Fault Detection in Heating, Ventilation and Air-Conditioning Systems

by

ROBERT W. LANOUE

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ABSTRACT

Energy savings obtained through optimal control of a heating, ventilation and air conditioning (HVAC) systems will be lost if the system is operating under the influence of a fault. The detection and repair of such faults becomes necessary to keep the system operating at the lowest possible energy consumption.

This thesis examines the application of fault detection methodologies developed by Pape [1989] to an actual HVAC system. The experimental work was conducted at the Joint Center for Energy Management (JCEM) located in Boulder, CO.

Pape's work utilizes changes in the total system power to indicate the presence of a fault. However the experimental results found that the inherent instrumentation inaccuracies were such that the presence of a fault could not be determined due to experimental noise.

Energy and mass balances were then applied to the complete system as well as five subsystems. The results from these energy and mass balances showed that significant unbalances could be determined, even with the presence of experimental noise. Utilizing the

the information from the system balances faults could be detected within the system and subsequent corrections could be applied. The energy and mass balances were found to be within the expected accuracy of the laboratories instrumentation after the corrections were applied.

The results of this work conclude that faults in a HVAC system can be identified through the use of energy and mass balances.

ACKNOWLEDGEMENTS

I'm finally going to finish this BAD ACTOR, all I need to do is drop this baby off in the library and I'm GOOD TO GO. It was an experience that I would not want to repeat, although one that I would not want to miss either. At times it was one hell of a fight to get up the motivation to continue, but then I'm just stubborn enough to not give up. Now that the adventure is coming to an end there are a few people who offered guidance and or help along the way that I would like to thank.

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three weeks we have planned in Central America, you'll have to read his thesis to find out how the trip went. I would also like to thank Osman for his help and a friendship that has been able to reach half way around the world. I know that I'm a better person having spent some time with such a wonderful person. I wish him and his family the best of luck in the future, and hope that our paths cross again. How he ever put up being in the same office as Jim, Jeff, Doug and I, I'll never know.

I would also like to thank Jeff's Mom and Dad for allowing me to temporarily adopt into their family. The fishing that I enjoyed so much was for the most part done from Mr T's boat, as was the water skiing. The hospitality offered by Jeff's mom and Grandparents was incredible, as was Mrs T's apple pie.

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Wisconsin has been great, thanks to all who did their part to make my stay as fun as it was.

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NOMENCLATURE

Roman Symbols

A - coefficient matrix

AHU - air handling unit

b - vector of regression coefficients

BEMCS - building energy management and control system

C - coefficient matrix

CMS - control management system

Cp - specific heat

d - vector of regression coefficients

DDC - direct digital control

E - coefficient matrix

f - vector of uncontrolled variables

F_{lm} - motor load factor

F_{um} - motor use factor

FSZ - full sized zone

g - scalar constant

h - enthalpy

HP - horse power

J - instantaneous operating cost

JCEM - Joint Center for Energy Management

LSIM - load simulator

M - vector of discrete control variables

$\dot{m}$ - mass rate of flow

OA - outside air

OACS - outside air conditioning station

P - power

Q - energy

R - universal gas constant

RH - relative humidity

T - dry bulb temperature

TMB - thermal mass box

u - vector of continuous control vectors

$\dot{V}$ - volumetric flow rate

VAV - variable air volume

Greek symbols

δ - uncertainty

ε - error term

ω - humidity ratio

ϕ - relative humidity

ρ - density

Miscellaneous symbols

$\oplus$ - forced balance

* - excessive balance

Additional Subscripts

atm - atmospheric

chw - chilled water

i - inlet condition

o - outlet condition

CHAPTER
ONE

INTRODUCTION

In the first section of this chapter, background information on why fault detection is necessary to keep a heating, ventilation and air conditioning system operating at the lowest possible energy consumption is presented. In section 1.2, the goals and objectives of this thesis are stated. Theoretical fault detection methodologies are discussed in the final section.

1.1 Background

Societies' energy consciousness is growing, due in part to both environmental concerns and energy prices. Commercial Heating, Ventilation, and Air Conditioning (HVAC) accounts for a large portion of the total energy usage. Over the past years there has been a considerable effort put toward reducing the energy consumption of HVAC systems. This has been accomplished through the use of Building Energy Management Control Systems (BEMCS). The main purpose of the BEMCS is to keep the system running at the point of lowest energy consumption, or optimal operating point, while maintaining the comfort of the individuals utilizing the building.

By using a BEMCS, energy savings can be realized; however, when the HVAC system operates with an operating problem (fault) these savings may be lost. The introduction of a fault can change the system's power usage without changing the independent variables that are being used to control the system. Under such conditions, the BEMCS will not have knowledge of the existence of the fault. Detection of faults in a HVAC system becomes an important aspect of keeping a HVAC system operating at its optimal level of performance.

1.2 Objective

The main purpose of this thesis is to explore the application of experimental fault detection on an actual heating, ventilation and air conditioning system. A specific fault detection methodology developed by Pape [1989] will be the initial focus of this work. Additional techniques of fault detection were also considered. The facility that was used during this testing was the Joint Center for Energy Management (JCEM) located in Boulder, CO. The JCEM combines a complete HVAC testing system with an extensive data acquisition system.

Pape's work is based upon the influence that faults have on the total system power, and uses the differences between the predicted and actual power consumptions of the system to determine if a fault is present. The predicted power consumption is determined through an optimization of system parameters. Operation of a HVAC system under optimal control will yield the lowest total system power consumption. If a fault is present in the system the power consumption will increase, thus increasing the difference between the predicted and actual power consumptions.

To test this fault detection methodology, several sets of experiments were performed on the JCEM. The first set of tests were used to determine the performance characteristics of the system. The second group of experiments examined how the system performed when faults were introduced into the system. The results of these experiments were examined to see if fault detection using the theoretical method developed by Pape is applicable on actual systems or if others methods would have to be employed.

1.3 Theoretical Fault Detection Methodologies

The power consumption of a HVAC system can be predicted using a biquadratic formula for the power as shown by Braun [1989]. These predicted values can then be compared to the measured values from a system. The residuals, i.e. $\widehat{P}_{\text{measured}} - \widehat{P}_{\text{predicted}}$, can then be examined to determine the presence of a fault in the system. Pape designed a representative HVAC system using manufactures' catalog data and then developed a computer simulation of the system using TRNSYS (Klein, et al. [1988]). Pape used randomly selected sets of forcing functions in conjunction with the computer simulation to generate the measured power consumption. The predicted power consumption was obtained from the biquadratic equation using the same sets of forcing functions. The curve fit did not agree exactly with the simulation, and there are differences between the two powers. Residuals were determined without the presence of a fault in the system, were shown to have a mean of zero.

Using the same set of forcing functions Pape showed that as faults of greater magnitude were introduced into the system the bias in the residuals shifted upward. This trend was shown graphically in Pape's work and has been reproduced in Figure 1.1 for reference. Figure 1.1 shows the residuals from a set forcing functions under fault conditions. The fault introduced in this case was an error in the chilled water set temperature. Error levels in one degree Fahrenheit increments, up to four degrees (E = 4 F) were examined. The increase in the residuals for small errors is slight, and the residual plot does not differ much from the zero fault condition. Pape concluded from this that faults of small magnitude would be difficult to detect.

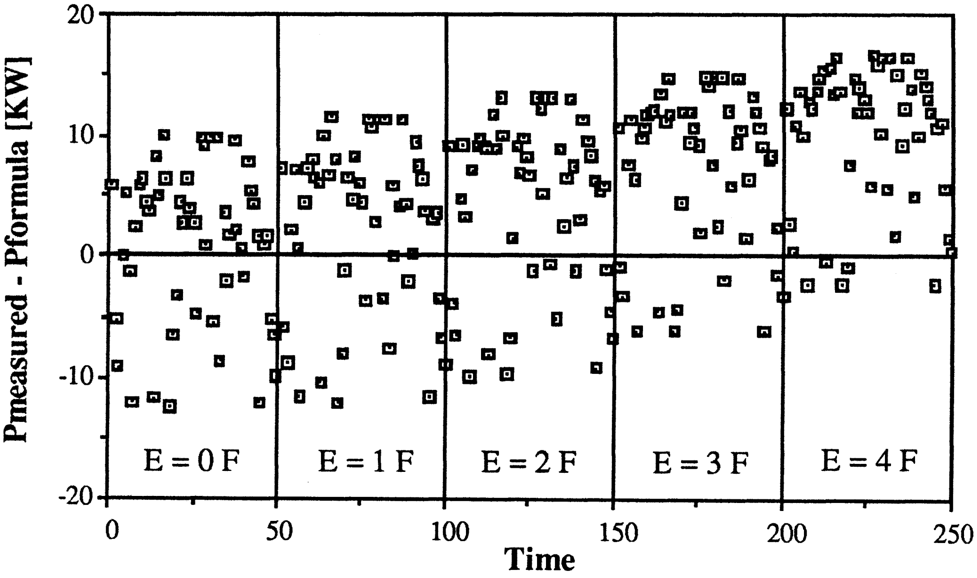

Figure 1.1 Differences in total power for increasing bias error in Tchw,set

Pape suggested several statistical methods for determining the presence of a fault by examining the residuals, which are outlined below.

Method A: Comparison between the system power $P_{measured}$ and $P_{predicted}$ for every measurements taken.

Method B: Comparison of trends in performance of the system under current operation and the system operating without fault (comparison of cumulative sum of residuals).

Method C: Comparison of sequence of consecutive operating data with a sequence of data obtained under operation without fault.

To determine whether or not a fault is located in the system each of the methods mentioned above tests the following inequality:

$$|\text{Measured Parameter - Predicted Parameter}| > \text{Threshold Value} \qquad (1.1)$$

The magnitude of the residual is then compared to a predetermined threshold value, with a fault being indicated when the magnitude of the fault parameter is greater than the threshold value. The threshold value can be determined through the use of the student T test. The magnitude of the threshold value is determined by the confidence level used in the T test. The higher the confidence level the larger the faults must be to be detected. If the confidence level is to small, nonfault conditions may be flagged as fault conditions.

Figure 1.2 shows the two confidence levels, 95 and 99%, examined by Pape. Residuals with values higher or lower than the limits defined by the confidence level used will be flagged as fault conditions. It can been seen in Figure 1.2 that when using a 99% confidence level only faults of 4 degrees Fahrenheit could be detected. Since each method suggested by Pape uses different parameters to determine the residual, the value of the residual will vary from method to method. Therefore, a trade off exists when employing the different methods as the magnitude and speed at which a fault can be detected varies . Pape suggested using all three of these methods in conjunction with each other so larger errors can be found quickly and smaller errors could be detected after a period of time.

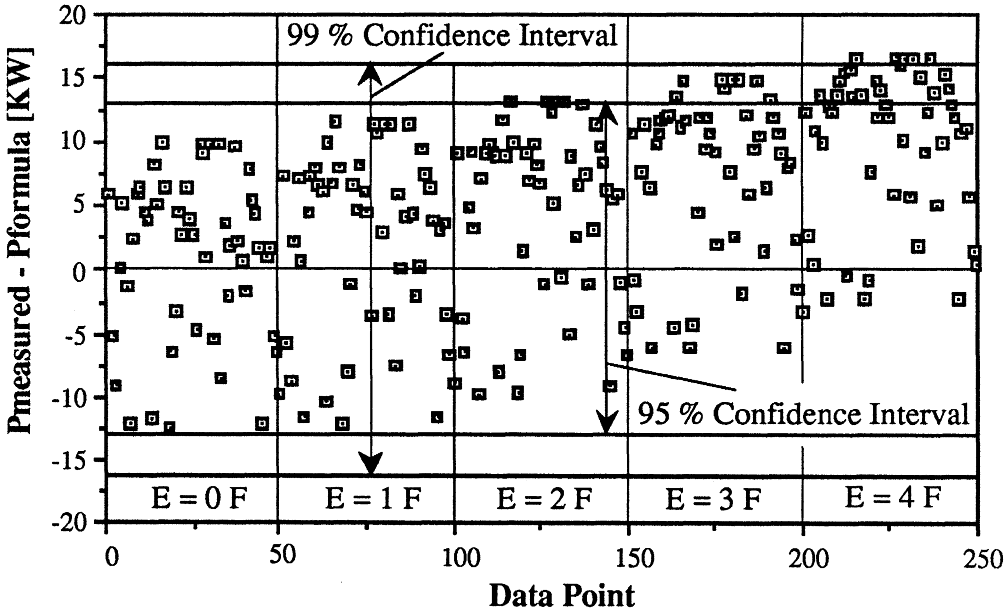

Figure 1.2 95% and 99% confidence intervals for residuals with bias error

The fault detection methods developed by Pape were applied to a HVAC system to determine if these theoretical methods could be used to detect faults within the system. This was accomplished by conducting a series of experiments in the JCEM laboratory.

CHAPTER
TWO

Experiments

In the first part of this chapter the laboratory facilities utilized during the experiments are reviewed. The layout, equipment, instrumentation and control strategies used during testing are described. In section 2.2 the experimental design and a methodology for optimal control are discussed. A description of the experiments that were conducted is included as section 2.3.

2.1 The Joint Center for Energy Management

2.1.1 INTRODUCTION

The Joint Center for Energy Management (JCEM), located near the campus of the University of Colorado at Boulder, is a full sized heating, ventilating and air conditioning (HVAC) experimental laboratory. The purpose of the laboratory is to test HVAC systems and components or control strategies of such systems. As shown in Figure 2.1, the main components of the laboratory include an outside air conditioning system (OACS) (not shown), an air handling unit (AHU), variable air volume (VAV) boxes, a full size zone (FSZ), a thermal mass box (TMB), two load simulators (LSIM-1, LSIM-2), a boiler, a chiller, and an air cooled condenser (not shown). The HVAC system at the JCEM may be considered to be made up of two loops; a water loop (see Figure 2.6) and an air loop.

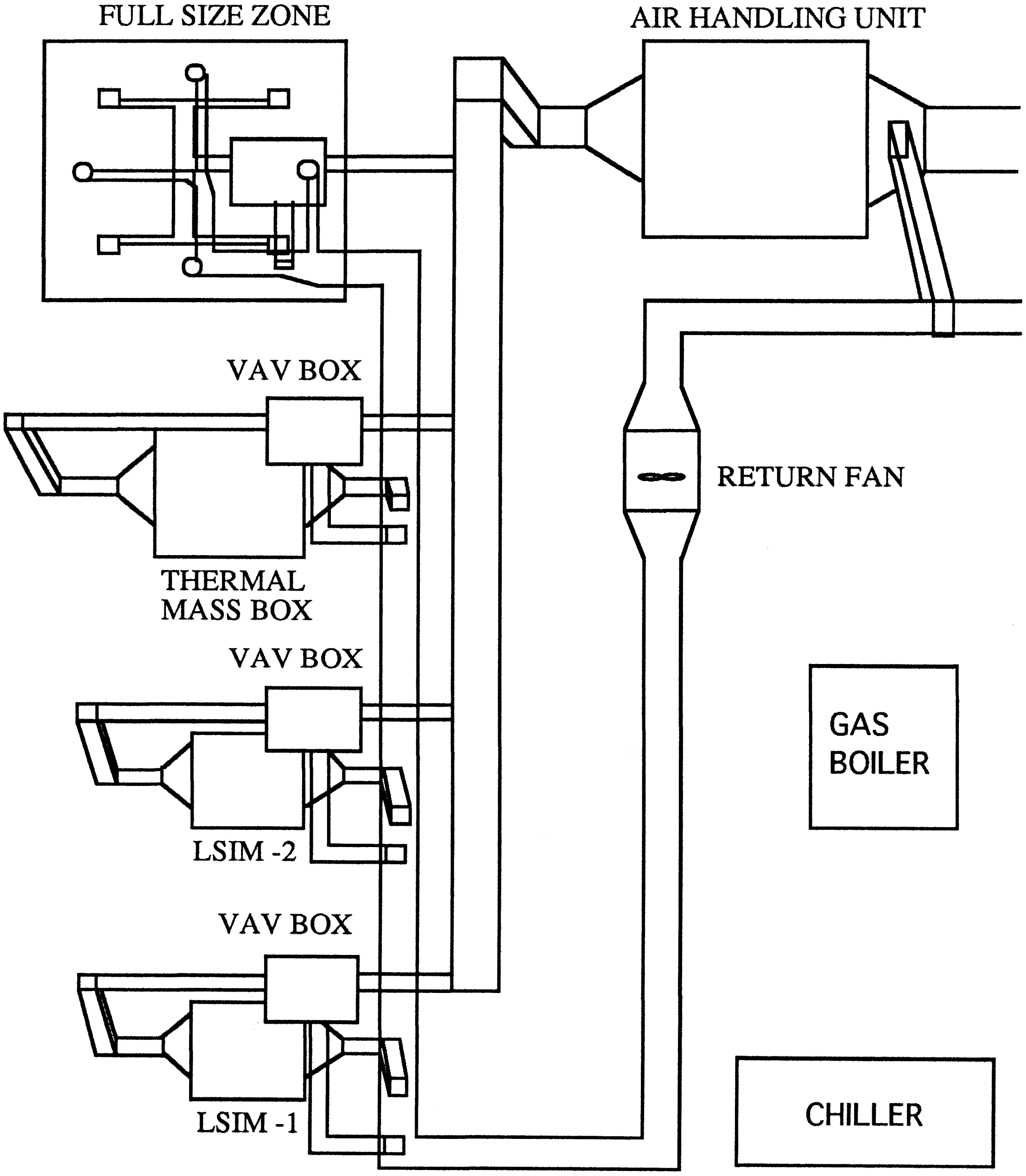

Figure 2.1 Approximate layout of air loop laboratory equipment

2.1.2 LABORATORY EQUIPMENT

The laboratory is equipped with a complete direct digital control (DDC) system which contains 230 analog inputs, 10 digital outputs, 30 analog outputs and 90 virtual points. The analog inputs are used to collect data from a wide variety of positions around the laboratory. Examples of readings that can be obtained include: temperatures, pressures, humidities, air and water flow rates, fan speeds, and power consumption data. Through the use of the ten digital outputs, equipment in the laboratory can be toggled on or off. The thirty analog outputs are used to control various pieces of equipment, including fan or pump speeds and valve positions. The virtual points have the flexibility to combine any of the measured values in equations to calculate a variety of items, such as densities, temperature differences, heat transfer rates, and loads. Each of the different data acquisition points is shown symbolically in Table 2.1; the number inside of the symbol represents the actual point number on the data acquisition system. These symbols are also shown on the individual component diagrams throughout this section.

SYMBOL	ACQUISITION TYPE
94	Analog Input
238	Digital Output
249	Analog Output

Table 2.1 Symbolic representation for data acquisition points

The AHU (shown in Figure 2.2) used in the laboratory consists of a chilled water coil, a hot water coil, and a supply fan. The cooling coil is rated at a mass rate of flow of 40 gpm, while the supply fan is rated for 12,000 cfm. The supply fan is driven by a 15 bhp electric motor with variable speed control capabilities. The motor of the supply fan is mounted outside of the air flow, and therefore does not add heat to the airstream. The AHU is also equipped with another heat exchanger (not shown in Figure 2.2) which is connected to the hot water system. This additional heat exchanger allows the laboratory to conduct both heating and cooling experiments. The AHU in the laboratory has extensive instrumentation to allow monitoring of a variety of measurements. It should be noted that this level of instrumentation is not commonly found in use today on actual HVAC systems. The approximate locations of the data acquisition points, used in this experimental work for the air handling unit, are shown in Figure 2.2.

For the experiments that were run, only three of the four zones were utilized. The full sized zone was not used and was isolated from the system. The thermal mass box and the two load simulators were used. This was done because the supply fan is rated for a volumetric flow rate of 12,000 cfm; the combined rated volumetric flows of the three zones.

The laboratory utilizes load simulators to impose loads on the chiller, much like actual rooms or regulated spaces in a building. To allow for the greatest flexibility in testing, both the hot and cold water coils of the load simulator were installed in each of the three zones (thermal mass box and load simulators 1 & 2). The combination of these coils allows for cooling loads to be imposed when the AHU is in the air conditioning mode and heating loads to be imposed when the AHU is in the heating mode. Each zone can be controlled individually to allow testing under a variety of room conditions. In the experiments performed under this work, only cooling loads were considered. Therefore, the hot water coils were isolated from the system.

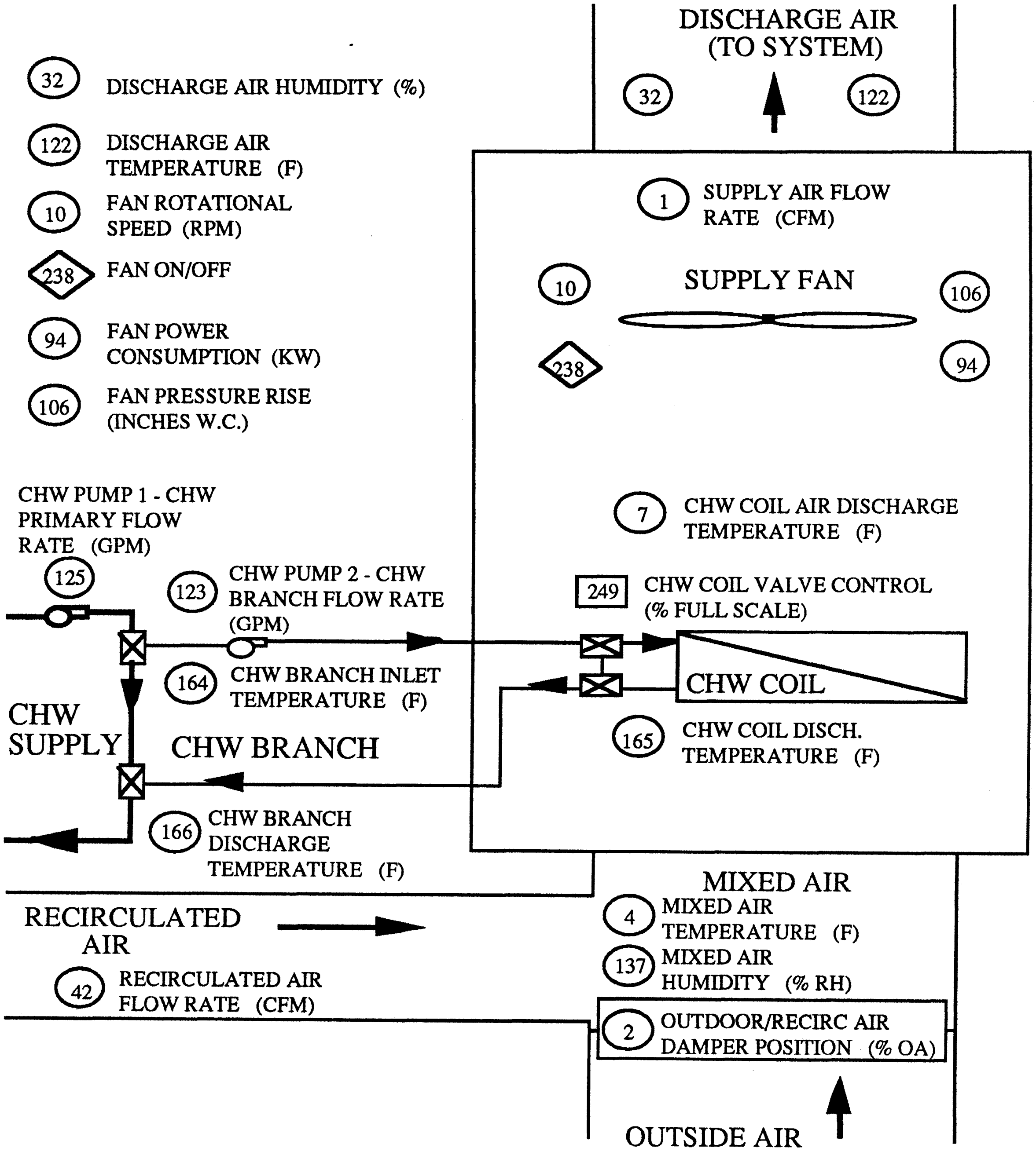

Figure 2.2 AHU-1 modified to show only the features used during testing

The thermal mass box, shown schematically in Figure 2.3, simulates a 2000 square foot room in a building containing significant thermal mass. The thermal mass is achieved through the use of water storage in PVC pipes. During this experimental work there was no water stored in the pipes, although the pipes themselves supplied some thermal mass to the zone. The thermal mass box differs from the load simulators only in the ability to vary its thermal mass and by the use of an auxiliary fan. The fan unit is controlled so as to offset the increased flow restriction caused by the pipes.

The data acquisition points for the two load simulators, shown in Figure 2.4, are similar to the thermal mass box without the fan unit. Each of the zones is capable of imposing loads of up to 45 MBTUH (100%) on the air handling unit cooling coil. The zones are also equipped with a steam injection system, described in more detail in the following paragraphs. Through the use of load simulators, the laboratory can replicate a variety of actual room conditions in a building, such as size, or room content. The room conditions that may be simulated vary from an equipment room which imposes only sensible load, to a class room which imposes both sensible and latent loads.

The hot water needed for use in the laboratory is produced by a gas boiler, which delivers saturated steam at 275 degrees F and approximately 10 psi. The steam generated by the boiler is used to produce a hot water supply and for steam injection. The hot water supply is obtained by mixing steam with water in a condenser. The system is controlled so that a constant temperature supply of water is available. To maintain the hot water set temperature, the control system monitors and varies the amount of steam that enters the condenser. The control system also varies the amount of hot water that is delivered to the zone heat exchangers, and thus regulates the loads imposed on the system.

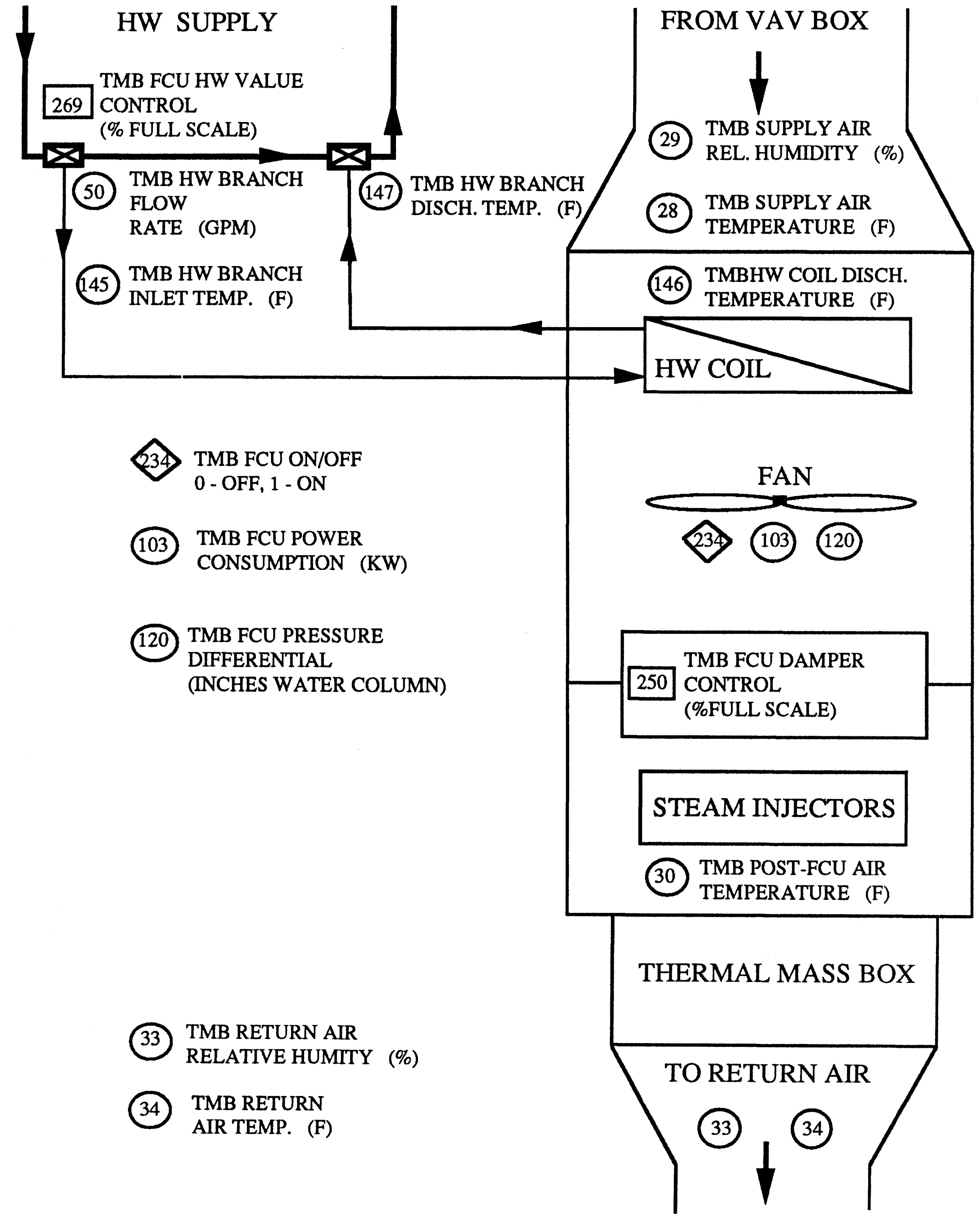

Figure 2.3 TMB modified to show only the features used during testing

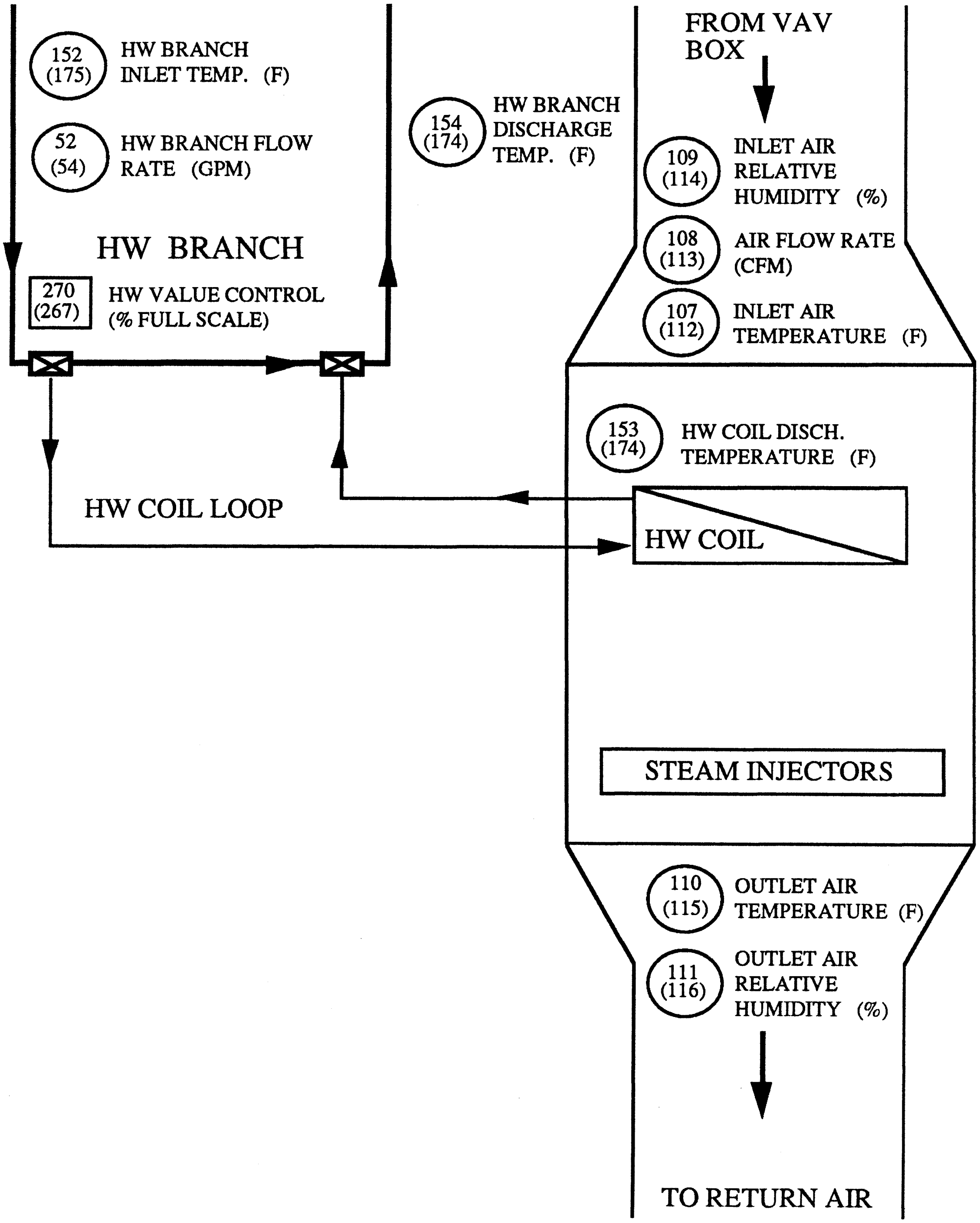

Figure 2.4 Load simulators modified to show only the features used during testing

Each of the zones is controlled individually to allow different loads to be imposed on each of the three zone simulators. This flexibility allows the laboratory to simulate a wide range of room conditions. It should be noted that although the hot water system is controlled to a specific temperature at the condenser, the temperature of the hot water delivered to the zones may vary from zone to zone due to losses to the environment. The control system compensates for these temperature losses by adjusting the individual flows through each of the zones such that the desired loads will be imposed.

The steam produced is also for direct injection into the air stream. Direct injection allows for the introduction of latent loads into the system. This injection allows the simulation of a room occupied by personnel, or a location where water vapor is being released into the room air (for example a locker room). Since steam is injected into the airstream, the temperature of the airstream does not appreciably increase, although the relative humidity of the air stream does. The amount of steam injected into the system is monitored through the control system, which varies the amount of steam to maintain the desired humidity. The overall change in the humidity of the return air is the driving force for the percentage of latent load that the chiller needs to meet. Since the return fan is located downstream of the zone load heat exchangers and supplies ample mixing to the airstream, all of the steam injected into the system was performed in only one zone. For the experiments that were run for this work, only the steam injection system for load simulator one (LSIM-1) was used.

The chiller is a fifty ton, three stage, reciprocating, prepackaged Trane unit utilizing R-22 as the refrigerant. The refrigerant transfers heat to either a heat recovery condenser or an air-cooled condenser. The air-cooled condenser, which was used exclusively during all experimental work is located outside the laboratory and is subject to fluctuations in the ambient conditions. The air cooled condenser has six electric fans which can be controlled by the data acquisition system. The fans are coupled in pairs, and at least two fans are on whenever the chiller is operating. Should the chiller cycle off at any time during an experiment, all operating fans on the air cooled condenser will shut off.

