# ENGINEERING EXPERIMENT STATION

## COLLEGE OF ENGINEERING

DEVELOPMENT OF COMPUTER CONTROL ROUTINES
FOR A LARGE CHILLED WATER PLANT

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# ABSTRACT

The primary goal of this project is to identify computer control strategies to reduce the cost of electricity consumed by the chilled water plant of a large commercial facility. A computer simulation tool was constructed based on TRNSYS, a transient simulation program developed at the University of Wisconsin Solar Energy Lab. Several new components were developed for the simulation to model the plant equipment and controllers.

The facility served by the chilled water plant consists of 1.4 million square feet of floor space with functions divided between offices, manufacturing, and warehouse. Chilled water is produced in a separate plant by four 1250-Ton centrifugal chillers with electric motors. A unique feature of the chilled water plant is five 100,000 gallon storage tanks for chilled water. These tanks are used to reduce the chiller load on summer days to reduce the peak electric demand. Two other areas where energy conservation strategies can be applied are variable-speed pumps and the cooling tower which has six cells and two-speed fans in each cell. All of the control strategies studied can be implemented on a minicomputer system designed for control and performance monitoring.

Detailed performance data from the actual system was studied for four separate time periods from April to July, 1983. Each data tape contained 218 data points at 15-minute intervals for about two and one-half days. This data was used to compare with the computer models, first on a component level and then a system level.

The simulation task was separated into two parts, plant and buildings. The buildings and air-handlers were simulated to define the chilled water load as a function of time. In this manner, the expensive building simulations were only required once. The simulated chilled water load was compared with measured loads for a mild July day. Maximum and minimum loads compared well, but deviation was significant at morning start-up and during the second shift. Much of the deviation can be explained by the discrepancy between scheduled internal loads in the simulation and measured electric loads. Part of the difference is also likely due to incorrect modeling of the zone heat transfer and equipment performance.

For the plant simulation, comparison between simulated and measured performance was quite good. All of the components with some empirical bases were calibrated with the measured data. Many of the components were totally analytical and required no calibration. The simulated plant electric demand was then compared with measurements for a two-day period in July. The average difference was only 1.1%, while the RMS error for the 15-minute points was 158 kW, on the order of 10%.

In the process of developing control strategies, a subsystem was identified for which control strategies could be explicitly defined. The subsystem includes the chillers, cooling tower, primary pumps, and condenser pumps. Optimum control strategies for cooling tower fan speed, condenser pump flow rate, and number of chiller were defined. When simulated for July, these strategies resulted in a combined savings of $495 or about 1.4% of the plant electric bill. The annual impact was a savings of $4,440 or about 1.6% of the plant portion of the electric bill.

For the storage tanks, the control variable studied was the start-time for mode 2 which is the mode where the storage tanks are used to reduce the chiller loading to limit the peak demand. For July, the best start-time was 8:00 a.m., but the annual simulation showed that this was not necessarily the best time for the other summer months. The annual savings was $5,449 or 2.0% of the plant bill. The reduction in billing demand was 161 kW, about half of the demand-limiting potential of storage.

Subcooling of the storage tanks at night to increase the daytime cooling capacity was studied for July. Even a reduction of only 1 F caused an increase in the utility bill. Apparently, the increased chiller operating costs outweighed the reduction in peak demand.

The final control strategy studied was the use of automatic reset of the chiller setpoint to maintain the chilled water supply temperature closer to the desired value. Reset resulted in an annual savings of $4,353 or 1.6% of the plant electric bill.

The combination of all the strategies but subcooling reduced the utility bill by $14,242 or 5.2% of the plant electric bill. Consumption was reduced 252.2 MWh and peak demand by 197 kW.

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## NOMENCLATURE

| | |
|---|---|
| $c_l$ | Specific heat of liquid water |
| E | Effectiveness |
| $\eta$ | Efficiency |
| h | Enthalpy of a pure substance |
| $h_l$ | Enthalpy of liquid water at the adiabatic saturation temperature |
| $h_m$ | Enthalpy of an air-water vapor mixture per mass of dry air |
| $h_s$ | Sigma energy of an air-water vapor mixture per mass of dry air |
| $h_{s@li}$ | Sigma energy evaluated at the water inlet temperature |
| KWR | Chiller kilowatt ratio, the actual electric demand divided by the design electric demand |
| $\dot{m}$ | Mass flow rate |
| PLR | Chiller part-load ratio, the actual load divided by the design load |
| $\dot{Q}_c$ | Total site cooling load |
| R | Tower capacity factor |
| Range | Temperature difference, usually referring to water |
| t | Temperature |

$t^*$ Adiabatic saturation temperature or thermodynamic wet-bulb temperature

TCHWR Chilled water return temperature

TCHWS Chilled water supply temperature

TCWR Condenser water return temperature, also the water temperature entering the cooling tower

TCWS Condenser water supply temperature, also the water temperature leaving the cooling tower

TWB Ambient wet-bulb temperature

w Humidity ratio, the ratio of the mass of water vapor in an air-vapor mixture to the mass of dry air

WAR Reference water-air ratio

Subscripts

a dry air

i inlet

l liquid water

o outlet

v water vapor

# 1. SCOPE OF PROJECT

Use of computers for monitoring and control of HVAC equipment is a relatively new field, partly in response to the significant increases in fuel prices which started a decade ago. At that time, though, computer technology was still quite expensive. Building energy conservation efforts were directed more at architectural elements such as insulation and glazing. It was some time before heating, ventilating and air-conditioning (HVAC) equipment and controls manufacturers responded to the need for reduction in fuel use. Continuing advances in the controls field have now led to the use of computers for HVAC applications, primarily for large facilities where the additional costs can be offset by the reduced fuel bills. This project deals with an actual facility which has a minicomputer system designed to monitor and control many of the HVAC control functions.

## 1.1 Project Goals

The primary goal of this project is to identify computer control strategies to reduce the cost of electricity consumed by the chilled water plant. In order to study the many different options and to assess the long-range impact on energy bills, a computer simulation tool was developed based on TRNSYS (1), a component-based transient simulation program developed at the University of Wisconsin Solar Energy Lab. Since TRNSYS has mainly been used for solar system analysis, several new components were developed to model the plant equipment and control functions.

A unique feature of this project is that performance data was available on the complete system and on individual components. Therefore, each modeled component was compared with the actual data and where applicable, the models were calibrated to improve the overall simulation accuracy.

## 1.2 The System and Facility

The facility is located in Charlotte, North Carolina on a site comprising about 700 acres. Ten interconnected buildings with a total of 1.4 million square feet of floor space are served by the central chilled water plant. The site is multi-function, divided between offices, manufacturing, and warehouse. Energy efficient practices have been used throughout the site and include high-efficiency lighting, variable volume fans and enthalpy economizers for the air-handling units.

The chilled water system is designed to meet a load of 6000 Tons. Figure 1.1 shows the major system components and the interconnection as modeled in the TRNSYS simulation. Chilled water is provided by four 1250-Ton centrifugal chillers with electric motors. In addition, another 1250-Ton chiller with a steam turbine drive was installed for periods of electrical shortage or outage.

A unique component of the chilled water system is five 100,000 gallon storage tanks for chilled water. Water chilled and stored at night can be used during the day to reduce the peak electrical demand. Because the amount of stored energy is limited, control can have a significant impact on the demand reduction.

Another major component in the plant is the cooling tower. Heat from the chiller condensers is rejected to the ambient at the cooling tower and thus the cooling tower operation affects the condenser temperature and ultimately, the chiller electric use. The tower has six individual cells which are operated in a one-to-one correspondence with chillers. Each cell has a two-speed fan which can be controlled by computer.

The other major chilled water system components are the pumps. Both the condenser pumps (6) and secondary pumps (4) have variable-speed motors on half of the pumps, the other half being fixed-speed. Though the secondary pumps are controlled by sensors in the buildings, the condenser pumps can be controlled by computer. The primary pumps are fixed-speed, but their flow can be adjusted by controlling an automatic valve on each chiller evaporator.

There are five possible modes of chilled water system operation. The mode numbers assigned to each mode are consistent with those used in the actual system. The most common mode is designated mode 1 and is illustrated in Figure 1.2. The bold lines indicate the flow path of the chilled water in each mode. In this mode, the storage tanks are not used and the site load is met entirely by the chillers. Normally, primary pump flow exceeds secondary pump flow and some of the water leaving the chiller bypasses the site and mixes with the warmer water returning from the site. Chiller flow is typically constant and the temperature difference across the evaporator changes in response to the site load.

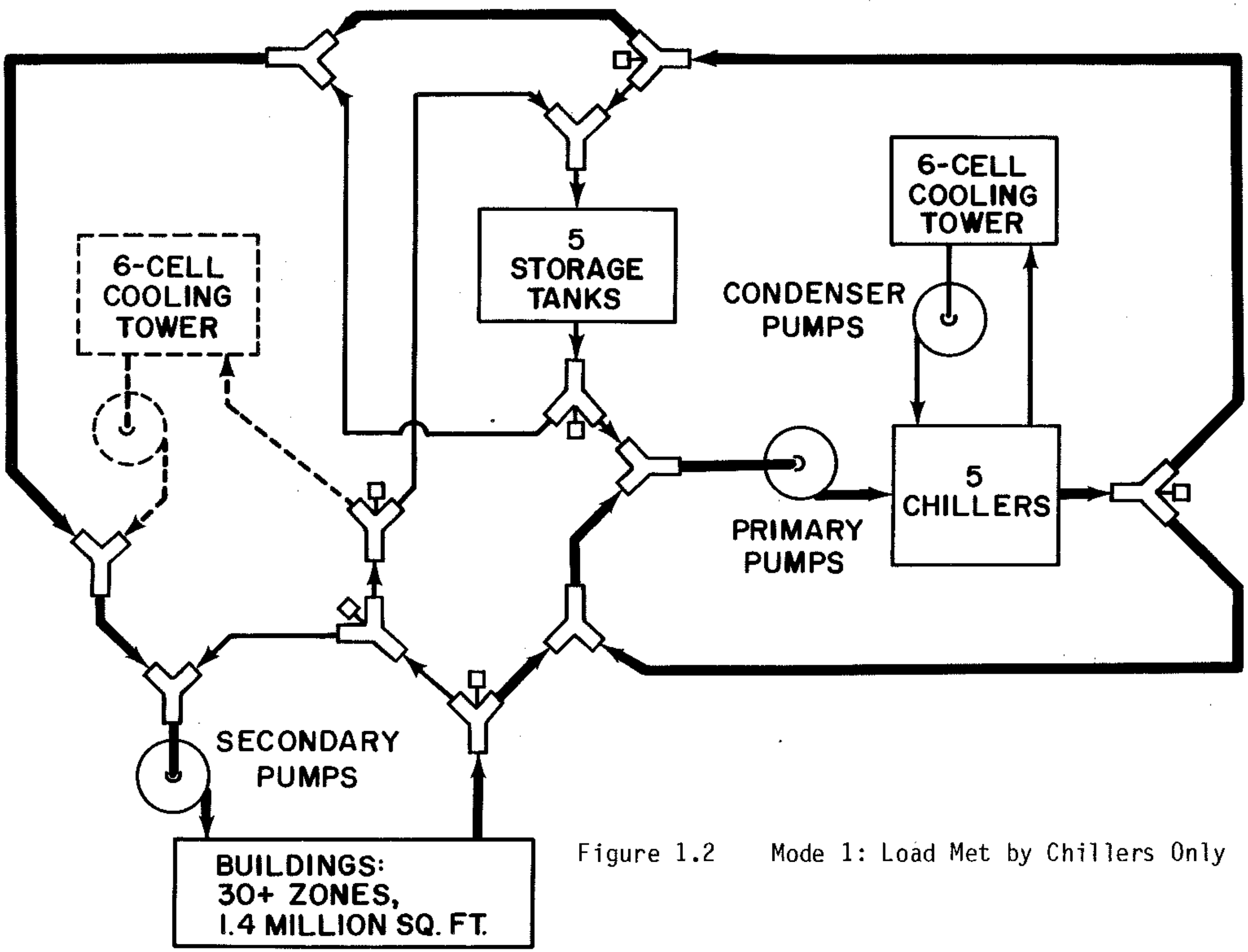



Figure 1.2 Mode 1: Load Met by Chillers Only

Mode 2 is shown in Figure 1.3. In this mode, the storage tanks are used in conjunction with the chillers to meet the load. Storage flow is controlled indirectly by controlling the primary pump flow through use of the evaporator valves.

The complimentary mode to mode 2 is mode 7, shown in Figure 1.4. Here, the chillers are used to meet the site load and to supply chilled water to the tanks. As in mode 2, the storage flow is controlled via the evaporator flow valves.

Mode 3, shown in Figure 1.5, is like mode 2 except that the chillers are turned off and storage meets the entire load. This mode can occur when the site load and water flow rate are below the limit on storage, typically during the colder part of the year. At this time though, electric demand is not near peak and the only benefit of storage is the potentially higher chiller efficiency resulting from equipment operation at night, rather than day.

Mode 5 is shown in Figure 1.6. This cycle is called a strainer cycle or water economizer. In this mode, chilled water from the cooling tower is filtered and sent directly to the site, bypassing the need for the chillers. This mode can occur in cold weather when the tower alone can produce the desired chilled water temperatures. However, fouling in the chilled water loop has resulted in this mode being deactivated. Because of this and the small amount of chilled water load occurring at these times, this mode is not studied.

Modes 4 and 6 are missing because they are modes which can only operate if there is no site load. Because of computer cooling loads, there is a site load year round, 24 hours a day.

