DESCRIPTION AND VERIFICATION OF A BUILDING ENERGY MEASUREMENT SYSTEM

by

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Chapter 1

Introduction

Project Background

Since the "energy crisis" in the earlier 1970s there has been an increase in energy conservation research. Included in this research is the study of conservation of building energy consumption. The U.S. Army Construction Engineering Research Laboratory (CERL) has been responsible for the U.S. Army building energy conservation research efforts. The U.S. Federal government has given CERL the task of quantifying the improvements in building thermal energy preformances. As part of fulfilling the task, CERL initiated a program which they entitled "Design, Build and Operate Energy Efficient Buildings" at Fort Riley, Kansas. The program was designed to quantify the amount of energy conserved by new Army buildings over similar buildings built around 1975.

Presently, there are four Battalion Headquaters-Classroom type buildings under study. All the buildings are located on Custer Hill, Fort Riley, Kansas and are shown on a map located in the Appendix A. The buildings are single story and feature: cinder block construction, outside face brick, and a built-up roof with a metal deck. The buildings are designed for similar uses and can be proportioned approximately to their area uses as follows: classrooms 35%, clerical 17%, office 25%, projection rooms 5%, storage 4%, restrooms 8%, and corridor 6%.

There are two identical approximately 11,000 sqft old buildings (designed and built in the early 1970s) which are currently being monitored. The old buildings are identified by number -- Building 8025 and Building 8037. In the cooling season, these buildings receive chilled water from a main chiller located at Custer Hill. In each building, the chilled water circulates through three multizone air handling units which supply cool air to the zones. In the heating season, the buildings receive high pressure steam from a central boiler located on Custer Hill. The steam is throttled down to a low pressure steam which supplies energy to a hot water loop via a heat exchanger. The hot water loop circulates warm water around to the building to heat the zones.

There are two new buildings which will be monitored along with the old buildings beginning June 1987. One of the new buildings is identified as Building 7108 which has a floor area of 12000 sqft. The other building has a floor area of 13000 sqft and is identified as Building 7108. Building 7108 houses a split system chiller and a hot water boiler which services both buildings. In addition, Building 7108 utilizes a heating/cooling constant volume multizone air conditioning unit. In contrast, the Building 7108 air conditioning system incorporates a variable air volume control strategy. In addition to studying the building thermal characteristics, the new chiller and boiler are being monitored.

Another goal of the study is to compare collected energy data to building detailed simulation predicitions. CERL is interested in comparing their building energy simulation program to the collected building energy data. CERL's building energy simulation program is called Building Loads Analysis and System Thermodynamics or BLAST for short. BLAST estimates cooling or heating loads on a hourly basis. BLAST requires as an input the following: hourly environmental conditions, building description (e.g., geometry and structure), and hourly internal loads (e.g., equipment an occupants).

It is noted that to aid in determining the internal loads electrical energy consumption data are collected in all the buildings in the study. Also, selected room temperatures along with domestic hot water energy usage are or will be recorded.

Scope of Project

Because the new buildings will not be monitored until June 1987, the program at Fort Riley has consisted of the task of monitoring on a hourly basis the environmental conditions and energy consumption in

Building 8025 and Building 8037. In order to accomplish this task, measurement schemes were first designed and the instrumentation and data acquisition equipment specified by CERL. Also, a professional contractor installed all of the building equipment and instumentation (except the data acquisition equipment). In addition, CERL technicians initially installed all weather data instrumentation. Kansas State University (KSU) and CERL personnel configured and maintained the data acquisition equipment. (It is noted that details of this assignment will not be included. However, information on the data acquisition equipment -- Acurex AutoCalc or AutoGraph is included in Appendix B). After the equipment had been specified and installed, the project was turned over to new a CERL team and KSU personnel. At that date the KSU-CERL Fort Riley project of accurately measuring the environmental conditions and the energy consumption in Building 8025 and 8037 using the existing measurement setup was initiated.

The task of monitoring the environmental conditions is accomplished with the use of two weather stations that were installed. Hourly averages of the wind speed and direction, dry bulb temperature, dew point temperature, solar insolation, and barometric pressure are recorded. Although not required for BLAST the hourly maximum and minimum wind speeds, dry bulb temperatures, and dew point temperatures are also recorded.

Building energy consumption in the cooling season is calculated by determining the change of energy in the chilled water between its inlet and outlet to the building. Another energy measurement measures the sum of the cold water energy changes between the inlet and outlet in each of the three air handler units. Heating energy consumption can be determined from the hot water loop measurement which simply measures the change in energy in the circulating water. In addition, the building's condensate usage measurement may be useful in determining the heating energy consumption. Therefore, in each season there are two measurements which indicate the amount of energy consumption. This fact is used to help verify energy data and identify suspicious data.

It is imperative that the collected data accurately reflect the true measurements and that error in the measurements be determined. The instrumentation previously discussed and the data acquisition equipment are sophisticated. An accurate measurement requires one to have knowledge of the instrumentation and equipment and an understanding of the system being monitored. One can not just install and turn on the equipment and instrumentation and be assured that the data collected are useful and accurate. Therefore, procedures and techniques need to be developed in order to assure that the data recorded indicate the true measurements (thus verifying the measurement) and to determine measurement accuracies. In this thesis, procedures and techniques are presented that were developed to verify the measurements. Also presented is a description of the building cooling and heating systems, the weather station instrumentation, and the energy measurement scheme and system components.

The verification procedures and techniques presented are intended to provide sufficient quantitative and/or qualitative evidence to confirm that the actual measurement indicates the true measurement within the instrumentation errors. It is noted that it is not the intent of this thesis to discuss the verification of every particular measurand and data but rather to present procedures which show that the collected data are accurate. Also, some of the procedures are designed to investigate dubious data and determine if these data are erroneous and incorrectable or if they can be corrected.

There are five remaining chapters. Chapter 2 describes the climatic measurement scheme and the methods and procedures used to verify the weather data. Chapter 3 is devoted to the description of the building cooling and heating systems and their energy measurement systems. Chapter 4 presents the verification of the building measurements systems. The procedures and techniques discussed in this chapter were used to help verify that the all the instrumentation and equipment were (or were not) working within their design specifications. Next, methods based on the fact that the two energy measurements should be in agreement were used to help verify the energy data on a continuous basis. Chapter 5 contains this and other continuous verification of actual data procedures along with some building thermal characteristics observed. Finally, conclusions are given in Chapter 6.

The nature of this project is more of a practical nature rather than a theoretical one. This thesis is intended to be used as a project guide for KSU and CERL personnel. Therefore, when possible examples and illustrations will be given.

Chapter 2

Verification of Weather Measurements

General Discussion

Essential to the modeling of a building's thermal performance are the environmental conditions with which the building thermally interacts. Two weather stations have been installed and maintained in order to document the environmental conditions. One of the weather stations is located on Custer Hill at the rear of Building 8025 and is approximately 250 ft east from Building 8037. The other weather station is located at Fort Riley's Marshall Airfield which is approximately 4 miles south of the two buildings. The two weather stations used are Climatronics Meteorological Monitoring systems (CMMS). The purpose of a CMMS is to continuously measure the outdoor wind speed, wind direction, dry bulb temperature, dew point temperature, barometric pressure, and solar radiation. The weather data collected at Custer Hill is primarily used for building thermal modeling, while the weather station at Marshall Airfield acts as a backup weather station. In addition to being a backup station, the Marshall Airfield station weather data is being used to compare the differences in climates between Custer Hill (located on the top of a hill) and Marshall Airfield (located in a valley). A second backup station also exists at Marshall Airfield, it is operated by the U.S. Air Force. The U.S. Air Force weather station at Marshall Airfield is designated an official weather station by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (1). This weather station compiles hourly weather observations which are made by trained observers.

The CMMS outputs weather conditions in continuous analog signals between 0 - 5 volts and some measurands have a second analog signal between 0 - 10 mv. A datalogger, Acurex AutoCalc or Acurex AutoGraph, scans and records the analog signal every 15 or 20 seconds. From this data hourly averages and extremities (high and low) of the measurement are calculated and stored. This data collection scheme theoretically gives a superior hourly "average" measurement as compared to the hourly measurement method currently being used at the Marshall Airfield U.S. Air Force weather station and many other official weather stations.

In order for weather data to be useful it must be accurate, this requires properly specified, installed, calibrated, and maintained instrumentation. The CMMS was selected by CERL because all measurement accuracies where within the BLAST weather data specifications. "Instructions For Meteorological Monitoring System"

(IFMMS) notebook (2) contains installation and calibration procedures. In verifying the installation process, a number of instrumentation components were determined to be improperly installed. As suggested in the IFMMS notebook, the calibration procedures were modified to incorporate the data logger being used. The fundamental principle to the modified calibration technique was to use the Acurex as a precision voltmeter to minimize instrumentation errors. This eliminated any errors that may have been introduced if the Climatronics instrumentation were calibrated with any other precision voltmeter. Also, systematic errors introduced by the Acurex are eliminated by calibration.

Since there are different measurements (wind speed, solar radiation, etc.), the equipment installation, measurement verification, calibration, and maintenance highlights for each measurement will be discussed separately. In addition, several of the instruments were compared against a secondary measurement and these comparisons will be discussed. Also, calibration modifications will be included which when used with the IFMMS notebook completely documents the adopted calibration technique. Again as discussed in Chapter 1, it is not the intent to discuss the verification of every particular measurand data but rather present procedures and documentation which give strong evidence to support that the collected data are accurate.

Verification of Installation and Measurement

Wind Speed and Direction Measurements

Instrumentation
Climatronics' Wind Monitor Translator P/N 101291
Wind Speed Range 0-100 mph Accurarcy ± 1 mph
Wind Direction Range 0-360 deg Accuracy ± 3 deg

An appropriate anemometer was unavailable for comparison to the Climatronics' wind speed instrumentation. However, the wind speed data when compared with the data obtained by the U.S. Air Force weather station at Marshall Airfield were in agreement. As directed in the Climatronics' IFMMS notebook the wind direction indicator had to be properly zeroed. By hand rotating the wind vane, it was determined that the wind direction measurement system was working in equilibrium. Later, the Marshall Airfield Climatronics wind direction measurements were compared against a similar U.S. Air Force wind direction indicator. The comparison revealed that the wind direction measurements were within ± 5 degrees of each other.

Dry Bulb Temperature Measurement

Instrumentation
Climatronics' Dry bulb sensor P/N 100092-2
Air: Extended Range ± 50 C Accuracy ± 0.10 C

An initial inspection revealed that the direction and orientation of the TS-series shields did not comply with the Climatronic's IFMMS notebook installation specification. After correcting the misdirection and misorientation, dry bulb temperatures were compared against a high quality mercury thermometer which was placed in the aspirator. The Climatronics' dry bulb measurements were in good agreement (within ± 1.5 F) with the laboratory standard mercury thermometer readings. Also, the Climatronics' dry bulb thermistor at Marshall Airfield was checked with an ohm meter. Not only did the thermistor's resistance increase with the outside dry bulb temperature but it gave the correct resistance values for a given temperature. It is noted that in the verification processes it was determined that the actual circuitry did not match the Climatronics Aspirator Assembly drawing 100325 components. Additional information on the thermistor's resistance actual versus manufacturer resistance and a sketch of the actual Aspirator circuitry are included in the Appendix C.

Dew Point Temperature Measurement

Instrumentation
Climatronics' Dew Point Sensor P/N 1001197
Range ± 50 C Accuracy ± 0.5 C

The Dew Point sensor is also part of the dry bulb instrument apparatus and therefore was also improperly directed and orientated. The instrument was horizontal instead of vertical and facing down (to avoid debris and moisture -- rain or snow). Remarkably, there seemed to be no damage to the instrument. A clear desiccant tube (which should have been removed) protected the dew point sensor's bobbin wick but caused erroneous dew point temperature readings. After proper installation, maintenance, and calibration, the dew point measurement was verified by a U.S. Air Force weather station's certified meteorologist (3). The meteorologist compared a Climatronics' dew point reading with the Marshall Airfield Air Force dew point reading and other relevant meteorological readings. The meteorologist concluded that the Climatronics' measurement was accurate (to within ± 1 F). Based on this assessment and secondary measurements at Custer Hill (see maintenance section), there is reason to believe that when operating properly the dew point measurement accurarcy is ± 0.5 C as claimed by the manufacturer.

Solar Insolation

Initial investigations revealed that the Climatronics' pyranometers were improperly mounted. A special rod was constructed to allow the Custer Hill pyranometer to be attached to the south side of the Climatronics tower (to avoid shadowing) approximately 25 feet above grade. Similarly, a rod mounting for the Marshall Airfield pyranometer was attached on a southern guard rail on top of the old air tower at Marshall Airfield approximately 60 feet above grade. Both pyranometers were checked monthly to assure that they were level and to inspect the clearness of their glass domes.

Both Climatronics' pyranomators (Marshall Airfield and Custer Hill) were compared to a Model PSP Eppley Radiometer. When factory calibrated the Eppley's accuracy is verifiably within ± 1% of the reading (at least for the angle of insolation at which the tests were run). The Eppley's factory calibration date had expired, but it is believed that the Eppley's accuracy is still well within ± 5% of the reading. The Climatronics' pyranometers compared favorably with Eppley Radiometer. The procedure, test data and results are as indicated below.

Procedure

The first step in the verification procedure was to check the Climatronics pyranometers with the Eppley

Radiometer. A voltmeter measured the induced EMF (voltage) of each pyranometer. The voltage was then converted into solar insolation (in Langleys) by using manufacturer's voltage-solar insulation equations. The next step was to compare the Climatronics system (pyranometer sensor, transmitter, and the Acurex) with the Eppley Radiometer. In this process, the Acurex displayed the Climatronics system reading and a voltage meter was used to measure the Eppley Radiometer voltage output. Finally, the Eppley Radiometer voltage reading was converted into solar insolation and compared to the Climatronics' system measurement.

Pyranometers

#1 EPPLEY RADIOMETER
Model PSP Serial Number: 1827F3
The Eppley Laboratory, Inc.
Accurarcy ± 0.5% of reading when calibrated
Expected Accuracy within ± 5% of reading

#2 CLIMATRONICS SOLAR RADIATION SENSOR P/N 100507
Model MK1-G Serial Number: 3510
Field Accuracy ± 5%

#3 CLIMATRONICS SOLAR RADIATION SENSOR P/N 100507
Model MK1-G Serial Number: 3556
Field Accuracy ± 5%

Note #2 is used at Marshall Airfield
#3 is used at Custer Hill

Test Data and Results

Comparison between #1 and #2
Marshall Airfield measurement vs Eppley Radiometer
Using Direct EMF signals

Date: May 26, 1986 Ambient Temperature 75 F
Time: 14:00 Relative Humidity < 90%

Solar Insolation, Langleys

Pyranometer	#1	#2	Deviation
	1.34	1.36	0.02
	1.31	1.35	0.04
	1.30	1.34	0.04
	1.30	1.31	0.01
	1.30	1.32	0.02
	1.30	1.33	0.03
Average	1.308	1.355	0.027

Average of #1 and #2 = 1.3315 Langleys
Five percent of 1.3315 = 0.0666

Using the Acurex with #2 and EMF signal #1

Solar Insolation, Langleys

Measurement	#1	#2	Deviation
	1.35	1.39	0.04
	1.38	1.41	0.03
	1.38	1.43	0.05
	1.37	1.43	0.06
Average	1.37	1.43	0.05

Average of #1 and #2 = 1.395 Langleys
Five percent of 1.395 = 0.042

Comparison between #1 and #3
Custer Hill measurement vs Eppley Radiometer
Using Direct EMF signals

Date: June 3, 1986 Ambient Temperature 75 F
Time: 10:30 Relative Humidity < 90%

Solar Insolation, Langleys

Pyranometer	#1	#3	Deviation
	0.746	0.760	0.014
	0.746	0.758	0.012
	0.746	0.764	0.018
	0.746	0.760	0.014
	0.746	0.766	0.020
	0.746	0.764	0.018
	1.028	1.045	0.017
	1.035	1.046	0.011
	1.028	1.037	0.009
Average	0.840	0.856	0.016

Average of #1 and #3 = 0.848 Langleys
Five percent of 1.3315 = 0.042

Using the Acurex with #3 and EMF signal #1

Solar Insolation, Langleys

Measurement	#1	#3	Deviation
	0.817	0.840	0.023
	0.789	0.804	0.016
	0.747	0.768	0.021
	0.549	0.573	0.024
	0.535	0.577	0.042
	0.578	0.595	0.017
	0.563	0.581	0.008
	0.465	0.485	0.020
	0.380	0.397	0.017
	0.394	0.403	0.009
	0.437	0.422	0.015
Average	0.585	0.567	0.017

Average of #1 and #3 = 0.576 Langleys
Five percent of 1.395 = 0.028

Notice that the all of the deviations between the solar insolations measurements were within ± 5% of the average measurand. Based on these test results, it was then concluded that the solar insolations measurements at

Custer Hill and Marshall Airfield represents their true measurand within the accuracy of instrumentation at the time of the test.

Barometric Pressure
Instrumentation
P/N Climatronics' Barometric Pressure Sensor
Range 600 to 1100 mbw Accuracy ± 0.08% of reading

The Climatronics' barometeric pressure transducer at Marshall Airfield is located two stories below the top of the old air tower roof (approximately 40 feet above grade) in an abandoned but still air conditioned room. The Custer Hill Climatronics barometeric pressure sensor is located below the Acurex in Building 8025's mechanical room. Although the barometeric pressure transducers are located inside "pressurized" buildings they are assumed to accurately indicate the outside barometric pressures. This assumption is valid at least for all relevant thermodynamic applications because the maximum pressurization is only around 0.5 mb (4). The barometeric pressure readings have compared favorably against the Marshall Airfield Air Force barometric pressure data (within 4 mbar for the Marshall Airfield CMMS barometric pressure reading).

Weather Instrumentation Calibration

A modified calibration procedure based on the Climatronics' IFMMS notebook was developed in an effort to minimize instrumentation errors. The procedure utilizes the Acurex (the final measurand output) to monitor the output of the Climatronics' six transmitters - wind speed & direction, dry bulb temperature, dew point temperature, barometric pressure, and solar radiation. The programmed Acurex displays the output of a designated transmitter as the true measurand (not in volts). The method minimizes error because calibration is respect to the Acurex (the acting voltmeter) and any systematic error in the Acurex is eliminated.

The CMMS mainly consists of the individual sensors-transducers (e.g., a pyranometer) and their signal conditioners (terminology adopted from Beckwith, (5)). The signal conditioners take the sensor-transducer signals and output a linear voltage signal. In the case of the CMMS, only the signal conditioners require calibration. The signal conditioner is referred to as a translator in the IFMMS notebook and all translators draw electrical power from the same power supply. The power supply and individuals translators are calibrated in a CMMS calibration.

After the initial calibration, CMMS instrumentation drift characteristics were studied. Based on this study, it was decided to have CMMS calibration approximately every five weeks. Also, biweekly collected weather data were continuously studied to determine the need for additional calibrations and/or maintenance of equipment. More information on maintenance will be covered in the maintenance section.

Several of the Climatronics transmitters output both a 0-5 volt signal and a 0-10 mv signal. The 0-5 volt signal output can be zeroed and spanned but, the 0-10 mv signal can only be spanned. The IFMMS notebook states that it is unnecessary to zero the 0-10 mv signal. However, the 0-10 mv transmitter signals had a noticable and an uncorrectable zero shifts. For this reason, it was decided to use the 0-5 volt signals for the primary measurements.

The modified calibration procedure is documented in Appendix D. This documentation covers all the modifications of the IFMMS notebook calibration instructions and was used with the IFMMS as guide for a proper CMMS calibration.

Maintenance

Crucial to any project that utilizes instrumentation and equipment is the maintenance of the instrumentation and equipment. Biweekly sight inspections were used to observe instrumentation and equipment problems and correct and/or document the problems. In addition, weekly data checks via phone modem did provide more frequent checks and allow detection of "unseen" problems (instrumentation drift, natural disasters, and unforeseen instumentation and equipment failure). All known equipment problems and erroneous data were documented in monthly reports and by CERL personnel (6) in order to ensure that only "good" weather data would be used in a thermal building analysis program.

The Climatronics' equipment did not require a scheduled maintenance program. It was the purpose of the biweekly trips and weekly data reviews to discover any equipment problems. Perhaps the best way to present an account for maintenance is to describe the maintenance which was required.

Maintenance Required

There were a few hardware problems at the beginning of the project and some occassional translator problems which occured as the result of a calibration strain. Most of the more interesting maintenance was required when lighting struck the weather station tower at Custer Hill and when ball bearings required replacement on the anemometers at Custer Hill and at Marshall Airfield.

Somewhere around August 8, 1986, it was discovered that the Custer Hill weather station tower had probably been hit by lightning earlier in the week. The outer sleeve (Figure 3 in the Motor Aspirated Shield section of the Climatronics' IMMS notebook) was no longer attached to the Dew Point Shield unit and was never located (a replacement part was later fabricated at KSU and installed). A low vertical truss section member sustained a slash probably due to an electrical arcing between the "ground wire" and the tower. The arcing occured because the tower was a better ground than the "ground" rod. Actually the "ground" rod was not a true ground rod rather it was a four foot long (two feet in ground) plain steel reinforcing concrete rod. The arcing could have been avoided if a proper grounding rod had been used. A copper claded grounding rod was later purchased and installed to prevent future lightning damage.

In addition, the dew point sensor inner sleeve and the dew point sensor bobbin wick were left hanging by their sensor and power cords. When hanging, water came in contact with the wick and caused arcing and washed away the wick's LiCl solution. Without an appropriate amount of LiCl on the dew point wick, the dew point sensor readings are meaningless. A Climatronics (IFMMS notebook's Section 8.0 -- Dew Point Sensor Section) maintenance procedure was then performed on the wick. In order to continue taking weather data at Custer Hill, the aspirated shield unit was replaced (dry bulb/ dew point sensors) with the Marshall Airfield's aspirated unit. On August 15, the Custer Hill dew point sensor was compared with a reliable EG&G Model 911 Dew-All Digital Analyzer dew point measuring system (a chilled mirror type dew point sensor). The comparison revealed that the Climatronics' dew point measurement readings were erroneous. The problem was with the dew point sensor wick (it was probably not impregnated correctly: Later, a procedure to field impregnate the wick was developed, this procedure is discussed in the following paragraph). In addition to the dew point sensor wick problem, it was discovered that a damaged Climatronics Surge Protector ground was affecting the dew point measurement. As a result, Custer Hill dew point data from approximately August 8-25 were erroneous.

Throughout the project there have been problems with the dew point measurements at both Custer Hill and Marshall Airfield. At times, the dew point instruments have indicated dew point temperatures at around -20 C which was at least 15 C below the actual dew point measurement (as indicated by the U.S. Air Force weather station at Marshall Airfield). It appears that the major problem was with contamination or inappropriately "charging" (with LiCl 8% by weight) of the dew point sensors' LiCl impregnated fiber glass wick. To alleviate the problem, the LiCl impregnated wicks had to be cleaned and recharged as directed in the Climatronics IFMMS notebook's Dew Point maintenance guide section. It is noted, that in modification to the procedure the wick needed to be immersed in the LiCl solution for about 15 minutes in order to thoroughly saturate the wick (modification of step F in the procedure). Also for field maintenance, drying of the wick can be accomplished with a hair blow dryer (CAUTION: care must be taken not to damage the wick).

In the process of searching for the error in the dew point temperature measurement, a General Eastern - Dew 10 dew point temperature measurement system which has an accuracy of ± 1 F was installed at Custer Hill and used December 1986 thru January 1987. The DEW 10 is a cooled mirror dew point sensor which uses a 100 ohm platinum RTD resistance to measure the dew point temperature. In order to convert the RTD resistance into a current signal for the Acurex, use was made of an existing and fortunately compatible (100 ohm platinum) HYCAL temperature transmitter. The transmitter used was the cold water supply temperature transmitter which was not in use in the heating season. The DEW 10 measurement system was later used in conjunction with Marshall Air Force station data to verify that the Climatronics dew point temperature measurements were accurate and reliable. It is noted that in the event of future dubious data the LiCl impregnated wick should first be cleaned and then recharged.

Besides the problem with the dew point measurement, a few hours of erroneous solar radiation readings occured after the electrical storm. Defects were not observed in the examination of the pyranometer, cabling, surge protector, Climatronics' transmitter, and the Netpac input card (or in any of the other translators). Also, the previous pyranometer verification procedure (See Verification of Solar Insolation section) was repeated and the results indicated that the solar radiation measurement system was working properly. Table 2.1 shows the results of the verification. It seems the solar radiation measurement was erroneous for just a short period of time (less than two days). The erroneous data may have resulted from a pyranometer transducer problem or perhaps an Acurex CPU problem.

Table 2.1 : Verification of solar insolation measurement after lightning damage

Test Date: August 15, 1986   Temperature 75 F
Time: 15:00   Relative Humidity <90%

Custer Hill solar insolation measurement, Langleys	Eppley Radiometer in Langleys	%deviation
.563	.549	2.5
.481	.464	3.6
.535	.507	5.4
.554	.521	6.1
.561	.535	4.7
.576	.549	4.8
.584	.563	3.7

In a biweekly instrumentation and equipment inspection it was noticed that the anemometer flange bearings on the Climatronics' Young Wind Model 05102 at Marshall Air Field and at Custer Hill were noisy and needed to be replaced. These particular bearings were necessary because they allowed the propeller to freely spin and indicate the true wind speed. The Climatronics manual suggested that the vertical shaft bearings along with the flange bearings were likely to require replacement. Based on this recommendation the vertical shaft bearings along with the flange bearings were replaced (at the same time).

Verification of Weather Data on a Continuous Basis

Since weather data are being collected continuously, there is a need to continuously verify that the collected data corresponds precisely to the actual measurands. In practice, the primary weather measurements from the Custer Hill weather station are compared to backup Marshall Airfield CMMS measurements. If the comparison is favorable then the Custer Hill primary measurand data are valid (assuming properly calibrated instrumentation).

Computer programs were developed to take the weather data from the Acurex and manipulate the data into files acceptable to LOTUS (7). (LOTUS is a spread sheet type program that operates on an IBM compatible personal computer.) LOTUS graphs were created which would enhance ones ability to interpret the collected data. Figure 2.1 is a LOTUS plot of January wind speed data showing both the Custer Hill (identified as CH) CMMS and Marshall Airfield (identified as MAF) CMMS wind measurements. Considering that the weather stations are four miles apart and that they are at different elevations, the wind speed data show a compatible comparison. Figure 2.2 shows a graph of January wind direction data for both stations. Again the weather stations are in good agreement and the data are verified.