Other components used in the laboratory include variable air volume (VAV) boxes, a return fan, and two chilled water pumps. The VAV boxes modulate the flow of air to each zone; the control of the damper is achieved by sensing the pressure drop across the damper. The VAV boxes are also equipped with secondary fans, auxiliary heaters, and have the capability to recirculate air through the zone; although none of these features were used during this experimental work. Figure 2.5 shows a schematic of a typical VAV box, for use in conjunction with Table 2.2. Table 2.2 contains the actual data points from the control and monitoring system for each of the three zones that where used.

Zone	Acquisition Point				
	A	B	C	D	E
TMB	27	102	128	24	25
LSIM-2	XX	101	130	179	127
LSIM-1	XX	99	129	180	126

Table 2.2 VAV box data acquisition points

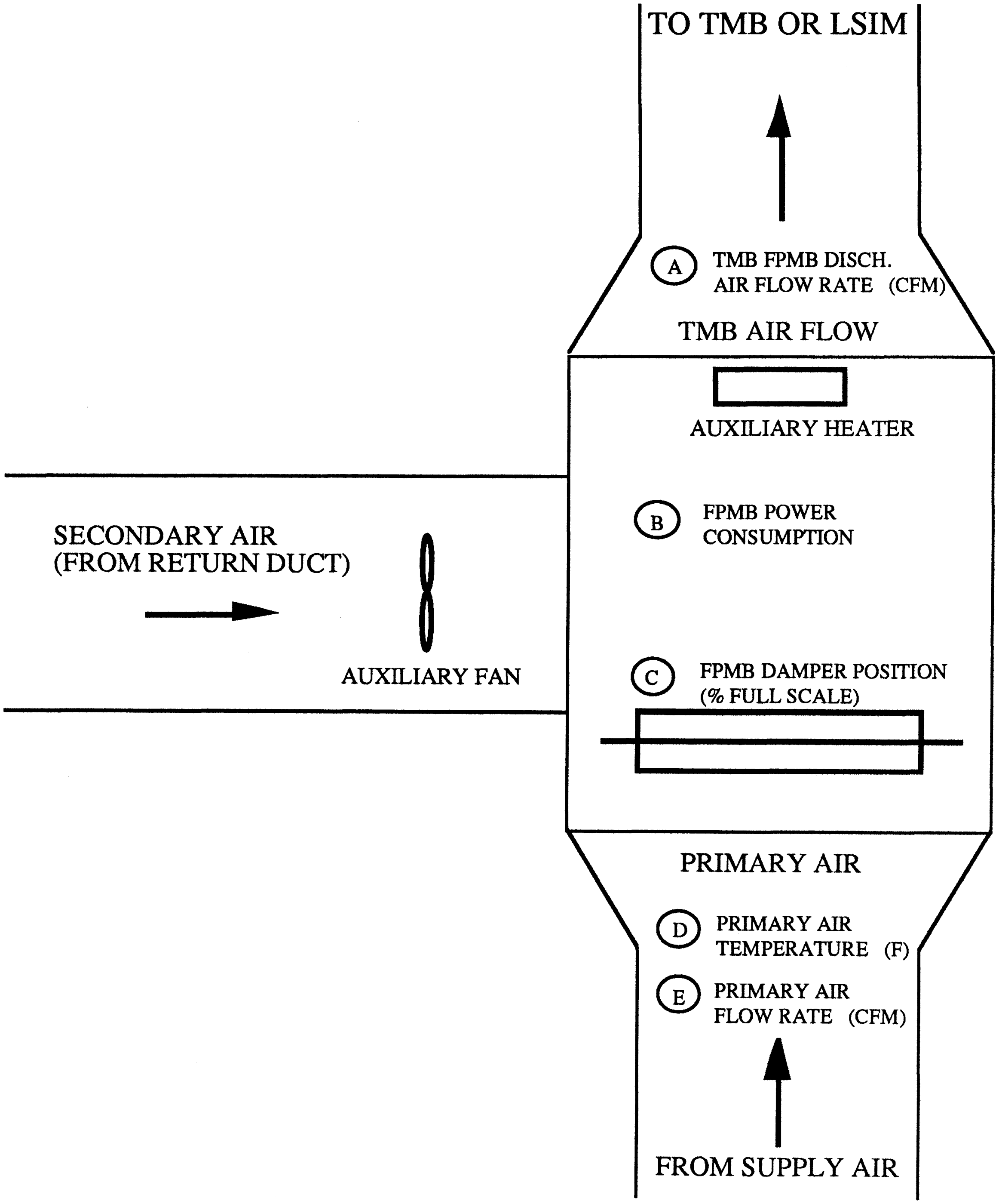

Figure 2.5 VAV box data acquisition points

The chilled water system, shown in Figure 2.6, consists of a primary and secondary loop. The chilled water system in the laboratory also consists of piping to each zone cooling coil (not shown in Figure 2.6) to allow heating loads to be imposed on any or all of the load simulators. The zone cooling coils were not used during this experimental work and were isolated from the system. The primary/secondary loop system was incorporated for increased temperature control capabilities. The primary loop is driven by a 1.5 bhp pump and supplies an approximately constant flow rate of 120 gpm.

A three way valve diverts flow as necessary to the secondary loop, maintaining the inlet side of the loop at the temperature which was specified for the chilled water supply. The secondary loop also has the capabilities of distributing flow to the three zones and the AHU cooling coil. The secondary loop is driven by a variable speed 3.0 bhp pump, which controls the mass rate of flow of through the secondary loop. Another three way valve distributes flow through the AHU cooling coil as necessary to achieve the desired supply air temperature.

The chilled water system has three storage tanks for a total capacity of 500 gallons. These tanks are used to increase the volume of the chilled water which recirculates in the loops. This additional volume is used to represent additional piping, which may be found in an actual system, between the chiller and the coiling coil(s). The additional mass of water supplied by the storage also helps to dampen fluctuations in the chilled water return temperature under varying load conditions.

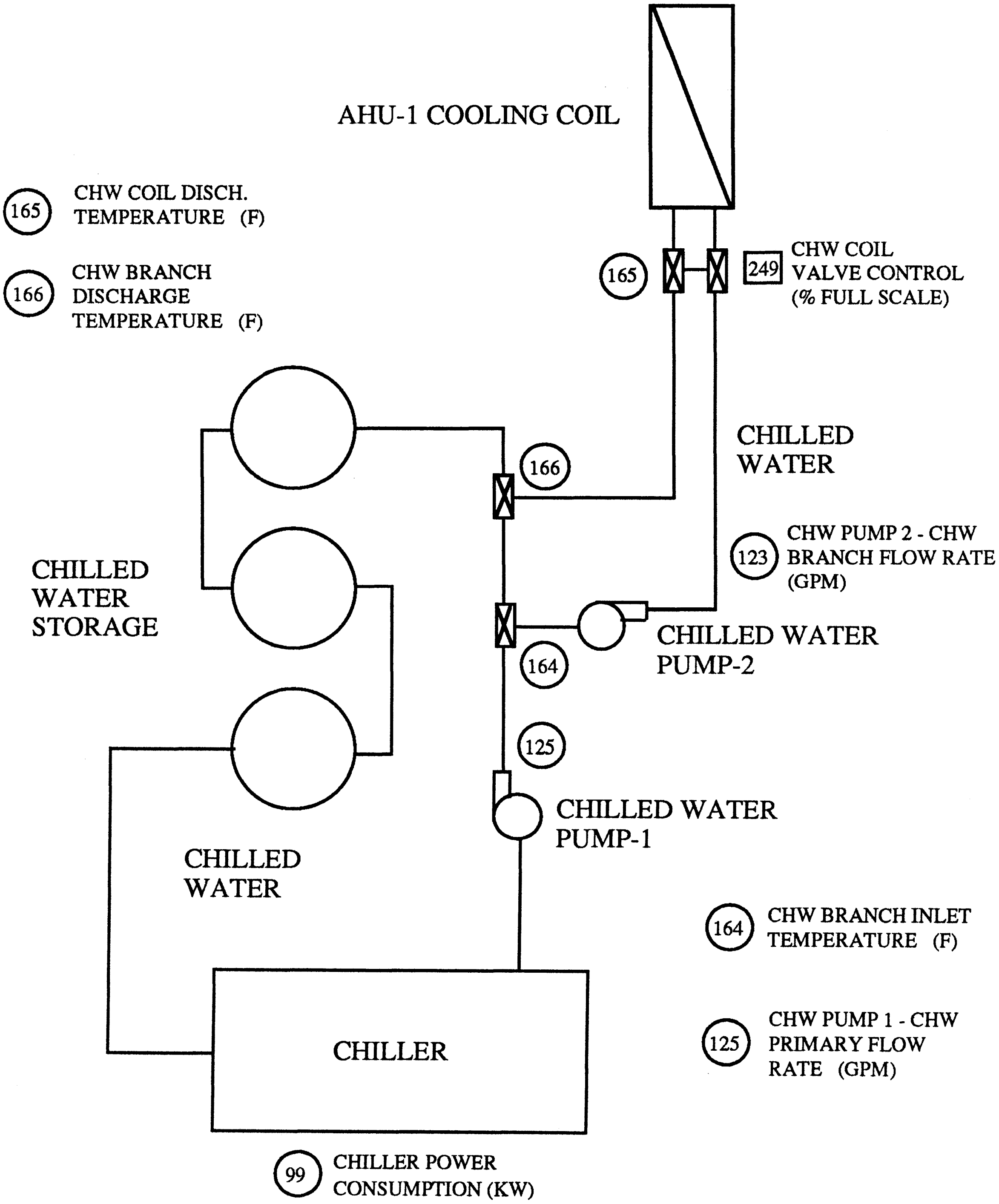

Figure 2.6 Chilled water system

2.1.3 DATA ACQUISITION

Preliminary experiments were run to obtain data from the laboratory equipment under known conditions. These experiments supplied information about the actual equipment; for example the maximum possible load that could be imposed on the cooling coil (300 MBTUH) and the maximum temperature difference that could be achieved across the cooling coil (26 F). This type of information was of great value when future experiments had to be designed. These tests also allowed the accuracy of the laboratory instrumentation to be determined.

As a means of checking the accuracy of the laboratory data acquisition system, energy balances were conducted around the cooling coil of the air handling unit. This cooling coil was chosen for two reasons; it is representative of the load that the chiller must satisfy and a variety of the types of sensors used in the laboratory are used to collect the data needed to perform the energy balances. The actual accuracy of the laboratory results will then be compared to the expected accuracy of the instrumentation as found through a statistical analysis known as an uncertainty analysis.

2.1.3.1 Uncertainty Analysis

Through the use of an uncertainty analysis on the data collected during preliminary experiments and the accuracy of the laboratory instrumentation, it is possible to gain some valuable insight into the accuracy of the data acquisition system. A table showing the various measurements that are used in the laboratory, along with the method of acquisition and the accuracy of those measurements, was obtained from Peter Curtiss, a member of the JCEM staff, and has been reproduced below for reference.

MEASUREMENT	METHOD	ACCURACY
Temperature - air	Individually calibrated RTD's	0.25 F
Temperature - water	Individually calibrated RTD's	0.1 F
Pressure	Absolute and differential transducers	1.0 % Full Scale
Humidity	Thin-film sensors individually calibrated with chilled mirror	3.0 - 5.0% RH
Airflow	Pitot tube array	3 %
Water flow	Turbine and venturi meters	2 %
Fan speed	Optical tachometer	1 %
Power	Custom measurement system	1 %

Table 2.3 Reported accuracy of laboratory instrumentation

The relative humidity sensors are accurate to 3% in the 10% < RH < 90% range and are accurate to 5% in the RH < 10% and Rh > 90% ranges. The larger error (5%) will be considered in the uncertainty analysis, as relative humidity readings in both the 3 and 5% error ranges occur in the system.

Considering energy balances on the AHU cooling coil, the following equations apply to the air side:

$$Q_{air} = \dot{m}\,\Delta h \qquad (2.1)$$

where

$$\dot{m}=\rho_{air}\dot{V}_{air} \tag{2.2}$$

$$\Delta h = h_{air,o} - h_{air,i} \tag{2.3}$$

$$h_{air\ in} = h(T_{air,i},P_{atm},RH_{air,i}) \tag{2.4}$$

$$h_{air\ out} = h(T_{air,o},P_{atm},RH_{air,o}) \tag{2.5}$$

$$\rho_{air} = \left(\frac{P_{atm}}{R\ (T_{supply\ air})}\right) \tag{2.6}$$

Similarly, the water side equations are:

$$Q_{water} = \dot{m}Cp\Delta T \tag{2.7}$$

where

$$\dot{m}=\rho_{water}\dot{V}_{water} \tag{2.8}$$

The volumetric flow rate and the temperatures, entering and exiting the cooling coil, were measured directly.

An uncertainty analysis uses the first order Taylor series expansion as an estimate of the uncertainty of a given measurement. The uncertainty in the heat transfer across the water side of a cooling coil is given by Equation 2.9. For complete details on the development of Equation 2.9 see Holman [1978].

$$\frac{\delta q_{water}}{q_{water}} = \left[\left(\frac{\delta \dot{V}_{chw}}{\dot{V}_{chw}}\right)^2 + \left(\frac{\delta T_{chw,o}}{\Delta T}\right)^2 + \left(\frac{\delta T_{chw,i}}{\Delta T}\right)^2\right]^{\frac{1}{2}} \qquad (2.9)$$

Substituting the given accuracy of the data acquisition system into equation 2.1, and using the minimum averaged difference in temperatures from experimental data, the uncertainty of $\dot{Q}_{water}$ can be expressed as:

$$\frac{\delta q_{water}}{q_{water}} = \left[(0.02)^2 + \left(\frac{0.1}{6.034}\right)^2 + \left(\frac{0.1}{6.034}\right)^2\right]^{\frac{1}{2}} = 3.08\% \qquad (2.10)$$

Similarly the uncertainty of the heat transfer across the air side of the cooling coil is given by:

$$\frac{\delta q}{q} = \left(\left(\frac{\delta P_{atm}}{P_{atm}}\right)^2 + \left(\frac{\delta \dot{V}_{air}}{\dot{V}_{air}}\right)^2 + \left(\frac{\delta T_{supply\ air}}{(T_{supply\ air})}\right)^2 + \left(\frac{\delta h_{air,i}}{h_{air,i}}\right)^2 + \left(\frac{\delta h_{air,o}}{h_{air,o}}\right)^2\right)^{\frac{1}{2}} \qquad (2.11)$$

Substituting the accuracy of the data acquisition system and using the average minimum temperature difference from the experiments, the uncertainty of Q_{air} can be expressed as:

$$\frac{\delta q_{air}}{q_{air}} = \left((0.005)^2 + (0.005)^2 + \left(\frac{0.05}{56.15+459.67)}\right)^2 + (0.05\ )^2 + (0.05)^2\right)^{\frac{1}{2}} = 7.75\% \qquad (2.12)$$

The results of the uncertainty analysis on the AHU-1 cooling coil show that the energy balances on both the air and water sides are within the 10% error that the laboratory personnel believed would be realistic.

2.1.3.2 Experimental Energy Balances

The experimental results were used to conduct energy balances on the cooling coil of the air handling unit (AHU-1). A representation of the system being considered is shown in Figure 2.7. For clarity, the system is considered to be made up of two separate parts, a water loop and an air loop

These calculations assume that the air-stream (actually an air-water vapor mixture) behaves as an ideal gas and has constant specific heat over the range of temperatures that are being considered. The specific heat of liquid water is also assumed to be constant.

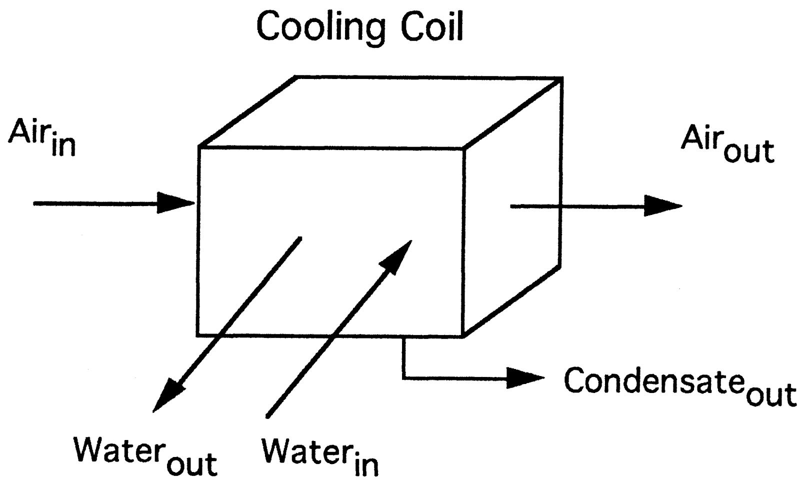

Figure 2.7 Schematic of the AHU-1 cooling coil

The inlet and outlet states of the air-stream are supplied by the laboratory instrumentation and are outlined below. The numbers in square brackets, [ ], are the corresponding data acquisition points in the laboratory.

$\dot{V}$ air in = $\dot{V}$ air out = $\dot{V}$[1] (cfm)
Atmospheric pressure (5430 ft above sea level) = P[121] (psig)
AHU discharge relative humidity = RH[32]/100
AHU inlet relative humidity = RH[137]/100
AHU inlet temperature = T[4] (F)
AHU discharge temperature = T[122] (F)
Cooling coil discharge temperature = T[7] (F)

The conservation of mass equation for the air-stream is then:

$$\dot{m}_{air}\omega_i - \dot{m}_{air}\omega_o - \dot{m}_{condensate} = 0 \qquad (2.13)$$

Solving the conservation of mass equation for the mass of the condensate.

$$\dot{m}_{water} = \dot{m}_{air}(\omega_i - \omega_o) \qquad (2.14)$$

The humidity ratios were found using lookup tables, which are part of the computer facilities at the JCEM, using the corresponding data points. The functions that were used are shown.

$$\omega_i = \omega\,(T_{air,i}, P_{atm}, RH_{air,i}) \tag{2.15}$$

$$\omega_o = \omega\,(T_{air,o}, P_{atm}, RH_{air,o}) \tag{2.16}$$

Note that the temperature of the air handling unit (AHU-1) chilled water cooling coil (T[7]) discharge temperature is used when possible. Although for the calculation of the AHU-1 discharge humidity ratio the relative humidity (RH[32]) and the temperature (T[122]) sensors at the outlet location are used.

An energy balance on the air side of the cooling coil is

$$Q_{coil} = \dot{m}_{air}(h_{air,\,i} - h_{air,\,o}) - \dot{m}_{water}h_{water,\,o} \tag{2.17}$$

The enthalpies of the air at the inlet and outlet states were also found using the computer based lookup tables and the functions shown below.

$$h_{air,i} = h(T_{air,i}, P_{atm}, RH_{air,i}) \tag{2.18}$$

$$h_{air,o} = h(T_{air,o}, P_{atm}, RH_{air,o}) \tag{2.19}$$

The enthalpy of the condensate was found using;

$$h_{water} = Cp\,(T\text{-}32) \tag{2.20}$$

Where h_{water} is equal to zero at 32 degrees F.

The equation that was used to calculate the enthaply of the condensate assumes that the temperature of the condensate leaving the cooling coil is the average temperature between the AHU-1 intake and discharge air temperatures. The equation is shown below.

$$h_{water} = Cp\left(\left(\frac{T_{air,i}+T_{air,coil,\,o}}{2}\right) - 32\right) \tag{2.21}$$

A similar analysis was conducted on the water side of the cooling coil. The mass rates of flow in and out of the coil are equal, assuming constant specific heat, so only the conservation of energy equation was needed. The inlet and outlet enthalpies of the water were considered to be only functions of temperature; thus the energy equation could be written as follows

$$Q_{coil} - \left(\dot{V}\rho Cp\Delta T\right)_{water} = 0 \tag{2.22}$$

The results from the energy balances performed on the initial experiments are shown in Table 2.4 and are labeled with the three digit date and a letter. The letter is used to signify the order during that day in which the experiments were run.

EXPERIMENT	Q AIR SIDE (Btu)	Q WATER SIDE (Btu)	|% DIFFERENCE|
611A	163954	172519	5.0
	175067	177304	1.3
	174944	176842	1.1
	177539	180613	1.7
611B	216125	208395	3.6
	214005	203647	4.8
	199902	196480	1.7
	203709	196397	3.6
	203019	195426	3.7
612A	300581	282844	5.9
	311471	294616	5.4
	309953	296954	4.2
	308474	300450	2.6
	323474	312845	3.3
	279932	302844	7.6
	230194	276043	16.6
	247170	268379	7.9
	231869	255453	9.2
	232797	250187	7.0
	232212	242938	4.4
	238507	241594	1.3
	241588	250898	3.7
	253889	248155	2.3
	232470	248630	6.5
	167915	228062	26.4
	192634	211302	8.8
	222091	234384	5.2
	201436	216267	6.9
	199289	216279	7.9

EXPERIMENT	Q AIR SIDE	Q WATER SIDE	|% DIFFERENCE|
613A	271822	279850	2.9
	298809	296274	0.8
	299986	292921	2.4
	297736	305645	2.6
	303846	307936	1.3
	302164	291989	3.4
	291520	306162	4.8
	302517	308926	2.1
	286624	284887	0.6
613B	213209	225958	5.6
	199539	212922	6.3
	159758	170072	6.1
	163354	181282	9.9
	149784	157190	4.7
	145146	155304	6.5
	175984	199356	11.7
	179647	202913	11.5
	179405	197728	9.3

Table 2.4 Energy balances from initial experiments

For example, experiment 611B indicates that the data was collected during the second test of the eleventh of June. Data collected during the initial tests was collected at various time intervals. This accounts for the differences in the numbers of data points that are shown in each experiment. It should also be noted that experiment 611A considered only sensible loads and therefore had no condensation. For experiment 611A, the equation for calculating the enthalpy of the exhaust air was modified as shown below.

$$h_{air,o} = h\,(T_{air,\,o}, P_{atm}, \omega_i) \qquad (2.23)$$

2.1.3.3 Comparison of results

The energy balances performed on the preliminary experiments are within the predicted accuracy of the instrumentation in most cases. These results lend creditability to the accuracy of the laboratory instrumentation, and to the level of calibration under which the laboratory is kept. However, the preliminary tests show several instances where the percentage difference in the energy balances are larger than expected. These instances are due to changes in system parameters during the experiment. The 16.6% difference of test 612B occurs during the five minute interval in which control of the outside air damper was changed from approximately 30% outside air to 100% outside air. With 100% outside air the mixed air temperature changed by approximately five degrees in a very short period of time. The 26.4% difference in test 612B occurred when the ambient temperature dropped approximately seven degrees due to an afternoon rain shower. When the mixed air temperature changes rapidly as in the two cases above, the system is no longer at a "steady state" condition and during these transient conditions the thermal storage of the coil needs to be considered in the energy balances.

2.1.4 CONTROL STRATEGIES

Modifications were made by JCEM laboratory personnel to allow individual control of the components by the control system. The main components for the experiments performed in this study which were modified include the chiller, the supply fan, and the return fan. In addition, the secondary chilled water pump and air cooled condenser fan controls, as previously mentioned, were modified.

The chiller's internal thermostat was bypassed to allow control by the control system. Through experimental trial and error, control constants for the chiller were found so that an efficient response to changes in load or set points could be achieved. Under these control methods it was possible to set the supply temperature of the chilled water to a specified temperature. This type of control is very important in optimally controlling the system.

The supply fan can be controlled to operate under three different methods: maintaining a constant speed, maintaining a return air temperature or maintaining a specified duct static pressure. The return fan can be controlled in the same manner as the supply fan, in addition to being controlled to maintain a fraction of the supply fan speed. Although any combination of these control strategies can be theoretically achieved, due to physical limitations of the equipment only certain control strategies will allow control of system characteristics. During initial tests, the VAV box damper positions were in the fully opened position, and the supply fan was controlled to maintain a set return air temperature of 78 degrees F. The return fan was then controlled to 95% of the speed of the supply fan, resulting in approximately 95% of the flow of the supply fan. Under such conditions, the outside air damper could be set to achieve any desired level of outside air. As an approximation of fresh air requirements, a minimum of ten percent of the total flow was chosen.

In later testing, the dampers in the VAV boxes were allowed to modulate to control the return air temperature in each zone. Under these conditions with the supply fan controlled to a specified duct static pressure (1.75 inches of water), the specified outside air percentage was not being met.

In order to control the amount of outside air that was being brought into the system, it was necessary to change the control of the return fan to a duct static pressure of 1.0 inches of water and control the outside air damper with a feedback loop. Under these controls the amount of outside air would vary with changes in the supply air flow rate, while maintaining the percentage of outside air.

2.2 Estimation of Optimal Control

2.2.1 INTRODUCTION

Pape's fault detection analysis is based on the ability to determine whether a fault is present within a system. A fault is detected based on a change in the total system power. To establish a basis upon which the operation of a HVAC system could be judged, it was necessary to obtain performance data from the physical equipment. A series of experiments was designed to collect the needed data. With the use of this data, optimization techniques could be applied to the system and estimated optimal control settings could be determined.

2.2.2 EXPERIMENTAL DESIGN

A series of experiments was run to establish a data base for the performance of the HVAC system over a range of operating conditions. Six parameters where varied for these experiments : **1**, number of fans running on the air cooled condenser; **2**, outside air temperature (dry bulb); **3**, percentage load imposed on the zones; **4**, chilled water supply temperature; **5**, supply air temperature and **6**, sensible heat ratio (SHR). (Each of the factors has been assigned a number for reference during statistical manipulations.) Control of these variables is possible through the Control and Management System (CMS), with the exception of the outside air (OA) temperature. Due to fluctuations in the ambient conditions the outside air temperatures varied during the experiments. Table 2.5 outlines each parameter and the levels which were considered.

PARAMETER	LEVEL 1	LEVEL 2	LEVEL 3
1 # FANS	2	4	6
2 OA TEMP (F)	70	80	90
3 % LOAD	33	66	100
4 CHW TEMP (F)	50	45	40
5 AIR TEMP (F)	60	55	50
6 SHR (%)	70	80	90

Table 2.5 Parameters and levels considered during experimental design

Three levels of each parameter, or factor, were considered. Since all possible combinations of these factors at three levels would require 3^6 or 729 experiments, statistical experimental design methods were used to reduce the number of runs. By using statistical methods, the number of experiments that need to be run can be reduced while still providing the needed information about the system. The first step that was taken to reduce the number of experiments was to split the experiments into two groups of six factors each at two levels. By doing this the number of runs that would be needed to explore all possible combinations (full or complete factorial) would be 128 (2^*2^6). Fractional factorial methods were then employed to further reduce the required number of experiments.

Fractional factorial methods take advantage of inherent redundancy found in a full factorial test, by combining main variables with higher order interactions. A complete factorial of six factors each at two levels would require 64 runs. From these 64 experimental runs statistics can be calculated that estimate the following effects:

	main	interactions				
average	effects	2-factor	3-factor	4-factor	5-factor	6-factor
1	6	15	20	15	6	1

Table 2.6 Interaction effects of the fractional factorial

By using the fractional factorial methods it was possible to explore the widest range of system operation with the fewest number of experiments. The effects that can be estimated are not all of significant size (the higher order interaction terms tend to be smaller than the lower order interactions) and the smaller effects can be considered negligible. By using the fractional factorial method each of the main effects are confounded with higher order interactions. If the higher order terms are considered to be insignificant, then the six main effects can be determined with only eight experiments. Since tests were run over a several day period under changing atmospheric conditions, the results of these tests could not be analyzed statistically with meaningful results. Even though the statistical results were not useable in this case, the method for determining which tests to run proved useful.

The first fractional factorial test that was considered contained the higher levels of the parameters that were examined. Table 2.7 shows the parameters and the levels of each that were used in the fractional factorial design. The levels of each parameter were arranged into the fractional factorial design in such a manner that any physical limitations of the system did not effect the experiments. A HVAC system would not be operated at a high load condition with the minimum number of fans operating because of the reduced heat rejection capabilities. Another physical limitation is the physical size of the cooling coil in the AHU. If the supply air and chilled water temperatures are controlled to approximately the same value, the size of the cooling coil needed to meet control requirements increases rapidly as the two temperatures approach one another.

To determine the runs that should be conducted, each factor was randomly assigned a plus (+) and a minus (-) level. A design matrix was then established by filling in a table using standard order for fractional factorial designs. Standard order is achieved by filling the first column of the design matrix with successive minus and plus signs, the second column having successive pairs of minus and plus signs. The matrix is then completed in the same manner with the *k*th column having 2^{k-1} minus signs followed by 2^{k-1} plus signs. A completed design matrix specifies which level of each variable that will be considered during a particular experiment. A typical design matrix and the levels of the variables for the first and second groups is shown in Table 2.7. The statistical methods used are discussed in more detail in statistical text books such as Box et al.[1978]

PARAMETER	FRACTIONAL FACTORIAL 1		FRACTIONAL FACTORIAL 2	
1 # FANS	6 (+)	4 (-)	4 (+)	2 (-)
2 OA TEMP	90 (-)	80 (+)	80 (-)	70 (+)
3 % LOAD	100 (-)	66 (+)	66 (+)	33 (-)
4 CHW TEMP	40 (-)	45 (+)	45 (-)	50 (+)
5 AIR TEMP	50 (+)	55 (-)	55 (-)	60 (+)
6 SHR	90 (+)	80 (-)	80 (+)	70 (-)

	PARAMETER					
RUN	**1**	**2**	**3**	**4**	**5**	**6**
1	-	-	-	+	+	+
2	+	-	-	-	+	+
3	-	+	-	+	-	+
4	+	+	-	-	-	+
5	-	-	+	+	+	-
6	+	-	+	-	+	-
7	-	+	+	+	-	-
8	+	+	+	-	-	-

Table 2.7 Parameter levels considered and a sample experimental setup

2.2.3 ESTIMATION OF OPTIMAL CONTROL

As stated, in Chapter One, Pape's work [1989] focussed on whether or not a fault could be detected in a system that was operating at optimal conditions. An optimal operational scheme was not available for the HVAC system in the laboratory at the time the sixteen tests were run. An estimation of the optimal conditions was found using a system-based algorithm developed by Braun (1989).

Braun's method relates the total system power to the operational costs. This technique permits the optimal control variables to be determined while only measuring total system power. The optimal control points are found by minimizing

$$J = \text{function}(\mathbf{f}, \mathbf{M}, \mathbf{u}) \tag{2.24}$$

where J is the cost of operation, **f** is a vector of uncontrolled variables, **M** is a vector of discretely controlled variables and **u** is a vector of continuously controlled variables. Examples of each types of variables being considered would be; number of air cooled condenser fans in use (**M**), chilled water temperature (**u**), and outside air temperature (**f**).

Braun found that a quadratic function, in terms of the uncontrolled variables, could be used to generate approximate optimal operating points. A quadratic equation of the following type was used by Braun.

$$J(\mathbf{f}, \mathbf{M}, \mathbf{u}) = \mathbf{u}^T\mathbf{A} + \mathbf{b}^T\mathbf{u} + \mathbf{f}^T\mathbf{C}\mathbf{f} + \mathbf{d}^T\mathbf{f} + \mathbf{f}^T\mathbf{E}\mathbf{u} + g \tag{2.25}$$

Where **A, C, E** are coefficient matrices: **b** and **d** are coefficient vectors: and g is a scalar constant.

The coefficients were found using a regression curve fit which utilized the data collected in the initial sixteen experimental runs. The total system power consumption for each five minute interval (integrated average) obtained during the sixteen initial tests was used to fit a regression. Over two hundred and fifty points were used to find the twenty eight coefficients needed for use in conjunction with Braun's optimization method. The regression was programmed into the computer facilities at the JCEM by Peter Curtiss. The results of the regression are shown in Figure 2.8.

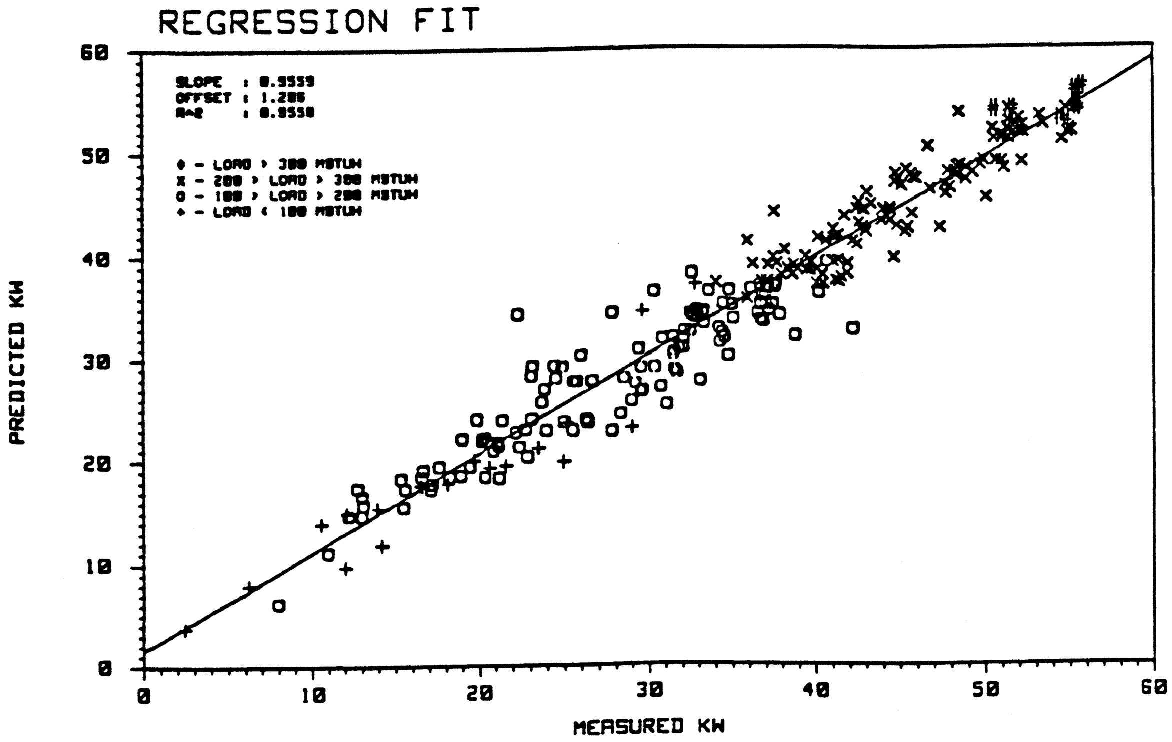

Figure 2.8 Regression fit form experimental data

A quadratic equation of the same form as equation 2.34 needs to be solved for each discrete variable level. If more than one variable exists the number of equation that need to be solved can become quite large. One approach that Braun suggests to reduce the number of equations that need to be solved in order to determine the optimal operating conditions is to treat some of the discrete variables as continuous variables. The discrete step that is closest to the optimal condition as determined by minimizing the cost function is then used during system operation. This approach was used for the air cooled condenser fans; thus only one equation needs to be solved to obtain the optimal operational conditions. Use of this method makes physical sense due for the following reason. The sixteen tests were collected over five minute intervals, with the integrated average being stored for the interval. For any five minute interval in which the chiller cycled off, the power consumption of the air cooled condenser fans could range from 0 to 1.5 KW per fan in operation, depending on the fraction of the time the chiller was off. Thus non-integer numbers of fans could be specified for any given five minute period.

