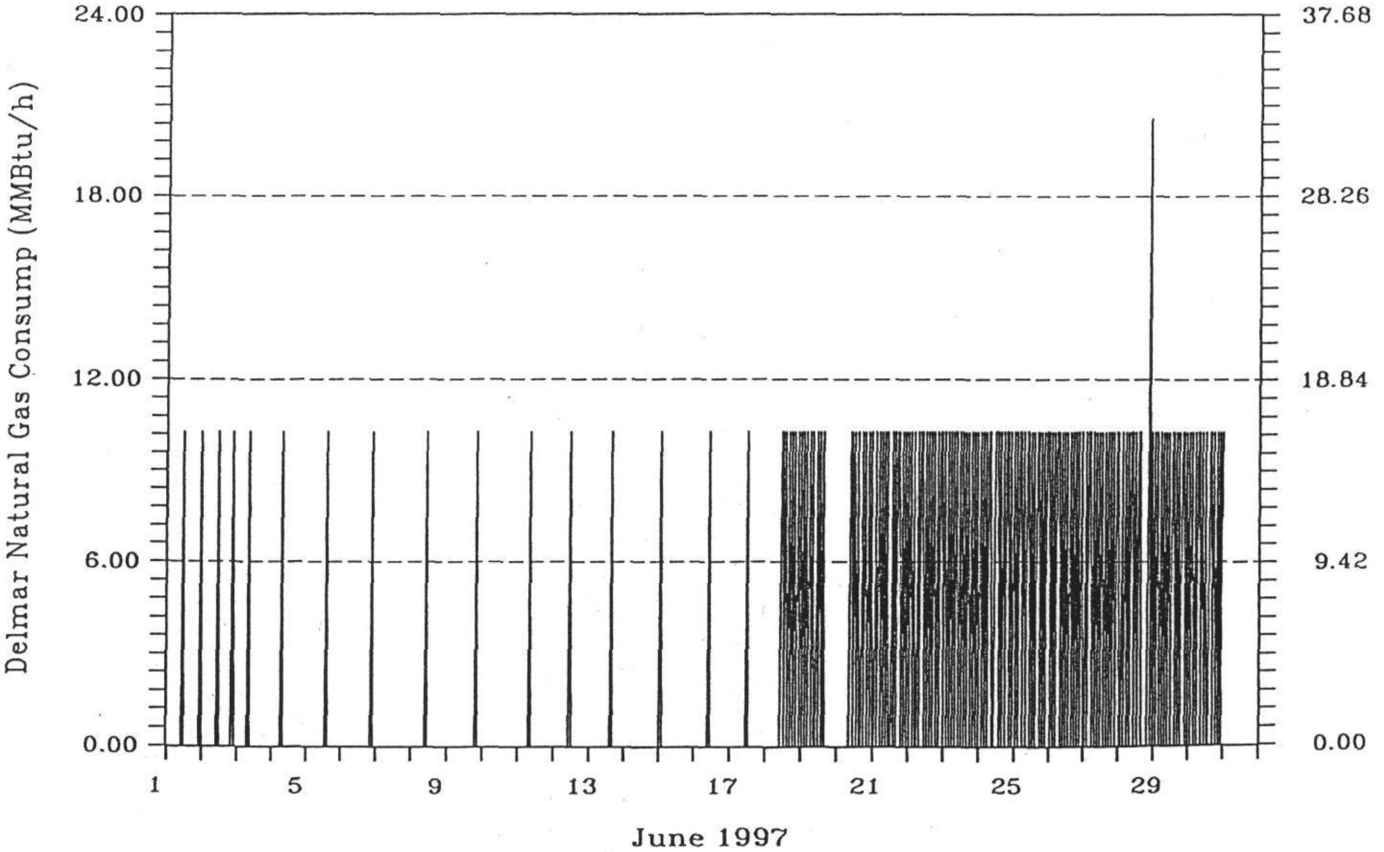
★ Chilled water energy use increased when compared to June 1996.


Jun 01 1996 – Jun 30 1997

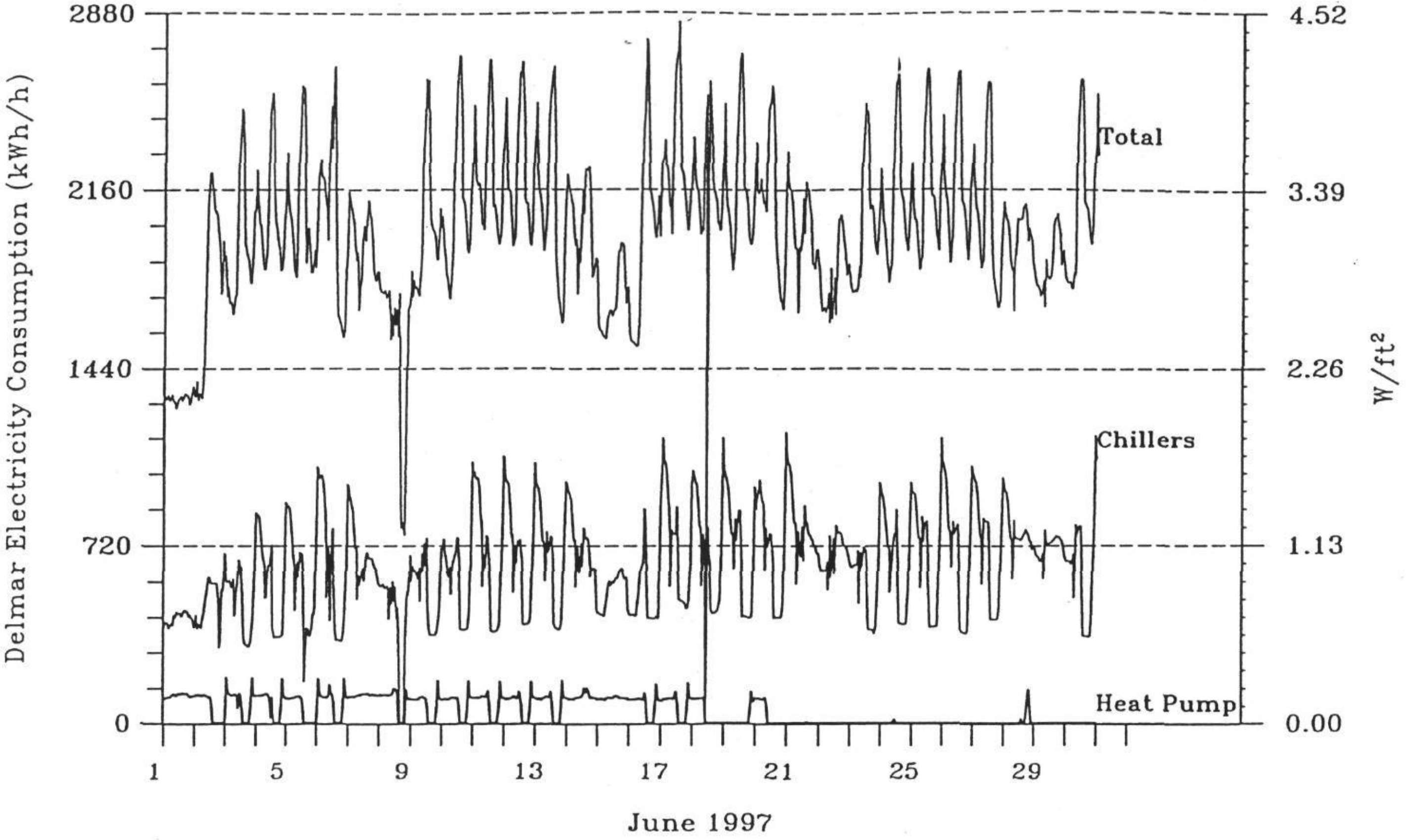

Jun 01 1996 – Jun 30 1997

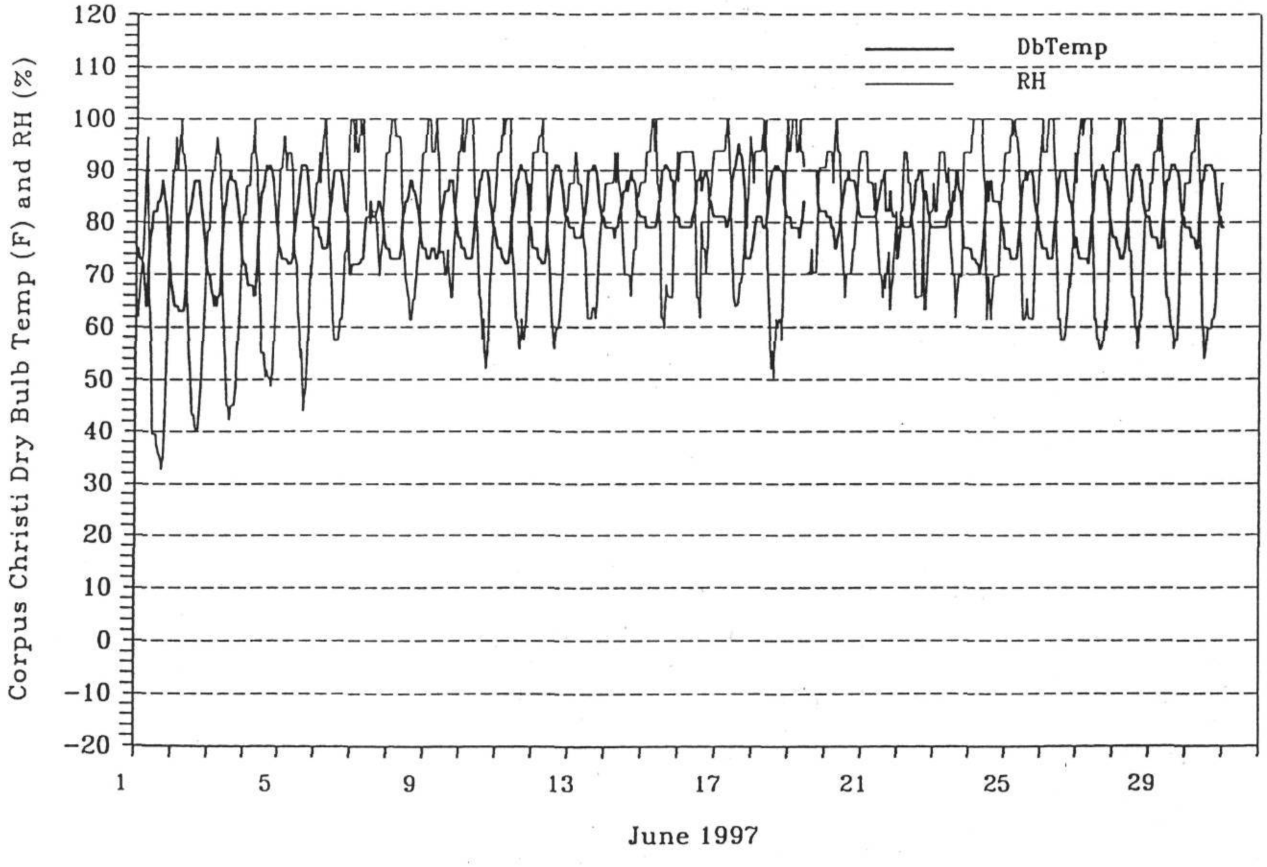
Data points for the current month are shown as letters. Points from this month last year are shown as +.
Monday through Sunday are represented as M,T,W,H,F,S,U. All other points are shown as *.





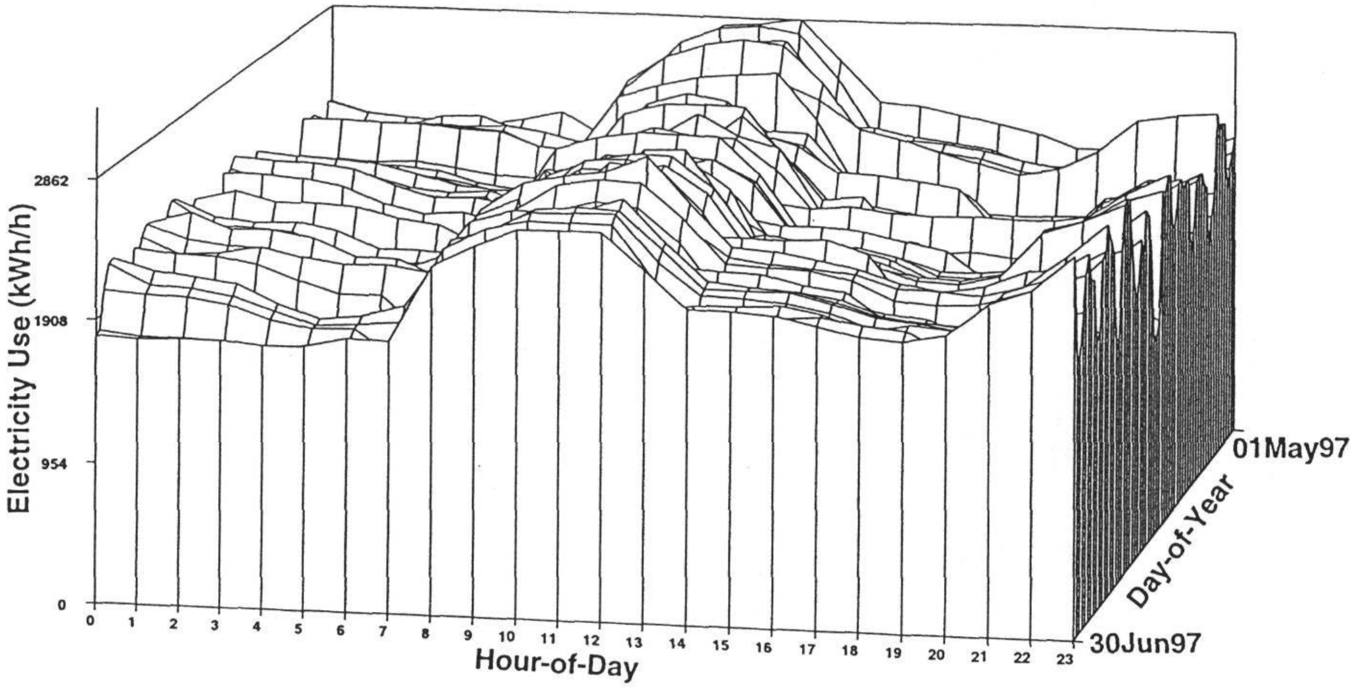
Delmar College - Whole Campus - June 1997



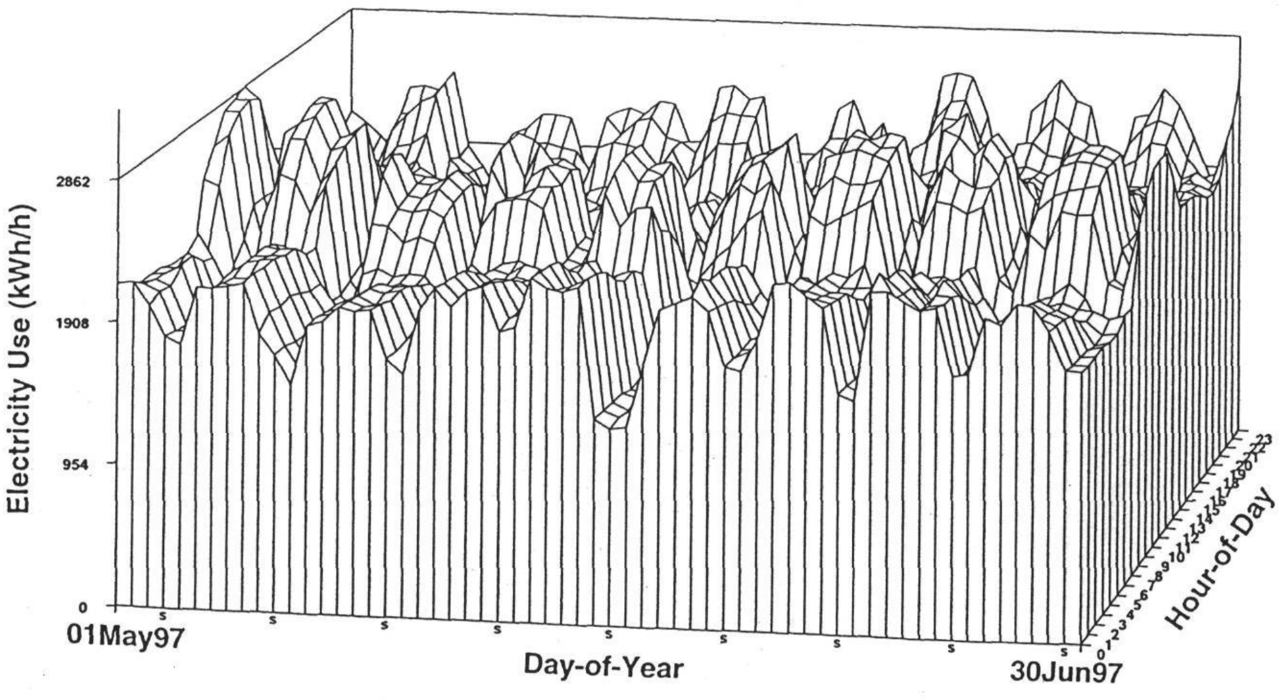


Delmar College - Whole Campus - June 1997

Whole-Building Electric



Whole-Building Electric



Sundays are marked with an "S"

DEL MAR COLLEGE

Building Envelope:

- 681,592 sq.ft.
- 23 buildings, built in 1940-present
- conditioned floor area: 636,707 sq.ft.
- walls: variable construction
- windows: N/A
- roof: built-up flat

Building Schedule:

- Monday - Friday 7:30 am to 12:00 midnight
- Saturday and Sunday - some buildings partially occupied

Building HVAC and Auxiliary Equipment

- information for the individual AHUs in each building is not available. Campus has a mixture of single duct, double duct constant volume, variable volume and DX units. All the new buildings have variable volume system with DDC control
- 1 - 1000 ton Trane Centrifugal Chiller
- 1 - 1000 ton Westinghouse Centrifugal Chiller
- several DX units, total cooling capacity 300 tons
- 2 hot water boilers, 300 hp each

HVAC Schedule

- 24 hrs/day

Lighting

- mixture of fluorescent, incandescent in the classrooms, offices, and corridors
- metal halides, H.P. sodium and L.P. sodium in the Gym, swimming pool, for parking and security lights

Proposed Maintenance and Operation Measures

- none

Proposed Retrofits

- thermal energy storage/industrial water source heat pump
- capacitors for power factor improvement
- interior lighting controls
- exterior lighting conversions
- fixture relamping
- total loan amount $1,157,404 with audit estimated savings of $287,930/yr

Status of Retrofits

- capacitors were installed in July 1992
- thermal storage system was completed in November 1993. The heat pump became operational on June 30, 1993

Delmar College

Whole Campus
636,702 square feet

Site Contact	LoanSTAR Metering Contact
Mr. Johnny L. White Director of Physical Facilities Delmar College Baldwin & Ayers Corpus Cristi, TX 78404 (512) 886–1242	Aamer Athar or Namir Saman 053 WERC Texas A&M University College Station, TX 77843-3123 (409) 845–9213

1996 Summary of Measured Energy Consumption and Savings

	Electricity				Electricity Demand				Hot Water/Steam/NG				Total	
	Consumption			Savings	Consumption			Savings	Consumption			Savings	Monthly	Cumulative
Month	kWh	$	%	$	kW	$	%	$	MMBtu	$	%	$	Savings	Savings
Jan	1186845	$34893	100	$-11	2460	$33262	100	$24661	7540	$29706	100	$12060	$36710	$36710
Feb	1275017	$37486	100	$-703	2741	$37059	100	$30518	7251	$28570	100	$8038	$37853	$74563
Mar	1243228	$36551	100	$-1233	2901	$39220	100	$27730	6365	$25080	100	$13215	$39712	$114275
Apr	1411140	$41488	100	$-1809	2732	$36942	100	$9723	3152	$12418	100	$18159	$26073	$140348
May	1420786	$41771	100	$-343	2771	$37468	100	$6852	3492	$13757	100	$10413	$16922	$157270
Jun	1438269	$42285	100	$-90	2847	$38490	100	$9180	2853	$11241	100	$9909	$18999	$176269
Jul	1516371	$44581	100	$-45	2935	$39687	100	$7363	2472	$9740	100	$10603	$17921	$194190
Aug	1523911	$44803	100	$-1276	2970	$40154	100	$8223	1452	$5722	100	$15579	$22526	$216716
Sep	1470262	$43226	100	$-1962	2942	$39775	100	$9255	525	$2070	100	$20740	$28033	$244749
Oct	1534345	$45110	100	$-2201	2959	$40008	100	$32127	680	$2678	100	$24460	$54386	$299135
Nov	1413828	$41567	100	$-2283	2957	$39979	100	$31934	2173	$8563	100	$23699	$53350	$352485
Dec	1167231	$34317	100	$-1618	2501	$33817	100	$21186	5140	$20250	100	$18727	$38295	$390780
Total	16601233	$488078		$-13574	33716	$455861		$218752	43095	$169795		$185602		$390780
EUI	26.1	$\frac{kWh}{ft^2yr}$			52954	$\frac{Btu}{ft^2yr}$			67684	$\frac{Btu}{ft^2yr}$				

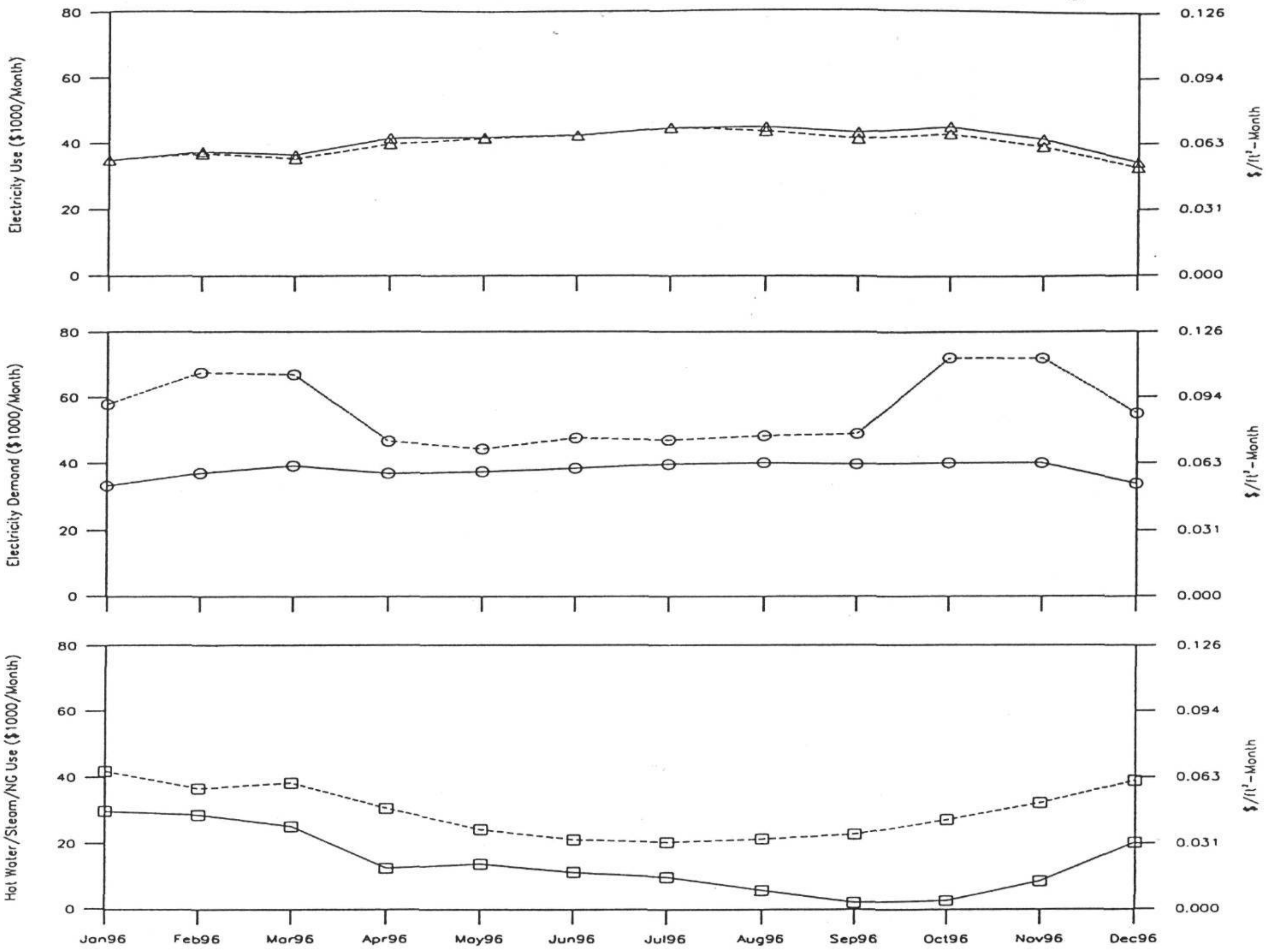
Comments

★ The percent columns indicate the number of hours reported in that month.