Figure 2.1

Weather Comparison — Jan Data

CH CMMS and MAF CMMS

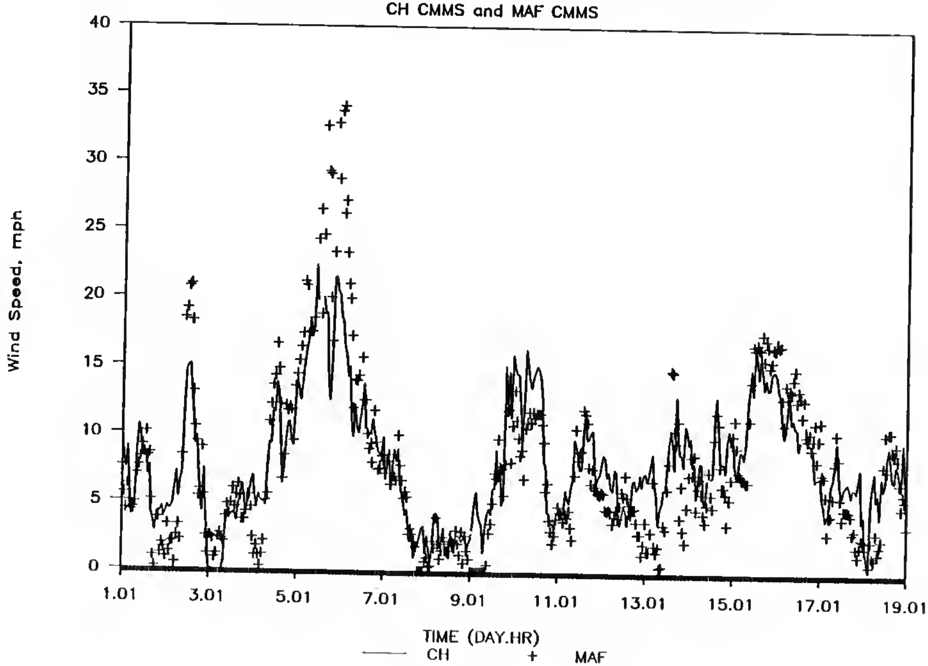
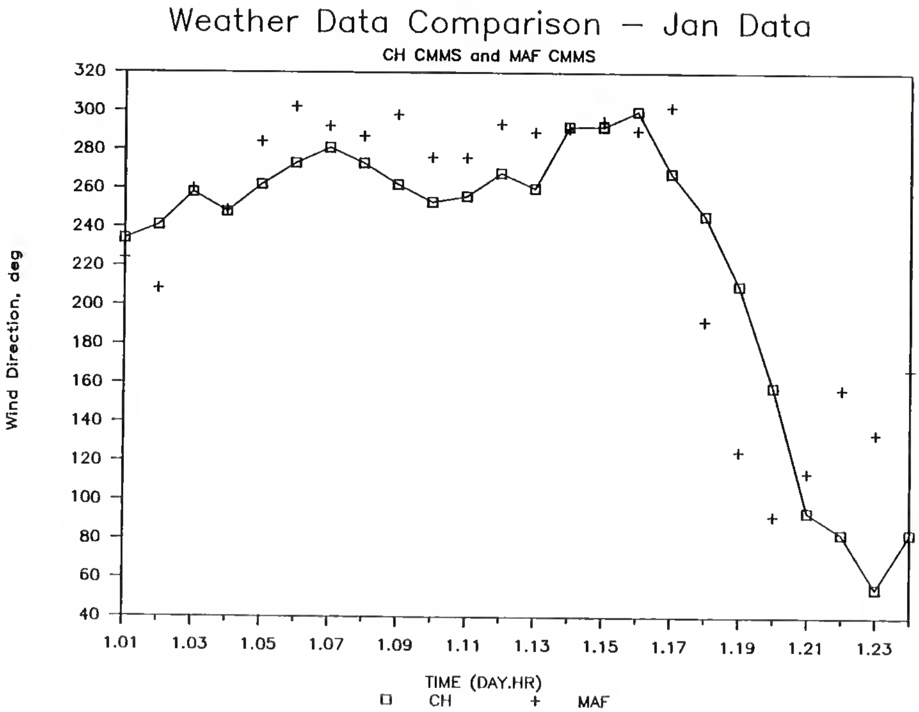


Figure 2.2


Weather Data Comparison – Jan Data
CH CMMS and MAF CMMS
Wind Direction, deg
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
1.01
1.03
1.05
1.07
1.09
1.11
1.13
1.15
1.17
1.19
1.21
1.23
TIME (DAY.HR)
CH
MAF

Dry bulb and dew point temperature measurements can also be verified using LOTUS plots. Figure 2.3 shows the verified CH and MAF dry bulb temperature measurements plotted for January 1, 1987. Figure 2.4 gives a graph of verified CH and MAF dew point temperature measurements.

Figure 2.5 is a January data comparison plot between the CH CMMS versus the MAF CMMS barometric pressure measurements. Notice that the two measurements track each other and that the MAF measurement is approximately 8 mmbar higher. This difference in pressure is primarily due to the difference in elevations between the two weather stations. Therefore the data are verified.

Finally, Figure 2.6 is a verification plot of showing the solar radiation measurements. The measurements agree within the accuracies of the two measurements thus validating the Custer Hill solar insolation measurements.

Figure 2.3

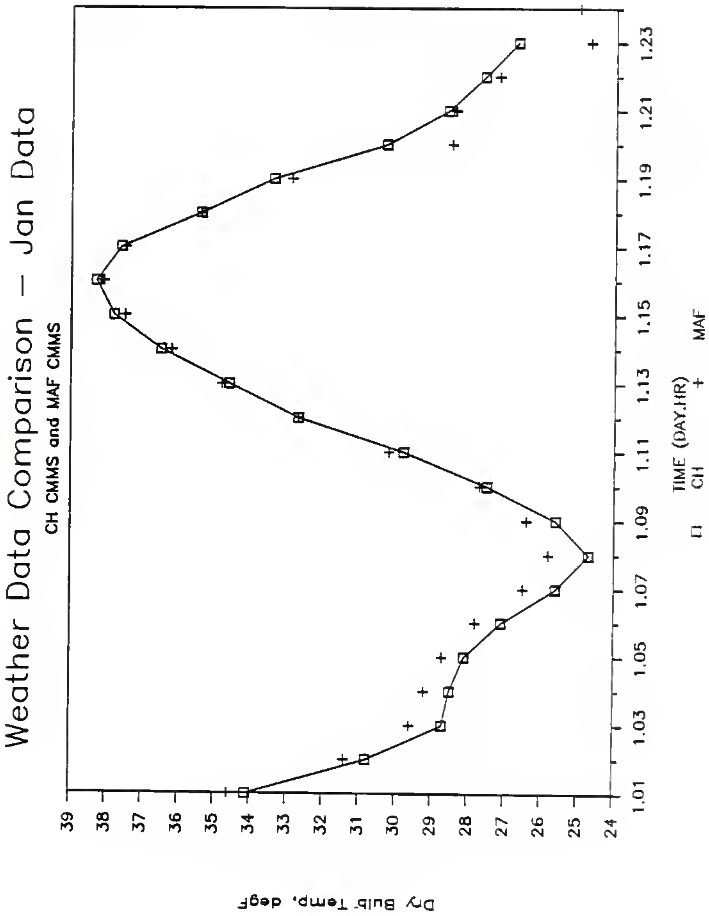

Weather Data Comparison — Jan Data
CH CMMS and MAF CMMS
Dry Bulb Temp, degF
TIME (DAY.HR)
CH
MAF
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
1.01
1.03
1.05
1.07
1.09
1.11
1.13
1.15
1.17
1.19
1.21
1.23

Figure 2.4

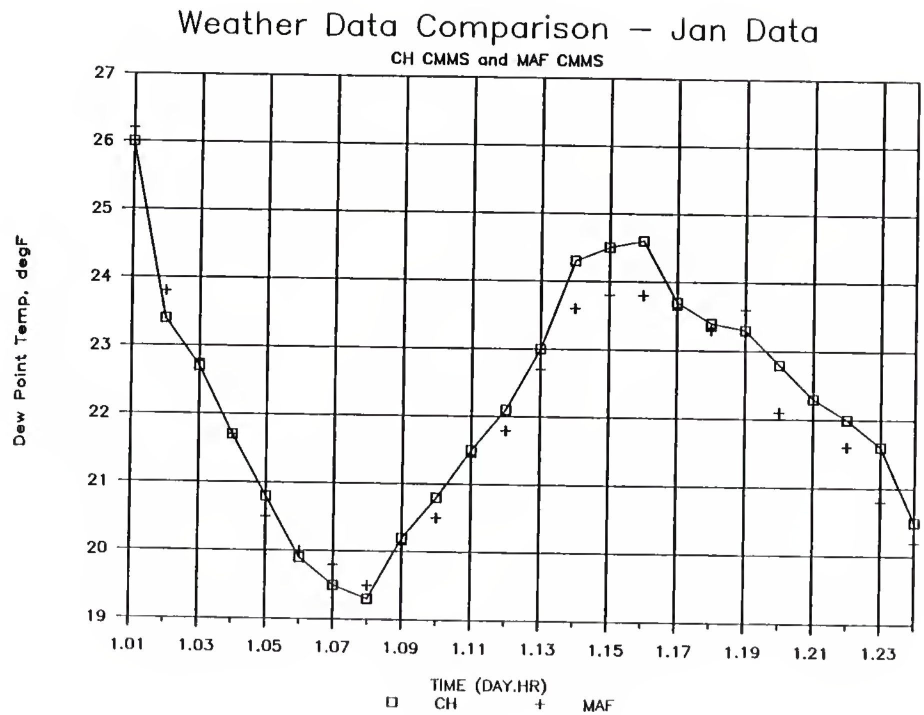
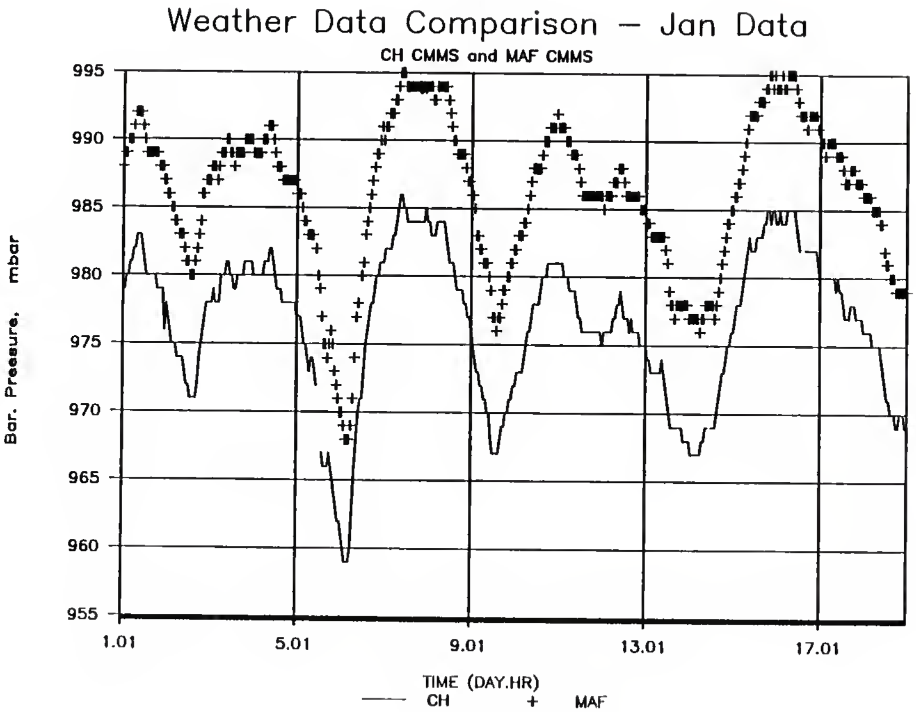

Weather Data Comparison — Jan Data
CH CMMS and MAF CMMS
Dew Point Temp, degF
27
26
25
24
23
22
21
20
19
1.01
1.03
1.05
1.07
1.09
1.11
1.13
1.15
1.17
1.19
1.21
1.23
TIME (DAY.HR)
CH
MAF

Figure 2.5

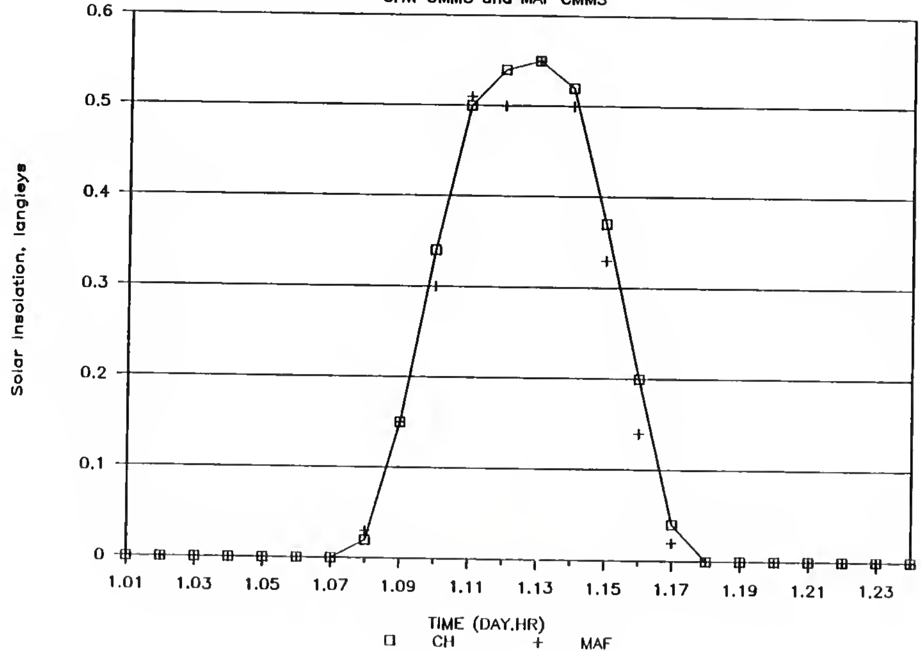


Weather Data Comparison — Jan Data
CH CMMS and MAF CMMS
Bar. Pressure, mbar
995
990
985
980
975
970
965
960
955
1.01
5.01
9.01
13.01
17.01
TIME (DAY.HR)
— CH
+ MAF

Figure 2.6

Weather Data Comparison – Jan Data

CHW CMMS and MAF CMMS



Chapter 3

Description of Building Cooling and Heating Systems and the Energy Measurement Systems

In this chapter a description of the building heating and cooling systems will be given. In addition, a description of the energy measurement systems are provided. Also, the relevant energy and error equations will be introduced.

Building Cooling Season Air Conditioning Description

The buildings cooling needs are met through a forced air multi-zone air conditioning system. Each building has three "air conditioning" units each servicing three to five zones. All zones have thermostats which modulate dampers to maintain desired space temperatures. Figure 3.1 shows the three air conditioning units. AC-1 and AC-3 utilize an economy cycle control schedule. When possible this control schedule calls for outside air and return air to be mixed to maintain a certain mixed air temperature. Also, when the outside temperature reaches a prescribed temperature the outside air damper closes to its minimum position. In contrast, AC-2 operates with a set constant mixture between outside air and return air.

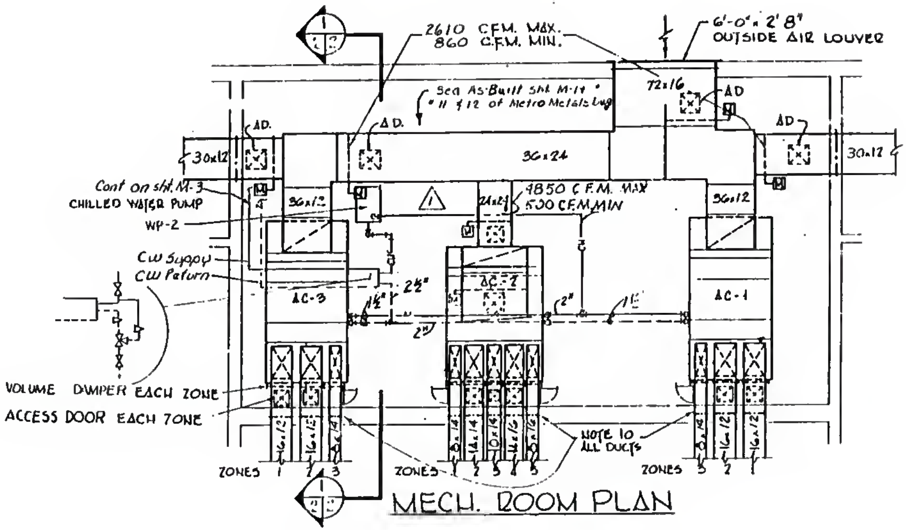


Figure 3.1 Blueprint of Three Air Conditioning Units

The air conditioning cooling coils are supplied with cold (chilled) water that comes from a central chiller located at Custer Hill. Figure 3.2 is a sketch of the cold (chilled) water piping. Chilled water enters the building and proceeds through a "booster" pump (not shown). The cold water then travels to the air handlers which are in a parallel configuration or it is by passed directly to the cold water return line. Water that enters the air handlers, goes through an air handler heat exchanger and is returned to the central chiller via the cold water return line. The bypass control valve is an on/off control device. When operating at outdoor temperatures above 55 F the valve directs all the flow to the air handling units. At outdoor temperatures below 55 F the incoming cold (chilled) water is bypassed directly to cold water return line (see Appendix E for details).

Building Energy Cooling Consumption Measurement System

There are two measurement schemes which are used to determine the hourly building cooling load. Both utilize the same type of equipment and instrumentation. The first scheme is to determine the building cooling load based on the flow rates and temperature drops in the main chilled water supply and return lines and basic thermodynamic equations and properties. The second scheme is to

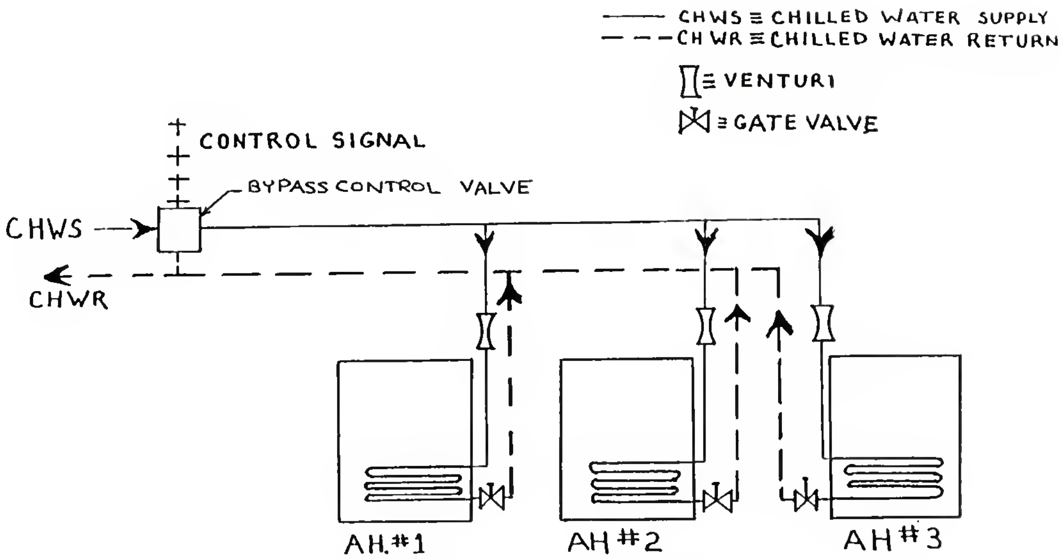


Figure 3.2 Sketch of Chilled Water Piping

determine the building cooling load from individual air handler cooling load measurements (same as in the above strategy) and summing the three air handler cooling load measurements.

The flow rate measurement system will be the first energy measurement system component to be described. The flow rate measurement system utilized the following equipment and instrumentation: a venturi meter, a pressure transducer/transmitter, and an appropriately configured data logger (Acurex). A venturi meter is a flow meter device that "outputs" a differential pressure which can be related to a flow rate. This relationship between differential pressure "output" and volumetric flow rate for the designated venturi meters will be addressed at the beginning of the next section. Because there are a number of components and relations, the flow rate measurement system description merits most of the energy measurement system discussion. Next, the temperature measurement system which incorporates RTDs (resistance temperature detectors) and a data logger will be discussed. Also necessary to an energy consumption measurement are the energy and error relationships and equations. These energy and error equations will be presented as needed.

Flow Rate Measurement System

Volumetric Flow Rate vs Differential Pressure Relation

Marc's Handbook For Mechanical Engineers (8) develops the following volumetric flow rate vs differential pressure relation. (It is noted that $\dot{V}$ is used here instead of Q.)

$$\dot{V} = KYA\sqrt{\frac{2\Delta P}{\rho}} \tag{3.1}$$

$\dot{V}$ = Volumetric flow rate

K = Flow coefficient

Y = Expansion factor

A = Area of primary element, i.e., pipe area

ΔP = Differential pressure

ρ = Density of fluid

K needs to be determined experimentally and is normally provided by the venturi manufacturer. In the manufacturer's (Aeroquip) venturi meter information which was received, the relationship was given in a manner similar to the above format. Shown below are the relationships that relate flow rate with differential pressures for the venturi meters which were used.

Air Handler Flow vs. Pressure Differential Equation

Aeroquip Venturi meter: Nominal diameter 1.5 in.

Beta Ratio = 0.563

$$\dot{V} = 4.46\sqrt{\Delta P} \qquad (3.2)$$

where,

$\dot{V}$ = Volumetric Flow Rate, gpm

ΔP = Differential Pressure, in. H_2O

Main Flow Rate vs. Pressure Differential Equation

Aeroquip Venturi Meter: Nominal diameter 2.0 in.

Beta Ratio = 0.636

$$\dot{V} = 10.01\sqrt{\Delta P} \qquad (3.3)$$

In general the manufacturer provided the flow vs. pressure differiential graphs which were manipulated into the equation form:

$$\dot{V} = c\sqrt{\Delta P} \qquad (3.4)$$

where,

c = constant, gpm/(in. $H_2O)^{1/2}$

Notice that the only variable is the differential pressure. The flow coefficient, compressibility (essentially 1.0 for all relevant water conditions (15-70 psia and 40-190 F), water density, and venturi area were all combined into one constant. This relationship is valid because water thermodynamic properties are essentially constant for flow calculations when water temperatures range between 40 - 60 F (see Error Analysis section). Also, the K values (which are a function of Reynolds number and beta ratio) are essentially constant over the relevant measurand flow rates. Additional venturi flow vs differential pressure relationship information is included in the Appendix F.

The differential pressure is an input to a Viatran differential pressure transducer/transmitter. This transducer utilizes a diaphram and a strain gage to output an appropriate current signal for a differential pressure input. A 4-20 ma output corresponds to a 0-100 in. H_2O input. The data logger (Acurex) input card converts the current signal into a voltage signal. This voltage signal is converted into an appropriate flow rate by the Acurex. The Acurex records the flow rates every minute.

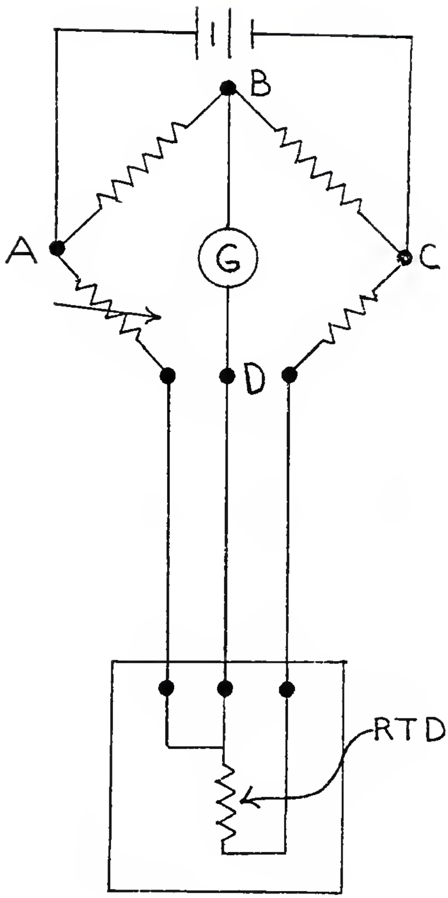
Temperature differences are determined by separately measuring cold water line temperatures and then taking the difference between the cold water supply temperature and its corresponding cold water return temperature. The temperature measurement equipment/instrumentation consists of an RTD (resistance temperature detector), a HYCAL temperature transmitter, and an appropriately configured data logger (Acurex).

A RTD is simply a temperature sensitive resistor. All of the in-building temperatures are measured with platinum (nominal 100 ohms) RTDs. In all of the water RTD is protected with a thermally conductive probe which also serves to average the temperature at the measurement location. Each RTD is connected to a Hy-Cal Model CT-810 current temperature transmitter which contains an electrical bridge and is set up much like the one in Figure 3.3. The arrangement is called the Siemen's lead arrangement and it is used to compensate for the RTD's lead resistances. The temperature transmitter outputs a linear 4 ma (zero) - 20 ma (span) current designated by the RTD's resistance and electric bridge setup. An Acurex input board converts the milliamp signal into a voltage signal. The Acurex reads the voltage signal and computes and stores the correct temperature every minute.

Associated with any measurement is the need for an error analysis and sensitivity analysis. The study's primary goal is to determine the building thermal energy consumption. Hence there is a need to determine the error in the energy consumption data. In determining this error it is necessary and informative to determine errors due the venturi meter, pressure transducer, RTD temperature transmitter, and the Acurex data logger.

Sensitivity Analysis

The energy transfer to the chilled supply water in the cooling mode is given by



RTD CIRCUIT

Figure 3.3 Electrical Bridge with Siemen's Lead Arrangement

$$\dot{Q} = \dot{m}c_p \, \Delta T \qquad (3.5)$$

$\dot{Q}$ = instantaneous heat into the chilled water

$\dot{m}$ = mass flow rate of supply water

c_p = specific heat at constant pressure

ΔT = Difference between return and supply water temperatures.

For pipe flow,

$$\dot{m} = \rho \dot{V} \qquad (3.6)$$

ρ = density of fluid

$\dot{V}$ = volumetric flow rate

and combining (3.5) and (3.6)

the result is $\dot{Q} = \rho c_p \, \dot{V} \, \Delta T$ (3.7)

$$\text{or} \qquad \dot{Q} = \dot{Q}(\rho, c_p, \dot{V}, \Delta T) \qquad (3.8)$$

Taking the total derivative of (3.8),

$$d\dot{Q} = \frac{\partial \dot{Q}}{\partial \rho} d\rho + \frac{\partial \dot{Q}}{\partial c_p} dc_p + \frac{\partial \dot{Q}}{\partial \dot{V}} d\dot{V} + \frac{\partial \dot{Q}}{\partial \Delta T} d\Delta T \qquad (3.9)$$

in terms of a sensitivity analysis (3.9) becomes

$$E_{\dot{\rho}} = \frac{\partial \dot{Q}}{\partial \rho} E_{\rho} + \frac{\partial \dot{Q}}{\partial c_p} E_{c_p} + \frac{\partial \dot{Q}}{\partial \dot{V}} E_{\dot{V}} + \frac{\partial Q}{\partial \Delta T} E_{\Delta T} \qquad (3.10)$$

where in general, E_x is the absolute error in x.