Using the method mentioned above, along with the coefficient matrices and vectors generated from the original sixteen experiments and a specified level for each uncontrolled variable, the cost function was minimized. The optimal conditions for the controlled variables were then determined for use in future experiments.

Application of this method to an actual building would require sufficient information about the building system be gathered to obtain the coefficients necessary to fill the **A**, **C**, **E** matrices and the **b** and **d** vectors. Once these matrices and vectors are known, the cost function could be minimized and the optimal operating conditions of the controlled variables determined. Information on the operating characteristics of the building would be supplied to the building energy management control system (BEMCS) through a network of sensors placed throughout the building. Changes in the uncontrolled variables could effect the optimal conditions under which the system should be operated. Therefore at a given interval, the BEMCS should recalculate the systems optimal set points by minimizing the cost function with the current levels of uncontrolled variables.

One disadvantage of obtaining control set points while minimizing the cost function, as noted by Braun, is the inability to place constraints on the controls. The regression may return unacceptable values for the controlled variables. For instance an optimal chilled water temperature may be below freezing, or a chilled water temperature of 43 (F) and a supply air temperature of 45 (F) under a cooling coil load of 300 MBTUH. The effectiveness of the cooling coil in the air handling unit limits the exiting temperatures of both the water and air for given inlet temperatures. These physical limitations of the equipment need to be considered when choosing the optimal operating conditions. For the loads imposed on the zones (50% and 75%) during the experiments it was determined that a minimum temperature difference of nine or eleven degree F for the 50% and 75% load levels respectively, was necessary between the chilled water supply and the supply air temperatures. The necessary temperature differences were determined through a trial and error process.

Other constraints that needed to be imposed on the optimized variables include limiting the number of air cooled condenser fans to integer values. A minimum chilled water temperature of 40 degrees F and a maximum of 55 degrees F was also imposed. The minimum chilled water temperature was set to 40 F due to the chiller freeze protection setting of 38 F. Should the water temperature reach a temperature below 38 F the chiller would shut down automatically. The supply air temperature was also limited to the range of 40 degrees F to 75 degrees F.

2.3 System Fault Experiments

2.3.1 INTRODUCTION

Once the characteristics of the system were determined and an estimation of optimal control was established, the performance of the system could be examined under the influence of a fault. Faults on both the air and water sides of the system were examined. The air loop fault resulted in a reduction in air flow, while the water loop faults affected the chilled water supply temperature.

2.3.2 AIR LOOP FAULTS

The air loop faults were introduced into the system through the use of a blast gate. The blast gate was located between the main supply duct and the ducting which leads to LSIM-1. By partially closing the blast gate the mass rate of flow of air to the load simulator could be restricted. This type of fault was used to replicate a condition of a duct being partially collapsed, an obstruction of some sort in the duct, or frozen dampers in a VAV box. The initial position of the blast gate was marked for reference before adjusting the gate position to give the desired flow restriction. The flow rate levels that were examined were 95%, 90%, 80%, 70%, and 60% of nominal flow. When referring to a fault, the corresponding level of restriction (5, 10, 20, 30 and 40%) or the no fault (0 restriction) condition will be used. The positioning of the blast gate for each desired level of fault was found through experimentation. Once the desired air flow rate was achieved, the blast gate was marked for future reference.

Each morning the laboratory equipment was turned on and allowed to reach "steady state" during which time the following procedures were followed:

> The CMS was taken off standby mode and placed in ready mode.
> The points and rules files for the experiments were uploaded.
> Integral feed back loop constants were reset.
> The blast gate was positioned for the desired level of fault .
> A data file was created for the first experiment.

The points and rules files make up the heart of the control and management system; allowing the information from a specific experiments to be used during a test or saved for future reference. The points file consists of the unit conversion equations that are used in the data acquisition system. The rules file contains the control strategies, set points and control constants. With the control system being separated into two sections, changes can be made to set points and control variables without changing the conversion equations used by the control management system. This allows changes to be made to the system while the system is in operation.

During this warm-up period, the chiller brings the chilled water and supply air temperatures down to the approximate experimental levels. Once the system displayed "steady state" behavior, experimental testing could be conducted.

Under a specific load and room thermostat setting, the optimizing program was run to determine the set points for the supply air and chilled water temperature and the number of fans that should be used on the air cooled condenser. The optimization program then output a list of possible combinations of the three variables that would satisfy the load conditions along with the predicted energy consumption. From the list of possible combinations the lowest predicted energy consumption was determined. The set points for the three controlled variables were then entered into the CMS. The system was then allowed to stabilize under these operating conditions. Upon determining that the loads were being met, data was collected for that particular blast gate setting.

Data for each flow condition were collected by the CMS and output to a data file as five minute integrated averages. A minimum of fifty minutes of data was collected under each flow condition. After sufficient data were collected, the data file was closed and the positioning of the blast gate was moved to the next condition to be considered. The system was then allowed to return to steady state before collecting data under that fault condition. It should be noted that under a fault condition of this type, none of the variables that were used to optimize the system were changed. Therefore, the conditions set by the optimizing program could be used for the various fault conditions being considered.

Air loop faults were conducted at two level of loads; 50 and 75% of the maximum load simulator coil load, 45 MBTUH, at each of the fault levels mentioned previously.

2.3.3 WATER LOOP FAULTS

Water loop faults were implemented by modifying the temperature of the chilled water which was supplied to the AHU cooling coil. These experiments were used to replicate a chilled water sensor error. The optimizing program was then used to determine the set points for the controlled variables. The CMS was then programmed to change the chilled water temperature by a predetermined amount. The control equation used during these tests is shown below:

$$\text{Actual Temperature} = \text{"Optimal Tchw"} - \text{Fault} \qquad (2.33)$$

Where the actual temperature is the temperature that is delivered to the cooling coil, and the optimal Tchw is the chilled water temperature as determined by the optimizing program. The fault levels that were considered included -4, -2 , 0, 2, and 4 degree F increments.

These experiments were conducted using the same method as the air loop faults. The chilled water temperature was allowed to vary from the optimal condition to determine how the system is affected by such a fault. Water loop faults were also conducted on the 50 and 75% load levels of the load simulator hot water coil capacity.

2.3.4 LIMITATIONS/DIFFICULTIES

Several aspects of the JCEM system caused operational difficulties during this experimental work. The 50 ton chiller is oversized, so, therefore, the system could not be tested under full chiller power. The chiller was able to meet the highest loads imposed during testing while only operating in second stage. The load levels that were imposed on the chiller were in the 15 to 30% of the maximum load level. The 75% load level imposed on the load simulator hot water coils, represented the 30% load level on the chiller. The 50% load level on the zones translates to approximately 15% of the total chiller load. Had the chiller been sized closer to the system, small changes in chiller operation would have caused more noticeable changes in the chiller power consumption.

The freeze protection control built into the chiller controls also affected the experimental runs. The chilled water set temperature under the water loop fault of +4 degrees F called for the water to be delivered at 41 and 39 degrees F for the 75% and 50% load levels, respectively. Under this testing the temperature oscillated around the set point. If the chilled water temperature dropped below 38 degrees F, the freeze protection controls shut down the chiller and invalidated the tests. The fluctuations of the system varied with atmospheric temperature and other variables, so it was possible at times to run water loop faults at the +4 level. Experimental results were obtained for each of these load levels, although replication of these results was not possible during the current testing period due to time and weather constraints.

CHAPTER

THREE

System Balances

The first section of this chapter describes the method and means for applying mass and energy balances to the HVAC system located at the JCEM. The second section discuses the results of mass and energy balances conducted on the air loop fault experiments for both the 50 and 75% load levels. The water loop fault experiments are examined in a similar manner in the third section. Conclusions reached from these balances are covered in the last section of the chapter.

3.1 Introduction

In order to detect faults in a HVAC system accurate measurements of system parameters are necessary. Energy and mass balances can be utilized as a means of verifying the accuracy of these measurements. Unbalances determined through the application of energy and mass balances can be used to detect faults located in the system. Even with the existence of inherent sensor measurements, significant unbalances occurring in the system can be identified.

Energy and mass balances were used to verify the experimental results obtained from the testing performed at the JCEM laboratory. The HVAC system was divided into subsystems. Figure 3.1 shows a schematic of the system (labeled system 6) and outlines the five subsystems which were considered. The variables that were directly measured in each subsystem are labeled in the schematics e.g. Figure 3.2. Mass balances were used to check that the measurements of both air and water (water vapor) flow rate were accurate. Energy and mass balances were conducted on the entire system as well as the five main subsystems. The five subsystems include the following areas:

1. Fresh air intake / Exhaust discharge
2. AHU-1 cooling coil
3. Supply ducting - from the AHU to the load simulators
4. Load simulators
5. Return ducting - from the load simulators to the exhaust discharge
6. Total system

The experiments with introduced faults in both the air and water loops were used as the basics for instrumentation evaluation. Zone load levels of 50 and 75% will be examined in each of the six systems for both fault conditions. The energy balances conducted in each of the six systems will use the following equations as needed.

For heat transfer in the air side loop

$$Q_{air} = \dot{V}\rho\Delta h \tag{3.1}$$

where Δh is the difference between the enthalpy entering and leaving the subsystem.
For heat transfer in water side loop

$$Q_{water} = \dot{V}\rho Cp\Delta T \tag{3.2}$$

The water side equations assume that the density and Cp of the water is constant over the range of temperatures that are being considered.

To normalize the results of the mass and energy balances, the results have been divided by the respective values across the coiling coil. For example any air flow unbalance in system 1 would be divided by the air mass rate of flow across the cooling coil and then multiplied by 100 to obtain a percent unbalance. Similarly the water mass flow rate entering the cooling coil and the energy removed from the airstream by the chilled water were used to normalize the results from the water mass and energy balances respectively.

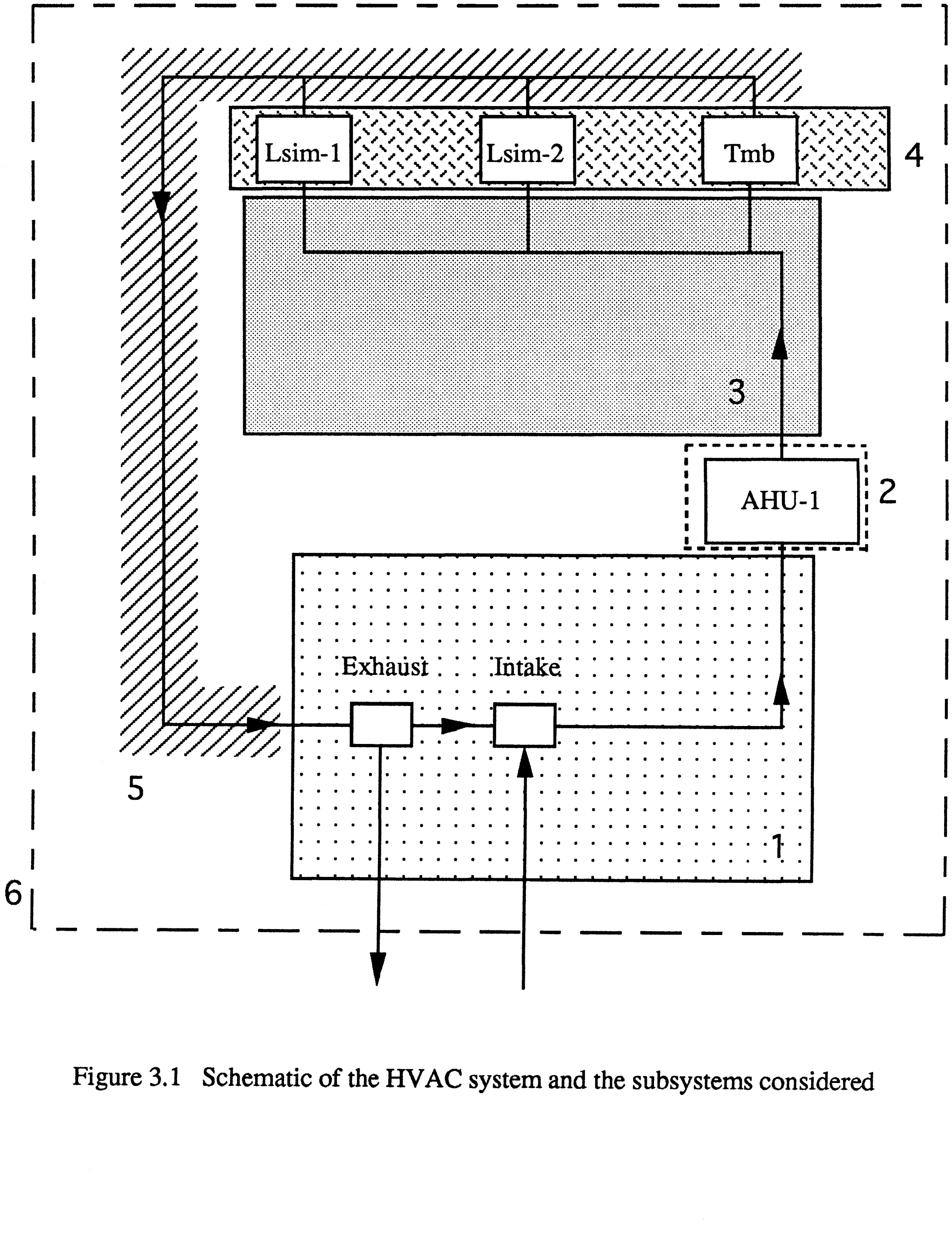

Figure 3.1 Schematic of the HVAC system and the subsystems considered

3.2 Air Loop Faults - Mass and Energy Balances

While section 2.3.2 described the manner in which the faults were introduced into the air loop, this section focuses on the effects those faults have on the system.

3.2.1 SYSTEM 1

System 1 consists of the duct work between the exhaust damper and the cooling coil of AHU-1; This system also includes the ducting into which the fresh air which is brought into the system and mixed with the recirculated air. The outdoor/recirculation damper is controlled to allow the predetermined amount of fresh air to enter the system; 10% outside air was used in these experiments. The actual outside air damper and the exhaust damper are controlled off of the outdoor/recirculation damper. Ideally the dampers would modulate to allow the desired mass flow rate of outdoor air into the system. Figure 3.2 shows a schematic of system 1

Mass balances for both air and water and energy balances were conducted on this system. The exhaust and recirculated airstreams were considered to have the same properties as the return air. The exhaust air mass flow rate was found through subtraction, and the intake air mass flow rate was calculated using the outdoor air density and the difference between the mixed and recirculated air flows. Since the exhaust and intake mass rates of flow were calculated, the mass balance calculation on the air is exact. This assumes there were no error in the instrumentation used in the calculations. Mass balances were also conducted on the water flow rate in the system, the results of these water mass balances are outlined in Table 3.1.

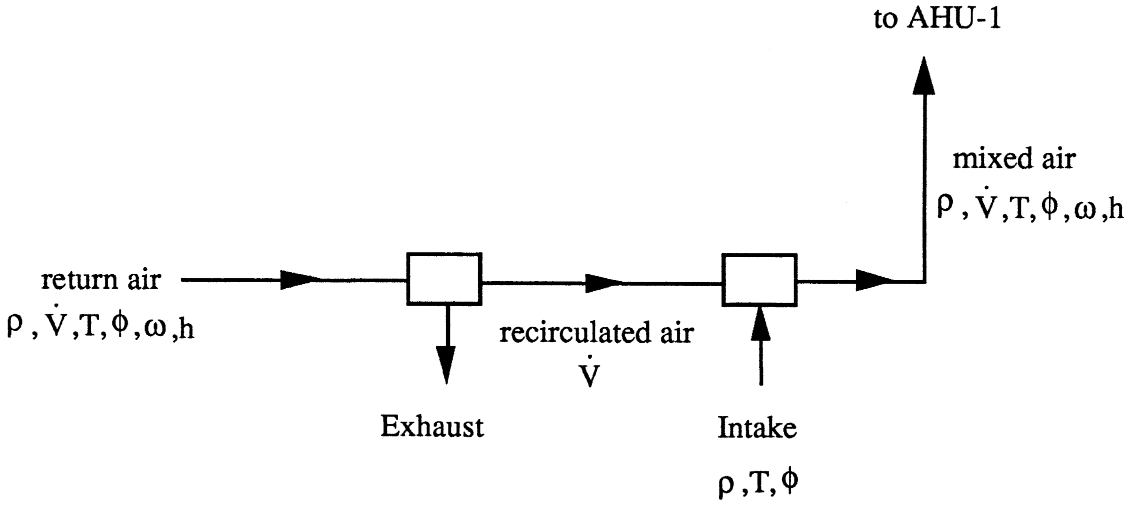

Figure 3.2 System 1 exhaust/recirculation ducting

An energy balance was also conducted around the system and the percentage unbalances are shown in Table 3.2. The density of the mixed air and the volumetric flow rate used for the inlet conditions of the AHU are actually measured at the outlet of the AHU. These values were used on the inlet side of the AHU since the mass rate of flow of air is conserved across the cooling coil.

% Reduction in Flow	% Unbalance - Water Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	13.18	13.99	12.66	11.19
5	14.29	13.69	11.51	11.67
10	13.75	14.53	12.43	12.04
20	14.63	15.729	12.26	12.73
30	14.76	14.54	11.56	13.74
40	14.38	14.25	12.76	14.10

Table 3.1 System 1 - water mass flow rate unbalances

% Reduction in Flow	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	24.43	26.68	30.89	28.59
5	27.46	27.46	28.43	27.61
10	26.10	28.95	31.13	28.83
20	28.73	30.50	30.14	32.25
30	29.31	27.98	29.32	34.07
40	28.19	29.25	31.36	33.30

Table 3.2 System 1 - energy unbalances

Examining the results of the mass and energy balances for system 1, the existence of a fault in the instrumentation is probable. Further examination of the other subsystems will be needed to determine the location of the instrumentation in which the fault is located.

3.2.2 SYSTEM 2

System 2, shown in Figure 3.3, consists of the AHU-1, which includes of the coiling coil and the supply fan. Mass and energy balances were conducted on both the water and air sides of the coil. The energy added to the air-stream by the supply fan was obtained from ASHRAE [1989] for a fan with its motor outside of the airstream and has been reproduced below.

$$q_{em} = 2425 \text{ HP } F_{LM} F_{UM} \tag{3.3}$$

Where Hp is the horse power rating of the fan, F_{LM} is the motor load factor, and F_{UM} is the Motor use factor. The actual power consumption of the supply fan, converted to BTU/hr was substituted into equation (3.3) in place of (2425 HP). This accounts for the fact that the fan was not running at the rated power (15 HP). The motor load factor, 0.87, was obtained from a table in ASHRAE. The motor use factor was given a value of unity, as the fan runs during the entire time the HVAC system is in use.

The mass balances for both the air and water were assumed to balance exactly It was assumed that the mass rate of flow of the air across the coiling coil was conserved, and that any change in humidity ratio of the air was due to condensation on the cooling coil. Since the mass flow rate of condensate was not measured, it was determined by using the change in humidity ratio and the mass flow rate of air across the coil.

The results of the energy balances performed on system 2 are shown in Table 3.3. The temperatures used to perform the energy balances in this section account for the energy input of the fan.

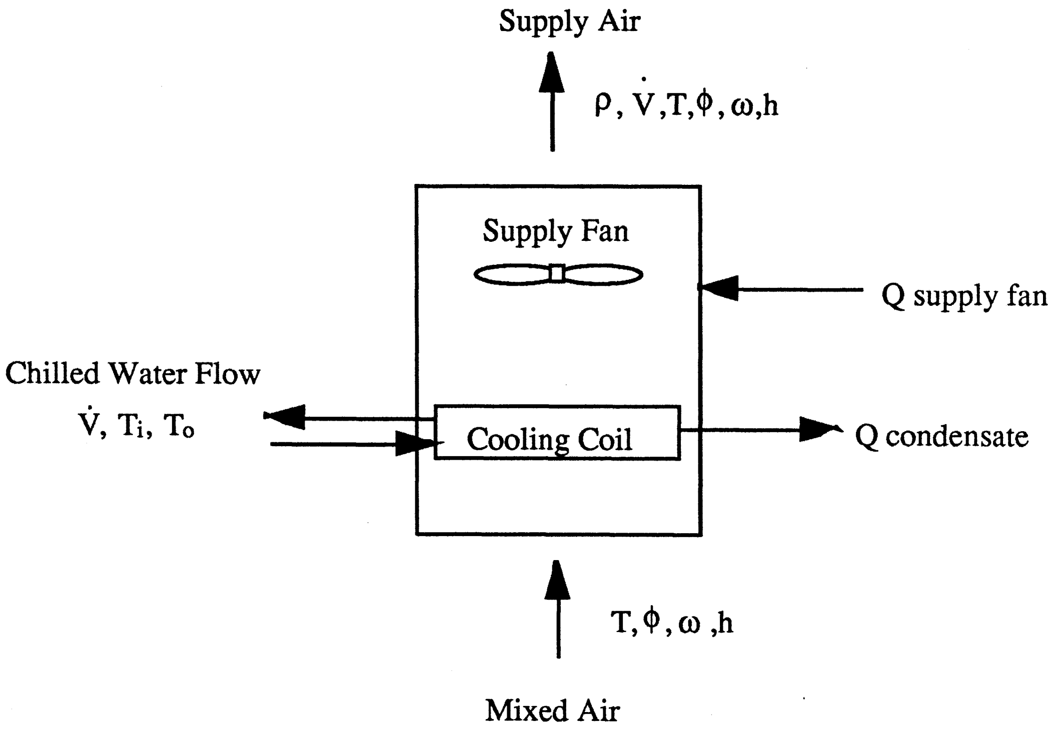

Figure 3.3 System 2 Air Handling Unit 1

The energy unbalances across the cooling coil are within the expected accuracy of the instrumentation, and for this reason the coiling coil will be used as a starting point for further examination later in this chapter.

% Reduction in Flow	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	12.19	12.91	6.15	11.74
5	10.77	15.33	12.72	10.58
10	11.36	13.15	8.46	13.39
20	10.90	11.49	9.33	9.09
30	12.23	11.57	10.80	8.56
40	14.07	14.49	11.43	11.49

Table 3.3 System 2 - energy unbalances

3.2.3 SYSTEM 3

System 3 is made up of the supply air ducting from the AHU to each of the zones. Figure 3.4 shows a schematic of the system, with the inputs and outputs labeled. The results of the air and water mass balances are shown in Table 3.4 and 3.5. While the results of the energy balances are shown in Tables 3.6.

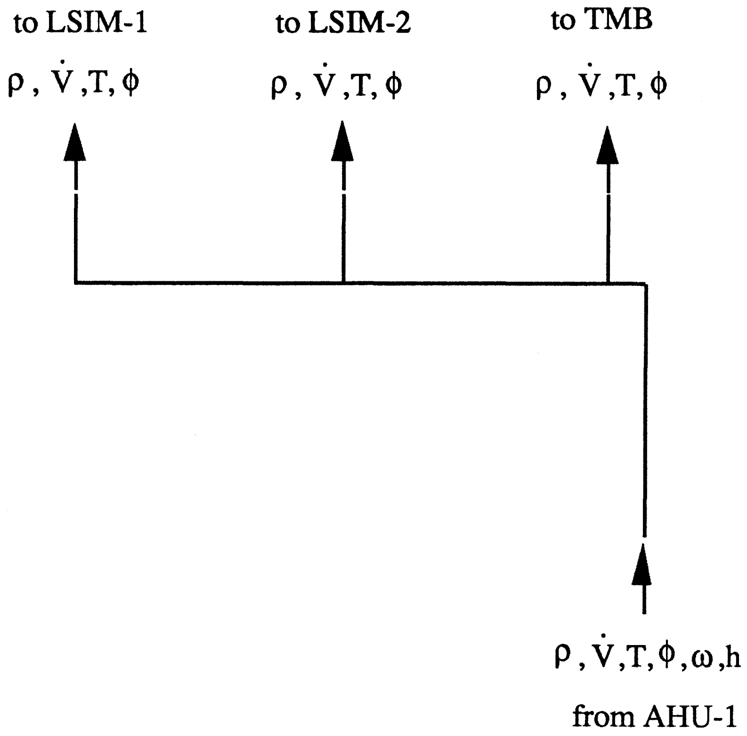

Figure 3.4 System 3 supply ducting

% Reduction in Flow	% Unbalance - Air Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	16.46	16.84	13.34	12.57
5	16.91	17.14	13.15	12.59
10	17.12	17.08	13.25	13.39
20	16.98	17.10	12.94	12.80
30	16.99	16.98	12.87	13.26
40	16.39	16.28	13.09	14.33

Table 3.4 System 3 - air flow rate unbalances

% Reduction in Flow	% Unbalance - Water Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	22.18	23.76	20.28	19.16
5	23.06	23.90	19.65	19.26
10	23.92	23.93	20.02	19.89
20	23.33	23.76	19.70	19.64
30	23.61	23.96	19.40	20.01
40	22.83	22.92	18.66	20.65

Table 3.5 System 3 - water flow rate unbalances

% Reduction in Flow	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	33.43	37.23	49.11	48.27
5	34.91	38.66	46.36	47.29
10	37.67	39.13	46.19	50.80
20	37.57	36.39	46.10	47.53
30	37.90	39.21	47.52	48.34
40	37.05	38.79	41.05	47.72

Table 3.6 System 3 - energy unbalances

Examining the results of the mass and energy balances conducted over system 3, errors larger than expected from instrumentation occur. These results shown that a fault is present in or around system 3.

3.2.4 SYSTEM 4

The fourth system that was considered contains the load simulators. Energy balances were performed on each of the zones; a typical zone is shown in Figure 3.5. Mass balances on the air and water vapor flow rates across each hot water coil were conserved. However energy balances between the air and water sides of the hot water coils were conducted. The differences in the air energy across the zone were considered to be the result of the heat transferred to the air. Differences in the hot water entering and exiting temperatures across the hot water coil were used to calculate the energy transferred from the water. No losses were considered in the zones; all of the energy transferred from the water is transferred into the air. Any differences between the loses from the water and gains by the air were attributed to errors in instrumentation. These differences for each of the three zones are shown in Table 3.7.- 3.9

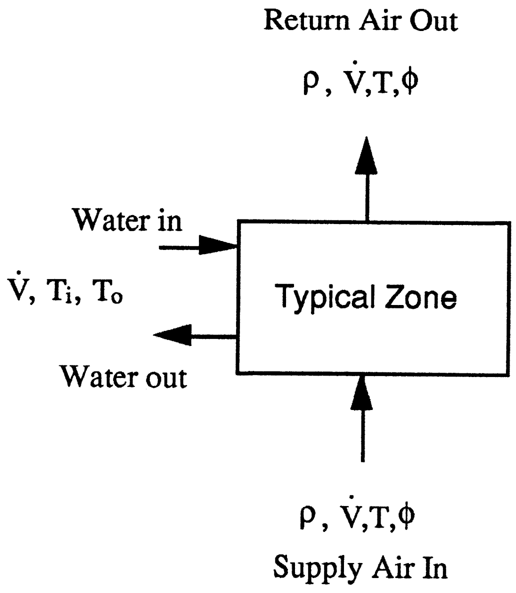

Figure 3.5 System 4 typical zone load simulator

% Reduction in Flow	% Energy Unbalance - TMB			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	5.49	4.56	2.59	2.78
5	4.22	4.98	2.74	3.14
10	4.14	4.15	2.74	3.62
20	4.09	3.67	2.73	2.82
30	4.26	3.88	2.55	2.64
40	4.12	4.37	2.54	2.38

Table 3.7 TMB energy unbalances

% Reduction in Flow	% Energy Unbalance - LSIM-2			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	- 6.19	- 5.65	- 6.98	- 6.71
5	- 6.13	- 5.36	- 7.26	- 6.78
10	- 5.70	- 5.10	- 6.85	- 8.02
20	- 5.59	- 5.01	- 6.93	- 7.70
30	- 5.69	- 5.19	- 7.22	- 7.54
40	- 5.88	- 6.14	- 7.18	- 7.48

Table 3.8 LSIM-2 energy unbalances

The energy unbalance in the LSIM-1 considers the necessary steam injection to satisfy the water balance across the zone. The steam injectors are located down stream from the hot water coil but prior to the relative humidity sensor. The amount of steam that is injected into the airstream is not measured directly, but was calculated using the mass flow rate of air and the change in humidity across the zone.

% Reduction in Flow	% Energy Unbalance - LSIM-1			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	- 2.07	- 1.94	- 1.34	- 1.34
5	- 2.09	- 2.12	- 1.42	- 1.29
10	- 2.03	- 1.98	- 1.30	- 1.19
20	- 1.78	- 1.95	- 1.22	- 1.24
30	- 1.46	- 1.86	- 1.00	- 1.18
40	- 2.01	- 1.53	- 0.87	- 0.67

Table 3.9 LSIM-1 energy balances

3.2.5 SYSTEM 5

System 5 considers the return ducting from the load simulators to the exhaust/recirculation damper. The return fan is positioned inside the return ducting, and has both the fan and the motor in the air-stream. Figure 3.6 shows a schematic of the system considered while Tables 3.10 - 3.12 show the results of the mass and energy balances.

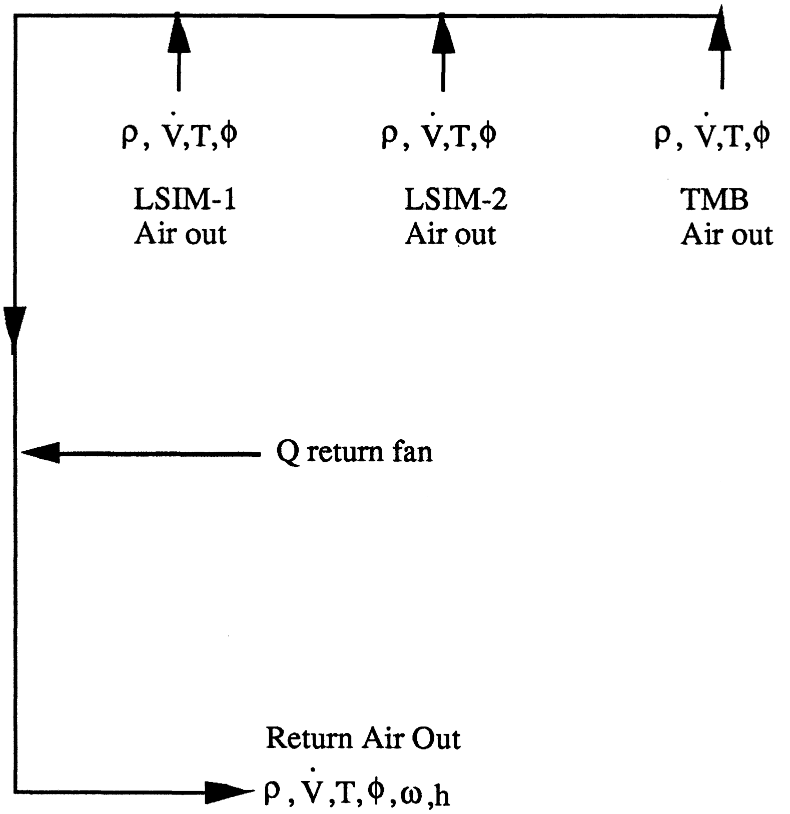

Figure 3.6 System 5 return ducting

% Reduction	% Unbalance - Air Mass Rate of Flow			
in Flow	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	- 24.61	- 24.87	- 15.16	- 14.28
5	- 23.61	- 24.33	- 15.27	- 14.56
10	- 23.82	- 24.59	- 15.37	- 13.73
20	- 23.71	- 24.73	- 15.81	- 13.68
30	- 24.89	- 24.79	- 15.60	- 13.95
40	- 25.09	- 25.29	- 16.74	- 17.89

Table 3.10 System 5 - air mass flow rate unbalances

% Reduction in Flow	% Unbalance - Water Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	- 60.56	- 61.31	- 41.88	- 39.32
5	- 61.27	-61.78	- 43.48	- 38.65
10	- 60.09	- 61.03	- 43.52	- 41.34
20	- 60.00	- 61.88	- 43.69	- 41.39
30	- 61.16	- 59.84	- 41.86	- 41.58
40	- 60.66	- 60.20	- 46.72	- 49.50

Table 3.11 System 5 - water mass flow rate unbalances

% Reduction in Flow	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	- 134.06	- 137.85	- 99.53	- 96.69
5	- 133.02	- 143.54	- 108.94	- 92.61
10	- 129.77	- 133.37	- 104.24	- 109.06
20	- 129.55	- 129.76	- 105.42	- 102.37
30	- 132.96	- 128.13	- 98.07	- 98.04
40	- 135.97	- 141.16	- 112.06	- 120.46

Table 3.12 System 5 - energy unbalances

The presence of a fault is apparent in system 5 when the results of the mass and energy balances conducted on the system are examined. Energy unbalance errors of this magnitude suggest errors in the relative humidity sensors. While air and water unbalances suggest a flow rate fault or leakage in the system.

3.2.6 SYSTEM 6

System 6 is a combination of all of the previous systems, and considers the entire air side loop as well as the energy gains supplied by the hot water system and the losses to the chilled water system. Figure 3.7 shows all of the inputs and outputs that were considered for this system. The results of the air and water mass balances that were performed are shown in Table 3.13 and 3.14. While the results of the energy balances are shown in Table 3.15.