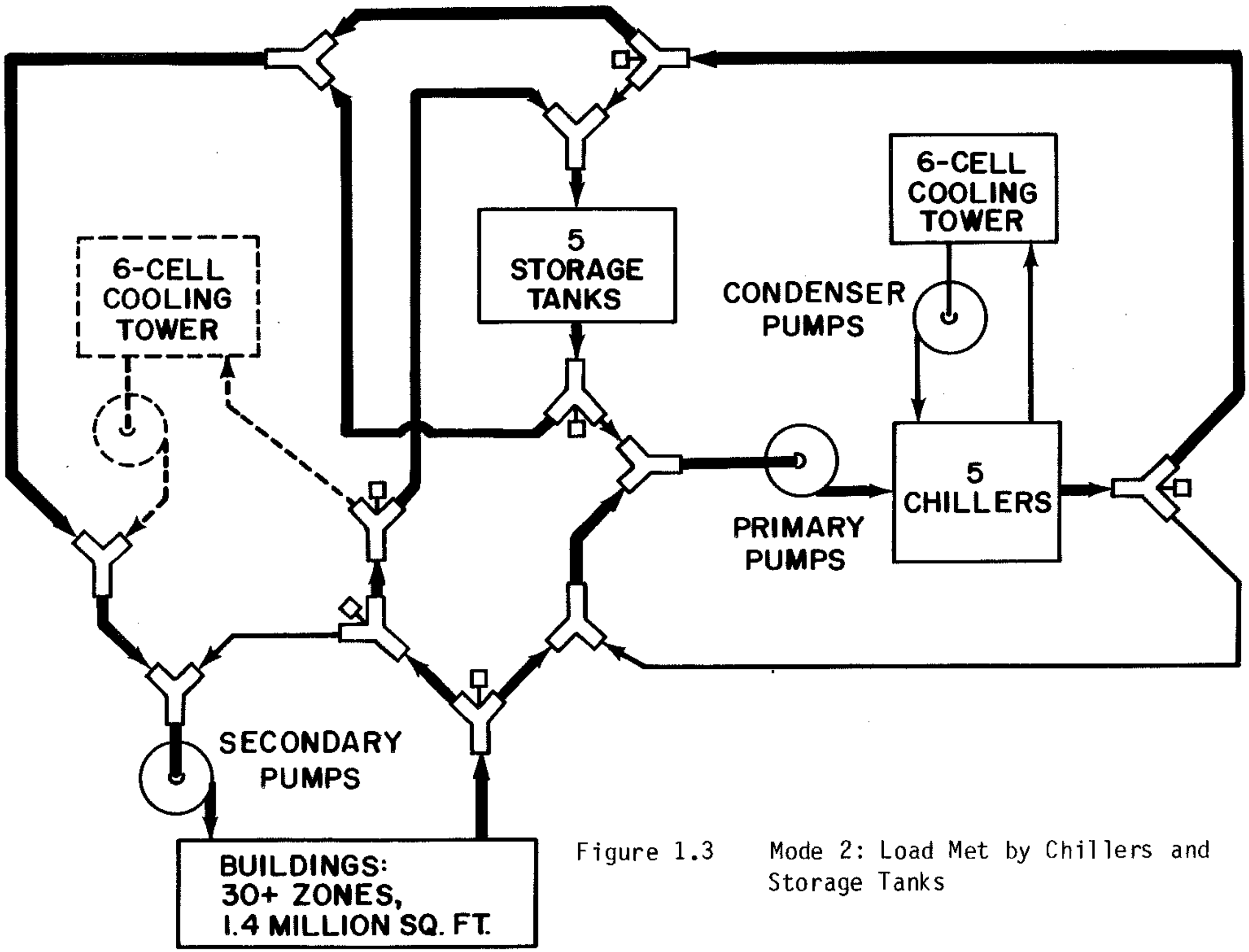



Figure 1.3 Mode 2: Load Met by Chillers and Storage Tanks

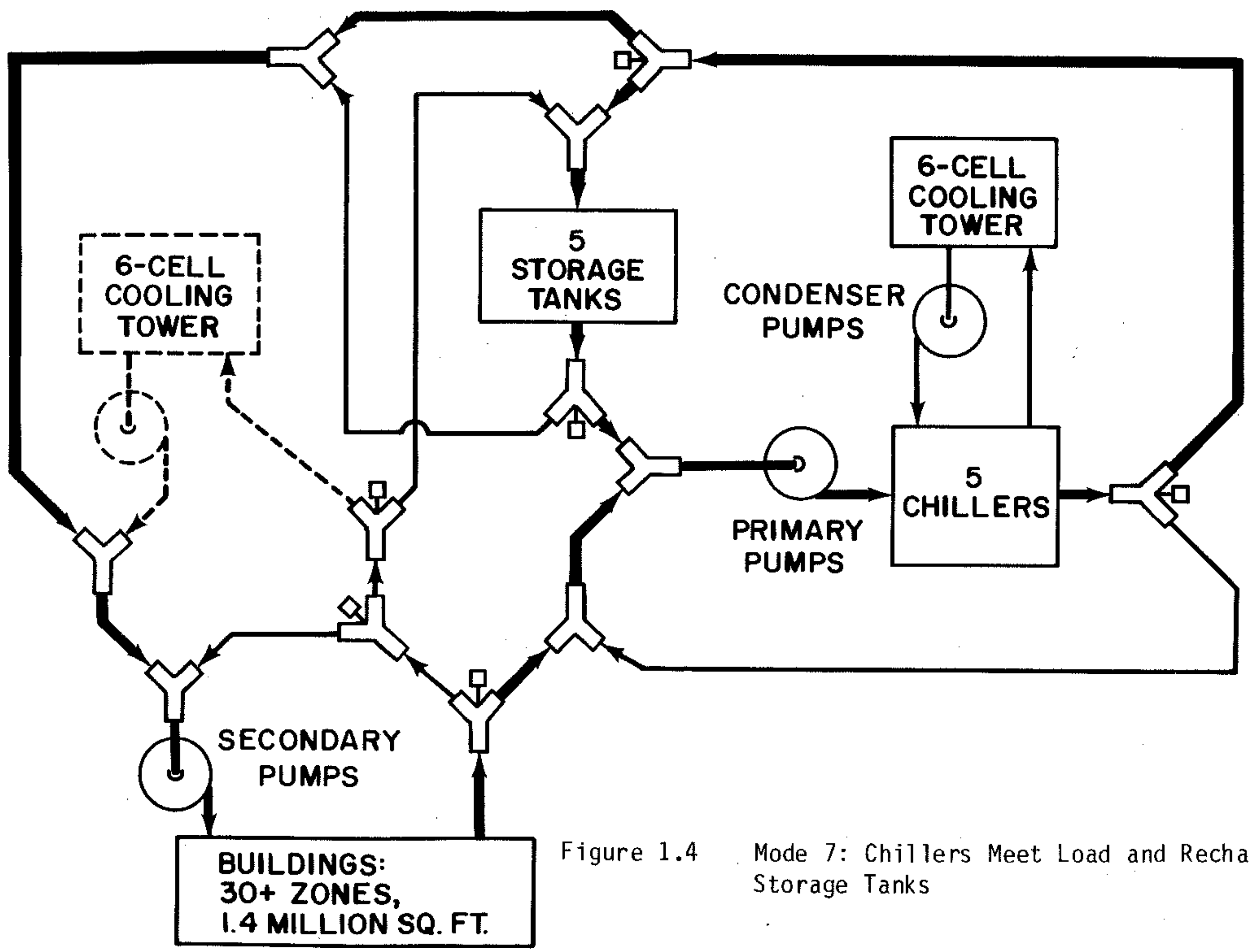



Figure 1.4 Mode 7: Chillers Meet Load and Recharge Storage Tanks

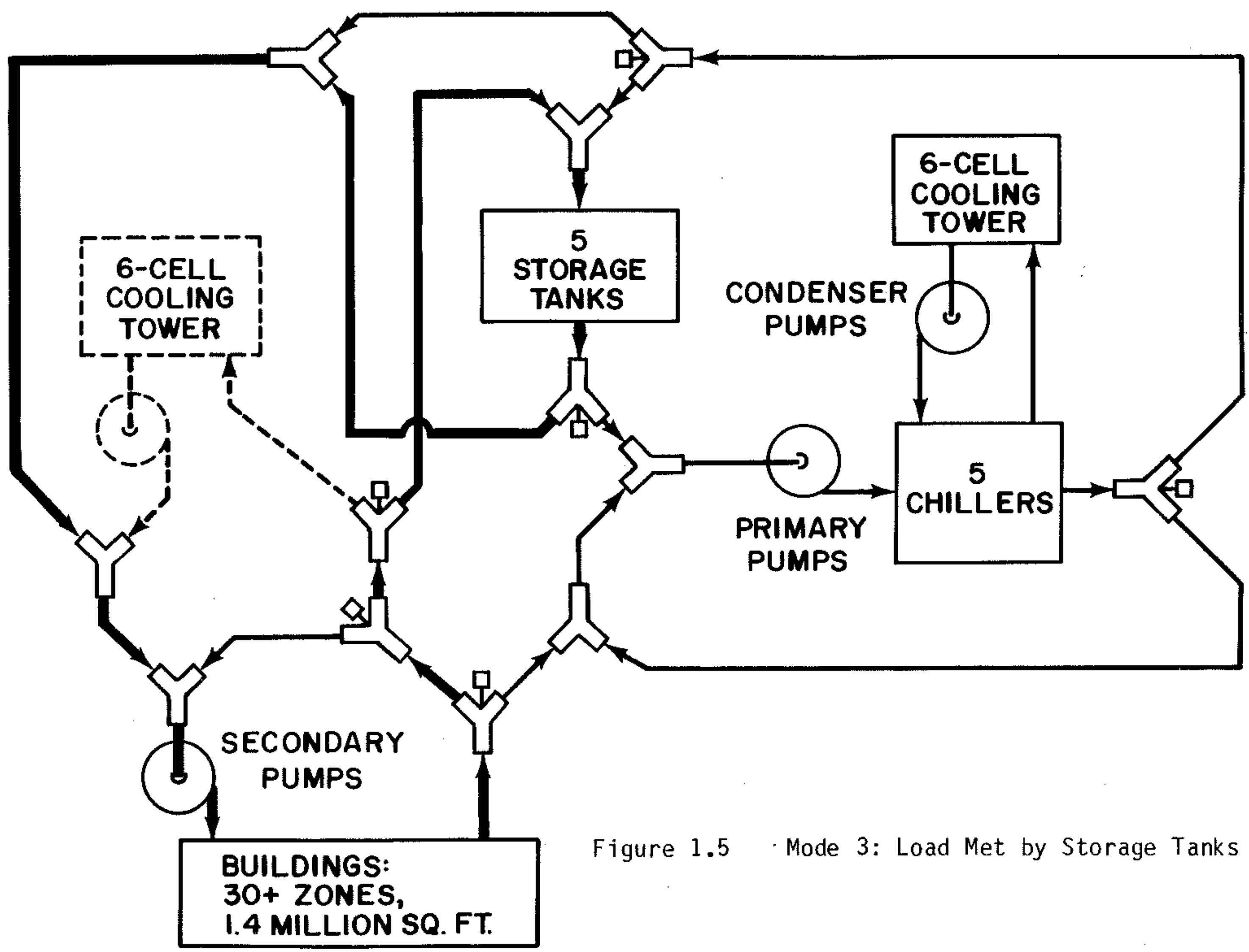



Figure 1.5 Mode 3: Load Met by Storage Tanks

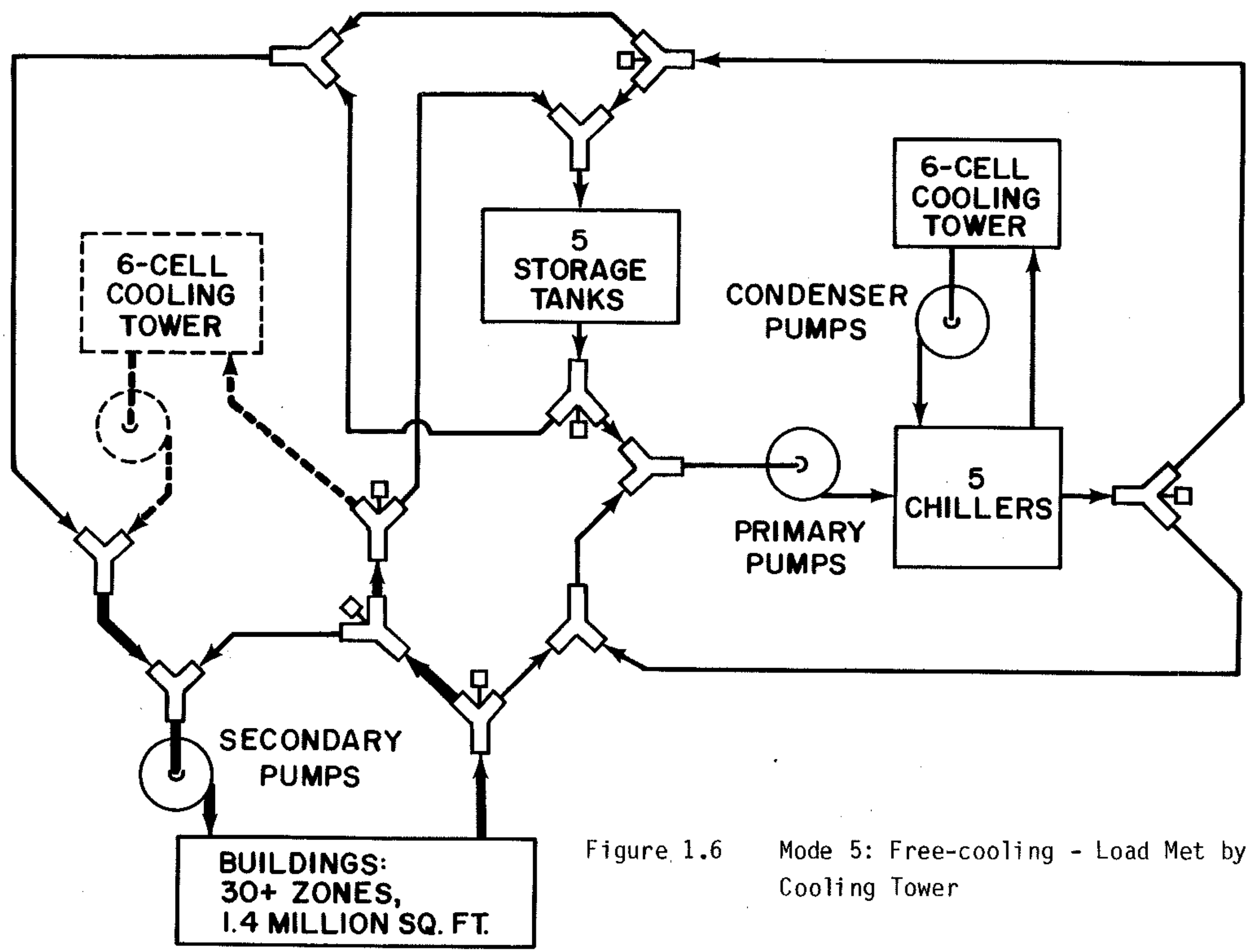



Figure 1.6 Mode 5: Free-cooling - Load Met by Cooling Tower

## 1.3 Potential for Reduction of Energy Costs

Much of the significance of energy conservation strategies is dictated by the reduction in operating costs. These savings are highly dependent on the utility rate structure for the fuel or fuels involved. In this case, only electricity is required for the chilled water plant. The rate structure for the local electric utility includes both a consumption and demand charge, but no time-of-day pricing. The presence of time-of-day pricing would add to the benefit of the storage tanks.

Regardless, the potential for reduction of electric bills still exists through demand reduction and reduction in usage. Demand reduction can be especially effective because the billing demand is based on the maximum monthly demand (30-minute demand period) for the previous 12 months.

### 1.3.1 Peak Demand Limiting

The primary purpose of the storage tanks was to reduce the peak chiller load and thus, the site electrical demand. There are two limits to the demand limiting capability of the storage tanks.

One limit is the total storage capacity. The actual usable volume of each 100,000 gallon tank is only 69,500 gallons because of the placement of inlet and outlet piping. Further, to eliminate mixing of warm and chilled water, one tank is effectively empty. Thus, as cold water is drawn from one tank, the tank previously emptied is filled with warm water. Therefore, the total volume of usable stored water is about 280,000 gallons. At a temperature difference (range) of 10 F, this is an energy storage capacity of 1950 Ton-hours (23.4 MMBtu).

A second storage limit is the maximum water flow rate through storage. Plant personnel indicate that hydraulic and operational constraints result in a maximum storage flow of 1500 GPM. At a range of 10 F, this is a cooling rate of 630 Tons (7.5 MMBtu/hr.). The peak site cooling loads are 3500 Tons.

Assuming that the chiller operates at its design coefficient of performance (COP) of 5.5, then a reduction of 630 Tons would reduce the chiller power demand by about 400 kW. At current rates, this would save about $13,000 a year. This is an approximate upper limit on the demand limiting potential of storage. If this rate were maintained, storage would be depleted in just over three hours. Therefore, even though a reduction of 400 kW is possible, storage may run out before the peaking period is over. Computer simulation is obviously needed to study the nature of the load and the reduced energy costs resulting from the various control strategies.

### 1.3.2 Reduced Electrical Consumption

The other major potential for computer control is reduction of energy consumption through improvement in the plant operating efficiency. The primary energy users in the plant are the chillers. Though much smaller in demand than the chillers, the pumps and cooling tower fans also require significant energy.

One example of control and its effect on efficiency is the cooling tower fan speed. At some point in the operation of a cooling tower and chiller, it becomes advantageous to change fan speeds. Suppose the fan were on low speed and the load on the chiller (and tower) is low. At high fan speed, the condenser water temperature would be cooler and chiller power would be less. However, at these conditions, the reduction in chiller demand is often less than the increase in fan power. Therefore, it would be better to run on low speed. As load is increased, the chiller power reduction will eventually exceed the fan power increase and it would be more efficient to run on high speed. The computer model was used to define the control routines for the possible operating conditions.

### 1.4 Simulation Methodology

Modeling of such a large facility is a time consuming and expensive undertaking. Though the interest of this study is the chilled water plant, the chilled water load must also be modeled since it is the primary input to the plant model. This means that models were also required for the numerous buildings and the air-handling equipment.

In order to reduce computer costs and the modeling effort, the simulation was separated into the plant model and the chilled water load model. The buildings and air-handling equipment were simulated only once (after debugging and sensitivity analysis) and the individual zone loads totaled to define the chilled water load as a function of time. Typical Meterological Year (TMY) weather data for Charlotte, North Carolina were input to this part of the simulation (2). The chilled water load, along with the site electrical loads and pertinent weather data, were stored for use as input to the plant model. In this manner, multiple plant runs were carried out without having to simulate the chilled water load each time. This results in significant savings because the chilled water load simulation is quite expensive due to the many zones required (15).

A possible drawback to this methodology is that there is no dynamic feedback from the plant model to the load model. For example, a change in chilled water supply temperature will alter the temperature and humidity conditions of the air leaving the cooling coil in the air-handlers. This could affect both the chilled water load and the fan power consumption.

This brings up an important distinction between the plant and load models. Emphasis was on an engineering model of the plant more so than the chilled water load. This is not to say that the load model is not of equivalent complexity and accuracy of other large building simulation programs. The actual building zones and air-handlers required many approximations and assumptions to manage the modeling task. Further, the accuracy of modeling the internal gains from equipment, lights and people is directly dependent on the accuracy of the assumed load schedules input to the simulation. Since over half of the total cooling load is due to internal gains, the simulated load is very sensitive to these inputs. Unfortunately, the equipment load varies from day to day and hour to hour as a result of production changes, tests, maintenance, and many other reasons. For this study, the internal load was assumed to be constant for each of three shifts. Measured electrical demand is compared with this assumption later.

Finally, the additional complexities of the actual zone heat transfer, fan system behavior, and cooling coil performance result in instantaneous predicted loads that can be significantly different than measured loads. Total daily loads and peaks compare much better, but the load profile is important too because of the limited storage system and peak demand charge. The response of the plant simulation should be much more accurate due to the smaller number of components and somewhat simpler performance characteristics. It is expected that although predicted savings in this report might differ from actual, they will be close enough to permit a judgement on their monetary value which is ultimately their application.

## 2. DEVELOPMENT OF THE PLANT MODEL

The TRNSYS plant model is composed of the various plant components - chillers, pumps, cooling tower, valves, piping, controls - with several input and output features. In simulation, the chilled water circulates around the loop as shown in Figures 1.1 to 1.6.

Rather than attempt a detailed hydraulic model of the complex chilled water piping and controls as part of the plant simulation, certain flow control assumptions were made and tested. Pumping power for the three major pumping arrays - primary, secondary and condenser - was correlated to flow rate using measured data. The only hydraulic feature explicitly modeled is the time delay nature of the long chilled water supply and return pipes to the site.

The chiller and cooling tower models use manufacturer's performance data. While the chiller model is entirely based on curve fits, the cooling tower model has a theoretical basis which permits reliable extrapolation beyond the range of the manufacturer's data.

By far the most difficult task in the modeling was identification and development of the control functions. In many strategic ways, the plant is controlled manually in response to changing loads and environmental conditions. The complexity of each operator made it difficult to define simple, logical control routines for the simulation. A process of trial and error and increasing understanding of the plant response through simulation finally led to the base case control strategies.

As a logical process of calibrating the TRNSYS simulation model, measured performance data were compared with simulations. First, each major component was examined and adjustments made where necessary to improve the agreement. After all components were tested, the entire plant simulation was run using only two measured inputs: total chilled water load and ambient wet-bulb temperature. The simulated plant electric demand was then compared with measured data as the test of the validity of the simulation.

The measurements in this section were from four separate data tapes. Each tape has about two and a half days of continuous operation with about 218 points recorded every 15 minutes. The dates covered by the four tapes are 4/30-5/2, 5/30-6/1, 6/17-6/19, and 7/19-7/21, all in 1983.

When those components with well established models (chillers and cooling towers) were compared with measured data, there were some discrepancies. The perplexing problem was deciding how much of the discrepancy was due to measurement error and how much to model inaccuracies. Where possible, error estimates of the measurements were made and the test of model validity is whether the discrepancy between measured and predicted is not significantly larger than the estimated error.

Listings of the components described here are contained in Appendix A along with descriptions of the parameters, inputs, and outputs. The TRNSYS deck for the plant simulation is listed in Appendix B.

## 2.1 Components

### 2.1.1 Chillers

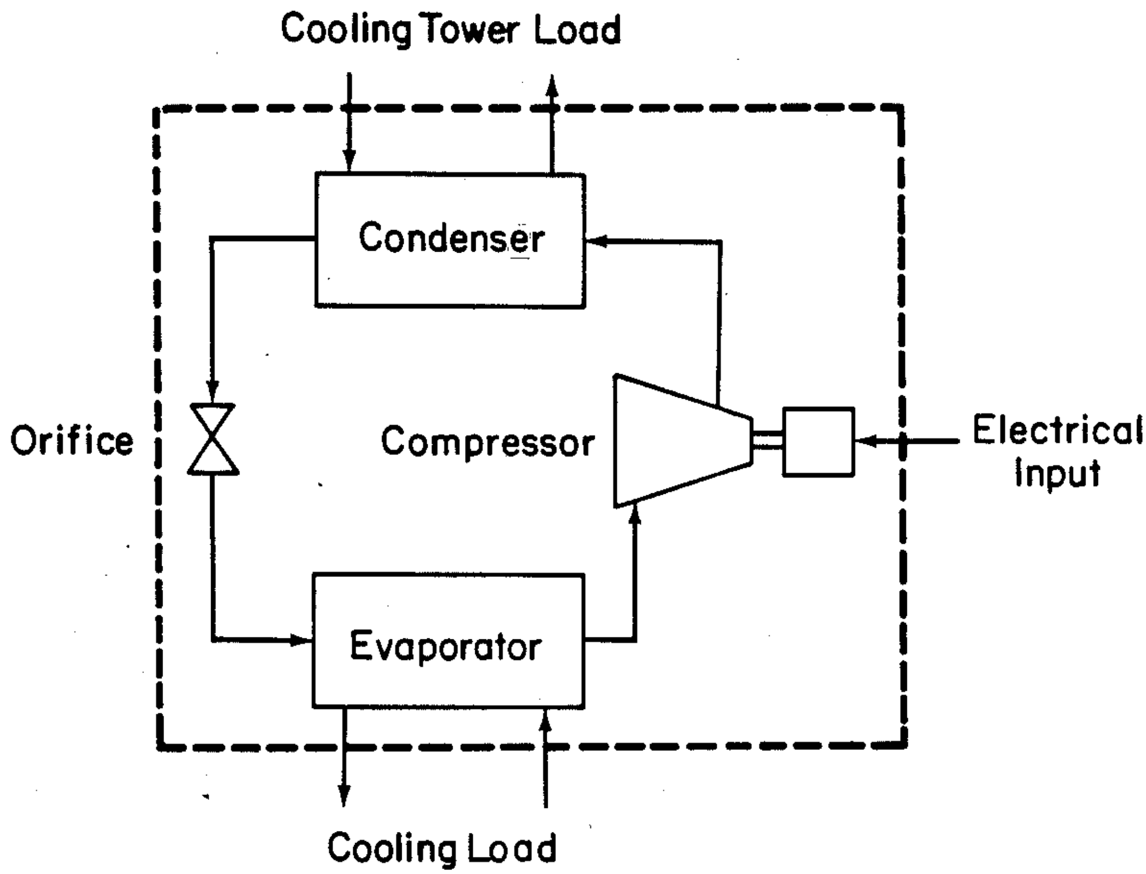
#### 2.1.1.1 Model Development

A chiller is a refrigeration machine that produces chilled water for air conditioning needs. The four electric-driven chillers in this study have centrifugal, two-stage compressors. As the load varies on the water side of the evaporator, the built-in chiller controls attempt to maintain a constant leaving water temperature. This is accomplished by automatic adjustment of the refrigerant flow rate with pre-rotation vanes at the compressor inlet.

The evaporator load and electrical input are rejected at the condenser to a cooling tower by a separate water stream. Figure 2.1 shows a system schematic and steady-state energy balance.

A technique for modeling centrifugal chillers is described by Stoecker (3) and was used as the basis for this model. The model assumes steady-state behavior and is a combination of curve fits to manufacturer's data. The three major parameters affecting the chiller performance are the 1) chilled water load, 2) leaving chilled water temperature (chilled water supply temperature), and 3) leaving condenser water temperature (condenser water return temperature). There are also a few small empirical, correction factors that will be discussed later.

The presentation of performance data by manufacturers is usually very general and is primarily meant for equipment selection. Unfortunately, this is all that was available for the TRANE chillers in




**ENERGY BALANCE:**

Cooling Load + Electrical Input = Cooling Tower Load

Figure 2.1 Chiller Schematic Showing System Boundary and Energy Balance

this study. Repeated requests for more detailed and specific data went unanswered by the manufacturer.

Available performance data from TRANE was presented in the form of one figure, shown in Figure 2.2. This figure relates the actual chiller electrical demand to the actual load and condenser water return temperature for a chilled water supply temperature of 44 F. This applies to all centrifugal chillers made by this manufacturer above a certain size. A biquadratic equation was fit to these curves for use in the model and is listed in Appendix C. The curves are made specific by using the design load and design power consumption with the ratios. This figure covers only two of the three major parameters. The effect of chilled water supply temperature on power consumption is not known.

In order to approximate the effect of different chilled water supply temperatures, data from another manufacturer (YORK 550-Ton chiller) was used. The impact on chiller power is shown in Figure 2.3. Two different condenser water return temperatures were investigated and the relative change in power demand does not appear too sensitive to this parameter. Therefore, a quadratic relationship was fit to the data and is the second empirical curve used to model the chiller power.

To summarize thus far, the effect of the three main parameters is accounted for by figures 2.2 and 2.3. To find the chiller power, first the part-load ratio is determined by dividing the actual load by the design load. Then, the kilowatt ratio is determined from Figure 2.2 for the appropriate condenser water return temperature (this temperature is dependent on the power consumption so in the model an

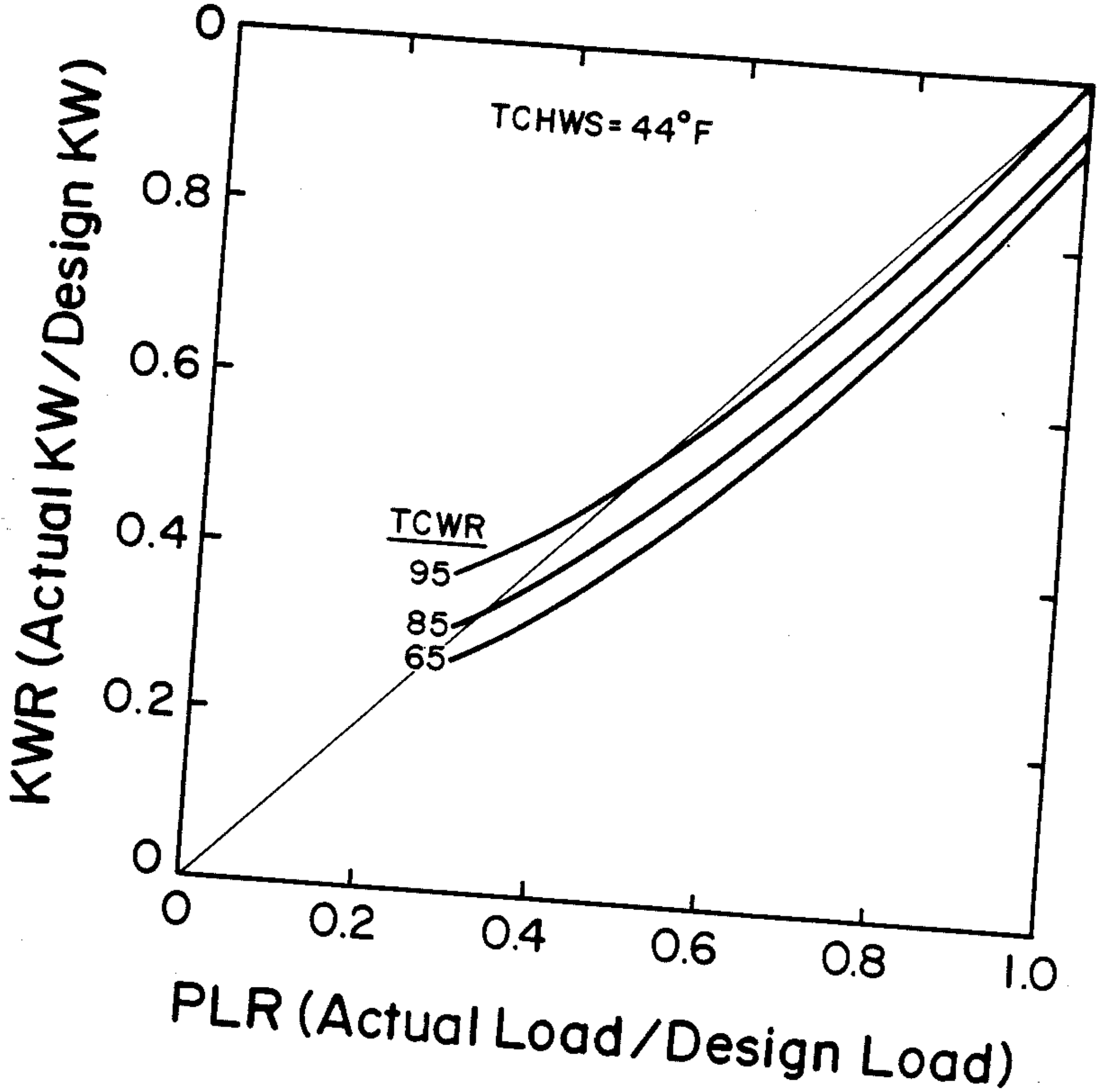



Figure 2.2 Manufacturer's Performance Curves for Centrifugal Chillers

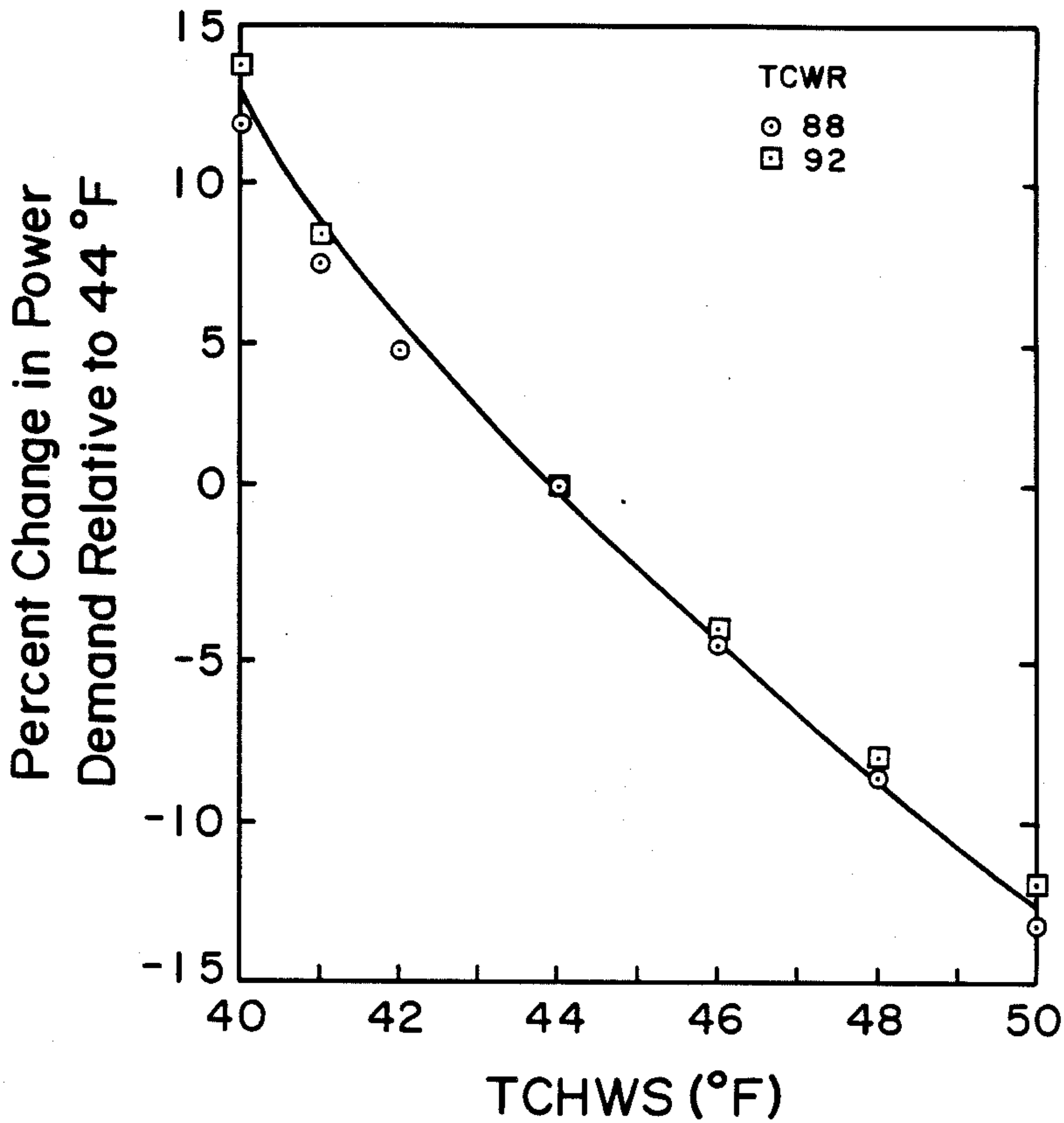



Figure 2.3 Effect of Chilled Water Supply Temperature on Chiller Power Consumption

iterative loop is required). Next, the actual chilled water supply temperature is used in Figure 2.3 to find the power adjustment and the total power consumption.