Noting that the relationship between relative error and absolute error is given by

$$e_X = \frac{E_X}{X} \qquad (3.11)$$

where X is the measured variable

E_X is the absolute error in X

e_X is the relative error in X.

and from (3.10) the following is obtained

$$e_{\dot{Q}}\dot{Q} = \frac{\partial \dot{Q}}{\partial \rho} \rho \, e_\rho + \frac{\partial \dot{Q}}{\partial c_p} c_p \, e_{c_p} + \frac{\partial \dot{Q}}{\partial \dot{V}} \dot{V} e_{\dot{V}} + \frac{\partial T}{\partial \Delta T} \Delta T \, e_{\Delta T} \qquad (3.12)$$

Divide both sides of (3.12) by $\dot{Q}$ to get

$$e_{\dot{Q}} = \frac{\partial \dot{Q}}{\partial \rho} \frac{\rho}{\dot{Q}} e_\rho + \frac{\partial \dot{Q}}{\partial c_p} \frac{c_p}{\dot{Q}} e_{c_p} + \frac{\partial \dot{Q}}{\partial \dot{V}} \frac{\dot{V}}{\dot{Q}} e_{\dot{V}} + \frac{\partial Q}{\partial \Delta T} \frac{\Delta T}{\dot{Q}} e_{\Delta T} \qquad (3.13)$$

Evaluating the partial derivatives and using equation (3.7), equation (3.13) equates to

$$e_{\dot{Q}} = e_\rho + e_{c_p} + e_{\dot{V}} + e_{\Delta T} \qquad (3.14)$$

However,

$$\dot{V} = c \sqrt{\Delta P} \qquad (3.15)$$

or $\dot{V} = f(c, \Delta P)$

so that

$$d\dot{V} = \frac{\partial \dot{V}}{\partial c} dc + \frac{\partial \dot{V}}{\partial \Delta P} d\Delta P \qquad (3.16)$$

Using eqn. (3.11), (3.15) and (3.16), equation (3.16) equates to

$$e_{\dot{V}} = e_c + \frac{1}{2} e_{\Delta P} \qquad (3.17)$$

Substituting equation (3.17) into 3.14 the result is

$$e_{\dot{Q}} = e_{\rho} + e_{c_p} + e_{c} + \frac{1}{2}\, e_{\Delta P} + e_{\Delta T} \qquad (3.18)$$

Error Analysis

From (3.18) the relative error equation is given by

$$e_{\dot{Q}} = \pm \sqrt{e_{\rho}^{2} + e_{c_p}^{2} + e_{c}^{2} + (0.5\, e_{\Delta P})^{2} + e_{\Delta T}^{2}} \qquad (3.19)$$

Attaching the I.P. system of units for the measurand of equation (3.7), equation (3.7) resolves to be

$$Q = 8.020833\, \rho\, c_p \dot{V} \Delta T \qquad (3.20)$$

where

8.020833 is a conversion factor,

$\dot{Q}$ = rate of heat transfer, $\frac{Btu}{hr}$

ρ = density of water, $\frac{lb_m}{ft^3}$

c_p = specific heat at constant pressure, $\frac{Btu}{lb_m \cdot F}$

$\dot{V}$ = volumetric flow rate, gpm

ΔT = difference between supply and return temperatures, F.

Water pressures in the cold water line are within a 15 - 70 psia pressure range. In this range and for a fixed temperature between 40 and 190 F, the density of compressed liquid water does not vary with pressure (9).

In addition, the specific heat at constant pressure is also independent of pressure for a fixed temperature over the 15 - 70 psia pressure range. However, the water density and specific heat vary with the water temperature. Table 3.1 shows the product of density, specific heat, and the conversion factor for relevant chilled water temperatures.

Table 3.1: Product of density, specific heat at constant pressure, and the conversion factor for relevant chilled water temperatures.

Pressure range 15 - 70 psia Temperature	$\rho * c_p * 8.020833$ in $\frac{\text{Btu}}{\text{hr}\cdot\text{gpm}\cdot\text{F}}$
40 F	500.676
50 F	500.676
60 F	500.363

Note linear interpolation used when needed

From the previous discussion and Table 3.1, the product of $\rho c_p * 8.020833$ equal to 500.67 $\frac{\text{Btu}}{\text{hr}\cdot\text{gpm}\cdot\text{F}}$ would result in an error smaller than 0.0626%. Hence, equation (3.20) can be reduced to

$$\dot{Q} = 500.67 * \dot{V} * \Delta T \qquad (3.21)$$

where,

$\dot{Q}$ in $\frac{Btu}{hr}$, $\dot{V}$ in gpm and ΔT in F.

which introduces an error so small that it can be disregarded. Therefore, the relative error equation can be reduced to

$$e_{\dot{Q}} = \sqrt{e_c^2 + (0.5*e_{\Delta P})^2 + (e_{\Delta T})^2} \tag{3.22}$$

Aeroquip venturi meter information indicates that regardless of the flow (Appendix F)

$$e_{\dot{Q}} = \pm\ 0.02 \tag{3.23}$$

The final task in ascertaining the relative error in energy consumption measurements is to determine $e_{\Delta P}$ and $e_{\Delta T}$.

Determination of $e_{\Delta P}$

The venturi differential pressure is measured with a Viatran Pressure Transducer Model 323. This transducer outputs 4 - 20 ma signal according to the differential pressure it measures. The Acurex converts this current signal into a number ranging from 0 to 110 via an input card precision resistor and an A/D converter.

The relevant errors in the process are as follows:

$E_{\text{pressure transducer}} = \pm\ 0.25$ in H_2O

$E_{\text{Acurex analog accuracy}} = \pm\ 0.015$ in H_2O

$$E_{Acurex\ roundoff} = \pm\ 0.012 \text{ in } H_2O$$

$$E_{Acurex\ least\ count} = \pm\ 0.05 \text{ in } H_2O$$

The absolute error in the differential pressure is calculated by taking the rms of the above terms to obtain

$$E_{\Delta P} = \pm\ 0.256 \text{ in } H_2O$$

Therefore, the relative error is

$$e_{\Delta P} = \pm \frac{0.256 \text{ in } H_2O}{\Delta P}$$

where ΔP has units of H_2O.

In terms of the volumetric flow rate the relative differential pressure error is

$$e_{\Delta P} = \pm \frac{0.256 \text{ in. } H_2O\ c^2}{\dot{V}^2} \qquad (3.24)$$

where c^2 has units of gpm/(in. $H_2O)^{½}$ and $\dot{V}^2$ is in gpm.

Hence, the relative error depends on the inverse of the square of the volumetric flow rate.

Determination of $e_{\Delta T}$

The temperature difference is defined by taking the difference between the cold water return temperature and the cold water supply temperature. In order to determine $e_{\Delta T}$, $e_{\Delta T}$ must be related to the errors in the cold water supply and return temperature measurements. This relationship is derived as follows

Define T_R = Return temperature, F

T_S = Supply temperature, F

therefore, $\Delta T = T_R - T_S$.

Also, $\Delta T = \Delta T\ (T_R, T_S)$

The total differential is

$$d\Delta T = \frac{\partial \Delta T}{\partial T_R} dT_R + \frac{\partial \Delta T}{\partial T_S} dT_S$$

where

$$\frac{\partial \Delta T}{\partial T_R} = \frac{\partial (T_R - T_S)}{\partial T_R} = 1$$

and

$$\frac{\partial \Delta T}{\partial T_S} = \frac{\partial (T_R - T_S)}{\partial T} = -1 .$$

Therefore,

$$d\Delta T = (1)\ dT_R - (1)\ dT_S$$

or

$$E_{\Delta T} = E_{T_R} - E_{T_S} \tag{3.25}$$

Up to this point the parameters in equation (3.7) have been determined from independent measurements. For example, the flow rate measurement consisted of a venturi meter, a pressure transducer/transmitter, and an Acurex. The temperature difference parameter utilizes two possibly dependent temperature measurements. The reason for the possible dependence is that the temperature measurements employ a common data logger (Acurex). (It is noted that the errors introduced by the Acurex for all measurements have been included in the error analysis). It is conservative to assume that the temperature difference parameter incorporates two independent measurements. This assumption is conservative because common errors introduced by the Acurex would tend to cancel each other. The errors would cancel because the temperature difference parameter involves a difference of two temperature measurements. For example, a common Acurex error of 0.1 F in a temperature measurement would be eliminated in the temperature difference determination.

From the reasoning in the previous paragraph the temperature measurements are treated as being independent, therefore an rms is taken to obtain

$$E_{\Delta T} = \pm \sqrt{(E_{TR})^2 + (-E_{TS})^2} \qquad (3.26)$$

where $e_{\Delta T}$ is related to $E_{\Delta T}$ by

$$e_{\Delta T} = \frac{E_{\Delta T}}{\Delta T} \qquad (3.27)$$

The next step is to determine the absolute errors in E_{TR} and E_{TS}.

Temperature Measurement Error

As described earlier, HyCal matched temperature transmitters output the supply of return temperatures in a 4 - 20 ma current signal. The Acurex converts this current signal to a number ranging from 0 to 100 via an input card 25 ohm precision resistor and an A/D converter. Also, the temperature transmitters are zeroed and spanned with a precision decade box which simulates an RTD resistance.

The relevant errors in the process are as follows:

$$E_{\text{temperature transmitter}} = \pm\ 0.25°F$$

$$E_{\text{Acurex analog signal}} = \pm\ \frac{0.00012\ *(\text{Temperature, °F})}{2.5}$$

$$E_{\text{Acurex A/D round off}} = \pm\ 0.012°F$$

$$E_{\text{least count}} = \pm\ 0.05°F$$

$$E_{\text{Calibration}} = \pm\ 0.1°F$$

$$E_{\text{Calibration Input}} = \pm\ 0.0468°F$$

For cooling $E_{\text{Acurex Analog Signal}} = \frac{0.00012\ (55°F)}{2.5} =$ 0.00264 F for the worst case. Using the above components and taking a root mean square (rms) combination

$$E_{TR} = E_{TS} = ((0.25)^2 + (0.00264)^2 + (0.012)^2$$

$$(0.05)^2 + (0.1)^2 + (0.0468)^2)^{½} = \pm\ 0.278°F$$

Therefore the absolute error in temperature difference is:

$$E_{\Delta T} = \pm \sqrt{(0.278)^2 + (0.278)^2} = \pm\ 0.39°F$$

$$E_{\Delta T} = \pm\ 0.39°F \tag{3.28}$$

$$e_{\Delta T} = \pm \frac{0.39°F}{\Delta T} \tag{3.29}$$

where, ΔT is in °F.

It should be noted that it was difficult to achieve a 0.0°F zero at calibration. Repeated calibration seemed to strain the temperature transmitters and caused large drifts. For these reasons, it was not always desirable or possible to achieve a precisely calibrated zero. If such a zero was achieved via calibration or software correction (for both return and supply temperature comments). The error would be reduced to

$$e_{\Delta T} = \pm \frac{0.37}{\Delta T} \tag{3.30}$$

where, ΔT has units of °F.

Substituting (3.23), (3.24), (3.30) into equation (3.22) the relative error in the energy measurement is

$$e_{\dot{Q}} = \pm \sqrt{(0.02)^2 + [0.5(\frac{0.256c^2}{\dot{V}^2})]^2 + (\frac{0.39}{\Delta T})^2} \tag{3.31}$$

where

c^2 has units of gpm/(in. $H_2O)^{½}$,

$\dot{V}$ is in gpm, and

ΔT is in °F.

Building Heating Description For Building 8025 & 8037

The buildings are heated "internally" by hot water which circulates through wall fin convector and cabinet unit heaters. Wall fin convectors heat output is generally controlled by "air conditioning" thermostats. In the heating mode, hot supply water passes through the convectors while in the non-heat mode a bypass valve prevents hot water from flowing into the convectors. The hot water supply temperature is theoretically set in an inverse manner to the outside dry bulb temperature. Originally, heat addition could also be varied with the use of convector dampers, however it was discovered that nearly all the dampers were removed. The cabinet unit heaters are controlled by individual thermostats and manual/automatic/off fans. These cabinet unit heaters are on/off heat devices with the amount of heat delivered depending on the hot supply water temperature and the fan setting.

The hot water heating loop is supplied via a heat exchanger with heating energy from high pressure steam. The high pressure steam is delivered to the buildings from a central boiler located on Custer Hill. Figures 3.4 and 3.5 show the Steam - Hot Water Heating system input. Steam at around 100 psig enters the building from below ground level. A pressure gauge downstream from the

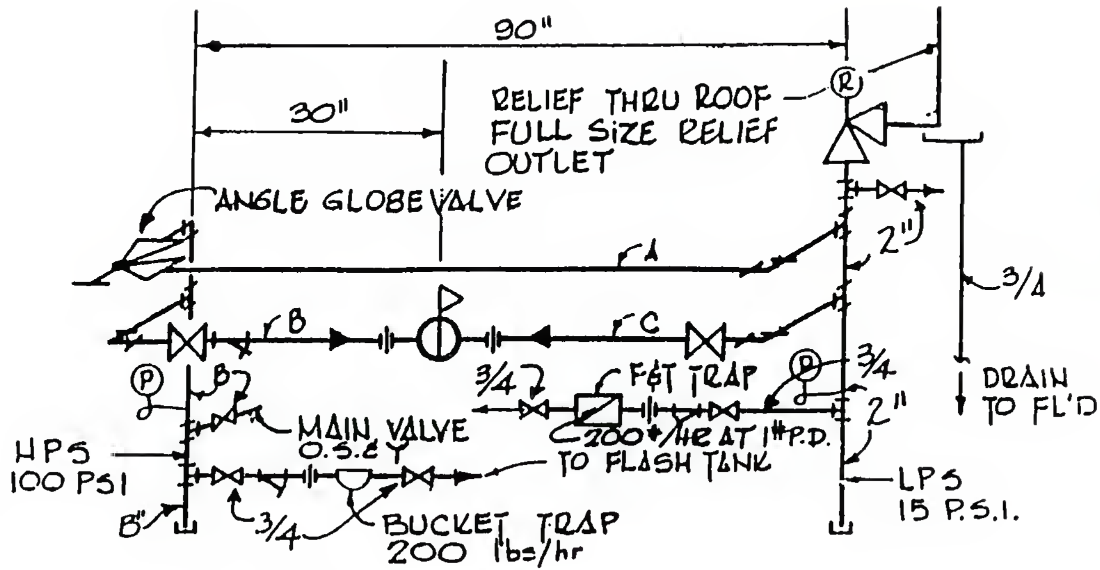


Figure 3.4 Steam-Hot Water Loop Heating System -- High Pressure Steam to Low Pressure Steam Section

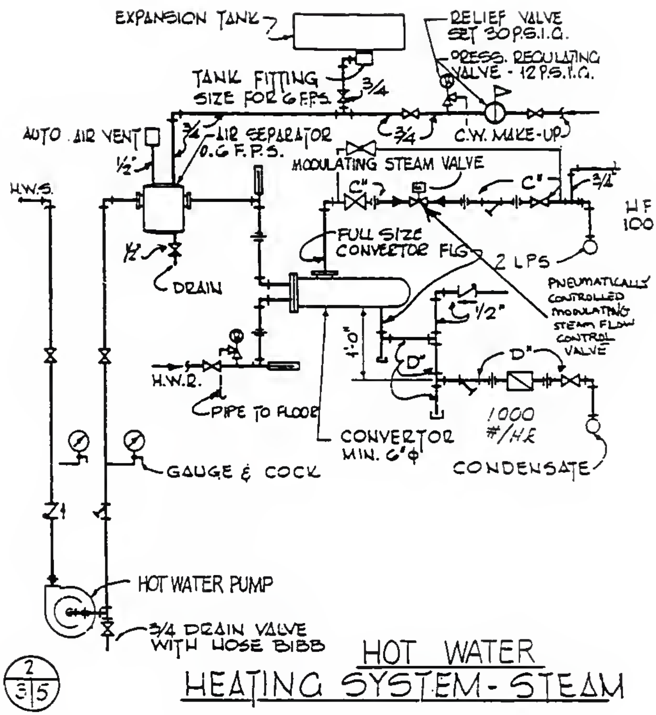


Figure 3.5 Steam-Hot Water Loop Heating System — Low Pressure Steam to Hot Water Loop Section

entrance indicates the steam pressure at the gauge point in psig. The steam is then reduced to a lower pressure via a pressure reducer. The steam next reaches a pneumatically controlled modulating steam valve which controls the amount of steam input in response to the outside air temperature and the hot water supply temperature.

The heating control schedule specified calls for the HWS temperature to be 200 F when the outside dry bulb temperature is 0 F. When the outside dry bulb temperature is 70 F the schedule calls for the HWS temperature to be 80 F. Inbetween these set points the hot water supply temperature varies in a linear manner. However, the heating control schedule apparently adopted was issued by Johnson Controls. In this control schedule the set points are 195 F and 70 F which correspond to the outside dry bulb temperatures of 0 F and 60 F, respectively. Again, inbetween the setpoints the hot water supply temperature versus outside dry bulk temperature varies in a linear manner. It should be noted that there is another controller which turns the hot water loop pump off and closes the valve to prevent incoming steam when the outside air thermostat is at 60 F or higher.

Steam traps are placed throughout the steam loop to remove condensate from wet steam. The condensate is then returned to the condensate return pump which pumps the condensate back to the boiler. The steam that reaches the heat exchanger warms the returning hot water and then it condenses. This condensate is also returned to the boiler via the condensate return pump.

Building Heating Energy Consumption Measurement

Similar to the cooling energy measurement, there are two independent measurements which determine the building heating energy consumption (in this case, one primary and the other a secondary measurement). In the primary measurement, heat addition into the hot water loop is determined from flow rates and temperature drops in the hot water supply and return lines. This scheme is identical to the cooling energy measurement system and utilizes the same equipment and instrumentation. The secondary measurement scheme measures the amount of steam condensate and correlates that measurement to the overall building heating energy consumption. This measurement acts as a check for the primary measurement.

Hot Water Loop Heating Energy Consumption Measurement

As stated above, the hot water loop heating energy measurement scheme is identical to the cooling energy measurement scheme and utilizes the same kind of equipment and instrumentation. Therefore, the only differences in any of the relationships developed for the cooling energy measurement scheme (e.g., volumetric flow rate relationships, energy equation, etc.) are due to differences in water temperatures which affect water properties. Because many relationships are identical, only more salient relations will be discussed.

Volumetric Flow Rate vs Differential Pressure

The venturi used in the hot water loop is identical to the venturi in the main cold water supply and is located in the hot water supply line. Therefore without correcting for different fluid properties the volumetric flow vs differential pressure relationship is

$$\dot{V} = 10.01\sqrt{\Delta P} \qquad (3.31)$$

The above relationship can be modified to include the effects of temperature on water properties by using information provided by the venturi manufacturer. The manufacturer presents this information in graphical form shown in Figure 3.6. Thus at any temperature, equation 3.3 can be modified to incorporate the different fluid properties (basically the different water densities). Project data shows that the hot water temperature at the venturi is in general between 120 F and 160 F. Therefore,

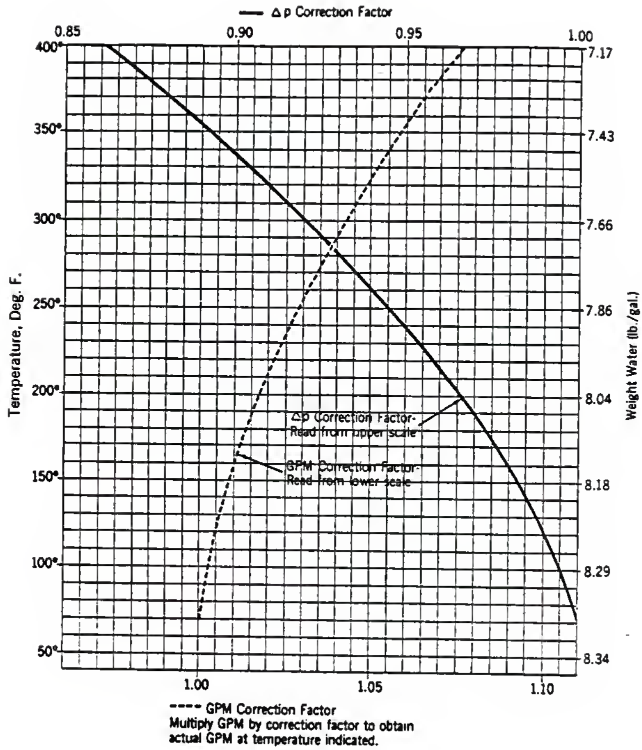


Figure 3.6 Manufacturer's Flow Rate Correction for Temperature
Source: Aeroquip Literature

a constant correction factor of 1.0075 will represent correction factors within ± 0.0025 or less than 0.3% error. If this typical value is accepted (this acceptance is appropriate because it introduces a negligible error) the hot water loop volumetric flow rate vs differential pressure relationship becomes

$$\dot{V} = 10.085\sqrt{\Delta P} \qquad (3.32)$$

Error Analysis

Recall in the cooling season error analysis that $\dot{Q} = 8.020833\rho c_p \dot{V}\Delta T$ equation (3.20) was reduced to $\dot{Q} = 500.67*\dot{V}*\Delta T$ equation (3.21) with a negligible error being introduced. The reduction was valid because the product of specific heat and density had virtually no variability with pressure and very small dependence on temperature for the relevant pressure and temperature ranges. Table 3.2 shows the product of density, specific heat, and the conversion factor for relevant hot water temperatures (9). It is noted that there was essentially no variability in the product of specific heat and density with pressure over the 15 - 70 psia range.

Table 3.2: Product of density, specific heat at constant pressure, and the conversion factor for relevant hot water temperatures

Pressure ranges 15 - 70 psia

Temperature	$8.020833\rho c_p \frac{Btu}{hr \cdot gpm \cdot F}$
100 F	494.775
110 F	493.857
120 F	495.113
140 F	492.378
160 F	489.374
165 F	488.482
170 F	487.589
190 F	485.994

* Note linear interpolation used when needed

Once one has knowledge of the temperature (hot water supply and return temperature) it is a simply matter to compute the $8.020833*\rho*c_p$ in the energy equation. Heating data indicate that in general the temperature is between 100 F and 165 F and pressure ranges from 15 - 70 psia.

For this temperature range, a product of $8.020833\rho c_p$ equal to 492.378 would result in an error less than 0.8 %. Hence, equation (3.20) can be reduced to

$$\dot{Q} = 492.378 * \dot{V} * \Delta T \tag{3.33}$$

where,

$\dot{Q}$ = heat energy into hot water loop, Btu

$\dot{V}$ = volumetric flow rate, gpm

ΔT = difference in supply and return temperatures, F which introduces an error sufficiently small (0.8%) that it can be disregarded.

The cooling measurement error analysis revealed that

$$e_{\dot{Q}} = \pm \sqrt{e_\rho^2 + e_{c_p}^2 + e_c^2 + (0.5\ e_{\Delta P})^2 + e_{\Delta T}^2} \tag{3.19}$$

Since the error in the product of $\rho * c_p$ is negligible as it was in the cooling measurement equation the relative error in the heating energy measurement is

$$e_{\dot{Q}} = \pm \sqrt{e_c^2 + (0.5\ e_{\Delta P})^2 + e_{\Delta T}^2} \tag{3.34}$$

Errors in the venturi meter, differential pressure, and temperature difference are independent, therefore substituting equations (3.23), (3.24), (3.30) results in

$$e_{\dot{Q}} = \pm \sqrt{(0.02)^2 + (\frac{0.256c}{\dot{V}^2}) + (\frac{0.39}{\Delta T})^2} \tag{3.35}$$

Demonstration of Relative Error Equations

To demonstrate the error in a typical cooling energy consumption measurement, verified data from Building 8025 on September 17,1987 was chosen to analyze. For this day there was always a cooling load on the system. The average temperature difference in the main lines was 3.0 F with a corresponding cold water supply volumetric flow rate of 68.6 gpm. Therefore, from equation (3.31) the relative error in the measurement is

$$e_{\dot{Q}} = \pm \sqrt{(0.02)^2 + [0.5 \ (\frac{0.256(10.01)^2}{(68.6)^2})]^2 + (\frac{0.39}{3})^2}$$

$$e_{\dot{Q}} = \pm \sqrt{(0.02)^2 + (0.0027)^2 + (0.13)^2}$$

$$e_{\dot{Q}} \approx \pm \ 13\%.$$

In order to demonstrate the heating hot water energy consumption measurement, verified February 26, 1987 was chosen. On this day the average water temperature drop in the main lines of Building 8025 was 3.3 F with a corresponding flow rate of 46.7 gpm. Substituting the appropriate values into equation (3.35), the equation equates to

$$e_{\dot{Q}} = \pm \sqrt{(0.02)^2 + [0.5 \ \frac{(0.0256)(10.085)^2}{(46.67)^2}]^2 + (\frac{0.39}{3.3})^2}$$

$$e_{\dot{Q}} = \pm \sqrt{(0.02)^2 + (0.0060)^2 + (0.118)^2}$$

$$e_{\dot{Q}} \approx \pm 12\% .$$

Building 8037 February 26, 1987 energy data will also be demonstrated because typically this building has higher (than Building 8025) temperature differences and lower volumetric flow rates. The daily average temperature drop was 6.2 F with a corresponding flow rate of 24 gpm. Equation (3.35) for these values becomes

$$e_{\dot{Q}} = \pm \sqrt{(0.02)^2 + [0.5 \frac{0.0256)(10.085)^2}{(24)^2}]^2 + (\frac{0.39}{0.2})^2}$$

$$e_{\dot{Q}} = \pm \sqrt{(0.02)^2 + (0.02269)^2 + (0.0629)^2}$$

$$e_{\dot{Q}} \approx \pm 7\% .$$

Condensate Return Heating Energy Consumption Measurement

In this measurement system, the amount of condensate returned to the boiler is measured. This can in theory be correlated to the amount of heating energy consumed. As described earlier, high pressure steam enters the building and a pressure gauge near the steam inlet indicates the pressure. The exact condition of the entering steam is unknown but in general it is wet steam. A steam trap near the steam inlet removes the condensate from the incoming wet steam. This high pressure condensate travels to a flash tank where some of the condensate is flashed to low pressure steam while the rest travels as a low pressure condensate to the condensate return pump. It is noted that the condensate return pump is an on/off float controlled pump. The rest of the high pressure steam is throttled to a low pressure and modulated to the hot water - steam heat exchanger as required. In these processes, condensate is returned to the condensate return pump with the help of steam traps as needed.

Classical thermodynamics will be used here to examine the difficulties involved in determining the energy consumption from a condensate return measurement system. By the first law of thermodynamics:

$$\dot{Q} = \dot{m}\,(h_s - h_c)$$

$\dot{Q}$ = amount of heating energy transferred to building in an hour

$\dot{m}$ = hourly rate at which condensate is returned

h_s = average enthalpy of steam entering building

h_c = enthalpy of condensate in the tank prior to leaving building.

The most significant variable in terms of magnitude is the enthalpy of the incoming steam. Unfortunately, there is one major problem in determining this property: the incoming stream quality is unknown. A very wet steam has a noticably lower enthalpy compared to the enthalpy of dry steam. A minor problem is that the accuracy of pressure gage is unknown and it was not feasible to continuously monitor this pressure gage. However, wet steam with an incoming high pressure between 105 psia and 125 psia has an enthalpy between 1188.0 Btu/lb and 1191.1 Btu/lb (9). Hence, the incoming steam enthalpies vary insignificantly with pressure (over the relevant pressure ranges).

Another property which needs to be determined is the enthalpy of the condensate prior to leaving the tank. The temperature of the condensate in the condensate tank prior to leaving the tank should be between 80 F and 200 F. Therefore, the corresponding enthalpies are between 48.1 Btu/lb and 168.1 Btu/lb. This enthalpy could be determined precisely if the condensate temperature in the condensate return tank was monitored.

Clearly, the greatest obstacle in using the secondary measurement system is determining the incoming steam quality. It is possible to determine a typical incoming steam quality by combining the hot water loop measurement with the condensate return measurement. Such an attempt was not made directly. However, collected heating data has shown that the condensate usage is "proportional" to the actual heating energy consumption. A proportionality "constant" for each building was empirically determined and is generally time invariant. In principle, this empirical constant could be used to determine a typical steam quality for each building. Chapter 5 will address some of these matters in greater detail.