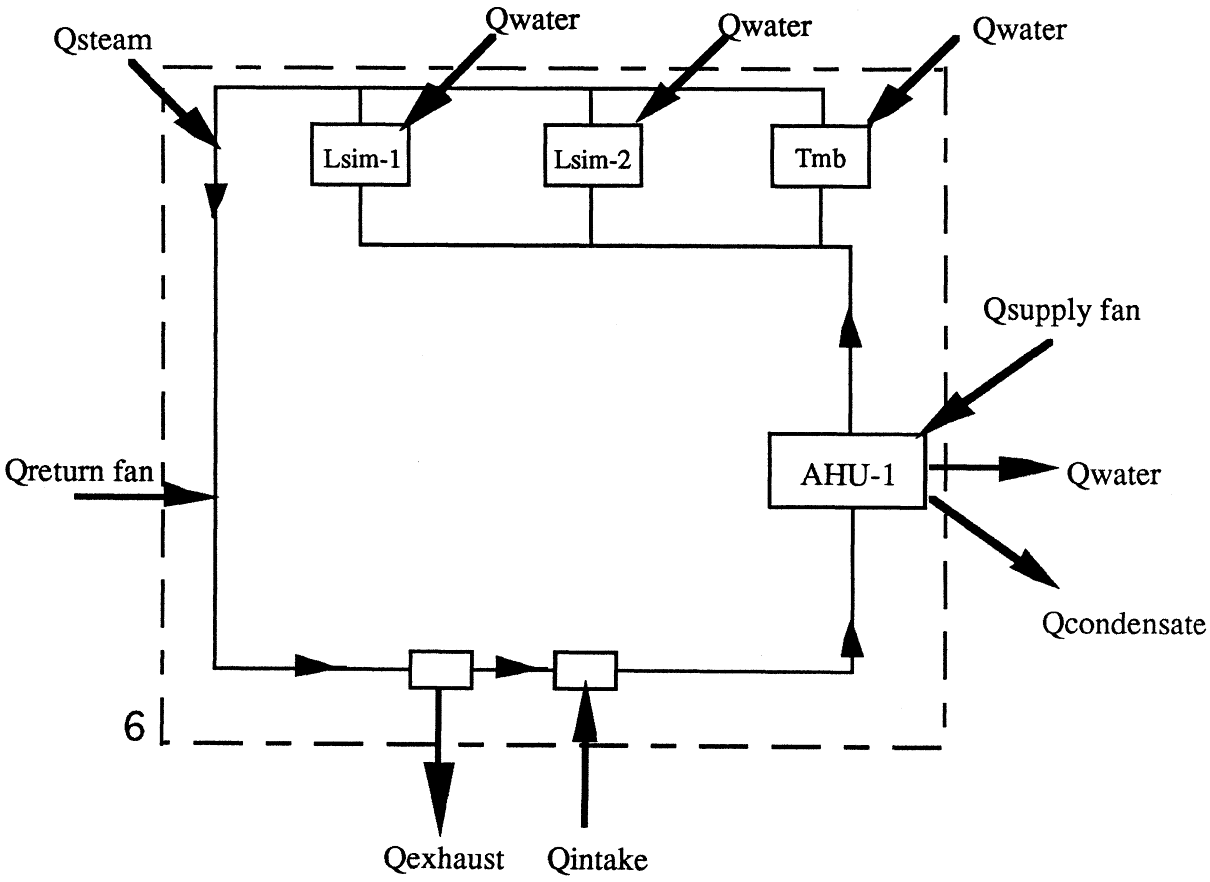

Figure 3.7 System 6 overall system inputs/outputs

% Reduction in Flow	% Unbalance - Air Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	- 8.15	- 7.78	- 1.82	- 1.70
5	- 6.85	- 6.91	- 2.12	- 1.96
10	- 6.87	- 7.22	- 2.12	- 0.34
20	- 6.95	- 7.32	- 2.87	- 0.88
30	- 7.59	- 7.51	- 2.73	- 0.69
40	- 8.40	- 8.78	- 3.65	- 3.56

Table 3.13 System 6 - air flow rate unbalances

% Reduction in Flow	% Unbalance - Water Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	- 20.26	- 18.72	- 6.66	- 7.09
5	- 19.33	- 19.70	- 10.01	- 5.91
10	- 17.88	- 17.92	- 8.82	- 7.44
20	- 17.51	- 17.61	- 9.42	- 7.01
30	- 18.15	- 16.92	- 8.74	- 5.84
40	- 18.70	- 18.60	- 12.40	- 11.79

Table 3.14 System 6 - water flow rate unbalances

% Reduction in Flow	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
0	- 73.66	- 72.17	- 37.42	- 34.50
5	- 71.80	- 73.52	- 40.90	- 35.25
10	- 70.04	- 71.46	- 40.80	- 31.85
20	- 68.90	- 71.13	- 42.73	- 34.26
30	- 71.12	- 70.29	- 38.96	- 31.49
40	- 72.96	- 73.80	- 45.95	- 45.62

Table 3.15 System 6 - energy unbalances

The results from the energy and mass balances that were conducted over the system and the corresponding subsections show that faults are presence in HVAC system that was used for this testing. Further examination of the types and locations of these faults will be examined in section 3.4, after a similar analysis is performed for the water loop experiments that were conducted.

3.3 Water Loop Faults-Mass and Energy Balances

The water loop fault experiments were described in section 2.3.3. The effects of introducing faults on the system is examined in this section. The inability to replicate some fault conditions, due to the chillers freeze protection, is the reason for the blank entries in some of the tables of results.

The actual chilled water temperature supplied to the cooling coil was determined by the following equation:

$$\text{Actual Temperature} = \text{"Optimal Tchw"} - \text{Fault} \quad (3.4)$$

Where the fault can be expressed in degrees deviation from the set temperature, and is referred to as "Degrees from optimal" in the result tables.

3.3.1 SYSTEM 1

The results of mass and energy balances applied to system 1 (see Figure 3.2) under water loop fault conditions is shown in Tables 3.16 - 3.17. The air mass flow rates again balance by default, as the outside and exhaust air mass flow rates are found algebraically.

Degrees from "Optimal"	% Unbalance - Water Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	12.52	12.84	12.65	12.67
- 2	11.53	13.18	12.80	13.10
0	11.87	12.83	13.56	12.59
2	11.46	12.49	12.38	11.87
4	12.37			12.78

Table 3.16 System 1 - water mass flow rate unbalances

Degrees from "Optimal"	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	31.72	32.07	31.66	33.03
- 2	25.35	28.47	32.75	27.08
0	23.32	23.02	31.82	24.60
2	21.14	22.24	31.49	24.73
4	22.15			25.72

Table 3.17 System 1 - energy unbalances

The results form the water loop experiments are consistent with the air loop experiments in that they show unbalances which indicate the presence of a fault.

3.3.2 SYSTEM 2

The mass balances for both the air and the water for system 2 (see Figure 3.3) were met by default. The air mass flow rate was assumed to be conserved across the cooling coil. The water mass flow rate across the coil was also conserved as any difference in the water mass flow rate across the coil was considered to have condensed on the coil. The amount of condensate again being found algebraically. The unbalances found through the application of energy balances on this system are shown in Table 3.18.

Degrees from "Optimal"	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	28.98	17.43	20.83	16.56
- 2	24.61	22.02	17.18	16.81
0	22.11	17.46	13.19	15.80
2	16.76	13.70	10.27	12.76
4	12.90			9.89

Table 3.18 System 2 - energy unbalances

The energy unbalances across the cooling coil indicate larger imbalances than excepted. Further examination of the other subsystems is necessary before conclusions can be reached.

3.3.3 SYSTEM 3

The supply duct (see Figure 3.4) was also examined under water fault conditions. The results of the air and water mass balances are shown below in Table 3.19 and Table 3.20.

The results from the mass balances conducted on system 3 are approximately the same as the result from the air loop experiments. However the energy unbalances are larger for the water loop experiments than they are for the air loop experiments.

Degrees from "Optimal"	% Unbalance - Air Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	16.27	15.89	13.97	13.76
- 2	16.72	17.33	14.19	14.25
0	16.77	17.27	14.74	14.43
2	16.87	17.33	14.32	14.50
4	16.75			14.45

Table 3.19 System 3 - air mass flow rate unbalances

Degrees from "Optimal"	% Unbalance - Water Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	22.88	22.15	20.02	20.39
- 2	22.13	22.24	20.16	20.37
0	21.82	21.98	20.91	20.38
2	21.86	22.05	20.20	20.51
4	21.73			20.52

Table 3.20 System 3 - water mass flow rate unbalances

The results of the energy balance for system 3 are shown below in Table 3.21.

Degrees from "Optimal"	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	51.75	57.20	58.43	62.13
- 2	46.53	50.02	535.23	53.46
0	41.35	40.97	52.95	48.63
2	39.37	37.98	51.2	49.11
4	36.60			48.80

Table 3.21 System 3 - energy unbalances

3.3.4 SYSTEM 4

Energy and mass balances were also applied to each of the load simulators in system 4 (see Figure 3.5). The air and water flow rates across the hot water coils were considered to be steady state, thus balancing automatically. The results of the energy balances between the hot water and the air flow through the zones are shown in Tables 3.22 - 3.24. The steam injected into the system, calculated by the change in humidity ratio across the zone, has been considered in the energy balances for LSIM-1.

Degrees from "Optimal"	% Energy Unbalance - TMB			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	7.61	19.07	6.19	5.61
- 2	5.41	6.81	4.41	3.92
0	4.29	5.92	2.57	3.29
2	3.85	5.77	5.22	3.45
4	3.92			3.21

Table 3.22 TMB energy unbalances

Degrees from "Optimal"	% Energy Unbalance - LSIM-2			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	- 7.71	- 5.68	- 8.50	- 8.17
- 2	- 6.49	- 7.52	- 7.74	- 7.21
0	- 6.22	- 6.27	- 6.89	- 6.95
2	- 5.82	- 5.93	- 7.05	- 6.53
4	- 5.62			- 6.55

Table 3.23 LSIM-2 energy unbalances

Degrees from "Optimal"	% Energy Unbalance - LSIM-1			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	- 1.90	6.96	- 1.56	- 1.20
- 2	- 1.97	-1.50	- 1.56	- 1.49
0	- 1.71	- 1.43	- 1.51	- 1.61
2	- 1.61	- 1.66	- 1.16	- 1.21
4	- 1.80			- 1.18

Table 3.24 LSIM-1 energy unbalances

3.3.5 SYSTEM 5

The results of energy and mass balances applied to system 5 (see Figure 3.6) are shown in Tables 3.25 - 3.27. The energy balance for system 5 considers the energy of the steam that was injected in system 4 as well as the energy added to the airstream by the return fan.

Degrees from "Optimal"	% Unbalance - Air Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	- 24.40	-26.73	- 16.54	- 15.30
- 2	- 24.52	- 26.09	- 16.40	- 15.55
0	- 24.51	- 27.17	- 16.44	- 15.82
2	- 24.59	- 27.33	- 16.79	- 15.64
4	- 24.74			- 15.61

Table 3.25 System 5 - air flow rate unbalances

Degrees from "Optimal"	% Unbalance - Water Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	- 57.66	- 56.42	- 44.91	- 39.89
- 2	-58.44	- 61.13	- 46.66	- 42.62
0	- 59.92	- 64.12	- 46.95	- 42.23
2	- 60.13	- 64.22	- 45.15	- 40.72
4	- 61.16			- 41.05

Table 3.26 System 5 - water flow rate unbalances

Degrees from "Optimal"	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	- 172.24	- 173.19	- 124.83	- 107.73
- 2	- 152.10	- 161.42	- 123.10	- 103.55
0	- 145.22	- 150.37	- 117.70	- 95.39
2	- 138.65	- 144.93	- 101.91	- 92.64
4	- 136.38			- 90.20

Table 3.27 System 5 - energy unbalances

The results from the energy and mass balances again show that faults are present in this system. The energy unbalance in the water loop experiments are again larger than the air loop.

3.3.6 SYSTEM 6

The combination of all of the subsystems into an overall system (see Figure 3.7) allowed mass and energy balances to be applied once again. The results from the mass balances are shown in Table 3.28 and Table 3.29. While the results from the energy balance on the system is shown on Table 3.30.

Degrees from "Optimal"	% Unbalance - Air Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	- 8.33	- 10.84	- 2.57	- 1.54
- 2	- 7.80	- 8.75	- 2.21	- 1.30
0	- 7.74	- 9.89	-1.70	- 1.40
2	- 7.72	- 10.00	- 2.47	-1.14
4	- 7.99			- 1.16

Table 3.28 System 6 - air flow rate unbalances

Degrees from "Optimal"	% Unbalance - Water Mass Rate of Flow			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	- 19.41	-16.00	-8.00	- 3.65
- 2	- 19.15	- 18.97	- 9.43	- 5.13
0	- 19.78	- 20.88	- 8.93	- 5.21
2	- 19.74	- 21.68	- 8.81	- 4.77
4	- 20.70			- 4.78

Table 3.29 System 6 - water flow rate unbalances

Degrees from "Optimal"	% Energy Unbalance			
	50% exp 1	50% exp 2	75% exp 1	75% exp 2
- 4	- 73.30	- 64.17	- 34.51	- 25.52
- 2	- 70.68	- 72.77	- 36.53	- 34.07
0	- 70.92	- 78.16	- 38.34	- 33.90
2	- 71.47	- 79.87	- 37.17	- 32.20
4	- 74.46			- 32.87

Table 3.30 System 6 - energy unbalances

The results form the water loop experiments also conclude that faults exist in the system. The water loop experiments showed larger energy unbalances than the air loop experiments. This tends to indicate that errors larger than expected may exists in temperature sensors in the system.

3.4 Fault Detection Using Energy Balances

From the results of applying energy and mass balances to the HVAC system at the Joint Center of Energy Management it becomes apparent that faults exist in the system and that errors larger than expected are present in the readings given by the instrumentation. The first part of this section will examine the results of the system balances to determine if faults exist and if the probable locations of the fault can be determined. Subsequent sections will examine several scenarios in which corrections have been applied and or faults located and accounted for in an attempt to reduce the percentage error of the mass and energy balances to within the experimental errors that were expected.

3.4.1 75% Load Level Air Loop Experiment

The results for a 75% load level experiment were chosen and were examined to see if probable locations of faults could be found within the system. The experiment that was chosen was run under 75% zone load levels, and without any additional fault imposed on the system. A zero fault experiment was chosen so that any system effects as a result of the introduced fault could be eliminated. Figure 3.8 summarizes the percentage errors that were found from the water, air and energy balances. The errors for each system were determined by examining the differences between the input and outputs of each system (IN - OUT = ERROR). The errors were normalized by the coil values as described in section 3.1.

According to the uncertainty analysis that was performed earlier on the cooling coil and the expected accuracy of the instrumentation, energy and mass balances should be achieved within approximately 10 %. Examining the results of such balances shows that in several instances errors in excess of 10% were found. The subsystems in which the energy or mass balances yield errors greater than 10% indicate probable locations of faults or are directly effected by a fault in a previous subsystem.

Several balances in Figure 3.8 - 3.10 are indicated as "forced balance", these balances were determined algebraically or were balanced exactly by determining an unknown air or water flow rate. Excessive unbalances in these figures are also marked with asterisks.

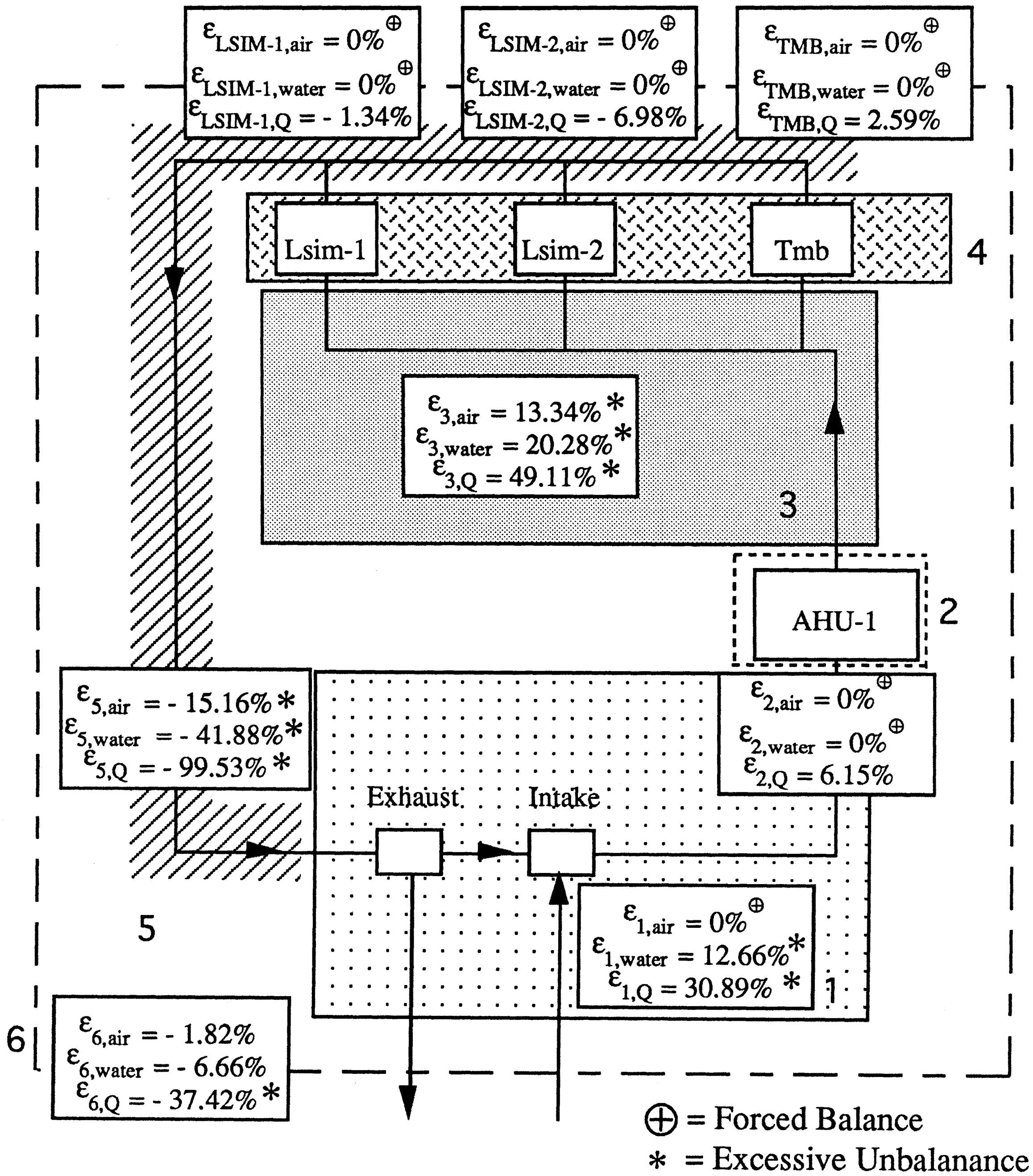

Figure 3.8 Overview of the 75% load level - air loop experiment energy and mass balances

3.4.2 System Corrections and Fault Location

The results of the energy and mass balances on the cooling coil in the AHU were within excepted accuracy, given that the mass flow rates of air and water were conserved across the coil. The basis for any corrections made to the system or fault detection will assume that the error measured across the cooling coil is correct (ie. the instrumentation used in these measurements are calibrated within expected accuracy). The choice for using the cooling coil as the starting point of such an analysis is again due to the fact that the cooling coil load directly relates to the chillers power consumption, the largest contributor to total system power.

With the cooling coil measurements assumed correct, the remainder of the system can then be examined to locate possible corrections and fault locations. A series of scenarios will be examined, with each scenarios results being applied in in conjunction with the results from other scenarios.

3.4.2.1 SYSTEM AIR LOSS / GAINS

The first inconsistency that will be examined is the mass rate of flow of air in the system. The percentage lost in the air mass flow rate of system 2 (supply duct) is close to the gains of system 5 (return duct) . This discrepancy could be caused by different possibilities:

1) Leakage could occur from system 3 and into system 5.

2) The air flow rate measurements, and temperatures (used to calculate air densities) could be out of calibration at one or more locations around the system.
3) Air could flow through the full size zone and return back into the system via the return duct.
4) Air could flow out of the VAV boxes through the reheat ducting into the return duct.

Each of these possibilities will be considered.

The system has two flow rate measurements located at the VAV boxes, one enters the box and one that leaves. The readings from these two sensors at each of the three zones are within expected accuracy of each other. This rules out possibility #4) that air flow through the reheat ducting. These measurements also lend credibility to the air flow measurements at the VAV boxes and diminishes the second possibilities. The full size zone was physically isolated from the system and air flow measurements for the zone are minimal, eliminating #3) as a possibility.

If the air flow rates and temperature readings are assumed correct at the AHU cooling coil, then the difference in the air flow rates into and out of the supply ducting would have to be due to leakage (possibility #1). Leakage was observed at several places on the actual system, although the complete system was not examined to determine the number or magnitude of leaks. With the presence of leakage out of the supply ducting, air must also leak into the return duct to meet the air mass flow rate balances in the system. The leakage of air from the supply duct and the intake of air in the return duct can also be tied to the control theories used with the fans as explained below.

Both the supply and return fans were controlled to maintain a specified duct static pressure. To reach the specified duct pressure a certain flow rate of air flow was required, this air being drawn across the cooling coil. The supply fan would then have supply more air with the presence of leakage. The return fan on the other hand was drawing air from the return duct. With some of the air being supplied to the system being lost through leakage, the return fan still attempted to deliver the return air at the specified duct static pressure. The imbalance in the amount of air being delivered through the zones and the amount of air required to meet the duct static pressure causes a low pressure area to be formed in the return ducting prior to the return fan. This slight vacuum is the driving force behind the infiltration of air into the system. Figure 3.9 outlines the system errors in each of the zones, considering sufficient leakage from system 2 to meet the air mass flow rate balance. The air which is assumed to leak out of the system is considered to be at the same humidity ratio as the air leaving the coiling coil. Gains into system 5 necessary to balance the air mass flow rate and the effect of the gains on the overall system (system 6) are also shown in Figure 3.9. The air brought into the system was assumed to have the same characteristics and properties as the outside air.

Forcing the air mass flow rates to balance in system 3 and 5 assumes the inherent inaccuracies of the instrumentation in these systems are negligible. This assumption is not totally correct, but does allow the best approximation of system performance, and allows corrections to be applied to the system. If the actual system could be retested with all of the ducting sealed of leaks, an approximation for the inherent errors in the instrumentation used in these systems could be obtained.

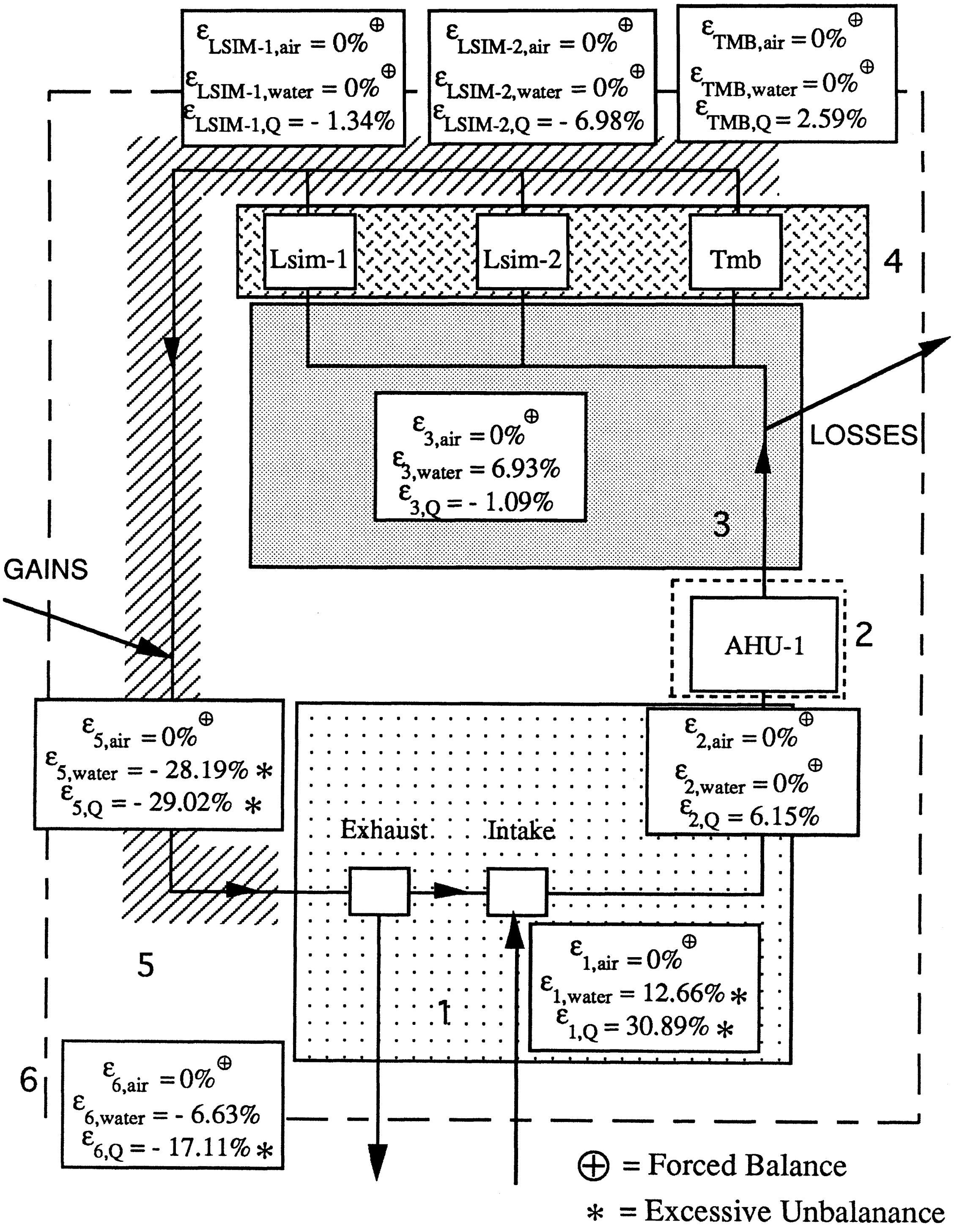

Figure 3.9 Overview of the 75% load level - air loop experiment energy and mass balances, considering losses and gains

Upon examining possible explanations for the unbalances that exist across the supply ducting, the presence of leakage is the most feasible since the other explanations considered were disproved. Valuable system information is obtainable through the use of energy and mass balances even with the existence of leaks in the system. By utilizing these balances and the measurements taken on the system, the presence of leakage could be hypothesized.

3.4.2.2 RELATIVE HUMIDITY SENSOR ERRORS

When the results of the energy and mass balances, including the losses and gains into and out of the ducting, are examined (Figure 3.9) unbalances larger than expected still exist in systems 1 and 5. The mass flow rate of water and energy balances in system 5 are negative, implying that more energy and water leaves the system than enters. The reverse is true in system 1. This situation indicates a fault. In this case the fault is probably in the relative humidity sensor in the return duct; the indicated relative humidity is too high. This error is then compounded as the relative humidity sensor reading is then used in conjunction with a psychrometric program to calculate enthalpies and humidity ratios. Calculating the humidity ratio leaving the return duct, assuming the gains mentioned in section 3.4.2.1 and that the water balance is satisfied, the humidity ratio should be 0.01126 lb water/lb dry air. Compared to the measured value of 0.01434 lb water/lb dry air. This is a - 21.48 % difference which is larger than the expected inaccuracy inherent in the instrumentation. When this fault is compensated for the energy and mass imbalances are brought closer to the expected accuracy of the laboratories instrumentation. Figure 3.10 shows the energy and mass imbalances errors when both the loss/gains and relative humidity sensor errors are accounted for.

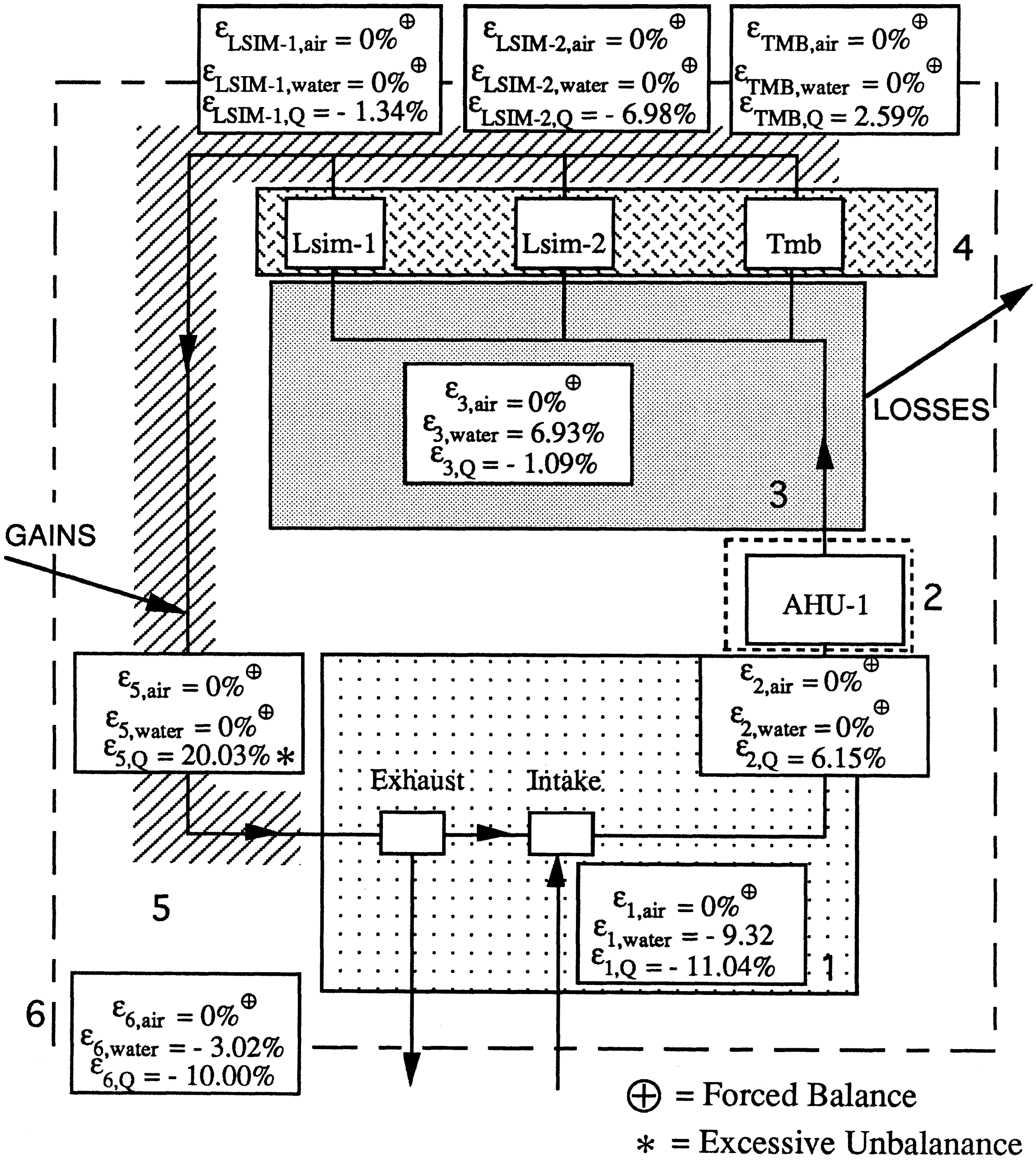

Figure 3.10 Overview of the 75% load level - air loop experiment energy and mass balances, considering losses, gains and relative humidity sensor errors

It should be noted that by forcing the water mass flow rate balance in system 5, a considered chance in the relative humidity ratio was necessary. By implementing this change a water imbalance of -28.19% was corrected to 0%, while the energy balance went form -29.02% to a 20.03% difference. This assumed that there was no inherent error in the relative humidity readings at the three load simulators or in the return duct. Errors in these readings would effect the water mass balance and the energy balance for the system.

Other errors in the relative humidity sensors can be seen in the calculation of the humidity ratios of the air streams entering the three load simulators. These readings should be the same as the humidity ratio leaving the AHU cooling coil, as no water vapor is introduced into the system and no condensation is assumed in the supply duct. The differences between the relative humidities of the AHU and the TMB, LSIM-2 and LSIM-1 are 7.65%, - 7.29% and - 8.82% respectively. When the 5% inaccuracy of the relative humidity senors is considered a 10 % difference is possible, assuming that the measurement at AHU is reading inaccurately by 5% also. Therefore at least one of the sensors is exhibiting errors in its readings of more than five percent.

Through the use of mass and energy balance the presence of a probable system faults can be determined. In this case the following faults were found:

1) Leaks into and out of the ducting
2) Errors in at least one of the relative humidity sensors located in system 3
3) The relative humidity sensor in the return ducting is not within expected accuracy

The general location of the sensors which are suppling the faulty readings to the control management system have also been determined. Faults in the system can then be flagged for maintenance personal to expedite repairs, thus keeping the HVAC system operating at its optimal or as near optimal as the accuracy of the sensors which are employed in the measurements of system parameters.

CHAPTER
FOUR

Experimental Results

This chapter examines the results obtained from the application of Pape's fault detection methods to the experimental results obtain at the JCEM. Section 4.2 considers the water loop faults and the air loop faults. Conclusions reached from examining these experimental results are covered in the final section of this chapter.

4.1 Introduction

If a system is operating at its optimal condition, the power consumption of the total system should be at the lowest possible level. Therefore if a fault occurs in the system the power consumption is expected to increase. The overall change in power consumption is a function of the changes that occur in each of the components that make up the system. The magnitude of change for each component is directly related to its variation of power as a function of its independent variable. The steeper the power curve, the larger the change in component power consumption.

Pape's work is based upon a system operating at its optimal set points and considers the change between the measured and predicted total powers to determine if a fault is present in the system. Optimal control was estimated through the use of a system-based algorithm developed by Braun, and was programmed into the computer facilities at the JCEM by laboratory staff

4.2 Influence Of Fault On The System Power

To explore the effects of the presence of a faults on an HVAC system, a series of faults were methodically introduced into the system. The operation of the system under the influence of these faults was then examined. Under the premise of optimal control, any deviation from the optimal set points should increase the total power consumption of the system; however, introducing of fault conditions into the system did not always increase total system power. The findings of this experimental work are outlined below.

4.2.1 WATER LOOP EXPERIMENTS

Using the fault detection methodology developed by Pape, changes in the total system power were examined as faults in the chilled water temperature were introduced. Under the influence of a single set of forcing functions and different load levels, the changes in system power were determined. An example of the results of Pape's work is shown in Figure 4.1. Experiments were also conducted on the system at the JCEM which considered similar faults. The results of these experiments are shown in Figure 4.2 and 4.3, for the 50 and 75% load level conditions respectively. Each experimental load level considered was replicated and is identified by number (ie. 50% - 2 would be the second test at the 50% load level).

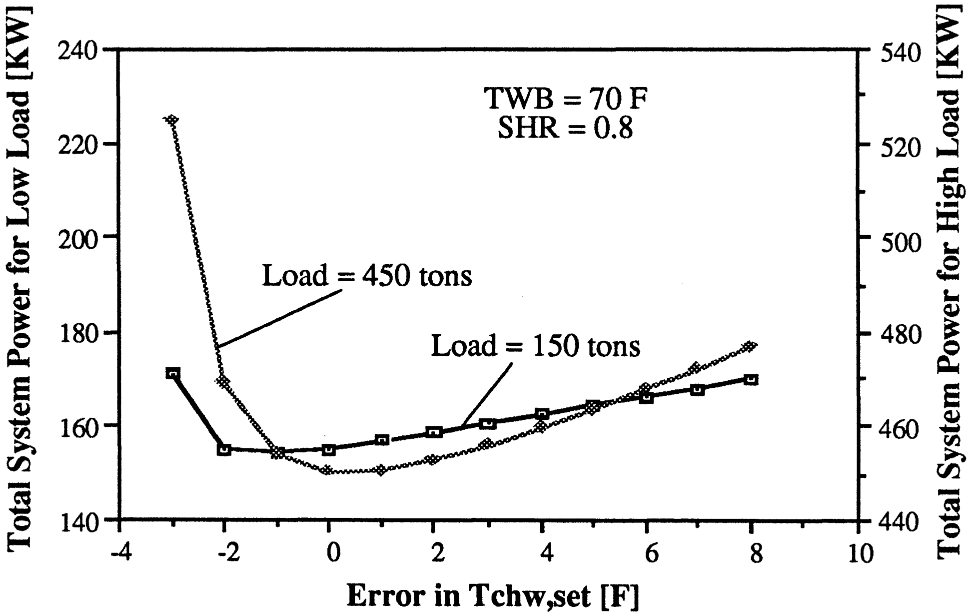

Figure 4.1 Total system power as a function of the error in Tchw,set

Figures 4.2 and 4.3 show how the total system is effected under the influence of faults. Fault levels of -4, -2, +2, and +4 as well as the non-fault (0) condition were considered under each load level (50 and 75% of the AHU cooling coil capacity). The power consumptions shown in these figures is the average of the all of the data point taken during the experiment.