★ The LoanSTAR monitoring began in November 1991.

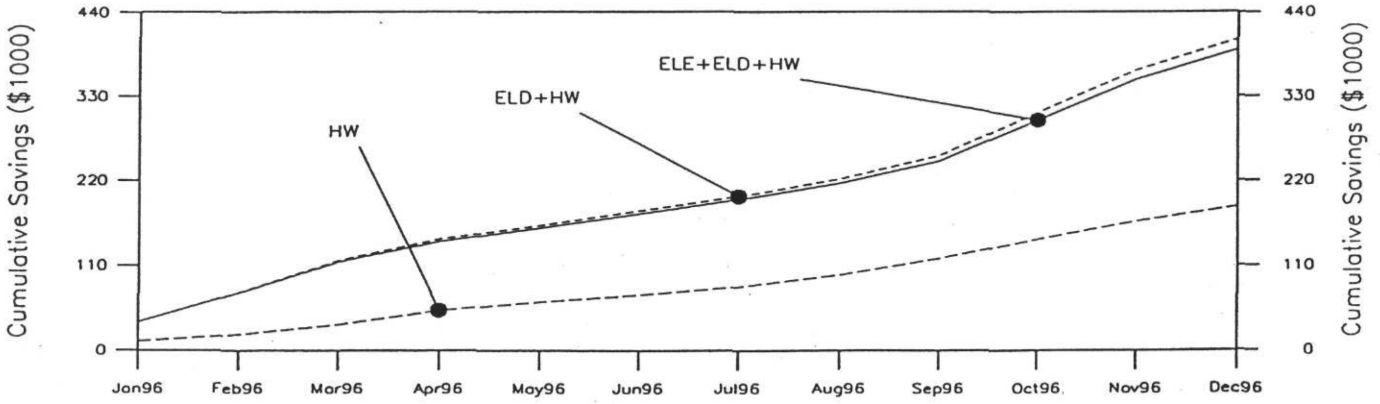
★ The unit cost used for estimating the electricity costs are: $0.02940/kWh (ELE), $6.00/MMBtu (CW), and $3.94/MMBtu (NG).

★ The audit estimated savings for the thermal storage and heat pump retrofit are: $98,292 (NG), $184,788 (ELED), -$45,000 (ELE), and $238,000 (Total).



Solid line represents measured energy use while the dashed line indicates the energy that would have been consumed had the retrofit not been installed

△ Electric ○ Cooling ☐ Heating



Delmar College - Whole Campus

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Site #144

Midland County Courthouse
Midland, TX

Internal melt - ice

```
144       Wed Aug 21 13:56:15 1996          1

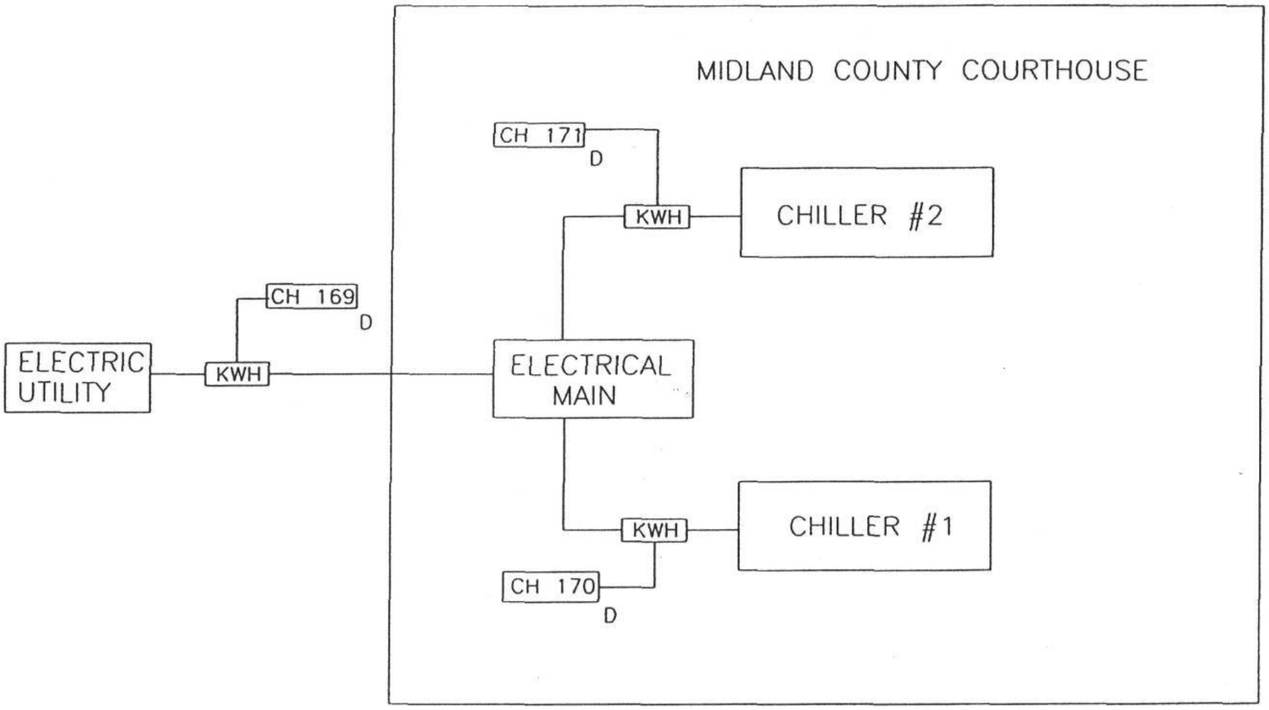
Chid     cp   Description
------------------------------------------
   9      1   Whole Bldg (kWh/h)
   0      2   Chiller #1 (kWh/h)
   1      3   Chiller #2 (kWh/h)
```

Date MM/DD/YY (YY DDD)	Time HH:mm	Raw-Data lin pos	coln pos	Arch coln pos	Name of Channel	Archive Units	Arch Format	Conv'n Code	Conv'n Constants	Error Code	Error Constants	Channel Description
03/12/90	00:00	1	0	0	Begin	MidlandCounty						Beginning date
03/12/90	00:00	1	1	1	Site	-	I3	2	0 144	0		Site #
03/12/90	00:00	1	1	2	Mon-Raw	MM	I3	1		0		Month
03/12/90	00:00	1	2	3	Mon-Raw	DD	I3	1		0		Day
03/12/90	00:00	1	3	4	Mon-Raw	YY	I3	1		0		Year
03/12/90	00:00	1	3	5	Greg-Jul	MMDDYY	I5	24	1 2	0		Gregorian Date to Julian
03/12/90	00:00	1	4	7	Time	HH mm	I5	16	5	0		Time
03/12/90	00:00	1	3	6	Greg-Dec	DDD.frac	F10.4	28		0		Gregorian Date to Jul.Decimal
03/12/90	00:00	1	6	8	WBldg	F9.3	F9.3	1		1	0 5000	Whole Bldg (kWh/h)
03/12/90	00:00	1	7	9	Chlr 1	F9.3	F9.3	1		1	0 5000	Chiller #1 (kWh/h)
03/12/90	00:00	1	8	10	Chlr 2	F9.3	F9.3	1		1	0 5000	Chiller #2 (kWh/h)
03/11/99	23:00	1	0	0	End	MidlandCounty						

ELECTRICAL MONITORING DIAGRAM
MIDLAND COUNTY COURTHOUSE

LEGEND

K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL

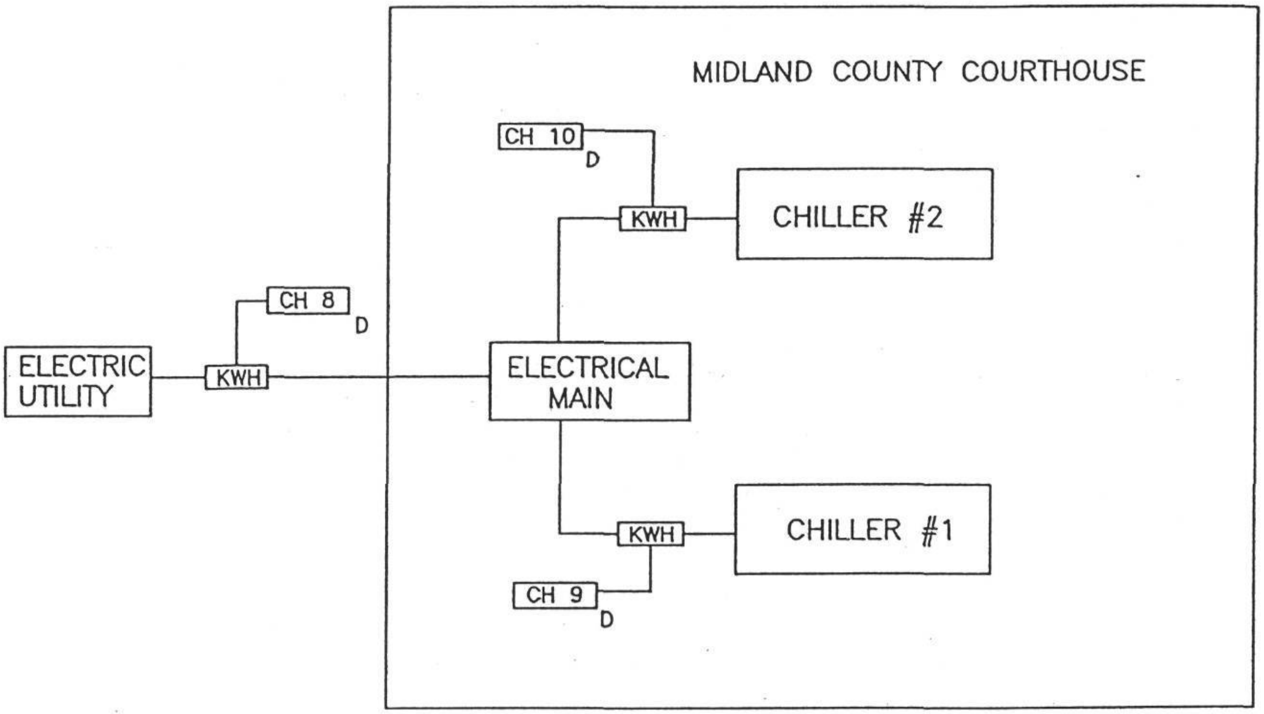


ELECTRICAL MONITORING DIAGRAM

MIDLAND COUNTY COURTHOUSE

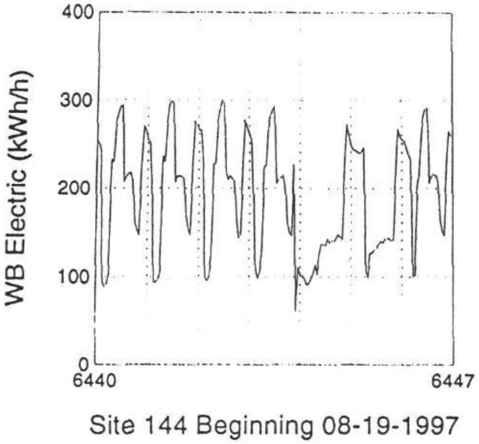
LEGEND

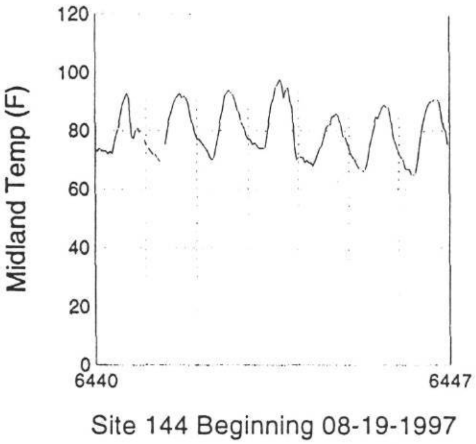
K—KWH CHANNEL
A—ANALOG CHANNEL
D—DIGITAL CHANNEL

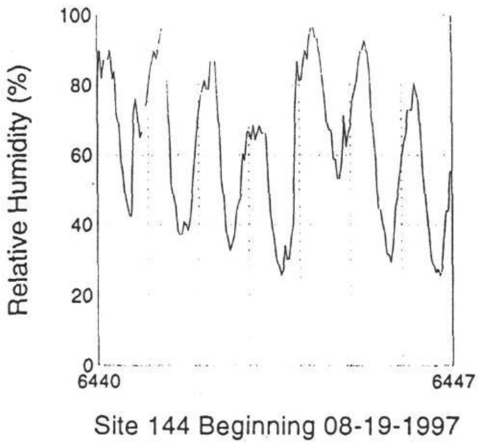


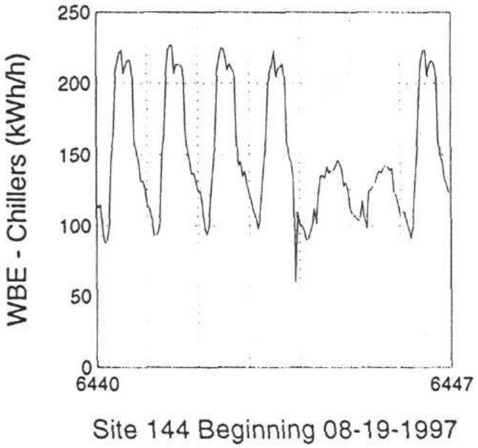
MIDLAND CO. COURTHOUSE – SITE 144

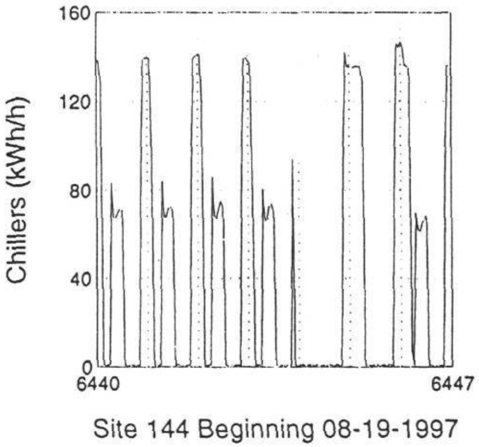
Site 144 Page 1

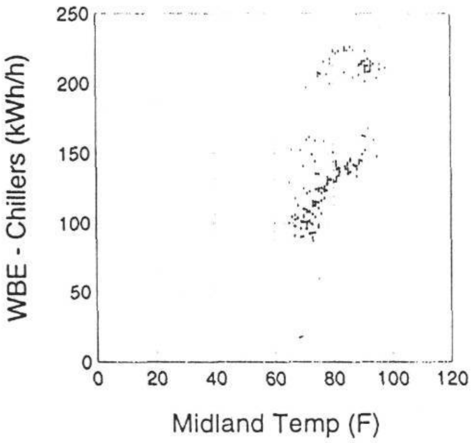


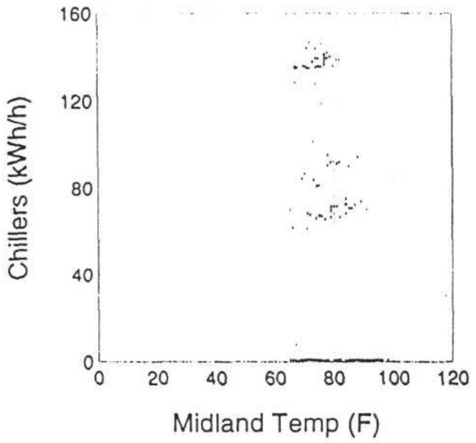


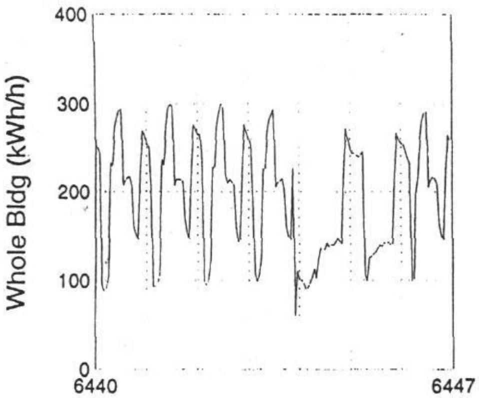




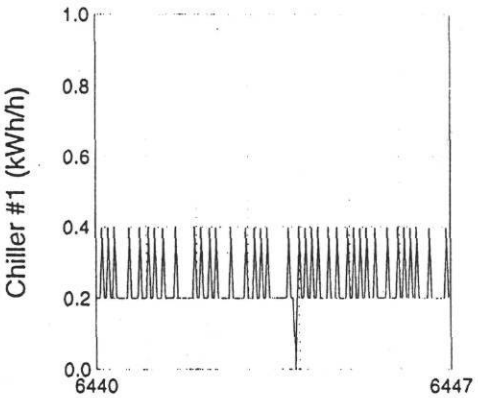




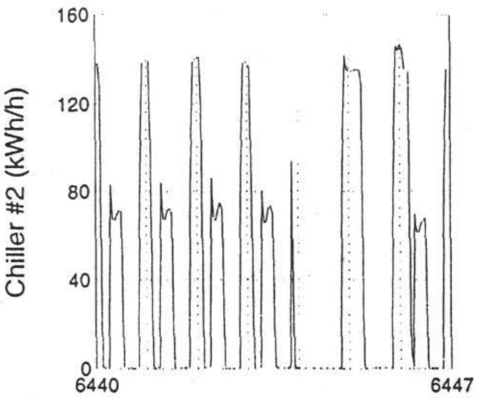




Site 144 Beginning 08-19-1997



Site 144 Beginning 08-19-1997



Site 144 Beginning 08-19-1997

Midland County Courthouse

90,100 square feet

Site Contact	LoanSTAR Metering Contact
Mr. Bill Decker	Aamer Athar or Namir Saman
Facility Management Director	053 WERC
Suite 003	Texas A&M University
Midland County Courthouse	College Station, TX 77843-3123
200 West Wall	(409) 845–9213
Midland, TX 79701	
(915) 688–8940	

Summary of Energy Consumption

	Measured Use	% hours reported	Unit Cost	Estimated Cost
Electricity	131372 kWh	100	$0.03000	$3941
Peak 60 Minute Demand	312 kW	100	$10.72	$3345
Chiller Electricity	30546.1 kWh	100	$0.030	$916

Peak 60 minute demand was recorded at 1200 Monday 06/30/97.
There were 720 hours in this month.

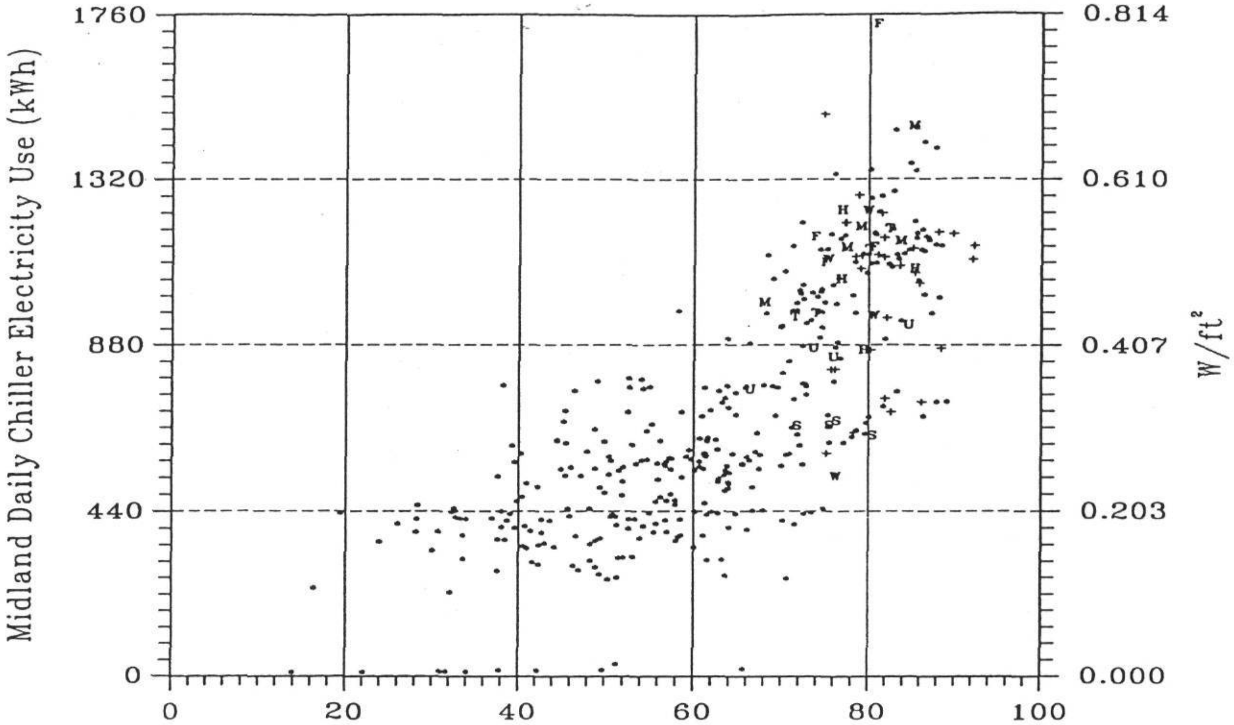
Monthly Retrofit Savings

	Measured Savings		Audit Estimated Savings	
Electricity (kWh)	44227	$1327	37913	$1137
Electricity Demand (kW)	120	$1286	145	$1554
Monthly Total		$2613		$2691
Total to Date*	(57 months)	$109916	(57 months)	$151889

*Measured savings include construction period. Audit estimated savings do not.