Chapter 4

Verification of Measurement Systems

General Discussion

In order to assure that measurements are accurate, there must be conclusive evidence that the measurand data corresponds precisely with the actual measurand. The process of verifying data depends on the measurement and the equipment and instrumentation. In many cases, the instrumentation and equipment only requires yearly or seasonally verification. An example is the volumetric meters which measure the domestic hot water and condensate returned. In other cases, equipment and instrumentation must be checked on a nearly continuous basis. Equipment and instrumentation are calibrated and checked biweekly. In addition, weekly measurement checks through software have provided a tool for verifying data and investigating suspicious data. For example, in the cooling energy measurement system the independent energy measurements are compared against each other (sum of the three air handler load versus the main cooling load measurement systems comparison). A favorable agreement (along with properly calibrated instrumentation) gives strong evidence that the data accurately represents the true measurand and hence the data are verified.

As discussed above, the process of verifying data depends on the measurement and equipment and instrumentation used. Therefore, each measurement system verification will be discussed separately (except for the water and air temperature measurements). The first verification to be discussed is the verification of the cooling and hot water loop energy measurement system data. Then the verification and brief description of the volumetric flow meters will be discussed. Verification of the electric meter energy consumption measurements will not be included in this report. Also ommitted is a discussion on the domestic hot water (electric type) energy consumption measurement which uses a volumetric flow meter and domestic water supply and return temperature measurements. (It is noted that the domestic hot water measurement scheme may be inadequate.)

Verification of the Cooling and Hot Water Loop Energy Measurement Systems

General Discussion

In determining the building energy consumption (cooling or heating) with the cooling and hot water loop energy measurement systems, a number of independent measurements are taken. Therefore, each measurement needs to be verified, i.e., the flow rate and temperature measurements must compare accurately with their true measurand. In order to have accurate measurements, equipment must be properly installed, calibrated, and maintained. Also, experience with some of the instrumentation (namely the temperature transmitters) has revealed that the instruments occasionally have large drifts a few hours after a calibration which causes erroneous data. Therefore, the data needed to be checked frequently (weekly) for dubious phenomenon.

In a couple of instances, data conflicted with building heating or cooling air conditioning design control schedules. In the process of investigating the validity of the data, it was discovered that the actual building air conditioning operation was in disagreement with design specifications. Examples of these investigations will be discussed in this chapter and in Chapter 5.

Flow Rate Measurement System Verification

The flow rate measurement system uses a venturi meter along with a pressure transducer which outputs a current signal read by the Acurex. This flow rate measuring system consists of two components which need to verified: the venturi meter and the pressure transducer. It is unfeasible to install additional meters to verify that the venturi meters are within their specified accuracy -- ± 2% of true value (gpm). The system was installed by a professional and inspected by other experts and it is believed that the venturi meters were installed correctly. This normally means (industry's experiences with venturi meters) the venturi will stay within the manufacterer's specified accuracy. In addition, a venturi meter does not require maintenance unless the venturi taps become obstructed with dirt, pipe scale, or other contaminants. In the event of a venturi tap clog, the clog can be removed with a wire brush or by back flushing. Weekly data checks of flow measurements and pressure transducer line bleeding techniques were used to identify possible improper venturi tap conditions.

To measure the differential pressure from a venturi meter a Viatran 323 differential pressure transducer was used. The pressure transducers have a pressure range of 0-100 inches of water that correspond to a 4-20 ma signal output.

The pressure transducer is the only instrumentation that requires a calibration in the flow rate measurement system. Initially, calibration followed only the manufacturer's calibration technique guidelines. Later, a new calibration was developed because the original procedure lacked one key element -- a proper pressure transducer bleeding technique (this is discussed more in the next paragraph). Also, the calibration procedure developed uses the entire pressure measurement system: pressure transducer, all relevant electric leads, and a data logger (Acurex) to reduce systematic errors. The calibration technique involves a "standard" two point calibration -- zero and span. In order to zero the pressure transducer, a zero differential pressure is inputed. This is accomplished, as shown in Figure 4.1, by fully closing valves 1 & 2 and opening valve 3. The opening of valve 3 allows the pressure differential across the diaphragm to be reduced to zero. The transducer is spanned by electronically simulating full scale pressure (or a designated pressure very near 100 in H_2O). This is accomplished by shorting pins 3 and 4. Required adjustments can be made by adjusting zero and span resistor pots located on the front panel of the transducer.

Remarkably, bleeding of the transducers was never discussed in the available copies of the manufacturer's transducer literature. Unbled transducers contain "air pockets" which apparently caused fluctuating differential pressure readings. An initial and inadequate method for bleeding the transducers "bled" the transducers at a

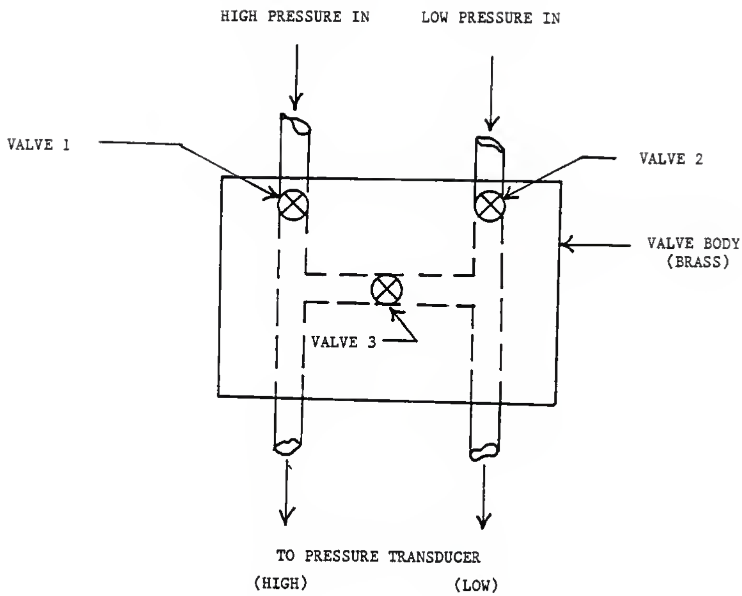


Figure 4.1 Valve Arrangement for Zeroing Pressure Transducer

pressure line fitting just outside the transducer. It was observed that after this bleeding technique the transducers would show unfavorable fluctuations. During a detailed examination of the transducers, it was discovered that four screws -- two on each side -- could be used to bleed the transducer. After bleeding the transducers with the side screws, the transducers showed favorable stability characteristics.

A scheme was developed to verify that the pressure transducers were working properly. Figure 4.2 is a sketch of the equipment setup used in the verification method. A positive gage pressure is applied to the transducer's high pressure port and to the manometer's high pressure port. The transducer's low pressure port is exposed to atmospheric pressure along with the manometer's other port. It is noted that the pressure transducer was calibrated before the procedure. Pressures were applied in 10 mmHg steps throughout a 0-200 mmHg range (as read by the manometer). Appendix G contains the results of a test and additional comments. One bad transducer was found with this technique. It should be noted that this check on the pressure transducers verifies that the measurements are approximately correct. The available manometer was not sufficiently accurate to verify that

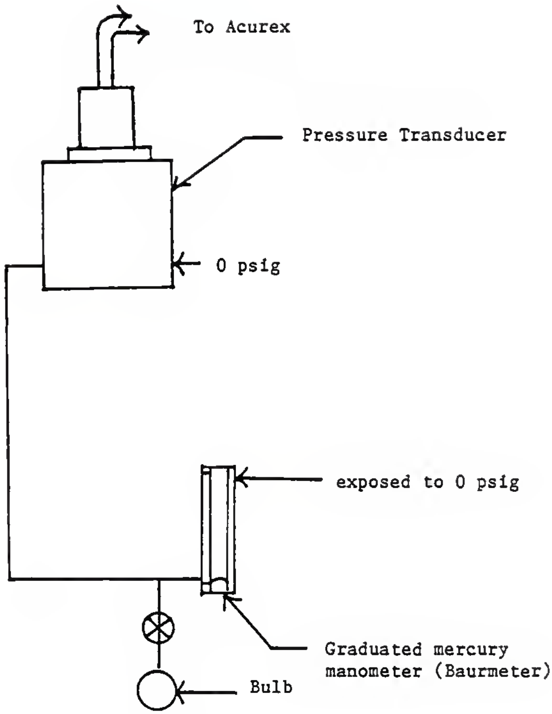


Figure 4.2 Sketch of Equipment Setup
used in Pressure Transducer Verification

the pressure transducers comply with their manufacturer's accuracy specifications.

Continuous checks of the volumetric flow rate data also provided verification of flow measurements. Examples of continuous volumetric flow rate data checks are included in Chapter 5. In general, the results of these checks along with favorable pressure transducer stability (after bleeding) have indicated that the volumetric flow rate data are reliable and accurate. An example of how flow data was used in an investigation which helped to learn about some unusual building cooling system characteristics will be presented. It is noted that an energy balance verifies that the flow measurements are accurate.

Dubious Flow Data Investigation

This example demonstrates how the volumetric flow rate and cooling energy consumption data was used in an investigation to help determine actual building cooling season operating characteristics. Early in the project, it was noticed that volumetric flow rate data collected indicated that the amount of water flow through the air handlers was not equal to the amount water flow through the main lines. This mass imbalance was initially thought to have been due to the bypass valve (see cooling description in Chapter 3). However, a copy of the control schedule was located (in the mechanical equipment room) and the problem was discussed with a U.S. Corps of Engineers engineer (10) in charge of Building 8025 & 8037 HVAC operations. From the information gathered, it was learned that the bypass scheme is an on/off device, i.e., either the supply flows through the air handling units or it never enters the air handling units (it is bypassed). The engineer stated that it is very unlikely that the bypass valve would leak over 1 gpm. The problem was then thought to be with the pressure transducers. An improved calibration procedure which incorporated a better pressure transducer bleed technique was then developed (this was discussed earlier). However, the incoming data still indicated a mass imbalance.

A test was conducted and it was concluded that there is flow in the bypass when the system is in the on state (see control schedule). Figure 4.3 is a sketch of the cold water piping.

Flow through an air handler can be prevented by closing a gate valve in the air handler's cold water return line. With the system "on", the air handlers' gate valves were closed and it was observed that there was flow in the main line. For this to occur, the flow must have gone through the bypass piping. Also, the system was

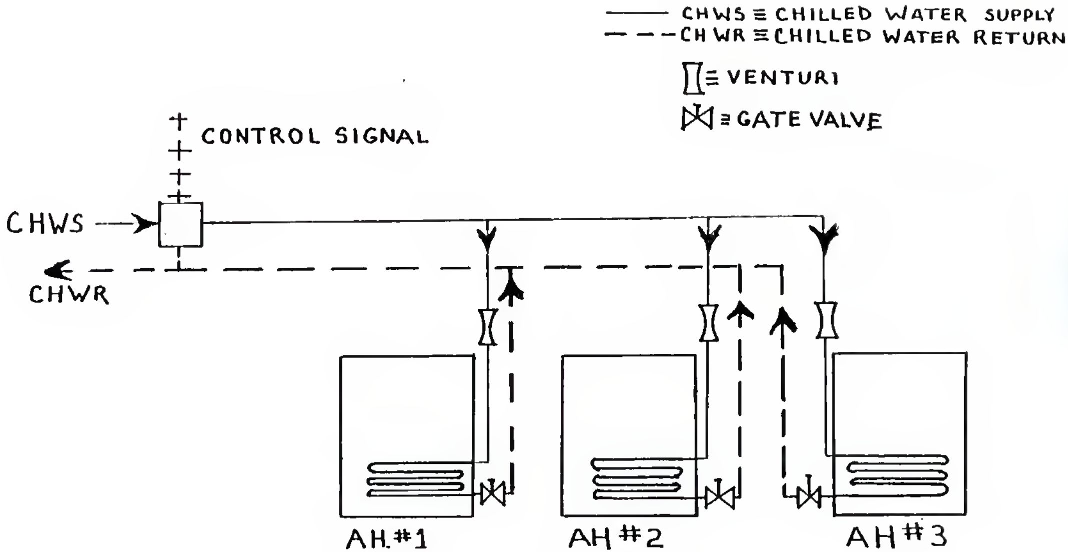


Figure 4.3 Sketch of Chilled Water Piping

tested in the "on" state with different combinations of air handlers on and air handlers off (gate valve closed). These tests also confirm flow through the bypass. The results of the tests are included in the Appendix H.

Note that because there is flow thru the bypass when the system is on, proper data collection does not require the sum of the three air handlers' flow rates be equal to the system flow rate. However, an energy balance is still required (and did exist after the pressure transducers were properly bled), i.e., the sum of the three air handlers energy cooling load must be equal to the cooling load in the main chilled water lines.

Temperature Measurement Verification

The temperature measuring system was discussed earlier in Chapter 3. Figure 4.4 is a schematic of the Transmitter-RTD installation. The transmitter outputs a linear 4 - 20 milliamp current corresponding to its RTD input. In general the RTD and temperature transmitters were installed correctly. However, it is important to note that on the transmitter to RTD shielded cable, the shield is tied only at the transmitter. In several cases, the aluminum foil shield was touching the RTD's housing and therefore grounding the shield there. This created current ground loops which caused instrumentation problems

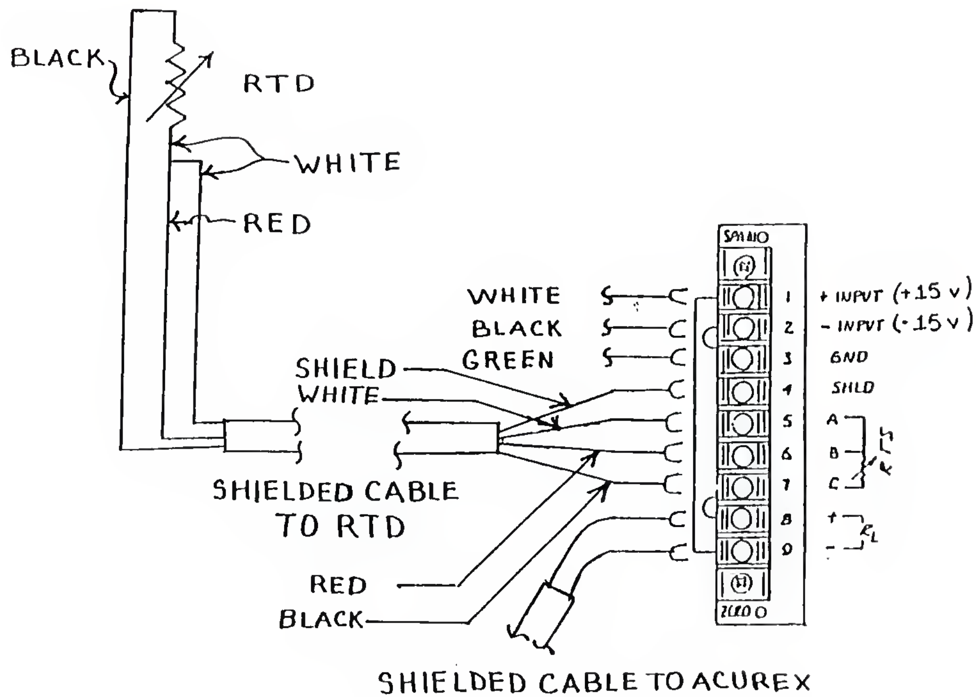


Figure 4.4 RTD-Transmitter Installation

and erroneous data. After eliminating these grounds and developing an appropriate calibration technique, the temperature measurements were very reliable as long as there was little temperature transmitter drift.

It was not feasible to install additional RTD sensors to verify that the temperature transmitters were within their specified accuracy. Although, it is possible to cut through pipe insulation and use thermocouples to obtain an estimate of the water temperature (outside pipe temperature), one would not expect accuracies (actual water temperature) to be better than ± 1 F. These accuracies of the check are unacceptable.

The air temperature measurement scheme is identical to the water temperature scheme with exception of the temperature transmitter ranges (air:40 - 100 F; water:0 - 250 F). The RTD temperature transmitters are placed adjacent to wall temperature thermostat thermometers. The RTD temperature measurements were compared periodically (trimonthly) with the wall thermostat thermometers. In general, the temperature measurements were in within ± 2 F of each other.

A temperature transmitter calibration technique was developed based on the Hy-Cal operation and maintenance manual calibration scheme. In the technique, "definite" temperatures are simulated (i.e., RTD resistances with

Siemen's lead arrangement) and the transmitter's outputs are adjusted to match the inputs. A known resistance (decade box set resistance) simulates the "definite" temperatures according to known platinum ohm resistance vs. temperature characteristics. To minimize error, the Acurex is used to monitor the output of the transmitters (just as in normal operation). The programmed Acurex displays the output of a transmitter as a temperature (the true measurand). To fulfill calibration requirements, the Acurex which has a precision resistor (25 ohm ± 0.05 % accuracy) and a precision voltmeter is used directly in the calibration. Calibrating directly with respect to the Acurex eliminates systematic errors do to the Acurex. Appendix I gives a discussion and description of a temperature transmitter calibration procedure (valid for water and air measurements).

During the cooling season there were sometimes temperature transmitter drifts a few hours after the calibration, up to a couple of degrees Fahrenheit. This drift would drastically affect energy consumption calculations in the measurement system containing the temperature transmitter. Therefore it was necessary to continuously validate the temperature measurements. In practice, the temperature measurements were checked at least weekly via software (modem downloading of data and

LOTUS spread sheets). A number of different techniques were developed to properly identify dubious data and verify the collected data. Examples of these techniques will be discussed in Chapter 5.

Verification of Energy Consumption Measurement Algorithm

In any time varying study involving data loggers it is important that appropriate software be developed and properly utilized. As previously indicated, temperatures and flow rates were recorded every minute. It is desired to use this data to compute hourly thermal energy consumption data. At the beginning of the project an inaccurate algorithm was used. In this algorithm, an Acurex program first averaged all the temperatures and flow rates for an hour then it computed the difference in average temperatures and the respective average flow rate. The product of the average hourly temperature difference and respective average flow rate was used to compute the hourly energy consumption. One of the problems with this algorithm is that temperatures are being weighted into energy consumption calculation even when they have no relation to energy consumption. Dubious data was soon noticed and the inaccurate algorithm discovered.

For energy consumption to be properly calculated it must be determined by using instantaneous temperature differences along with their corresponding flow rates. Mathematically this can be demonstrated by,

$$Q = \int_{t_b}^{t_f} \dot{m} * c_p \, \Delta T \, dt$$

where

Q = hourly energy

t_b = beginning of hour

t_f = end of hour

t = time

$\dot{m}$ = mass flow rate

c_p = specific heat at constant pressure

ΔT = temperature difference

Notice,

$$\int_{t_b}^{t_f} \dot{m} c_p \Delta T \, dt \neq \int_{t_b}^{t_f} \dot{m} \, dt \int_{t_b}^{t_f} c_p \Delta T \, dt.$$

All of the energy consumption data calculated from by the original algorithm may not be erroneous. Consider the case in which the flow rate is constant then

$$\int_{t_b}^{t_f} \dot{m} * c_p * \Delta T \, dt = \int_{t_b}^{t_f} \dot{m} \int_{t_b}^{t_f} c_p * \Delta T \, dt.$$

In this case the original (an generally incorrect) algorithm will work.

The Acurex was programmed to calculate energy consumption using the correct algorithm. The data logger recorded measurands and calculated energy consumption every minute. Next, the minutely energy consumption data was summed to determine hourly energy consumption. Hourly building energy consumption data were stored by the Acurex and downloaded to a PC via modem. Later, the raw Acurex output data was manipulated into a more usable form.

Verification of Volumetric Flow Meters

Volumetric water flow meters were installed to measure domestic hot water usage and the amount of condensate with accuracies within ± 2%. The water meters were Badger Industrial Magnetic Drive Disc meters with a magnetic drive gear train adapter, direct reading indicator, and pulse output (resistance) (Badger Model MS-ER1). These meters are designed for liquids with temperatures up to 250 F. A test was conducted to determine the accuracy and reliability of the volumetric water meters. Water was allowed to flow through the domestic hot water meter and was collected volumetric in a measurement beaker. The volume of water in the beaker was compared to the direct reading indicator on the water meter. The flow measurements were in consistent agreement (within ± 1%). Also, the water meter's direct reading indicator agrees exactly with the meter's pulse output. It is noted that the volumetric meter pulses every gallon.

The condensate usage meters could not be tested in the field. However, Chapter 5 will show that the condensate usage energy measurements are in excellent agreement with the hot water loop measurement. Also, the reading indicator on the condensate meter agrees exactly with the meter's pulse output. Therefore, there is strong evidence that the condensate meter accurately measures the amount of condensate.

Verification of Energy Data on a Continuous Basis

Essential to the project are accurate building energy consumption data. As mentioned in Chapter 3, there are two independent energy consumption measurements being taken for both heating (hot water loop and condensate return) and cooling (main chilled water line's cooling energy load and sum of three air handlers cooling energy load) energy consumption measurements. In order for two independent (heating cooling) energy measurements to be accurate both need to indicate (or nearly indicate) identical energy consumption measurements on a continuous basis. This thesis will refer to this two equal energy independent measurement, event as an *energy balance*. An energy balance along with the proper calibration of instrumentation gives strong evidence to support that all relevant energy consumption measurements are accurate.

In practice, individual measurements (e.g., water temperature measurements) are normally investigated for dubious data only when an energy balance does not exist. In the event of an energy imbalance, temperature measurements are first investigated because of the temperature transmitters (earlier) tendency to drift after a calibration. Flow rates are also investigated for suspicious data.

Chapter 5 is devoted to providing actual examples of verified energy measurements, erroneous energy measurements, and dubious data investigations. Chapter 5 will include some of the highlights of the October 1986 - February 1987 heating season data. Also included is a discussion of the 1986 summer cooling data. Unfortunately some of this cooling data will be difficult to validate. Finally, in some of the examples, dubious data were verified and some peculiar building HVAC operating characteristics were revealed.

Chapter 5

Data Verification and Observed Building Thermal Characteristics

In this chapter, examples of how energy data are verified on a continuous basis along with suspicious data investigations will be discussed. Examples from the heating energy consumption measurements are presented first because all of the heating energy consumption data have been verified. Then examples from the cooling energy consumption measurements are given. Unfortunately, it will be difficult to determine the accuracy of some of the cooling energy data because in these cases there was not an energy balance (see Chapter 4 for definition of energy balance).

Verification of Heating Energy Consumption Measurements and Suspicious Data Investigation Procedures

The first part of this section presents some theoretical background for the continuous energy measurement verification procedures. Symbols and definitions that have been developed will be presented as needed. Next, an example of an investigation of unusual Building 8037 heating energy consumption data will be discussed. The purposes of the example are to illustrate some continuous heating energy measurement verification procedures and suspicious data investigation tools. Additional purposes include describing Building 8025 and Building 8037 heating season thermal characteristics and demonstrating the theoretical based verification procedures and the LOTUS plots developed which are used in data verification procedures and investigations.

Verification of Heating Energy Measurement

Background and Terminology

The primary measurement for heating energy consumption is from the hot water loop measurement and the secondary measurement is from the condensate return flow measurement. The condensate return measurement acts as a backup measurement system and as a verification tool for the primary measurement. In addition to the condensate usage measurement, a heating consumption prediction based on the Degree Day method has proven to be useful in verifying data and in identifying dubious data (at least for the two buildings being tested). In order to identify data based on the hot water loop measurements, condensate return measurements, and degree data predictions for the plots shown in this thesis the following symbols are used:

Act = energy consumption from hot water loop measurement

CR = energy consumption based on condensate usage

Pre = degree day based predicted energy consumption

Note that in order to clarify the building, the suffix 37 will be added to Building 8037 data and the suffix 25 will be added to Building 8025 data (e.g., Act 37).

Several months of heating energy consumption data have revealed that the amount of condensate return is directly proportional to the amount of heating energy consumed. Furthermore, for every month there is a constant when multiplied by the amount of daily condensate returned (in gallons) very nearly equals the daily hot water loop energy consumption measurement for all days. In equation form,

CR = (amount of condensate return)*constant

where,

The monthly constant has been between 6 and 8.

CR in kBtu

This means that the amount of condensate directly tracks the building energy consumption in a very consistent manner. For example, if the CR decreases and the Act increases "noticably" then the Act data are suspicious.

As mentioned earlier, the prediction based on the degree day method has been useful in verifying data and identifying suspicious data. The prediction is generally defined as

$$Pre = ((65 - OSDBT)*10/C) \text{ in kBtu} \quad (5.1)$$

where,

OSDBT = outside dry bulb temperature (in degrees Fahrenheit)

C = constant

Initially C values were varied until a good correlation between Pre and Act occured (with hourly data points). Data have shown that the C value for a building remains nearly invariant from month to month. This fact is crucial because past consumption data (indicated by C) can be used to predict the present energy consumption. In general, C values range between 2.3 (this along with C=2.5 were typical values for Building 8037) and 2.7 (typical value for Building 8025). It is noted that equation 5.1 gives the hourly predicted energy consumption. To obtain the daily predicted energy consumption one would simply sum all 24 hourly predicted energy consumption values.

Dubious Building 8037 Heating Energy Data

During the early part of the 1986 - 1987 heating season it was noticed that the heating energy consumption in Building 8037 was non-responsive to outside weather conditions. In fact, the heating energy consumption was essentially constant (with the exception of a sudden 25% energy increase observed in early January) prior to

January 27, 1987. This essentially constant energy consumption was comparable to the corresponding maximum energy consumption of Building 8025. Figure 5.1 shows validated Pre, Act25, and Act37 data plotted against time for the month of December. (It is noted that Pre was used here just to establish building energy consumption trends. That is, it was not closely adjusted to match Building 8025s energy consumption data). Note that Building 8025s consumption tracks the predicted energy consumption as expected.

A building on-site investigation of the "problem" was conducted on January 16, 1987 and serval observations were noted. One, the sudden 25% energy increase in early January was not due to a mechanical room unit heater which was thought to have been in continuous operation. Two, there was continuous operation of a thermostat controlled ventilation exhaust fan located in the mechanical room. The ventilation exhaust fan thermostat setting was set at 40 F. The fan may have been set at 40 F to dry out thoroughly wet hanging ceiling insulation batts caused most likely by a leaky roof and wet weather of that week. Three, outside air intake dampers on each of the three air conditioning units were closed. Although the dampers were apparently properly closed, the air in the duct beyond the dampers was "cold" and it seemed drafty.