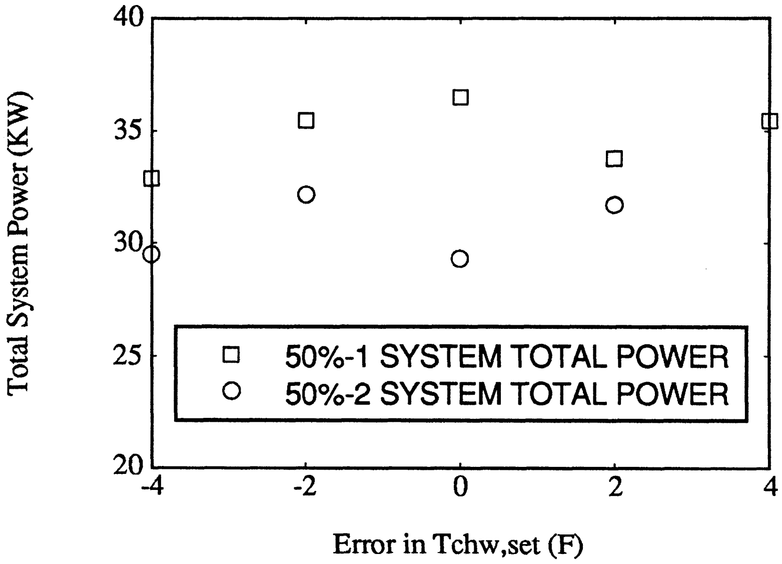

Figure 4.2 50% Load Level - Total system power as a function of error in Tchw,set

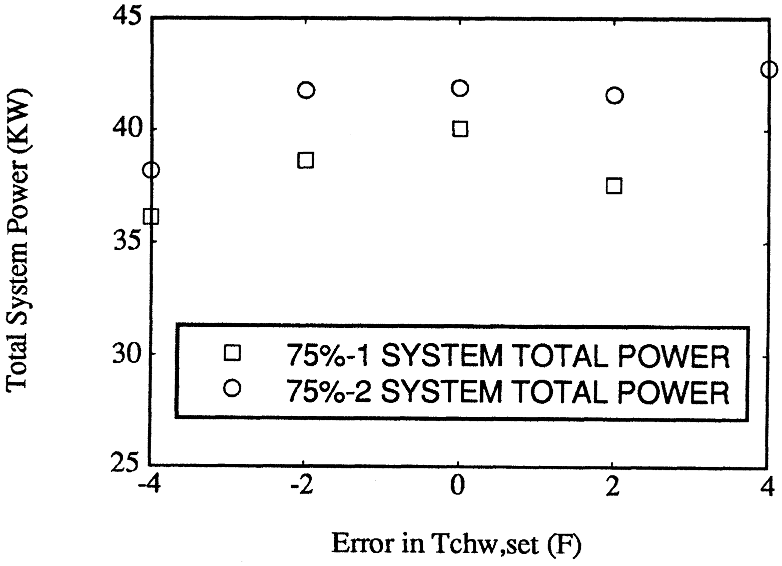

Figure 4.3 75% Load Level - Total system power as a function of error in Tchw,set

Variations in system power with the introduction of faults are within the ten percent accuracy that can be expected from the laboratory instrumentation. Considering these inherent inaccuracies, the changes in total system power over the range of faults considered is minimal. These results show that the system power curve is relatively flat when faults effecting the temperature of the chilled water are introduced. The flattening of the system power curve with a decrease in load can also be seen in Figure 4.1. Although additional experimental work would be required verify this trend. With the total power curve of system being flat, the detection of faults through measured changes in system power will be more difficult than for a system which experiences large changes in power consumptions.

The residuals, (Power measured - Power predicted), from the experiments were also examined to see how they changed with increasing fault. The results for both the 50 and 75% load levels are show in Figures 4.4 and 4.5 respectively.

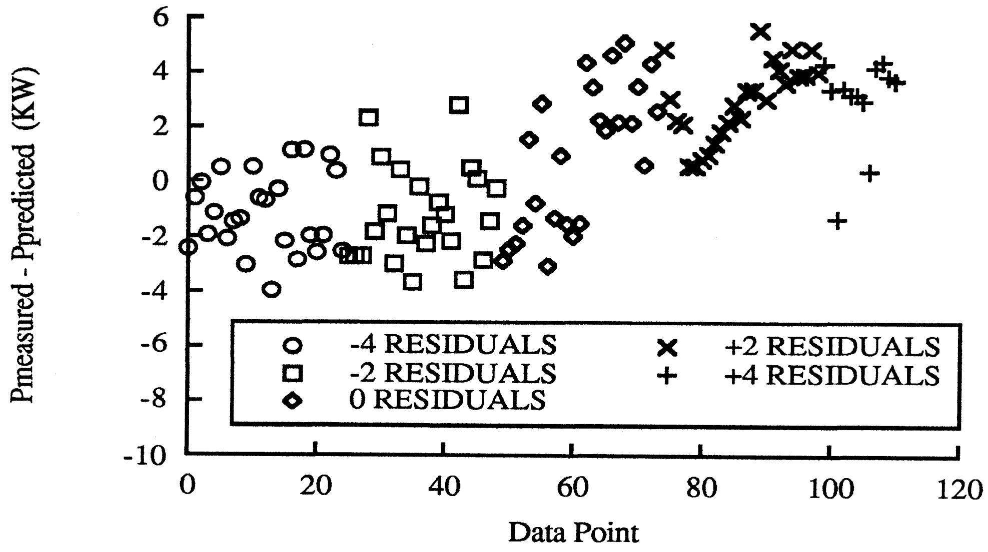

Figure 4.4 50% Load Level - Variations in the residuals as a function of fault

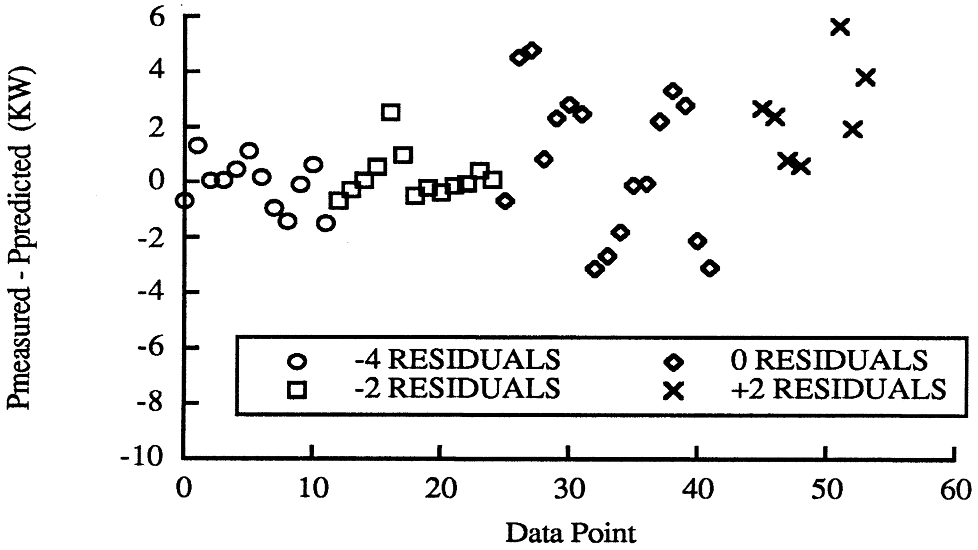

Figure 4.5 75% Load Level - Variations in the residuals as a function of fault

Figures 4.4 and 4.5 show the residuals generated for each time interval (approximately 5 minutes) over which data was taken during the experimental work. The replications of each load level are shown in Figure 4.4 with each of the fault conditions being designated by a different symbol. Figure 4.5 shows only the first replicate under the 75% load level. These residual plots do not show the shift with increasing fault as shown in Figure 1.1. It should be noted that the residuals shown in Figure 1.1 were determined form a set of forcing functions, where the residuals in Figure 4.4 and 4.5 were generated under a single set of forcing functions.

The residuals for the zero fault condition cover a range of values which include most of the residuals from the fault conditions. Only residuals with magnitudes greater than the largest value of the zero fault condition could be flagged as fault conditions without indicating non-fault conditions. When the inaccuracy inherent in the instrumentation is considered detection of a faults of the magnitudes considered here would be unlikely.

4.2.1 AIR LOOP EXPERIMENTS

A similar examination was conducted when faults in the air loop were considered. Pape did not considered this type of fault in his work, so a direct comparison is not available. The influence of faults on the system power consumption and the residuals generated under such fault conditions will be examined.

Figures 4.6 and 4.7 show the total system power under the influence of faults for the 50 and 75% load level conditions respectively.

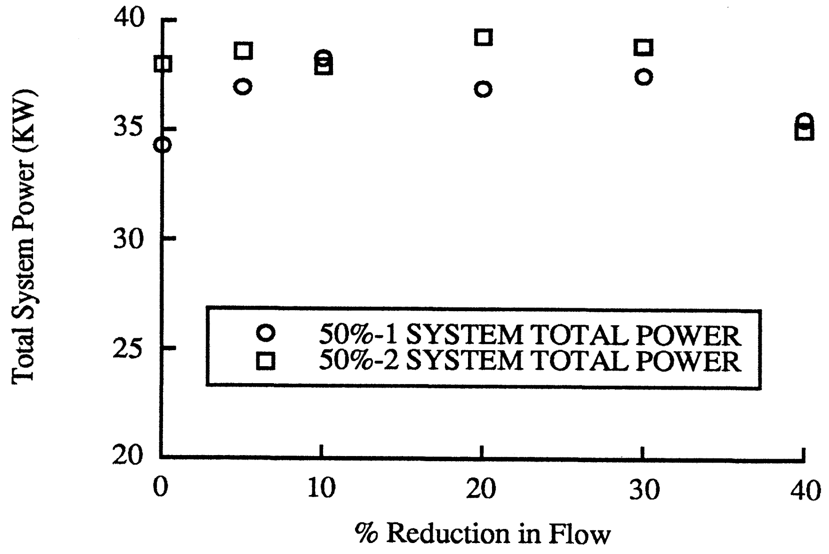

Figure 4.6 50% Load Level - Total system power as a function of flow restriction

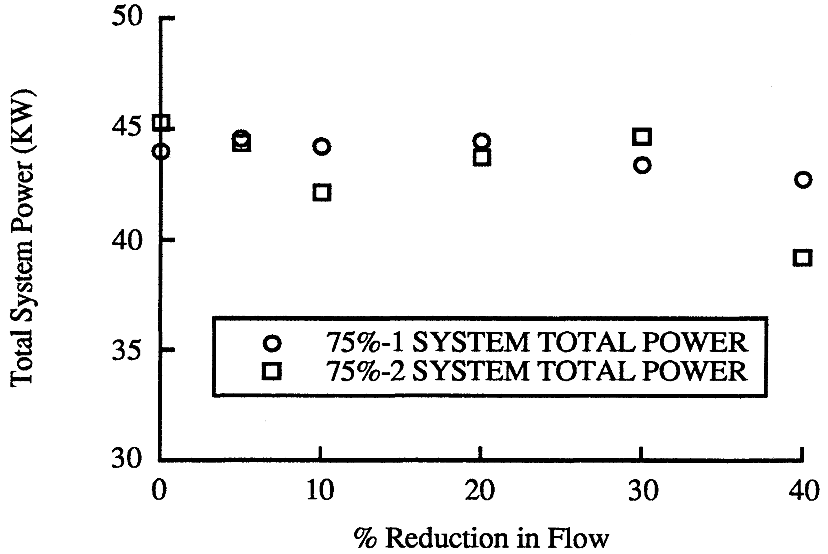

Figure 4.7 75% Load Level - Total system power as a function of flow restriction

The results for the air loop faults also show a fairly flat system power curve. The variation in the values under the different fault levels are again within the excepted accuracy of the laboratory instrumentation. Faults of this type will be difficult to detect by examining the change in the total system power.

Under the 75% load condition and the 40% reduction in flow, the room temperature in load simulator one (the zone which is the affected by the fault) could not be met. This in itself is a fault condition, which can be identified by the building energy management system. Detection being possible due to increasing room temperatures. The 30% flow reduction at the 75% load level was just able to maintain the specified return air temperature. Under 50% load conditions the return air temperature could be maintained for all fault levels.

The individual residuals for each data point generated by these experiments were also examined, the results are shown in Figures 4.8 and 4.9. The residuals for fault conditions are also within the range of the residuals of the non-fault condition. The exception to this is the residuals for the 75% load level with 40% reduction in flow, the condition that could already be flagged as a fault . It should also be noted that only a few residuals at this condition were significantly larger than the non-fault condition.

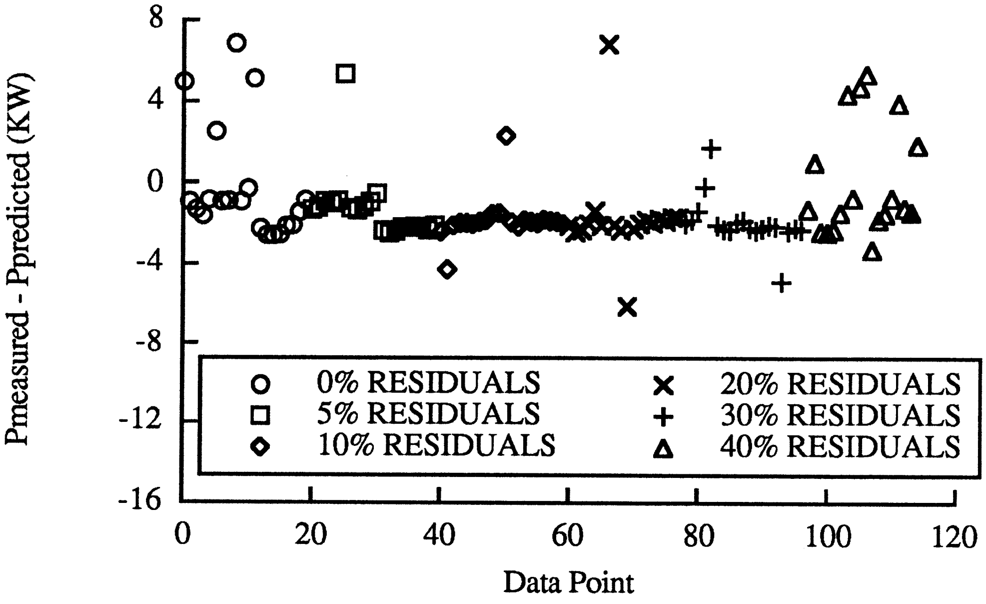

Figure 4.8 50% Load Level - Variations in the residuals as a function of fault

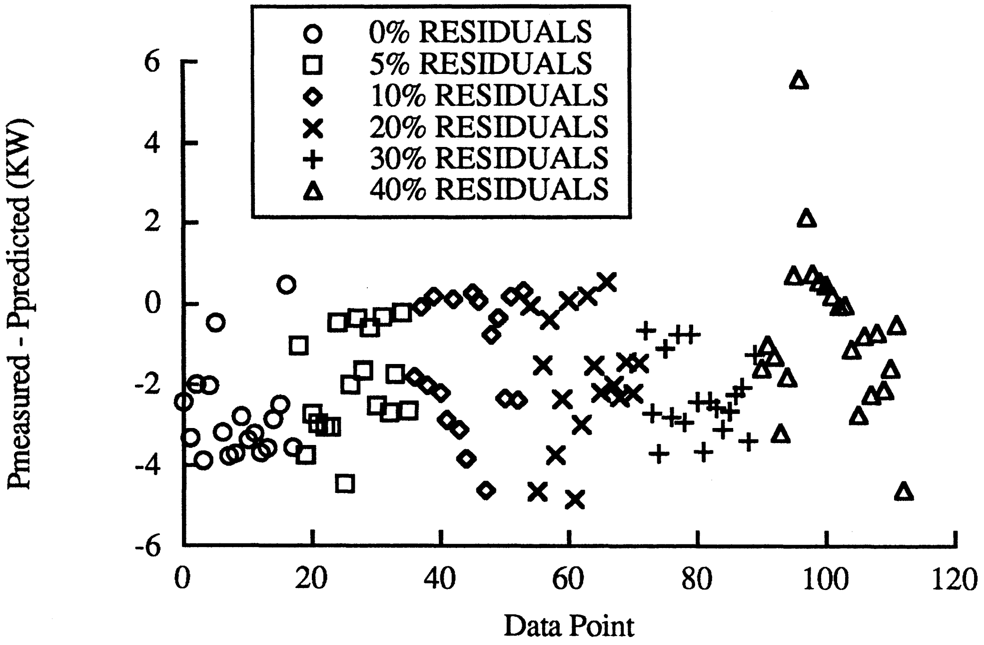

Figure 4.9 75% Load Level - Variations in the residuals as a function of fault

4.3 Conclusions

After examining the results of the experiments and applying Pape's fault detection methodology, the detection of faults in a system at low load levels will be difficult if not impossible. Experimental noise from the inherent inaccuracies of the instrumentation conceal the presence of faults in most cases. Pape's work, conducted by computer simulation, was not subject to this experimental noise. The load levels considered by Pape were also on the order a magnitude larger.

To detect faults in a system operating under low load conditions another method of fault detections needs to be considered. As described in Chapter three, energy and mass balances were used. Through the use of energy and mass balances, not only was it possible to detect faults system but it was also possible to determine their general location.

CHAPTER
FIVE

CONCLUSIONS & RECOMMENDATIONS

In this chapter, the conclusions of this work are presented. The results of the experimental work and the fault detection methodology used are summarized. Recommendations for future work are also reviewed.

5.1 Conclusions

The main objective of this thesis was to determine if faults could be detected in an actual HVAC system. The first methodology tested, was developed by Pape [1989], and utilizes changes in total system power to determine if faults could be detected.

Results from experimental tests showed that noise in the instrumentation produced residuals over a wide range of values, for the non-fault condition. The experiments conducted with faults imposed on the system also produced residuals within the range of the non-fault experiments. Thus the determination of a fault was not likely. The fault detection methodology presented by Pape was too analytical to be applied to an actual system which contains experimental noise.

Due to this fact another more fundamental approach to fault detection was applied. Energy and mass balances were conducted over the complete system and 5 subsystems. The results of these energy and mass balances where then examined to see if faults could be determined within the system.

Upon examining the results of the system balances faults were determined to exist in the HVAC system used during testing. Corrections were then applied to the system to account for the presence of the faults. When the corrections were applied to the system the energy and mass balances were able to be brought within expected levels of unbalance. The application of energy and mass balances can be an effective fault detection method, even on a system which has some experimental noise. The inherent inaccuracy and calibration of the instrumentation will be the determining factors in how closely the system balances.

In order to conduct energy balances instrumentation different from what currently exists in many HVAC systems will be necessary. System parameters have to be monitored and recorded at numerous locations around the system. The amount of instrumentation that will be needed will be determined by the number of subsystems over which energy and mass balances are to be conducted. The BEMCS must also have psychrometeric capabilities, as enthalpies will be needed for the energy balances.

5.2 Recommendations For Future Work

The following recommendations can be made for changes to the JCEM laboratory:

1. Seal all ducting to eliminate as many points of leakage/infiltration as possible, as to establish air mass flow rate energy balances
2. Set up on line energy balances for each subsystem which can be used to verify that instrumentation is properly calibrated and also be monitored during future testing
3. Replace the chiller with a unit that is sized properly for the laboratory equipment, this will allow the system to be tested under full operating range of the chiller
4. Insulate the supply ducting to limit heat transfer into the ducting.
5. Measure the mass flow rate of condensate from the AHU cooling coil
6. Measure the mass flow rate of steam that is injected into the system
7. Establish duplicate measurements where possible to allow checks to be made on instrumentation accuracy
8. Implement instrumentation to measure air flows not currently measured (ie. exhaust air, outside air)

The following recommendations can be made for future work in the area of fault detection:

1. Apply energy and mass balances to a larger HVAC system (400 tons)
2. Examine if Pape's methodology will be valid for large HVAC systems
3. Examine the characteristics of a different types of faults

4. Examine changes in the optimal set points, if system characteristics are gathered when the VAV dampers are allowed to modulate.
5. Develop an expert system which will use energy and mass balances to determine the probable location of faults

APPENDIX A

AIR LOOP - 50% LOAD LEVEL DATA

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
LAB PRESSURE [121]	12.2648	12.2516	12.2489	12.249	12.2506	12.2557		12.2809	12.2699	12.2615	12.2507	12.2495	12.2609
SYSTEM 1 *** INTAKE / EXHAUST ***													
RETURN AIR													
VDOT [37]	5359.22	5489.19	5588.00	5586.45	5582.98	5552.62		5514.21	5658.83	5693.85	5688.80	5695.30	5501.06
TEMP [38]	80.67	81.53	81.37	80.81	80.82	80.11		81.00	81.18	81.44	81.40	81.12	79.97
DENSITY [339]	0.0618	0.0612	0.0612	0.0611	0.0617	0.0618		0.0618	0.0618	0.0617	0.0616	0.0616	0.0618
RH * 100 [39]	45.3296	44.9926	45.9869	47.0279	47.0503	47.0430		45.5351	45.0239	47.0329	46.6009	47.3347	47.2950
ENTHALPY [353]	32.84	33.32	33.51	33.49	33.48	32.98		33.14	33.15	33.93	33.84	33.83	32.96
HUMIDITY RATIO [354]	0.0124	0.0126	0.0128	0.0129	0.0129	0.0126		0.0126	0.0125	0.0132	0.0131	0.0132	0.0126
RECIRCULATED AIR													
VDOT [42]	4257.76	4383.93	4458.93	4454.56	4442.19	4391.65		4386.13	4513.93	4552.01	4534.66	4513.39	4337.31
TEMP [38]	80.67	81.53	81.37	80.81	80.82	80.11		81.00	81.18	81.44	81.40	81.12	79.97
DENSITY [339]	0.0618	0.0612	0.0612	0.0611	0.0617	0.0618		0.0618	0.0618	0.0617	0.0616	0.0616	0.0618
RH * 100 [39]	45.3296	44.9926	45.9869	47.0279	47.0503	47.0430		45.5351	45.0239	47.0329	46.6009	47.3347	47.2950
Enthalpy (EES)	32.69	33.20	33.40	33.32	33.33	32.82		32.96	32.95	33.76	33.61	33.63	32.79
MIXED AIR													
VDOT [1]	4730.38	4871.81	4955.29	4948.05	4936.63	4877.94		4868.31	5035.38	5053.79	5037.62	5037.59	4821.10
TEMP [4]	79.65	79.96	79.92	79.38	79.39	78.79		79.73	79.79	80.07	80.26	80.14	78.49
RH * 100 [137]	40.8050	40.0529	40.5507	41.5948	41.2920	41.7713		41.2754	39.8805	40.9240	40.3681	41.0078	42.4955
HUMIDITY RATIO [290]	0.0107	0.0106	0.0108	0.0108	0.0108	0.0107		0.0109	0.0106	0.0109	0.0108	0.0109	0.0108
ENTHAPLY [276]	30.79	30.7418	30.9519	30.7093	30.7561	30.5950		30.9981	30.7443	31.0940	30.8872	31.0973	30.5435
OUTSIDE AIR													
VDOT([1*334]-	707.27	766.97	782.49	782.39	742.38	726.05		726.46	775.36	754.38	761.50	779.88	716.32
[42*339])/[345]													
TEMP [161]	83.46	85.09	83.95	83.65	83.92	82.71		82.81	83.85	84.23	84.80	84.40	81.17
DENSITY [345]	0.0609	0.0607	0.0608	0.0609	0.0609	0.0610		0.0611	0.0610	0.0609	0.0608	0.0608	0.0612
RH * 100 [134]	35.8193	30.0640	31.0212	30.3350	27.6197	32.7225		37.6316	29.8017	25.5202	25.2680	26.3484	35.6076
Humidity Ratio (EES)	0.0105	0.0093	0.0092	0.0089	0.0082	0.0093		0.0108	0.0088	0.0076	0.0077	0.0079	0.0097
Enthalpy (EES)	31.55	30.60	30.27	29.88	29.13	30.10		31.71	29.79	28.59	28.81	28.97	30.09

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
SYSTEM 1 CONTINUED													
EXHAUST AIR													
VDOT [37-42]	1101.46	1105.26	1129.07	1131.89	1140.79	1160.97		1128.08	1144.9	1141.84	1154.14	1181.91	1163.75
TEMP [38]	80.67	81.53	81.37	80.81	80.82	80.11		81.00	81.18	81.44	81.40	81.12	79.97
DENSITY [339]	0.0618	0.0617	0.0617	0.0617	0.0609	0.0610		0.0611	0.0610	0.0609	0.0608	0.0608	0.0612
RH * 100 [39]	45.3296	44.9926	45.9869	47.0279	47.0503	47.0430		45.5351	45.0239	47.0329	46.6009	47.3347	47.2950
Enthalpy (EES)	32.69	33.20	33.40	33.32	33.33	32.82		32.96	32.95	33.76	33.61	33.63	32.79
Humidity Ratio (EES)	0.0122	0.0124	0.0126	0.0127	0.0127	0.0124		0.0123	0.0123	0.0130	0.0128	0.0129	0.0124
SYSTEM 2 *** COOLING COIL ***													
AIRSIDE - IN													
VDOT [1]	4730.38	4871.81	4955.29	4948.05	4936.63	4877.94		4868.31	5035.38	5053.79	5037.62	5037.59	4821.10
TEMP [4]	79.65	79.96	79.92	79.38	79.39	78.79		79.73	79.79	80.07	80.26	80.14	78.49
RH * 100 [137]	40.8050	40.0529	40.5507	41.5948	41.2920	41.7713		41.2754	39.8805	40.9240	40.3681	41.0078	42.4955
HUMIDITY RATIO [290]	0.0107	0.0106	0.0108	0.0108	0.0108	0.0107		0.0109	0.0106	0.0109	0.0108	0.0109	0.0108
ENTHAPLY [276]	30.79	30.7418	30.9519	30.7093	30.7561	30.5950		30.9981	30.7443	31.0940	30.8872	31.0973	30.5435
AIRSIDE - OUT													
VDOT [1]	4730.38	4871.81	4955.29	4948.05	4936.63	4877.94		4868.31	5035.38	5053.79	5037.62	5037.59	4821.10
TEMP [122]	52.01	51.99	52.01	52.06	51.96	51.82		52.09	52.02	52.47	52.12	52.46	52.09
DENSITY [334]	0.0647	0.0647	0.0647	0.0646	0.0647	0.0647		0.0648	0.0648	0.0647	0.0647	0.0646	0.0647
HUMIDTY RATIO [291]	0.0093	0.0094	0.0095	0.0094	0.0094	0.0094		0.0095	0.0094	0.0095	0.0094	0.0096	0.0095
ENTHALPY [277]	22.52	22.54	22.68	22.65	22.61	22.51		22.73	22.55	22.87	22.59	22.92	22.69
ENTHALPY(h2o) (EES)	17.729	17.695	17.703	17.79	17.709	17.583		17.769	17.688	18.124	17.788	18.149	17.835
TEMP [7]	49.6295	49.5959	49.6038	49.6908	49.6095	49.4833		49.6695	49.5883	50.0244	49.6887	50.0487	49.7357
MDOT CONDENSATE	25.6594	24.1362	26.1298	25.5215	25.4745	25.4827		26.6169	24.6368	26.7376	26.3707	26.2407	23.9427
Qcondensate (MBTUH)	0.4549	0.4271	0.4626	0.4540	0.4511	0.4481		0.4730	0.4358	0.4846	0.4691	0.4762	0.4270
SUPPLY FAN POWER	3.05	3.08808	3.13858	3.14375	3.14038	3.11531		3.12307	3.17703	3.17684	3.18344	3.19348	3.11244
Qsupply fan calc	9.05	9.17	9.32	9.33	9.32	9.25		9.27	9.43	9.43	9.45	9.48	9.24
WATERSIDE - IN													
VDOT [123]	48.49	52.92	60.12	58.33	58.73	54.68		58.89	60.94	60.74	60.65	60.49	49.61
TEMP [164]	42.45	42.45	42.59	42.67	42.61	42.48		42.70	42.60	42.85	42.33	42.82	42.78

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
SYSTEM 2 CONTINUED													
WATERSIDE - OUT													
VDOT [123]	48.49	52.92	60.12	58.33	58.73	54.68		58.89	60.94	60.74	60.65	60.49	49.61
TEMP [166]	48.36	48.04	47.60	47.73	47.62	47.67		47.67	47.42	47.81	47.40	47.82	48.27
Qwater {123*(166-164)	142.99	147.87	150.70	147.46	146.90	141.92		146.47	146.84	150.47	153.58	151.18	136.14
*.4998} (MBTUH)													
SYSTEM 3 *** SUPPLY DUCT ***													
IN													
AHU-1													
VDOT [1]	4730.38	4871.81	4955.29	4948.05	4936.63	4877.94		4868.31	5035.38	5053.79	5037.62	5037.59	4821.10
TEMP [122]	52.01	51.99	52.01	52.06	51.96	51.82		52.09	52.02	52.47	52.12	52.46	52.09
DENSITY [334]	0.0647	0.0647	0.0647	0.0646	0.0647	0.0647		0.0648	0.0648	0.0647	0.0647	0.0646	0.0647
HUMIDTY RATIO [291]	0.0093	0.0094	0.0095	0.0094	0.0094	0.0094		0.0095	0.0094	0.0095	0.0094	0.0096	0.0095
ENTHALPY [277]	22.52	22.54	22.68	22.65	22.61	22.51		22.73	22.55	22.87	22.59	22.92	22.69
OUT													
TMB													
VDOT [27]	1160.33	1240.7	1241.61	1252.35	1256.42	1268.75		1220.67	1251.22	1274.67	1284.17	1296.21	1280.4
TEMP [28]	62.17	61.82	61.87	61.68	61.65	61.24		61.92	61.84	62.00	61.75	61.88	61.15
DENSITY [338]	0.0635	0.0634	0.0634	0.0634	0.0635	0.0635		0.0636	0.0635	0.0635	0.0634	0.0634	0.0636
RH * 100 [29]	64.1230	64.2237	64.1242	64.8049	64.5032	65.1955		64.2736	63.6455	63.9320	63.6780	64.1895	66.0220
Enthalpy (EES)	24.87	24.69	24.70	24.69	24.63	24.49		24.73	24.59	24.74	24.56	24.72	24.55
Humidity Ratio (EES)	0.0091	0.0091	0.0091	0.0091	0.0090	0.0090		0.0091	0.0090	0.0091	0.0089	0.0091	0.0091
LSIM-2													
VDOT [113]	1293.17	1284	1346.34	1353.91	1354.7	1315.34		1244.47	1348.42	1346.11	1341.32	1343.31	1260.58
TEMP [112]	57.98	58.23	57.81	57.62	57.54	57.27		58.52	57.89	58.24	58.01	58.12	57.61
DENSITY [344]	0.0640	0.0639	0.0639	0.0639	0.0640	0.0640		0.0640	0.0640	0.0639	0.0639	0.0639	0.0640
RH * 100 [114]	70.0941	69.148	70.2706	71.2816	71.1275	71.5069		69.0841	69.7664	70.3878	69.9357	70.5928	71.537
Enthalpy (EES)	23.26	23.29	23.19	23.22	23.15	23.04		23.43	23.16	23.45	23.26	23.42	23.24
Humidity Ratio (EES)	0.0086	0.00857	0.00858	0.00864	0.0086	0.00855		0.00863	0.00853	0.00872	0.0086	0.00872	0.00866

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
SYSTEM 3 CONTINUED													
LSIM-1													
VDOT [108]	1555.69	1586.12	1582.87	1563.14	1549.94	1554.5		1646.72	1637.12	1633.05	1616.63	1606.41	1553.81
TEMP [107]	59.93	60.05	60.04	59.79	59.76	59.26		59.74	59.88	60.26	60.16	60.29	59.15
DENSITY [342]	0.0637	0.0637	0.0636	0.0637	0.0637	0.0638		0.0638	0.0638	0.0637	0.0636	0.0636	0.0638
RH * 100 [109]	64.6634	64.0815	64.0807	64.9577	64.6387	65.5547		65.0603	63.9942	64.3141	63.6863	64.2584	66.5951
Enthalpy (EES)	23.63	23.62	23.62	23.60	23.54	23.38		23.56	23.50	23.77	23.63	23.79	23.46
Humidity Ratio (EES)	0.0085	0.0085	0.0085	0.0085	0.0085	0.0084		0.0085	0.0084	0.0086	0.0085	0.0086	0.0085
SYSTEM 4 *** ZONES ***													
AIRSIDE													
IN => SEE SYSTEM 3 OUT													
OUT													
TMB													
VDOT [27]	1164.09	1240.7	1241.61	1252.35	1256.42	1268.75		1220.67	1251.22	1274.67	1284.17	1296.21	1280.4
TEMP [34]	78.74	78.65	78.81	78.59	78.53	78.22		78.89	78.88	78.80	78.83	78.76	77.90
RH * 100 [33]	34.2271	34.1961	33.9080	34.3316	34.0323	34.3534		33.9605	33.5478	33.7659	33.3409	33.7848	35.0500
Enthalpy (EES)	28.29	28.24	28.25	28.24	28.13	28.04		28.28	28.17	28.20	28.10	28.19	28.05
LSIM-2													
VDOT [113]	1293.17	1284.00	1346.34	1353.91	1354.70	1315.34		1244.47	1348.42	1346.11	1341.32	1343.31	1260.58
TEMP [115]	77.33	77.92	76.54	76.08	76.02	76.12		78.34	76.44	76.58	76.53	76.64	77.12
RH * 100 [116]	42.2693	41.3306	42.5977	43.4682	43.2726	43.3639		41.2414	42.2572	42.7181	42.2783	42.7697	42.8617
Enthalpy (EES)	29.65	29.77	29.27	29.21	29.12	29.20		29.98	29.10	29.31	29.17	29.37	29.68
LSIM-1													
VDOT [108]	1546.79	1586.12	1582.87	1563.14	1549.94	1554.50		1646.72	1637.12	1633.05	1616.63	1606.41	1553.81
TEMP [110]	78.23	78.05	78.35	78.10	78.14	77.49		76.97	77.41	78.07	78.28	78.48	77.05
RH * 100 [111]	40.0416	41.3306	44.3802	46.0591	47.0972	45.6315		42.7807	41.6855	48.6615	48.3562	49.4777	45.7543
Enthalpy (EES)	29.60	29.85	30.88	31.18	31.49	30.66		29.55	29.54	31.86	31.94	32.39	30.40
Humidity Ratio (EES)	0.0099	0.0102	0.0110	0.0114	0.0116	0.0110		0.0101	0.0100	0.0120	0.0120	0.0124	0.0109