The chilled water supply temperature is set and is the main control parameter directly input to the chiller itself. Internally, the chiller adjusts the refrigerant pre-rotation vanes in an attempt to maintain the setpoint. The result of this built-in control loop is that the chilled water temperature varies as load varies in a manner similar to that in Figure 2.4. Thus, at low loads the actual chilled water temperature is lower than the desired setpoint. In the model, chilled water supply temperature is determined based on the part-load ratio, setpoint, and the relationship in Figure 2.4.

A final more subtle influence on the chiller performance is the water-side temperature difference (range). There are two conflicting effects in the evaporator as the range varies for a given load. One, the water-side convective heat transfer coefficient goes down as range goes up and flow goes down, tending to increase power. Two, as range goes up for a set outlet water temperature, the mean water temperature rises and reduces the effective temperature difference between water and refrigerant. Thus, the evaporator side refrigerant temperature should increase, tending to reduce power consumption.

The manufacturer provides adjustment factors based on actual water range as shown in Figure 2.5 for the evaporator. The three sets of points are for three different evaporator heat exchanger sizes with one pass having the least heat transfer area and three pass the most. The temperature correction read from the vertical axis is added to the

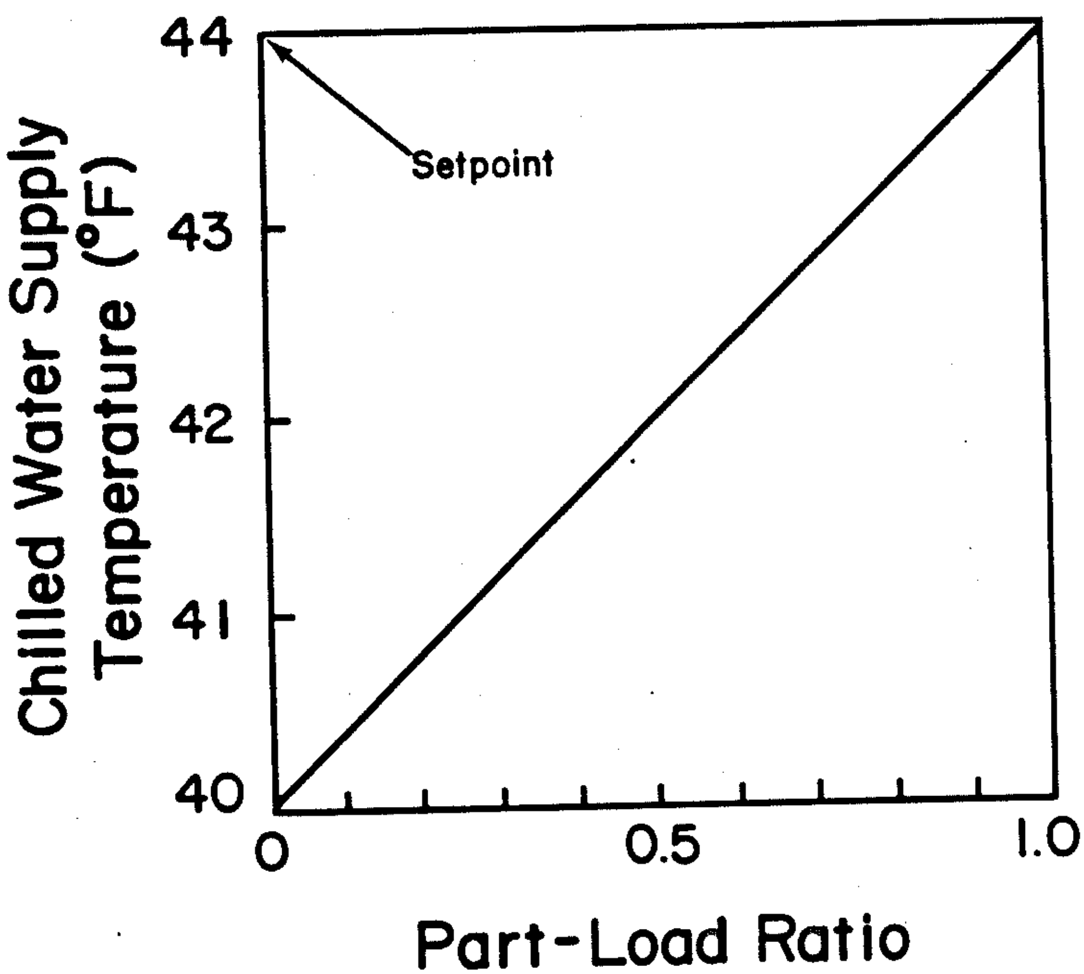



Figure 2.4 Effect of Load on Actual Chilled Water Supply Temperature

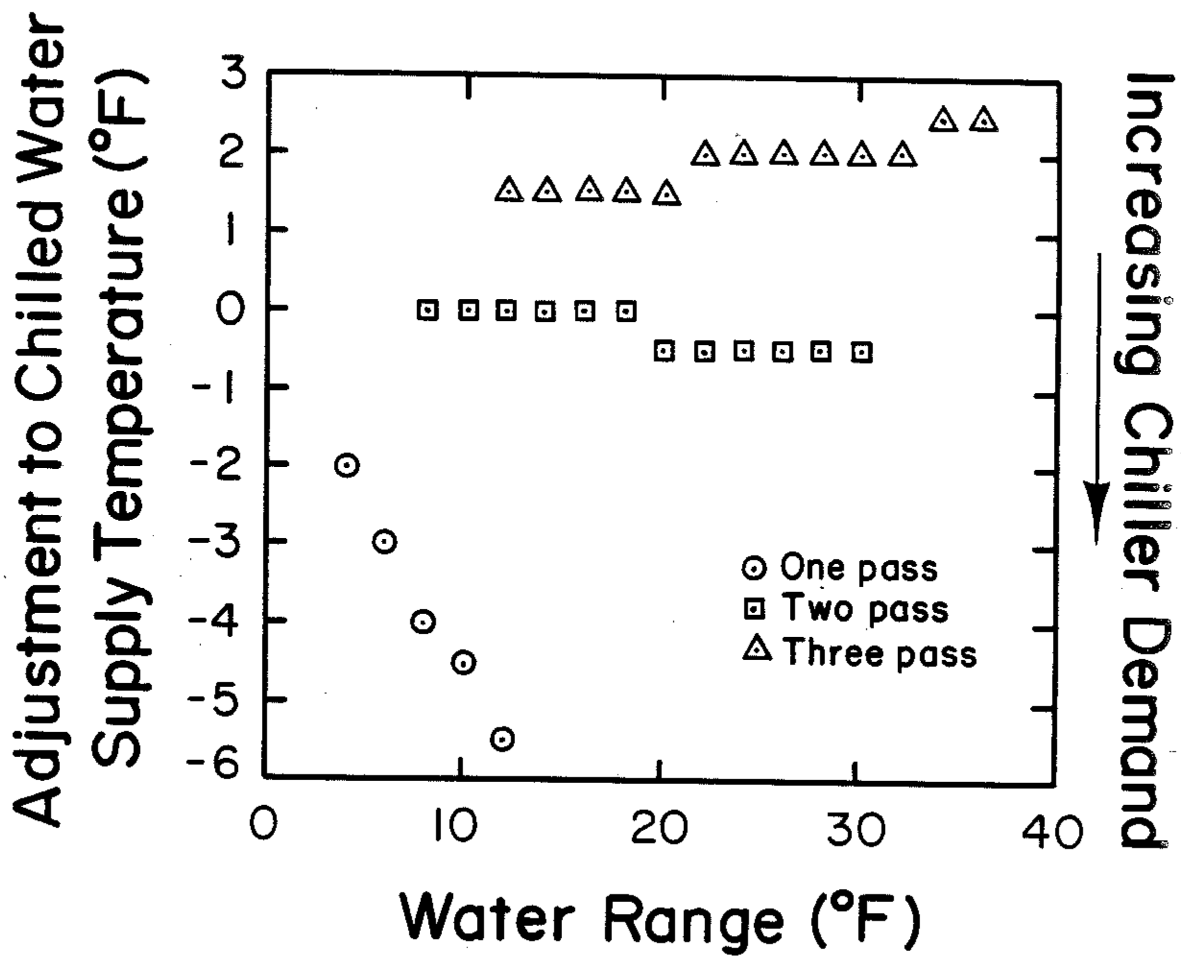



Figure 2.5 Effect of Water Range on Chiller Demand

actual chilled water supply temperature before using Figure 2.5. The small one-pass evaporator is quite sensitive to water range while the two-pass and three-pass evaporators show little effect of range variation. For the TRANE chillers, two-pass evaporators are installed and water range is never higher than 15 F. Therefore, no adjustment is necessary for water range. A similar conclusion is true for the condenser side.

2.1.1.2 Model Calibration

Data needed to predict chiller performance are subject to significant fluctuation. This is particularly true for the evaporator chilled water load. This load is derived on the water side from a drag-disc type flowmeter and temperature measurements upstream and downstream of the evaporator. The main source of the load fluctuation is fluctuation in the water flow reading. The chiller does not respond quickly enough to notice these load fluctuations.

To illustrate the problem and solution, the measured data were used to predict chiller power consumption. The measured inputs to the simulation were chilled water load, chilled water supply temperature, condenser water supply temperature and condenser water flow rate. Only chillers 2 and 3 had a significant data base.

First, Figure 2.6 shows the predicted and measured electric demand for chiller 2 and the 15-minute data. There is considerable scatter which is largely due to the water flow oscillations. To smooth these oscillations, the data shown in Figure 2.6 were averaged for an hour and the results are plotted in Figure 2.7. There does appear to be a

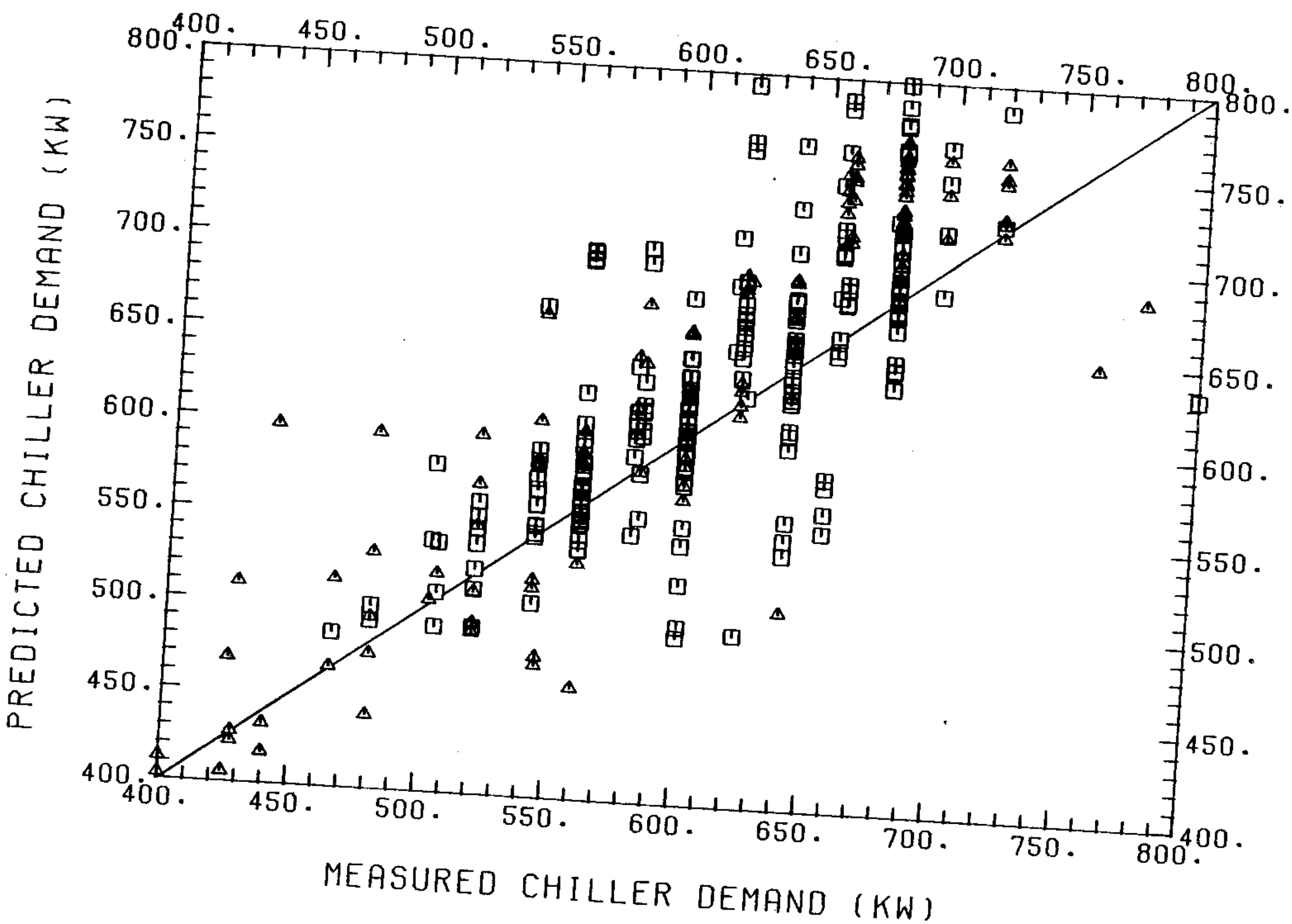



Figure 2.6 Comparison of Predicted and Measured Demand for Chiller 2 Using 15-Minute Instantaneous Data

bias towards overestimation of the electric demand, with 95% of the data within +19% and -2% as shown.

To establish some criteria for the measurement error, an energy balance was performed on the chiller to yield:

$$\begin{matrix}\text{Chilled Water Load} + \\ \text{Compressor Demand}\end{matrix} = \begin{matrix}\text{Condenser Heat} \\ \text{Rejection Rate}\end{matrix} \qquad [2.1]$$

Neglecting heat transfer with the plant environment, the performance data should balance this equation. Any measurement errors should show up as an unbalance of energy unless they happen to be compensating.

This balance was performed on the data from chiller 2 and the left side of equation [2.1] was anywhere from 5 to 40% less than the right side. With this much error in the energy balance, the predicted demand seems to adequately predict the performance. The distributions of the calculated energy unbalances are shown in Figure 2.8 for the two chillers. Both chillers have energy unbalances as high as 30 to 40%. In general, chiller 2 has higher energy unbalances than chiller 3.

For comparison, Figures 2.9 and 2.10 show the simulated demand of chiller 3 for 15-minute points and one-hour averages, respectively. For this chiller, the agreement is better as are the energy balances, typically -5 to -15%.

Since the simulation model based on manufacturer's performance curves results in predicted chiller demand within the range of energy unbalances based on measurements, the manufacturer's curves are assumed to be valid for simulation purposes.

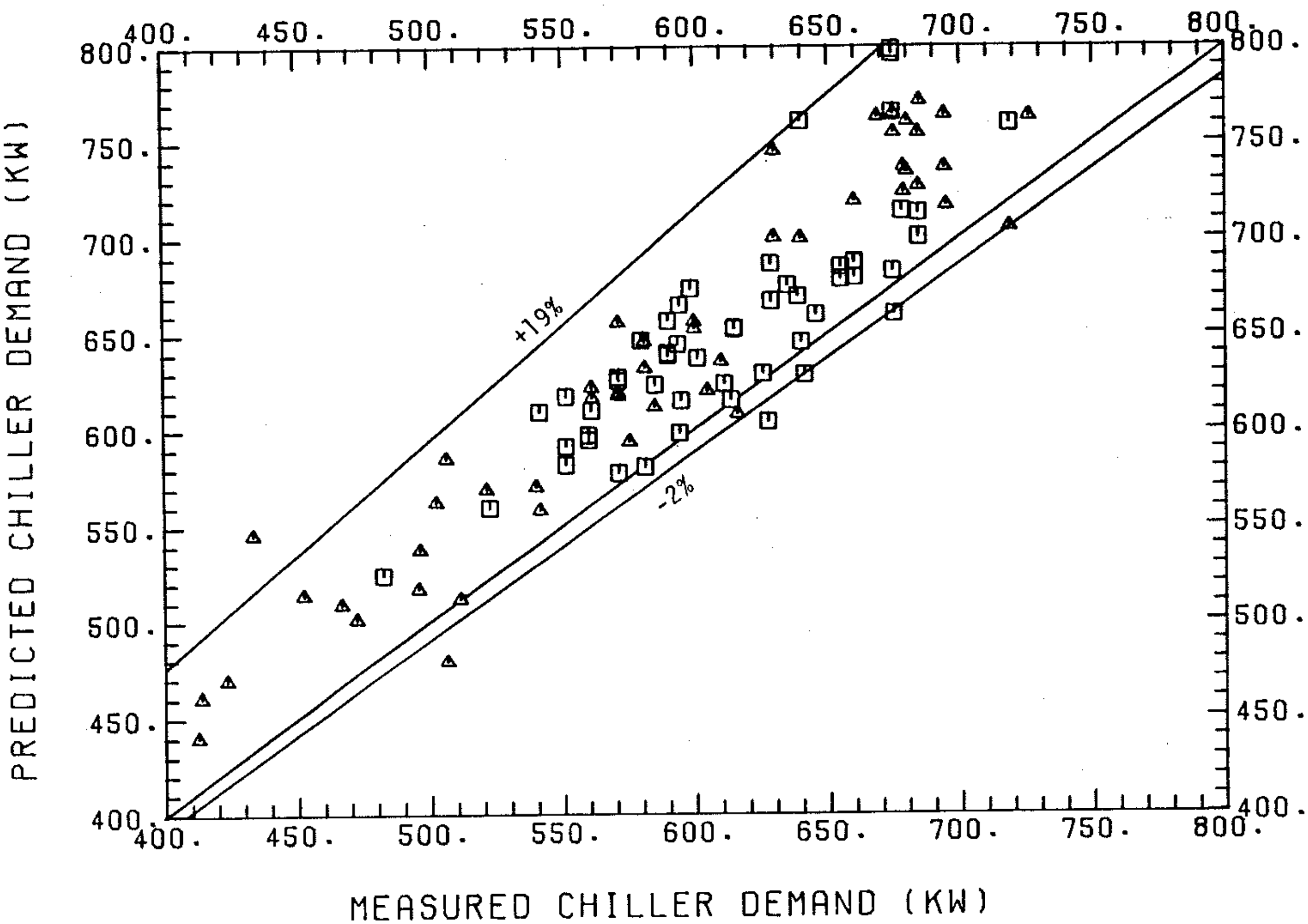



Figure 2.7 Comparison of Predicted and Measured Demand for Chiller 2 Using 1-Hour Average Data