Figure 5.1

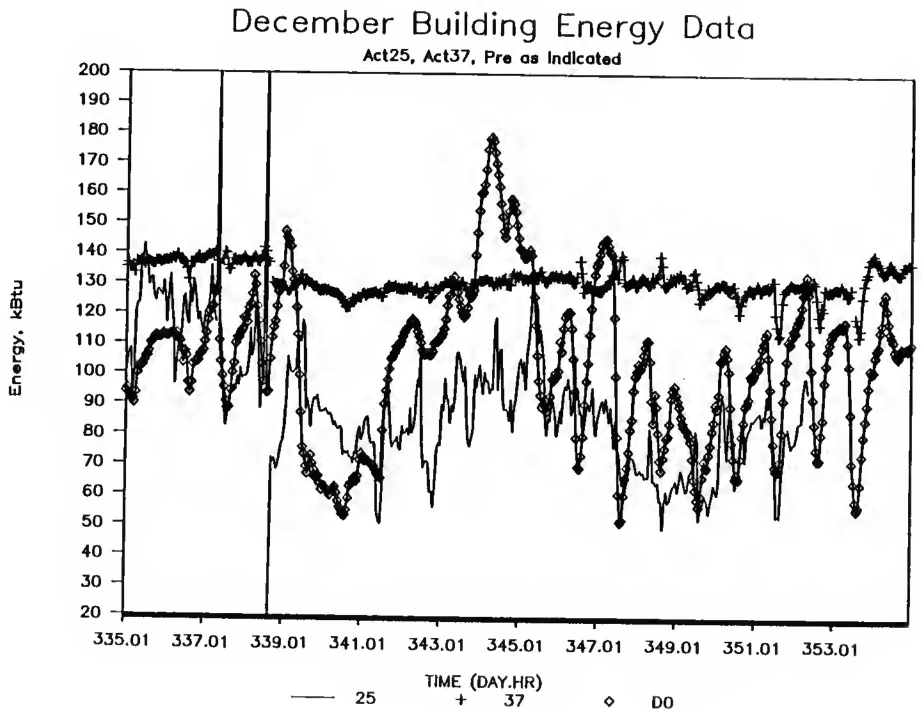

December Building Energy Data
Act25, Act37, Pre as Indicated
Energy, kBtu
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
335.01
337.01
339.01
341.01
343.01
345.01
347.01
349.01
351.01
353.01
TIME (DAY.HR)
25
+ 37
◇ DO

Figure 5.2 is a schematic of damper - outside air intake setup. It is noted that there was to be no attempt to block air flow at the intake louver even though this duct is not designed to be used in the heating season. Four, there seemed to be more occupants in Building 8037 (at least the parking lot was more fully occupied).

All of the above observations suggest that Building 8037 heating system was undersized. However, Building 8037 is identical to Building 8025 which was performing in a predictable manner (its energy consumption was varying with the ambient conditions). Therefore it was concluded that the problem was probably not with the heating system design. Furthermore, it was believed that the problem was probably due to a malfunction in Building 8037 heating system controls. Both Building 8025 and Building 8037 heating controls systems were then investigated.

As discussed in Chapter 3, the hot water supply (HWS) temperature in the hot water loop was designed to be controlled according to the outside dry bulb temperature controlled according to the control schedule. Figure 5.3 is the actual HWS temperature vs outside dry bulb temperature for Building 8025. The outside temperature data is from the Custer Hill weather station and has been verified. The HWS temperature is measured with the hot

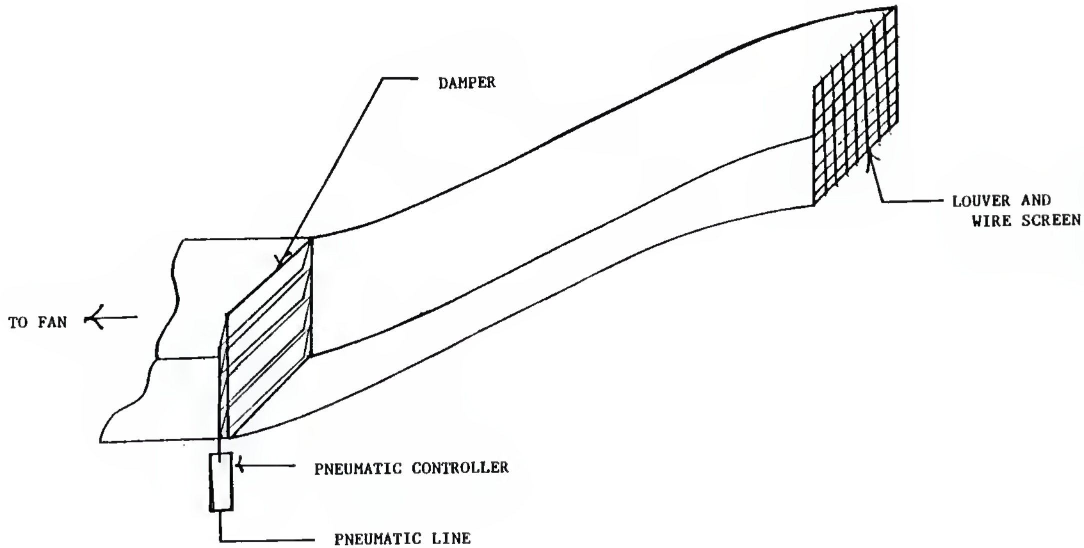
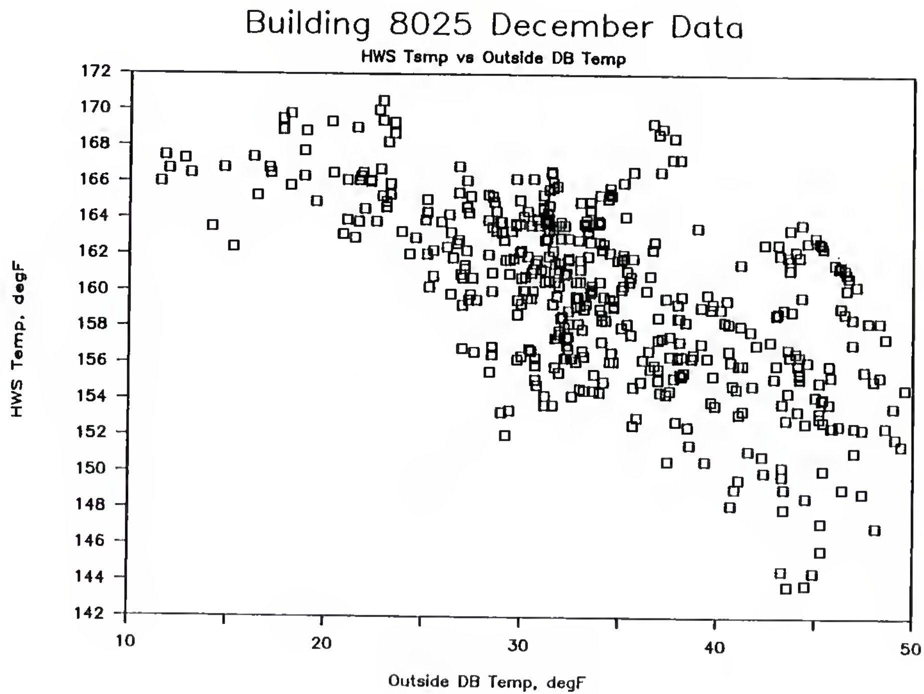


Figure 5.2 Schematic of Damper-Outside Air Intake Setup

Figure 5.3



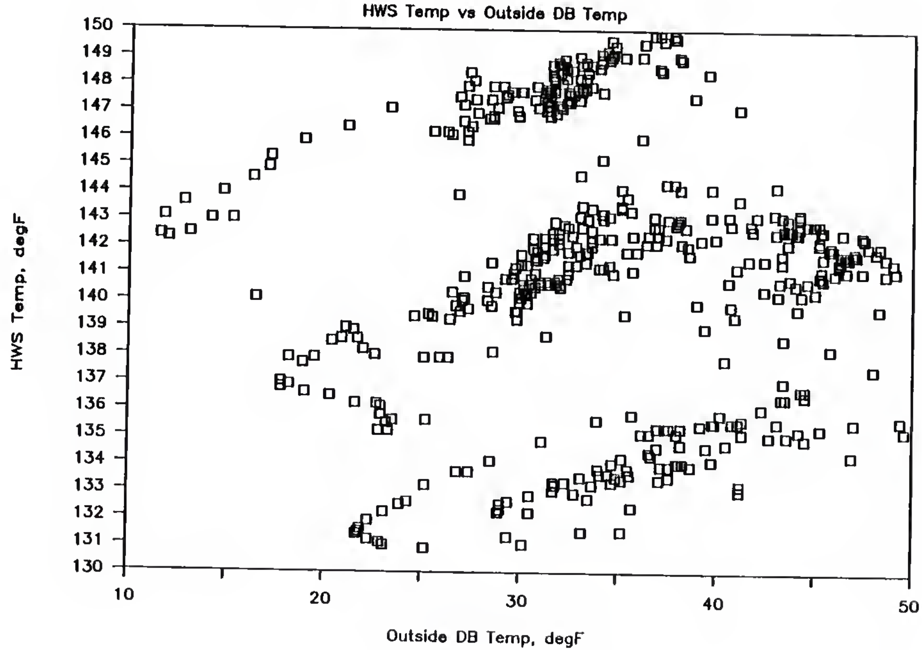
Building 8025 December Data
HWS Temp vs Outside DB Temp
HWS Temp, degF
172
170
168
166
164
162
160
158
156
154
152
150
148
146
144
142
10
20
30
40
50
Outside DB Temp, degF

water loop heating consumption measurement's HWS temperature measurement and it is accurate to within ± 0.3 F. Outside dry bulb temperatures ranged from 10 - 50 F in December. According to the control schedule, the HWS should have a corresponding range of 171.7 - 98.3 F. The HWS temperature corresponded favorably to its control schedule at a outside temperature of 10 F. However, at the higher outside temperatures (50 F), HWS temperatures did not adequately lower. (That is, the HWS temperature did drop with higher outside temperatures, but the drop was not large enough). Due to this phenomenon the system has a stronger than designed capacity to warm the building on mild heating days.

Similarly, Figure 5.4 shows the HWS temperature vs. outside air dry bulb temperature plot for Building 8037. Notice the astounding features of Figure 5.4: 1.) The HWS supply temperature increases with outside temperature instead of decreasing which clearly violates the control strategy. 2.) The HWS temperatures in Building 8037 are lower than in Building 8025 (150-130 F vs 172-142 F). 3.) The three apparent groupings were developed in a chronologic manner i.e., each group occured in a different part of the month. The above phenomena was believed to have been a result of a malfunctioning pneumatically controlled steam flow control valve. If

Figure 5.4

Building 8037 December Data



the valve "sticks" (in this case three times) at various openings then a fixed amount of steam (energy) enters into the building. In this case, the HWS temperature will track the heating load which is basically a positively sloped linear function of the outside dry bulb temperature instead of according to the prescribed control schedule (which basically calls for tracking in an inverse manner to the outside temperature).

From the above discussion, it is evident that there were some "major" problems in the heating control system for Building 8037 and "minor" control problems for Building 8025. The next logical matter to investigate deals with the occupants thermal comfort and their impact on the control system (namely thermostat adjustment). Figures 5.5 and 5.6 each show a plot of two room air temperatures (Room 103 and Room 122) and the outside dry bulb air temperature for the month of December. Basically, the room temperatures in Building 8025 are independent of outside air temperature. However, Building 8037 air temperatures are somewhat dependent on the outside temperature. Figures 5.7 and 5.8 demonstrate these facts in more "powerful" direct graphs of room air temperatures vs. outside dry bulb air temperatures. Figure 5.7 shows a basically constant air temperature of 74 F independent of outside air temperatures. Figure 5.8

Figure 5.5

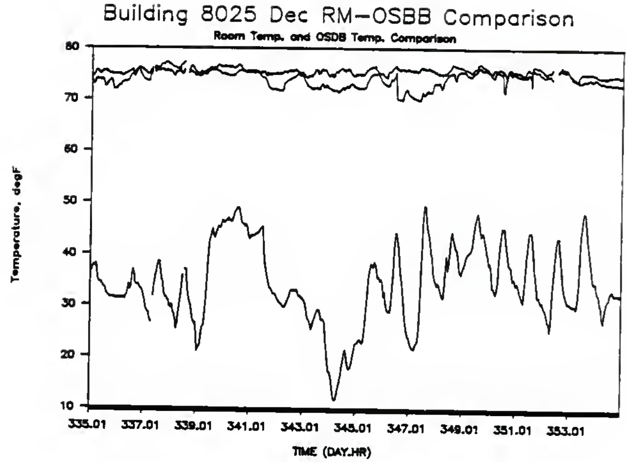


Figure 5.6

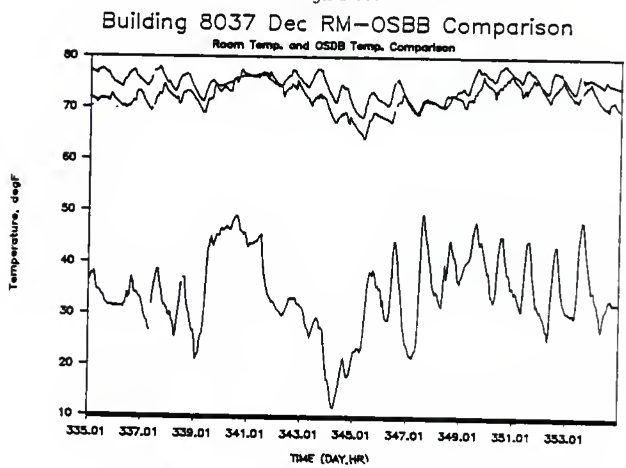


Figure 5.7

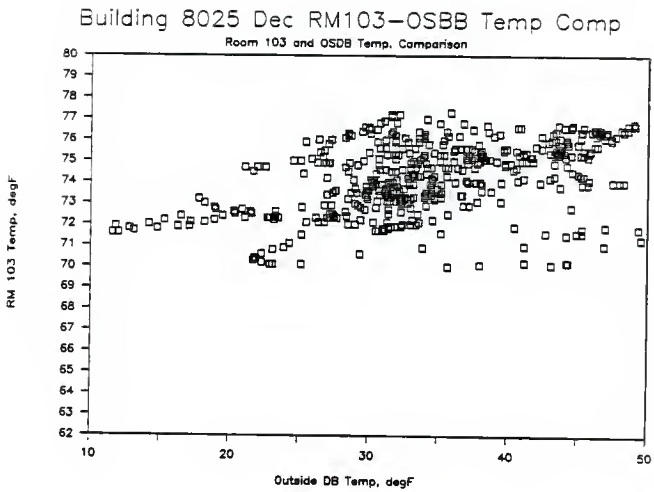
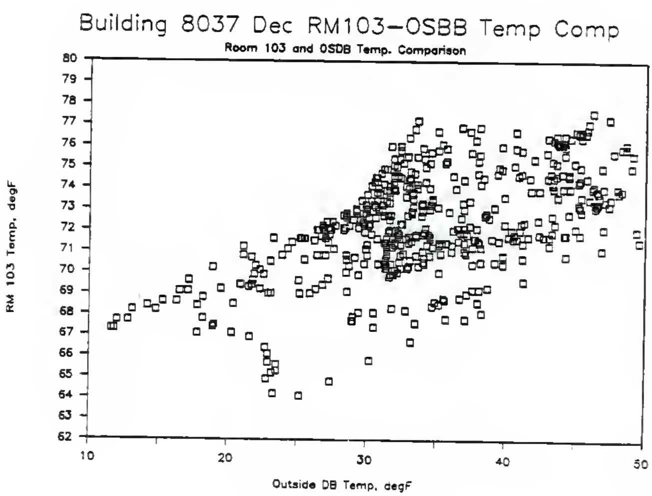


Figure 5.8



shows the apparent room air temperature dependence on the outside air temperature. Notice the wide range of room air temperatures -- 63 F - 78 F. This maybe why the occupants during a second on-site investigation (January 27, 1987) stated that Building 8037 had large "swings" in temperature leaving them dissatisfied with the building heating. However, the occupants in Building 8025 also complained of large temperature "swings". During the investigation the outside air temperatures were near 60 F (and during days in which the temperature was lower) it was noticed that several windows were opened in both buildings and some thermostats were set on full scale (continuously calling for heat). This observation suggests that the occupants may have been attempting to regulate room temperatures by opening windows. Occupants also expressed that they feel the heating system can not bring a room that has been unheated to a desirable temperature within a reasonable amount of time.

In addition to the previously mentioned occupant surveys and the as designed building heating control schedule (Chapter 3), the second building onsite inspection revealed two additional building thermal operating characteristics valid for both buildings. The first was a very common observation: thermostat settings were turned to the highest setting, i.e., the rooms always demanded heat. The second observation was that nearly all the convection dampers on the wall fin convectors were removed. Originally, heat addition could be varied with the use of convection dampers. Also, it is noted that the Building 8037 mechanical room ventilation exhaust fan was still in its continuous operation mode with a 40 F setting.

This problem and previously discussed information was presented to Fort Riley engineers in a meeting on January 27, 1987. Based on the information, the engineers believed that a pneumatic control valve was improperly installed. The engineers immediately scheduled heating system controls maintenance and thermostat setback. Sometime around that meeting date, it was observed and verified that Building 8037s energy consumption was improved. Apparently, maintenance on the buildings heating control system and possibly thermostat setbacks attributed to the improved building energy consumption data. The next text task was to verify Building 8037 improved energy data. This verification process used will be discussed in detail to demonstrate the continuous energy measurement verifications procedure and other useful suspicious data investigation tools.

As mentioned earlier, the Pre data are useful in predicting building energy consumption. Recall that there exists a C value for which a good correlation between Pre and Act exist. Examples of good correlations for hourly data are shown in Figures 5.9 and 5.10. An example of how Pre can be used is demonstrated in Figure 5.11. Figure 5.11 shows a plot of Building 8037 January Energy Data. Notice in days 1 - 25 that Act is rather invariant compared to Pre. In days 28 - 31 there is a strong correlation between Act and Pre. The time periods just mentioned are the before and after the maintenance on the heating controls system. Notice the improved building energy consumption characteristics (Act tracking Pre). In this example, the degree day based prediction helped identify a building heating systems controls defect and verify the collected data.

Figure 5.12 shows the strong correlation between Act, Pre, and CR for Building 8037 February Data. This graph gives strong evidence that the collected data is valid. Note that the building's energy consumption varies with outside conditions (Act and Pre) in a favorable manner. Also, notice that at times there are observable deviations between Pre and Act. However, their trends are basically the same. These deviations may be due to factors not considered in the Degree Day method such as variances in solar radiation and internal heat loads. Also, observe

Figure 5.9

Building 8025 January Data

Act and Pre Hourly values as Indicated

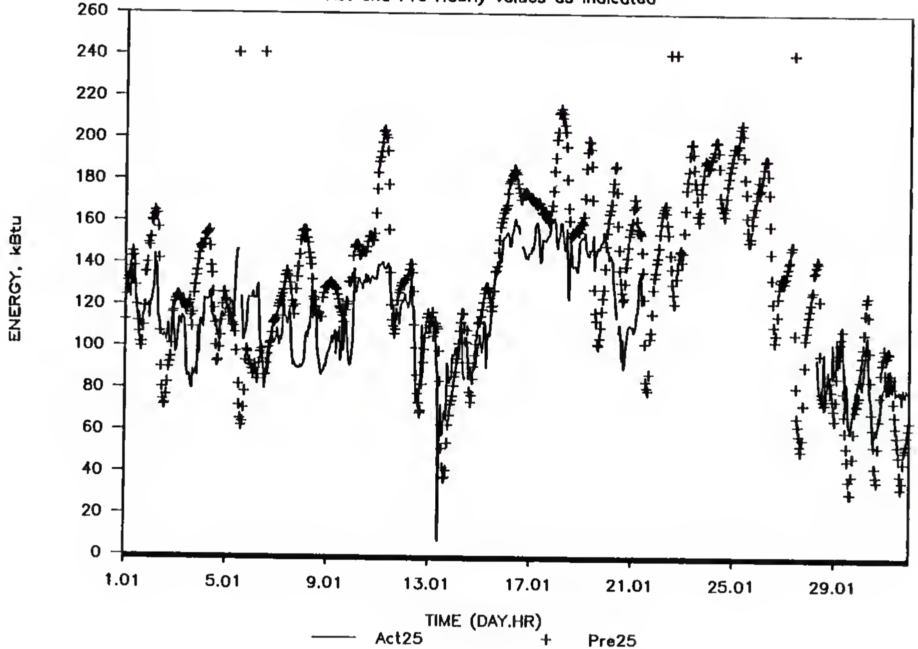


Figure 5.10

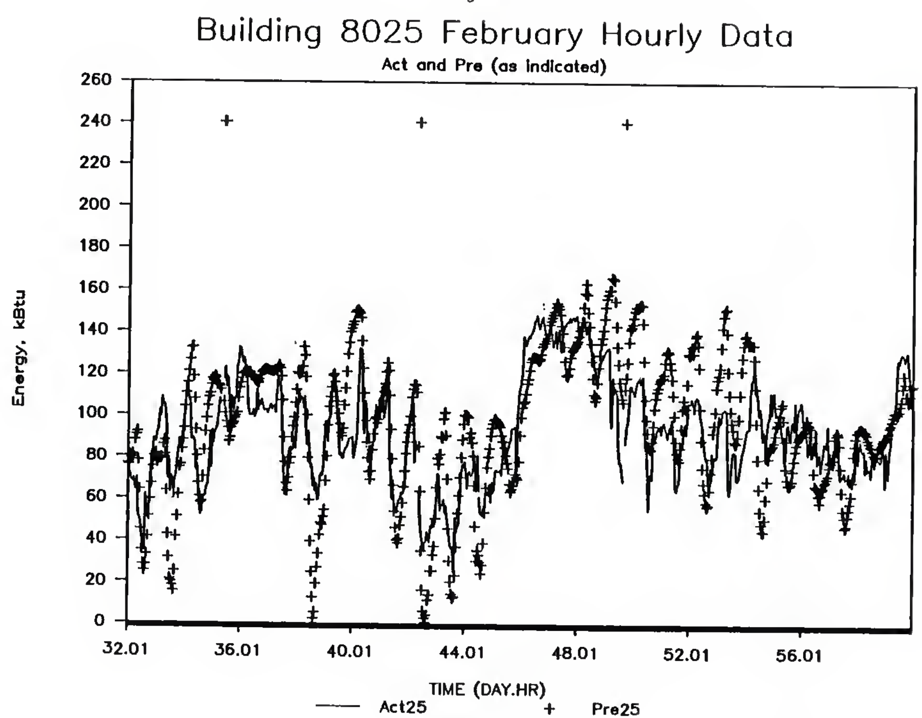

Building 8025 February Hourly Data
Act and Pre (as indicated)
Energy, kBtu
260
240
220
200
180
160
140
120
100
80
60
40
20
0
32.01
36.01
40.01
44.01
48.01
52.01
56.01
TIME (DAY.HR)
Act25
Pre25

Figure 5.11

Building 8037 January Energy Data

Act, Pre, CR ae Indicated

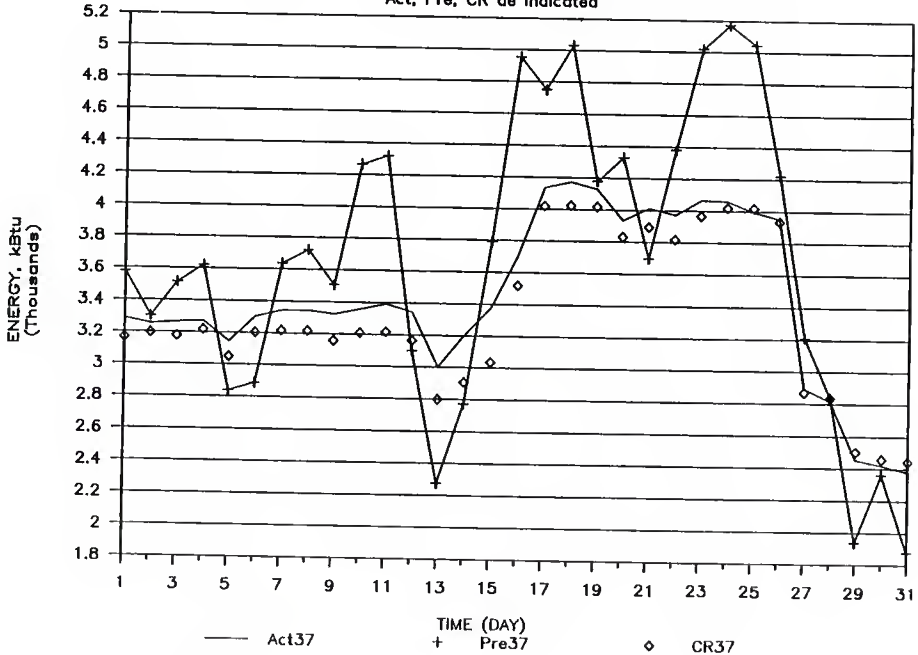
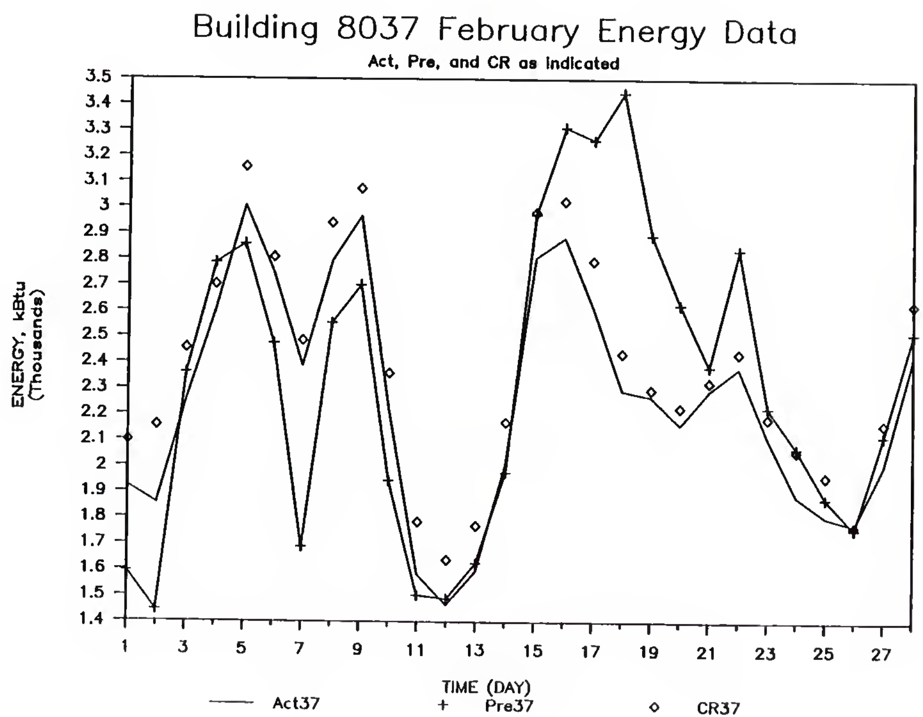


Figure 5.12



Building 8037 February Energy Data
Act, Pre, and CR as Indicated
ENERGY, kBtu (Thousands)
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1
3
5
7
9
11
13
15
17
19
21
23
25
27
TIME (DAY)
Act37
Pre37
CR37

that the Act measurement is in good agreement with CR, thereby further validating the Act measurement.

The most astounding result of Building 8037's heating control system maintenance is shown in Figure 5.13. The plot shows Hot Water Supply temperature versus outside dry bulb temperature. The heating system controls corresponds very closely to its design control schedule. The "scatter" of points around 60 F probably coincides with the heating system in the off state. Figure 5.14 shows the Act, Pre, and CR data for January and February. Again note the impact the heating system control maintenance the had on the building thermal performance.