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
SYSTEM 4 CONTINUED													
WATERSIDE													
IN													
TMB													
BRANCH VDOT [50]	11.98	11.96	11.99	11.98	11.99	11.98		12.01	12.01	12.02	11.97	12.01	11.95
% FLOW TO COIL[348]	16.44	16.06	16.15	15.98	15.96	15.67		16.59	16.12	16.18	16.16	16.06	15.55
COIL FLOW RATE	1.97	1.92	1.94	1.91	1.91	1.88		1.99	1.94	1.94	1.93	1.93	1.86
TEMP [145]	110.54	110.40	110.32	110.23	110.20	110.15		110.30	110.23	110.20	110.16	110.17	110.10
LSIM-2													
BRANCH VDOT [54]	12.55	12.57	12.53	12.55	12.55	12.56		12.61	12.57	12.56	12.58	12.58	12.58
% FLOW TO COIL [318]	13.23	13.56	12.88	12.76	12.66	12.79		13.94	12.96	12.92	12.91	13.00	13.32
COIL FLOW RATE	1.66	1.71	1.61	1.60	1.59	1.61		1.76	1.63	1.62	1.62	1.63	1.67
TEMP [175]	111.04	110.91	110.82	110.72	110.69	110.64		110.78	110.71	110.67	110.62	110.64	110.59
LSIM-1													
BRANCH VDOT [52]	11.22	11.21	11.23	11.25	11.25	11.25		11.21	11.22	11.23	11.24	11.24	11.23
% FLOW TO COIL [321]	15.26	15.03	15.20	15.08	14.97	14.84		14.63	14.93	14.90	15.13	15.28	14.69
COIL FLOW RATE	1.71	1.69	1.71	1.70	1.68	1.67		1.64	1.67	1.67	1.70	1.72	1.65
TEMP [152]	110.73	110.60	110.50	110.41	110.38	110.32		110.47	110.40	110.37	110.32	110.33	110.27
OUT													
TMB													
TEMP [146]	87.22	86.43	86.53	86.22	86.14	85.61		86.97	86.53	86.50	86.40	86.34	85.32
LSIM-2													
TEMP [174]	83.49	84.10	82.62	82.17	82.16	82.23		84.57	82.58	82.83	82.65	82.74	83.31
LSIM-1													
TEMP [153]	83.74	83.37	83.50	83.23	82.66	83.15		82.37	82.83	83.05	83.27	83.45	82.32

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
SYSTEM 5 *** RETURN DUCT ***													
IN => SEE SYSTEM 4 AIRSIDE OUT													
OUT													
RETURN AIR													
VDOT [37]	5359.22	5489.19	5588.00	5586.45	5582.98	5552.62		5514.21	5658.83	5693.85	5688.80	5695.30	5501.06
TEMP [38]	80.67	81.53	81.37	80.81	80.82	80.11		81.00	81.18	81.44	81.40	81.12	79.97
DENSITY [339]	0.0618	0.0612	0.0612	0.0611	0.0617	0.0618		0.0618	0.0618	0.0617	0.0616	0.0616	0.0618
ENTHALPY [353]	32.84	33.32	33.51	33.49	33.48	32.98		33.14	33.15	33.93	33.84	33.83	32.96
HUMIDITY RATIO [354]	0.0124	0.0126	0.0128	0.0129	0.0129	0.0126		0.0126	0.0125	0.0132	0.0131	0.0132	0.0126
AIR MASS BALANCES													
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY AIR FLOW ACROSS THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %													
SYSTEM 1 INTAKE/EXHAUST *****FORCED BALANCE **********													
IN													
RETURN AIR													
VDOT [37]	5359.22	5489.19	5588.00	5586.45	5582.98	5552.62		5514.21	5658.83	5693.85	5688.80	5695.30	5501.06
DENSITY [339]	0.0618	0.0612	0.0612	0.0611	0.0617	0.0618		0.0618	0.0618	0.0617	0.0616	0.0616	0.0618
Mdot RETURN air (lb/hr)	19862.3	20162.9	20509.1	20483.3	20671.5	20589.1		20450.0	20972.8	21078.6	21036.0	21053.2	20407.8
OUTSIDE AIR													
DENSITY [345]	0.0609	0.0607	0.0608	0.0609	0.0609	0.0610		0.0611	0.0610	0.0609	0.0608	0.0608	0.0612
VDOT([1*334]-	707.27	766.97	782.49	782.39	742.38	726.05		726.46	775.36	754.38	761.50	779.88	716.32
[42*339])/[345]													
Mdot OUTDOOR air (lb/hr)	2586.1	2794.7	2856.4	2857.4	2710.4	2657.8		2664.5	2835.9	2755.1	2775.7	2844.5	2630.7
OUT													
MIXED AIR													
VDOT [1]	4730.38	4871.81	4955.29	4948.05	4936.63	4877.94		4868.31	5035.38	5053.79	5037.62	5037.59	4821.10
DENSITY [334]	0.0647	0.0647	0.0647	0.0646	0.0647	0.0647		0.0648	0.0648	0.0647	0.0647	0.0646	0.0647
Mdot MIXED air(lb/hr)	18366.2	18897.8	19221.6	19190.5	19158.1	18942.0		18930.9	19565.5	19606.7	19544.0	19528.7	18721.3

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
AIR BALANCES CONTINUED													
EXHAUST AIR													
VDOT [37-42]	1101.46	1105.26	1129.07	1131.89	1140.79	1160.97		1128.08	1144.9	1141.84	1154.14	1181.91	1163.75
DENSITY [339]	0.0618	0.0617	0.0617	0.0617	0.0609	0.0610		0.0611	0.0610	0.0609	0.0608	0.0608	0.0612
Mdot EXHAUST air (lb/hr)	4082.2	4089.0	4177.8	4190.9	4165.0	4249.8		4137.6	4187.6	4170.2	4206.8	4310.9	4274.0
ZONE 2 AHU-1 *** BALANCES BY DEFAULT ***													
IN													
VDOT [1]	4730.38	4871.81	4955.29	4948.05	4936.63	4877.94		4868.31	5035.38	5053.79	5037.62	5037.59	4821.10
DENSITY [334]	0.0647	0.0647	0.0647	0.0646	0.0647	0.0647		0.0648	0.0648	0.0647	0.0647	0.0646	0.0647
OUT													
VDOT [1]	4730.38	4871.81	4955.29	4948.05	4936.63	4877.94		4868.31	5035.38	5053.79	5037.62	5037.59	4821.10
DENSITY [334]	0.0647	0.0647	0.0647	0.0646	0.0647	0.0647		0.0648	0.0648	0.0647	0.0647	0.0646	0.0647
SYSTEM 3 SUPPLY DUCT													
IN													
VDOT [1]	4730.38	4871.81	4955.29	4948.05	4936.63	4877.94		4868.31	5035.38	5053.79	5037.62	5037.59	4821.10
DENSITY [334]	0.0647	0.0647	0.0647	0.0646	0.0647	0.0647		0.0648	0.0648	0.0647	0.0647	0.0646	0.0647
Mdot(lb/hr)	18366.2	18897.8	19221.6	19190.5	19158.1	18942		18930.9	19565.5	19606.7	19544	19528.7	18721.3
OUT													
TMB													
VDOT [27]	1164.09	1240.7	1241.61	1252.35	1256.42	1268.75		1220.67	1251.22	1274.67	1284.17	1296.21	1280.4
DENSITY [338]	0.0635	0.0634	0.0634	0.0634	0.0635	0.0635		0.0636	0.0635	0.0635	0.0634	0.0634	0.0636
Mdot(lb/hr)	4432.4	4722.6	4724.6	4766.9	4783.2	4836.2		4656.6	4769.4	4854.2	4888.1	4932.3	4883.7
LSIM-2													
VDOT [113]	1293.17	1284.00	1346.34	1353.91	1354.70	1315.34		1244.47	1348.42	1346.11	1341.32	1343.31	1260.58
DENSITY [344]	0.0640	0.0639	0.0639	0.0639	0.0640	0.0640		0.0640	0.0640	0.0639	0.0639	0.0639	0.0640
Mdot(lb/hr)	4962.7	4921.3	5162.7	5194.1	5198.8	5052.5		4778.0	5178.7	5163.4	5142.6	5148.6	4840.6

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
AIR BALANCES CONTINUED													
SYSTEM 3 CONTINUED													
LSIM-1													
VDOT [108]	1555.69	1586.12	1582.87	1563.14	1549.94	1554.5		1646.72	1637.12	1633.05	1616.63	1606.41	1553.81
DENSITY [342]	0.0637	0.0637	0.0636	0.0637	0.0637	0.0638		0.0638	0.0638	0.0637	0.0636	0.0636	0.0638
Mdot(lb/hr)	5947.7	6057.4	6044.0	5971.5	5922.0	5947.8		6307.6	6263.9	6239.6	6172.0	6131.0	5948.9
LOSSES&ERRORS(LB/HR)	3023.4	3196.44	3290.29	3257.92	3254.08	3105.48		3188.68	3353.38	3349.52	3341.29	3316.72	3048.05
(IN-OUT)													
LOSSES %	16.46	16.91	17.12	16.98	16.99	16.39		16.84	17.14	17.08	17.10	16.98	16.28
ZONE 4 LOAD SIMULATORS *****BALANCES BY DEFAULT******													
TMB IN AND OUT													
VDOT [27]	1164.09	1240.7	1241.61	1252.35	1256.42	1268.75		1220.67	1251.22	1274.67	1284.17	1296.21	1280.4
DENSITY [338]	0.0635	0.0634	0.0634	0.0634	0.0635	0.0635		0.0636	0.0635	0.0635	0.0634	0.0634	0.0636
LSIM-2 IN AND OUT													
VDOT [113]	1293.17	1284.00	1346.34	1353.91	1354.70	1315.34		1244.47	1348.42	1346.11	1341.32	1343.31	1260.58
DENSITY [344]	0.0640	0.0639	0.0639	0.0639	0.0640	0.0640		0.0640	0.0640	0.0639	0.0639	0.0639	0.0640
LSIM-1 IN AND OUT													
VDOT [108]	1555.69	1586.12	1582.87	1563.14	1549.94	1554.5		1646.72	1637.12	1633.05	1616.63	1606.41	1553.81
DENSITY [342]	0.0637	0.0637	0.0636	0.0637	0.0637	0.0638		0.0638	0.0638	0.0637	0.0636	0.0636	0.0638
ZONE 5 RETURN DUCT													
IN													
TMB OUT													
VDOT [27]	1164.09	1240.7	1241.61	1252.35	1256.42	1268.75		1220.67	1251.22	1274.67	1284.17	1296.21	1280.4
DENSITY [338]	0.0635	0.0634	0.0634	0.0634	0.0635	0.0635		0.0636	0.0635	0.0635	0.0634	0.0634	0.0636
LSIM-2 OUT													
VDOT [113]	1293.17	1284.00	1346.34	1353.91	1354.70	1315.34		1244.47	1348.42	1346.11	1341.32	1343.31	1260.58
DENSITY [344]	0.0640	0.0639	0.0639	0.0639	0.0640	0.0640		0.0640	0.0640	0.0639	0.0639	0.0639	0.0640

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
AIR BALANCES CONTINUED													
SYSTEM 5 CONTINUED													
LSIM-1 OUT													
VDOT [108]	1555.69	1586.12	1582.87	1563.14	1549.94	1554.5		1646.72	1637.12	1633.05	1616.63	1606.41	1553.81
DENSITY [342]	0.0637	0.0637	0.0636	0.0637	0.0637	0.0638		0.0638	0.0638	0.0637	0.0636	0.0636	0.0638
OUT													
RETURN AIR													
VDOT [37]	5359.22	5489.19	5588.00	5586.45	5582.98	5552.62		5514.21	5658.83	5693.85	5688.80	5695.30	5501.06
DENSITY [339]	0.0618	0.0612	0.0612	0.0611	0.0617	0.0618		0.0618	0.0618	0.0617	0.0616	0.0616	0.0618
LOSSES&ERRORS(LB/HR)	-4519.6	-4461.6	-4577.8	-4550.7	-4767.5	-4752.6		-4707.8	-4760.7	-4821.5	-4833.4	-4841.2	-4734.6
(IN-OUT)													
LOSES %	-24.61	-23.61	-23.82	-23.71	-24.89	-25.09		-24.87	-24.33	-24.59	-24.73	-24.79	-25.29
WATER BALANCES													
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY WATER FLOW ACROSS THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %													
SYSTEM 1													
ERRORSandLOSSES(lb/hr)	26.02	28.75	28.58	30.27	30.42	29.17		28.86	28.46	31.09	33.05	30.99	28.74
E&L=(WVRHOE)ret*60+(WVRHOE)out*60-(WVRHOE)ex*60-(WVRHOE)mix*60													
ERRORS %	13.18	14.29	13.75	14.63	14.76	14.38		13.99	13.69	14.53	15.73	14.54	14.25
SYSTEM 2 ****** FORCED BALANCE *******													
Mdot COND (LB/HR)	25.66	24.14	26.13	25.52	25.47	25.48		26.62	24.64	26.74	26.37	26.24	23.94
Mdot CONDENSATE=(WVRHOE)mix*60-(VWRHOE)supply*6													
SYSTEM 3													
E&L (lb/hr)	38.09	40.83	43.47	42.31	42.66	40.47		42.70	43.79	44.80	43.66	44.79	40.73
E&L = (MdotWin-Sum(MdotWout))													
ERRORS %	22.18	23.06	23.92	23.33	23.61	22.83		23.76	23.90	23.94	23.76	23.96	22.92

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
WATER BALANCES (CON)													
SYSTEM 4													
Steam Injection Calculated	8.1841	10.1704	15.4606	17.0128	18.7846	15.4465		10.3066	10.1037	21.4079	21.9599	23.2856	14.0335
STEAM PRESSURE [131]	11.48	11.38	11.42	11.38	11.37	11.30		11.41	11.47	11.37	11.36	11.35	11.33
Steam Enthalpy (EES)	1151.74	1151.79	1151.77	1151.79	1151.79	1151.82		1151.77	1151.75	1151.79	1151.79	1151.80	1151.81
SYSTEM 5													
Using CALCULATED STEAM	-103.97	-108.47	-109.21	-108.80	-110.49	-107.56		-110.17	-113.21	-114.24	-113.71	-111.85	-106.96
ERRORS%	-60.55	-61.27	-60.09	-59.99	-61.16	-60.66		-61.31	-61.78	-61.03	-61.88	-59.84	-60.20
ENERGY BALANCES													
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY Qh2o OF THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %													
SYSTEM 1 - intake/exhaust													
LOSSES & ERRORS (%)	24.43	27.46	26.10	28.73	29.31	28.19		26.68	27.46	28.95	30.50	27.98	29.25
l&e= ((MHex-MHex-MHrec)/qh2o cooling coil)*100													
SYSTEM 2 - COOLING COIL													
LOSSES & ERRORS (%)	12.19	10.77	11.36	10.90	12.23	14.07		12.91	15.33	13.15	11.49	11.57	14.49
l&e=(((Mair(Hair,in-Hair,o)*0.06+MCp(Ti-To)h2o*0.4998-Mair(Wi-Wo)air*Hh2o*0.06)+QFAN)/qh2o cooling coil)*100													
SYSTEM 3 - SUPPLY DUCT													
LOSSES & ERRORS (%)	33.43	34.91	37.67	37.57	37.90	37.05		37.23	38.66	39.13	36.39	39.21	38.79
l&e= (((MHair,i -MHtmb,i-MHlsim2,i-MHlsim1,i)*0.06)/qh2o cooling coil)*100													
SYSTEM 4 - LOAD SIMULATORS													
TMB LOSSES&ERRORS (%)	5.49	4.22	4.14	4.10	4.27	4.12		4.56	3.98	4.15	3.68	3.88	4.37
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998)/qh2o cooling coil)*100													

EXPERIMENT	829a	829b	829C	829D	829E	829F		830a	830b	830c	830d	830e	829G
ENERGY BALANCES (CON)													
Lsim2 LOSSES&ERRORS(%	-6.19	-6.13	-5.70	-5.59	-5.69	-5.88		-5.65	-5.36	-5.10	-5.01	-5.19	-6.14
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998)/qh2o cooling coil)*100													
Lsim1 L&Ew/ calc stm inj	-2.07	-2.09	-2.03	-1.78	-1.46	-2.01		-1.94	-2.12	-1.98	-1.95	-1.86	-1.53
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998+Qstm)/qh2o cooling coil)*100													
SYSTEM 5 - RETURN DUCT													
USING CALCULATED STEAM l&e = (((MHtmb + MHlsim2 + MHlsim1 - MHreturn)*0.06+Qsteam+Qreturn fan)/qh2o cooling coil)*100													
LOSSES & ERRORS (%)	-134.06	-133.02	-129.77	-129.55	-132.96	-135.97		-137.85	-143.54	-133.37	-129.76	-128.13	-141.16
R FAN energy input(mbtu	2.5958	2.6784	2.7524	2.7793	2.7735	2.7859		2.7140	2.8194	2.8473	2.8222	2.8326	2.7916
R FAN power con (KW)	0.7608	0.785	0.80667	0.81457	0.81286	0.81651		0.79543	0.82632	0.8345	0.82714	0.8302	0.81816
SYSTEM 6													
AIR BALANCE													
LOSSES & ERRORS (%)	-8.15	-6.85	-6.87	-6.95	-7.59	-8.40		-7.78	-6.91	-7.22	-7.32	-7.51	-8.78
L&E = Moutside - Mexhaust													
WATER BALANCE ********USES CALCULATED STEAM INJECTION*************													
LOSSES & ERRORS (%)	-20.26	-19.33	-17.88	-17.51	-18.15	-18.70		-18.72	-19.70	-17.92	-17.61	-16.92	-18.60
L&E = (MdotW)stm + (MdotW)outside - (MdotW)exhuast - (Mdot) condensate													
ENERGY BALANCE *******CONSIDERS CALCALTED STEAM INJECTION********													
LOSSES & ERRORS (%)	-73.66	-71.80	-70.04	-68.90	-71.12	-72.96		-72.17	-73.52	-71.46	-71.13	-70.29	-73.80
L&E = Qoutside+Qsfan+Qrfan-Qccoil-Qcond+Qtmb+Qlsim2+Qlsim1+Qsteam-Qexhaust													

APPENDIX B

AIR LOOP - 75% LOAD LEVEL DATA

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
LAB PRESSURE [121]	12.16	12.15	12.14	12.14	12.12	12.13		12.11	12.11	12.18	12.17	12.16	12.17
SYSTEM 1 *** INTAKE / EXHAUST ***													
RETURN AIR													
VDOT [37]	8104.76	8022.29	7991.87	7999.13	7955.33	7411.04		8438.93	8394.61	8141.22	8193.73	8047.74	7141.55
TEMP [38]	81.01	81.47	82.06	81.81	80.80	82.32		80.49	81.05	80.24	81.11	81.41	82.37
DENSITY [339]	0.06117	0.06108	0.06098	0.06099	0.06103	0.06089		0.06097	0.06089	0.06136	0.06122	0.06117	0.06111
RH * 100 [39]	51.7514	49.4703	50.0213	50.3652	51.8962	48.1423		52.1445	51.6683	50.8232	51.1958	51.3871	48.0908
ENTHALPY [353]	35.08	34.69	35.29	35.24	34.95	34.92		34.80	35.06	34.25	34.97	35.29	34.93
HUMIDITY RATIO [354]	0.0143	0.0139	0.0143	0.0143	0.0143	0.0139		0.0142	0.0143	0.0138	0.0142	0.0144	0.0139
RECIRCULATED AIR													
VDOT [42]	6904.51	6798.9	6774.05	6728.21	6706.44	6169.49		7187.77	7128.38	7038.39	7039.49	6919.07	5966.25
TEMP [38]	81.01	81.47	82.06	81.81	80.80	82.32		80.49	81.05	80.24	81.11	81.41	82.37
DENSITY [339]	0.0612	0.0611	0.0610	0.0610	0.0610	0.0609		0.0610	0.0609	0.0614	0.0612	0.0612	0.0611
RH * 100 [39]	51.7514	49.4703	50.0213	50.3652	51.8962	48.1423		52.1445	51.6683	50.8232	51.1958	51.3871	48.0908
Enthalpy (EES)	35.02	34.67	35.30	35.23	34.95	34.91		34.80	35.09	34.14	34.92	35.21	34.88
MIXED AIR													
VDOT [1]	7665.53	7554.05	7521.65	7475.93	7450.92	6856.34		7988.34	7923.41	7821.85	7822.38	7691.12	6629.02
TEMP [4]	80.30	80.61	81.01	80.93	79.81	81.23		79.84	80.52	79.52	80.15	80.45	80.52
RH * 100 [137]	45.6157	43.5542	44.0357	44.2441	45.1557	42.8023		45.5067	44.8166	45.5178	45.5803	45.3108	43.4845
HUMIDITY RATIO [290]	0.0122	0.0120	0.0122	0.0122	0.0120	0.0119		0.0122	0.0122	0.0120	0.0122	0.0122	0.0118
ENTHALPY [276]	32.55	32.42	32.65	32.72	32.28	32.42		32.43	32.65	32.19	32.50	32.53	32.18
OUTSIDE AIR													
VDOT([1*334]-	1073.95	1077.92	1072.31	1068.71	1056.88	1000.79		1131.49	1120.93	1090.12	1101.70	1093.29	936.98
[42*339])/[345]													
TEMP [161]	86.47	88.10	88.15	88.28	86.84	89.41		87.27	85.02	83.46	86.05	86.84	82.26
DENSITY [345]	0.0601	0.0599	0.0598	0.0598	0.0599	0.0597		0.0598	0.0600	0.0605	0.0602	0.0601	0.0606
RH * 100 [134]	30.8955	28.6869	27.8302	28.1042	24.0358	28.6351		27.1272	30.5682	38.0617	33.4104	30.1177	37.884
Humidity Ratio (EES)	0.0100	0.0098	0.0096	0.0097	0.0080	0.0103		0.0091	0.0095	0.0112	0.0107	0.0096	0.0108
Enthalpy (EES)	31.79	31.95	31.66	31.84	29.53	32.73		30.91	30.86	32.37	32.43	31.73	31.55

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
SYSTEM 1 CONTINUED													
EXHAUST AIR													
VDOT [37-42]	1200.25	1223.39	1217.82	1270.92	1248.89	1241.55		1251.16	1266.23	1102.83	1154.24	1128.67	1175.3
TEMP [38]	81.01	81.47	82.06	81.81	80.80	82.32		80.49	81.05	80.24	81.11	81.41	82.37
DENSITY [339]	0.0612	0.0611	0.0610	0.0610	0.0610	0.0609		0.0610	0.0609	0.0614	0.0612	0.0612	0.0611
RH * 100 [39]	51.7514	49.4703	50.0213	50.3652	51.8962	48.1423		52.1445	51.6683	50.8232	51.1958	51.3871	48.0908
Enthalpy (EES)	35.02	34.67	35.30	35.23	34.95	34.91		34.80	35.09	34.14	34.92	35.21	34.88
Humidity Ratio (EES)	0.0142	0.01379	0.01423	0.01421	0.01418	0.01382		0.01412	0.01426	0.01357	0.01409	0.01378	0.01378
SYSTEM 2 *** COOLING COIL ***													
AIRSIDE - IN													
VDOT [1]	7665.53	7554.05	7521.65	7475.93	7450.92	6856.34		7988.34	7923.41	7821.85	7822.38	7691.12	6629.02
TEMP [4]	80.30	80.61	81.01	80.93	79.81	81.23		79.84	80.52	79.52	80.15	80.45	80.52
RH * 100 [137]	45.6157	43.5542	44.0357	44.2441	45.1557	42.8023		45.5067	44.8166	45.5178	45.5803	45.3108	43.4845
HUMIDITY RATIO [290]	0.0122	0.0120	0.0122	0.0122	0.0120	0.0119		0.0122	0.0122	0.0120	0.0122	0.0122	0.0118
ENTHALPY [276]	32.55	32.42	32.65	32.72	32.28	32.42		32.43	32.65	32.19	32.50	32.53	32.18
AIRSIDE - OUT													
VDOT [1]	7665.53	7554.05	7521.65	7475.93	7450.92	6856.34		7988.34	7923.41	7821.85	7822.38	7691.12	6629.02
TEMP [122]	57.09	56.77	57.02	56.98	56.53	56.24		57.01	57.25	56.89	57.17	57.04	55.92
DENSITY [334]	0.0635	0.0635	0.0635	0.0634	0.0634	0.0635		0.0633	0.0633	0.0637	0.0636	0.0636	0.0636
HUMIDITY RATIO [291]	0.0111	0.0108	0.0110	0.0110	0.0109	0.0107		0.0110	0.0111	0.0109	0.0111	0.0111	0.0106
ENTHALPHY [277]	25.72	25.31	25.57	25.62	25.35	25.04		25.61	25.74	25.44	25.69	25.64	24.90
ENTHALPY(h2o) (EES)	22.73	22.37	22.56	22.60	22.24	21.99		22.59	22.84	22.56	22.75	22.62	21.65
TEMP [7]	54.62	54.26	54.45	54.49	54.14	53.89		54.49	54.74	54.46	54.65	54.52	53.54
MDOT CONDENSATE	32.95	33.40	33.19	33.47	32.71	32.15		34.48	34.46	32.91	33.59	32.90	30.67
Qcondensate (MBTUH)	0.7488	0.7470	0.7487	0.7564	0.7274	0.7071		0.7788	0.7870	0.7424	0.7642	0.7443	0.6639
SUPPLY FAN POWER	4.45	4.39	4.36	4.34	4.37	4.10		4.68	4.67	4.52	4.50	4.42	3.97
Qsupply fan calc	13.20	13.03	12.94	12.87	12.96	12.18		13.89	13.85	13.41	13.36	13.12	11.78
WATERSIDE - IN													
VDOT [123]	59.30	60.50	60.09	59.66	61.06	59.02		60.45	59.88	58.70	58.54	60.62	53.97
TEMP [164]	44.73	44.73	44.64	44.71	44.82	44.76		44.68	44.75	44.88	44.73	44.69	44.60

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
SYSTEM 2 CONTINUED													
WATERSIDE - OUT													
VDOT [123]	59.30	60.50	60.09	59.66	61.06	59.02		60.45	59.88	58.70	58.54	60.62	53.97
TEMP [166]	51.47	51.10	51.24	51.27	50.99	50.98		51.19	51.43	51.33	51.49	51.20	51.09
Qwater {123*(166-164)	199.64	192.51	198.07	195.72	188.28	183.38		196.79	199.99	189.20	197.74	197.39	175.09
*.4998} (MBTUH)													
SYSTEM 3 *** SUPPLY DUCT ***													
IN													
AHU-1													
VDOT [1]	7665.53	7554.05	7521.65	7475.93	7450.92	6856.34		7988.34	7923.41	7821.85	7822.38	7691.12	6629.02
TEMP [122]	57.09	56.77	57.02	56.98	56.53	56.24		57.01	57.25	56.89	57.17	57.04	55.92
DENSITY [334]	0.06352	0.06352	0.06345	0.06344	0.06343	0.0635		0.06333	0.06327	0.06365	0.06357	0.06357	0.06357
HUMIDITY RATIO [291]	0.01111	0.01082	0.011	0.01103	0.01089	0.01067		0.01103	0.0111	0.01091	0.01108	0.01107	0.01063
ENTHALPHY [277]	25.72	25.31	25.57	25.62	25.35	25.04		25.61	25.74	25.44	25.69	25.64	24.90
OUT													
TMB													
VDOT [27]	2094.88	2035.17	2028.93	2039.03	2096.21	2059.02		2081.4	2060.7	1893.63	1976.69	2033.4	2061.25
TEMP [28]	60.77	60.93	61.22	61.01	60.25	60.56		60.67	60.91	61.80	61.70	61.35	60.26
DENSITY [338]	0.0631	0.0630	0.0629	0.0630	0.0630	0.0630		0.0629	0.0628	0.0630	0.0636	0.0636	0.0638
RH * 100 [29]	74.8902	73.0275	73.0747	73.77	74.8213	73.586		74.4172	74.0151	71.3472	72.2748	73.1171	73.8266
Enthalpy (EES)	25.75	25.58	25.78	25.75	25.44	25.44		25.66	25.76	25.85	25.94	25.85	25.26
Humidity Ratio (EES)	0.0103	0.0101	0.0102	0.0102	0.0101	0.0100		0.0102	0.0102	0.0101	0.0102	0.0102	0.0099
LSIM-2													
VDOT [113]	2098.78	2081.13	2075.01	2082.92	2122.94	2100.58		2100.95	2084.86	2376.62	2358.98	2363.57	1839.29
TEMP [112]	60.41	60.26	60.62	60.50	59.65	59.89		60.23	60.51	59.96	60.26	60.21	59.26
DENSITY [344]	0.0631	0.0631	0.0630	0.0630	0.0630	0.0631		0.0629	0.0628	0.0633	0.0632	0.0632	0.0633
RH * 100 [114]	76.1139	74.7633	74.8991	75.4879	76.8888	75.6066		76.1971	75.742	76.5968	76.486	76.725	75.9302
Enthalpy (EES)	25.70	25.41	25.67	25.69	25.36	25.31		25.64	25.76	25.47	25.65	25.66	24.93
Humidity Ratio (EES)	0.0103	0.01007	0.01023	0.01027	0.01015	0.01006		0.01028	0.01033	0.01019	0.01029	0.01031	0.00985

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
SYSTEM 3 CONTINUED													
LSIM-1													
VDOT [108]	2499.73	2499.96	2477.51	2441.53	2324.08	1853.27		2857.59	2836.68	2560.47	2524.94	2313.93	1796.57
TEMP [107]	62.1678	62.1219	62.4503	62.2878	61.551	62.5841		61.655	61.9522	61.7328	62.2706	62.3239	61.8489
DENSITY [342]	0.06	0.06	0.06	0.06	0.06	0.06		0.06	0.06	0.06	0.06	0.06	0.06
RH * 100 [109]	70.3511	68.9222	68.8979	69.4887	70.6364	67.4035		71.3781	71.1136	70.5336	70.0923	69.6988	68.4869
Enthalpy (EES)	25.943	25.697	25.908	25.903	25.627	25.759		25.821	25.976	25.681	25.963	25.939	25.44
Humidity Ratio (EES)	0.0101	0.0099	0.0100	0.0101	0.0100	0.0099		0.0101	0.0102	0.0100	0.0101	0.0101	0.0097
SYSTEM 4 *** ZONES ***													
AIRSIDE													
IN => SEE SYSTEM 3 OUT													
OUT													
TMB													
VDOT [27]	2094.88	2035.17	2028.93	2039.03	2096.21	2059.02		2081.4	2060.7	1893.63	1976.69	2033.4	2061.25
TEMP [34]	77.54	77.96	78.28	78.24	77.30	77.72		77.53	77.88	78.78	78.88	78.51	77.40
RH * 100 [33]	40.4767	39.1985	39.1679	39.2792	39.8746	39.3408		39.9636	39.3356	38.6447	38.7684	39.0472	39.5336
Enthalpy (EES)	29.39	29.31	29.50	29.51	29.12	29.22		29.29	29.33	29.62	29.73	29.59	29.05
LSIM-2													
VDOT [113]	2098.78	2081.13	2075.01	2082.92	2122.94	2100.58		2100.95	2084.86	2376.62	2358.98	2363.57	1839.29
TEMP [115]	77.90	78.11	78.43	78.34	77.17	77.46		77.84	78.41	75.95	76.31	76.24	79.05
RH * 100 [116]	48.0310	46.7685	46.7984	47.0472	48.2549	47.3429		47.6255	47.0338	50.1986	50.1237	50.1516	45.1500
Enthalpy (EES)	31.69	31.49	31.72	31.73	31.29	31.23		31.59	31.81	30.92	31.16	31.13	31.65
LSIM-1													
VDOT [108]	2499.73	2499.96	2477.51	2441.53	2324.08	1853.27		2857.59	2836.68	2560.47	2524.94	2313.93	1796.57
TEMP [110]	78.83	78.62	79.18	79.24	79.38	83.97		76.41	76.84	77.47	78.48	80.17	83.59
RH * 100 [111]	52.8382	48.6184	50.8929	51.288	54.5485	41.9556		57.0064	58.1804	48.1951	50.6293	51.3122	41.7069
Enthalpy (EES)	33.70	32.36	33.42	33.58	34.65	34.06		33.10	33.75	31.42	32.81	34.25	33.68
Humidity Ratio (EES)	0.0135	0.0123	0.0132	0.0133	0.0142	0.0127		0.0135	0.0140	0.0117	0.0128	0.0137	0.0124

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
SYSTEM 4 CONTINUED													
WATERSIDE													
IN													
TMB													
VDOT [50]	12.18	12.22	12.23	12.24	12.18	12.20		12.22	12.24	12.28	12.25	12.23	12.16
% FLOW TO COIL[348]	23.89	24.64	25.06	25.40	23.84	24.41		24.40	24.91	26.08	26.27	25.64	24.02
COIL FLOW RATE	2.91	3.01	3.07	3.11	2.90	2.98		2.98	3.05	3.20	3.22	3.14	2.92
TEMP [145]	110.64	110.58	110.51	110.39	110.22	110.34		110.25	110.26	110.67	110.53	110.41	110.29
LSIM-2													
VDOT [54]	12.84	12.85	12.85	12.87	12.85	12.82		12.88	12.91	12.79	12.79	12.78	12.88
% FLOW TO COIL [318]	20.78	21.08	21.41	21.51	20.80	20.87		21.24	21.71	19.57	19.94	19.97	22.33
COIL FLOW RATE	2.67	2.71	2.75	2.77	2.67	2.68		2.74	2.80	2.50	2.55	2.55	2.87
TEMP [175]	111.21	111.14	111.06	110.94	110.75	110.88		110.74	110.72	111.17	111.04	110.91	110.79
LSIM-1													
VDOT [52]	11.34	11.35	11.35	11.35	11.39	11.47		11.31	11.31	11.31	11.34	11.38	11.45
% FLOW TO COIL [321]	23.93	23.98	24.47	24.70	24.80	30.36		22.40	22.57	23.20	23.83	25.41	30.02
COIL FLOW RATE	2.71	2.72	2.78	2.80	2.83	3.48		2.53	2.55	2.62	2.70	2.89	3.44
TEMP [152]	110.88	110.816	110.737	110.619	110.425	110.556		110.425	110.42	110.855	110.716	110.591	110.47
OUT													
TMB													
TEMP [146]	87.23	88.01	88.38	88.36	86.83	87.49		87.44	87.91	89.52	89.32	88.61	86.96
LSIM-2													
TEMP [174]	85.97	86.08	86.41	86.31	85.24	85.48		85.89	86.42	83.95	84.35	84.20	87.23
LSIM-1													
TEMP [153]	85.85	85.80	86.25	86.33	86.25	91.13		83.54	83.82	84.91	85.62	87.07	90.73