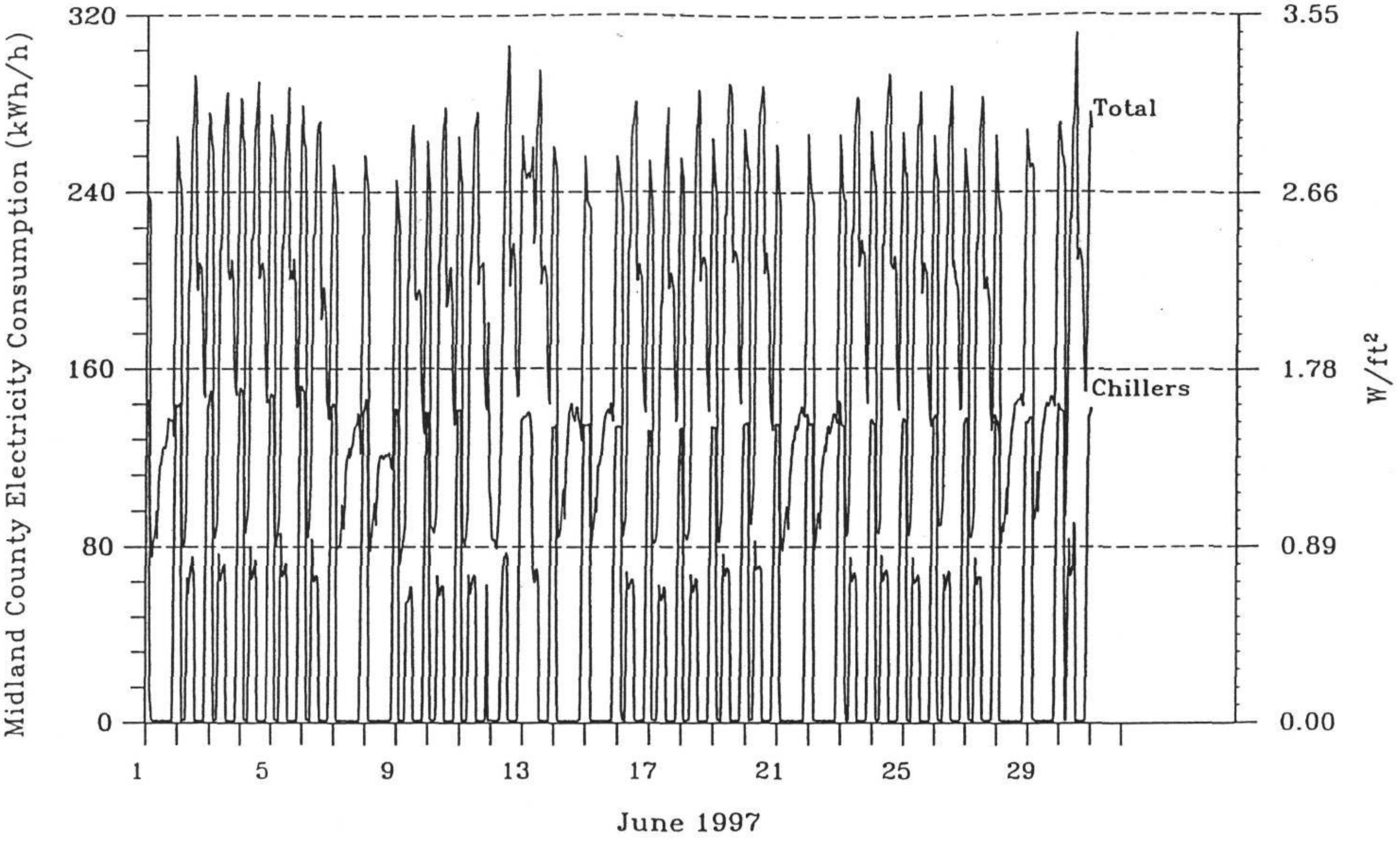
Comments

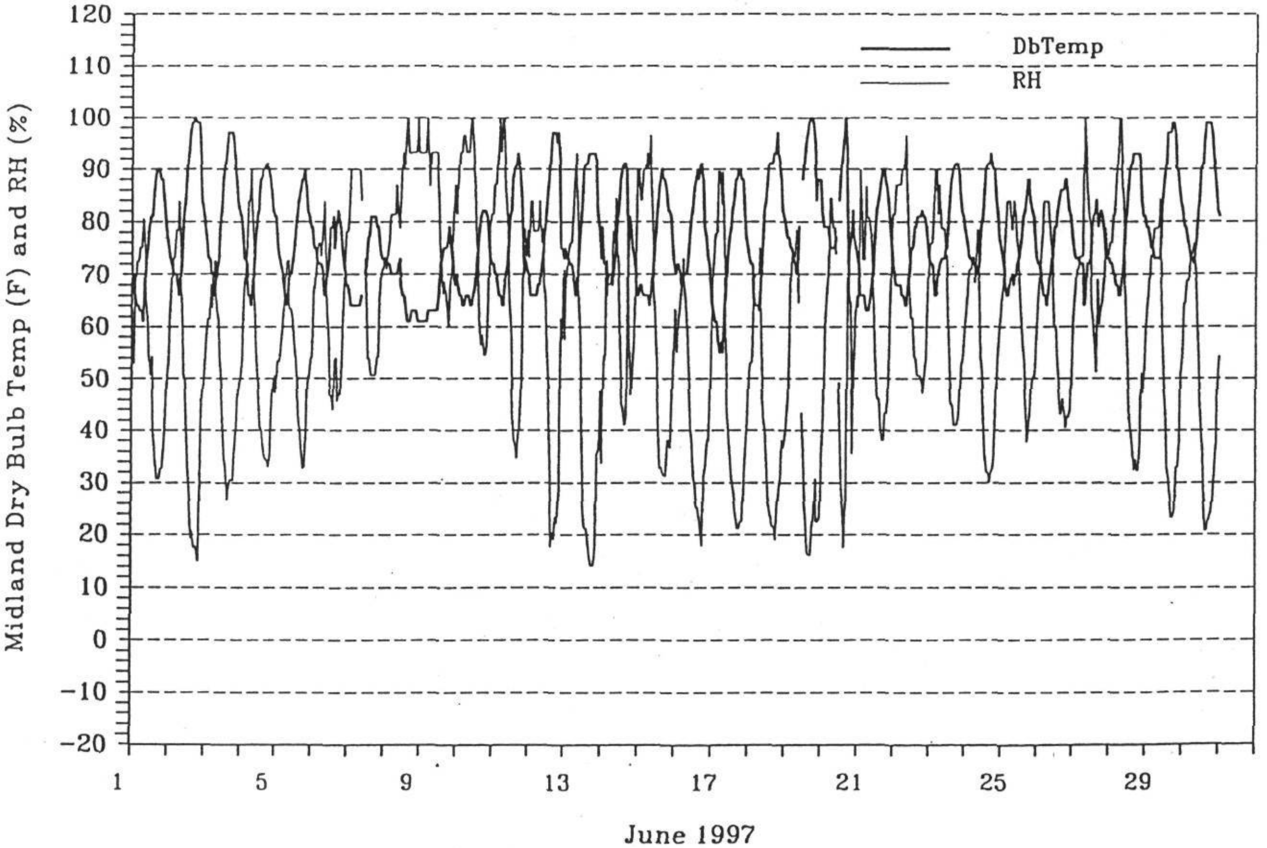
Jun 01 1996 – Jun 30 1997



Data points for the current month are shown as letters.
Monday through Sunday are represented as M,T,W,H,F,S,U.

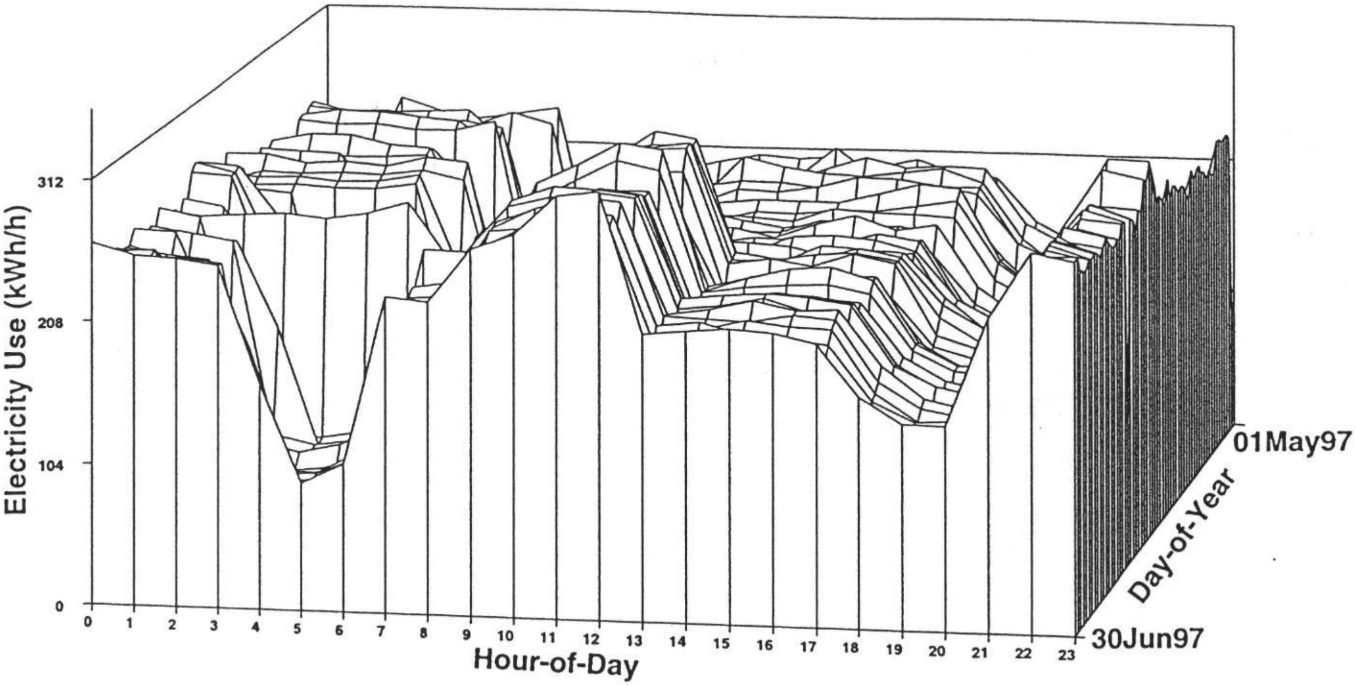
Points from this month last year are shown as +.
All other points are shown as *.



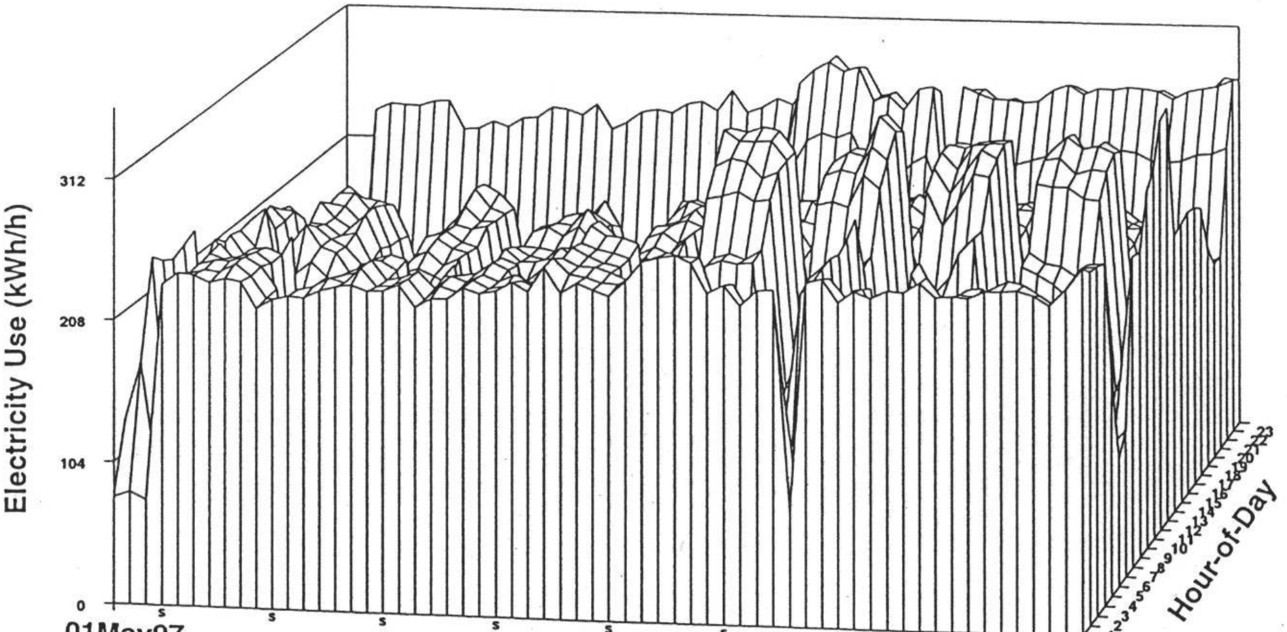


Midland County Courthouse - June 1997

Whole-Building Electric



Whole-Building Electric



Sundays are marked with an "S"

MIDLAND COUNTY COURTHOUSE

Courthouse:
- 90,100 sq.ft.
- five story and a basement; constructed in 1930
- the building is constructed with reinforced concrete foundation, structure, and walls
- exterior walls have plaster and interior walls are wood or metal studs with painted gypsum board
- windows are slightly tinted, single glaze with metal frame
- flat roof is built-up with gravel ballast. roof is insulated
- fifth floor houses a jail. Other floors house courtrooms and offices for support personnel
- jail operates 24 hours/day, 365 days/year
- other floors usually operate from 6:00 am to 8:00 pm six days/week

HVAC Equipment:
- 4 15 h.p. AHUs
- 1 10 h.p. AHU
- 1 3 h.p. AHUs
- 1 43 h.p. heating strip
- 7 rooftop packaged air conditioning units
- 1 3.4 MMBtu (input) boiler
- 1 7.5 h.p. CHWP
- 1 210 ton screw chiller

Lighting:
- 945 2 lamp fixtures (34 watts) (operates 2756 hours/year)
- 142 2 lamp fixtures (34 watts) (operates 8760 hours/year)

Recommended ECRMs:
- Energy Management System
- occupancy sensors
- modify chiller piping and control
- electronic ballasts

Date of Retrofit:
- Energy Management System & thermal storage was completed in August 1992
- 2-85 ton chillers were replaced by one 210-ton screw chiller on 5/14/92. One of the old chillers has been taken out while one will be used as a backup
- lighting modifications are still in progress

Comments:
- the W/ft^2 scale on the electricity consumption graph is only valid for the total electricity consumption
- demand reported on the first page is the peak demand. It is not used for calculating the demand savings from the thermal storage system. Billed demand based on the on-peak demand is used to calculate the demand savings

Midland County Courthouse

90,100 square feet

Site Contact

Mr. Bill Decker
Facility Management Director
Suite 003
Midland County Courthouse
200 West Wall
Midland, TX 79701
(915) 688–8940

LoanSTAR Metering Contact

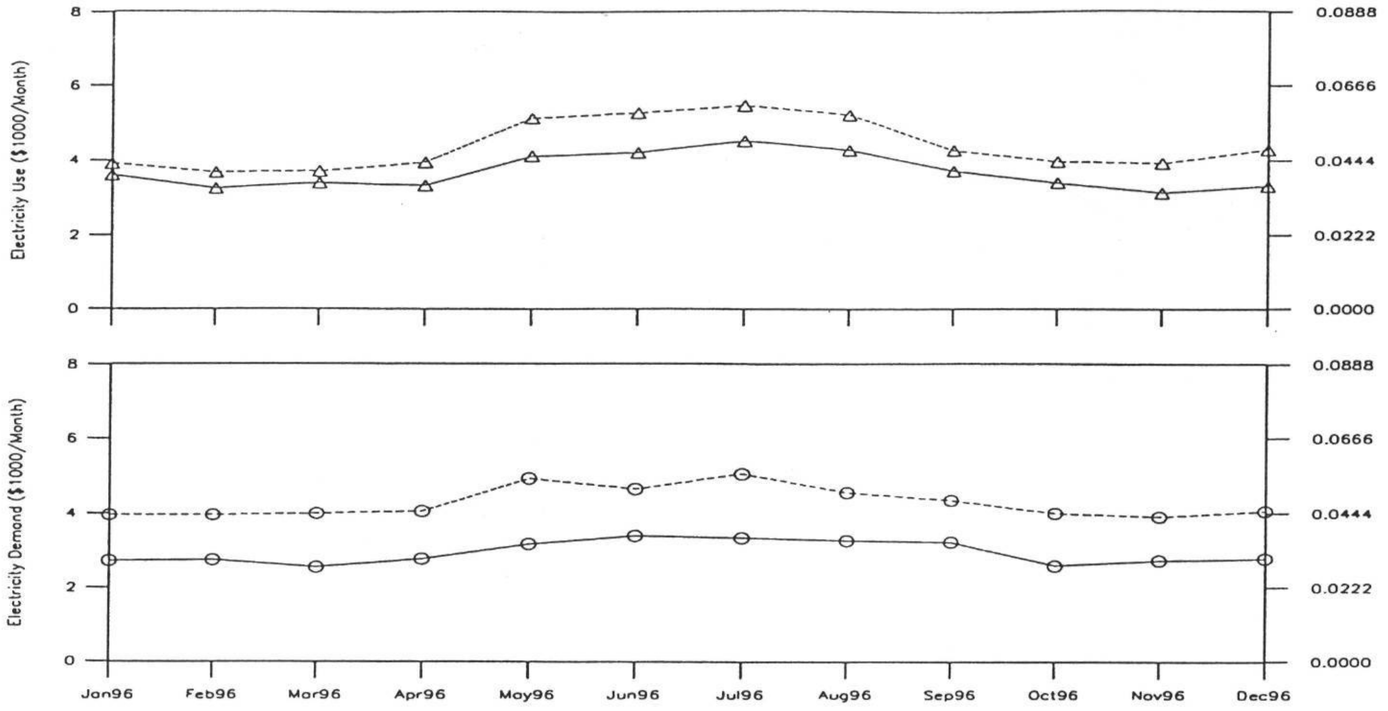
Aamer Athar or Namir Saman
053 WERC
Texas A&M University
College Station, TX 77843-3123
(409) 845–9213

1996 Summary of Measured Energy Consumption and Savings

	Electricity				Electricity Demand				Hot Water/Steam/NG				Total	
	Consumption			Savings	Consumption			Savings	Consumption			Savings	Monthly	Cumulative
Month	kWh	$	%	$	kW	$	%	$	MMBtu	$	%	$	Savings	Savings
Jan	120372	$3611	100	$315	254	$2727	100	$1233	not metered			N/A	$1548	$1548
Feb	108345	$3250	100	$437	256	$2749	100	$1211	not metered			N/A	$1648	$3196
Mar	112932	$3388	100	$327	238	$2551	100	$1447	not metered			N/A	$1774	$4970
Apr	110920	$3328	100	$621	259	$2774	100	$1286	not metered			N/A	$1907	$6877
May	137421	$4123	100	$1006	296	$3173	100	$1758	not metered			N/A	$2764	$9641
Jun	140172	$4205	100	$1066	317	$3396	100	$1265	not metered			N/A	$2331	$11972
Jul	150185	$4506	100	$940	312	$3340	100	$1715	not metered			N/A	$2655	$14627
Aug	142717	$4282	100	$937	304	$3263	100	$1297	not metered			N/A	$2234	$16861
Sep	124158	$3725	100	$551	301	$3229	100	$1126	not metered			N/A	$1677	$18538
Oct	112796	$3384	100	$573	241	$2586	100	$1415	not metered			N/A	$1988	$20526
Nov	103962	$3119	100	$799	254	$2727	100	$1179	not metered			N/A	$1978	$22504
Dec	110496	$3315	100	$977	259	$2779	100	$1276	not metered			N/A	$2253	$24757
Total	1474476	$44236		$8549	3291	$35294		$16208						$24757
EUI	16.4	$\frac{kWh}{ft^2yr}$			36526	$\frac{Btu}{ft^2yr}$								

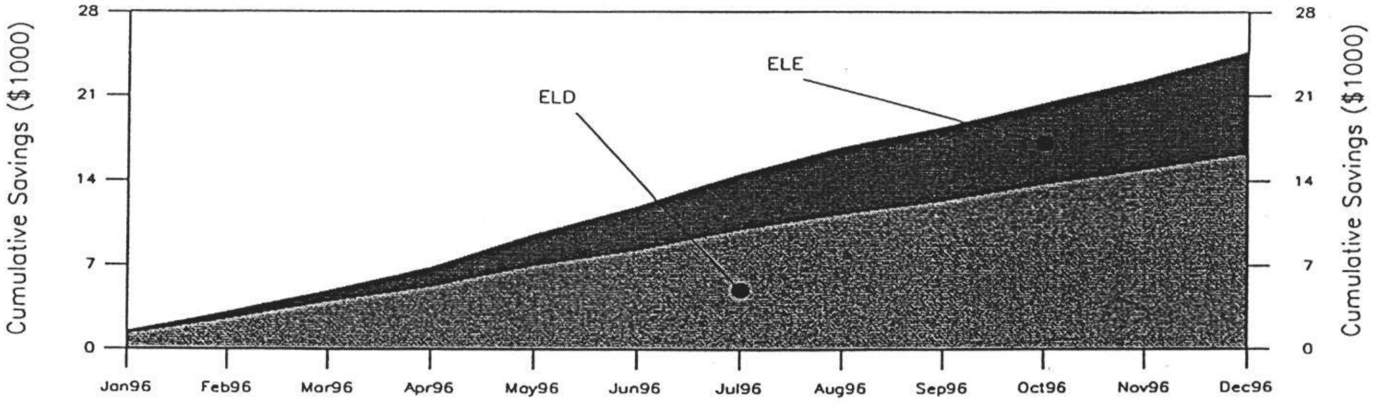
Comments

- ★ **The percent columns indicate the number of hours reported in that month.**
- ★ **The LoanSTAR monitoring began in December 1991.**
- ★ **All the proposed retrofits were completed in August 1992.**
- ★ **The unit costs used for estimating the audit and measured savings are: $0.0300/kWh and $10.72/kW-mo (ELED).**
- ★ **Audit estimated savings from the completed retrofits are: $12,600 (ELE), $18,300 (ELED), and $30,900 (Total).**