Figure 5.15 shows the behavior of Room 122 temperature as a function of outside dry bulb temperature. Notice that the temperature of the room is independent of the outside temperature indicating properly operating and designed system. In addition, the room temperature is fairly constant between 70 and 74 F. Figure 5.16 is a similar plot for Room 103. In this case, room temperatures vary with outside air temperatures below 45 F. Also, the room temperature range is larger (compared to Room 122) 68 F to 78 F. This characteristic may be due to a high thermostat setting and an undersized heating unit. It is noted that the February Room 103 temperature characteristics are slightly improved over December's

Figure 5.13

Building 8037 February Data

HWS Temp vs Outside DB Temp

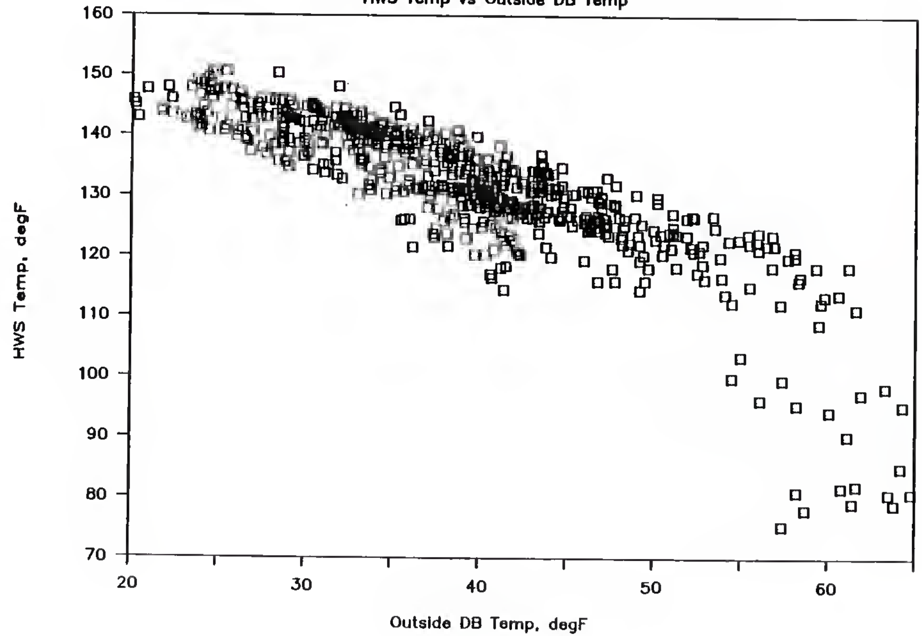


Figure 5.14

BUILDING 8037 JAN 1 – FEB 28, 1987

Act, Pre(DD), and CR as Indicated

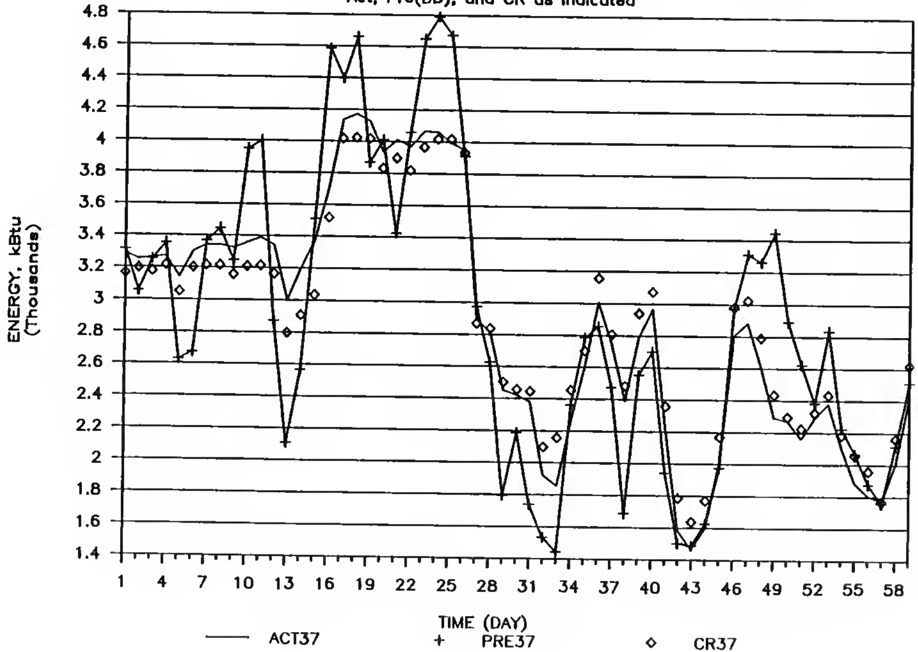


Figure 5.15

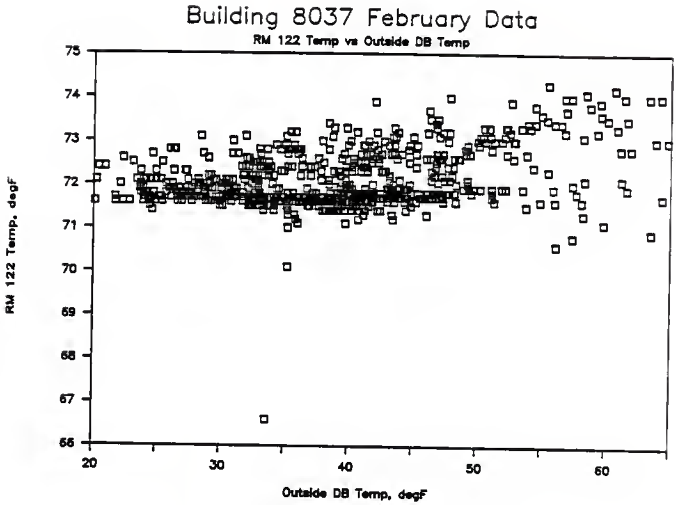
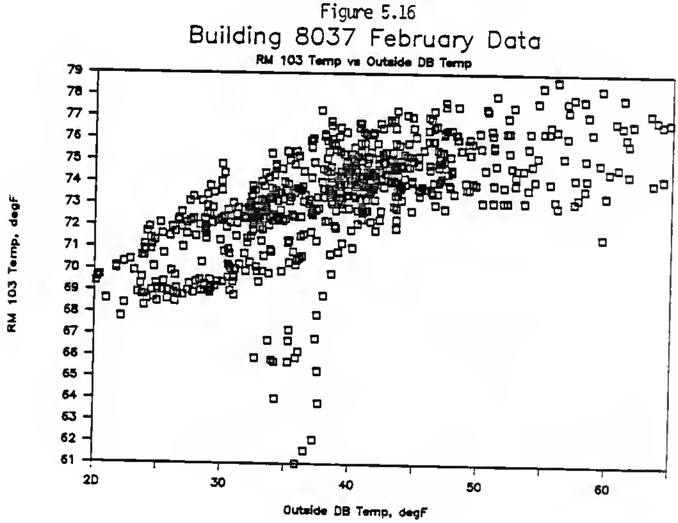


Figure 5.16



characteristics. In December, temperatures ranged from 65 F to 78 F while in February temperatures ranged from 68 F to 78 F. The improvement is due to the heating system controls maintenance which increased the HWS temperature and therefore the heating capacities.

After eliminating the Building 8037 heating system controls problem, Building 8025 and Building 8037 thermal energy characteristics were compared. In order to fairly compare Building 8037 energy consumption (Act37) with Building 8025 energy consumption, one must be assured that Building 8025 energy consumption data (Act) are validated (note Building 8037 energy consumption data were verified earlier). Figure 5.17 shows February Building 8025 energy data plots. Pre, and CR correspond favorably with the Act data points giving strong evidence that the data are correct. Figure 5.18 shows a plot of January 1 - February data, this plot indicates that the Act25 measurement is also valid in January (with the exception of lost data between January 21 - 27). Figure 5.19 notes that the HWS temperature vs outside dry bulb temperature control schedule is identical to its December schedule.

Figure 5.20 shows a January 1 - February 28 comparison of energy consumption between Building 8025 and Building 8037. In the period prior to the Building 8037 maintenance (January 27), Building 8037 energy

Figure 5.17

Building 8037 February Energy Data

Act, Pre, and CR as indicated

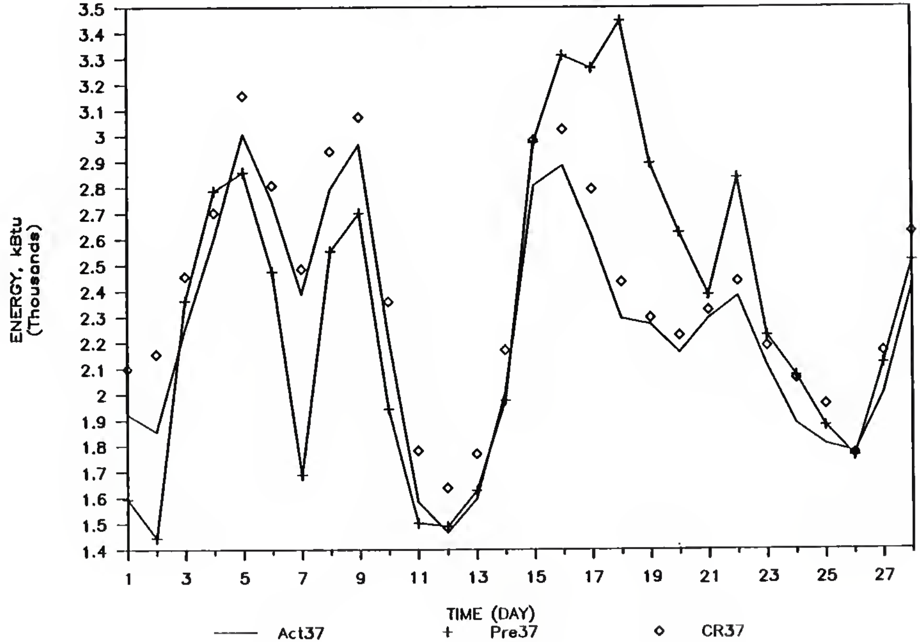
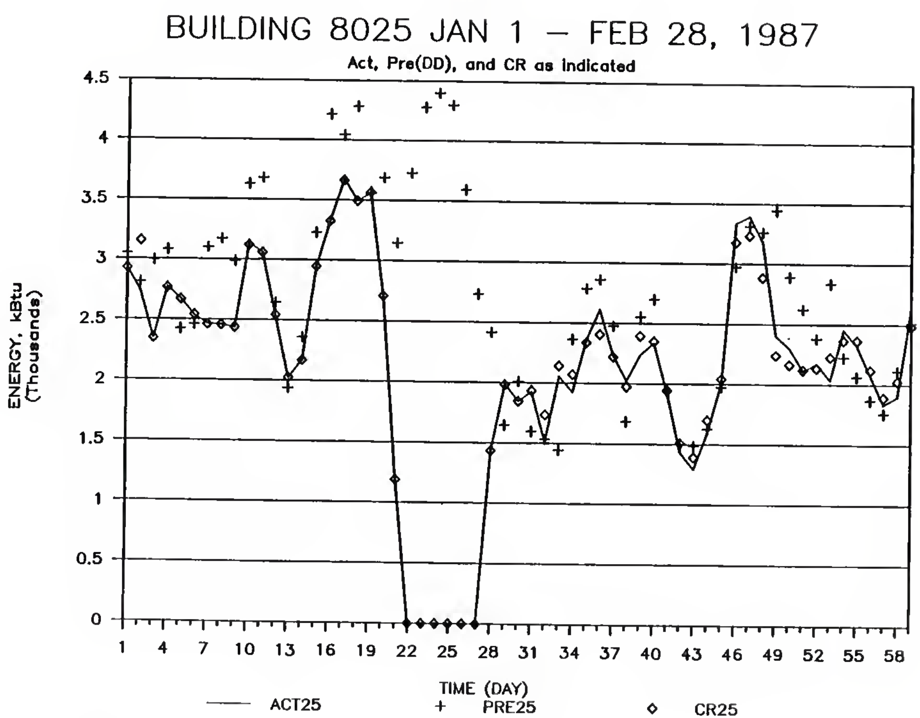


Figure 5.18



BUILDING 8025 JAN 1 – FEB 28, 1987
Act, Pre(DD), and CR as Indicated
ENERGY, kBtu (Thousands)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58
TIME (DAY)
ACT25
PRE25
CR25

Figure 5.19

Building 8025 February Data

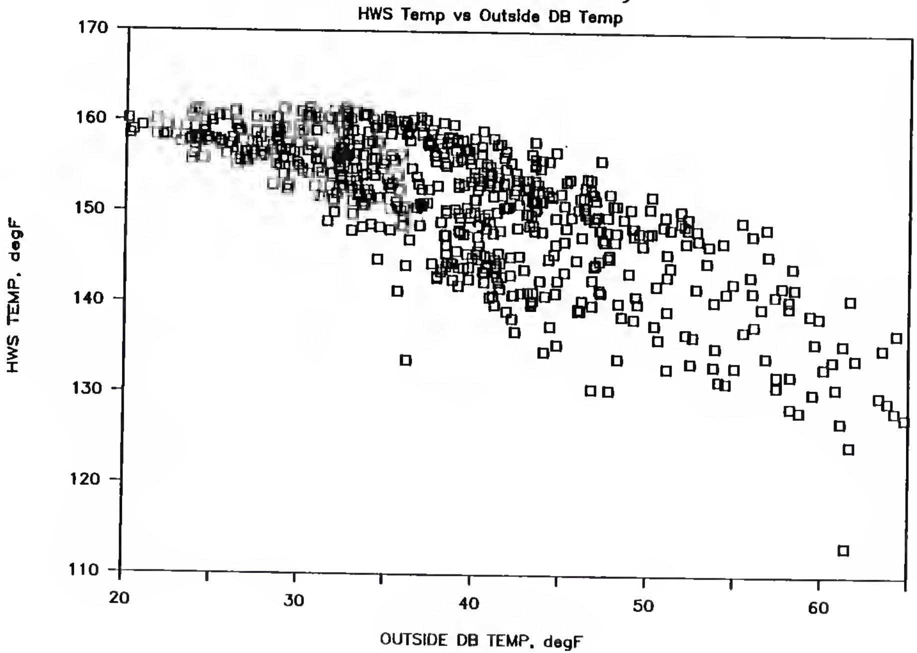
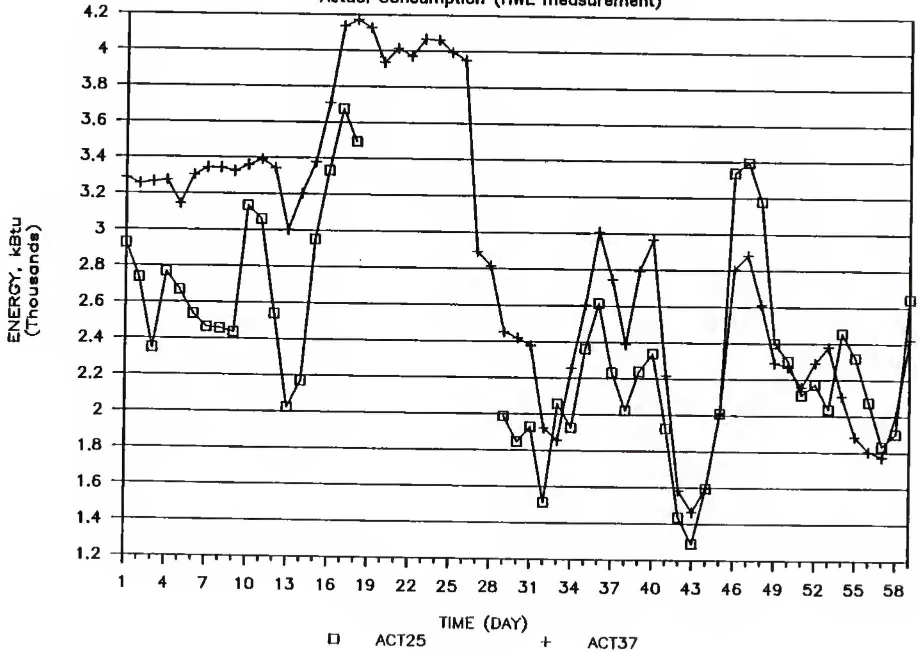


Figure 5.20

BUILDING COMPARISON, JAN 1 – FEB 28

Actuol Coneumption (HWL measurement)



consumption was much higher than Building 8025. After the maintenance, the buildings energy consumption characteristics were at about the same level. In fact, Building 8037 energy consumption at various days was even lower that Building 8025 energy consumption.

Figure 5.20 also notes that some Building 8025 energy data was missing. No data collection scheme is free from errors and the problem that occured here was due to human error. However, it is interesting to note that it may be possible to replace the lost Act data with the Pre predicted energy consumption data.

From the results of this investigation, one may make some interesting observations. First, the energy data was used to find a problem in the building heating system controls and to help understand the building's actual operating conditions. Second, energy consumption in a building was reduced. Third, occupant thermal comfort may have increased while the energy consumption decreased. Fourth, the buildings are operating as they were designed so that a fair energy consumption comparison between old buildings vs new buildings is possible. Fifth, similar energy consumption level in the two buildings adds additional evidence that collected data are valid.

Cooling Season Measurements

In this section the continuous cooling energy measurement verification procedures will be presented. Also presented is some of the 1986 cooling season energy consumption data. Unfortunately an energy balance did not exist for most of the data prior to September 1986 data and therefore it will be difficult to determine the accuracy of this data. It may be possible to correct the "erroneous" data but a procedure has not yet been developed. Several of the causes for the problems have been discussed in Chapter 4 and they include: drifting temperature transmitters, inaccurate energy algorithm, and insufficiently bled pressure transducers. The verification procedures and the cooling season energy measurement problems are best presented through examples. An example of good data will first be presented followed by examples of dubious data. Also included in this section are some of the building cooling load consumption characteristics and a prediction method which appears to be promising.

In the cooling energy consumption measurement there are two independent measurements: cooling load in the main lines (identified as MAIN) and the cooling load in the sum of the three air handler loads (identified as

SUM). In order for an energy balance to occur these measurements must be equal (for both measurements to be valid). Figure 5.21 shows in general an energy balance (MAIN = SUM) for Building 8025 in September. Because there is an energy balance and knowing that the components were properly calibrated, there is strong evidence to support that the data are accurate to within the known instrumentation errors (discussed in Chapter 3).

Figure 5.22 shows the September Building 8025 volumetric flow rates. Notice that the flow rate data are at times slightly negative. The below zero flow data were probably due to zero shifts in the pressure transducers or an inadequately bled pressure transducer. These below zero flow characteristics explain some of the negative energy values shown in Figure 5.21. Flow data also indicate that the larger flows occur in the air handlers closest to the main supply lines. This phenomenon is reasonable because there is less flow resistance to the air handlers closest to the main supply lines (and assuming that each air handler has the same flow resistance).

Figure 5.23 shows the September outside dry bulb temperatures plotted with Building 8025 main cold water supply temperatures. Notice that at times the outside dry bulb temperature was below the cold water supply

Figure 5.21

Building 8025 September Energy Data

Main and Sum as Indicated

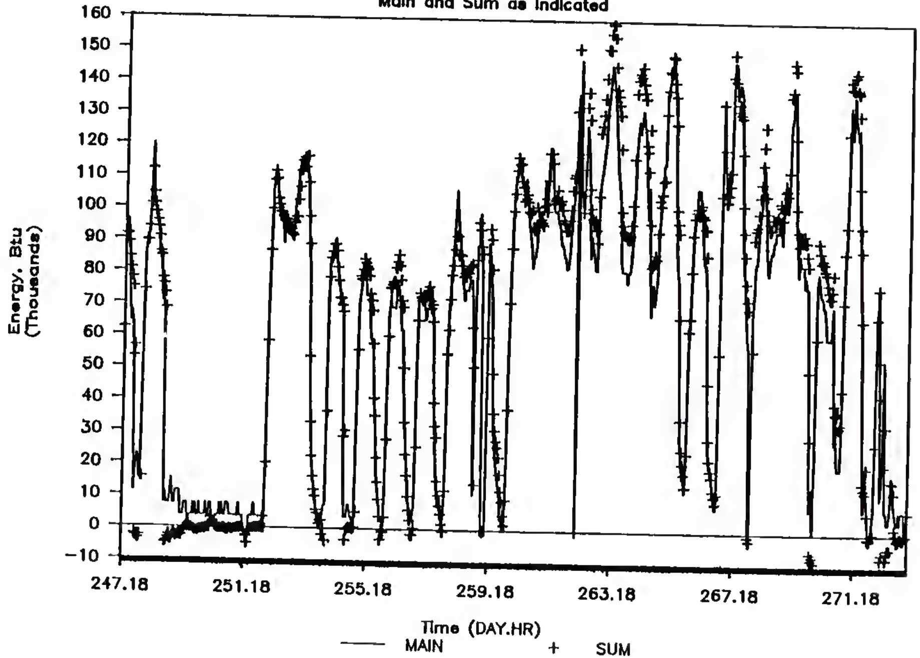


Figure 5.22

Building 8025 September Data

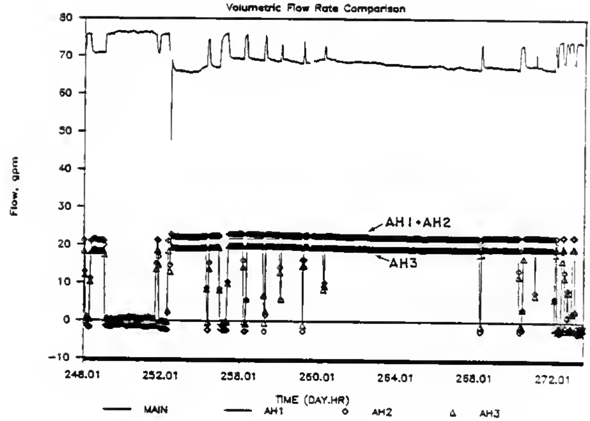
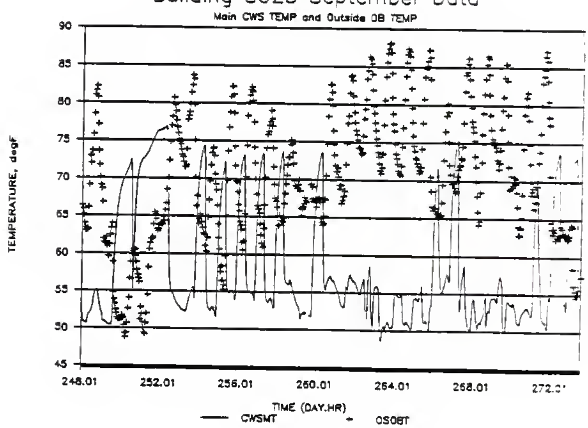


Figure 5.23

Building 8025 September Data



temperature. This means that the central chiller was actually pumping water which was warmer than outside air. However, Figure 5.23 with Figure 5.22 show that this water (warmer than ambient air) was not circulating through the air handling units. Therefore, the possibility of the outside air cooling the cold water is unlikely to cause the negative energy data because in this situation there is no flow in the air handler units. The data also suggests that when the cold water supply temperature is above 60 F the chiller is in a no load "off" status. Also, when there is a demand on the main chiller for cooling, the chiller supplies cold water at different supply temperatures. It is believed the supply temperature in this case may be dependent on the main chiller loading (an indication of the main chiller loading is the outside dry bulb temperature).

Since the energy data for Building 8025 has been verified for this month (September), these data can be used to further study the building cooling system characteristics. Figure 5.24 shows the September Building 8025 Room 103 and Room 122 air temperatures. Room temperatures range from 69 F to 77 F. Figure 5.25 shows the room temperatures plotted along with the corresponding main cold water supply temperatures. Notice at times the cold water supply temperatures are

Figure 5.24

Building 8025 September Data

Room Air Temperature Comparison

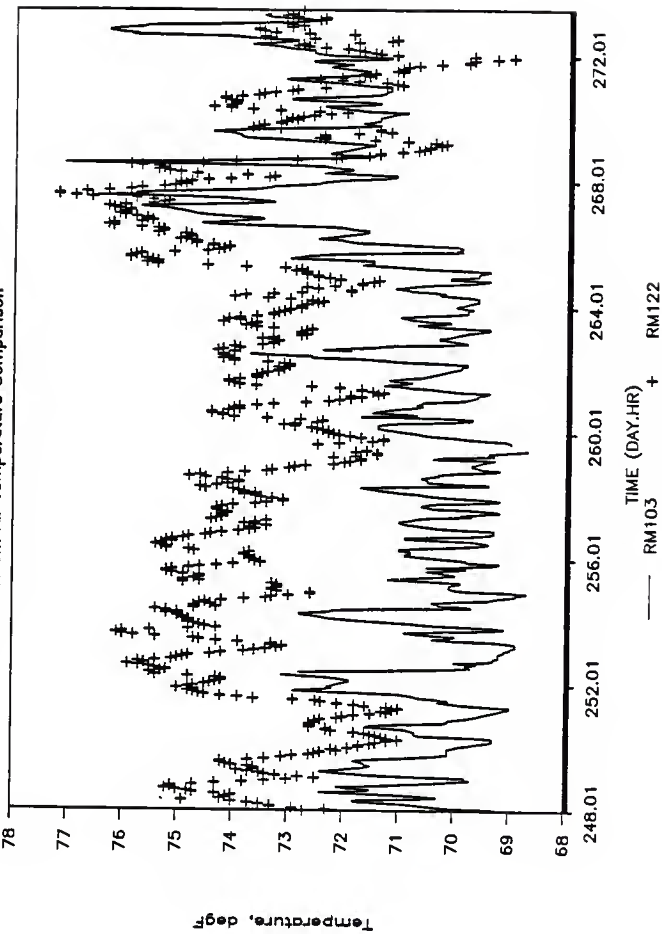
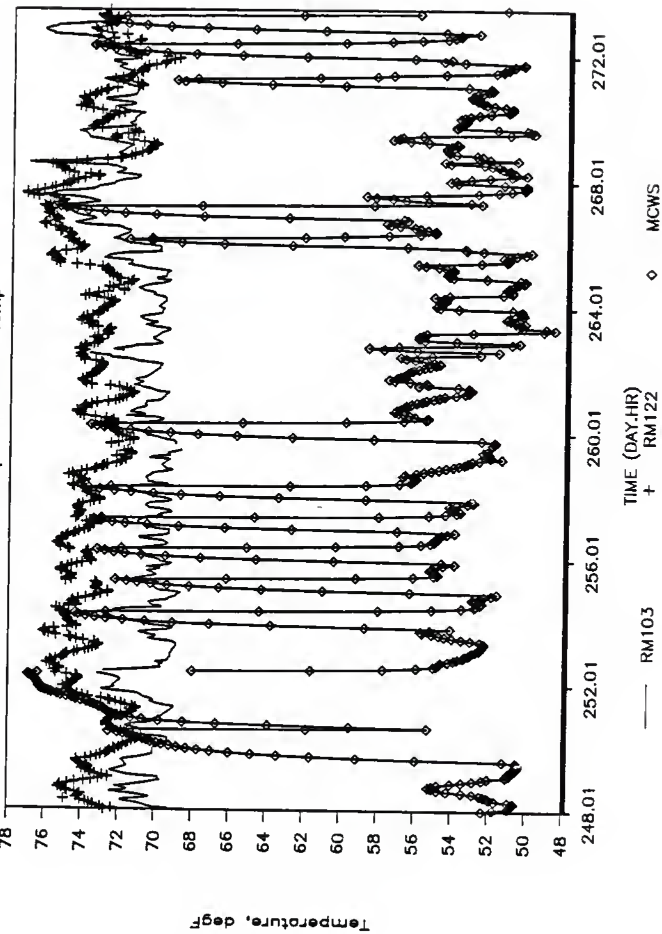


Figure 5.25

Building 8025 September Data

Room Air Temp and Main CWS Temp



higher than the room air temperatures. This means that it is possible for a room calling for cooling to receive warm air (negative energy measurement would occur in this case if there is flow through the air handlers). The situation is estimated to be likely only when the corresponding outside air temperatures are between 60 F and 65 F and the main chiller is in the "off state" (see cooling control schedule included in the Appendix J for some supporting evidence).