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
SYSTEM 5 *** RETURN DUCT ***													
IN => SEE SYSTEM 4 AIRSIDE OUT													
OUT													
RETURN AIR													
VDOT [37]	8104.76	8022.29	7991.87	7999.13	7955.33	7411.04		8438.93	8394.61	8141.22	8193.73	8047.74	7141.55
TEMP [38]	81.01	81.47	82.06	81.81	80.80	82.32		80.49	81.05	80.24	81.11	81.41	82.37
DENSITY [339]	0.0612	0.0611	0.0610	0.0610	0.0610	0.0609		0.0610	0.0609	0.0614	0.0612	0.0612	0.0611
ENTHALPY [353]	35.08	34.69	35.29	35.24	34.95	34.92		34.80	35.06	34.25	34.97	35.29	34.93
HUMIDITY RATIO [354]	0.0143	0.0139	0.0143	0.0143	0.0143	0.0139		0.0142	0.0143	0.0138	0.0142	0.0144	0.0139
AIR MASS BALANCES													
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY AIR FLOW ACROSS THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %													
SYSTEM 1 INTAKE/EXHAUST *****FORCED BALANCE **********													
IN													
RETURN AIR													
VDOT [37]	8104.76	8022.29	7991.87	7999.13	7955.33	7411.04		8438.93	8394.61	8141.22	8193.73	8047.74	7141.55
DENSITY [339]	0.0612	0.0611	0.0610	0.0610	0.0610	0.0609		0.0610	0.0609	0.0614	0.0612	0.0612	0.0611
Mdot RETURN air (lb/hr)	29746.1	29400.1	29240.7	29272	29130.8	27075.5		30871.3	30668.9	29972.7	30097.2	29536.8	26185.2
OUTSIDE AIR													
DENSITY [345]	0.0601	0.0599	0.0598	0.0598	0.0599	0.0597		0.0598	0.0600	0.0605	0.0602	0.0601	0.0606
VDOT([1*334]- [42*339])/[345]	1073.95	1077.92	1072.31	1068.71	1056.88	1000.79		1131.49	1120.93	1090.12	1101.70	1093.29	936.98
Mdot OUTDOOR air (lb/h	3873.9	3873.4	3850.0	3835.2	3799.1	3583.0		4059.8	4036.0	3959.1	3978.7	3941.1	3408.6
OUT													
MIXED AIR													
VDOT [1]	7665.53	7554.05	7521.65	7475.93	7450.92	6856.34		7988.34	7923.41	7821.85	7822.38	7691.12	6629.02
DENSITY [334]	0.0635	0.0635	0.0635	0.0634	0.0634	0.0635		0.0633	0.0633	0.0637	0.0636	0.0636	0.0636
Mdot MIXED air(lb/hr)	29214.9	28790	28634.9	28456.4	28356.7	26122.7		30354.1	30078.8	29871.6	29836.1	29335.5	25284.4

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
AIR BALANCES CONTINUED													
EXHAUST AIR													
VDOT [37-42]	1200.25	1223.39	1217.82	1270.92	1248.89	1241.55		1251.16	1266.23	1102.83	1154.24	1128.67	1175.3
DENSITY [339]	0.0612	0.0611	0.0610	0.0610	0.0610	0.0609		0.0610	0.0609	0.0614	0.0612	0.0612	0.0611
Mdot EXHAUST air (lb/hr	4405.2	4483.5	4455.8	4650.8	4573.2	4535.9		4577.0	4626.0	4060.2	4239.8	4142.4	4309.4
SYSTEM 2 AHU-1 ****** FORCED BALANCE ******													
IN													
VDOT [1]	7665.53	7554.05	7521.65	7475.93	7450.92	6856.34		7988.34	7923.41	7821.85	7822.38	7691.12	6629.02
DENSITY [334]	0.0635	0.0635	0.0635	0.0634	0.0634	0.0635		0.0633	0.0633	0.0637	0.0636	0.0636	0.0636
OUT													
VDOT [1]	7665.53	7554.05	7521.65	7475.93	7450.92	6856.34		7988.34	7923.41	7821.85	7822.38	7691.12	6629.02
DENSITY [334]	0.0635	0.0635	0.0635	0.0634	0.0634	0.0635		0.0633	0.0633	0.0637	0.0636	0.0636	0.0636
SYSTEM 3 SUPPLY DUCT													
IN													
VDOT [1]	7665.53	7554.05	7521.65	7475.93	7450.92	6856.34		7988.34	7923.41	7821.85	7822.38	7691.12	6629.02
DENSITY [334]	0.0635	0.0635	0.0635	0.0634	0.0634	0.0635		0.0633	0.0633	0.0637	0.0636	0.0636	0.0636
Mdot(lb/hr)	29214.9	28790	28634.9	28456.4	28356.7	26122.7		30354.1	30078.8	29871.6	29836.1	29335.5	25284.4
OUT													
TMB													
VDOT [27]	2094.88	2035.17	2028.93	2039.03	2096.21	2059.02		2081.4	2060.7	1893.63	1976.69	2033.4	2061.25
DENSITY [338]	0.0631	0.0630	0.0629	0.0630	0.0630	0.0630		0.0629	0.0628	0.0630	0.0636	0.0636	0.0638
Mdot(lb/hr)	7930.0	7694.2	7662.1	7701.4	7919.9	7779.4		7850.2	7763.5	7162.5	7539.5	7755.8	7884.3
LSIM-2													
VDOT [113]	2098.78	2081.13	2075.01	2082.92	2122.94	2100.58		2100.95	2084.86	2376.62	2358.98	2363.57	1839.29
DENSITY [344]	0.0631	0.0631	0.0630	0.0630	0.0630	0.0631		0.0629	0.0628	0.0633	0.0632	0.0632	0.0633
Mdot(lb/hr)	7951.02	7879.16	7844.78	7874.69	8029.81	7947.75		7930.25	7860.76	9022.12	8942.42	8956.98	6986.73

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
AIR BALANCES CONTINUED													
SYSTEM 3 CONTINUED													
LSIM-1													
VDOT [108]	2499.73	2499.96	2477.51	2441.53	2324.08	1853.27		2857.59	2836.68	2560.47	2524.94	2313.93	1796.57
DENSITY [342]	0.0629	0.0629	0.0628	0.0628	0.0628	0.0627		0.0627	0.0627	0.0631	0.0629	0.0629	0.0630
Mdot(lb/hr)	9437.0	9430.3	9333.8	9198.2	8758.5	6975.3		10757.1	10666.5	9686.3	9535.2	8732.8	6791.0
LOSSES&ERRORS(LB/HR)	3896.91	3786.32	3794.32	3682.06	3648.47	3420.17		3816.53	3788.13	4000.8	3819.03	3889.92	3622.37
(IN-OUT)													
LOSSES %	13.34	13.15	13.25	12.94	12.87	13.09		12.57	12.59	13.39	12.80	13.26	14.33
SYSTEM 4 LOAD SIMULATORS ****** FORCED BALANCE ******													
TMB IN AND OUT													
VDOT [27]	2094.88	2035.17	2028.93	2039.03	2096.21	2059.02		2081.4	2060.7	1893.63	1976.69	2033.4	2061.25
DENSITY [338]	0.0631	0.0630	0.0629	0.0630	0.0630	0.0630		0.0629	0.0628	0.0630	0.0636	0.0636	0.0638
LSIM-2 IN AND OUT													
VDOT [113]	2098.78	2081.13	2075.01	2082.92	2122.94	2100.58		2100.95	2084.86	2376.62	2358.98	2363.57	1839.29
DENSITY [344]	0.0631	0.0631	0.0630	0.0630	0.0630	0.0631		0.0629	0.0628	0.0633	0.0632	0.0632	0.0633
LSIM-1 IN AND OUT													
VDOT [108]	2499.73	2499.96	2477.51	2441.53	2324.08	1853.27		2857.59	2836.68	2560.47	2524.94	2313.93	1796.57
DENSITY [342]	0.0629	0.0629	0.0628	0.0628	0.0628	0.0627		0.0627	0.0627	0.0631	0.0629	0.0629	0.0630
SYSTEM 5 RETURN DUCT													
IN													
TMB OUT													
VDOT [27]	2094.88	2035.17	2028.93	2039.03	2096.21	2059.02		2081.4	2060.7	1893.63	1976.69	2033.4	2061.25
DENSITY [338]	0.0631	0.0630	0.0629	0.0630	0.0630	0.0630		0.0629	0.0628	0.0630	0.0636	0.0636	0.0638
LSIM-2 OUT													
VDOT [113]	2098.78	2081.13	2075.01	2082.92	2122.94	2100.58		2100.95	2084.86	2376.62	2358.98	2363.57	1839.29
DENSITY [344]	0.0631	0.0631	0.0630	0.0630	0.0630	0.0631		0.0629	0.0628	0.0633	0.0632	0.0632	0.0633

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
AIR BALANCES CONTINUED													
SYSTEM 5 CONTINUED													
LSIM-1 OUT													
VDOT [108]	2499.73	2499.96	2477.51	2441.53	2324.08	1853.27		2857.59	2836.68	2560.47	2524.94	2313.93	1796.57
DENSITY [342]	0.0629	0.0629	0.0628	0.0628	0.0628	0.0627		0.0627	0.0627	0.0631	0.0629	0.0629	0.0630
OUT													
RETURN AIR													
VDOT [37]	8104.76	8022.29	7991.87	7999.13	7955.33	7411.04		8438.93	8394.61	8141.22	8193.73	8047.74	7141.55
DENSITY [339]	0.0612	0.0611	0.0610	0.0610	0.0610	0.0609		0.0610	0.0609	0.0614	0.0612	0.0612	0.0611
LOSSES&ERRORS(LB/HR)	-4428.1	-4396.4	-4400	-4497.7	-4422.6	-4373		-4333.7	-4378.1	-4101.9	-4080.1	-4091.3	-4523.2
(IN-OUT)													
LOSES %	-15.16	-15.27	-15.37	-15.81	-15.60	-16.74		-14.28	-14.56	-13.73	-13.68	-13.95	-17.89
WATER BALANCES													
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY WATER FLOW ACROSS THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %													
SYSTEM 1													
ERRORSandLOSSES(lb/hr	45.26	39.70	43.30	42.60	39.48	39.68		41.31	43.00	43.22	46.35	49.13	42.21
E&L=(WVRHOE)ret*60+(WVRHOE)out*60-(WVRHOE)ex*60-(WVRHOE)mix*60													
ERRORS %	12.66	11.51	12.43	12.26	11.56	12.76		11.19	11.67	12.04	12.73	13.74	14.10
SYSTEM 2 ****** FORCED BALANCE *******													
Mdot COND (LB/HR)	32.95	33.40	33.19	33.47	32.71	32.15		34.48	34.46	32.91	33.59	32.90	30.67
Mdot CONDENSATE=(WVRHOE)mix*60-(VWRHOE)supply*6													
SYSTEM 3													
E&L (lb/hr)	65.84	61.23	63.07	61.82	59.89	52.03		64.13	64.29	64.86	64.95	64.98	55.48
E&L = (MdotWin-Sum(MdotWout))													
ERRORS %	20.28	19.65	20.02	19.70	19.40	18.66		19.16	19.26	19.89	19.64	20.01	20.65

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
WATER BALANCES (CON)													
SYSTEM 4													
Steam Injection Calculat	31.7271	22.614	29.1027	29.6735	37.3464	19.5658		36.1331	40.2446	16.8057	25.1347	31.4467	18.0845
STEAM PRESSURE	10.73	11.01	10.98	10.75	10.59	10.94		10.67	10.76	10.97	10.92	10.90	11.01
Steam Enthalpy (EES)	1152.06	1151.94	1151.95	1152.05	1152.11	1151.97		1152.08	1152.04	1151.96	1151.97	1151.98	1151.94
SYSTEM 5													
Using CALCULATED STE	-135.98	-135.46	-137.10	-137.14	-129.22	-130.26		-131.62	-129.05	-134.78	-136.85	-135.01	-132.98
ERRORS %	-41.88	-43.49	-43.52	-43.69	-41.86	-46.72		-39.32	-38.65	-41.34	-41.39	-41.58	-49.50
ENERGY BALANCES													
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY Qh2o OF THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %													
SYSTEM 1 - intake/exhaust													
LOSSES & ERRORS (%)	30.89	28.43	31.13	30.14	29.32	31.36		28.59	27.61	28.83	32.25	34.07	33.30
I&e= ((MHex-MHex-MHrec)/qh2o cooling coil)*100													
SYSTEM 2 - COOLING COIL													
LOSSES & ERRORS (%)	6.14	12.72	8.46	9.33	10.80	11.43		11.74	10.58	13.39	9.09	8.56	11.49
I&e=(((Mair(Hair,in-Hair,o)*0.06+MCp(Ti-To)h2o*0.4998-Mair(Wi-Wo)air*Hh2o*0.06)+QFAN)/qh2o cooling coil)*100													
SYSTEM 3 - SUPPLY DUCT													
LOSSES & ERRORS (%)	49.11	46.36	46.19	46.10	47.52	41.05		48.27	47.29	50.81	47.53	48.34	47.72
I&e= (((MHair,i -MHtmb,i-MHlsim2,i-MHlsim1,i)*0.06)/qh2o cooling coil)*100													
SYSTEM 4 - LOAD SIMULATORS													
TMB LOSSES&ERRORS (%	2.59	2.74	2.74	2.73	2.55	2.54		2.78	3.14	3.63	2.83	2.64	2.38
I&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998)/qh2o cooling coil)*100													

EXPERIMENT	827A	827B	827C	827D	827F	827E		827G	827H	828A	828B	828C	828D
ENERGY BALANCES (CON)													
Lsim2 LOSSES&ERRORS(	-6.98	-7.26	-6.85	-6.93	-7.22	-7.12		-6.71	-6.78	-8.02	-7.70	-7.54	-7.48
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998)/qh2o cooling coil)*100													
Lsim1 L&Ew/ calc stm in	-1.34	-1.42	-1.30	-1.22	-1.00	-0.87		-1.34	-1.29	-1.19	-1.24	-1.18	-0.67
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998+Qstm)/qh2o cooling coil)*100													
SYSTEM 5 - RETURN DUCT													
USING CALCULATED STEAM l&e = (((MHtmb + MHlsim2 + MHlsim1 - MHreturn)*0.06+Qsteam+Qreturn fan)/qh2o cooling coil)*100													
LOSSES & ERRORS (%)	-99.53	-108.94	-104.24	-105.42	-98.07	-112.06		-96.69	-92.61	-109.06	-102.37	-98.04	-120.46
R FAN energy input(mbt	5.3709	5.24343	5.1584	5.14161	5.16822	4.38688		5.9407	5.84155	5.42808	5.44378	5.21599	4.20587
R FAN power con (KW)	1.5741	1.5368	1.5118	1.5069	1.5147	1.2857		1.7411	1.7121	1.5909	1.5955	1.5287	1.2327
SYSTEM 6													
AIR BALANCE													
LOSSES & ERRORS (%)	-1.82	-2.12	-2.12	-2.87	-2.73	-3.65		-1.70	-1.96	-0.34	-0.88	-0.69	-3.56
L&E = Moutside - Mexhaust													
WATER BALANCE ********USES CALCULATED STEAM INJECTION*************													
LOSSES & ERRORS (%)	-6.96	-10.01	-8.82	-9.42	-8.74	-12.40		-7.09	-5.91	-7.44	-7.01	-5.84	-11.79
L&E = (MdotW)stm + (MdotW)outside - (MdotW)exhuast - (Mdot) condensate													
ENERGY BALANCE *******CONSIDERS CALCALTED STEAM INJECTION********													
LOSSES & ERRORS (%)	-37.42	-40.90	-40.80	-42.73	-38.96	-45.95		-34.50	-35.25	-31.85	-34.26	-31.49	-45.62
L&E = Qoutside+Qsfan+Qrfan-Qccoil-Qcond+Qtmb+Qlsim2+Qlsim1+Qsteam-Qexhaust													

APPENDIX C

WATER LOOP - 50% LOAD LEVEL DATA

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
LAB PRESSURE[121]	12.20	12.19	12.20	12.20	12.20		12.33	12.33	12.33	12.32
SYSTEM 1 *** INTAKE / EXHAUST ***										
RETURN AIR										
VDOT [37]	5559.10	5615.00	5635.40	5628.40	5613.40		5251.80	5257.10	5049.10	5021.30
TEMP [38]	81.29	80.85	79.58	79.46	79.95		79.51	79.87	80.30	80.80
DENSITY [339]	0.0614	0.0614	0.0615	0.0615	0.0615		0.0621	0.0621	0.0621	0.0619
RH * 100 [39]	47.8200	47.2190	46.4310	46.8140	45.9470		50.1330	47.3810	45.4370	44.8510
ENTHALPY [353]	34.07	33.53	32.44	32.43	32.58		33.51	32.93	32.63	32.82
HUMIDITY RATIO [354]	0.0134	0.0130	0.0123	0.0123	0.0123		0.0132	0.0126	0.0123	0.0123
RECIRCULATED AIR										
VDOT [42]	4432.30	4487.40	4503.80	4489.60	4466.10		4097.40	4157.60	3950.00	3912.40
TEMP [38]	81.29	80.85	79.58	79.46	79.95		79.51	79.87	80.30	80.80
DENSITY [339]	0.0614	0.0614	0.0615	0.0615	0.0615		0.0621	0.0621	0.0621	0.0619
RH * 100 [39]	47.8200	47.2190	46.4310	46.8140	45.9470		50.1330	47.3810	45.4370	44.8510
MIXED AIR										
VDOT [1]	4923.20	4989.10	5003.00	4989.70	4964.10		4554.80	4618.30	4389.60	4347.30
TEMP [4]	79.96	79.96	78.83	78.56	79.10		77.86	78.17	78.47	79.00
RH * 100 [137]	43.1220	42.0960	41.5960	43.1910	42.1330		45.8450	44.0290	42.4090	41.8910
HUMIDITY RATIO [290]	0.0115	0.0112	0.0107	0.0110	0.0108		0.0114	0.0110	0.0108	0.0108
ENTHALPY [276]	31.68	31.41	30.56	30.84	30.77		31.05	30.66	30.58	30.71
OUTSIDE AIR										
VDOT([1*334]- [42*339])/[345]	707.44	731.82	736.56	741.41	738.08		638.71	673.12	641.49	648.43
TEMP [161]	83.23	84.45	82.93	80.20	80.83		74.65	73.69	73.66	73.81
DENSITY [345]	0.0607	0.0605	0.0607	0.0610	0.0610		0.0623	0.0624	0.0624	0.0623
RH * 100 [134]	33.2280	30.1760	33.0720	44.2520	41.1440		46.2550	51.8810	51.4350	50.9290
Humidity Ratio (EES)	0.0097	0.0092	0.0096	0.0118	0.0111		0.0101	0.0110	0.0109	0.0108
Enthalpy (EES)	30.62	30.32	30.39	32.12	31.61		28.95	29.67	29.56	29.54

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
SYSTEM 1 CONTINUED										
EXHAUST AIR										
VDOT [37-42]	1126.80	1127.60	1131.60	1138.80	1147.30		1154.40	1099.50	1099.10	1108.90
TEMP [38]	81.29	80.85	79.58	79.46	79.95		79.51	79.87	80.30	80.80
DENSITY [340]	0.0614	0.0614	0.0615	0.0615	0.0615		0.0621	0.0621	0.0621	0.0619
RH * 100 [39]	47.8200	47.2190	46.4310	46.8140	45.9470		50.1330	47.3810	45.4370	44.8510
Enthalpy (EES)	33.96	33.47	32.35	32.37	32.45		33.21	32.67	32.41	32.58
Humidity Ratio (EES)	0.0132	0.0128	0.0121	0.0121	0.0121		0.0129	0.0123	0.0120	0.0120
SYSTEM 2 *** COOLING COIL ***										
AIRSIDE - IN										
VDOT [1]	4923.20	4989.10	5003.00	4989.70	4964.10		4554.80	4618.30	4389.60	4347.30
TEMP [4]	79.96	79.96	78.83	78.56	79.10		77.86	78.17	78.47	79.00
RH * 100 [137]	43.1220	42.0960	41.5960	43.1910	42.1330		45.8450	44.0290	42.4090	41.8910
HUMIDITY RATIO [290]	0.0116	0.0111	0.0105	0.0109	0.0108		0.0111	0.0108	0.0105	0.0106
ENTHALPY [276]	31.68	31.41	30.56	30.84	30.77		31.05	30.66	30.58	30.71
AIRSIDE - OUT										
VDOT [1]	4923.20	4989.10	5003.00	4989.70	4964.10		4554.80	4618.30	4389.60	4347.30
TEMP [122]	54.66	53.52	51.93	52.03	52.04		55.47	52.59	51.80	51.91
DENSITY [334]	0.0640	0.0641	0.0643	0.0644	0.0644		0.0646	0.0650	0.0650	0.0650
HUMIDITY RATIO [291]	0.0103	0.0098	0.0092	0.0093	0.0092		0.0102	0.0095	0.0092	0.0092
ENTHALPY [277]	24.22	23.54	22.55	22.65	22.58		24.50	23.13	22.56	22.56
ENTHALPY(h2o)	20.45	19.25	17.70	17.76	17.64		21.26	18.53	17.63	17.64
TEMP [7]	52.35	51.15	49.60	49.66	49.54		53.16	50.43	49.53	49.54
MDOT CONDENSATE	23.65	25.14	25.67	30.27	29.54		16.60	23.96	22.60	23.40
Qcondensate (MBTUH)	0.4837	0.4838	0.4543	0.5376	0.5210		0.3528	0.4439	0.3983	0.4127
SUPPLY FAN POWER	3.14	3.16	3.16	3.17	3.15		2.90	2.98	2.89	2.88
Qsupply fan calc	9.33	9.39	9.38	9.40	9.35		8.61	8.84	8.57	8.55
WATERSIDE - IN										
VDOT [123]	61.04	60.87	55.60	38.09	30.09		57.92	61.03	40.14	29.40
TEMP [164]	46.55	44.72	42.77	41.02	39.23		47.58	44.53	42.46	40.68

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
SYSTEM 2 CONTINUED										
WATERSIDE - OUT										
VDOT [123]	61.04	60.87	55.60	38.09	30.09		57.92	61.03	40.14	29.40
TEMP [166]	50.35	48.94	47.59	48.52	49.01		51.23	48.41	48.63	49.45
Qwater {123*(166-164)	116.11	128.33	133.82	142.83	147.02		105.52	118.07	123.87	128.78
*.4998} (MBTUH)										
SYSTEM 3 *** SUPPLY DUCT ***										
IN										
AHU-1										
VDOT [1]	4932.20	4989.10	5003.00	4989.70	4964.10		4554.80	4618.30	4389.60	4347.30
TEMP [122]	54.66	53.52	51.93	52.03	52.04		55.47	52.59	51.80	51.91
DENSITY [334]	0.0640	0.0641	0.0643	0.0644	0.0644		0.0646	0.0650	0.0650	0.0650
HUMIDITY RATIO [291]	0.0103	0.0098	0.0092	0.0093	0.0092		0.0102	0.0095	0.0092	0.0092
ENTHALPY [277]	24.22	23.54	22.55	22.65	22.58		24.50	23.13	22.56	22.56
OUT										
TMB										
VDOT [27]	1230.40	1274.40	1288.00	1291.20	1282.70		1118.50	1193.40	1197.80	1188.00
TEMP [28]	63.52	62.45	61.22	61.32	61.53		63.74	61.91	61.23	61.56
DENSITY [338]	0.0630	0.0631	0.0632	0.0632	0.0632		0.0636	0.0638	0.0639	0.0638
RH * 100 [29]	64.8950	64.7270	64.3970	65.0030	64.3450		64.6950	66.1710	65.7940	65.2260
Enthalpy (EES)	25.87	25.19	24.40	24.55	24.57		25.86	24.97	24.51	24.63
Humidity Ratio (EES)	0.0098	0.0094	0.0089	0.0090	0.0090		0.0097	0.0093	0.0090	0.0091
LSIM-2										
VDOT [113]	1336.40	1330.90	1343.60	1336.60	1321.50		1249.50	1314.60	1148.60	1114.90
TEMP [112]	59.86	59.05	57.59	57.56	57.79		59.84	57.63	57.99	58.50
DENSITY [344]	0.0640	0.0635	0.0637	0.0637	0.0637		0.0641	0.0644	0.0643	0.0642
RH * 100 [114]	71.8830	71.0230	70.8480	71.3580	70.4080		71.8530	72.9380	70.2430	68.9490
Enthalpy (EES)	24.69	24.08	23.19	23.23	23.24		24.56	23.38	23.24	23.37
Humidity Ratio (EES)	0.0095	0.0091	0.0086	0.0087	0.0086		0.0094	0.0088	0.0086	0.0086

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
SYSTEM 3 CONTINUED										
LSIM-1										
VDOT [108]	1602.10	1604.70	1589.10	1580.80	1591.20		1506.20	1362.90	1336.10	1347.30
TEMP [107]	61.62	60.88	59.38	59.38	59.67		61.53	59.77	59.23	59.58
DENSITY [342]	0.0632	0.0632	0.0634	0.0635	0.0634		0.0639	0.0641	0.0641	0.0640
RH * 100 [109]	66.5830	65.4520	65.2510	65.6180	64.5830		67.0560	66.7400	65.8400	64.9060
Enthalpy (EES)	24.97	24.36	23.45	23.50	23.51		24.88	23.79	23.35	23.43
Humidity Ratio (EES)	0.0094	0.0090	0.0085	0.0085	0.0085		0.0093	0.0087	0.0084	0.0084
SYSTEM 4 *** ZONES ***										
AIRSIDE										
IN => SEE SYSTEM 3 OUT										
OUT										
TMB										
VDOT [27]	1230.40	1274.40	1288.00	1291.20	1282.70		1118.50	1193.40	1197.80	1188.00
TEMP [34]	78.66	78.22	77.65	77.57	77.94		77.98	78.21	77.85	78.16
RH * 100 [33]	36.6280	35.9640	35.0070	35.7360	35.1150		35.9000	35.4670	34.9180	34.7100
Enthalpy (EES)	28.96	28.53	27.95	28.10	28.14		28.27	28.28	27.93	28.06
LSIM-2										
VDOT [113]	1336.40	1330.90	1343.60	1336.60	1321.50		1249.50	1314.60	1148.60	1114.90
TEMP [115]	78.34	77.75	76.25	76.16	76.56		77.18	76.48	78.63	79.69
RH * 100 [116]	44.1820	43.2220	43.0100	43.5250	42.7640		45.2740	44.3890	41.3410	40.1290
Enthalpy (EES)	30.87	30.24	29.24	29.31	29.36		30.29	29.61	30.14	30.47
LSIM-1										
VDOT [108]	1602.10	1604.70	1589.10	1580.80	1591.20		1506.20	1362.90	1336.10	1347.30
TEMP [110]	79.03	78.64	76.96	76.87	77.35		78.11	79.53	79.44	79.90
RH * 100 [111]	43.6920	44.2580	42.7000	41.5240	40.5590		49.5590	41.2470	38.9690	38.1970
Enthalpy (EES)	31.18	31.10	29.60	29.23	29.26		32.06	30.68	29.98	30.04
Humidity Ratio (EES)	0.0112	0.0112	0.0102	0.0099	0.0098		0.0122	0.0106	0.0100	0.0099

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
SYSTEM 4 CONTINUED										
WATERSIDE										
IN										
TMB										
VDOT [50]	11.98	11.95	11.95	11.96	11.96		11.51	11.97	11.95	11.96
% FLOW TO COIL[348]	16.81	15.95	15.42	15.31	15.90		24.59	16.27	15.85	16.22
COIL FLOW RATE	2.01	1.91	1.84	1.83	1.90		2.83	1.95	1.89	1.94
TEMP [145]	110.99	110.76	110.54	110.41	110.30		108.49	110.44	110.32	110.19
LSIM-2										
VDOT [54]	12.57	12.58	12.55	12.56	12.58		11.82	12.54	12.61	12.66
% FLOW TO COIL [318]	13.46	13.30	12.61	12.66	12.84		14.22	12.83	14.01	14.67
COIL FLOW RATE	1.69	1.67	1.58	1.59	1.61		1.68	1.61	1.77	1.86
TEMP [175]	111.52	111.30	111.08	110.93	110.81		108.93	110.93	110.81	110.68
LSIM-1										
VDOT [52]	11.24	11.25	11.22	11.22	11.23		10.60	11.26	11.26	11.25
% FLOW TO COIL [321]	15.33	15.21	14.48	14.48	14.84		22.12	15.76	15.85	16.21
COIL FLOW RATE	1.72	1.71	1.63	1.62	1.67		2.34	1.77	1.79	1.82
TEMP [152]	111.21	110.98	110.76	110.61	110.49		108.60	110.61	110.49	110.36
OUT										
TMB										
TEMP [146]	87.94	86.56	85.50	85.38	86.00		87.00	86.66	85.95	86.46
LSIM-2										
TEMP [174]	84.60	83.93	82.30	82.26	82.73		83.29	82.61	84.94	86.02
LSIM-1										
TEMP [153]	84.51	84.01	82.40	82.37	82.87		83.16	84.75	84.66	85.11

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
SYSTEM 5 *** RETURN DUCT ***										
IN => SEE SYSTEM 4 AIRSIDE OUT										
OUT										
RETURN AIR										
VDOT [37]	5559.10	5615.00	5635.40	5628.40	5613.40		5251.80	5257.10	5049.10	5021.30
TEMP [38]	81.29	80.85	79.58	79.46	79.95		79.51	79.87	80.30	80.80
DENSITY [339]	0.0614	0.0614	0.0615	0.0615	0.0615		0.0621	0.0621	0.0621	0.0619
ENTHALPY [353]	34.07	33.53	32.44	32.43	32.58		33.51	32.93	32.63	32.82
HUMIDITY RATIO [354]	0.0134	0.0130	0.0123	0.0123	0.0123		0.0132	0.0126	0.0123	0.0123
AIR MASS BALANCES										
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY AIR FLOW ACROSS THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %										
SYSTEM 1 INTAKE/EXHAUST *****BALANCES BY DEFAULT **********										
IN										
RETURN AIR										
VDOT [37]	5559.10	5615.00	5635.40	5628.40	5613.40		5251.80	5257.10	5049.10	5021.30
DENSITY [339]	0.0614	0.0614	0.0615	0.0615	0.0615		0.0621	0.0621	0.0621	0.0619
Mdot RETURN air (lb/hr)	20479.7	20685.7	20794.6	20768.8	20713.4		19568.2	19588.0	18812.9	18649.1
OUTSIDE AIR										
DENSITY [345]	0.0607	0.0605	0.0607	0.0610	0.0610		0.0623	0.0624	0.0624	0.0623
VDOT([1*334]-	707.44	731.82	736.56	741.41	738.08		638.71	673.12	641.49	648.43
[42*339])/[345]										
Mdot OUTDOOR air (lb/hr)	2576.5	2656.5	2682.6	2713.6	2701.4		2387.5	2520.2	2401.7	2423.8
OUT										
MIXED AIR										
VDOT [1]	4932.20	4989.10	5003.00	4989.70	4964.10		4554.80	4618.30	4389.60	4347.30
DENSITY [334]	0.0640	0.0641	0.0643	0.0644	0.0644		0.0646	0.0650	0.0650	0.0650
Mdot MIXED air(lb/hr)	18939.6	19188.1	19301.6	19280.2	19181.3		17654.4	18011.4	17119.4	16954.5

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
AIR BALANCES CONTINUED										
EXHAUST AIR										
VDOT [37-42]	1126.80	1127.60	1131.60	1138.80	1147.30		1154.40	1099.50	1099.10	1108.90
DENSITY [339]	0.0614	0.0614	0.0615	0.0615	0.0615		0.0621	0.0621	0.0621	0.0619
Mdot EXHAUST air (lb/hr)	4151.1	4154.1	4175.6	4202.2	4233.5		4301.3	4096.7	4095.2	4118.5
SYSTEM 2 AHU-1 *** BALANCES BY DEFAULT ***										
IN										
VDOT [1]	4932.20	4989.10	5003.00	4989.70	4964.10		4554.80	4618.30	4389.60	4347.30
DENSITY [334]	0.0640	0.0641	0.0643	0.0644	0.0644		0.0646	0.0650	0.0650	0.0650
OUT										
VDOT [1]	4932.20	4989.10	5003.00	4989.70	4964.10		4554.80	4618.30	4389.60	4347.30
DENSITY [334]	0.0640	0.0641	0.0643	0.0644	0.0644		0.0646	0.0650	0.0650	0.0650
SYSTEM 3 SUPPLY DUCT										
IN										
VDOT [1]	4932.20	4989.10	5003.00	4989.70	4964.10		4554.80	4618.30	4389.60	4347.30
DENSITY [334]	0.0640	0.0641	0.0643	0.0644	0.0644		0.0646	0.0650	0.0650	0.0650
Mdot(lb/hr)	18939.6	19188.1	19301.6	19280.2	19181.3		17654.4	18011.4	17119.4	16954.5
OUT										
TMB										
VDOT [27]	1230.40	1274.40	1288.00	1291.20	1282.70		1118.50	1193.40	1197.80	1188.00
DENSITY [338]	0.0630	0.0631	0.0632	0.0632	0.0632		0.0636	0.0638	0.0639	0.0638
Mdot(lb/hr)	4650.9	4824.9	4884.1	4896.2	4864.0		4268.2	4568.3	4592.4	4547.7
LSIM-2										
VDOT [113]	1336.40	1330.90	1343.60	1336.60	1321.50		1249.50	1314.60	1148.60	1114.90
DENSITY [344]	0.0640	0.0635	0.0637	0.0637	0.0637		0.0641	0.0644	0.0643	0.0642
Mdot(lb/hr)	5131.8	5070.7	5135.2	5108.5	5050.8		4805.6	5079.6	4431.3	4294.6