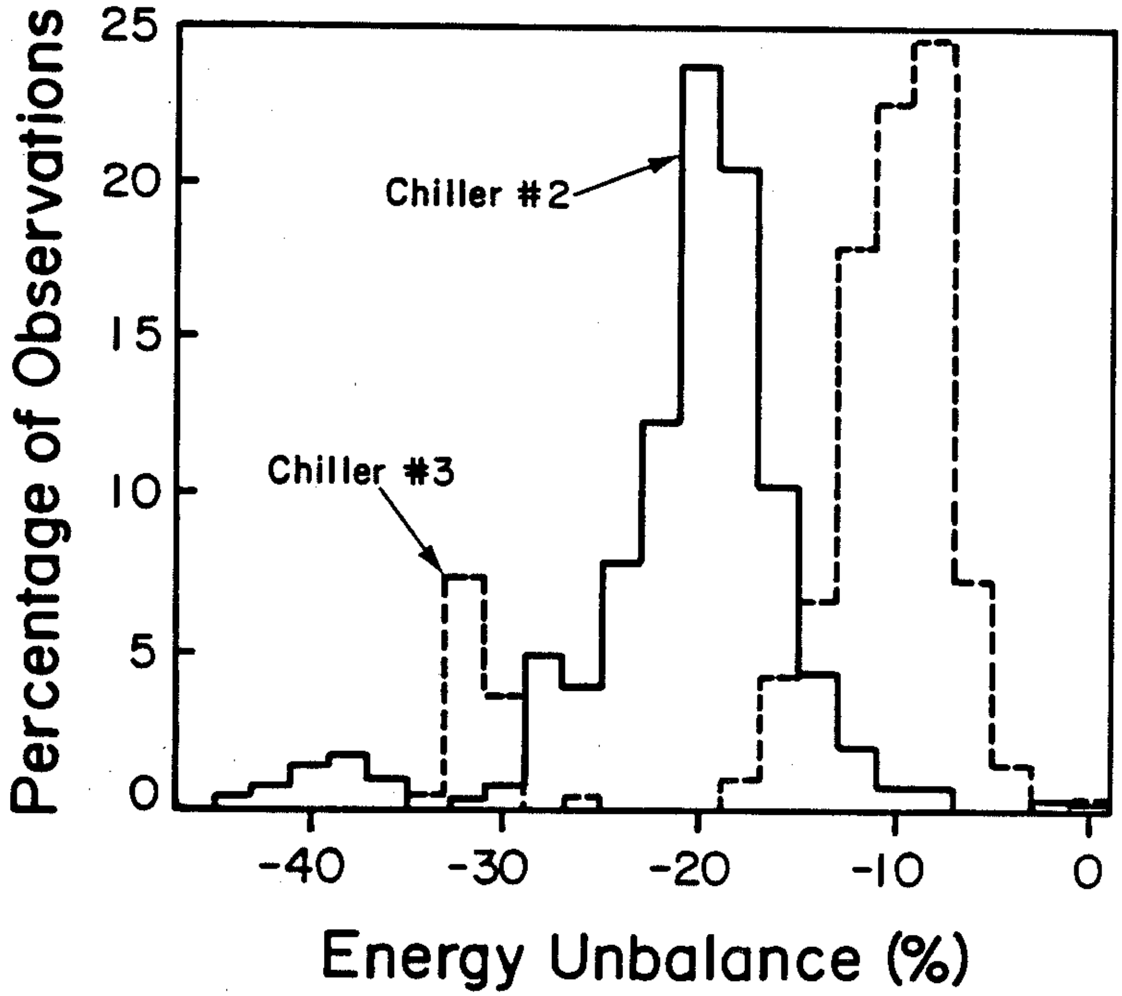



Figure 2.8 Distributions of Chiller Energy Unbalances

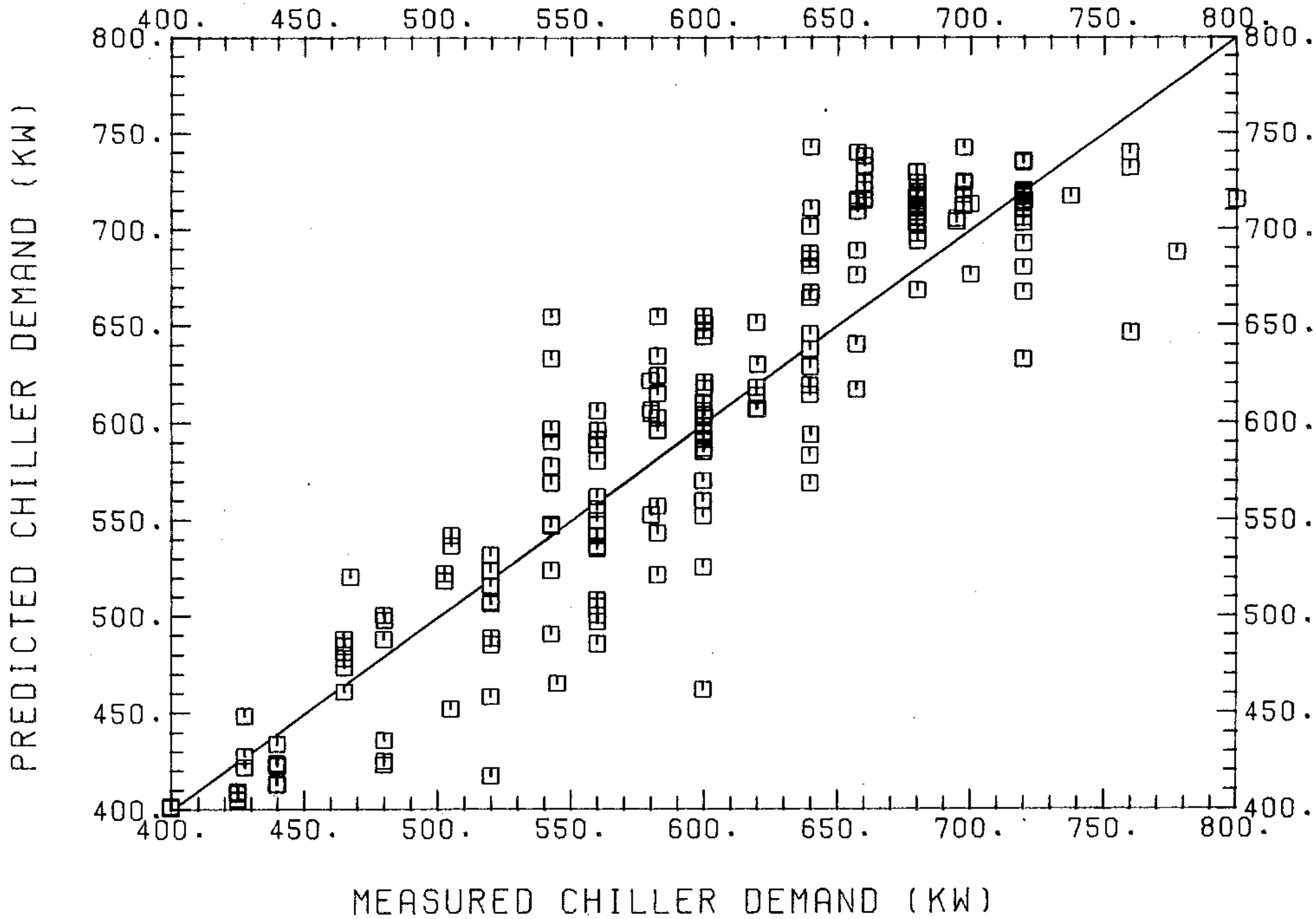



Figure 2.9 Comparison of Predicted and Measured Demand for Chiller 3 Using 15-Minute Instantaneous Data

### 2.1.2 Cooling Tower

#### 2.1.2.1 Model Development

A cooling tower is a device which utilizes ambient air as a heat sink to cool a stream of water, in this case from the chiller condensers. A schematic of an induced-draft, crossflow cooling tower is shown in Figure 2.11. Incoming water from the condenser is introduced into a basin in the top of the tower and then falls through holes in the bottom of the basin into the fill. The function of the fill is to break the water stream into a thin film with a large surface area exposed to the cooler air stream. Combined processes of heat and mass transfer occur in the fill and the result is that the air stream leaves at both a higher temperature and higher water vapor content than ambient. The water leaves at a cooler temperature than entering and at a slightly reduced mass flow rate due to evaporation in the fill. Thus, in a closed loop water system, makeup water must be added to the leaving water to balance the evaporative losses.

Towers can have multiple cells physically separated from each other with each cell having its own fan and water flow valve (open or closed). The Baltimore Air Coil (BAC) tower has six cells each rated at a water flow of 3125 GPM. At a water range of 15 F, the entire tower can exhaust heat at a rate of 11,800 Tons (1960 Tons/cell).

Air flow in cooling towers can be by natural convection or can be forced by a fan. In the subject tower, a two-speed fan is used to control air flow with low speed equal to half the high speed. It is assumed that the fan laws (4) prevail and at low speed, the volumetric

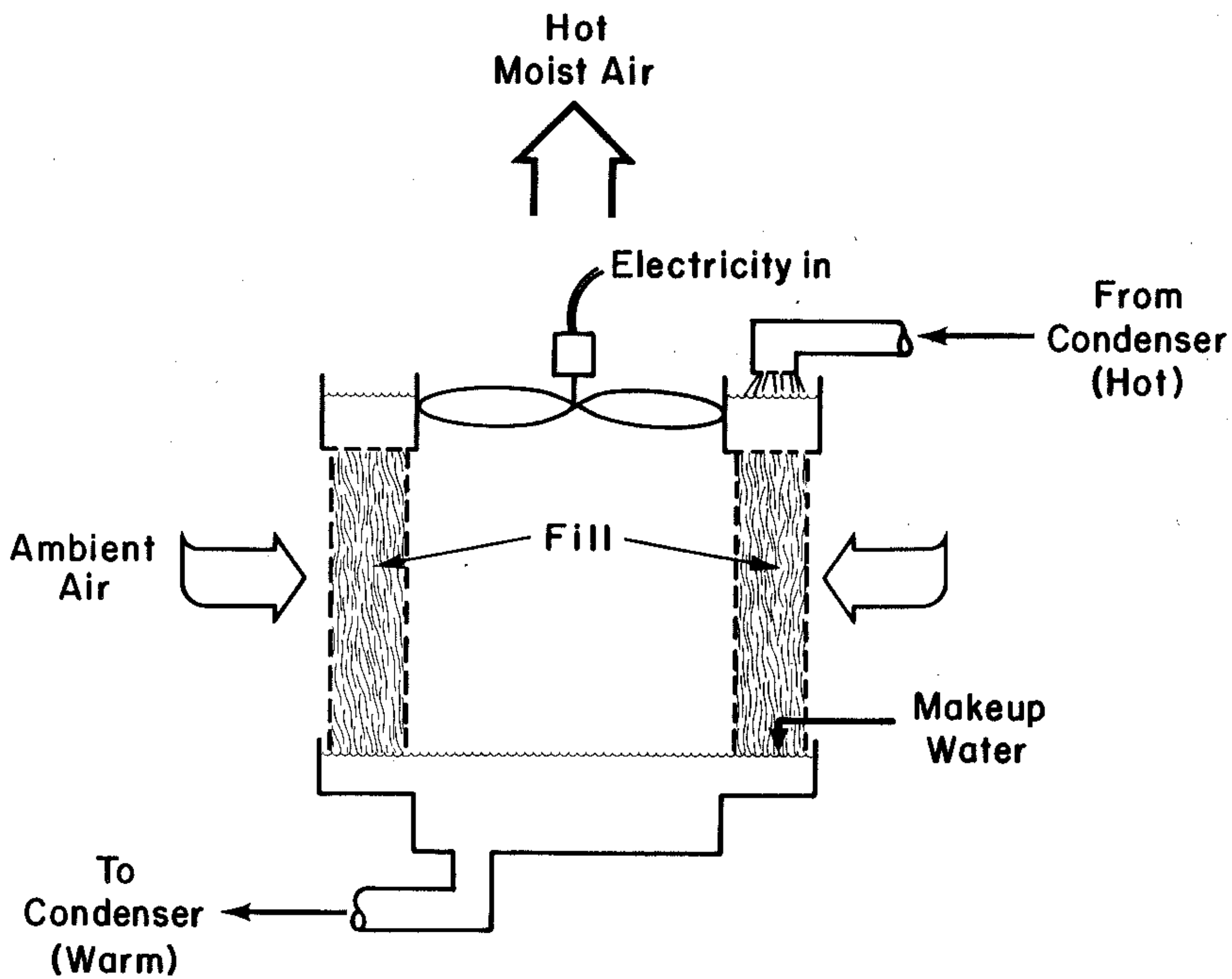



Figure 2.11 Schematic of an Induced-Draft, Crossflow Cooling Tower

flow rate is half the high-speed rated flow. Since the fan is on the air outlet side, actual air mass flow rate is dependent on the air density leaving the tower.

It is possible that a tower cell could be operated with the fan off if the leaving water temperature is too cold with the fan on low. The air flow rate under these conditions is highly variable and greatly influenced by wind speed and direction. Discussions with the tower manufacturer indicated that air flow with the fan off is about 10-15% of the high speed flow. Therefore, a value of 10% is used and should be of little consequence in this study since summer conditions are of primary interest.

The heat and mass transfer processes occurring in a cooling tower have been studied in detail (5) and the results form the basis of a commonly accepted analytical technique described by ASHRAE (6). The solution of the governing equations for each unique set of operating conditions involves repetitive numerical integration. Several assumptions are required to perform the analysis.

Whillier (7) recognized the complexity of the common technique and proposed a new method which does not require integration yet is nearly as accurate as the former method. This Whillier model was tested for the subject tower and very satisfactory results were obtained as shown in the next section. The basic theory underlying the Whillier model is explained here.

Using a control volume as shown in Figure 2.12 and assuming steady-state, the First Law of Thermodynamics yields:

$$\dot{m}_{ai}h_{ai} + \dot{m}_{vi}h_{vi} + \dot{m}_{li}h_{li} = \dot{m}_{ao}h_{ao} + \dot{m}_{vo}h_{vo} + \dot{m}_{lo}h_{lo} \qquad [2.2]$$

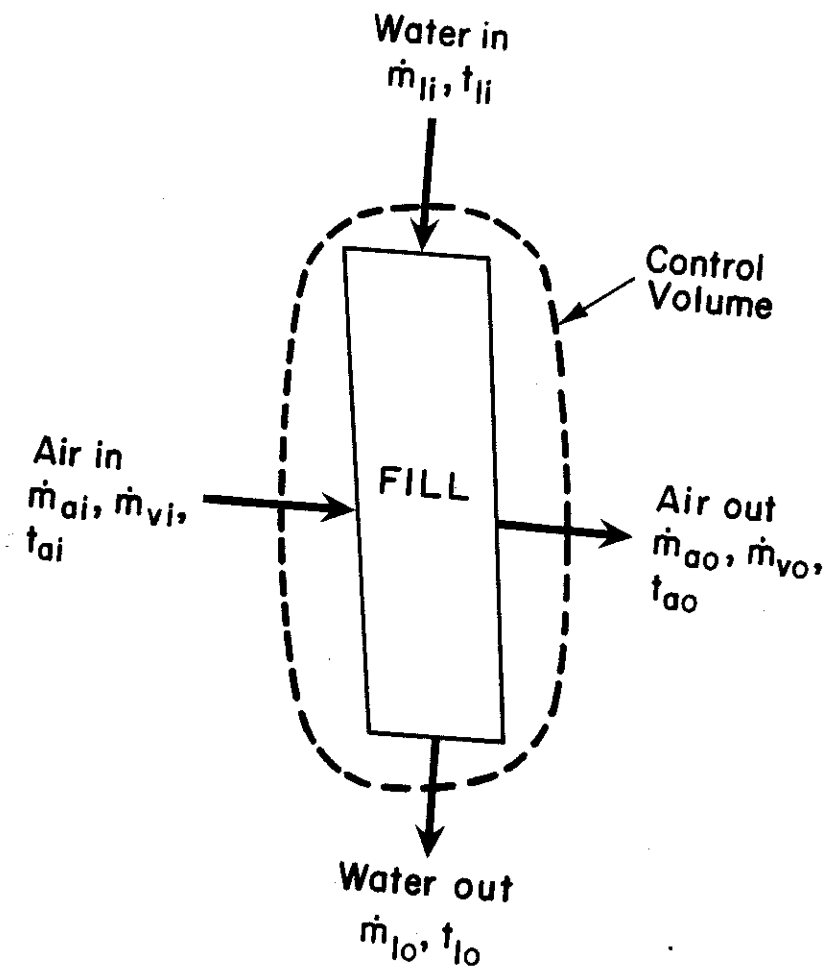



Figure 2.12 Cooling Tower Control Volume

Conservation of mass applied to the air stream yields:

$$\dot{m}_{ai} = \dot{m}_{ao} = \dot{m}_a \qquad [2.3]$$

Similarly, conservation of mass on the vapor and liquid streams yields:

$$\dot{m}_{vi} + \dot{m}_{li} = \dot{m}_{lo} + \dot{m}_{vo} \qquad [2.4]$$

Use of the humidity ratio yields:

$$w_i\dot{m}_a + \dot{m}_{li} = \dot{m}_{lo} + w_o\dot{m}_a \qquad [2.5]$$

or solving for the liquid flow rate leaving the tower:

$$\dot{m}_{lo} = \dot{m}_{li} - (w_o - w_i)\dot{m}_a \qquad [2.6]$$

Thus, the flow rate of liquid leaving the tower is less than that entering by the amount that evaporates. Combining the continuity equations with the First Law yields:

$$\dot{m}_a h_{ai} + w_i\dot{m}_a h_{vi} + \dot{m}_{li}h_{li} = \dot{m}_a h_{ao} + w_o\dot{m}_a h_{vo} + [\dot{m}_{li} - (w_o - w_i)\dot{m}_a]h_{lo} \qquad [2.7a]$$

This equation can be rearranged to yield:

$$\dot{m}_{li}(h_{li} - h_{lo}) = \dot{m}_a(h_{ao} + w_o h_{vo}) - \dot{m}_a(h_{ai} + w_i h_{vi}) - (w_o - w_i)\dot{m}_a h_{lo} \qquad [2.7b]$$

The parenthetical grouping in the first two terms on the right side of the equation is commonly referred to as the mixture enthalpy (per pound of dry air) and is the quantity usually found on a psychrometric chart. Substituting the mixture enthalpy yields:

$$\dot{m}_{li}(h_{li} - h_{lo}) = \dot{m}_a(h_{mo} - h_{mi}) - (w_o - w_i)\dot{m}_a h_{lo} \qquad [2.8]$$

In order to develop a tower heat exchange model with simple definitions of air and water efficiency and effectiveness, it is desirable to neglect the last term in this equation. Consideration of typical operating conditions shows that this term is usually 4-9% of the left side of the equation (7). Whillier found that a somewhat different grouping of terms can be used in order to reduce the error involved in the effectiveness development. A new term, sigma energy, is defined, a grouping first suggested by Carrier in 1911 (8):

$$h_s = \text{sigma energy} \qquad [2.9]$$
$$= h_m - wc_1 t_m^*$$

Carrier found that sigma energy is more convenient than mixture enthalpy in processes involving changes in moisture content.

The importance of sigma energy is demonstrated by consideration of the adiabatic saturation process, see Figure 2.13. The First Law yields:

$$\dot{m}_a h_{mi} + \dot{m}_1 h_1^* = \dot{m}_a h_{mo} \qquad [2.10]$$

From conservation of mass for the water:

$$\dot{m}_1 = \dot{m}_a (w_o - w_i) \qquad [2.11]$$

Subsituting and eliminating the air mass flow rate yields:

$$h_{mi} + (w_o - w_i) h_1{}^* = h_{mo} \qquad [2.12]$$

Now the specific heat of liquid water is introduced to define the enthalpy and the inlet and outlet terms are grouped together:

$$h_{mi} - w_i c_1 t^* = h_{mo} - w_o c_1 t^* \qquad [2.13]$$

The left and right sides are defined as the sigma energy of the inlet and outlet air respectively. Thus, in an adiabatic saturation process, sigma energy is effectively conserved and Carrier recognized this grouping as important in moist air processes. One property of sigma

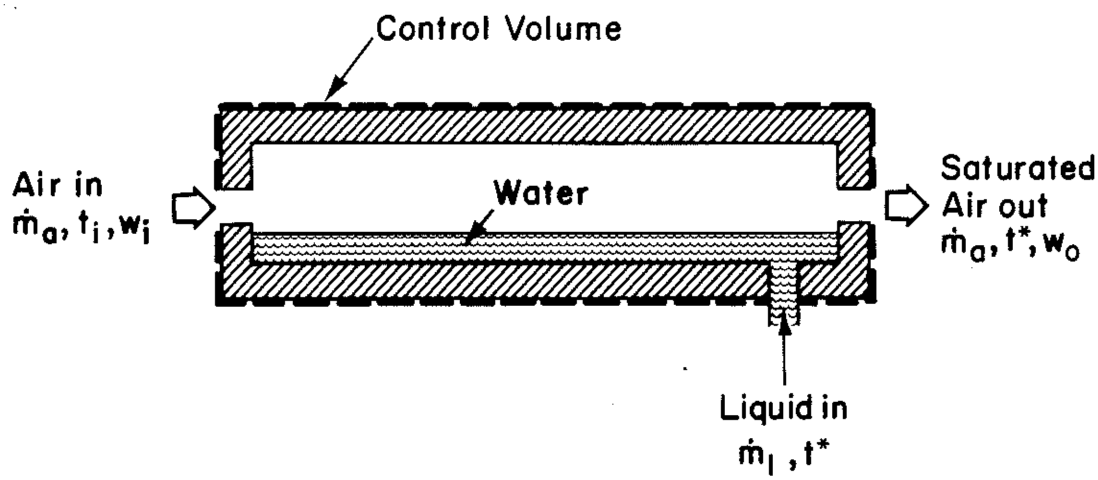



Figure 2.13 The Adiabatic Saturation Process

energy is that it is only a function of wet-bulb temperature.

If sigma energy and the specific heat of liquid water are substituted into equation [2.8] and manipulated, the result is:

$$\dot{m}_{li}c_l(t_{li}-t_{lo}) = \dot{m}_a(h_{so}-h_{si}) + \dot{m}_a c_l[w_o(t_{ao}-t_{lo})+w_i(t_{lo}-t_{ai})] \qquad [2.14]$$

The benefit is that the second term on the right side is only half as big in magnitude as the second term in equation [2.8] and is roughly 2-4% of the left side. Neglecting this term yields the approximate energy balance:

$$\dot{m}_{li}c_l(t_{li}-t_{lo}) = \dot{m}_a(h_{so}-h_{si}) \qquad [2.15]$$

This equation is the basis for the subsequent effectiveness development.

Whillier found that two useful efficiency terms can be defined for a cooling tower. They are based on the thermodynamic limitations on the two process streams. The water in a tower cannot be cooled below the inlet air wet-bulb temperature nor can the air leave at a wet-bulb temperature higher than the inlet hot water temperature.

$$\eta_l = (t_{li}-t_{lo}) \; / \; (t_{li}-t^*_{ai}) \qquad [2.16a]$$

$$\eta_a = (h_{so}-h_{si}) \; / \; (h_{s@li}-h_{si}) \qquad [2.16b]$$

The ratio of water flow rate to air flow rate can vary during operation due to the multiple fan speeds and variable-speed condenser water pumps. There is one combination of water and air flow rates such that if the inlet water cooled to the inlet air wet-bulb temperature, the air would heat up to a wet-bulb equal to the inlet water temperature. This is called the reference water-air ratio (WAR) and is analogous to equivalent thermal capacitance in sensible heat exchanger theory.

Using the approximate energy balance in equation [2.15], the reference water-air ratio can be derived:

$$WAR = (h_{s@li}-h_{si}) \;/\; [c_l(t_{li}-t^*_{ai})] \qquad [2.17]$$

This ratio is only a function of three independent variables: inlet water temperature, inlet air wet-bulb temperature and barometric pressure. Barometric pressure has a slight effect on the sigma energy calculation.

An operating tower will often have a ratio of water to air flow different than the reference value. Therefore, the tower capacity factor, R, is defined:

$$R = (\dot{m}_a/\dot{m}_l) \;/\; WAR \qquad [2.18]$$

Combination of equations [2.15] - [2.18] yields:

$$\eta_a = R\eta_l \qquad [2.19]$$

Because Whillier chose to define WAR and R as water to air ratios, R can have values greater than one.

Common heat exchanger effectiveness is correlated to $c_{min}/c_{max}$. In order to make this development consistent, the cooling tower effectiveness is defined such that:

$$E = \eta_l \quad \text{if } R \leq 1 \qquad [2.20a]$$

$$E = \eta_a \quad \text{if } R \geq 1 \qquad [2.20b]$$

Neither the air or water efficiencies or the effectiveness can be greater than one.