Solid line represents measured energy use while the dashed line indicates
the energy that would have been consumed had the retrofit not been installed

△ Electric ○ Cooling



Midland County, Courthouse

Courthouse:

- 90,100 sq.ft. Five story and a basement, constructed in 1930.
- The building is constructed with reinforced concrete foundation, structure, and walls.
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- Fifth floor houses a jail. Other floors house courtrooms and offices for support personnel.
- Jail operates 24 hours/day. 365 days/year.
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- 4 15 h.p. AHU's
- 1 10 h.p. AHU
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Date of Retrofit:

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- Lighting modifications are still in progress

Site #230

Austin Convention Center
Austin, TX

Internal melt - ice

```
230       Wed Jul 24 12:04:21 1996         1

Chid      cp   Description
-----------------------------------------
  55       1   MSBA Elec EGY MTRA(kWh/15min)
 466       2   MSBB Elec EGY MTRB(kWh/15min)
 467       3   Chil Elec EGY Chil(kWh/15min)
1468       4   Chiller Flow(gal/15min)
1469       5   Chiller Btu (kBtu/15min)
1470       6   Bldg Chwflow(gal/15min)
1471       7   Bldg ChwBtu(kBtu/15min)
1472       8   WBE Elec EGY MTRC(kWh/15min)
```

```
Date     Time  Raw-Data Arch Name of  Archive     Arch   Conv'n  Conv'n     Error Error      Channel
MM/DD/YY HH:mm lin coln coln Channel  Units       Format Code    Constants  Code  Constants  Description
(YY DDD)       pos pos  pos
-------- ----- --- ---  ---- -------- ----------- ------ ------- ---------- ----- ---------- -----------
#
07/03/90 00:00   1   0     0 Begin    ACC                                              Beginning date
07/03/90 00:00   1   1     1 Bldg. #  xx           I3       2    0 230         0             Building Number
07/03/90 00:00   1   1     2 Mon-Raw  MM           I3       1                  0             Month
07/03/90 00:00   1   2     3 Mon-Raw  DD           I3       1                  0             Day
07/03/90 00:00   1   3     4 Mon-Raw  YY           I3       1                  0             Year
07/03/90 00:00   1   3     5 Greg-Jul MMDDYY       I5      24    1 2           0             Gregorian Date to Julian
07/03/90 00:00   1   4     7 Time     HH mm        I5      16    5             0             Time
07/03/90 00:00   1   3     6 Greg-Dec DDD.frac    F10.4    28                  0             Gregorian Date to Jul.Decimal
07/03/90 00:00   1   6     8 MSBA MTA F9.3        F9.3      1                  1    -1 5000  MSBA Elec EGY MTRA(kWh/15min)
07/03/90 00:00   1   7     9 MSBB MTB F9.3        F9.3      1                  1    -1 5000  MSBB Elec EGY MTRB(kWh/15min)

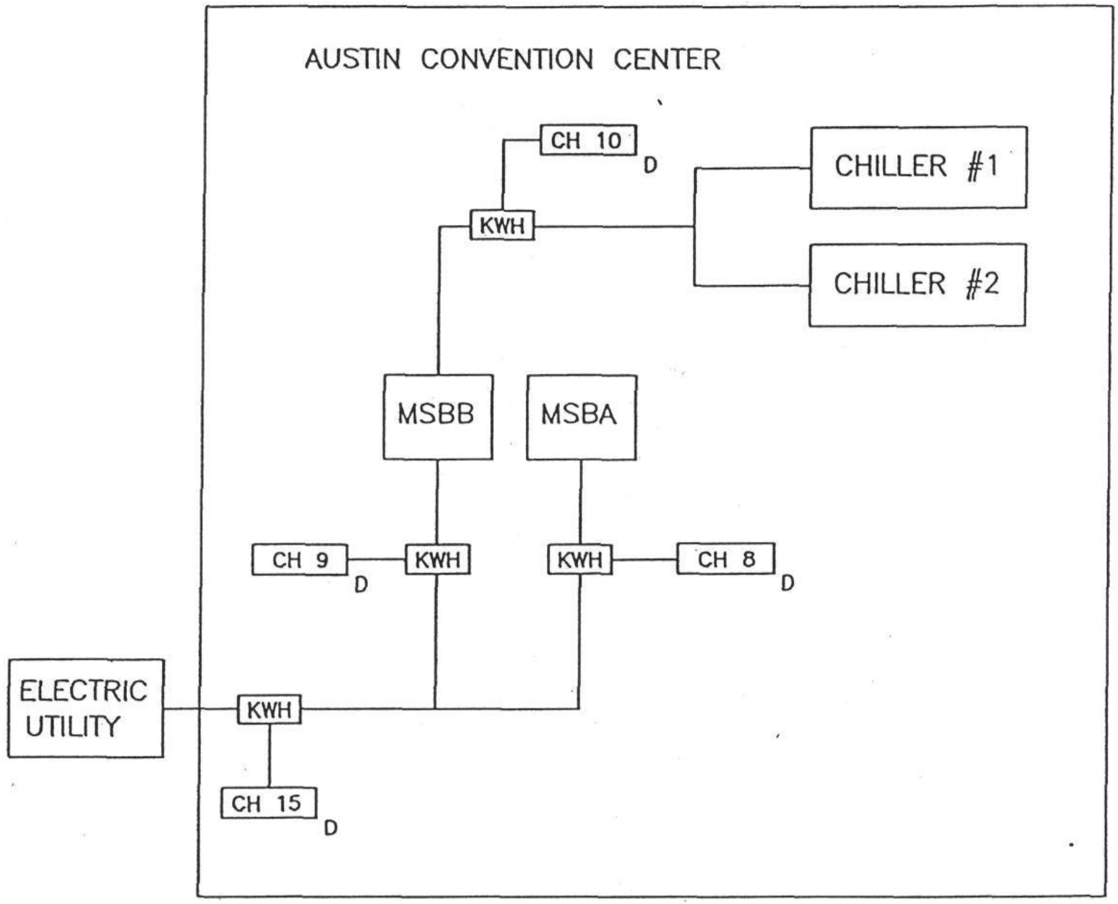
07/03/90 00:00   1   8    10 ChlrElec F9.3        F9.3      1                  1    -1 5000  Chil Elec EGY Chil(kWh/15min)
07/03/90 00:00   1   9    11 ChlrChwf F9.3        F9.3      1                  1   -1 100000 Chiller Flow(gal/15min)
07/03/90 00:00   1  10    12 ChlrBtu  F9.3        F9.3      1                  1    -1 5000  Chiller Btu (kBtu/15min)
07/03/90 00:00   1  11    13 BldgChwf F9.3        F9.3      1                  1   -1 100000 Bldg Chwflow(gal/15min)
07/03/90 00:00   1  12    14 BldgBtu  F9.3        F9.3      1                  1    -1 5000  Bldg ChwBtu(kBtu/15min)
07/03/90 00:00   1  13    15 WBE MTC  F9.3        F9.3      1                  1    -1 5000  WBE Elec EGY MTRC(kWh/15min)
03/11/99 23:00   1   0     0 End      ACC
```

ELECTRICAL MONITORING DIAGRAM

AUSTIN CONVENTION CENTER

LEGEND

K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL



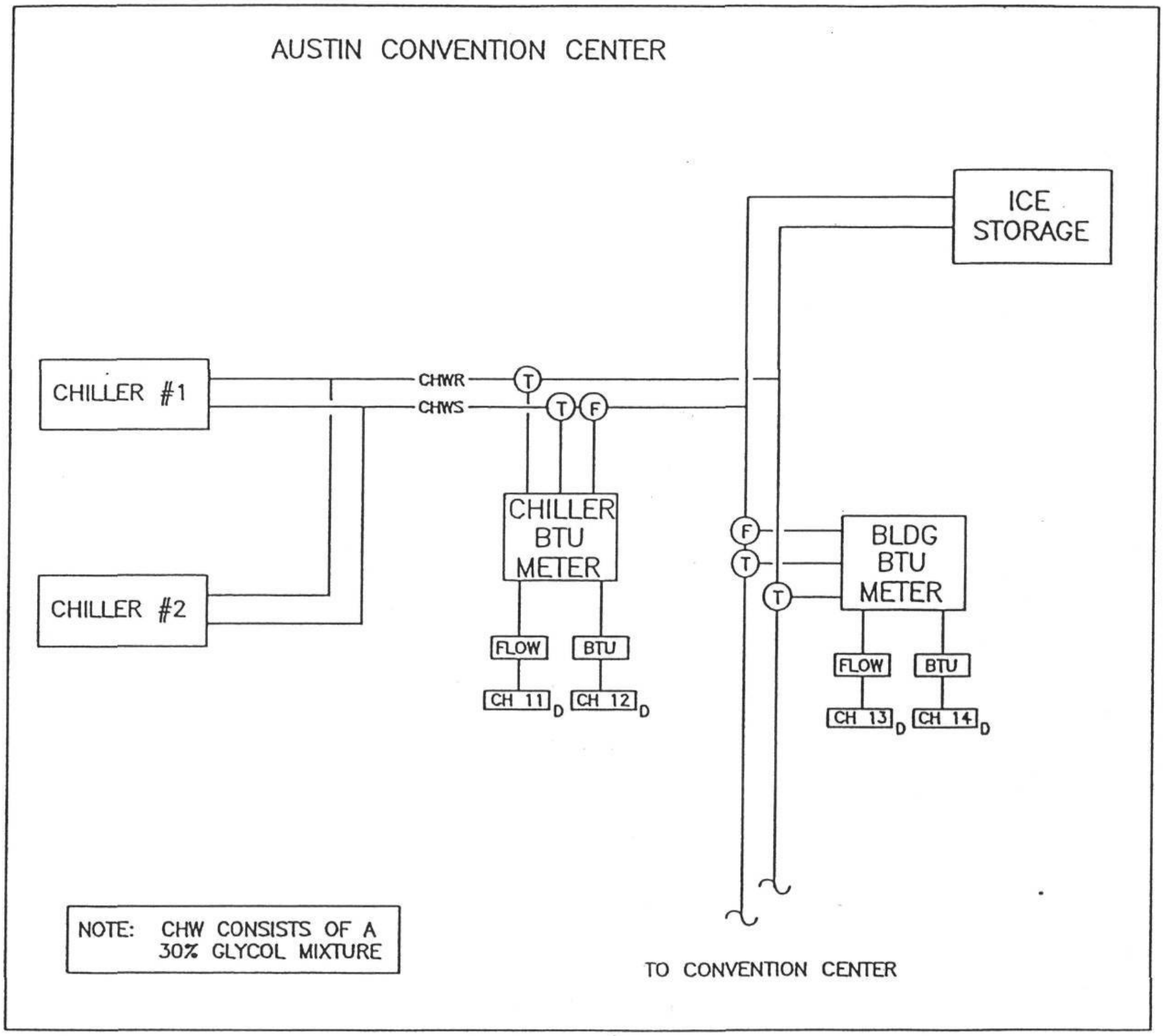
AUSTIN CONVENTION CENTER – SITE 230

THERMAL MONITORING DIAGRAM

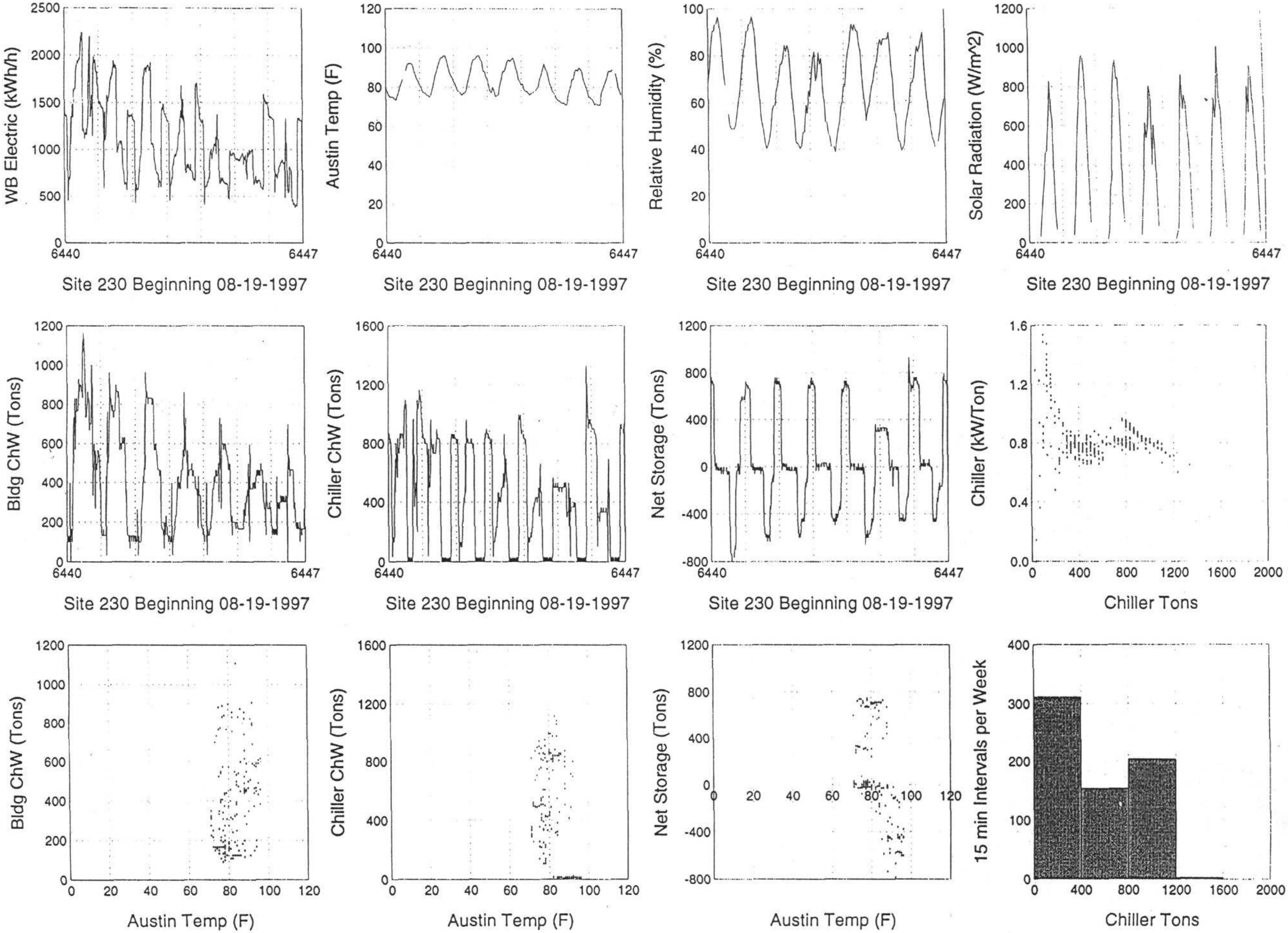
AUSTIN CONVENTION CENTER

LEGEND

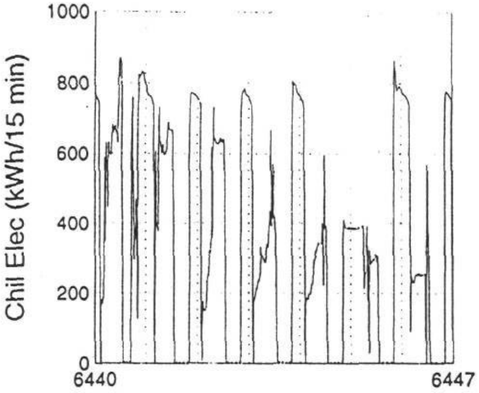
K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL



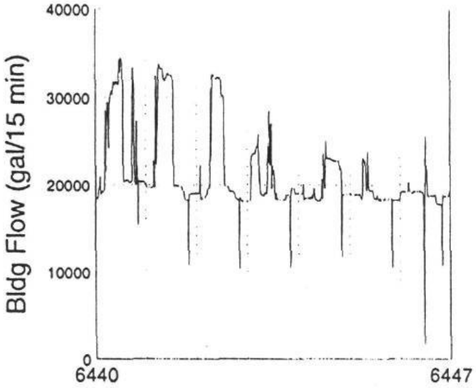
Site 230 Page 1



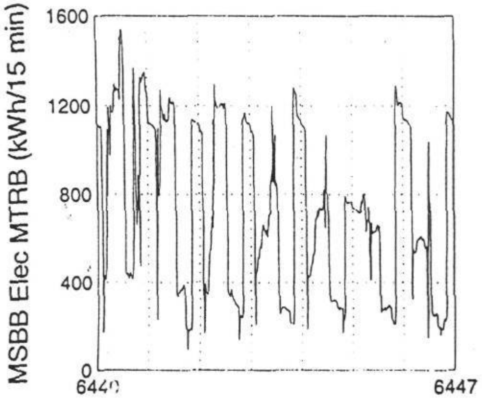
Site 230 Page 2



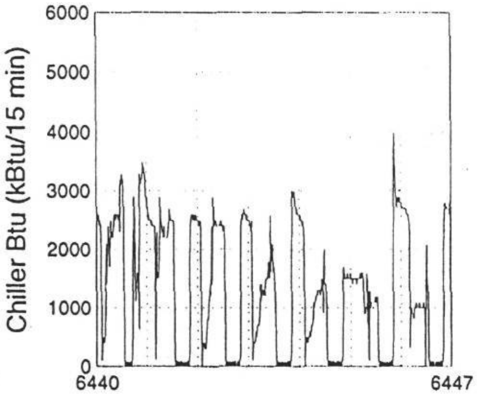
Site 230 Beginning 08-19-1997



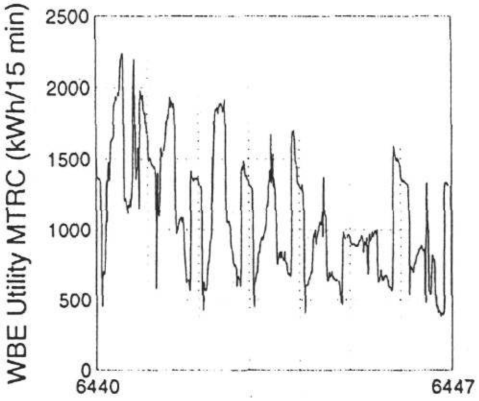
Site 230 Beginning 08-19-1997



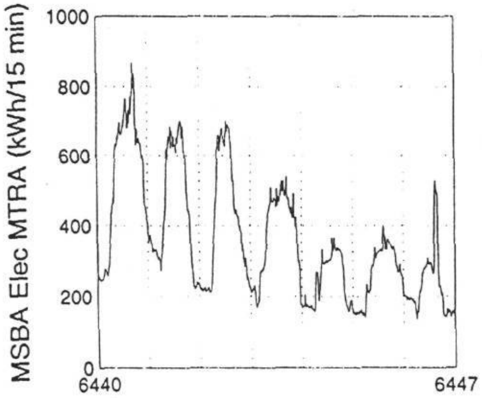
Site 230 Beginning 08-19-1997



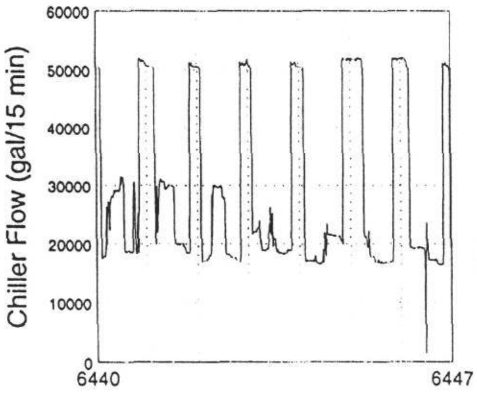
Site 230 Beginning 08-19-1997



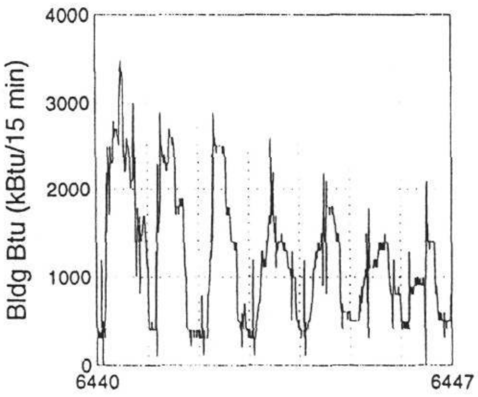
Site 230 Beginning 08-19-1997



Site 230 Beginning 08-19-1997



Site 230 Beginning 08-19-1997



Site 230 Beginning 08-19-1997

Austin Convention Center

City of Austin
174,456 square feet

Site Contact	LoanSTAR Metering Contact
Mr. Rudy Farias	Aamer Athar or Namir Saman
Facilities Maintenance Manager	053 WERC
Austin Convention Center	Texas A&M University
500 East First Street	College Station, TX 77843-3123
Austin, TX 78701	(409) 845–9213
(512) 404–4300	

Summary of Energy Consumption

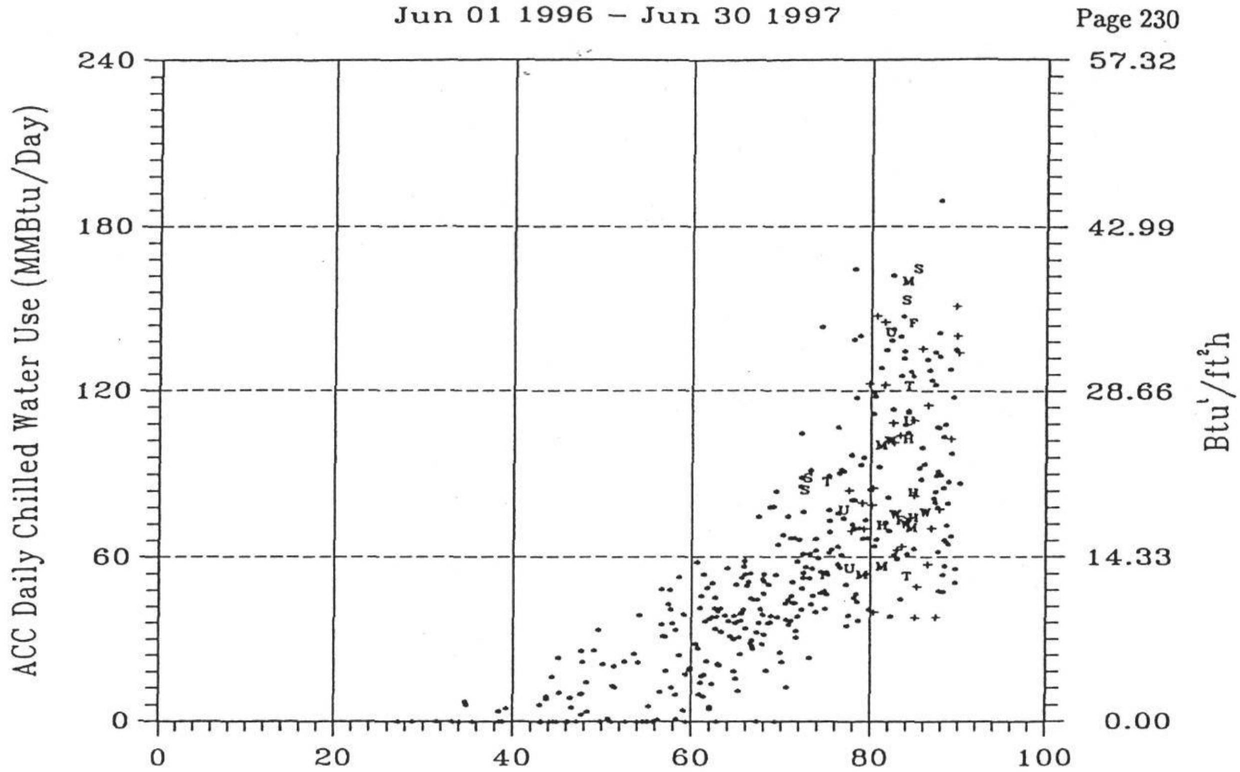
	Measured Use	% hours reported	Unit Cost	Estimated Cost
Electricity	671033 kWh	100	$0.06130	$41134
Peak 15 Minute Demand	2060 kW	100	-	-
Chilled Water Usage	2766.4 MMBtu	100	$5.000	$13832
Chilled Water Prod	3072.7 MMBtu	100	$5.000	$15364