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
AIR BALANCES CONTINUED										
SYSTEM 3 CONTINUED										
LSIM-1										
VDOT [108]	1602.10	1604.70	1589.10	1580.80	1591.20		1506.20	1362.90	1336.10	1347.30
DENSITY [342]	0.0632	0.0632	0.0634	0.0635	0.0634		0.0639	0.0641	0.0641	0.0640
Mdot(lb/hr)	6075.2	6085.0	6044.9	6022.8	6052.9		5774.8	5241.7	5138.6	5173.6
LOSSES&ERRORS(LB/HR)	3081.80	3207.45	3237.30	3252.64	3213.59		2805.86	3121.71	2957.14	2938.58
(IN-OUT)										
LOSSES %	16.27	16.72	16.77	16.87	16.75		15.89	17.33	17.27	17.33
ZONE 4 LOAD SIMULATORS *****BALANCES BY DEFAULT******										
TMB IN AND OUT										
VDOT [27]	1230.40	1274.40	1288.00	1291.20	1282.70		1118.50	1193.40	1197.80	1188.00
DENSITY [338]	0.0630	0.0631	0.0632	0.0632	0.0632		0.0636	0.0638	0.0639	0.0638
LSIM-2 IN AND OUT										
VDOT [113]	1336.40	1330.90	1343.60	1336.60	1321.50		1249.50	1314.60	1148.60	1114.90
DENSITY [344]	0.0640	0.0635	0.0637	0.0637	0.0637		0.0641	0.0644	0.0643	0.0642
LSIM-1 IN AND OUT										
VDOT [108]	1602.10	1604.70	1589.10	1580.80	1591.20		1506.20	1362.90	1336.10	1347.30
DENSITY [342]	0.0632	0.0632	0.0634	0.0635	0.0634		0.0639	0.0641	0.0641	0.0640
SYSTEM 5 RETURN DUCT										
IN										
TMB OUT										
VDOT [27]	1230.40	1274.40	1288.00	1291.20	1282.70		1118.50	1193.40	1197.80	1188.00
DENSITY [338]	0.0630	0.0631	0.0632	0.0632	0.0632		0.0636	0.0638	0.0639	0.0638
LSIM-2 OUT										
VDOT [113]	1336.40	1330.90	1343.60	1336.60	1321.50		1249.50	1314.60	1148.60	1114.90
DENSITY [344]	0.0640	0.0635	0.0637	0.0637	0.0637		0.0641	0.0644	0.0643	0.0642

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
AIR BALANCES CONTINUE	AIR BALANCE	AIR BALANCE	AIR BALANCE	AIR BALANCE	AIR BALANCE	AIR	AIR BALANCE	AIR BALANCE	AIR BALANCE	AIR BALANCE
SYSTEM 5 CONTINUED										
LSIM-1 OUT										
VDOT [108]	1602.10	1604.70	1589.10	1580.80	1591.20		1506.20	1362.90	1336.10	1347.30
DENSITY [342]	0.0632	0.0632	0.0634	0.0635	0.0634		0.0639	0.0641	0.0641	0.0640
OUT										
RETURN AIR										
VDOT [37]	5559.10	5615.00	5635.40	5628.40	5613.40		5251.80	5257.10	5049.10	5021.30
DENSITY [339]	0.0614	0.0614	0.0615	0.0615	0.0615		0.0621	0.0621	0.0621	0.0619
LOSSES&ERRORS(LB/HR)	-4621.87	-4705.03	-4730.35	-4741.23	-4745.75		-4719.66	-4698.29	-4650.64	-4633.22
(IN-OUT)										
LOSES %	-24.40	-24.52	-24.51	-24.59	-24.74		-26.73	-26.09	-27.17	-27.33
WATER BALANCES										
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY WATER FLOW ACROSS THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %										
SYSTEM 1										
ERRORSandLOSSES(lb/hr)	27.22	24.81	24.51	24.31	25.71		25.82	26.08	23.71	22.87
E&L=(WVRHOE)ret*60+(WVRHOE)out*60-(WVRHOE)ex*60-(WVRHOE)mix*60										
ERRORS %	12.52	11.53	11.87	11.46	12.37		12.84	13.18	12.83	12.49
SYSTEM 2 ******BALANCES BY DEFAULT*******										
Mdot COND (LB/HR)	23.65	25.14	25.67	30.27	29.54		16.60	23.96	22.60	23.40
Mdot CONDENSATE=(WVRHOE)mix*60-(VWRHOE)supply*6										
SYSTEM 3										
E&L (lb/hr)	44.67	41.49	38.80	39.11	38.47		39.89	37.93	34.55	34.36
E&L = (MdotWin-Sum(MdotWout))										
ERRORS %	22.88	22.13	21.82	21.86	21.73		22.15	22.24	21.98	22.05

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
WATER BALANCES (CON)										
SYSTEM 4										
Steam Injection Calculated	10.87	13.39	10.28	8.07	7.93	##	16.52	9.91	8.02	7.86
STEAM PRESSURE [131]	11.44	11.40	11.44	11.40	11.50		10.49	11.24	11.34	11.34
Steam Enthalpy (EES)	1151.76	1151.78	1151.76	1151.78	1151.74		1152.15	1151.84	1151.80	1151.80
SYSTEM 5										
Using CALCULATED STEAM	-112.60	-109.55	-106.53	-107.58	-108.28		-101.60	-104.27	-100.77	-100.06
ERRORS%	-57.66	-58.44	-59.92	-60.13	-61.16		-56.42	-61.13	-64.12	-64.22
ENERGY BALANCES										
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY Qh2o OF THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %										
SYSTEM 1 - intake/exhaust										
LOSSES & ERRORS (%)	31.72	25.35	23.32	21.14	22.15		32.07	28.47	23.02	22.24
l&e= ((MHex-MHex-MHrec)/qh2o cooling coil)*100										
SYSTEM 2 - COOLING COIL										
LOSSES & ERRORS (%)	28.98	24.61	22.12	16.76	12.90		17.43	22.03	17.46	13.70
l&e=(((Mair(Hair,in-Hair,o)*0.06+MCp(Ti-To)h2o*0.4998-Mair(Wi-Wo)air*Hh2o*0.06)+QFAN)/qh2o cooling coil)*100										
SYSTEM 3 - SUPPLY DUCT										
LOSSES & ERRORS (%)	51.75	46.53	41.35	39.37	36.60		57.20	50.02	40.97	37.98
l&e= (((MHair,i -MHtmb,i-MHlsim2,i-MHlsim1,i)*0.06)/qh2o cooling coil)*100										
SYSTEM 4 - LOAD SIMULATORS										
TMB LOSSES&ERRORS (%)	7.61	5.41	4.29	3.85	3.92		19.07	6.81	5.92	5.77
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998)/qh2o cooling coil)*100										

EXPERIMENT	902A	902B	902C	902D	902E		903A	903B	903C	903D
ENERGY BALANCES (CON)										
Lsim2 LOSSES&ERRORS(%	-7.71	-6.49	-6.22	-5.82	-5.62		-5.68	-7.52	-6.27	-5.93
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998)/qh2o cooling coil)*100										
Lsim1 L&Ew/ calc stm inj	-1.90	-1.97	-1.71	-1.61	-1.80		6.96	-1.50	-1.43	-1.66
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998+Qstm)/qh2o cooling coil)*100										
SYSTEM 5 - RETURN DUCT										
USING CALCULATED STEAM l&e = (((MHtmb + MHlsim2 + MHlsim1 - MHreturn)*0.06+Qsteam+Qreturn fan)/qh2o cooling coil)*100										
LOSSES & ERRORS (%)	-172.24	-152.10	-145.22	-138.65	-136.38		-173.19	-161.42	-150.37	-144.93
R FAN energy input(mbtu	2.7709	2.8105	2.8289	2.8419	2.8204		2.5378	2.5331	2.4266	2.3973
R FAN power con (KW)	0.8121	0.8237	0.8291	0.8329	0.8266		0.7438	0.7424	0.7112	0.7026
SYSTEM 6										
AIR BALANCE										
LOSSES & ERRORS (%)	-8.33	-7.80	-7.74	-7.72	-7.99		-10.84	-8.75	-9.89	-10.00
L&E = Moutside - Mexhaust										
WATER BALANCE ********USES CALCULATED STEAM INJECTION*************										
LOSSES & ERRORS (%)	-19.41	-19.15	-19.78	-19.74	-20.70		-16.00	-18.97	-20.88	-21.68
L&E = (MdotW)stm + (MdotW)outside - (MdotW)exhuast - (Mdot) condensate										
ENERGY BALANCE *******CONSIDERS CALCALTED STEAM INJECTION********										
LOSSES & ERRORS (%)	-73.30	-70.68	-70.92	-71.47	-74.46		-64.17	-72.77	-78.16	-79.87
L&E = Qoutside+Qsfan+Qrfan-Qccoil-Qcond+Qtmb+Qlsim2+Qlsim1+Qsteam-Qexhaust										

APPENDIX D

WATER LOOP - 75% LOAD LEVEL DATA

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
LAB PRESSURE[121]	12.24	12.22	12.19	12.19		12.20	12.18	12.16	12.16	12.16
SYSTEM 1 *** INTAKE / EXHAUST ***										
RETURN AIR										
VDOT [37]	7314.00	7359.00	7693.20	7406.50		7875.90	7882.70	7906.90	7904.40	7926.60
TEMP [38]	81.46	81.49	81.71	81.12		81.72	82.08	81.53	81.22	81.12
DENSITY [339]	0.0615	0.0614	0.0612	0.0613		0.0612	0.0611	0.0611	0.0611	0.0611
RH * 100 [39]	49.7570	48.3800	48.2790	51.2270		51.5560	49.3580	48.5700	49.0020	49.4040
ENTHALPY [353]	34.78	34.42	34.53	35.01		35.57	35.16	34.45	34.37	34.43
HUMIDITY RATIO [354]	0.0140	0.0136	0.0137	0.0142		0.0146	0.0142	0.0137	0.0136	0.0137
RECIRCULATED AIR										
VDOT [42]	6165.70	6218.30	6520.10	6241.60		6713.00	6705.40	6719.10	6738.70	6753.50
TEMP [38]	81.46	81.49	81.71	81.12		81.72	82.08	81.53	81.22	81.12
DENSITY [339]	0.0615	0.0614	0.0612	0.0613		0.0612	0.0611	0.0611	0.0611	0.0611
RH * 100 [39]	49.7570	48.3800	48.2790	51.2270		51.5560	49.3580	48.5700	49.0020	49.4040
Enthalpy (EES)	34.63	34.26	34.43	34.91		35.45	35.06	34.42	34.32	34.38
MIXED AIR										
VDOT [1]	6852.30	6907.50	7245.10	6933.90		7451.80	7452.20	7467.90	7484.90	7503.80
TEMP [4]	79.48	79.57	80.13	79.34		80.21	80.72	80.75	80.54	80.42
RH * 100 [137]	45.9420	44.8880	43.9780	45.0820		46.4300	43.6120	42.2260	42.8360	43.2320
HUMIDITY RATIO [290]	0.0121	0.0118	0.0117	0.0118		0.0125	0.0120	0.0116	0.0117	0.0117
ENTHALPY [276]	32.21	31.93	31.98	31.82		32.85	32.46	32.06	32.05	31.98
OUTSIDE AIR										
VDOT([1*334]- [42*339])/[345]	957.37	981.70	1049.78	992.88		1038.11	1076.11	1080.57	1080.49	1083.67
TEMP [161]	73.40	77.89	80.54	80.42		76.24	78.08	79.02	79.64	78.99
DENSITY [345]	0.0620	0.0614	0.0609	0.0609		0.0615	0.0611	0.0610	0.0609	0.0610
RH * 100 [134]	51.3610	46.3920	40.4580	26.1320		45.7660	38.3700	36.0160	37.2460	38.0500
Humidity Ratio (EES)	0.0108	0.0114	0.0109	0.0069		0.0106	0.0095	0.0092	0.0097	0.0097
Enthalpy (EES)	29.45	31.17	31.22	26.91		29.95	28.12	29.12	29.75	29.59

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
SYSTEM 1 CONTINUED										
EXHAUST AIR										
VDOT [37-42]	1148.30	1140.70	1173.10	1164.90		1162.90	1177.30	1187.80	1165.70	1173.10
TEMP [38]	81.46	81.49	81.71	81.12		81.72	82.08	81.53	81.22	81.12
DENSITY [340]	0.0615	0.0614	0.0612	0.0613		0.0612	0.0611	0.0611	0.0611	0.0611
RH * 100 [39]	49.7570	48.3800	48.2790	51.2270		51.5560	49.3580	48.5700	49.0020	49.4040
Enthalpy (EES)	34.63	34.26	34.43	34.91		35.53	35.06	34.42	34.32	34.38
Humidity Ratio (EES)	0.0138	0.0134	0.0135	0.0141		0.0144	0.0140	0.0135	0.0135	0.0136
2) COOLING COIL										
AIRSIDE - IN										
VDOT [1]	6852.30	6907.50	7245.10	6933.90		7451.80	7452.20	7467.90	7484.90	7503.80
TEMP [4]	79.48	79.57	80.13	79.34		80.21	80.72	80.75	80.54	80.42
RH * 100 [137]	45.9420	44.8880	43.9780	45.0820		46.4300	43.6120	42.2260	42.8360	43.2320
HUMIDITY RATIO [290]	0.0119	0.0117	0.0117	0.0116		0.0123	0.0118	0.0114	0.0115	0.0116
ENTHALPY [276]	32.21	31.93	31.98	31.82		32.85	32.46	32.06	32.05	31.98
AIRSIDE - OUT										
VDOT [1]	6852.30	6907.50	7245.10	6933.90		7451.80	7452.20	7467.90	7484.90	7503.80
TEMP [122]	56.89	55.98	56.05	56.03		58.09	56.80	55.93	55.97	55.97
DENSITY [334]	0.0640	0.0640	0.0639	0.0639		0.0637	0.0638	0.0638	0.0638	0.0638
HUMIDITY RATIO [291]	0.0108	0.0105	0.0105	0.0105		0.0113	0.0107	0.0103	0.0104	0.0104
ENTHALPY [277]	25.51	24.96	24.90	24.93		26.32	25.35	24.67	24.75	24.77
ENTHALPY(h2o)	22.69	21.72	21.68	21.70		23.71	22.40	21.51	21.58	21.55
TEMP [7]	54.59	53.62	53.58	53.60		55.61	54.30	53.41	53.48	53.44
MDOT CONDENSATE	27.89	31.03	32.78	30.84		29.90	31.09	31.73	33.52	35.04
Qcondensate	0.6329	0.6741	0.7107	0.6692		0.7090	0.6966	0.6826	0.7235	0.7550
SUPPLY FAN POWER	4.11	4.12	4.22	4.13		4.31	4.33	4.32	4.34	4.36
Qsupply fan calc	12.20	12.24	12.51	12.25		12.81	12.85	12.83	12.89	12.93
WATERSIDE - IN										
VDOT [123]	61.16	55.87	45.05	31.63		61.08	60.97	52.69	39.40	32.57
TEMP [164]	46.47	44.65	42.67	40.79		46.57	44.68	42.73	40.93	38.99

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
SYSTEM 2 CONTINUED										
WATERSIDE - OUT										
VDOT [123]	61.16	55.87	45.05	31.63		61.08	60.97	52.69	39.40	32.57
TEMP [166]	51.57	50.66	50.85	51.98		52.14	50.71	50.06	50.89	51.25
Qwater {123*(166-164)	155.65	167.75	184.20	176.78		169.88	183.94	192.95	196.19	199.46
*.4998} (MBTUH)										
SYSTEM 3 *** SUPPLY DUCT ***										
IN										
AHU-1										
VDOT [1]	6852.30	6907.50	7245.10	6933.90		7451.80	7452.20	7467.90	7484.90	7503.80
TEMP [122]	56.89	55.98	56.05	56.03		58.09	56.80	55.93	55.97	55.97
DENSITY [334]	0.0640	0.0640	0.0639	0.0639		0.0637	0.0638	0.0638	0.0638	0.0638
HUMIDITY RATIO [291]	0.0108	0.0105	0.0105	0.0105		0.0113	0.0107	0.0103	0.0104	0.0104
ENTHALPY [277]	25.51	24.96	24.90	24.93		26.32	25.35	24.67	24.75	24.77
OUT										
TMB										
VDOT [27]	1781.60	1812.40	2076.60	1818.40		1945.70	1934.00	1935.50	1946.80	1954.30
TEMP [28]	62.08	61.43	60.27	61.31		62.25	61.44	60.70	60.71	60.61
DENSITY [338]	0.0634	0.0633	0.0633	0.0632		0.0631	0.0631	0.0631	0.0631	0.0631
RH * 100 [29]	70.5830	70.2370	72.9800	70.4340		72.0650	70.8760	70.2510	70.4620	70.7310
Enthalpy (EES)	25.85	25.41	25.11	25.39		26.24	25.55	25.00	25.04	25.02
Humidity Ratio (EES)	0.0101	0.0098	0.0098	0.0098		0.0104	0.0099	0.0096	0.0096	0.0096
LSIM-2										
VDOT [113]	1869.40	1868.80	1855.80	1883.00		2045.80	2034.40	2041.00	2041.80	2047.20
TEMP [112]	59.88	59.26	59.48	59.10		60.90	60.33	59.65	59.60	59.51
DENSITY [344]	0.0636	0.0636	0.0634	0.0634		0.0633	0.0632	0.0632	0.0632	0.0632
RH * 100 [114]	76.5340	75.6850	74.6590	76.2430		76.4840	74.5290	73.6050	74.1080	74.2730
Enthalpy (EES)	25.34	24.85	24.87	24.85		26.04	25.40	24.84	24.88	24.86
Humidity Ratio (EES)	0.0101	0.0098	0.0097	0.0098		0.0105	0.0100	0.0097	0.0097	0.0097

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
SYSTEM 3 CONTINUED										
LSIM-1										
VDOT [108]	2293.60	2302.70	2303.90	2299.60		2489.80	2493.60	2485.70	2482.60	2489.90
TEMP [107]	61.71	61.18	61.50	60.82		62.68	62.14	61.40	61.31	61.21
DENSITY [342]	0.0634	0.0633	0.0632	0.0632		0.0631	0.0630	0.0630	0.0630	0.0630
RH * 100 [109]	71.1510	70.0510	68.6590	70.7300		71.0700	68.7950	68.0760	68.5380	68.7510
Enthalpy (EES)	25.70	25.22	25.23	25.13		26.35	25.66	25.10	25.11	25.09
Humidity Ratio (EES)	0.0100	0.0097	0.0096	0.0097		0.0104	0.0099	0.0096	0.0096	0.0096
SYSTEM 4 *** ZONES ***										
AIRSIDE										
IN => SEE 3) OUT										
OUT										
TMB										
VDOT [27]	1781.60	1812.40	2076.60	1818.40		1945.70	1934.00	1935.50	1946.80	1954.30
TEMP [34]	78.67	78.88	77.23	78.37		78.42	78.67	78.45	78.25	78.20
RH * 100 [33]	38.3850	37.3890	39.1300	37.2500		39.3390	37.3780	36.2590	36.5600	36.6370
Enthalpy (EES)	29.43	29.29	28.82	28.98		29.58	29.20	28.77	28.74	28.73
LSIM-2										
VDOT [113]	1869.40	1868.80	1855.80	1883.00		2045.80	2034.40	2041.00	2041.80	2047.20
TEMP [115]	79.37	78.91	79.34	78.63		79.04	78.65	78.04	77.82	77.79
RH * 100 [116]	45.7100	44.9100	43.9800	45.2540		47.3380	45.7190	45.0900	45.4810	45.5650
Enthalpy (EES)	31.94	31.43	31.48	31.37		32.23	31.53	30.97	30.93	30.94
LSIM-1										
VDOT [108]	2293.60	2302.70	2303.90	2299.60		2489.80	2493.60	2485.70	2482.60	2489.90
TEMP [110]	79.36	78.72	79.28	78.79		79.30	78.97	78.30	78.12	78.01
RH * 100 [111]	48.9280	46.1130	46.3960	55.4580		55.7050	53.8090	53.9800	54.2470	55.1500
Enthalpy (EES)	32.86	31.64	32.13	34.38		34.83	34.06	33.62	33.56	33.74
Humidity Ratio (EES)	0.01	0.01	0.01	0.01		0.01	0.01	0.01	0.01	0.01

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
SYSTEM 4 CONTINUED										
WATERSIDE										
IN										
TMB										
BRANCH VDOT [50]	12.26	12.28	12.17	12.26		12.25	12.27	12.26	12.27	12.25
% FLOW TO COIL[348]	26.94	27.25	23.74	27.22		26.35	25.95	25.45	25.45	25.29
COIL FLOW RATE	3.30	3.35	2.89	3.34		3.23	3.18	3.12	3.12	3.10
TEMP [145]	110.74	110.45	110.33	110.15		110.69	110.61	110.48	110.39	110.32
LSIM-2										
BRANCH VDOT [54]	12.88	12.88	12.90	12.99		12.88	12.89	12.87	12.88	12.90
% FLOW TO COIL [318]	22.20	22.12	22.61	22.17		22.21	21.75	21.32	21.24	21.28
COIL FLOW RATE	2.86	2.85	2.92	2.88		2.86	2.80	2.74	2.74	2.75
TEMP [175]	111.22	110.95	110.82	110.64		111.14	111.06	110.91	110.82	110.74
LSIM-1										
BRANCH VDOT [52]	11.33	11.32	11.35	11.33		11.34	11.35	11.33	11.34	11.34
% FLOW TO COIL [321]	24.57	24.45	24.90	24.31		24.51	24.06	23.69	23.61	23.53
COIL FLOW RATE	2.78	2.77	2.83	2.76		2.78	2.73	2.68	2.68	2.67
TEMP [152]	110.90	110.63	110.51	110.32		110.81	110.76	110.62	110.52	110.44
OUT										
TMB										
TEMP [146]	90.21	90.04	86.82	89.77		89.51	89.27	88.71	88.58	88.42
LSIM-2										
TEMP [174]	87.53	87.10	87.51	86.83		87.20	86.78	86.12	85.94	85.89
LSIM-1										
TEMP [153]	86.47	86.10	86.45	85.62		86.20	85.87	85.26	85.10	84.93

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
SYSTEM 5 *** RETURN DUCT ***										
IN => SEE 4) AIRSIDE OUT										
OUT										
RETURN AIR										
VDOT [37]	7314.00	7359.00	7693.20	7406.50		7875.90	7882.70	7906.90	7904.40	7926.60
TEMP [38]	81.46	81.49	81.71	81.12		81.72	82.08	81.53	81.22	81.12
DENSITY [339]	0.0615	0.0614	0.0612	0.0613		0.0612	0.0611	0.0611	0.0611	0.0611
ENTHALPY [353]	34.78	34.42	34.53	35.01		35.57	35.16	34.45	34.37	34.43
HUMIDITY RATIO [354]	0.0140	0.0136	0.0137	0.0142		0.0146	0.0142	0.0137	0.0136	0.0137
AIR MASS BALANCES										
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY AIR FLOW ACROSS THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %										
SYSTEM 1 INTAKE/EXHAUST *****FORCED BALANCE **********										
IN										
RETURN AIR										
VDOT [37]	7314.00	7359.00	7693.20	7406.50		7875.90	7882.70	7906.90	7904.40	7926.60
DENSITY [339]	0.0615	0.0614	0.0612	0.0613		0.0612	0.0611	0.0611	0.0611	0.0611
Mdot RETURN air (lb/hr)	26988.66	27110.56	28249.43	27241.11		28920.30	28897.98	28986.70	28977.53	29058.92
OUTSIDE AIR										
DENSITY [345]	0.0620	0.0614	0.0609	0.0609		0.0615	0.0611	0.0610	0.0609	0.0610
VDOT([1*334]-	957.37	981.70	1049.78	992.88		1038.11	1076.11	1080.57	1080.49	1083.67
[42*339])/[345]										
Mdot OUTDOOR air (lb/hr)	3561.4	3616.6	3835.9	3628.0		3830.6	3945.0	3954.9	3948.1	3966.2
OUT										
MIXED AIR										
VDOT [1]	6852.30	6907.50	7245.10	6933.90		7451.80	7452.20	7467.90	7484.90	7503.80
DENSITY [334]	0.06	0.06	0.06	0.06		0.06	0.06	0.06	0.06	0.06
Mdot MIXED air(lb/hr)	26312.8	26524.8	27777.7	26584.6		28480.8	28527.0	28587.1	28652.2	28724.5

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
AIR BALANCES CONTINUED										
EXHAUST AIR										
VDOT [37-42]	1148.30	1140.70	1173.10	1164.90		1162.90	1177.30	1187.80	1165.70	1173.10
DENSITY [339]	0.0615	0.0614	0.0612	0.0613		0.0612	0.0611	0.0611	0.0611	0.0611
Mdot EXHAUST air (lb/hr)	4237.2	4202.3	4307.6	4284.5		4270.2	4316.0	4354.5	4273.5	4300.6
SYSTEM 2 AHU-1 ****** FORCED BALANCE ******										
IN										
VDOT [1]	6852.30	6907.50	7245.10	6933.90		7451.80	7452.20	7467.90	7484.90	7503.80
DENSITY [334]	0.0640	0.0640	0.0639	0.0639		0.0637	0.0638	0.0638	0.0638	0.0638
OUT										
VDOT [1]	6852.30	6907.50	7245.10	6933.90		7451.80	7452.20	7467.90	7484.90	7503.80
DENSITY [334]	0.0640	0.0640	0.0639	0.0639		0.0637	0.0638	0.0638	0.0638	0.0638
SYSTEM 3 SUPPLY DUCT										
IN										
VDOT [1]	6852.30	6907.50	7245.10	6933.90		7451.80	7452.20	7467.90	7484.90	7503.80
DENSITY [334]	0.0640	0.0640	0.0639	0.0639		0.0637	0.0638	0.0638	0.0638	0.0638
Mdot(lb/hr)	26312.8	26524.8	27777.7	26584.6		28480.8	28527.0	28587.1	28652.2	28724.5
OUT										
TMB										
VDOT [27]	1781.60	1812.40	2076.60	1818.40		1945.70	1934.00	1935.50	1946.80	1954.30
DENSITY [338]	0.0634	0.0633	0.0633	0.0632		0.0631	0.0631	0.0631	0.0631	0.0631
Mdot(lb/hr)	6777.2	6883.5	7886.9	6895.4		7366.4	7322.1	7327.8	7370.6	7399.0
LSIM-2										
VDOT [113]	1869.40	1868.80	1855.80	1883.00		2045.80	2034.40	2041.00	2041.80	2047.20
DENSITY [344]	0.0636	0.0636	0.0634	0.0634		0.0633	0.0632	0.0632	0.0632	0.0632
Mdot(lb/hr)	7133.6	7131.3	7059.5	7162.9		7769.9	7714.4	7739.5	7742.5	7763.0

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
AIR BALANCES CONTINUED										
SYSTEM 3 CONTINUED										
LSIM-1										
VDOT [108]	2293.60	2302.70	2303.90	2299.60		2489.80	2493.60	2485.70	2482.60	2489.90
DENSITY [342]	0.0634	0.0633	0.0632	0.0632		0.0631	0.0630	0.0630	0.0630	0.0630
Mdot(lb/hr)	8724.9	8745.7	8736.4	8720.1		9426.4	9425.8	9395.9	9384.2	9411.8
LOSSES&ERRORS(LB/HR)	3677.14	3764.31	4094.93	3806.18		3918.03	4064.64	4123.90	4154.88	4150.76
(IN-OUT)										
LOSSES %	13.97	14.19	14.74	14.32		13.76	14.25	14.43	14.50	14.45
ZONE 4 LOAD SIMULATORS *****BALANCES BY DEFAULT******										
TMB IN AND OUT										
VDOT [27]	1781.60	1812.40	2076.60	1818.40		1945.70	1934.00	1935.50	1946.80	1954.30
DENSITY [338]	0.0634	0.0633	0.0633	0.0632		0.0631	0.0631	0.0631	0.0631	0.0631
LSIM-2 IN AND OUT										
VDOT [113]	1869.40	1868.80	1855.80	1883.00		2045.80	2034.40	2041.00	2041.80	2047.20
DENSITY [344]	0.0636	0.0636	0.0634	0.0634		0.0633	0.0632	0.0632	0.0632	0.0632
LSIM-1 IN AND OUT										
VDOT [108]	2293.60	2302.70	2303.90	2299.60		2489.80	2493.60	2485.70	2482.60	2489.90
DENSITY [342]	0.0634	0.0633	0.0632	0.0632		0.0631	0.0630	0.0630	0.0630	0.0630
SYSTEM 5 RETURN DUCT										
IN										
TMB OUT										
VDOT [27]	1781.60	1812.40	2076.60	1818.40		1945.70	1934.00	1935.50	1946.80	1954.30
DENSITY [338]	0.0634	0.0633	0.0633	0.0632		0.0631	0.0631	0.0631	0.0631	0.0631
LSIM-2 OUT										
VDOT [113]	1869.40	1868.80	1855.80	1883.00		2045.80	2034.40	2041.00	2041.80	2047.20
DENSITY [344]	0.0636	0.0636	0.0634	0.0634		0.0633	0.0632	0.0632	0.0632	0.0632

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
AIR BALANCES CONTINUED										
SYSTEM 5 CONTINUED										
LSIM-1 OUT										
VDOT [108]	2293.60	2302.70	2303.90	2299.60		2489.80	2493.60	2485.70	2482.60	2489.90
DENSITY [342]	0.0634	0.0633	0.0632	0.0632		0.0631	0.0630	0.0630	0.0630	0.0630
OUT										
RETURN AIR										
VDOT [37]	7314.00	7359.00	7693.20	7406.50		7875.90	7882.70	7906.90	7904.40	7926.60
DENSITY [339]	0.0615	0.0614	0.0612	0.0613		0.0612	0.0611	0.0611	0.0611	0.0611
LOSSES&ERRORS(LB/HR)	-4352.97	-4350.07	-4566.65	-4462.72		-4357.55	-4435.60	-4523.47	-4480.21	-4485.13
(IN-OUT)										
LOSES %	-16.54	-16.40	-16.44	-16.79		-15.30	-15.55	-15.82	-15.64	-15.61
WATER BALANCES										
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY WATER FLOW ACROSS THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %										
SYSTEM 1										
ERRORSandLOSSES(lb/hr)	40.21	40.13	44.19	38.75		45.12	44.86	41.89	39.76	42.84
E&L=(WVRHOE)ret*60+(WVRHOE)out*60-(WVRHOE)ex*60-(WVRHOE)mix*60										
ERRORS %	12.65	12.80	13.55	12.38		12.67	13.10	12.60	11.87	12.78
ZONE 2 ******BALANCES BY DEFAULT*******										
Mdot COND (LB/HR)	27.89	31.03	32.78	30.84		29.90	31.09	31.73	33.52	35.04
Mdot CONDENSATE=(WVRHOE)mix*60-(VWRHOE)supply*6										
SYSTEM 3										
E&L (lb/hr)	56.95	56.03	60.82	56.28		65.56	62.24	60.19	60.88	61.11
E&L = (MdotWin-Sum(MdotWout))										
ERRORS %	20.02	20.16	20.91	20.20		20.39	20.37	20.38	20.51	20.52

EXPERIMENT	904A	904B	904C	904D		905A	905B	905C	905D	905E
WATER BALANCES (CON)										
SYSTEM 4										
Steam Injection Calculated	22.60	17.05	20.44	38.72		37.99	36.85	37.30	37.26	39.06
STEAM PRESSURE [131]	10.98	10.98	11.13	10.52		10.42	10.82	10.71	10.88	10.76
Steam Enthalpy (EES)	1151.95	1151.95	1151.89	1152.14		1152.18	1152.02	1152.06	1151.99	1152.04
SYSTEM 5										
Using CALCULATED STEAM	-127.75	-129.70	-136.56	-125.78		-128.26	-130.21	-124.70	-120.89	-122.29
ERRORS%	-44.91	-46.66	-46.95	-45.15		-39.89	-42.62	-42.23	-40.72	-41.05
ENERGY BALANCES										
NOTE - ALL ERRORS AND LOSS TERM HAVE BEEN DIVIDED BY Qh2o OF THE COILING COIL AND THEN MULTIPLIED BY 100 TO GET %										
SYSTEM 1 - intake/exhaust										
LOSSES & ERRORS (%)	31.66	32.75	31.83	31.49		33.03	27.08	24.60	24.73	25.72
I&e= ((MHex-MHex-MHrec)/qh2o cooling coil)*100										
SYSTEM 2 - COOLING COIL										
LOSSES & ERRORS (%)	20.83	17.18	13.19	10.27		16.56	16.82	15.80	12.77	9.89
I&e=(((Mair(Hair,in-Hair,o)*0.06+MCp(Ti-To)h2o*0.4998-Mair(Wi-Wo)air*Hh2o*0.06)+QFAN)/qh2o cooling coil)*100										
SYSTEM 3 - SUPPLY DUCT										
LOSSES & ERRORS (%)	58.43	53.23	52.95	51.20		62.13	53.46	48.63	49.11	48.80
I&e= (((MHair,i -MHtmb,i-MHlsim2,i-MHlsim1,i)*0.06)/qh2o cooling coil)*100										
SYSTEM 4 - LOAD SIMULATORS										
TMB LOSSES&ERRORS (%)	6.19	4.41	2.57	5.22		5.61	3.92	3.29	3.45	3.22
I&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998)/qh2o cooling coil)*100										

EXPERIMENT	902A	902A	902A	902A		902A	902A	902A	902A	902A
ENERGY BALANCES (CON)										
Lsim2 LOSSES&ERRORS(%	-8.50	-7.74	-6.89	-7.05		-8.17	-7.21	-6.95	-6.53	-6.55
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998)/qh2o cooling coil)*100										
Lsim1 L&Ew/ calc stm inj	-1.57	-1.56	-1.51	-1.16	##	-1.20	-1.49	-1.61	-1.21	-1.18
l&e=(((M(Hair,i-Hair,o)*0.06)+(MCp(Ti-To)h2o*0.4998+Qstm)/qh2o cooling coil)*100										
SYSTEM 5 - RETURN DUCT										
USING CALCULATED STEAM l&e = (((MHtmb + MHlsim2 + MHlsim1 - MHreturn)*0.06+Qsteam+Qreturn fan)/qh2o cooling coil)*100										
LOSSES & ERRORS (%)	-124.83	-123.10	-117.70	-101.91		-107.73	-103.55	-95.39	-92.64	-90.20
R FAN energy input(mbtu	4.4762	4.4779	4.8362	4.5560		5.1194	5.0979	5.1183	5.1173	5.1473
R FAN power con (KW)	1.3119	1.3124	1.4174	1.3353		1.5004	1.4941	1.5001	1.4998	1.5086
SYSTEM 6										
AIR BALANCE										
LOSSES & ERRORS (%)	-2.57	-2.21	-1.70	-2.47		-1.54	-1.30	-1.40	-1.14	-1.16
L&E = Moutside - Mexhaust										
WATER BALANCE ********USES CALCULATED STEAM INJECTION*************										
LOSSES & ERRORS (%)	-8.00	-9.43	-8.93	-8.81		-3.65	-5.13	-5.21	-4.77	-4.78
L&E = (MdotW)stm + (MdotW)outside - (MdotW)exhuast - (Mdot) condensate										
ENERGY BALANCE *******CONSIDERS CALCALTED STEAM INJECTION********										
LOSSES & ERRORS (%)	-34.51	-36.53	-38.34	-37.17		-25.52	-34.07	-33.90	-32.20	-32.87
L&E = Qoutside+Qsfan+Qrfan-Qccoil-Qcond+Qtmb+Qlsim2+Qlsim1+Qsteam-Qexhaust										

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