The usefulness and validity of the Whillier model can be measured by comparing test data. A plot of effectiveness versus tower capacity factor should yield a simple curve (or better yet a straight line) which could then be used as the basis for performance prediction. In the simulation, inlet conditions are known and R can be calculated and used with the correlation to determine the effectiveness. This can be used with the efficiency definitions to obtain the outlet conditions. Data will be compared in section 2.1.2.2.

In addition to the Whillier effectiveness model, the cooling tower component has the ability to model the thermal response associated with the water in the tower basin and sump basin. The basins are modeled as fully mixed tanks with negligible heat transfer to the ambient or to other basins. As such, the outlet tank temperature responds in a first-order manner to changes in the inlet temperature. The time constant associated with the outlet water temperature is typically 10-16 minutes based on condenser flow rate and sump volume. Up to ten cells with individual fan control and basins can be modeled.

2.1.2.2 Model Calibration

The tower manufacturer was very cooperative in providing data and information on the tower operation. Data were presented in the form of three figures, one each for 90%, 100%, and 110% rated water flow and all for high fan speed. Figure 2.14 shows the 90% water flow chart. The water temperature leaving the tower (condenser water supply temperature) is related to ambient wet-bulb and the water range. The tower heat rejection load is directly proportional to the water range since water flow rate is constant. As load (range) increases, the water temperature increases. As wet-bulb increases, the water

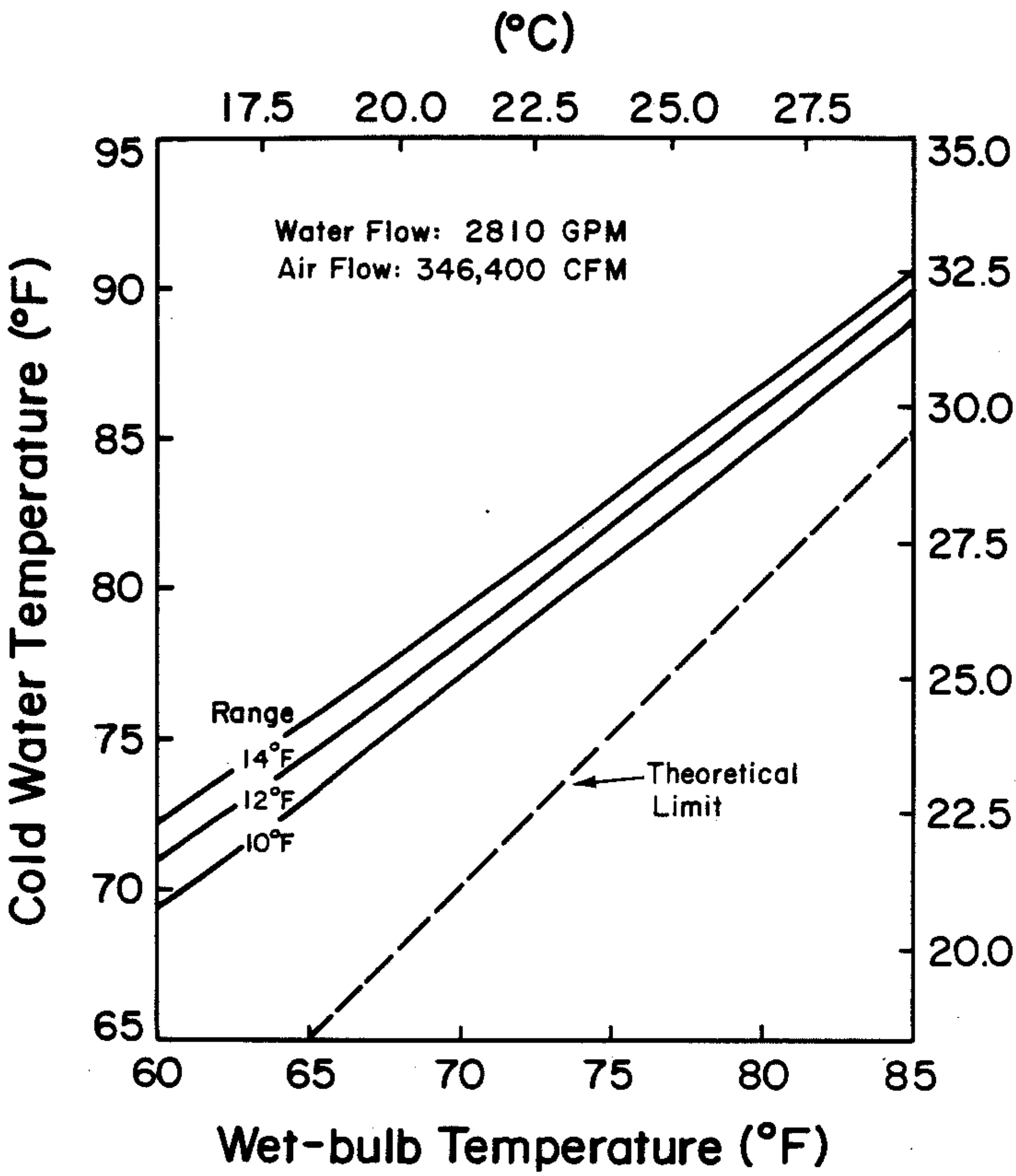



Figure 2.14 Cooling Tower Performance Curves From the Manufacturer

temperature approaches the wet-bulb temperature closer due to the higher energy capacity of the moist air. These curves were calculated by the manufacturer based on test results and an analytical model similar to the ASHRAE method (6).

To develop the effectiveness curve for this tower, discrete points were read from each figure. The cold water temperature leaving the tower was determined for each water flow, water range and wet-bulb temperature from 65 to 85 F in 5 F increments (total of 45 points). The data was processed using rated volumetric fan flow to obtain the air mass flow rate.

The resulting points are plotted in Figure 2.15, along with three possible correlation curves. The points indicated by triangles are for points where R is greater than 1 and 1/R is used as the abscissa to be consistent with the concept of $c_{min}/c_{max}$. For the Whillier model to be useful, the data should fall on a single curve. The data for R less than one lie on a different curve than for R greater than one. However the scales in Figure 2.15 cover a small range and tend to magnify the scatter. One test of the significance of the scatter is how well the effectiveness curve and the Whillier-based simulation model reproduce the manufacturer's data.

First, an explanation of the three curves on Figure 2.15 is necessary. The top curve is a line which is the result of a least-squares fit to all of the 45 points. Whillier suggests that the data should fit an equation of the form:

$$E = F/(F+(1-F)R) \quad \text{if } R>1 \text{ use } 1/R \text{ in this equation}$$

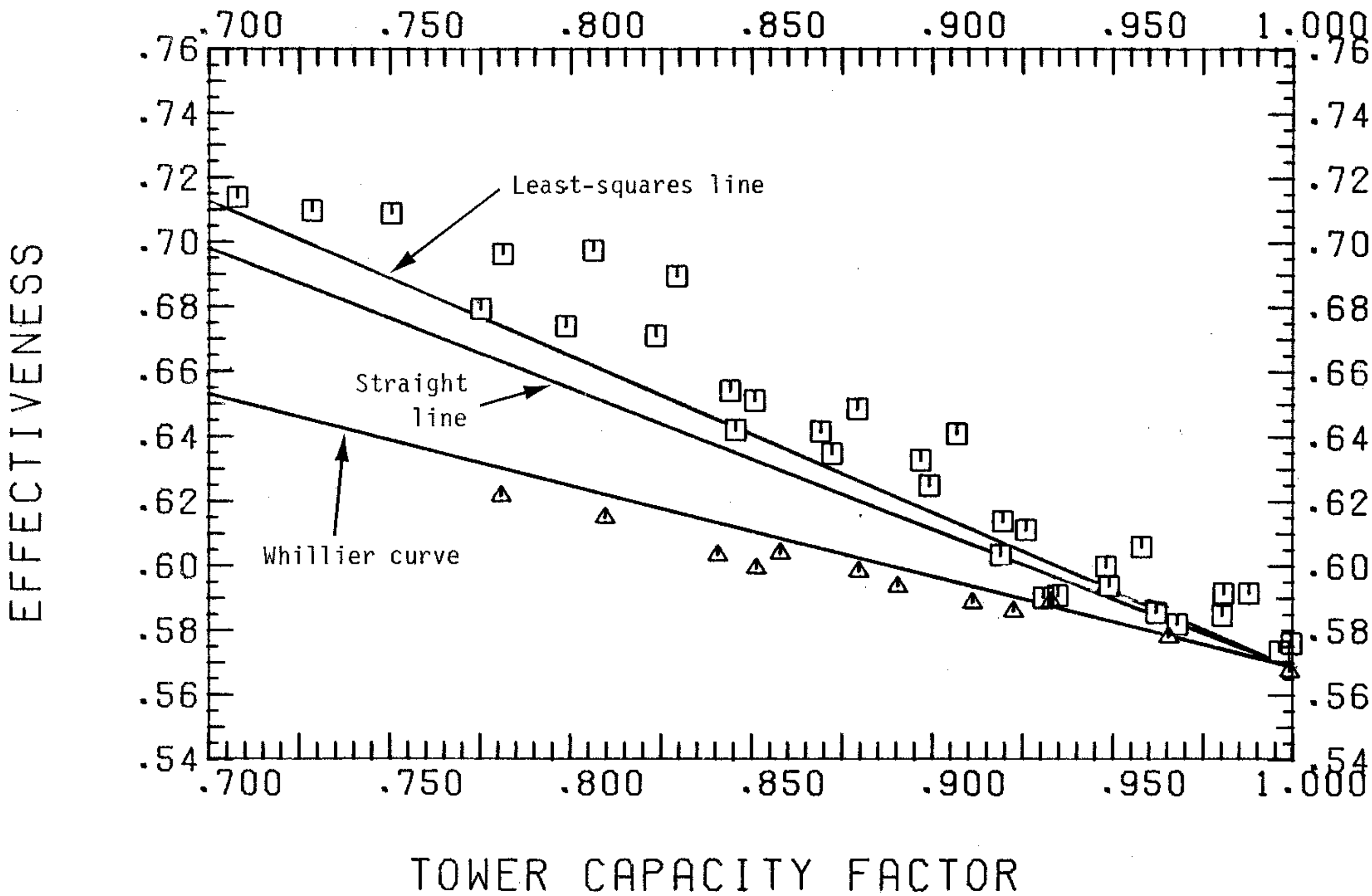



Figure 2.15 Cooling Tower Effectiveness Data Derived From the Manufacturer's Performance Curves

In this equation, when R equals one, E equals F and Whillier called F the tower factor of merit. For an F value of 0.57, based on the least-square line, Figure 2.16 shows the difference between the Whillier curve and a straight line connecting F and (0,1). There is no obvious reason that Whillier chose the fit in equation [2.23] for the data over the least-squares line. The only apparent advantage is that the effectiveness is completely described by the one parameter, F. However, a straight line connecting F and (0,1) also requires only F and appears to fit the data better (the middle line in Figure 2.15).

The three curves were used to predict performance for conditions on one of the manufacturer's performance curves using the rated water and air flow rates. The results are shown in Figure 2.17. Use of the least-squares line definitely results in better agreement than Whillier's curve. Further, though not shown on the figure, the third correlation line connecting (0,0) and (1,F) results in a prediction nearly identical to the least-squares line. Both of these correlation lines result in predicted water temperatures within 0.5 F of the manufacturer's data. Whillier's curve results in predicted values up to 1.5 F higher than the manufacturer's data. In the remaining modeling, the least-squares line is used for the effectiveness correlation, limited to a maximum value of one.

As a final check of the cooling tower model, predictions were compared with measured data. Measured wet-bulb temperature, condenser water return temperature, condenser water flow rate, and cell status were used as input to the cooling tower component to predict the condenser water supply temperature (water temperature leaving the

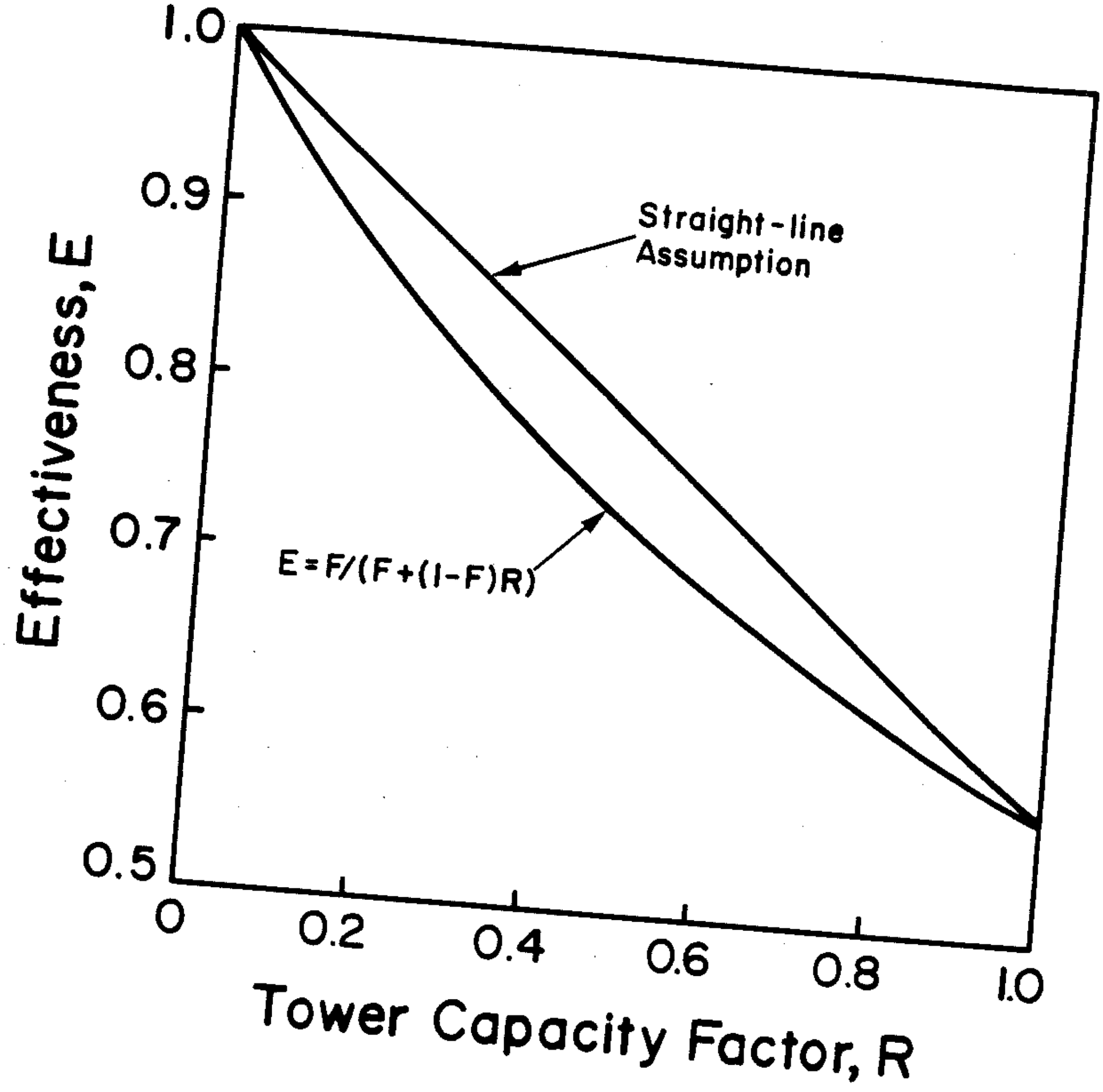



Figure 2.16 Comparison of Whillier's Curve With a Straight Line

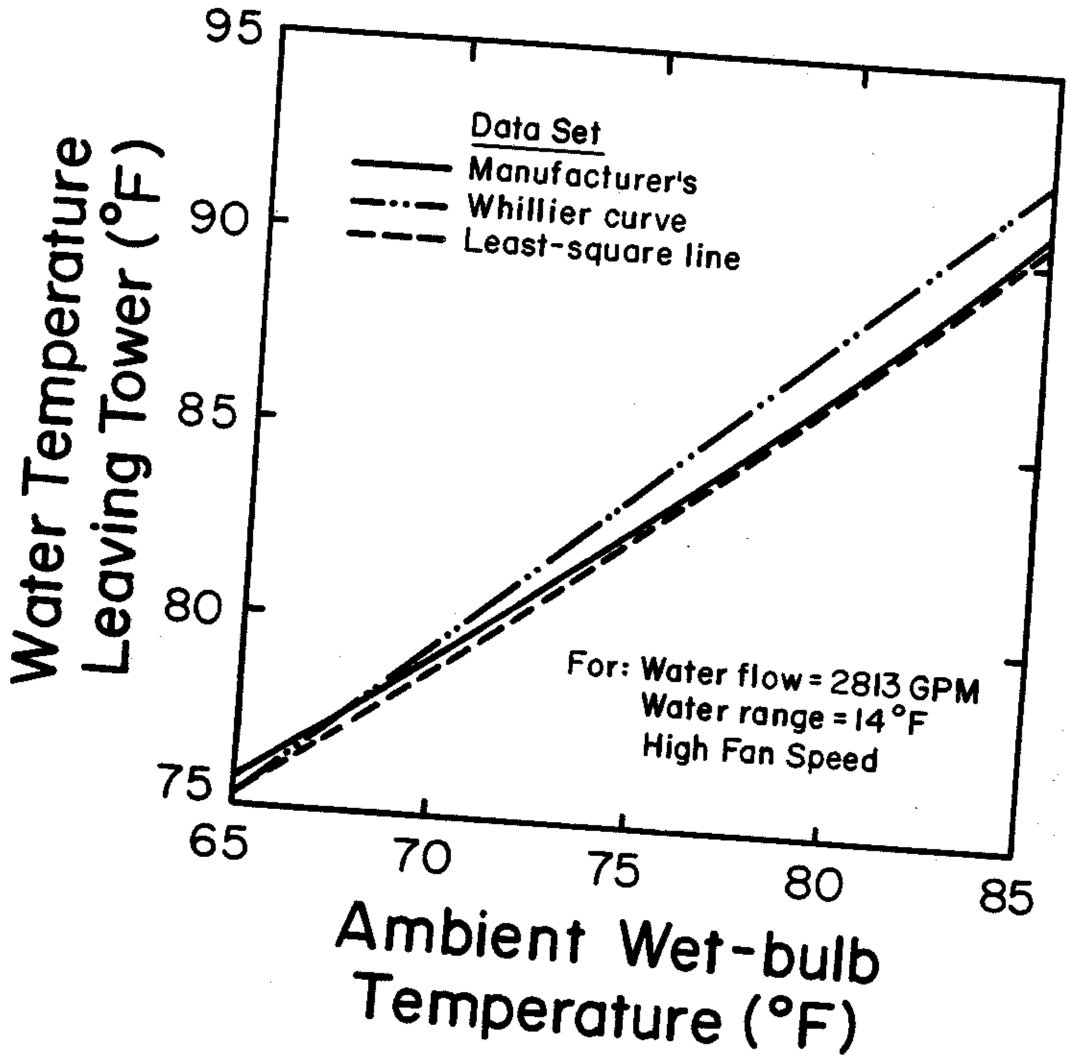



Figure 2.17 Predicted Cooling Tower Performance Curves

tower). As a first test, the data from the first tape was used and the tower was modeled with no sump volume. The predicted versus measured water temperatures are shown in Figure 2.18. While there is some scatter, there does appear to be good agreement. For comparison, the sump models were added and the results are shown in Figure 2.19. Addition of the sumps reduced the scatter which was apparently due to transients and the steady-state nature of the model without sumps. A portion of this data is presented in a different way in Figure 2.20, which shows the sequential nature of the measurements and predictions. Data and predictions in all these cases are at 15-minute intervals. This figure shows the better agreement of the cooling tower component with the sumps included.

The data from all four data tapes were used for comparison with the model including the sumps and the results are illustrated in Figure 2.21. Again, remarkably good agreement was obtained. There is a slight bias toward overprediction by 0.62 F on the average. The RMS error for all of the data points is 1.36 F. The water temperature measurements should be accurate to a few tenths of a degree Fahrenheit. However, the wet-bulb temperature is derived from a dew-point sensor and the error can probably be as high as a few degrees Fahrenheit. Since the leaving water temperature is highly dependent on the wet-bulb temperature, the RMS error of 1.36 F seems acceptable.