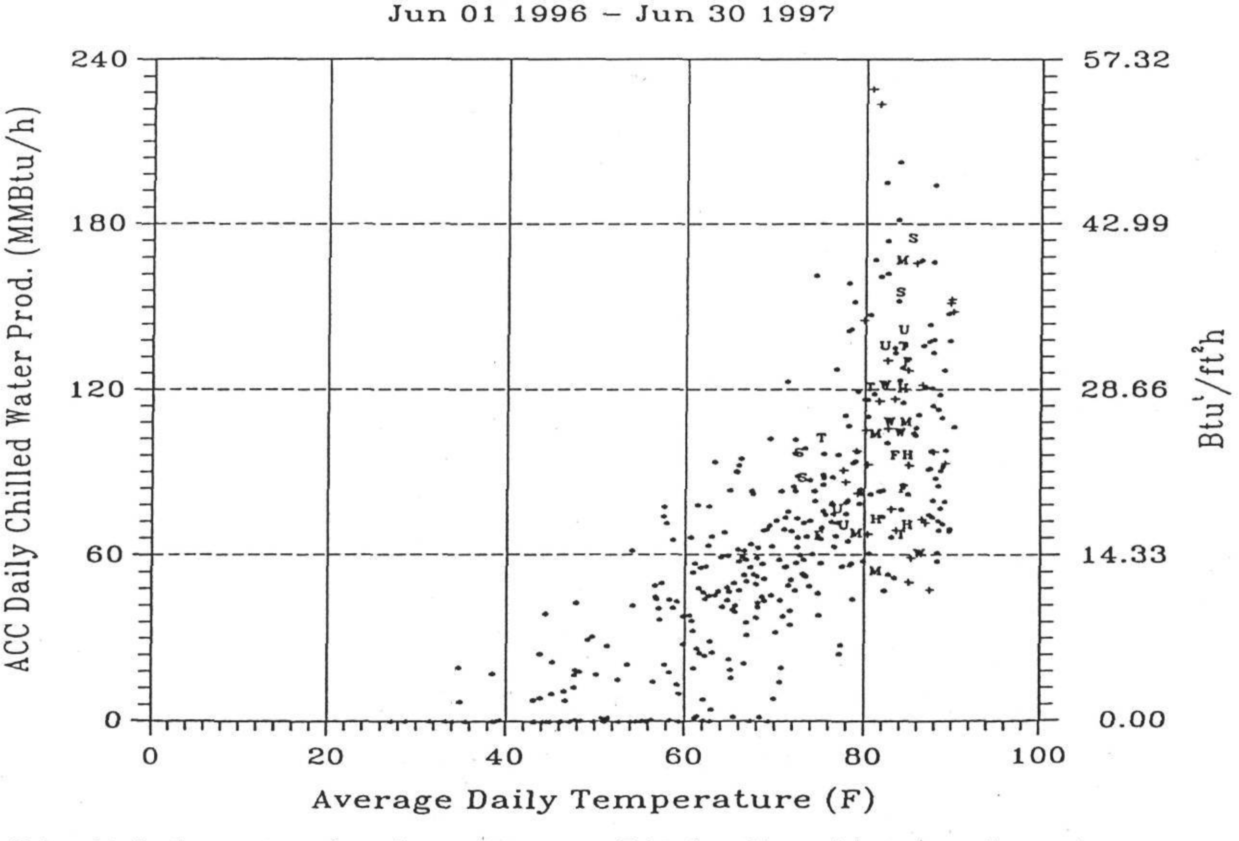
Peak 15 minute demand was recorded at 1930 Saturday 06/14/97.
There were 720 hours in this month.

Monthly Retrofit Savings

- All retrofits are in the bidding phase.
- Expected start date of construction is December 1997.

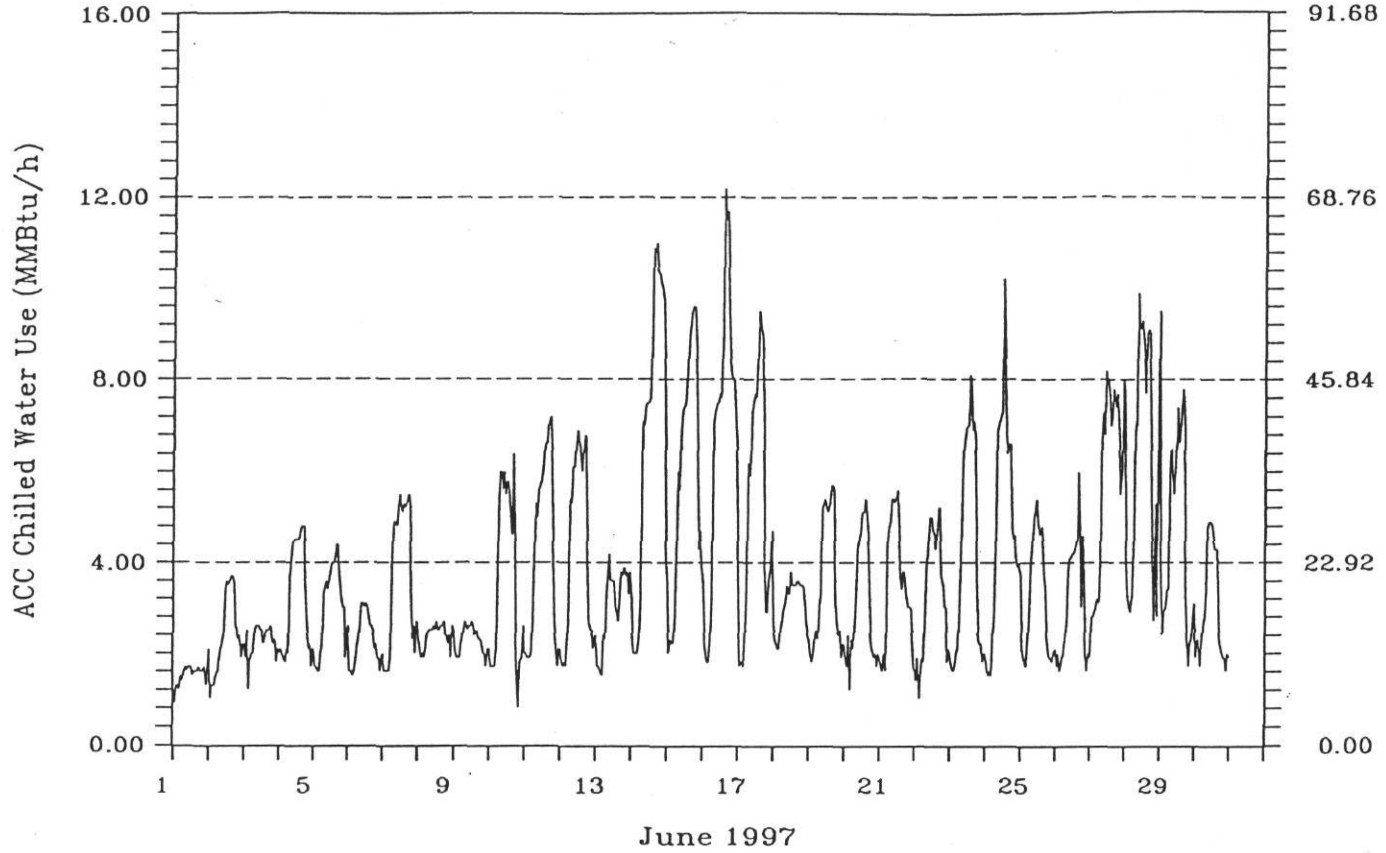
Comments

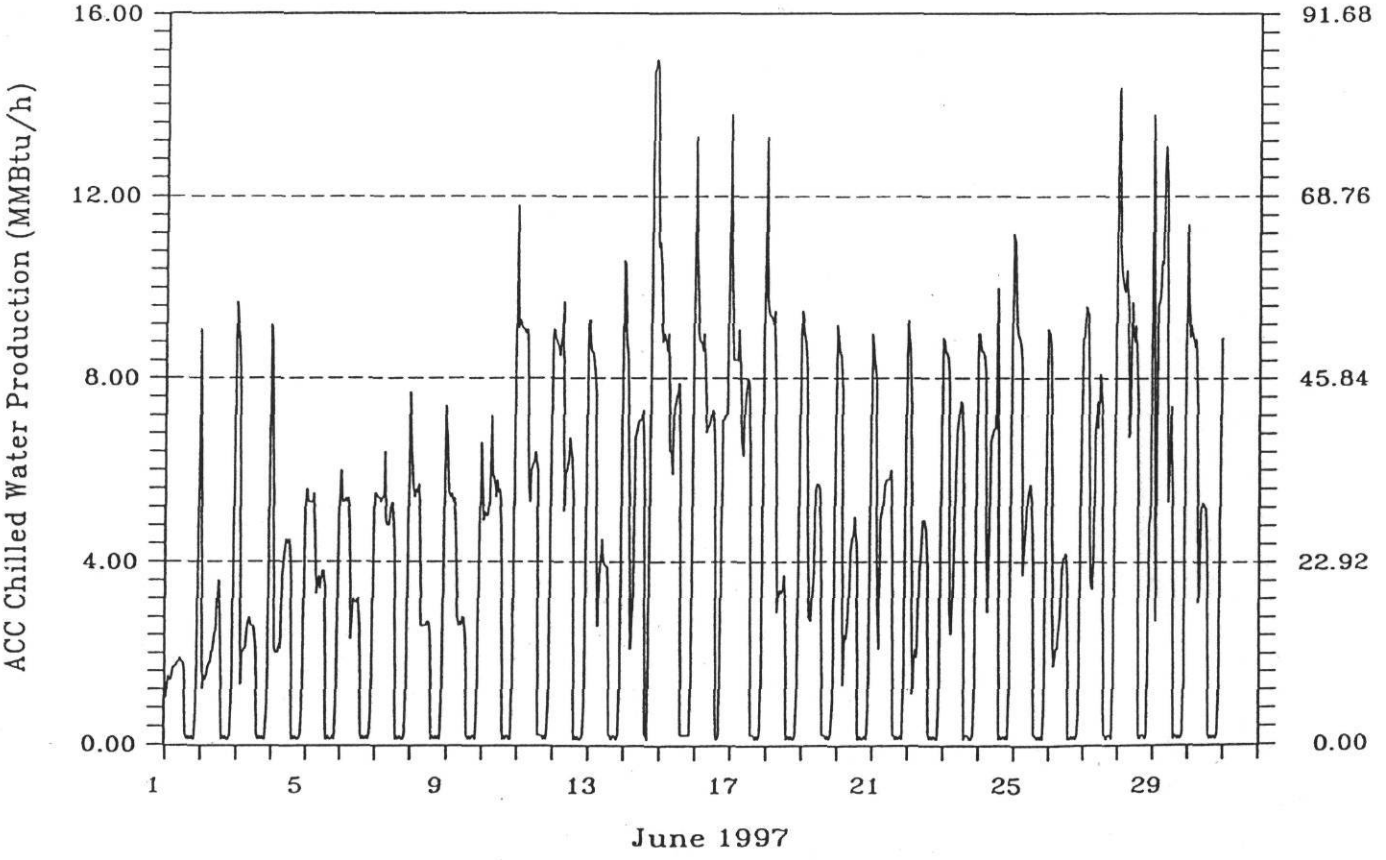


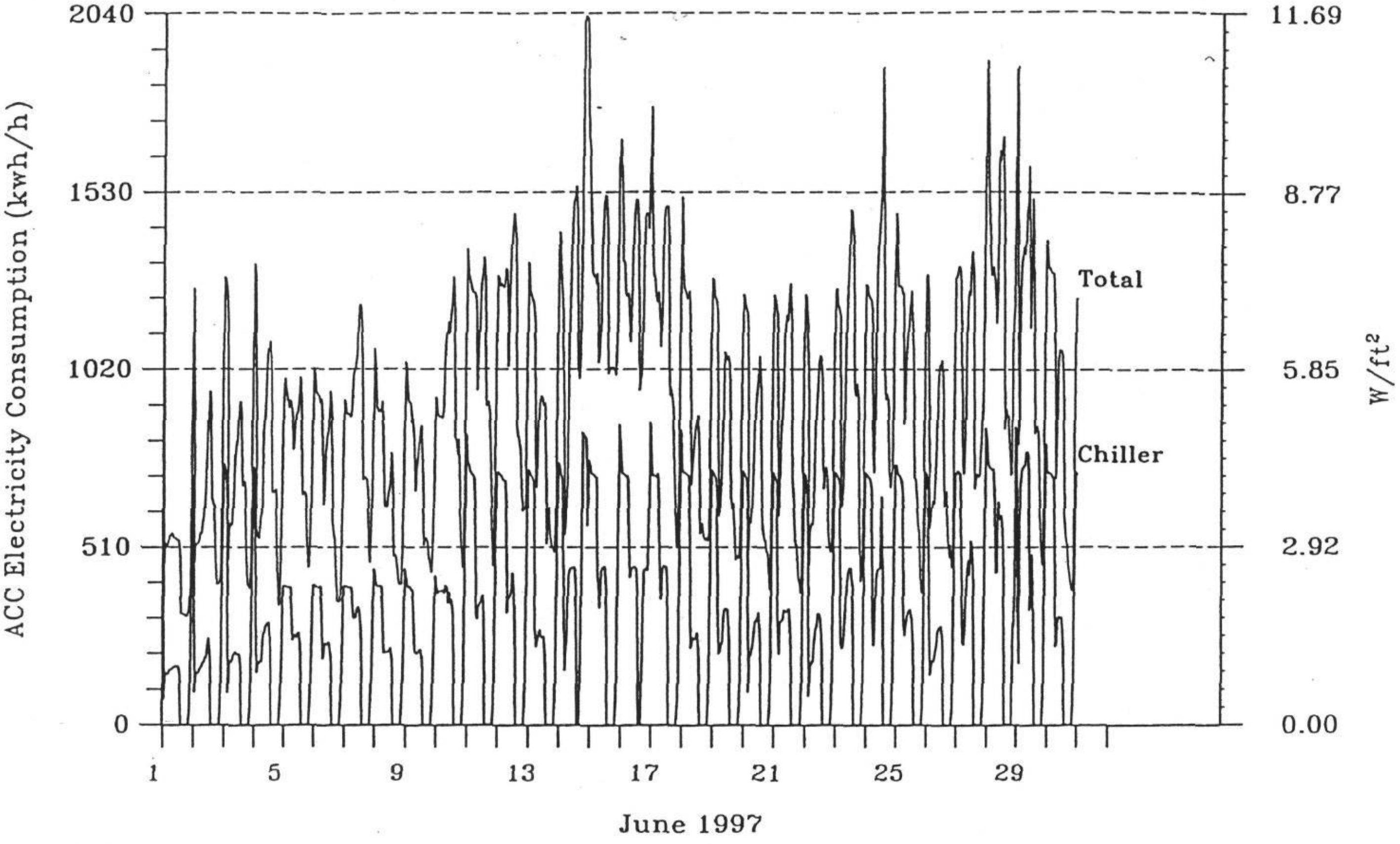


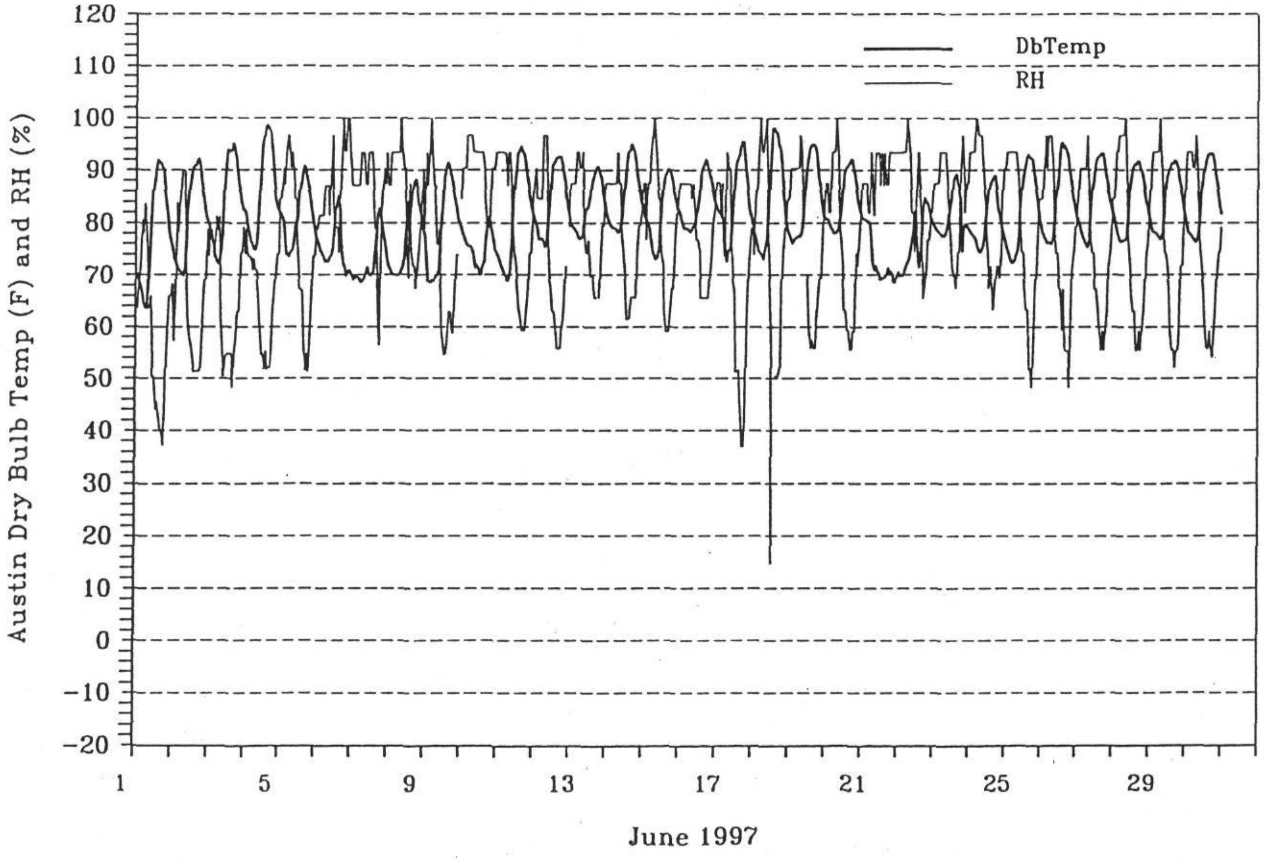
Data points for the current month are shown as letters.
Monday through Sunday are represented as M,T,W,H,F,S,U.

Points from this month last year are shown as +.
All other points are shown as *.