There have been three major problems contributing to some bad cooling data in the 1986 cooling season: inaccurate energy calculating algorithm, pressure transducers problems, and temperature transmitters problems. The initial energy algorithm incorrectly calculated cooling loads when there were non constant flow rates (Figure 5.22) and non constant cold water supply (and return) temperatures in the air handlers (Figure 5.23). The problems with the pressure transducers were probably due to inadequate bleeding techniques. Temperature transmitter problems occured randomly and usually after a calibration. Basically, the transmitters would demonstrate erratic drift characteristics.

The energy calculating algorithm was replaced with a correct algorithm and a new pressure transmitter bleeding procedure eliminated all flow rate problems (as evident in the hot water loop energy measurement system). Therefore the only foreseeable problems in the future cooling energy measurements are with the temperature transmitters. These problems also seemed to have been eliminated as proficiency in calibration techniques has improved.

In spite of the apparent elimination of the energy measurement system problems, it is useful to demonstrate some instrumentation error detection and verification techniques. Figure 5.21 (shown earlier) is a useful plot which shows the amount of flow through the air handlers and main cold lines. This plot can be used in a weekly check to investigate a particular flow rate measurement. Erroneous flow readings (and corresponding flow rates) from September Building 8025 air handler number 3 were discovered using this plot technique. Later, a faulty pressure transducer was removed for repair. The faulty data were replaced with flow data based on past flow rate characteristics and a knowledge of the flow data for the other two air handling units. Basically, past flow data revealed that the amount of flow in an air handler would remain relatively constant with respect to flow in the other air handlers. For example, if there was maximum flow in two of the air handlers there would a maximum amount of flow in the third air handler. It is noted that Figure 5.22 used the above substitution technique. Also substitute data, in this case, was used just to confirm the main energy cooling load measurement data (Figure 5.21).

Besides the flow rate error detection and verification schemes, there are a number of temperature measurement error detection and verification schemes. Most of the schemes deal with verifying the cold water supply temperatures. Note that since there is negligible heat addition in the lines from the main supply temperature measurement, all the cold water temperature measurements should be equal. Figure 5.26 shows the cold water supply temperatures in Building 8025 on a typical September day. Notice that all temperatures at a given time period are within 0.5 F. Also notice the main and air handler temperatures remain in a constant temperature order with air handler 1, air handler 2, main supply, and air handler in a highest temperature to lowest temperature arrangement. Because this arrangement is constant, this suggests that there are no significant drifts in the temperature transmitters. Figure 5.27 and Figure 5.28 demonstrates another valuable error detection and verification scheme. Here, air handler supply temperature data are plotted corresponding to another air handler supply temperature. In Figure 5.27 there is a near perfect (linear and nonvariant) supply temperature

Figure 5.26

Building 8025 September Data

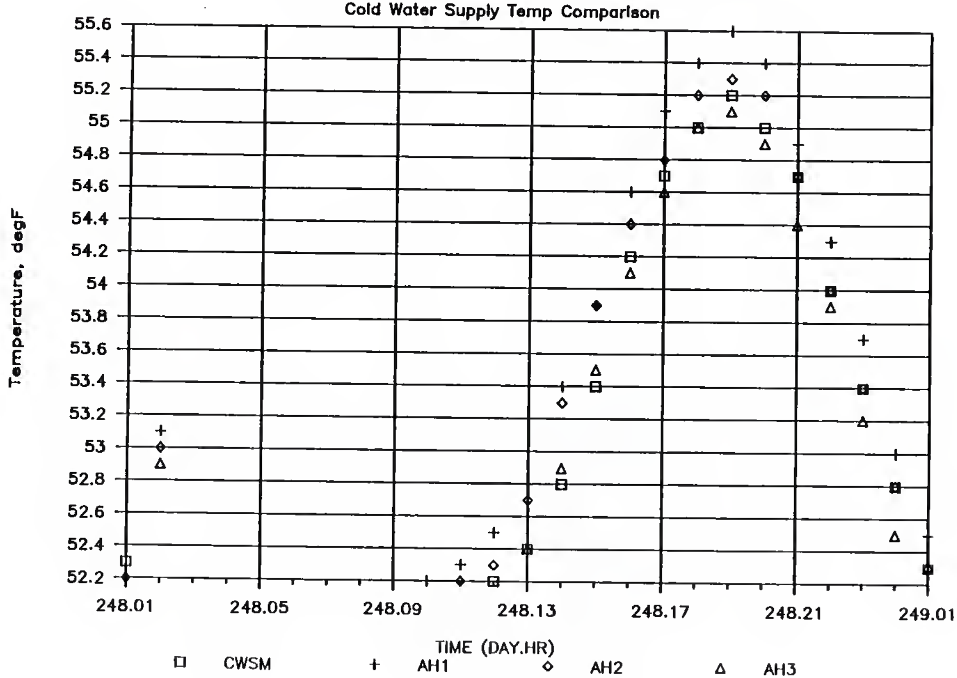


Figure 5.27

Building 8025 September Data

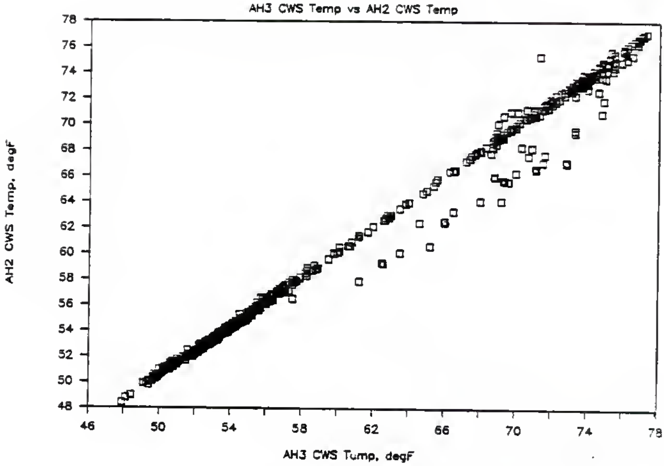
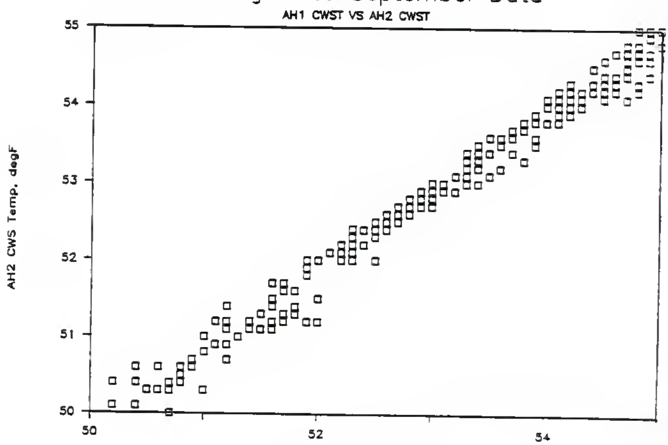


Figure 5.28

Building 8025 September Data



agreement. In Figure 5.28, the correlation is more variant but still linear.

The energy consumption prediction based on the Degree Day method was shown earlier to be a valuable tool in verifying heating season data and discovering dubious heating data. Current research indicates that a summer cooling load prediction based on the Degree Day method may also be useful in verifying data and in discovering suspicious data. Figures 5.29 and 5.30 show the hourly and daily predicted energy consumption versus actual energy consumption data for Building 8025 September data, respectively. The daily predicted energy consumption agrees very favorably with the actual energy consumption. The prediction is defined as

$$Pre = ((OSDBT - 59)*10/C) \text{ in kBtu} \qquad (5.2)$$

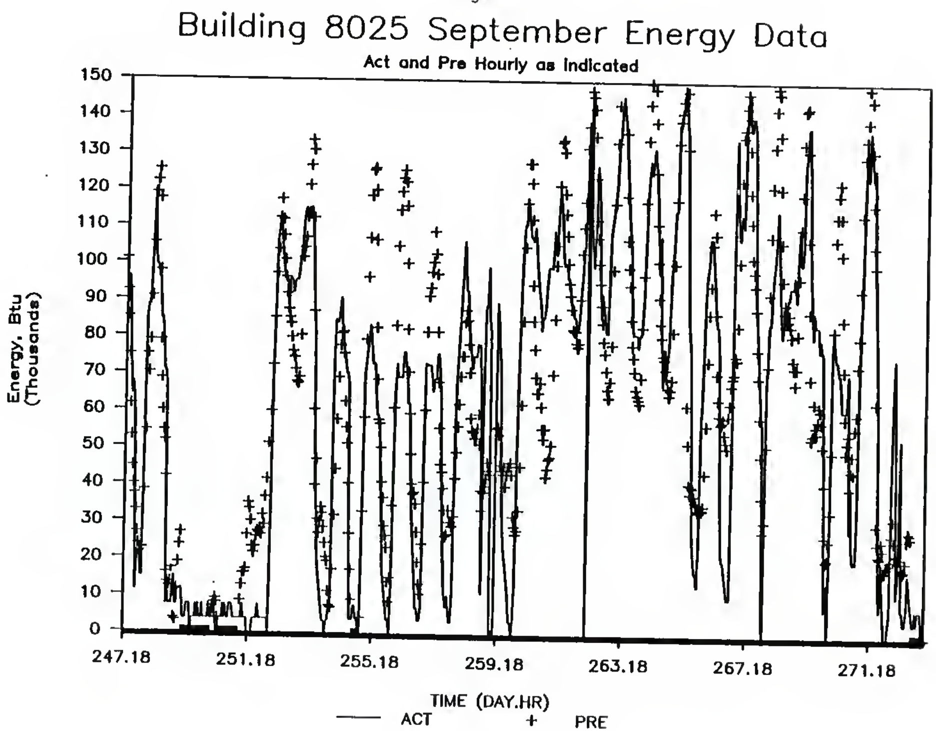
where,

OSDBT = outside dry bulb temperature (in degrees Fahrenheit)

C = constant

Notice that 59 F was used as a base temperature instead of the heating degree day base of 65 F. The constant C was determined to be 1.5 (for this case). Again C values were varied until a good correlation between Pre and Act occured (with daily data points). Equation 5.2 gives the hourly predicted energy consumption. To obtain the daily

Figure 5.29

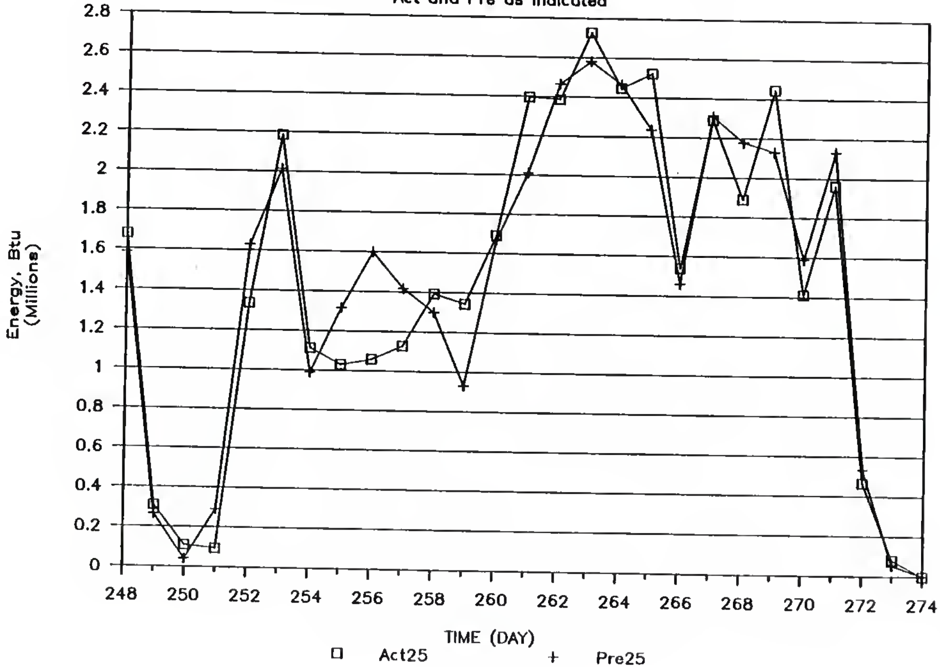


Building 8025 September Energy Data
Act and Pre Hourly as Indicated
Energy, Btu (Thousands)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
247.18
251.18
255.18
259.18
263.18
267.18
271.18
TIME (DAY.HR)
ACT
+ PRE

Figure 5.30

Building 8025 September Data

Act and Pre as indicated

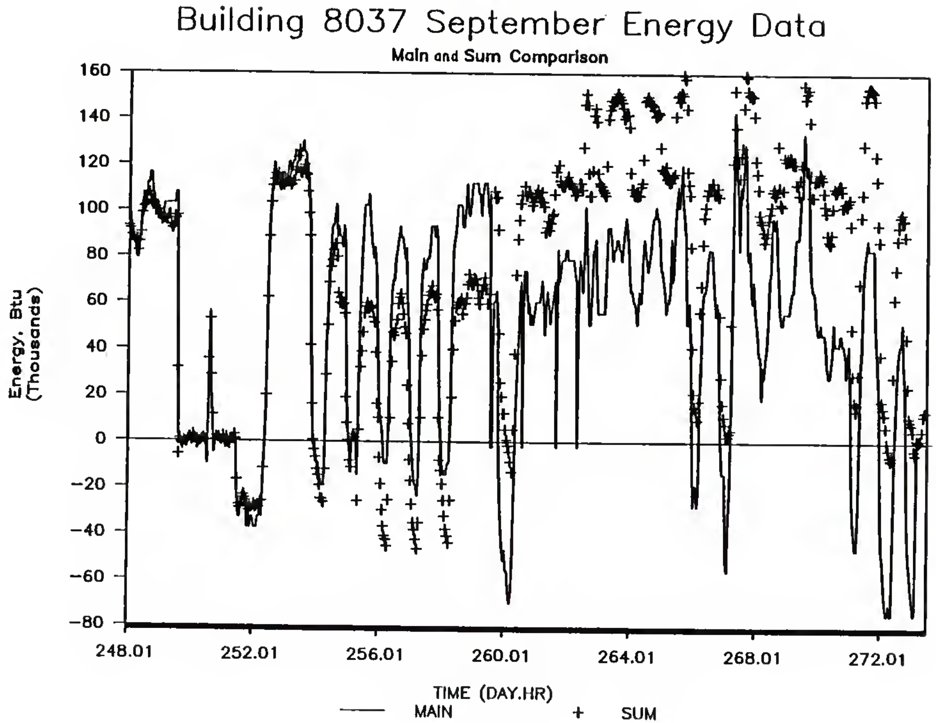


predicted energy consumption simply add all 24 hour "positive" hourly predicted energy consumption values.

Cooling energy consumption data from other months and from Building 8037 also supports that there is a strong correlation between outside dry bulb temperature and the cooling load. Furthermore it appears that there exists a degree day prediction (a base temperature and C value) which corresponds favorably to the actual energy consumption. Unfortunately, there was not enough verified data available to adequately develop this cooling energy prediction for either building. Therefore at this time, an energy prediction equation is unavailable for next cooling season. Again, strong correlation Figure 5.30 shown in supports a belief that a predicted energy consumption scheme can be developed for future cooling seasons.

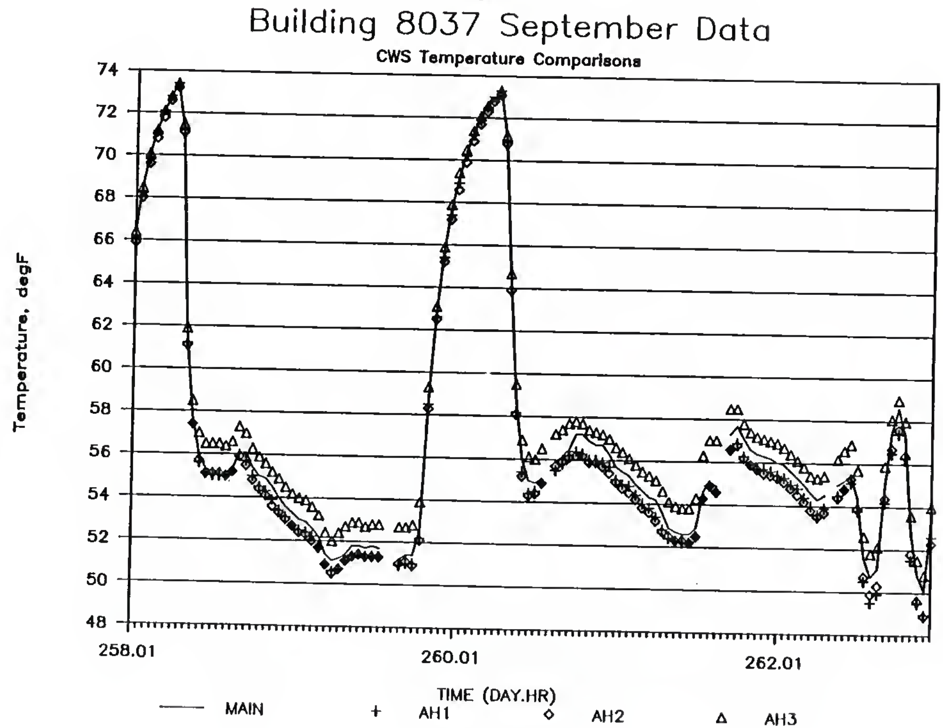
A great deal of cooling data other than September Building 8025 was collected in the 1986 cooling season. In general, it will be difficult to accurately determine the actual energy consumption for the majority of this building cooling data. Figure 5.31 gives an example of the problems in determining the actual energy consumption. Here the two Building 8037 September energy consumption measurements are at times in noticable disagreement. Figure 5.32 provides one possible reason for the the

Figure 5.31



Building 8037 September Energy Data
Main and Sum Comparison
Energy, Btu
(Thousands)
160
140
120
100
80
60
40
20
0
−20
−40
−60
−80
248.01
252.01
256.01
260.01
264.01
268.01
272.01
TIME (DAY.HR)
MAIN
+ SUM

Figure 5.32


Building 8037 September Data
CWS Temperature Comparisons
Temperature, degF
74
72
70
68
66
64
62
60
58
56
54
52
50
48
258.01
260.01
262.01
TIME (DAY.HR)
MAIN
+ AH1
◇ AH2
Δ AH3

disagreement -- the relatively large deviations in the supply measurement temperatures. Figure 5.33 suggests that the flow rate is rather stable and therefore is not a contributing factor in the erroneous data. Therefore the problems with the discrepancy in the energy measurements were probably due to temperature transmitter problems.

Despite the problems with the discrepancy in the energy measurements (such as in September Building 8037 energy data), the data have been very useful in describing the cooling system characteristics. Figure 5.34 shows the outside dry bulb temperature plotted along with the main cold water supply temperature. This graph supports the conclusions about the main chiller operation which was discussed earlier for the September Building 8025 case. However, Figure 5.35 which shows monthly flow data used along with Figure 5.34 describes two unique cooling system characteristics for Building 8037. One, when the main chiller pumps water around with the temperature above ambient air temperature, is definitely flow in the air handlers. In this case, the outside intake air may help cool the cold water and therefore the result is negative energy data. Two, the bypass control valve for Building 8037 is less active than the bypass control valve for Building 8025 which indicates a different bypass control temperature set point.

Figure 5.33

Building 8037 September Data

Volumetric Flow Rote Comporisons

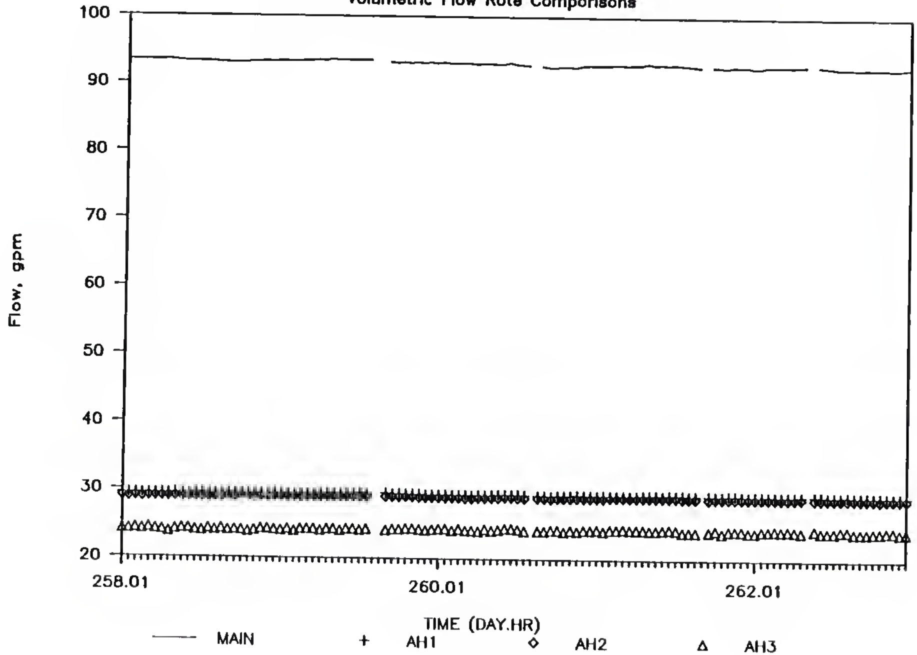


Figure 5.34
Building 8037 September Data

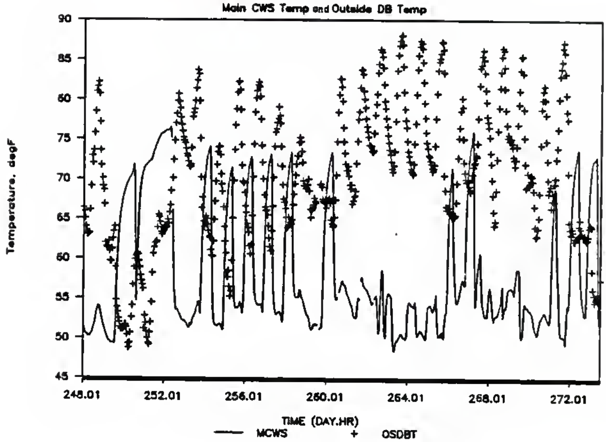
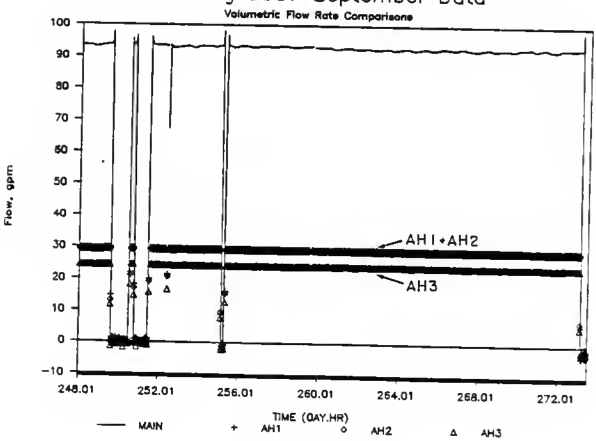


Figure 5.35
Building 8037 September Data



Finally, August Building 8025 energy consumption measurements are plotted in Figure 5.36. Notice the discrepancy in the main and sum measurements. Figure 5.37 shows a plot of typical cold water supply temperatures. Observe the behavior of the main cold water supply temperature. The cold water temperature varies relative to the other temperature measurements. This suggests that the cold water temperature transmitter is drifting and unstable. The drifting characteristic probably caused the discrepancy in the two cooling measurements.

As a final note, it is believed that the error detection and data verification schemes will be very helpful in assuring valid data in the future. Also, the past cooling season has been and will be useful in studying the building cooling system operation and energy consumption characteristics.

Figure 5.36

Building 8025 August Data

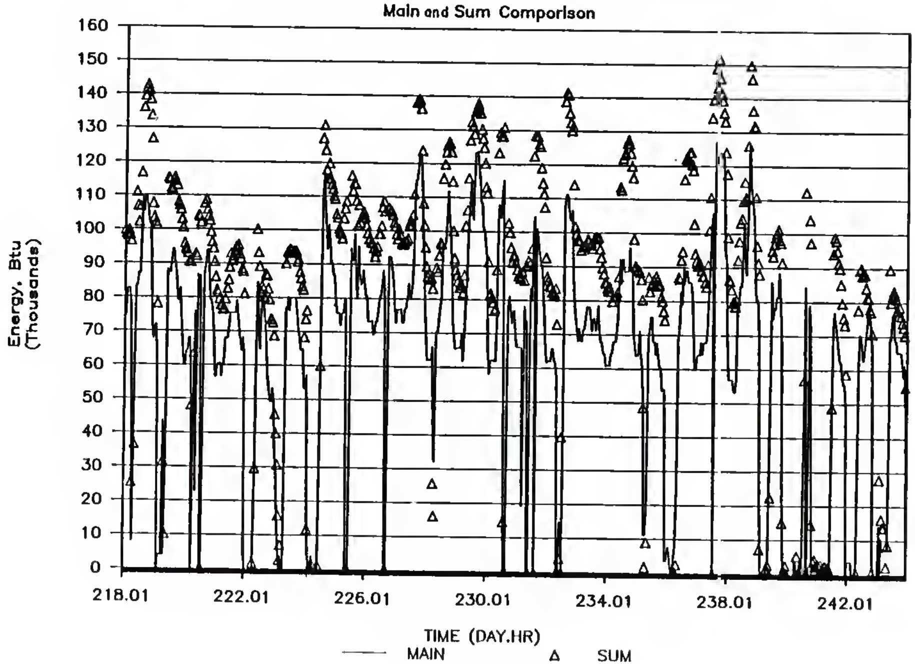
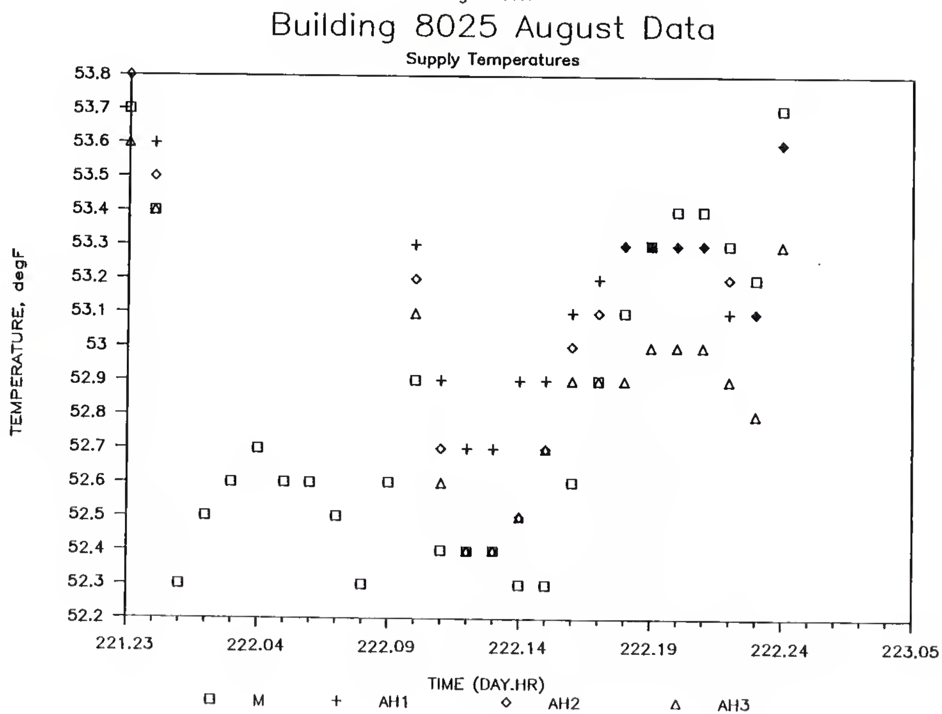


Figure 5.37



Building 8025 August Data
Supply Temperatures
TEMPERATURE, degF
53.8
53.7
53.6
53.5
53.4
53.3
53.2
53.1
53
52.9
52.8
52.7
52.6
52.5
52.4
52.3
52.2
221.23
222.04
222.09
222.14
222.19
222.24
223.05
TIME (DAY.HR)
M
AH1
AH2
AH3

Chapter 6

Conclusions

The purpose of the research reported in this thesis was to present the methods and techniques that were developed to verify environmental and building thermal energy consumption data. The problem of verifying the weather data was approached in the following sequentially manner: check and verify climatic instrumentation, formulate and implement proper calibration and maintenance procedures, and develop a scheme to verify data on a continuous basis. The solution to the problem of verifying the building thermal energy consumption required: understanding the building cooling and heating systems and the energy measurement system that were installed, checking and verifying instrumentation, developing and implementing proper calibration and maintenance procedures, deriving appropriate measurement relationships and algorithms, and developing methods and techniques to verify data (measurements) on a continuous basis.