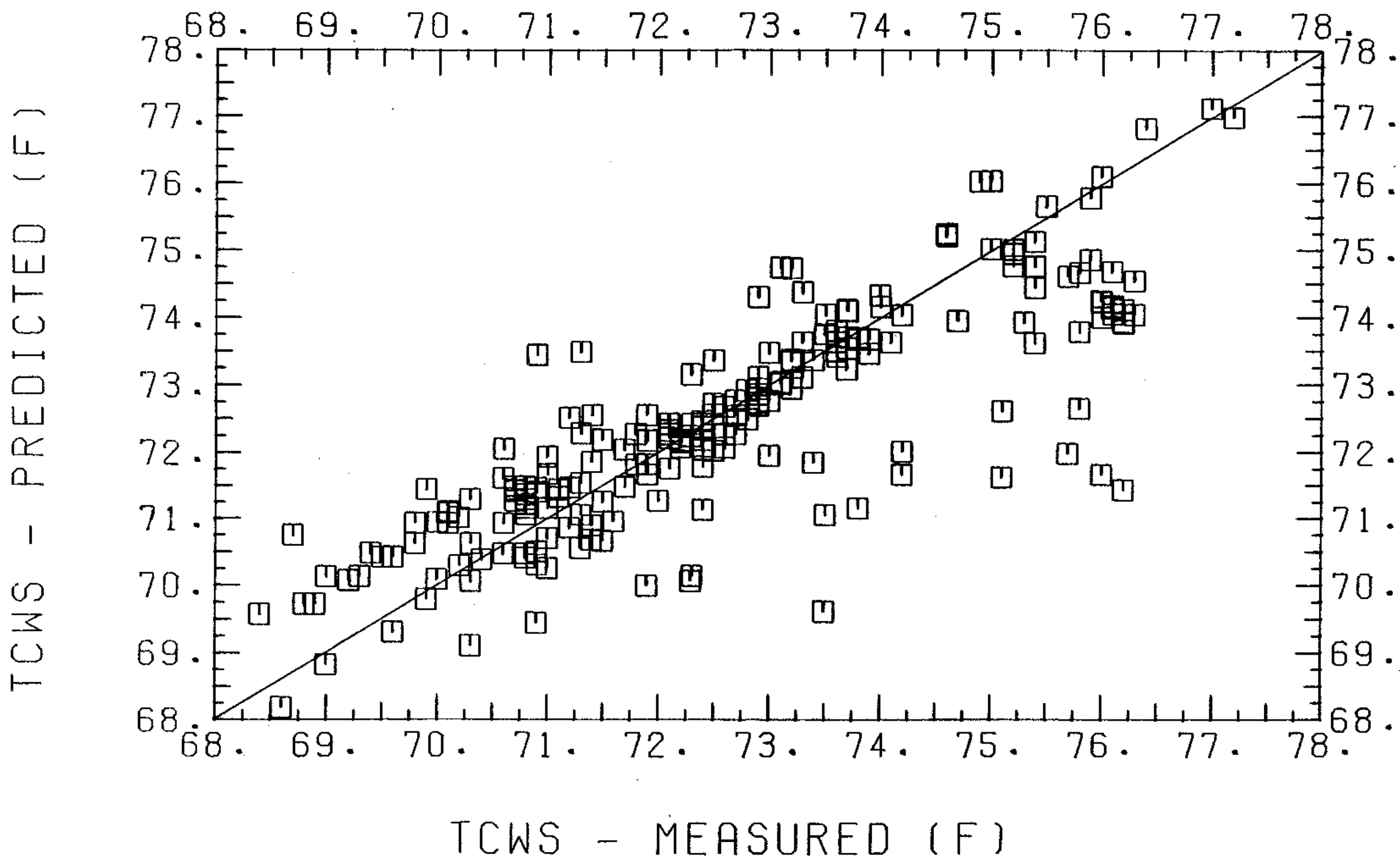



Figure 2.18 Predicted Condenser Water Supply Temperatures Using First Data Tape and No Sump Versus Measured Data

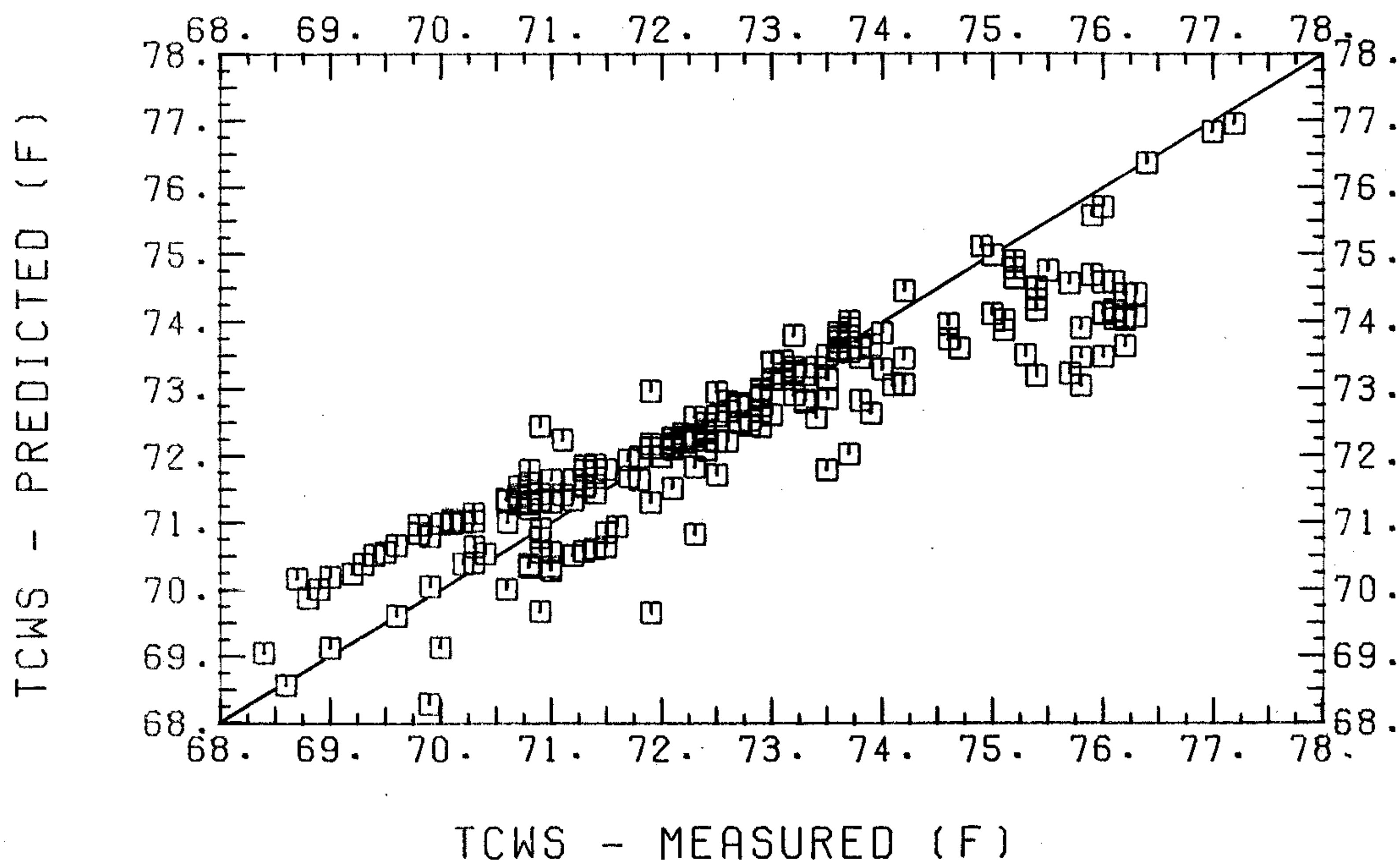



Figure 2.19 Predicted Condenser Water Supply Temperatures Using First Data Tape and Sump Versus Measured Data

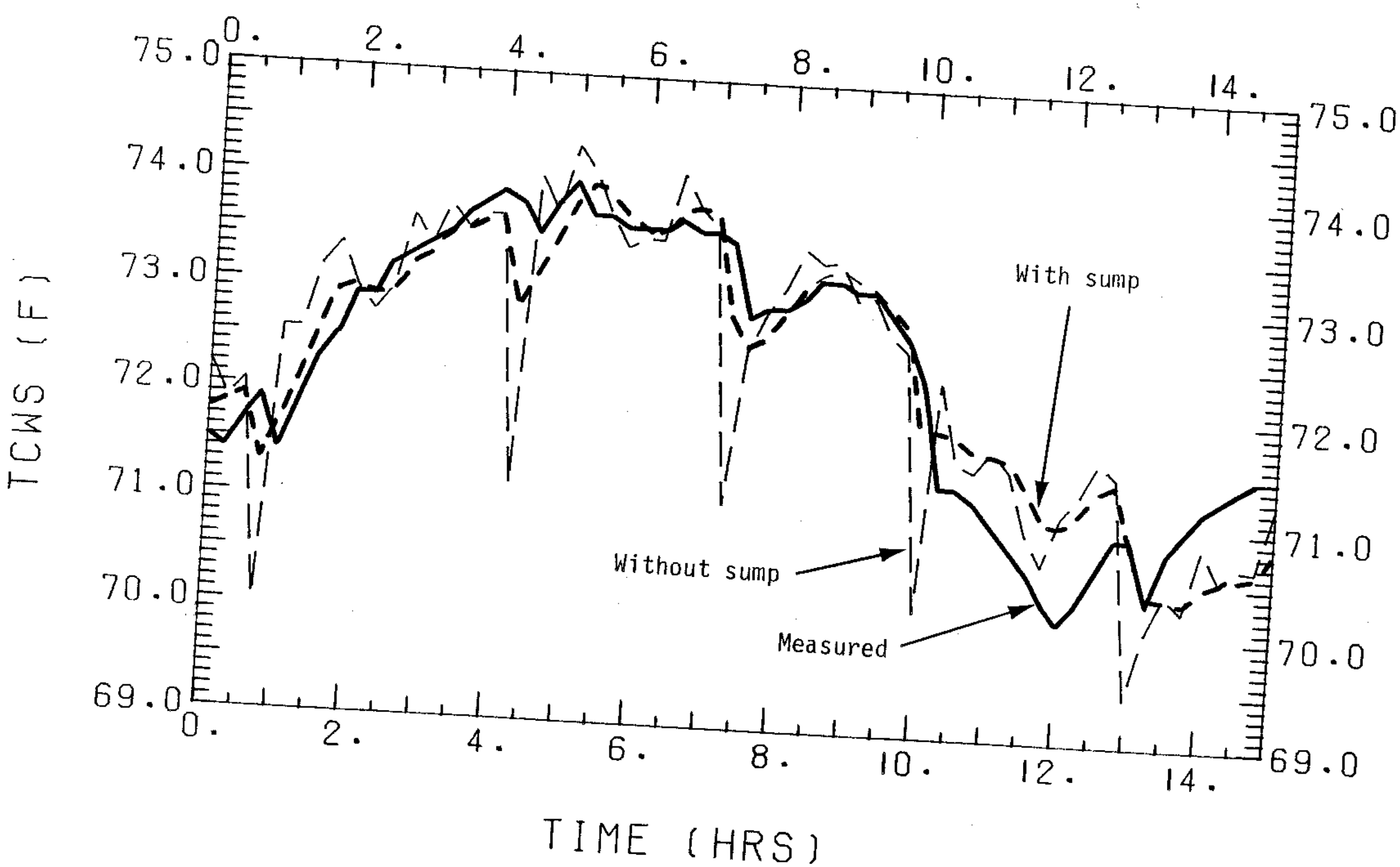



Figure 2.20 Predicted and Measured Condenser Water Supply Temperatures Versus Time

### 2.1.3 Pumps

#### 2.1.3.1 Model Development

There are three sets of electric-driven, centrifugal pumps in the plant: primary, secondary and condenser. The six primary pumps are designed to operate in a one-to-one correspondence with chillers and their main flow resistance is the two-pass evaporator. The pumps are fixed speed and their flow can only be controlled by automatic valves on each evaporator.

The four secondary pumps are designed to circulate the water through the site with the cooling coils as the primary source of resistance. Two of the pumps are variable-speed and two are fixed-speed. In operation, the variable-speed pumps are used until the flow rate becomes large enough that three pumps are needed. Then, constant full-speed operation is used for all pumps.

The six condenser pumps circulate water between the chiller condensers and the cooling tower. The main resistance is the condenser tubes. Three of the pumps are variable speed and half are fixed speed. As with the secondary pumps, the variable speed pumps are used up to the point when flow requirements dictate the use of four pumps. Then, all pumps are run at full speed. The condenser pumps run in a one-to-one correspondence with chillers, as do cooling tower cells.

As discussed earlier, the hydraulic system is quite large and complex. Detailed dynamic modeling of the water circuit would be extremely difficult and of questionable value. Therefore, the approach taken was to correlate the pump electric demand characteristics to flow

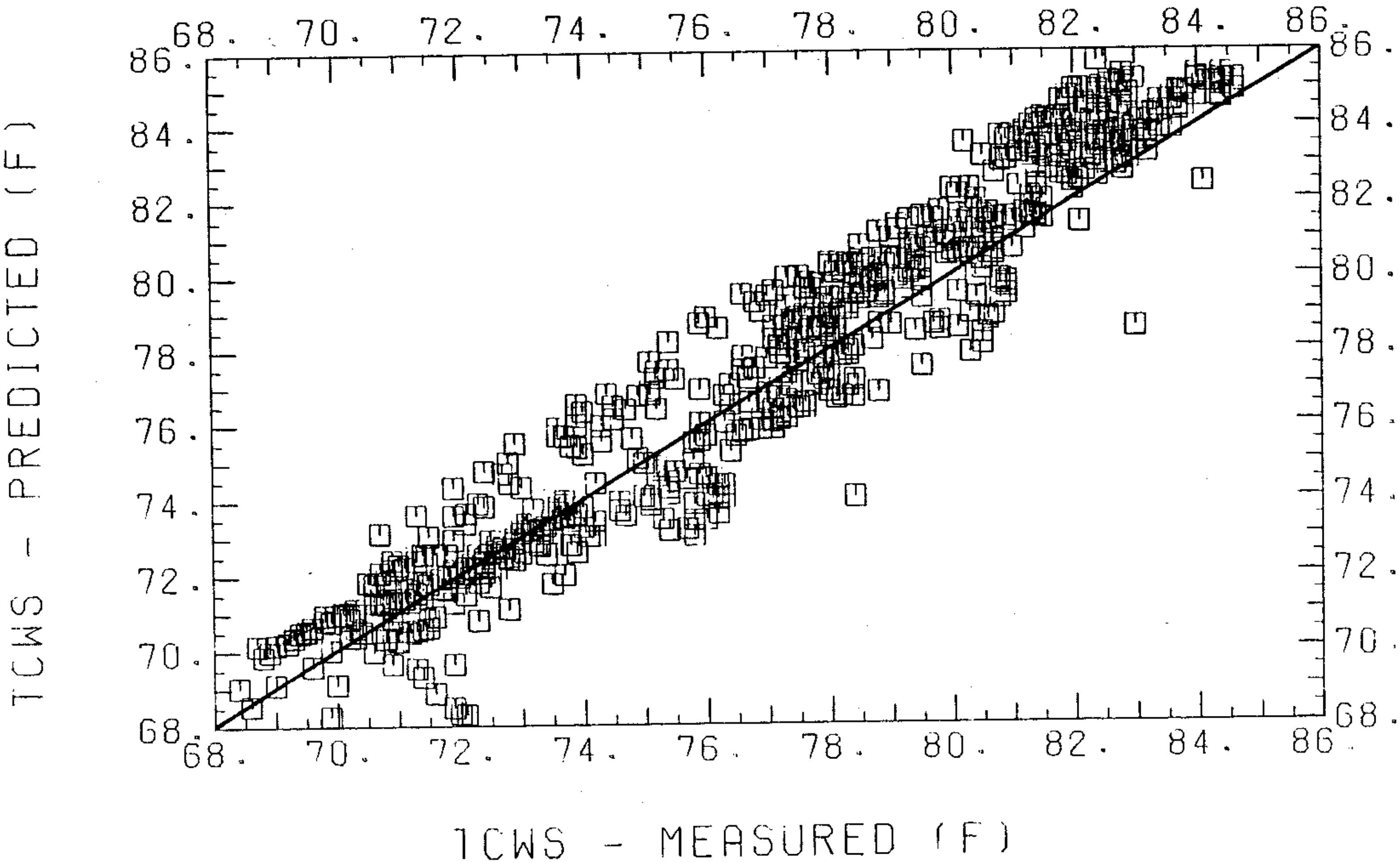



Figure 2.21 Predicted Condenser Water Supply Temperatures Using Four Data Tapes Versus Measured Data

rate. This is advantageous because flow rates are controlled and are essentially known at any time. Thus, it is easy to obtain the pump power with this model. In general, the model calibration results presented next show that this empirical method is a viable one.

2.1.3.2 Model Calibration

Each of the flow networks is made up of a combination of parallel and series flow paths. If there were no series paths and pump efficiency was constant, then the pumping power when two pumps are on should be twice the pumping power when one pump is on. In other words, the pumping power per pump should correlate well with flow per pump, regardless of the number of operating pumps. Since most of the pumping resistance should be in the parallel legs, this type of correlation was tried. The correlation to number of operating pumps was also investigated.

Though the data are scattered, there is no evidence that there is a dependence on the number of operating pumps for any of the three pump sets. This indicates that the parallel flow resistances dominate the picture.

The primary pump data are presented in Figure 2.22. Over the flow range studied, the per pump power consumption is essentially constant at 26 kW. The minimum flow is limited by sensors in the evaporator line that shut the chiller down if flow is below 1800 GPM. The modeled range is 1800-2500 GPM.

The secondary pump data is shown in Figure 2.23. Here, a quadratic curve was fit to the data with reasonably good success.

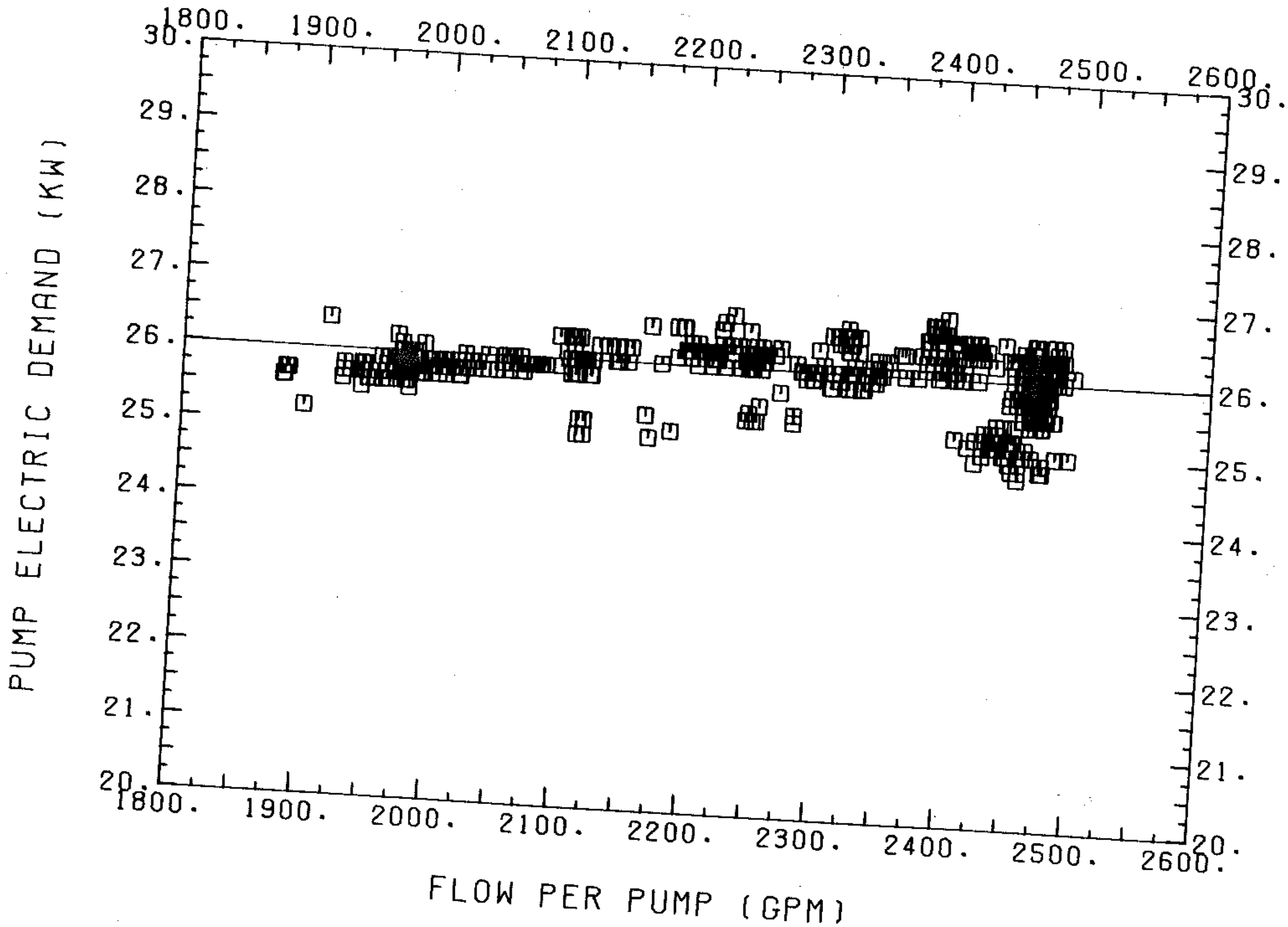



Figure 2.22 Measured Primary Pump Electric Demand Versus Flow Rate

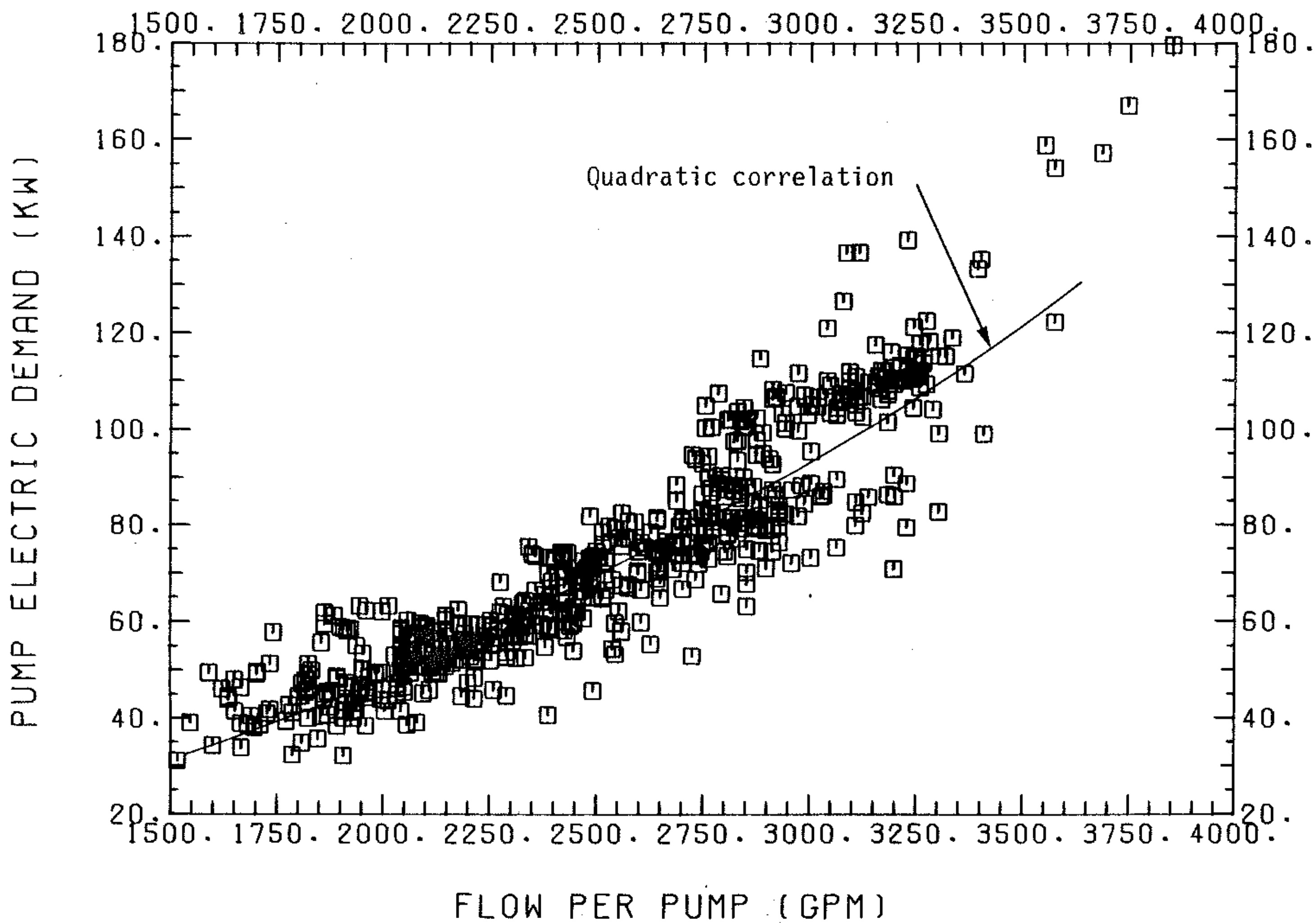



Figure 2.23 Measured Secondary Pump Electric Demand Versus Flow Rate

There is an R-squared (coefficient of determination) of 82% and a standard error of estimate of 10 kW. The coefficient of determination can be interpreted as the amount of variation in the dependent variable that is explained by the correlation. The standard error of estimate is a measure of how much the actual dependent variable differs from the predicted value (by the least-squares curve).

Figure 2.4 shows the condenser pump data. Again, a quadratic curve was fit to the data with an R-squared of only 41% but a standard error of estimate of 6 kW.