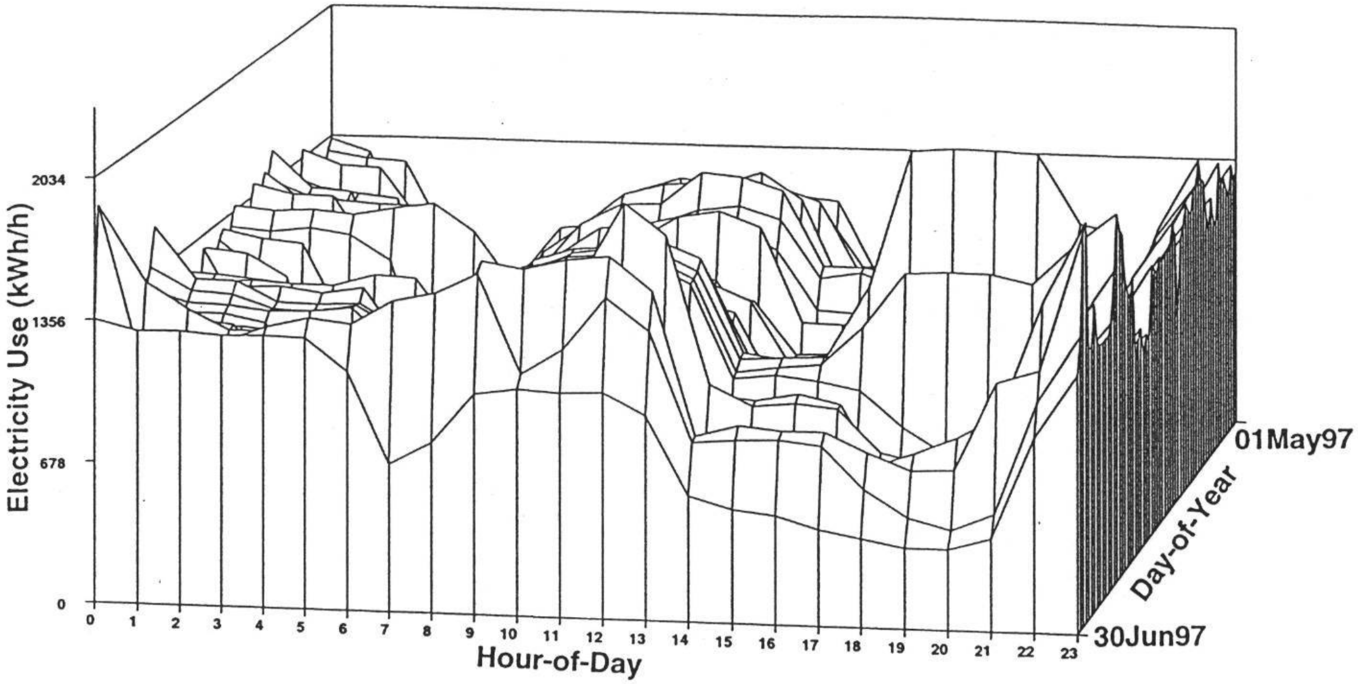

ACC Chilled Water Use (MMBtu/h)
16.00
12.00
8.00
4.00
0.00
91.68
68.76
45.84
22.92
0.00
Btu'/ft²h
1
5
9
13
17
21
25
29
June 1997


ACC Chilled Water Production (MMBtu/h)
16.00
12.00
8.00
4.00
0.00
91.68
68.76
45.84
22.92
0.00
Btu'/ft²h
1
5
9
13
17
21
25
29
June 1997

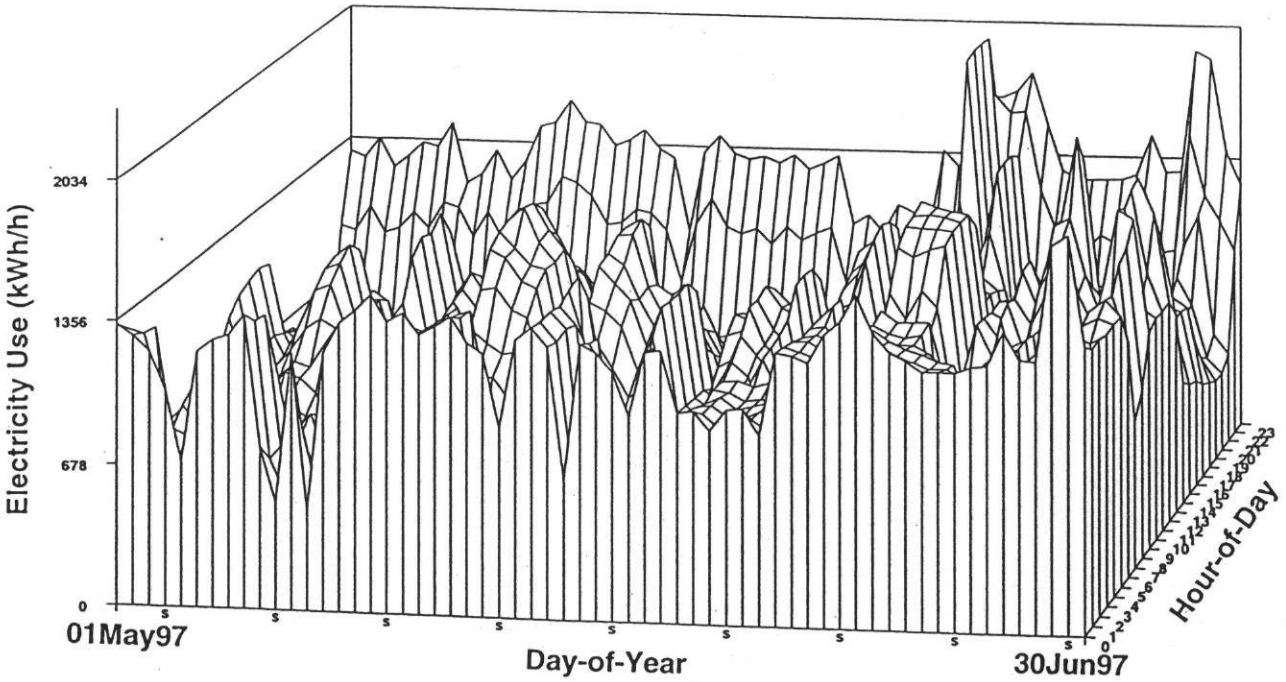

2040
1530
1020
510
0
11.69
8.77
5.85
2.92
0.00
ACC Electricity Consumption (kwh/h)
W/ft²
Total
Chiller
1
5
9
13
17
21
25
29
June 1997


120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
Austin Dry Bulb Temp (F) and RH (%)
DbTemp
RH
1
5
9
13
17
21
25
29
June 1997

Whole–Building Electric



Whole–Building Electric



Sundays are marked with an "S"

CITY OF AUSTIN

Austin Convention Center

Building Envelope:
- 411,000 gross sq.ft.; 174,456 sq.ft. conditioned area
- 3 floors; comprised of Exhibit Halls, Ballrooms and Meeting rooms
- walls: granite with no insulation
- roof: flat built-up roof

Building Schedule:
- occupancy depends on events scheduleed, varies a lot. No events at night

Building HVAC and Equipment:
- two electric centrifugal chillers
- one 150Hp gas boiler
- several AHU's ranging from 5Hp to 50Hp
- several pumps ranging from 30Hp to 125Hp
- 2-spd, 40Hp CT fans

HVAC Schedule:
- not available

Lighting:
- metal halides, incandescent and fluorescent

Proposed Retrofits:
- lighting controls
- variable volume pumping conversion
- control modifications for building pressurization

Status of Retrofits:
- all retrofits are in the bidding phase. Expected start date of construction is December 1997

Other Information:
- lighting can be programmed through computer

Austin Convention Center

City of Austin
174,456 square feet

Site Contact

Mr. Rudy Farias
Facilities Maintenance Manager
Austin Convention Center
500 East First Street
Austin, TX 78701
(512) 404–4300

LoanSTAR Metering Contact

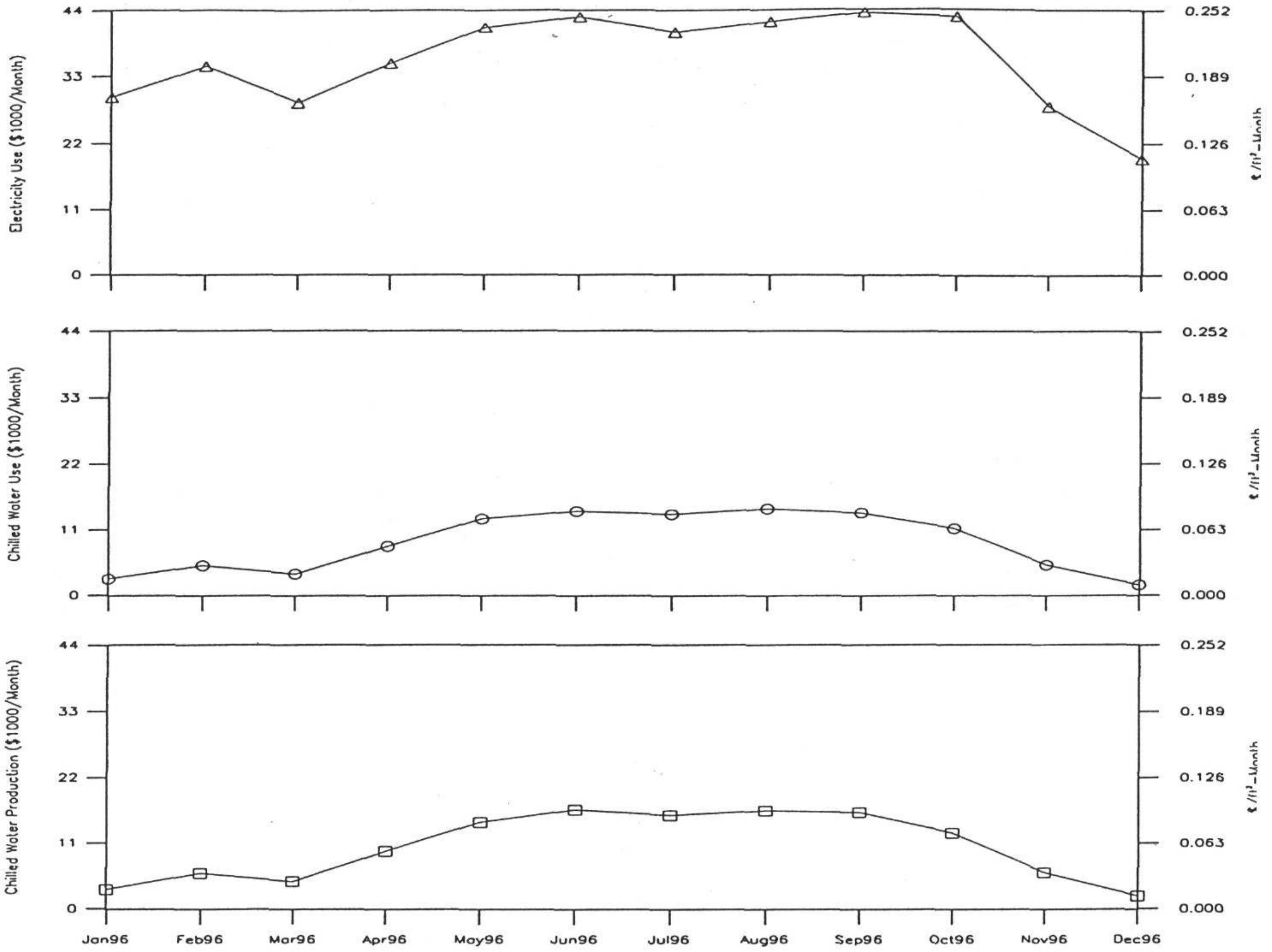
Aamer Athar or Namir Saman
053 WERC
Texas A&M University
College Station, TX 77843-3123
(409) 845–9213

1996 Summary of Measured Energy Consumption

	Electricity Consumption			Chilled Water Consumption			Chilled Water Production		
Month	kWh	$	%	MMBtu	$	%	MMBtu	$	%
Jan	483106	$29614	100	554	$2771	100	648	$3242	100
Feb	564930	$34630	100	999	$4997	100	1187	$5937	100
Mar	468100	$28695	100	723	$3615	100	908	$4538	100
Apr	573552	$35159	100	1642	$8209	100	1928	$9641	100
May	671325	$41152	100	2562	$12809	100	2889	$14447	100
Jun	700275	$42927	100	2819	$14096	100	3317	$16583	100
Jul	658037	$40338	100	2721	$13607	100	3137	$15683	100
Aug	686022	$42053	100	2907	$14535	100	3291	$16456	100
Sep	709785	$43510	100	2770	$13848	100	3235	$16177	100
Oct	698542	$42821	100	2234	$11170	100	2537	$12683	100
Nov	458585	$28111	100	1013	$5063	100	1211	$6054	100
Dec	318290	$19511	100	354	$1770	100	432	$2158	100
Total	6990549	$428521		21298	$106490		24720	$123599	
EUI	40.1	$\frac{kWh}{ft^2yr}$		122082	$\frac{Btu}{ft^2yr}$		141697	$\frac{Btu}{ft^2yr}$	

Comments

- ★ **The percent columns indicate the number of hours reported in that month.**
- ★ **The LoanSTAR monitoring began in July 1993.**
- ★ **The unit costs used for estimating energy costs are: $0.0613/kWh and $5.00/MMBtu (CW).**



The solid line indicates measured energy consumption

△ Electric ○ Cooling ☐ Chilled Water

CITY OF AUSTIN

Austin Convention Center

Building Envelope:

- 411,000 gross sq.ft., 174,456 sq.ft. conditioned area
- 3 floors, comprised of Exhibit Halls, Ballrooms and Meeting rooms
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- two electric centrifugal chillers
- one 150Hp gas boiler
- several AHU's ranging from 5Hp to 50Hp
- several pumps ranging from 30Hp to 125Hp
- 2-spd, 40Hp CT fans

HVAC Schedule:

- not avaliable

Lighting:

- metal halides, incandescent and fluorescent

Proposed Retrofits:

- lighting controls
- variable volume pumping conversion
- control modifications for building pressurization

Status of Retrofits:

- all retrofits are in construction phase

Other Information:

- lighting can be programmed through computer

Site #322

University of Houston - Clearlake
Houston, TX

Ice on coil

```
322       Tue Jul 30 12:05:41 1996        1

Chid     cp   Description
------------------------------------------
1629      1   Whole Bldg Elec (kW)
  30      2   Whole Bldg Gas (mcf/h)
  31      3   Whole Bldg Chw (kBtu/h)
1632      4   Whole Bldg Chw flow (gal/h)
1633      5   Chiller 1 Elec (kW)
1634      6   Chiller 2 Elec (kW)
1635      7   Chiller 3 Elec (kW)
1636      8   Ice Store Chw (kBtu/h)
```

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32290001.cht          Tue Jan 31 13:13:57 1995          1