The weather data collection scheme has been very reliable due in part to the fact that there were two weather stations installed. In addition, a U.S. Air Force weather station is in the vicinity and acts as a backup to the two weather stations. Weather data have proven to be helpful in predicting the energy consumption of the two old buildings. The prediction aids in the verification of building energy consumption measurements and in identifying dubious data. Also, weather data will be useful and necessary in the BLAST modeling of the old and new buildings.

The October 1986 - April 1987 heating season was a very successful season for the heating energy consumption and weather measurements. For this entire season, the two heating energy consumption measurements were in agreement. The accuracy of the heating energy measurements were approximately between 7 and 10 percent. The 1986 cooling season was less successful because the two cooling energy consumption measurements did not always correspond with each other. However, data late in the season were verified to be within the expected measurement errors (approximately 10%). Also, the cooling energy measurement is identical to the hot water loop measurement which was very successful in the heating season. Therefore, it is believed that the major problems in the cooling energy consumption measurement have been eliminated. Also, after calibration, temperature transducer problems will be eliminated when a new calibration by software scheme (not reported in this thesis) is further developed and implemented. Finally, dubious data identification and investigation methods which have been discussed will help reduce erroneous data.

BLAST or any energy estimator program requires as an input the amount of internal heat generation. The electric energy measurement along with occupant surveys may be useful in determining the internal heat load. It is noted that the room temperature measurements should be useful in a BLAST simulation of the buildings. These areas have not been researched and merit research.

As a final note, the new buildings will have the same type of energy measurement system and use similar instrumentation. Therefore, many of the verification procedures and techniques will be used to verify their energy measurements.

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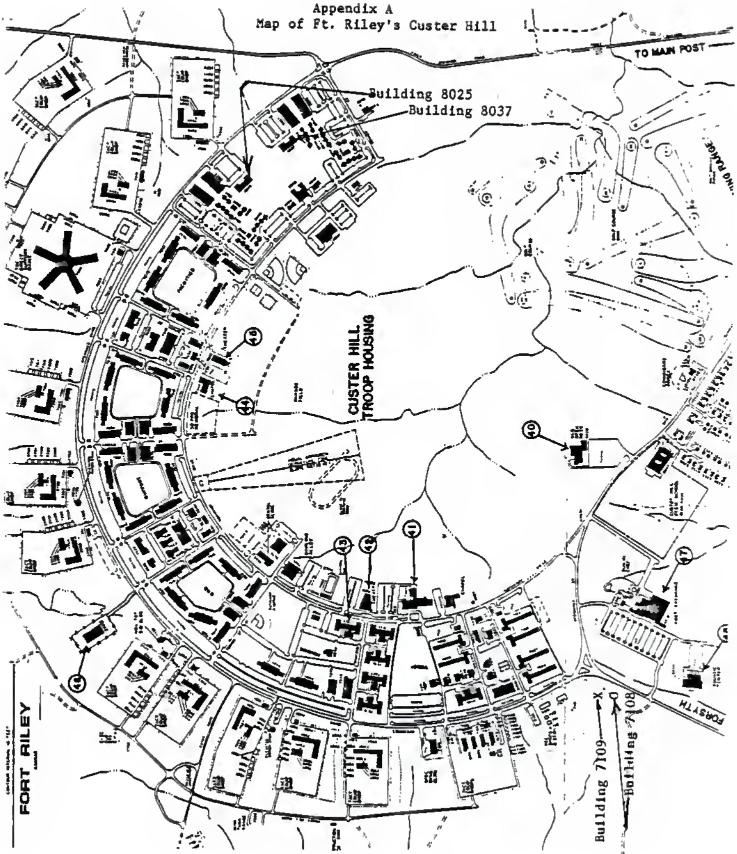
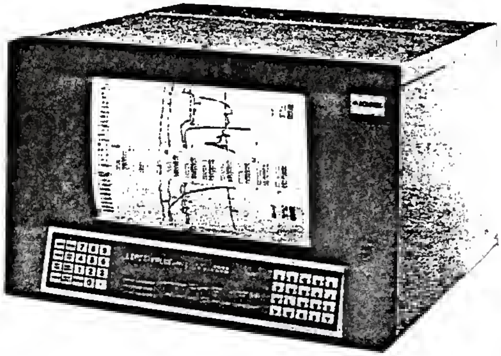
11. Telephone conversation with Climatronics technical service call engineer, May 1986.

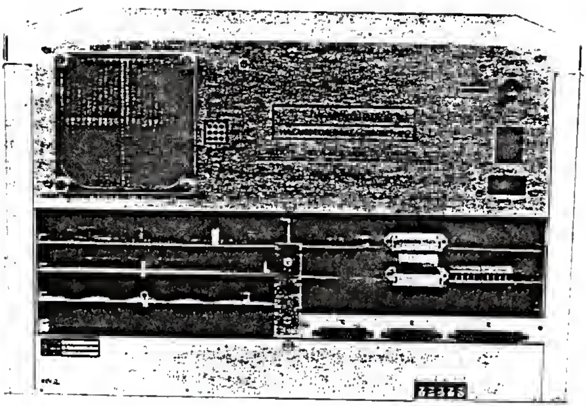
12. Swanson, Ken, mechanical engineer, Aeroquip Corporation a division of Gustin-Bacon, personal communication, March 3, 1987.

Appendix A
Map of Ft. Riley's Custer Hill



Appendix B
Acurex Information





Photos of the Acurex AutoGraph

Applicable Models

Surfaca mount enclosure
NEMA-4 enclosure
Card cage systems

Mechanical and Power (20 Channel)

Power requirements:	120/220 VAC, 50 or 60 Hz, 12W (with option 43170), 12 or 24 VDC, 11W
Dimensions:	3.4375 in. high, 15.25 in. wide, 11.5 in. deep (8.73 cm high, 38.74 cm wide, 29.21 cm deep)
Weight:	10 lb (4.5 kg)

Mechanical and Power (Multimodule)

Power requirements:	120/220 VAC, 50 or 60 Hz, 34W (with option 43190), 12 or 24 VDC, 11W
Dimensions (open style):	28.0 in. high, 28.0 in. wide, 5.0 in. deep
Dimensions (Nema 4):	30.0 in. high, 30.0 in. wide, 8.0 in. deep
Weight (open style):	30 lb
Weight (Nema 4):	110 lb

Environmental

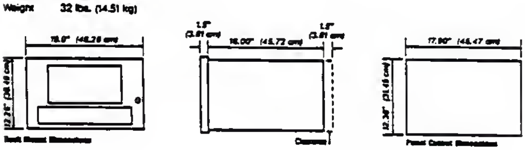
Operating temperature:	32° to 140°F (0° to 60°C)
Humidity:	Maximum — 10 to 95 percent relative humidity at 40°C, derate 2 percent relative humidity/°C, 40° to 60°C; Normal — 0 to 80 percent relative humidity at 0° to 30°C, derate 0.8 percent relative humidity/°C, 30° to 60°C
Operating altitude:	10,000 ft

System Performance

Throughput:	60 channels/sec
Accuracy:	±0.03 percent of reading plus 0.012 percent of range
Resolution:	14 bits, bipolar
Linearization accuracy:	±0.1°F
Thermocouple block uniformity:	±0.3°C
Noise rejection:	70-dB normal mode, 140-dB common mode
Conversion method:	Charge dispensing voltage-to-frequency
Maximum common mode voltage:	250V RMS, ±350V peak (Note: Continuous CMV of greater than 200V may degrade reed life.)
Maximum addresses:	16 Netpacs per loop (800 only)
Autozero and autocal:	300 ms (commanded by host)

Dimensions and Weight:

Dimensions (Bench)	12.25 in. x 19.50 x 19.00 in. (31.12 cm x 49.53 cm x 48.26 cm)
Weight	32 lbs. (14.51 kg)



Appendix C

Thermistor Resistance Comparison and Actual Aspirator Circuit

A digital voltmeter (Beckman) was used to measure the thermistor's resistances. A laboratory standard mecury thermometer measured the dry bulb temperature. The results of the actual thermistor's resistance versus the manufacturer's stated resistance comparison are shown below. Figure C.1 shows the actual Aspirator Circuitry.

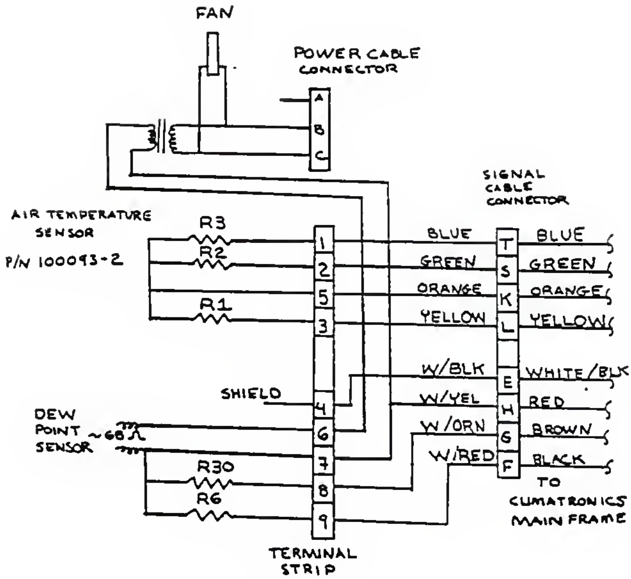
Test Results

Outside dry bulb temperature approximately = 19 C

Measured Resistance	Manufacturer's Resistance
R1 = 2.7 kohms	R1 = 2.614 kohms
R2 = 59.3 kohms	R2 = 58.49 kohms
R3 = 18.47 kohms	R3 = 18.40 kohms

Figure C.1

Actual Aspirator Circuit



Appendix D

Modified CMMS Calibration Procedure

Power Supply Calibration

Equipment Required

1. An Acurex programmed to read a 12 volt signal.
2. Adjustment Screwdriver.

Procedure

Use the Acurex as a voltmeter. Adjust the voltage to

+ 12.000 v then change configuration and adjust to

- 12.000 v as displayed on the front panel.

Wind Speed

Equipment-Software requirements

1. An Acurex programmed for measurand (in this case wind speed) and appropriate transmitter-Acurex connections.
2. Adjustment screwdriver.
3. Climatronics notebook for identification of components.

0-5 Volt Procedure

1. Switch the mode selector on the front panel to the ZERO position and adjust the wind speed zero pot.,

R14, for a reading of 0.0 mph (as shown on the front panel Acurex display).

2. Switch the mode selector to the SPAN position (this simulates a 50 mph wind) and adjust the Wind Speed Span pot., R13, till the display reads 50 mph.
3. Repeat 1 & 2 if necessary.

Wind Direction

Equipment-Software needed: same as for wind speed.

0-5 v Procedure

1. Switch the mode selector on the front panel to the ZERO position and adjust R34, the Zero Adjust Pot., for a 0 reading.
2. Switch the mode selector to the SPAN position and adjust R33 for a 360 reading.
3. Repeat 1 & 2 if necessary.

Dry Bulb Temperature

Equipment-Software needed: same as for wind speed and an Acurex programmed and wired for a low voltage reading.

0-5 v Procedure

1. Switch front panel switch to ZERO. Ground the junction of R2 and R3. Using the Acurex, measure the voltage between location 1 and ground, as shown in Figure D.1.

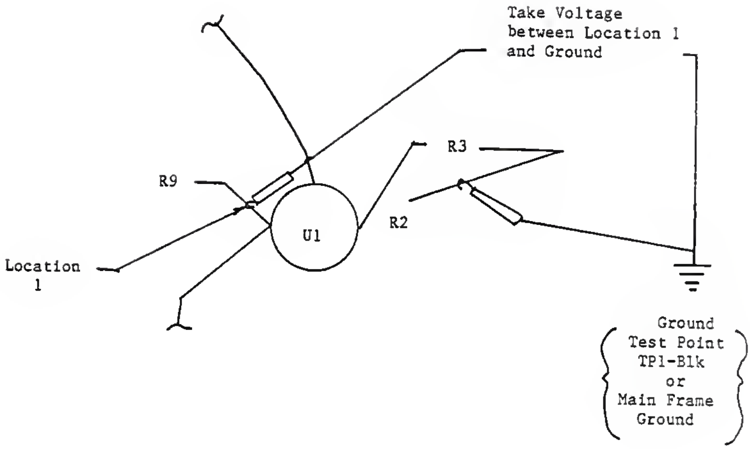


Figure D.1 CMMS Dry Bulb Temp. Calibration Connections

Note: There is an error in the CMMS notebook, and Climatronics has verified the above scheme is correct (11).

2. Now use the Acurex to measure the transmitter's output (units = degC). Adjust R54 for -50 degC.
3. Place the front panel switch to SPAN: adjust R15 till + 50 degC.
4. Repeat steps 1,2, and 3 as required.

Dew Point Temperature

Equipment-Software needed: same as for wind speed.

0-5 v Procedure

1. Switch mode selector to ZERO position. Adjust R8 tell Dew Point temperature reads -50 degC.
2. Switch mode selector to SPAN position. Adjust R10 tell Dew Point temperature reads +50 degC.
3. Repeat steps 1,2, and 3 as required.

Solar Radiation

Equipment-Software required same as for wind speed.

0-5 v Procedure

1. Switch mode selector to ZERO position and adjust the ZERO pot. till 0 langley.
2. Switch mode selector to SPAN position and adjust R11 till 2.5 langleys.
3. Repeat steps 1 and 2 as required.

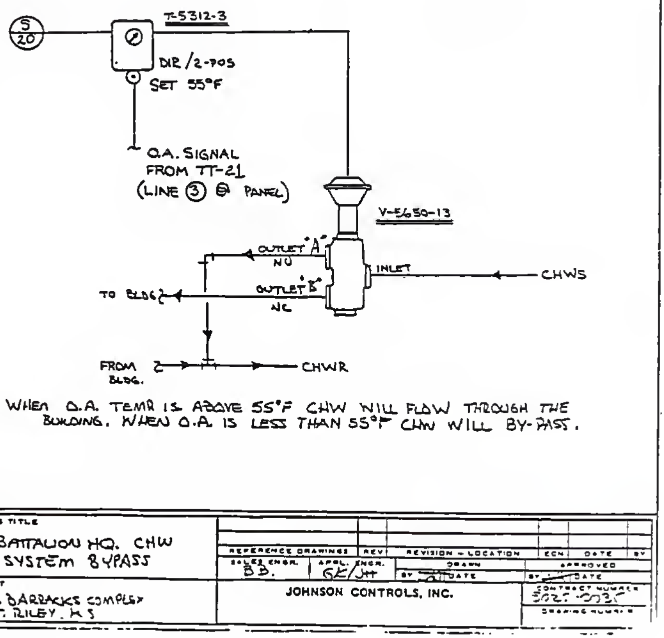
Barometric Pressure

Equipment-Software required same as for wind speed.

0-5 v Procedure (this translator does not have 0-10mv output)

1. Switch mode selector in the ZERO position and adjust R5 till 600 mb.
2. Switch mode selector in the SPAN position and adjust R7 till 1100 mb.
3. Repeat steps 1 and 2 as required.

Appendix E
Bypass Control Valve Schedule
Source: Johnson Controls schedule
located in Building 8025



Appendix F

Additional Venturi Flow Rate versus Differential Pressure Relationship Information

The manufacturer did not explicitly present the venturi flow rate vs differential pressure relation in the form of equation 3.4. Instead the manufacturer provided graphs of the relationships. Figure F.1 shows the manufacturer's flow vs. differential relationship for the 1.5 in. nominal diameter with Beta ratio equal to 0.563 in. Similarly, Figure F.2 graphically presents the manufacturer's flow vs. differential pressure relationship and the 2.0 in. nominal diameter with Beta ratio equal to 0.636 venturi flow meter. In order to convert the graphs into equation form, the constant c only needs to be solved for because flow is proportional to the square root of the differential pressure (12). The value of c can be determined by using the manufacturer's graphs and the following equation:

$$c = \text{Flow Rate (in gpm) at 100 in. } H_2O \text{ / } 10.$$

Once c has been determined, the traditional K value in equation 3.1 can be calculated. For the 1.5 nominal

Figure F.1 Flow vs Differiential Pressure Curves

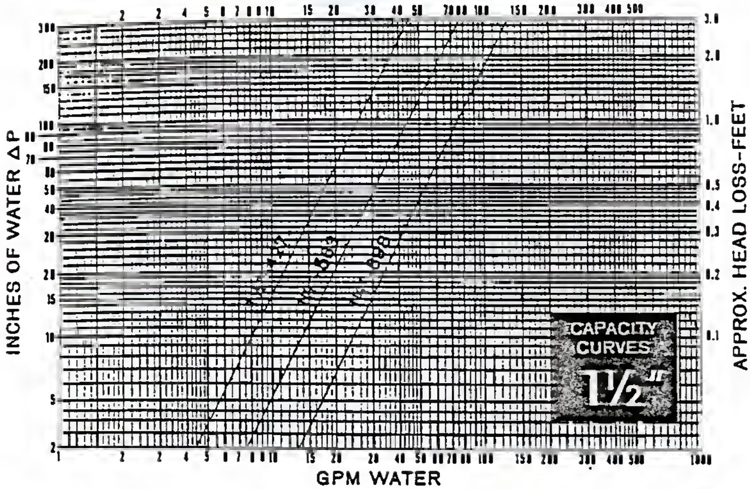
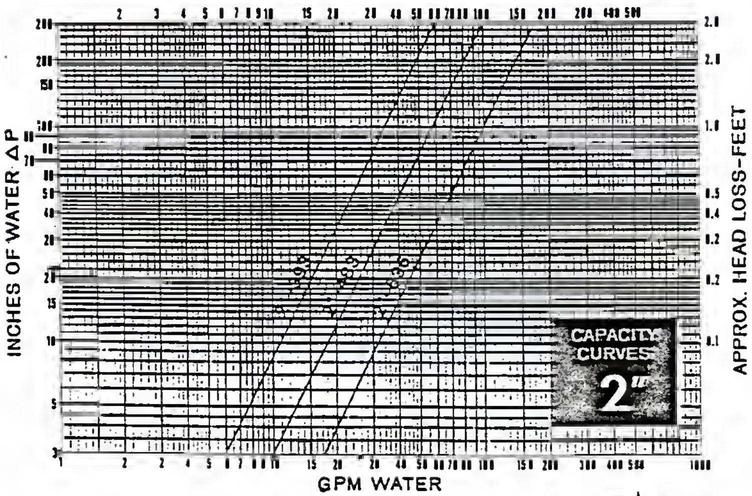


Figure F.2 Flow vs Differiential Pressure Curves



Aeroquip

diameter with Beta ratio 0.563 venturi this relationship between K and c is as follows:

$$K = c/5.677.$$

Where 5.677 is a constant which was determined from water properties, conversion factors, and 1.5 nominal diameter venturi parameters. (It is noted that the constant was determined with the cooling season water properties and that a correction to account for the different water properties for the hot water loop is required (see hot water loop measurement system for correction discussion.))

Appendix G

Results of a Pressure Transducer Verification Test

The results of a typical pressure transducer verification test are shown on the following page. It is noted that pressure transducer # 33 readings deviate as high as 10 mmHg from the manometer readings. This pressure transducer was returned to the manufacturer and replaced with a new one. The tests were conducted before each heating and cooling season. (It is noted that the new pressure transducer bleeding technique had not been developed prior to the test shown on the following page. However, it appears that this was not a problem because unbled transducers had problems only when there was a varing flow rate.)

Test Date: May 30, 1986

Transducers calibrated May 29, 1986

Manometer Reading (mmHg)	Building 8025 Pressure Transducer #				
	32	33	34	35	36
0	-0.2	-0.3	-0.1	-0.3	+0.1
20	21.0	20.0	20.0	20.6	22.2
40	39.2	38.5	40.6	41.2	40.2
60	60.0	57.1	59.7	61.8	60.8
80	80.3	76.2	80.0	80.6	79.9
100	101.1	96.1	99.3	100.3	99.4
120	119.2	113.8	119.1	120.2	120.0
140	139.5	133.0	139.5	140.8	140.3
160	159.2	152.6	159.3	161.2	160.3
180	179.0	171.2	179.2	180.6	180.2
200	198.8	189.8	199.0	200.8	200.0

Test Equipment

Manometer: Baurmeter, Stanby Model, W.A. Baum Co. Inc., N.Y. Scale = 0-300 mmHg, Least Count = 2 mmHg, and Overall Accuracy = ± 2 mmHg.

Appendix H

BYPASS TEST RESULTS

BUILDING 8025 DATE: SEPTEMBER 16,1986

TRANSMITTER WHITE LABEL #	MEASURAND FLOW FOR	AH #1 OFF	AH #1&2 OFF	AH #1&2&3 OFF
		Flow Rate in gpm		
34	AH #3	34.1	51.8	0
36	AH #2	40.8	0	0
37	AH #1	0	0	0
38	CWS	84.6	59.7	12.4

NOTE : All transducers were calibrated prior to the test.

BYPASS TEST RESULTS (continued)

BUILDING 8025 DATE : SEPTEMBER 3, 1986

TRANSMITTER WHITE LABEL #	MEASURAND FLOW FOR	AH #1&2&3 ON	AH #1&2&3 OFF
		Flow Rate in gpm	
34	AH #3	18.0	0
36	AH #2	20.9	0
37	AH #1	**	**
38	CWS	57.2	21.8

** : Transmitter sent back to Viatran

Note : All transducers calibrated prior to test.

The test was also conducted on Building 8037 and the test results indicated similar by pass control valve behavior.

Appendix I

Temperature Transmitter Calibration Procedure

Equipment Required

1. A programmed Acurex and proper connections.
2. An adjustment screwdriver, preferably a non-conductor.
3. A precision Decade resistance box.

Procedure

1. Make the proper connections as shown in Figure I.1.
2. Fill out the appropriate Temperature Data Sheet. (This step enables one to study the temperature transmitters drift characteristics).
3. Use the Temperature Data sheet to find the appropriate zero and span resistances. Using the resistance box, dial in the proper resistance. Note the lead resistances have been accounted for in the designated resistance.
4. Zero the transmitter by adjusting the zero resistance pot.
5. Span the transmitter by adjusting the span resistance pot.
6. Repeat 4 & 5 until the transmitter stays zeroed and spanned.
7. Reconnect transmitters (Figure 4.4).

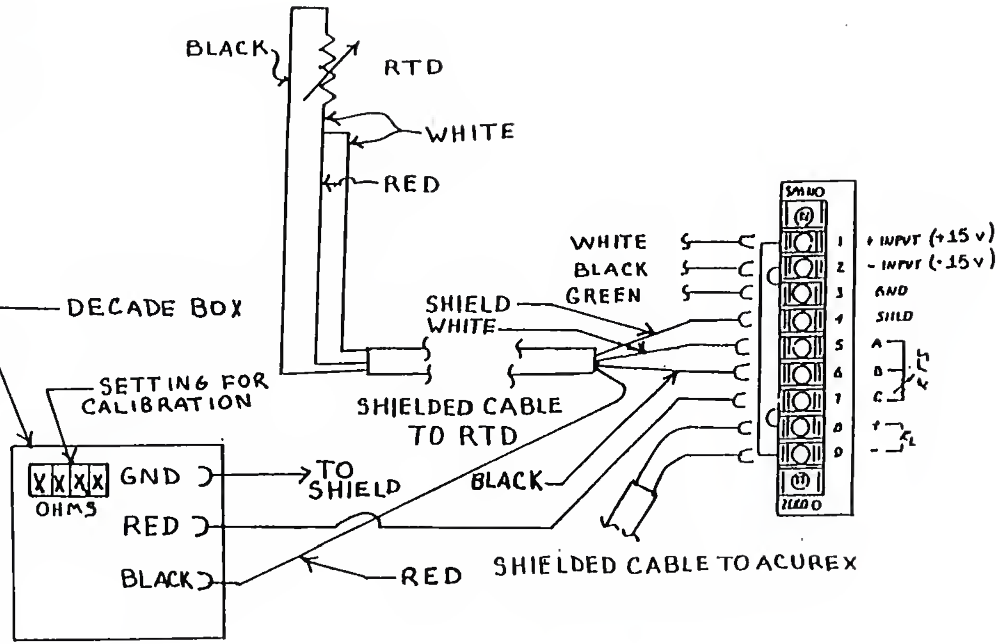


Figure I.1 RTD-Transmitter System Calibration Connections

DESCRIPTION AND VERIFICATION OF A BUILDING ENERGY MEASUREMENT SYSTEM

by

JON CHARLES ERICKSON

B.S., Kansas State University, 1985

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1987

Abstract

The Construction Engineering Research Laboratory initiated a program entitled "Design, Build, and Operate Energy Efficient Buildings" at Fort Riley, Kansas. The program was designed to quantify the amount of energy conserved by new Army buildings over similar buildings built around 1975. Another goal of the study is to compare energy data collected to detailed building simulations (BLAST). To achieve the project's goals the following is required: hourly environmental conditions, building description (e.g., geometry and structure), and hourly internal loads (e.g., equipment an occupants). To date, the program has concentrated on the task of monitoring on a hourly basis the environmental conditions and energy consumption in two adjacent old buildings (1975). This thesis reports the task of accurately measuring the environmental conditions and the energy consumption in the old buildings using existing measurement systems.

The weather data collection scheme has been proven to be very reliable due in part to the fact that there were two weather stations installed. The problem of verifying the weather data was approached in the following sequential manner: check and verify climatic instrumentation, formulate and implement proper

calibration and maintenance procedures, and develop a scheme to verify data on a continuous basis. Weather data were shown to be useful in predicting the energy consumption of the two old buildings. This prediction aids in the verification of building energy consumption measurements and in identifying suspicious data.

Instrumentation and equipment installation allowed for two independent energy consumption measurements on both the heating and cooling systems. The fact that there were two energy consumption measurements was used to help verify energy data and identify suspicious data. The solution to the problem of verifying the building thermal energy consumption required: understanding the building cooling and heating systems and the energy measurement systems that were installed, checking and verifying instrumentation, developing and implementing proper calibration and maintenance procedures, deriving appropriate measurement relationships and algorithms, and developing methods and techniques to verify data (measurements) on a continuous basis. As the result of the implementation of the verification of energy data techniques and procedures, the October 1986 - April 1987 heating season data collection has been very sucessful. The 1986 cooling season data was less sucessful but the future cooling data collection appears to be promising.

The data collected have also been very useful in studying HVAC system performance and energy consumption phenomena.