In general, the data exhibited significant scatter when plotted as discussed. Unfortunately, no good parameters were found for improving the quality of the correlation. On the other hand, pumping power is quite a bit smaller than the chiller power, typically 15-25%. Thus, there is little point of improving the pump correlations before a better chiller model is developed.

### 2.1.4 Storage Tanks

There are five, 100,000 gallon storage tanks for chilled water. They are above ground and are heavily insulated with four inches of polyurethane. To eliminate mixing of warm return water with the chilled water, one tank is filled while the one beside it is drained. Consequently, the storage capacity of one tank is not utilized.

There is also an unplanned limitation to the tank capacity. Because of the placement of the inlet and outlet piping, shown schematically in Figure 2.25, there is an inaccessible volume in the top and bottom of each tank. This results in an actual usable water

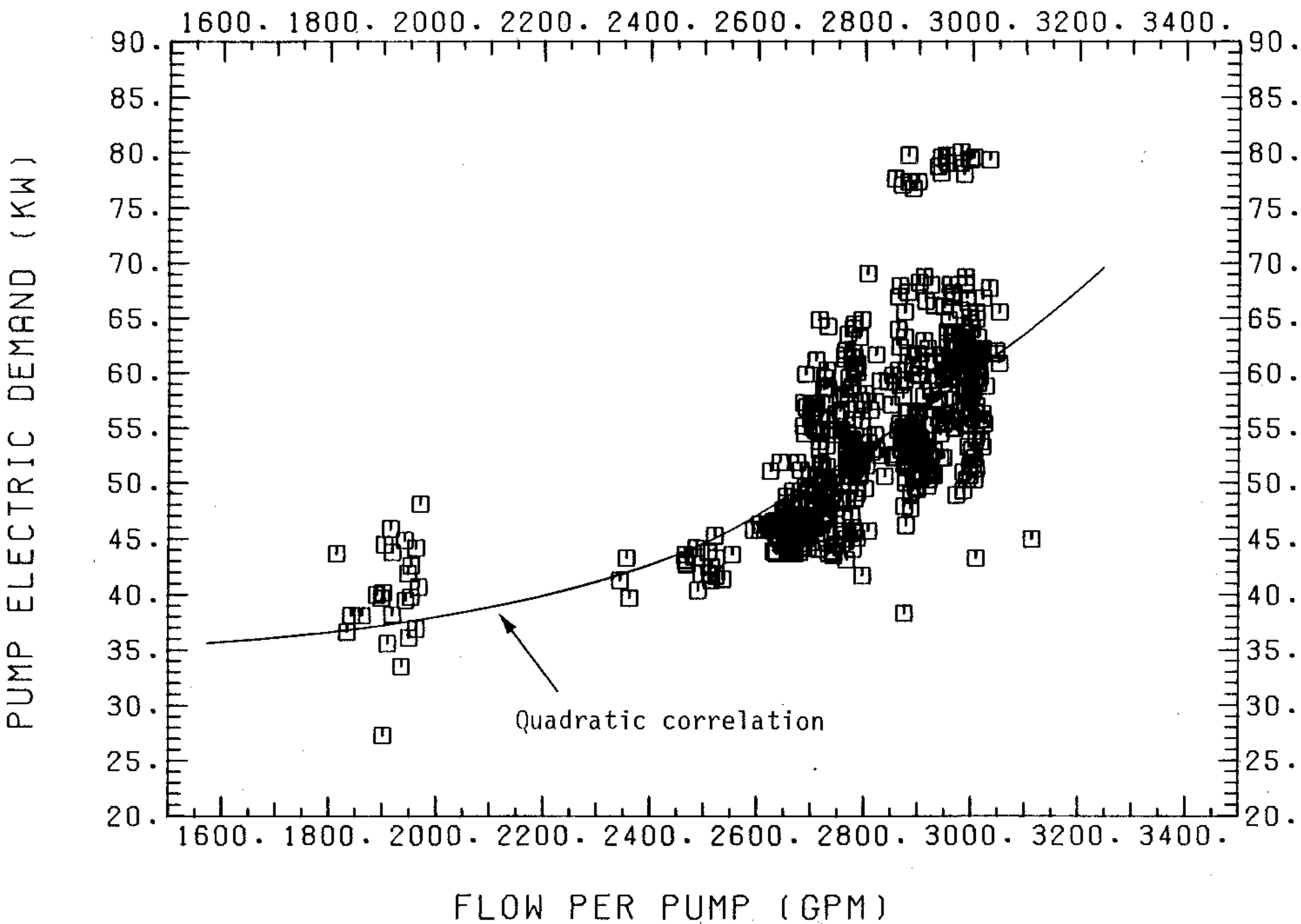



Figure 2.24 Measured Condenser Pump Electric Demand Versus Flow Rate

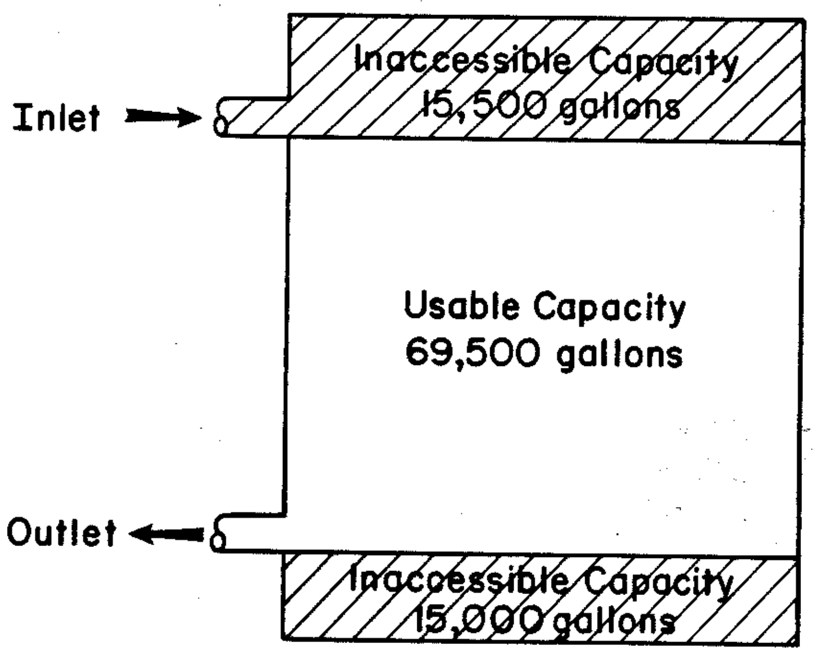



Figure 2.25 Storage Tank Capacity Limitations

volume of 69,500 gallons per tank for a total of 278,000 gallons.

The presence of the inaccessible capacity in the bottom of each tank is unfortunate because the temperature upon filling can only approach the temperature of the water being supplied. For example, suppose the tanks are being recharged at night and the temperature in each is 53 F. After being drained to the lower limit, chilled water at 44 F is supplied to the tank. Thus, the 69,500 gallons of chilled water mix with the 15,000 gallons of warm water and the result is a mixed temperature of about 45.6 F, which is 1.6 F higher than the chilled water supply temperature. Consequently, the tanks cannot supply as much cooling as if there were no residual water.

The computer model of each variable-volume storage tank assumes that the water is fully mixed. This is a good assumption in this case because of the piping configuration and the relatively high flow rates. This model is a standard TRNSYS component and no calibration was needed.

### 2.1.5 Site Chilled Water Circuit

#### 2.1.5.1 Model Development

The site chilled water circuit is a complex arrangement of supply and return piping, chilled water coils, and automatic valves. A simplified schematic of the system is shown in Figure 2.26. The buildings and coils are essentially all plumbed in parallel. Each air-handling unit (AHU) controls a corresponding automatic valve on the water circuit in an attempt to maintain the desired air temperature

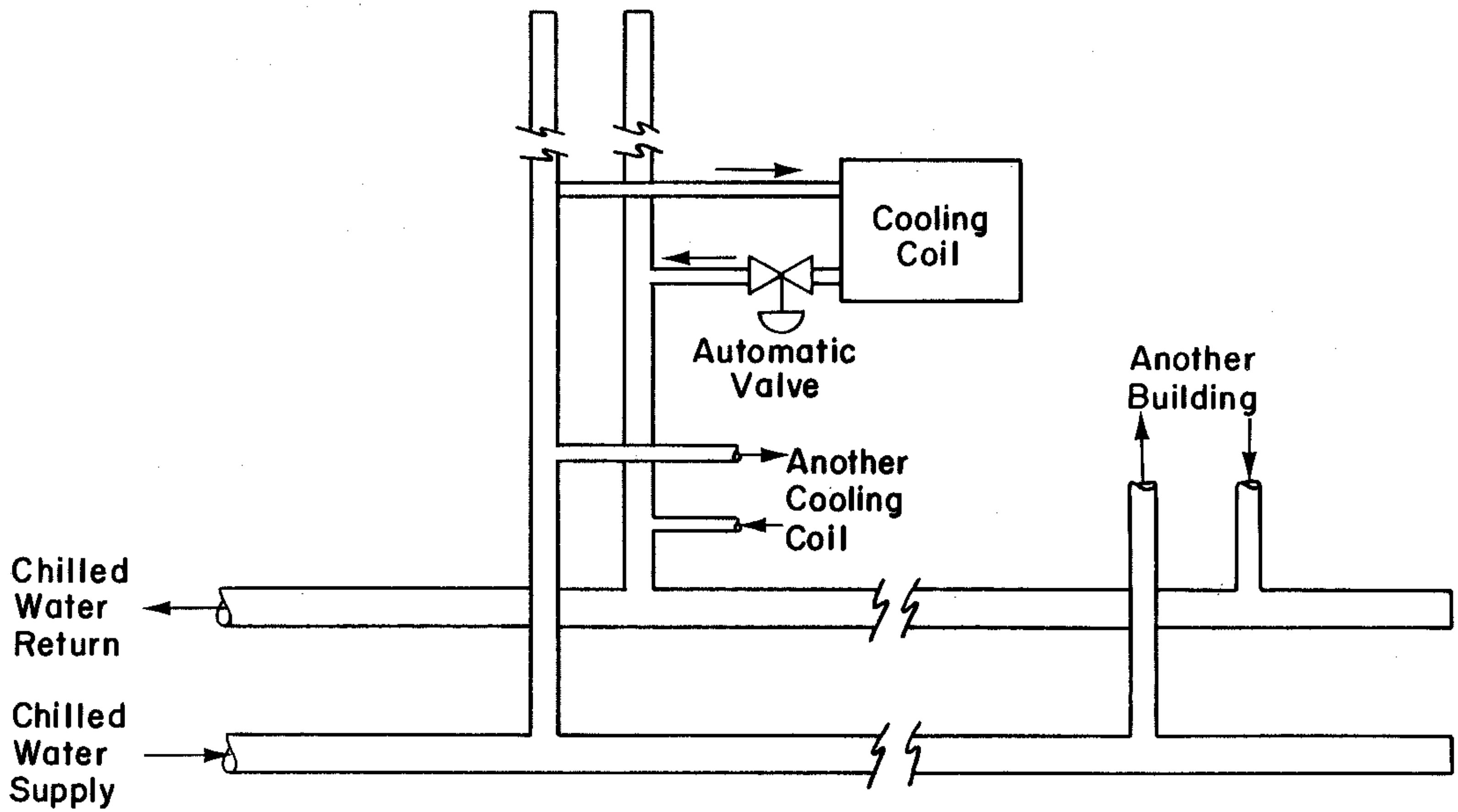



Figure 2.26 Schematic of the Site Chilled Water Circuit

leaving the AHU. Thus, as load goes up, the automatic valve opens up to allow more water to pass. Conversely, as load goes down, the valves close to reduce the water flow.

To control the secondary pumps, one or more pressure differentials are monitored at strategic coils. The variable-speed secondary pumps are then automatically adjusted to maintain a set differential pressure at the strategic coil or coils. Therefore, as load goes up and the automatic valves open, pressure differential drops, signaling the pumps to speed up and provide more flow.

An empirical approach was used to describe the site characteristics. The primary relationship desired was one relating the site water flow rate to the site chilled water load. Because of the variable-speed pumps and parallel flow circuits, a first guess of this relation was that flow would be directly proportional to the load. In other words, the temperature rise across the site would be constant. This basic hypothesis was tested and modified as described in the next section.

2.1.5.2 Model Calibration

To test the hypothesis that site flow is directly proportional to load, 15-minute data from the last two tapes were plotted and are shown in Figure 2.27. There definitely appears to be a proportionality as suspected. However, there seems to be another factor influencing the site flow rate.

A further examination of the data showed that the chilled water supply temperature ranged from about 40.5 to 46.0 F. Since the chilled

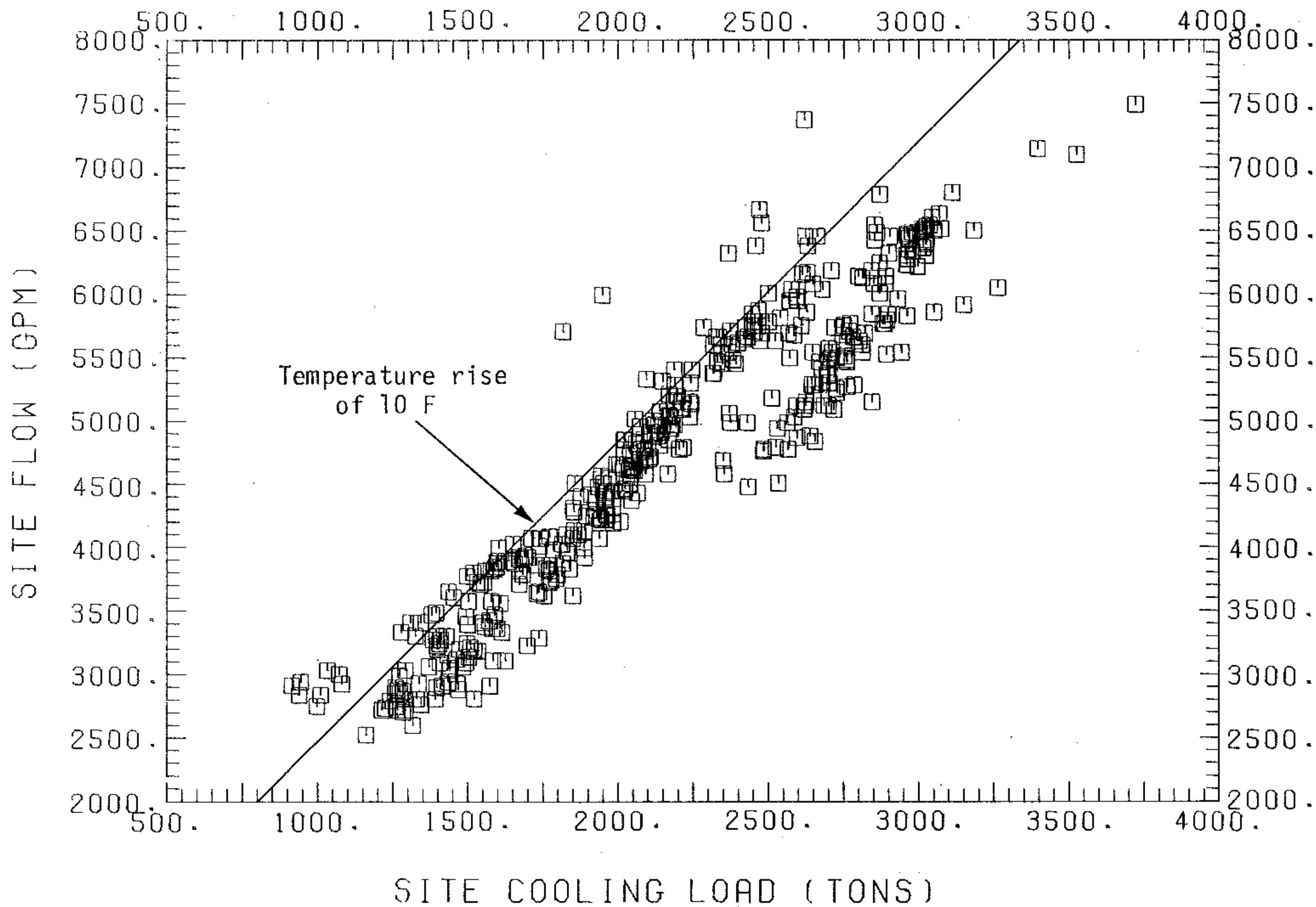



Figure 2.27 Measured Site Chilled Water Flow Rate Versus Cooling Load

water supply temperature affects the behavior of the cooling coil, this parameter was a tested as a correlating variable. The chilled water temperature rise was plotted versus the chilled water supply temperature in Figure 2.28. Rather than a constant proportionality factor, the chilled water temperature rise can be used as a variable proportionality factor relating the flow to the load. At steady-state, an energy balance on the water coils yields:

$$\dot{Q}_c = \dot{m}c_1(TCHWR\text{-}TCHWS) \qquad [2.21]$$

or rearranging:

$$\dot{m} = \dot{Q}_c \ / \ [c_1(TCHWR\text{-}TCHWS)] \qquad [2.22]$$

A least-squares line was fit to the data in Figure 2.28 to define the chilled water temperature rise as a function of supply temperature. There is some scatter to the data yet a trend is apparent. Some of the scatter is likely due to thermal transients in the chilled water system caused by the long pipe runs and changes in supply temperature. Some of the scatter may also be caused by the incorrectness of this simple correlation for this complex system. On the other hand, the correlation could be considered quite good given the system complexity.

The site chilled water circuit is described by the model:

$$\begin{aligned} \dot{m} &= f(\dot{Q}_c, TCHWS) \qquad [2.23] \\ &= \dot{Q}_c \ / \ [c_1(a_1 + a_2 TCHWS)] \end{aligned}$$

This relationship was used to predict the site flow rate and the predicted values are plotted versus the measured flow rate in Figure 2.29. The agreement is quite good with an RMS error between predicted

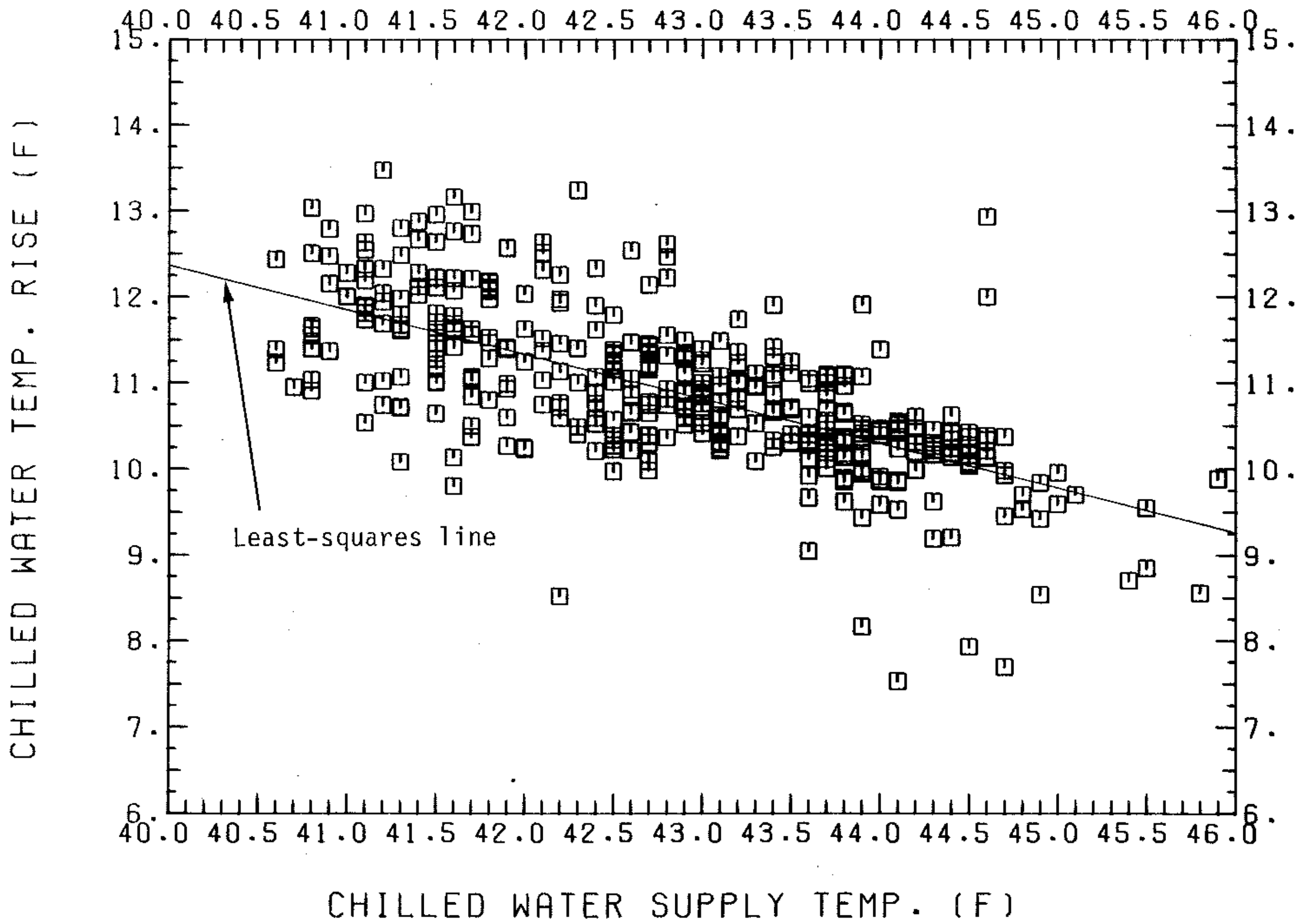



Figure 2.28 Measured Chilled Water Temperature Rise Through the Site Versus Chilled Water Supply Temperature

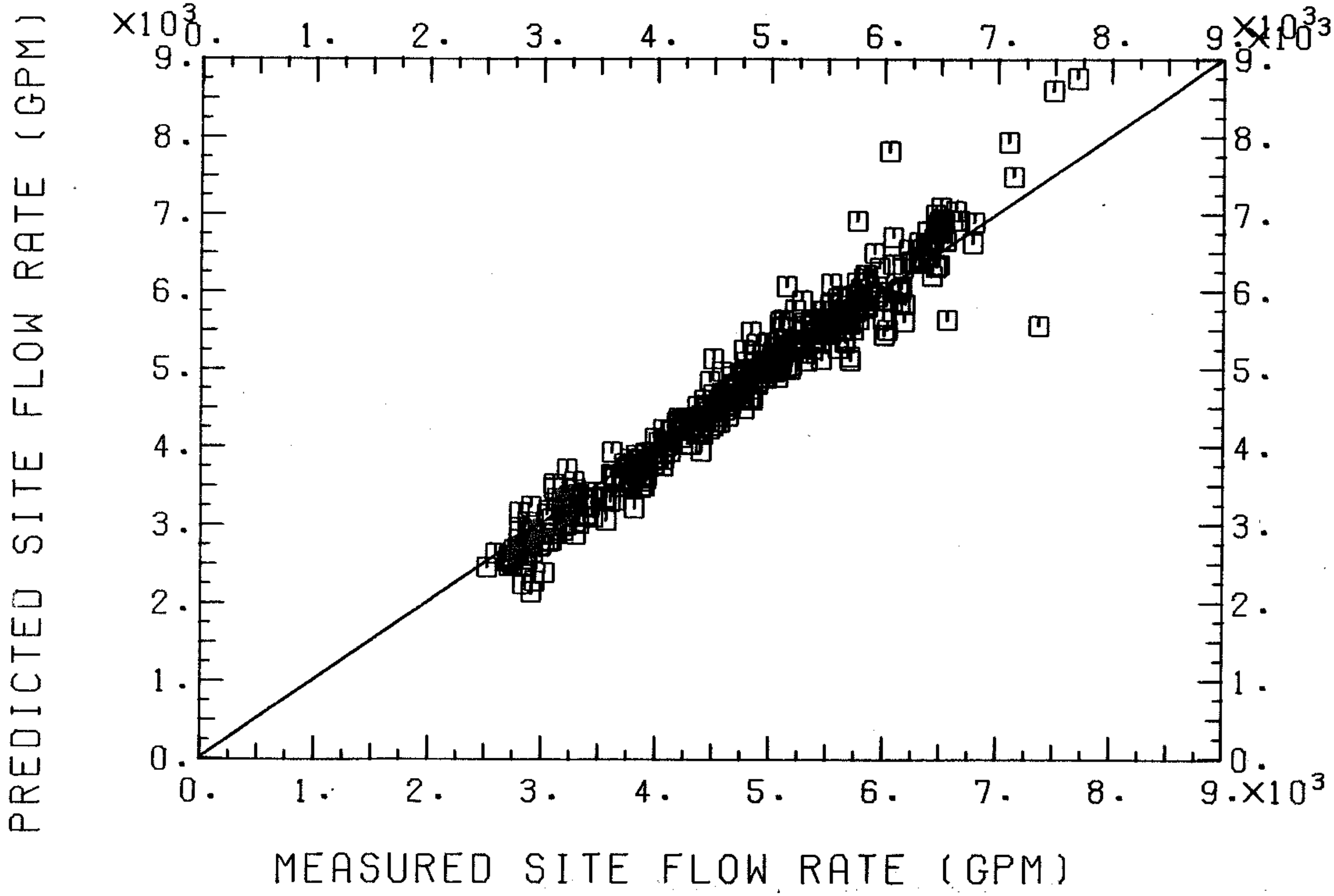



Figure 2.29 Predicted Site Flow Rate Versus Measured Data

and measured flow rate of 293 GPM. The average of the predicted values is only 16 GPM greater than the average of the measured values, about 0.3%.