Date     Time  Raw-Data Arch Name of  Archive      Arch   Conv'n  Conv'n     Error Error      Channel
MM/DD/YY HH:mm lin coln coln Channel  Units        Format Code    Constants  Code  Constants  Description
(YY DDD)       pos pos  pos
-------- ----- --- ---  ---- -------- ------------ ------ ------- ---------- ----- ---------- -----------
#
08/23/94 00:00  1   0    0   Begin    UHCL/Bayou Building                                     Beginning date
08/23/94 00:00  1   1    1   Site     -             I3      2     0 322        0              Site #
08/23/94 00:00  1   1    2   Mon-Raw  MM            I3      1                  0              Month
08/23/94 00:00  1   2    3   Mon-Raw  DD            I3      1                  0              Day
08/23/94 00:00  1   3    4   Mon-Raw  YY            I3      1                  0              Year
08/23/94 00:00  1   3    5   Greg-Jul MMDDYY        I5      24    1 2          0              Gregorian Date to Julian
08/23/94 00:00  1   4    7   Time     HH mm         I5      16    5            0              Time
08/23/94 00:00  1   3    6   Greg-Dec DDD.frac      F10.4   28                 0              Gregorian Date to Jul.Decimal
08/23/94 00:00  1   6    8   WBELEC   F9.3          F9.3    1                  1  -5 9999999 Whole Bldg Elec (kW)
08/23/94 00:00  1   7    9   WBGAS    F9.3          F9.3    1                  1  -5 9999999 Whole Bldg Gas (mcf/h)
08/23/94 00:00  1   8   10   WBCHWB   F9.3          F9.3    1                  1  -5 9999999 Whole Bldg Chw (kBtu/h)
08/23/94 00:00  1   9   11   WBCHWF   F9.3          F9.3    1                  1  -5 9999999 Whole Bldg Chw flow (gal/h)
08/23/94 00:00  1  10   12   CHL1     F9.3          F9.3    1                  1  -5 9999999 Chiller 1 Elec (kW)
08/23/94 00:00  1  11   13   CHL2     F9.3          F9.3    1                  1  -5 9999999 Chiller 2 Elec (kW)
08/23/94 00:00  1  12   14   CHL3     F9.3          F9.3    1                  1  -5 9999999 Chiller 3 Elec (kW)
08/23/94 00:00  1  13   15   ICECHWB  F9.3          F9.3    1                  1  -5 9999999 Ice Store Chw (kBtu/h)
12/31/99 23:00  1   0    0   End      UHCL/Bayou Building
```

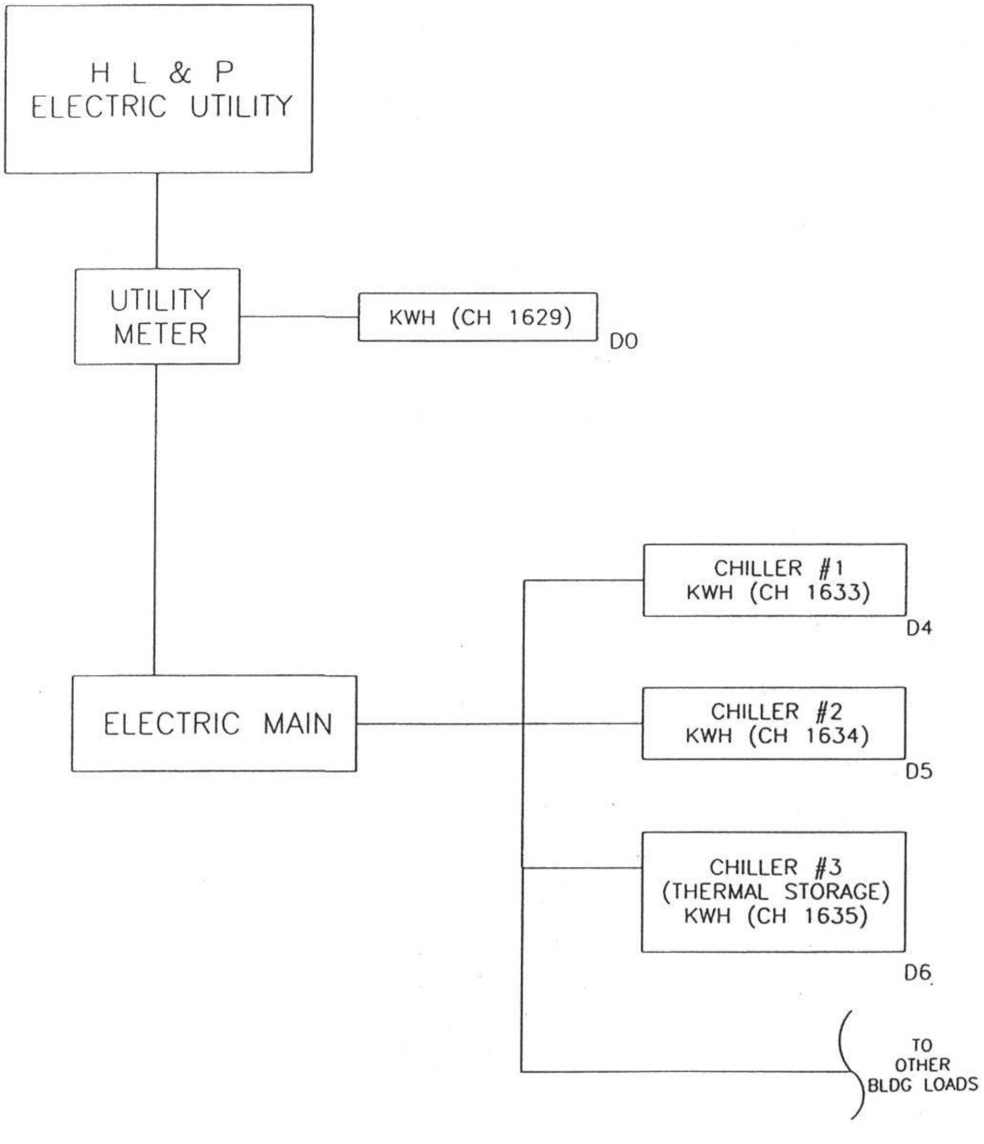
Ice storage is run from 1:15 pm - 12:45am

will be done on post retrofit

UNIVERSITY OF HOUSTON
CLEAR LAKE
ELECTRICAL MONITORING DIAGRAM

LEGEND

K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL

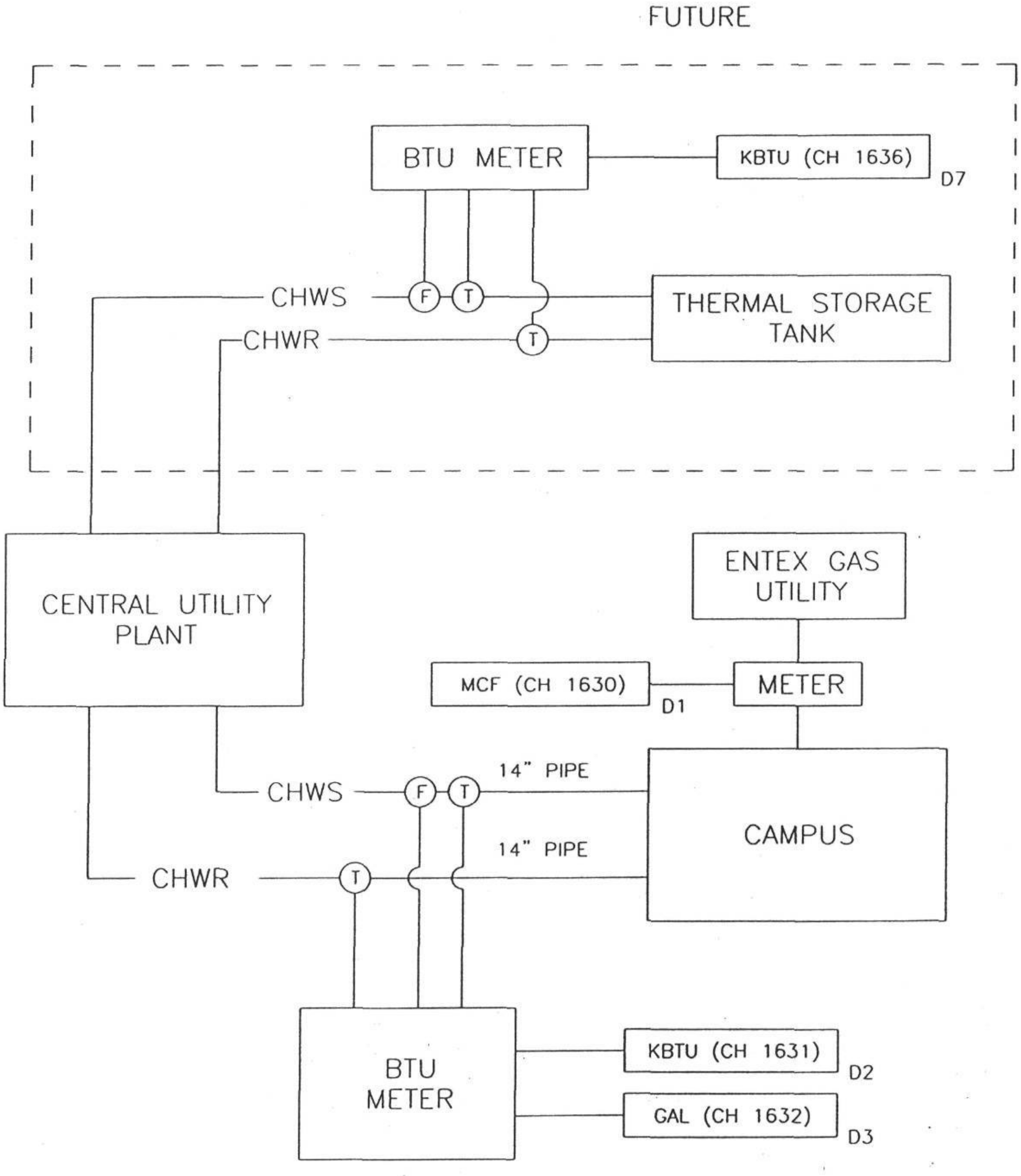


UNIVERSITY OF HOUSTON\CLEARLAKE-SITE 322

UNIVERSITY OF HOUSTON
CLEAR LAKE
THERMAL MONITORING DIAGRAM

LEGEND

K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL

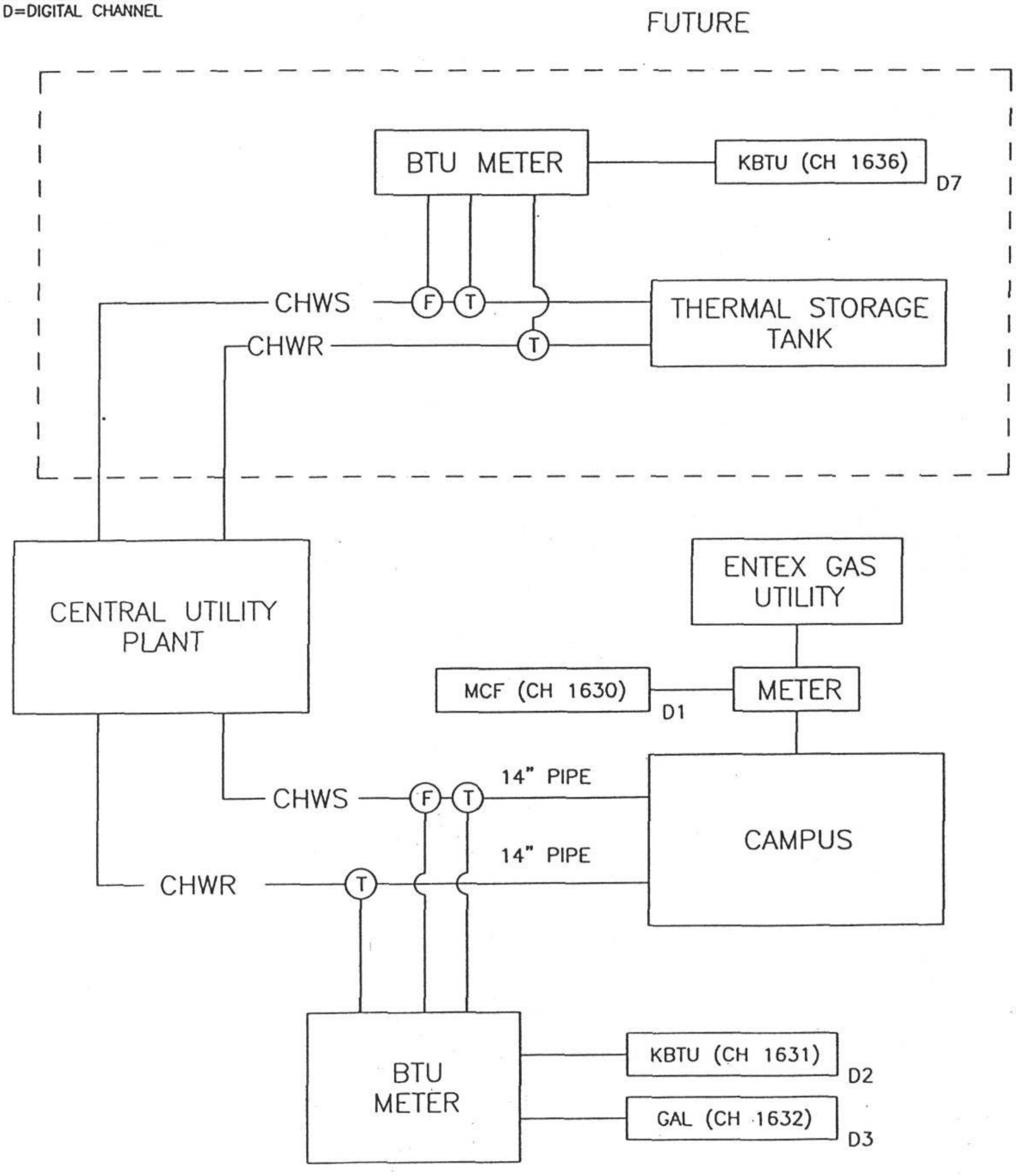


UNIVERSITY OF HOUSTON\CLEAR LAKE–SITE 322

THERMAL MONITORING DIAGRAM
UNIVERSITY OF HOUSTON CLEAR LAKE

LEGEND

K=KWH CHANNEL
A=ANALOG CHANNEL
D=DIGITAL CHANNEL



UNIVERSITY OF HOUSTON\CLEAR LAKE – SITE 322 (HOURLY DATA)

ELECTRICAL MONITORING DIAGRAM
UNIVERSITY OF HOUSTON CLEAR LAKE

LEGEND

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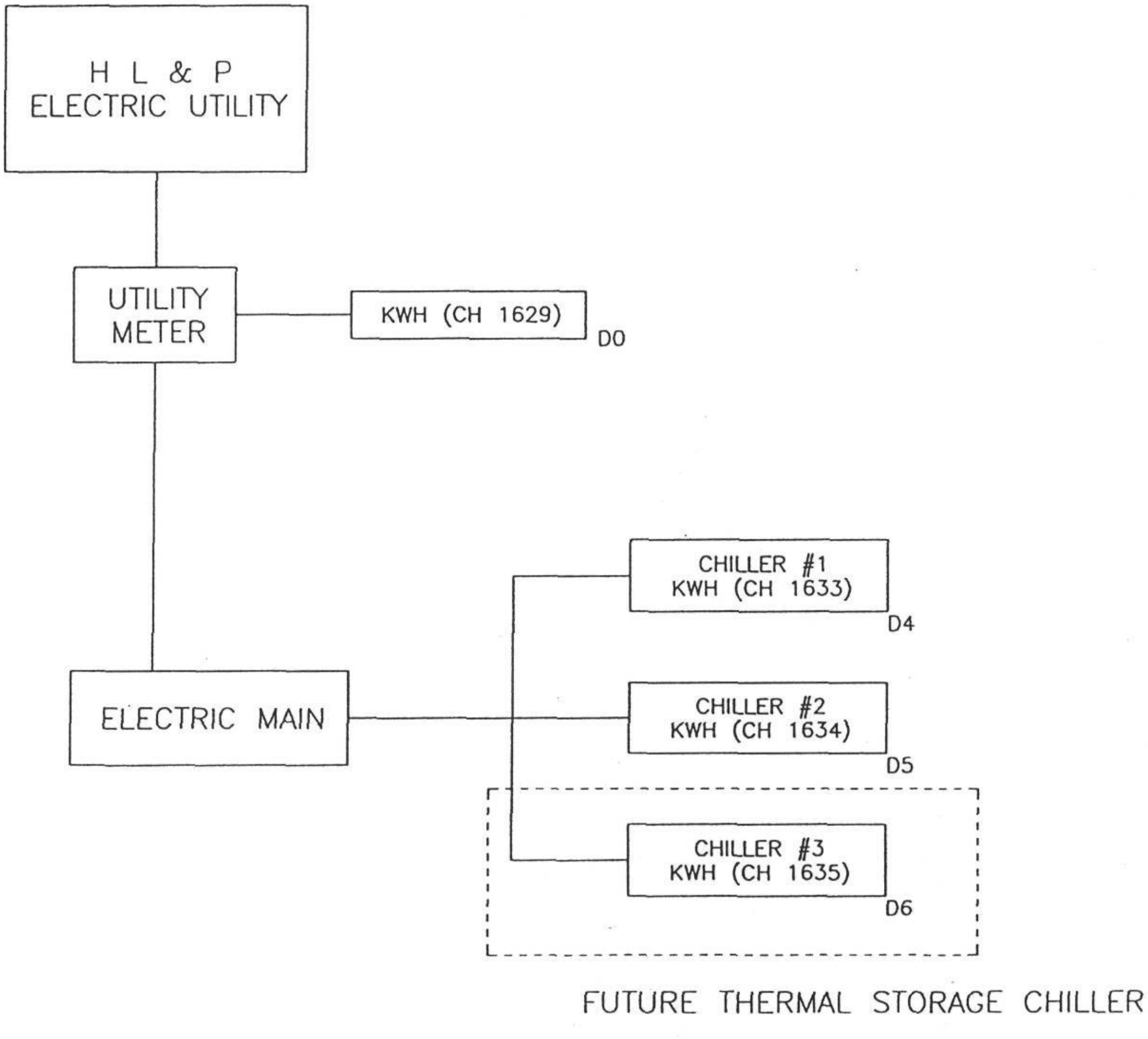
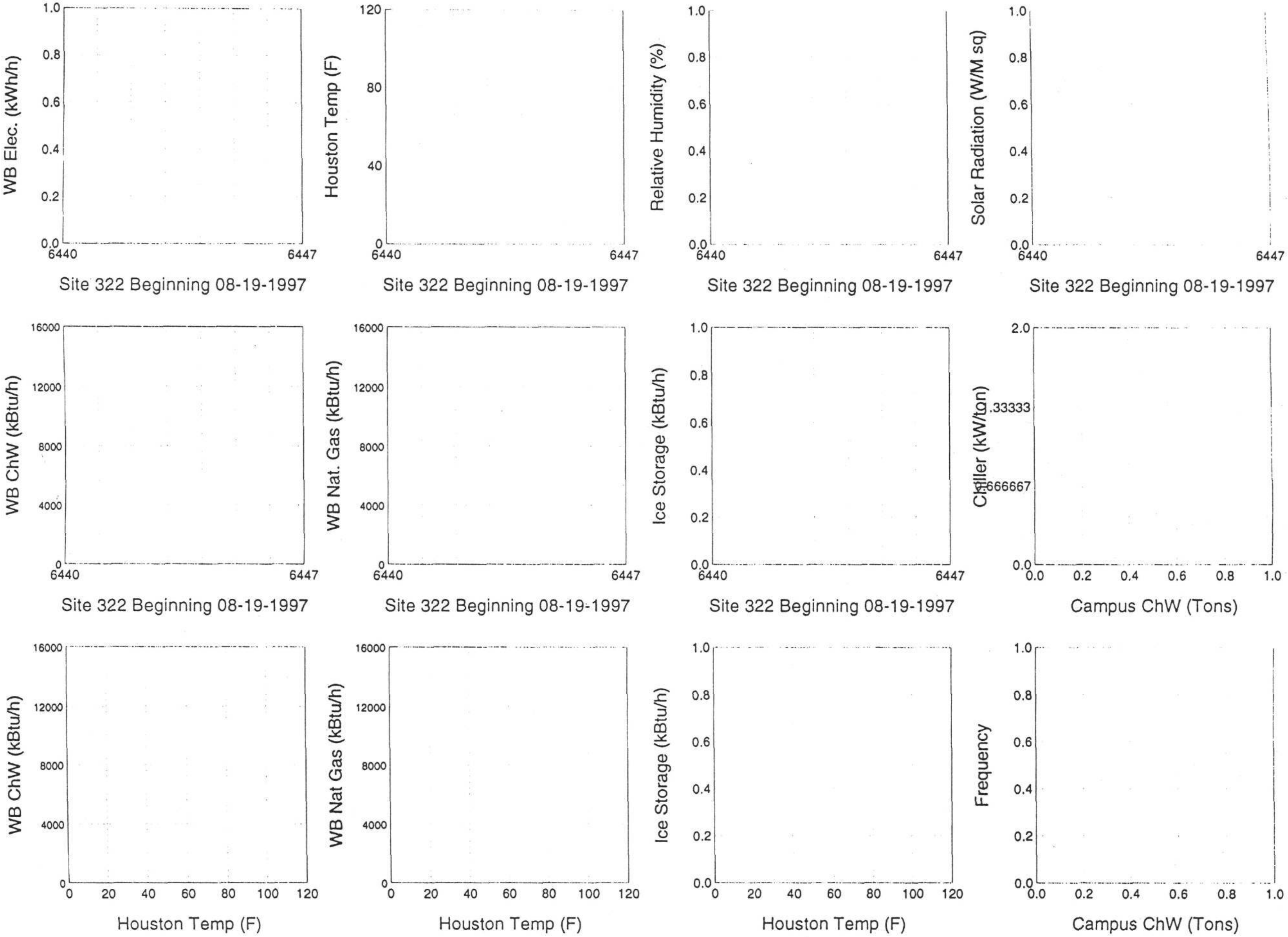
A=ANALOG CHANNEL
D=DIGITAL CHANNEL

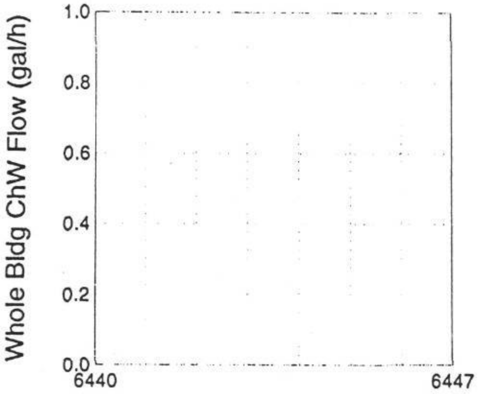


UNIVERSITY OF HOUSTON\CLEARLAKE - SITE 322 (HOURLY DATA)

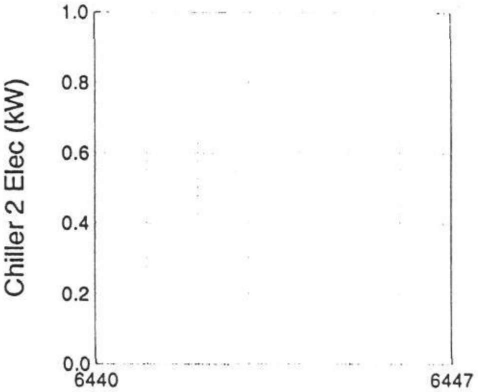
Site 322 Page 1



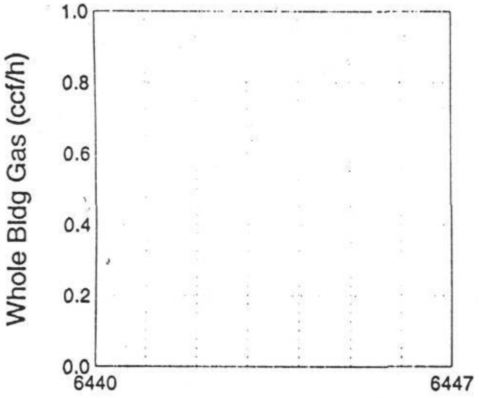
Site 322 Page 2



Site 322 Beginning 08-19-1997



Site 322 Beginning 08-19-1997



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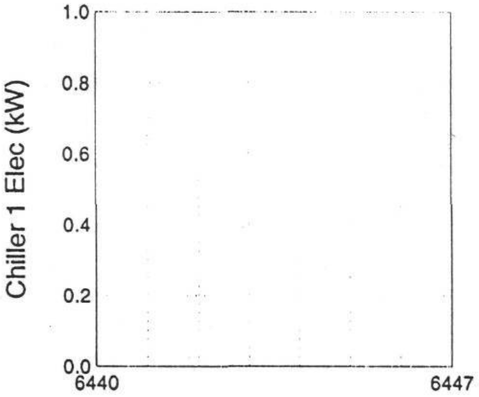
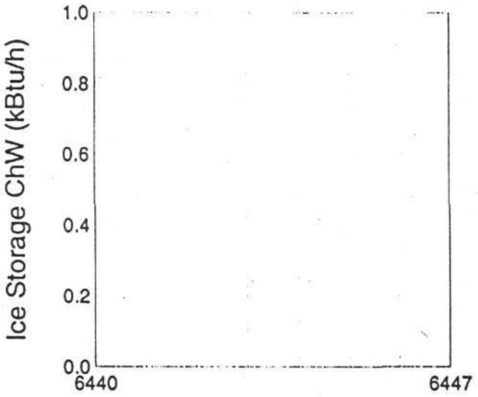
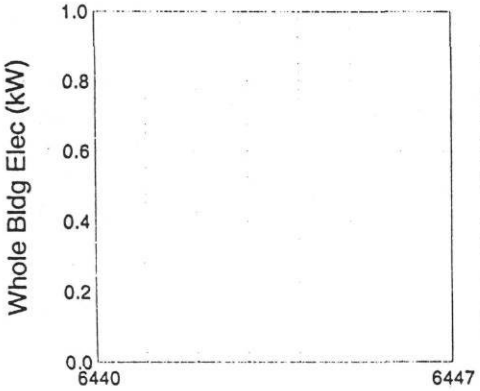


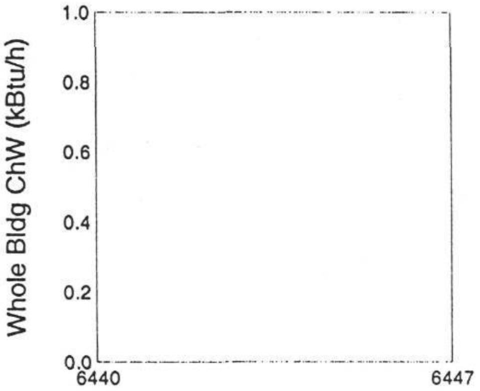
Site 322 Beginning 08-19-1997



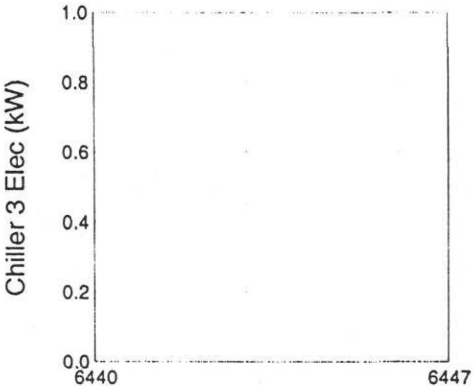
Site 322 Beginning 08-19-1997



Site 322 Beginning 08-19-1997



Site 322 Beginning 08-19-1997



Site 322 Beginning 08-19-1997

University of Houston - Clear Lake

460,576 square feet

Site Contact	LoanSTAR Metering Contact
Mr. Herald Johnson	Aamer Athar or Namir Saman
Director of Physical Plant	053 WERC
University of Houston - Clear Lake	Texas A&M University
2700 Bay Area Blvd. Box 222	College Station, TX 77843-3123
Houston, TX 79430	(409) 845-9213
(713) 283-2250	

Summary of Energy Consumption

	Measured Use	% hours reported	Unit Cost	Estimated Cost
Electricity	- kWh	-	$0.02700	-
Peak 60 Minute Demand	- kW	-	$12.19	-
Chilled Water	3952.9 MMBtu	77	$5.000	$19765
Natural Gas	107.1 MMBtu	77	$3.378	$362

No peak 60 minute demand was recorded this month.
There were 720 hours in this month.

Monthly Retrofit Savings

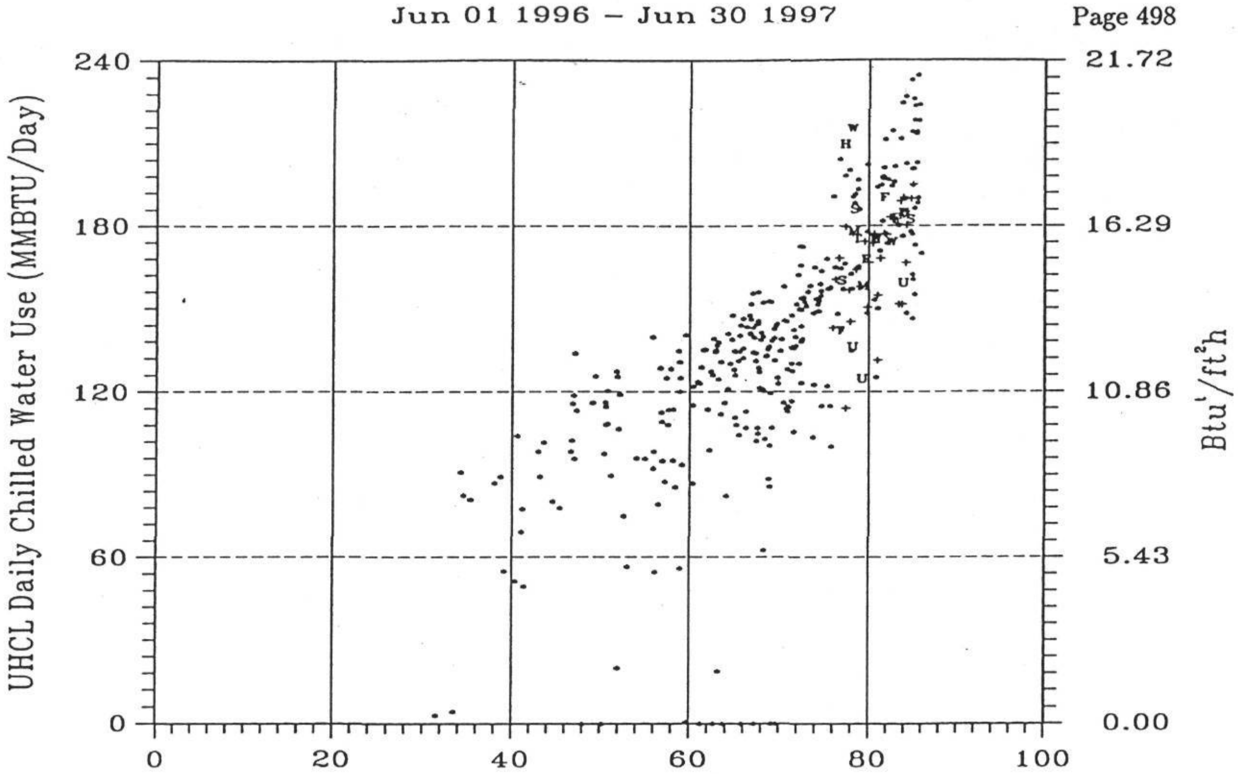
	Measured Savings		Audit Estimated Savings	
Electricity Demand (kW)	907	$11056	524	$6388
Monthly Total		$11056		$6388
Total to Date*	(17 months)	$128440	(14 months)	$89426

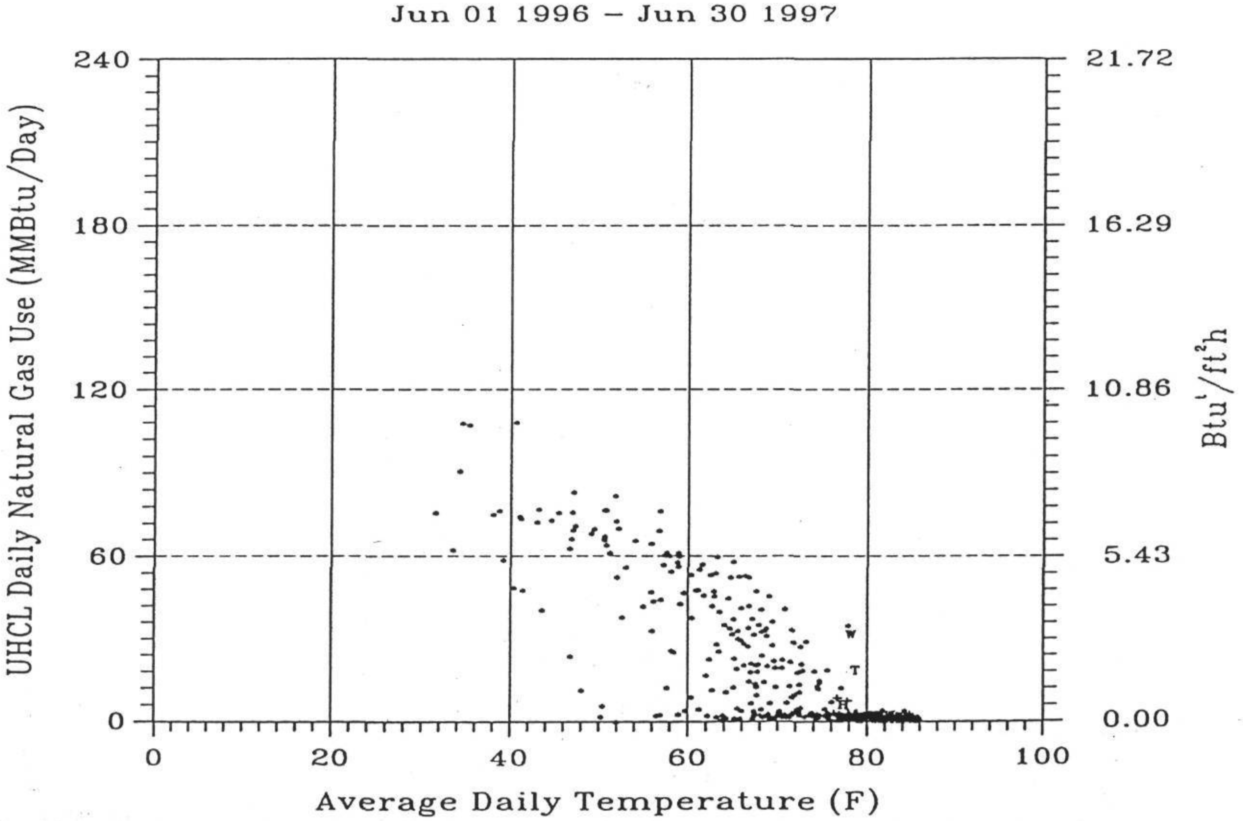
*Measured savings include construction period. Audit estimated savings do not.

Comments

★ Electricity consumption data are missing from 6/1/97 to 6/30/97 due to a monitoring hardware problem.

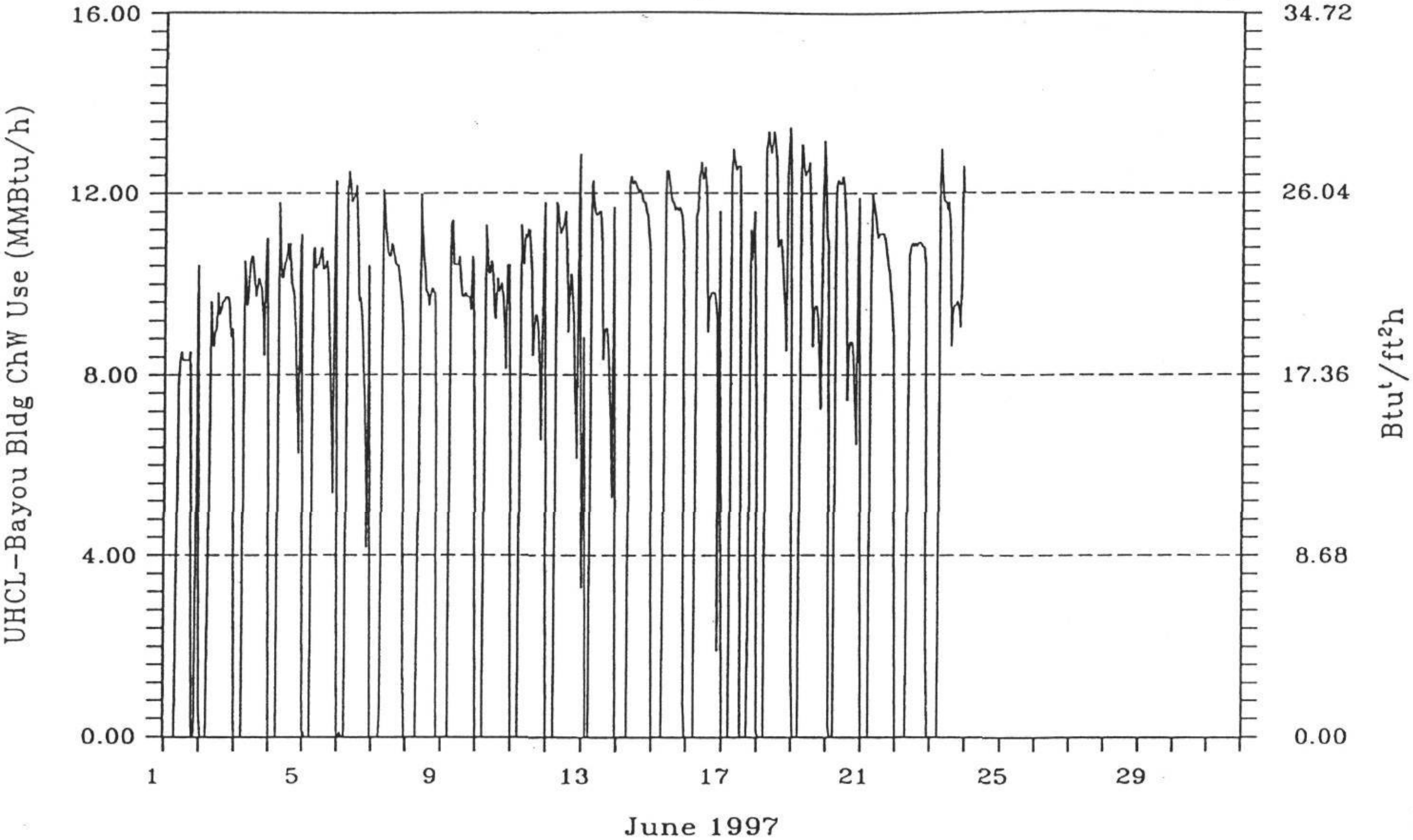
★ Chilled water and natural gas energy use data are missing from 6/24/97 to 6/31/97 due to a monitoring hardware problem.

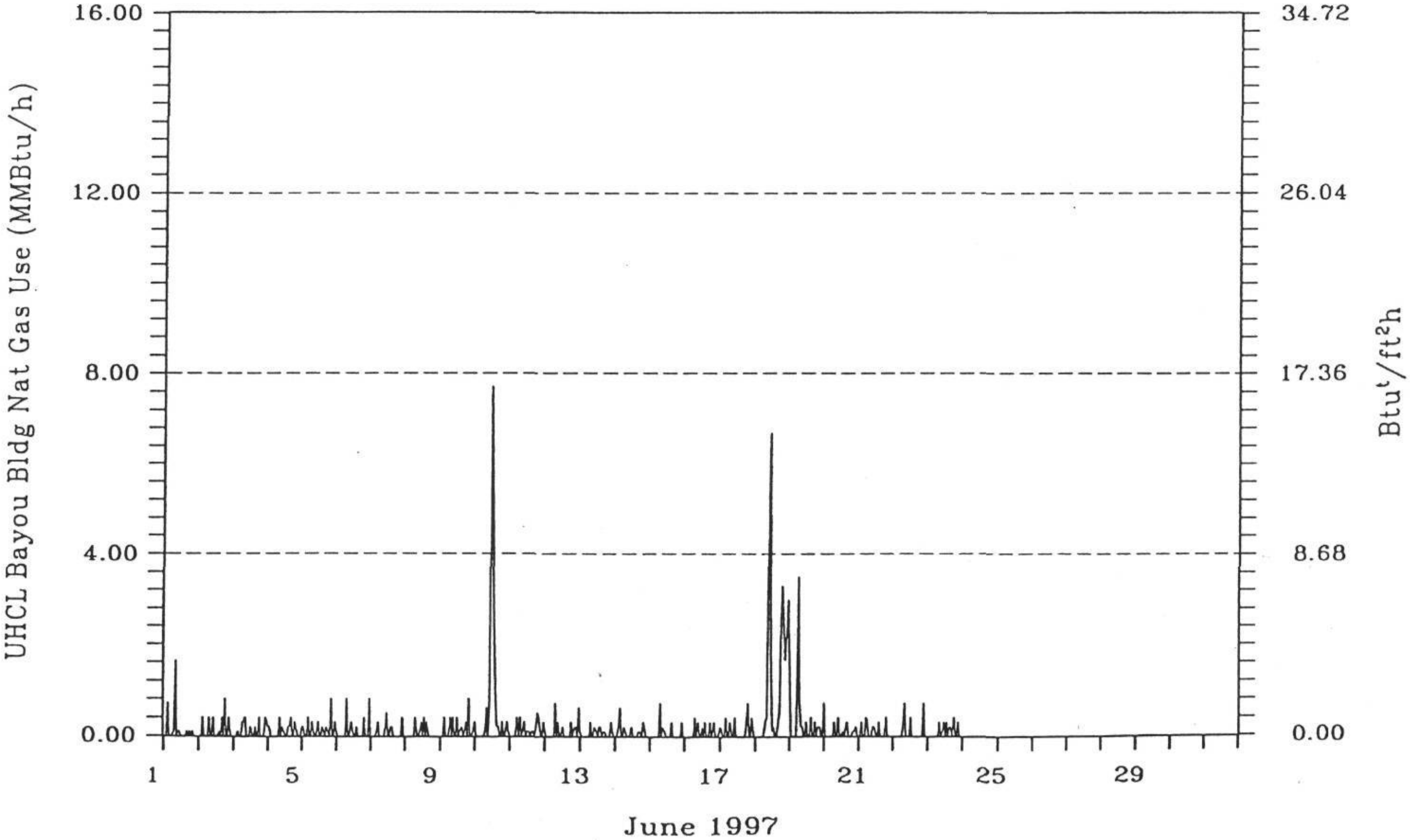


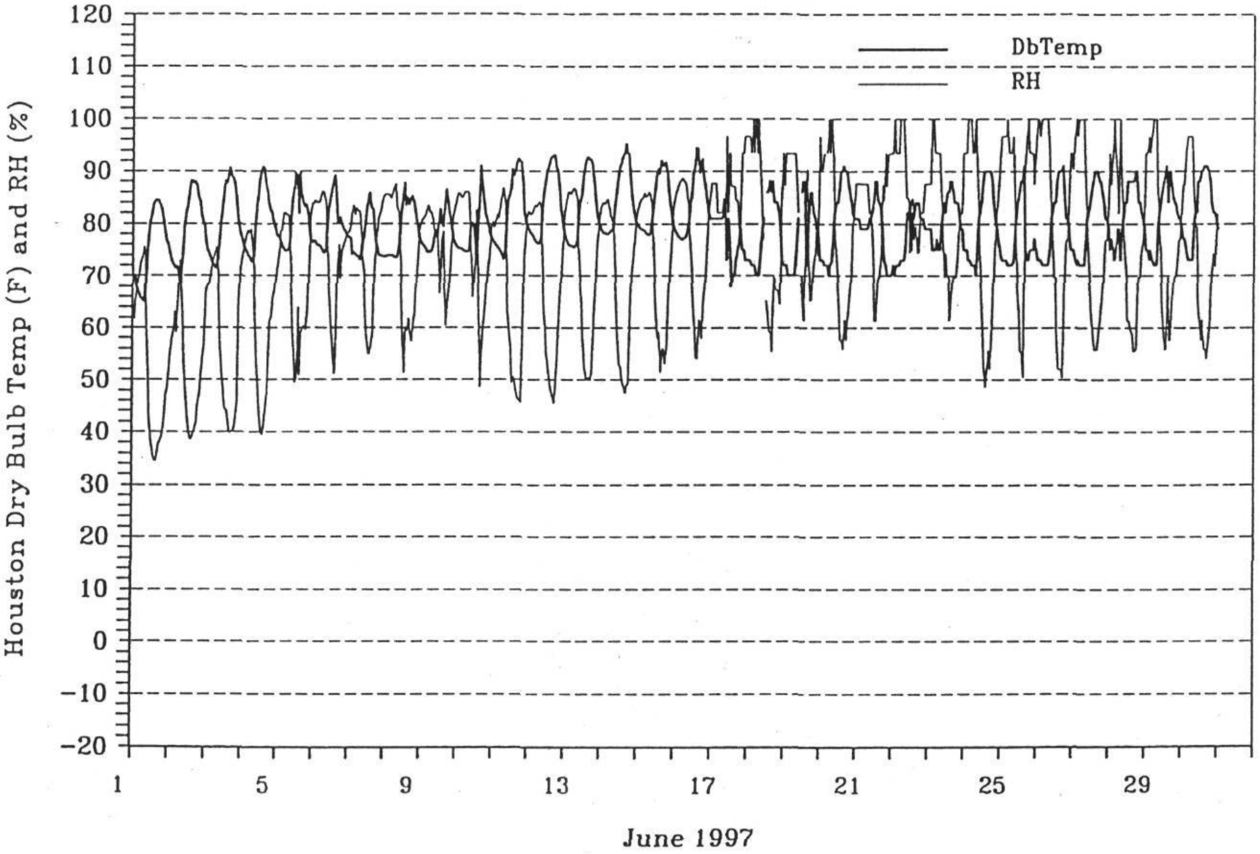


Data points for the current month are shown as letters.
Monday through Sunday are represented as M,T,W,H,F,S,U.

Points from this month last year are shown as +.
All other points are shown as *.


16.00
12.00
8.00
4.00
0.00
UHCL-Bayou Bldg ChW Use (MMBtu/h)
34.72
26.04
17.36
8.68
0.00
Btu^t/ft^{2}h
1
5
9
13
17
21
25
29
June 1997


16.00
12.00
8.00
4.00
0.00
UHCL Bayou Bldg Nat Gas Use (MMBtu/h)
34.72
26.04
17.36
8.68
0.00
Btu^t/ft^{2}h
1
5
9
13
17
21
25
29
June 1997



University of Houston - Clear Lake - June 1997

UNIVERSITY OF HOUSTON-CLEAR LAKE

Bayou Building

Building Envelope:
- 460,576 sq.ft.
- walls: precast
- roof: built up
- year of construction: 1975

Building Schedule:
- the average occupancy schedule is 8 am to 5 pm Monday through Friday

Building HVAC and Equipment:
- 3 chilled water pumps ranging from 40 - 50 hp
- 32 AHUs ranging from 30 - 75 hp
- 3 cooling tower fans, 50 hp each

HVAC Schedule:
- all HVAC equipment operates for 5,450 hours annually and is controlled by automation. Operating hours are 6:00 am to 10:00 pm

Lighting:
- 12,210 two lamp 40W fixtures

Completed Retrofits:
- thermal storage - December 1995

Other Information:
- electricity is supplied by Houston Lighting & Power and natural gas is supplied by General Land Office

University of Houston - Clear Lake

460,576 square feet

Site Contact
Mr. Herald Johnson
Director of Physical Plant
University of Houston - Clear Lake
2700 Bay Area Blvd. Box 222
Houston, TX 79430
(713) 283–2250

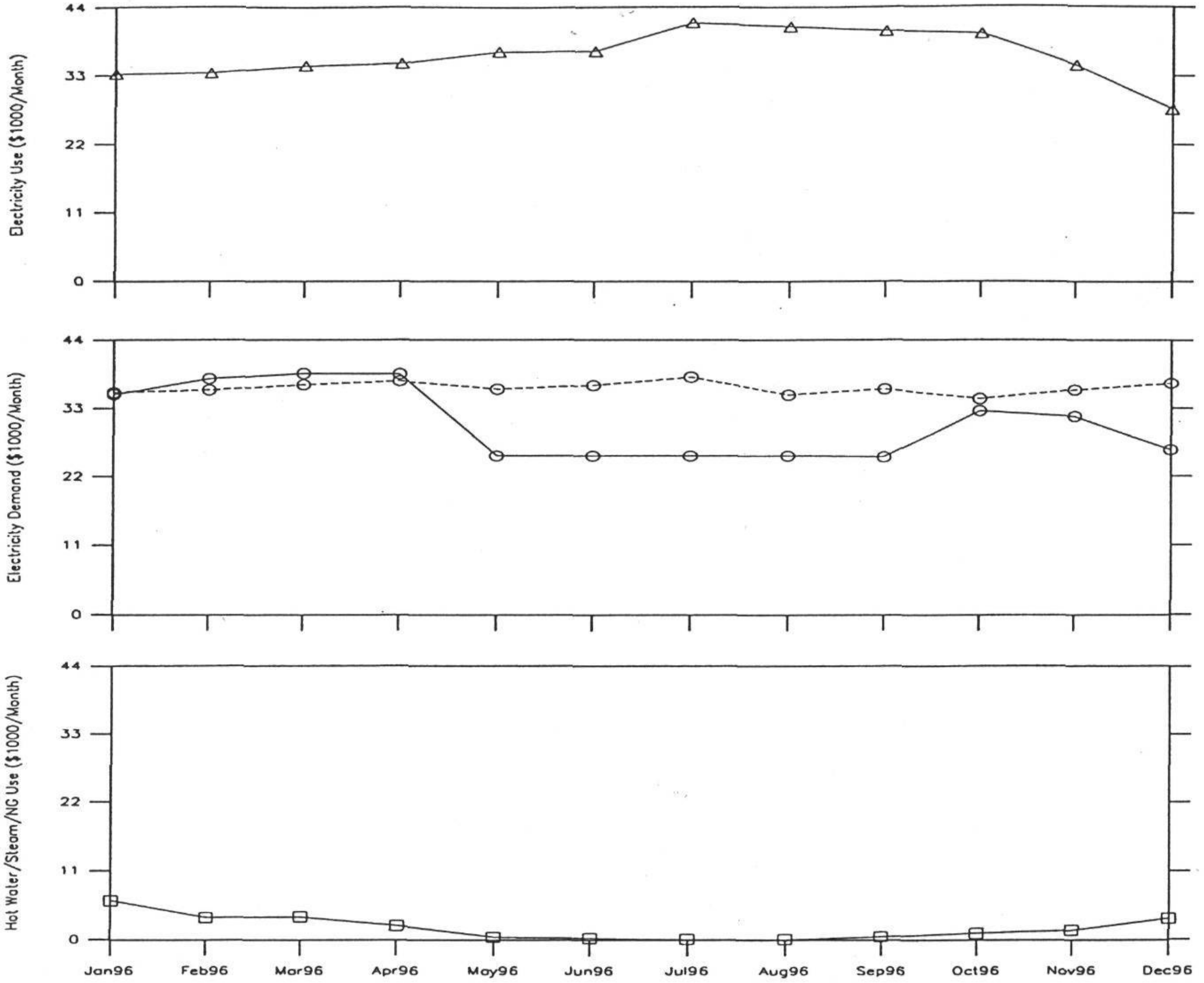
LoanSTAR Metering Contact
Aamer Athar or Namir Saman
053 WERC
Texas A&M University
College Station, TX 77843-3123
(409) 845–9213

1996 Summary of Measured Energy Consumption and Savings

	Electricity				Electricity Demand				Hot Water/Steam/NG				Total	
	Consumption			Savings	Consumption			Savings	Consumption			Savings	Monthly	Cumulative
Month	kWh	$	%	$	kW	$	%	$	MMBtu	$	%	$	Savings	Savings
Jan	1232280	$33272	100	N/A	2890	$35230	100	$353	1854	$6262	100	N/A	$353	$353
Feb	1237974	$33425	100	N/A	3102	$37810	100	$-1874	1058	$3573	100	N/A	$-1874	$-1521
Mar	1282004	$34614	100	N/A	3171	$38653	100	$-1839	1089	$3679	100	N/A	$-1839	$-3360
Apr	1295690	$34984	100	N/A	3162	$38548	100	$-1124	675	$2280	100	N/A	$-1124	$-4484
May	1366308	$36890	100	N/A	2078	$25331	100	$10753	137	$464	100	N/A	$10753	$6269
Jun	1368385	$36946	100	N/A	2078	$25331	100	$11370	91	$306	100	N/A	$11370	$17639
Jul	1537861	$41522	100	N/A	2078	$25331	100	$12762	40	$134	100	N/A	$12762	$30401
Aug	1515457	$40917	57	N/A	2078	$25331	57	$9851	41	$137	84	N/A	$9851	$40252
Sep	1488129	$40179	39	N/A	2065	$25172	39	$10947	154	$519	39	N/A	$10947	$51199
Oct	1471375	$39727	100	N/A	2674	$32596	100	$1962	315	$1064	100	N/A	$1962	$53161
Nov	1282487	$34627	100	N/A	2601	$31706	100	$4259	461	$1556	100	N/A	$4259	$57420
Dec	1025366	$27685	100	N/A	2156	$26282	100	$10780	1024	$3459	100	N/A	$10780	$68200
Total	16103316	$434788		$0	30133	$367321		$68200	6939	$23433		$0		$68200
EUI	35.0	$\frac{kWh}{ft^2yr}$			65424	$\frac{Btu}{ft^2yr}$			15065	$\frac{Btu}{ft^2yr}$				

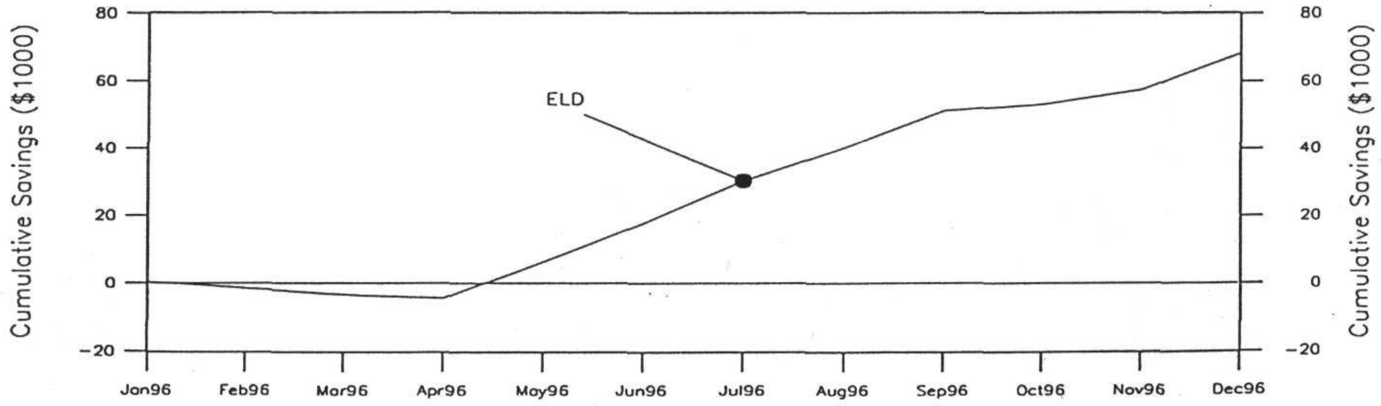
Comments

- ★ The percent columns indicate the number of hours reported in that month.
- ★ The LoanSTAR monitoring began in August 1994.
- ★ The unit costs used for estimating the energy costs and savings are: $0.027/kWh (ELE), $12.19/kW-mo (ELED), $5.00/MMBtu (CW), and $3.378/MMBtu (NG).
- ★ Electricity, chilled water and natural gas consumption data for parts of August and September 1996 are missing due to a monitoring hardware problem.
- ★ The audit estimated savings for the completed thermal storage system are $76,700 (ELED).



Solid line represents measured energy use while the dashed line indicates
the energy that would have been consumed had the retrofit not been installed

△ Electric ○ Cooling □ Heating



UNIVERSITY OF HOUSTON-CLEAR LAKE

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