### 2.1.6 Main Plant Control

In the modeling process, it was convenient to group most of the computer control routines into one TRNSYS component. The only computer controls not covered by this component are the cooling tower and condenser pump flow rate. The control routines that are covered in the main plant control include: mode selection, number of chillers, primary pump flow rate, and chilled water temperature setpoint. The basic operation of these strategies is patterned after the strategies implemented or planned for the actual computer system in the plant. In addition, modifications and other strategies are accomodated by the more general model.

#### 2.1.6.1 Mode Selection

As discussed in section 1.2, there are five basic operating modes for the system. To summarize, these are:

Mode 1: Chillers only

Mode 2: Storage used with chillers to meet load

Mode 3: Storage alone used to meet load

Mode 5: Freecooling, with cooling towers alone used to meet load

Mode 7: Chillers used to recharge tanks and meet load.

The free cooling mode, 5, is not considered because of its occurrence in winter, operational problems and because of the additional effort required for the modeling. The model can be modified to include this mode.

Mode 3, which is the use of storage alone, is an uncommon mode in the summer but is modeled. Thus, there are really only three basic operating modes of importance in the main cooling season: modes 1, 2 and 7. Mode 2 is used during the day to reduce the peak chiller load and consequently, the chiller electric demand. Mode 7 is used at night to recharge the tanks. When modes 2 or 7 are not activated, the default mode is 1 with chillers only.

A basic flowchart of the decision making within the mode selection routine is shown in Figure 2.30. In general, the storage modes, 2 (and 3) and 7, are scheduled to start at certain times of day. Also, mode 7 has a scheduled end-time so that it does not continue into the peak demand period. Mode 2, on the other hand, has only a scheduled start-time. Mode 2 is overridden by mode 7 so mode 2 could possibly stay on until mode 7 comes on again at night. However, mode 2 is typically activated in the morning and the tanks are usually exhausted by mid-afternoon.

2.1.6.2 Number of Chillers

The control of the number of operating chillers is specific to the mode of system operation. In all strategies studied though, the chillers are limited to 100% of design load.

In storage modes, 2 and 7, the number of chillers is dictated by the storage flow limits. The actual system has a maximum flow limit of 1500 GPM and the computer model has the capability to control the flow

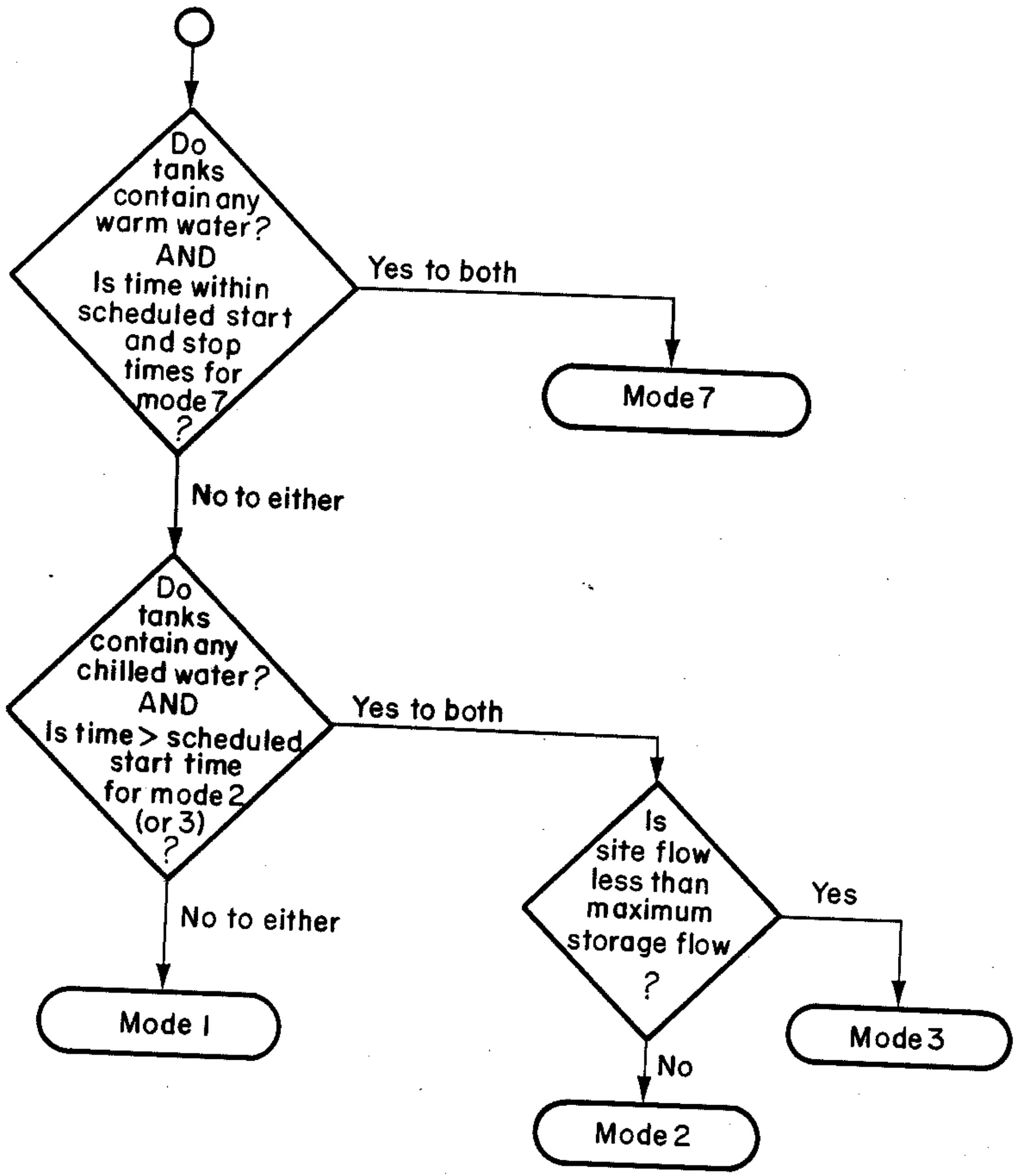



Figure 2.30 Flowchart of the Mode Selection Process

anywhere between a designated minimum and maximum. When in modes 2 or 7, the flow to storage is controlled by controlling the primary pump flow rate through use of the evaporator valves and the number of chillers. Site (secondary) flow is mainly a function of the coil cooling load and also a slight function of the chilled water supply temperature. By default then, the storage flow is the difference between the primary and secondary flows. In mode 2, the primary pumps must be controlled to flow less than the secondary. In mode 7, the opposite is true, the primary pumps must flow more than the secondary.

Primary pump flow can only be reduced to a certain point because there are built-in flow switches in the chiller evaporators. In practice, each pump can be varied from 1800-2500 GPM. Thus, there exists the possibility that a chiller may have to be turned on or off in order to keep the storage flow within the prescribed bounds.

In mode 1 with chillers only, the number of chillers can also be dictated by the temperature of water supplied to the site. Constraints in the buildings require that the chilled water supply temperature stay below 46 F. The chillers are typically set to produce 44 F water. At this temperature, the site temperature rise is about 10 F. When the site flow equals the maximum primary pump flow (2500 GPM), the load is only about 1050 Tons or 84% of design capacity of the chiller. As the load increases, the excess site flow causes some warm water to bypass the chillers and mix with the chilled water leaving the plant. Thus, the site sees a higher supply temperature and the site temperature rise goes down slightly. The net effect back at the plant is an increase in the temperature of the warm return water and an increase in the site flow.

In order to reach full load (1250 Tons), the chiller evaporator must have a temperature difference of 12 F on the water side. If the chilled water temperature leaving the chiller is 44 F, the warm return water must reach 56 F. To do this, the supply temperature would have to be greater than 46 F because at 46 F, Figure 2.28 shows that the temperature rise is 9.25 F. This results in a return temperature of 55.25 F.

There are two simple solutions to this problem. One is to turn on another chiller which is the method used in the simulation. Another answer is to reset the chiller chilled water temperature setpoint to a lower value. For example, if 43 F were set, the return water would only have to reach 55 F to reach full load at the chiller.

2.1.6.3 Primary Pump Flow Rate

In mode 1, primary pump flow is adjusted in an attempt to maintain the primary pump flow 0-500 GPM greater than the secondary pump flow. In this manner, the temperature of the chilled water supplied to the site is essentially the temperature leaving the chiller. As the load goes up, secondary pump flow eventually gets larger than the maximum primary pump flow and warm return water mixes with the chilled water and the site supply temperature goes up.

In mode 7, the primary pump flow is adjusted to maximize the flow to the storage tanks. In mode 2, a somewhat different technique is used to control the primary flow. This technique is based on the method carried out manually in the actual system.

When mode 2 is first activated, the number of chillers and primary pump flow are left at their previous condition, if storage flow is within limits. If the primary flow is greater than the secondary, then primary flow is adjusted to equal the secondary. As the site load and flow go up, the primary flow is maintained at the same setting and storage flow goes up to meet the added load (if storage flow is again within limits). Thus, as the site load goes up, the chiller load stays relatively constant because the primary pump flow and the site temperature rise are both relatively constant. If storage flow goes out of limits during mode 2, the flow is adjusted first and then the number of chillers in an attempt to keep storage flow near its upper limit.

2.1.6.4 Chilled Water Temperature Setpoint

The chilled water setpoint at the chiller is generally kept constant in the actual system. Two potential adjustments have been considered in this study. One is reduction of the setpoint during mode 7 in order to increase the cooling capacity of the storage tanks.

Another adjustment studied deals with the setpoint throttling range built into the internal chiller load control of each chiller. The actual chilled water supply temperature is only equal to the setpoint at full load. As load decreases, so does the chilled water supply temperature as shown in Figure 2.4. This reduction in temperature and resultant increase in chiller electrical demand can be counteracted by automatic reset of the chilled water setpoint.

### 2.1.7 Storage Tank Control

There are five storage tanks in the actual system and also in the simulation. The actual system has a separate, dedicated microprocessor to control the filling and draining of tanks. Similarly, a control component was also required in the modeling.

In the simulation, the storage tank control keeps track of which tank is being filled and which one is being emptied. When a tank empties (reaches its minimum usable capacity), the control shifts to the next tank and begins to empty it. At the same time, the tank which was just emptied should begin to fill. Herein is where difficulties arise in the simulation.

It is quite possible that a tank would more than empty in a given simulation time-step (30 minutes). There is no problem drawing the required amount from the initial tank until empty and then moving to the next tank for the remainder. The problem is in the filling of the tanks. When the initial tank fills, the remaining flow should be sent to the tank which empties this time-step. However, if this flow were sent during this time-step, it would effectively mix with what was going out. This mixing could be significant. For example, suppose the tank (tank A) being drained at the start of the time-step had 20,000 usable gallons left. If storage flow were near the maximum rate of 1500 GPM, then a total of 45,000 gallons of water would need to flow through storage. This would effectively drain the current tank and draw 25,000 gallons out of the next (tank B). If 25,000 gallons of water were sent to tank A this time-step, they would mix with the 20,000 going out. Thus, the water temperature leaving tank A would be roughly halfway between the chilled water supply and return temperatures.

To overcome this obstacle without going to very small time-steps or modifying the existing tank model, the storage control effectively holds the flow that would carry over until the next time-step. It is then added to the flow going into the now empty tank. In addition, the storage control signals the mode control to continue the same mode so that the carry-over flow is properly distributed.

A second unique function of the storage control, stemming from the time-step, is flow limiting when the tanks completely recharge or discharge. This is similar to the carry-over problem when tanks change but now there is no holding of flow. Rather, the storage control sets an output equal to the storage flow that is in excess of that required to complete the tank cycle. The main control responds by reducing the storage flow rate as required.

### 2.1.8 Storage Outlet Mixing Valve

A component was written to mix the flows leaving the five storage tanks. This is a simple routine in which the outlet temperature is the mass flow weighted average of the inlet water temperatures. The water flow rate leaving the valve is a sum of the flows entering. No validation was necessary.

### 2.1.9 Cooling Tower Control

The two-speed fans in each tower cell allow some degree of flexibility in tower fan control. At low speed, each cell fan draws a nominal 4 kW, while at high speed, the power demand is 24 kW. The basic tradeoff involved in lowering fan speed is the higher condenser water temperature and the resultant increase in chiller electrical demand.

Cooling tower controls can be grouped into four levels. The first two levels are adjusted manually and were not studied. The first and simplest level is constant speed setting. The second level is thermostatic control of the water temperature leaving the tower. An on-off type thermostat, with hysteresis, controls the fan speed to maintain the setpoint temperature within a few degrees, if possible. Unless the setpoint is adjusted as the ambient wet-bulb temperature and water load change, this simple control results in frequent fan cycling and little improvement over constant fan speed.

A third and more complex level is approach control. Instead of controlling water temperature which is highly dependent on the wet-bulb temperature, the difference between water temperature and wet-bulb (approach) is controlled within certain limits, if possible. With this level of control, the fan speed more correctly follows the load and should use less energy than the previous level. However, the best approach limits to use are not clearly defined. This control has already been implemented at the facility and is used as the base case for comparison.

The fourth and most complex level of control considered is that which models and/or measures component and system performance and chooses the control that results in minimum electrical demand. This level of control has been addressed by simulating the plant electrical demand for the many combinations of operating and control conditions and then finding the minimum demands and the control conditions for each combination of operating conditions.

### 2.1.10 Other Controls

There are a few control functions that are assumed to be built into the system and not adjustable as far as this study is concerned. In summary, they are:

1. Number of primary pumps equals the number of chillers.
2. Number of condenser pumps equals the number of chillers.
3. Number of cooling tower cells equals the number of chillers.

### 2.1.11 Special Outputs

The standard TRNSYS program has built-in output components such as printing, plotting, histograms and summaries. These were used extensively but a couple additional output capabilities were added to the program as components.

#### 2.1.11.1 Load Profile

To assist in studying the electrical demand and half-hourly profile, a component was written that writes output information monthly. The component has only one input, typically total electric demand, and over a month period, the following information is derived and printed for each half-hour demand interval over the day: mean, maximum and day of maximum, minimum and day of minimum, variance, and standard deviation. In addition, the component prints out the demand profile for the peak day of the month. The total electrical usage and peak 30-minute demand for the month are sent to the next special output, the utility bill.

2.1.11.2 Utility Bill

The utility bill is composed of two parts, a consumption charge and a demand charge. There is a flat rate for demand per kilowatt and is based on the maximum 30-minute average demand over the previous 12 months, called the billing demand. In effect then, the actual demand penalty for exceeding the billing demand is 12 times the monthly demand penalty.

The consumption charge is computed based on the consumption and the billing demand and in effect, there is a small demand charge built into the consumption charge. To illustrate, consider the example in Table 2.1. The explicit demand charge in the rate schedule is $2.46/kW, yet the effective charge from Table 2.1 is $2.71/kW, about $0.25 higher. The effective charge is a function of both the consumption and demand but appears to always be somewhat higher than the explicit rate.

Table 2.1 Effective Demand Charges

| Monthly Consumption (MWh) | Billing Demand (kW) | Bill ($) | Effective Demand Charge ($/kW) |
|---|---|---|---|
| 4247 | 7879 | 155,193 | - |
| | 9000 | 158,233 | 2.71 |
| | 10,000 | 160,946 | 2.71 |

## 2.2 Comparison of Overall Plant Simulation with Measurements

As a check of the entire plant simulation model, the model was used to predict the total plant electric demand for a two-day period in July for which good measurements were available. Only two measured inputs were used to force the plant simulation, total chilled water load and ambient wet-bulb temperature. All other controls and component models were as described in section 2.1.

The results are shown in Figure 2.31. A time-step of 15 minutes was used in the simulation to match the data interval. As can be seen from the plot, the agreement is quite good. The difference between the total consumption for the period shown is 1.1%, with the predicted lower than measured. The RMS error for the 15-minute points is 158 kW, which is on the order of 10%. However, error in the measured cooling load, wet-bulb and/or electric demand can account for the larger 15-minute discrepancies.

# 3. DEVELOPMENT OF THE SITE CHILLED WATER LOAD MODEL

The site is comprised of about ten main buildings with a total of over 30 air-handling units and zones. In addition, many of the buildings have distinct perimeter zones which have perimeter induction units with both cooling and heating capabilities. In order to model this large and complicated facility, many approximations were required.

Initially, all of the zones were to be lumped into one large zone with equivalent external surface areas and orientations and internal heat gains. This zone would have been served by one large air-handling unit (AHU). Thermal capacitance would have also been modeled in a lumped manner.

This initial approach was compared with the measured loads which led to the observation that actual loads were considerably smaller than the lumped model's predicted loads, particularly during the second and third shifts. It was then realized that certain zones were unoccupied for these shifts and that the appropriate AHUs were being shut down. Because of the load discrepancies and the scheduled shut-down of specific AHUs, a considerably more detailed approach was used.

The site was broken into several zones based primarily on the desire for unique AHU scheduling and actual zoning. In addition, physical position and geometry played a role in choosing zones. For example, the two, long, heavily glazed corridors were each modeled as a distinct zone. As a result, there were 15 unique zones defined as illustrated in Figure 3.1.

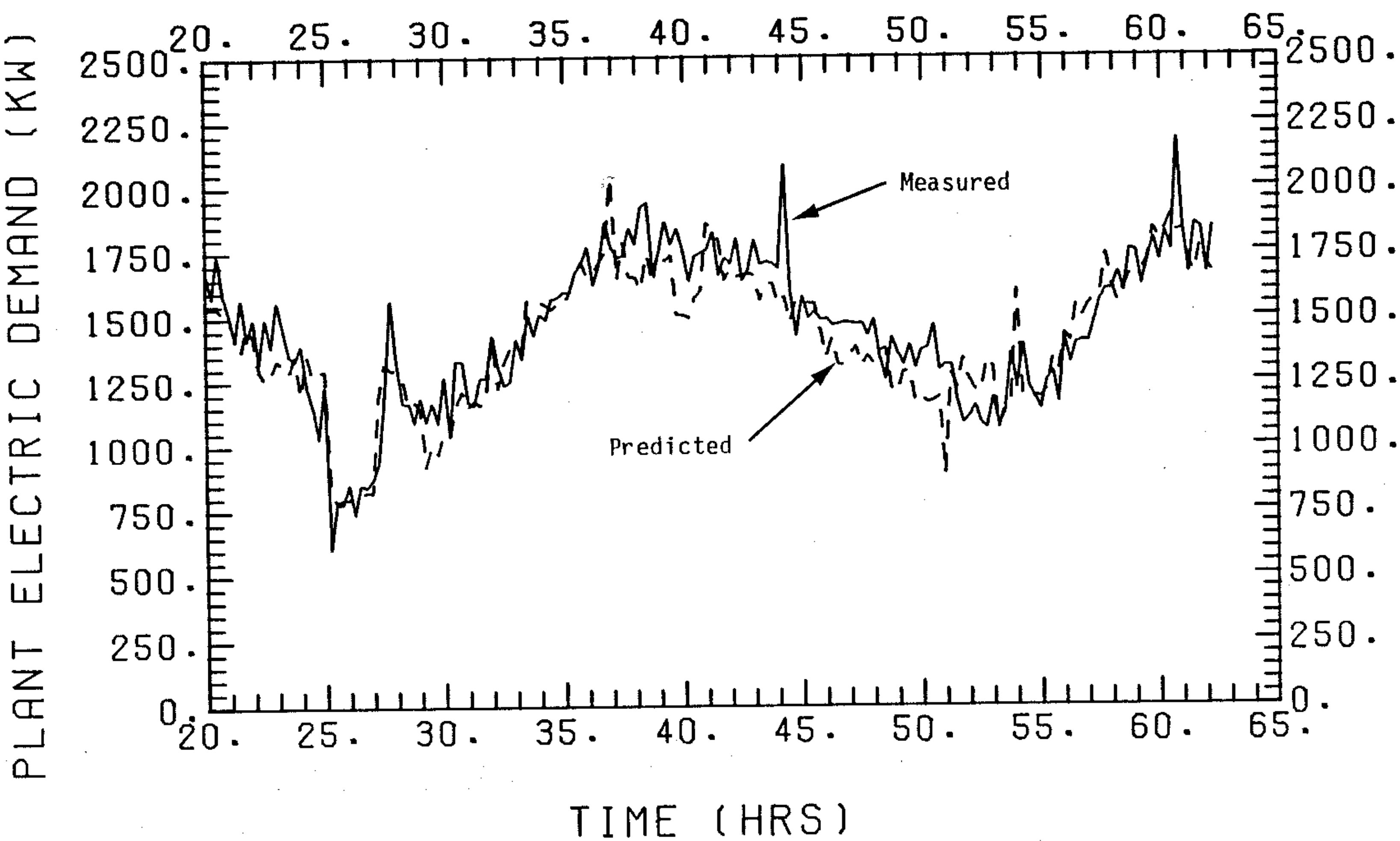



Figure 2.31 Simulated Plant Electric Demand Versus Measured Data

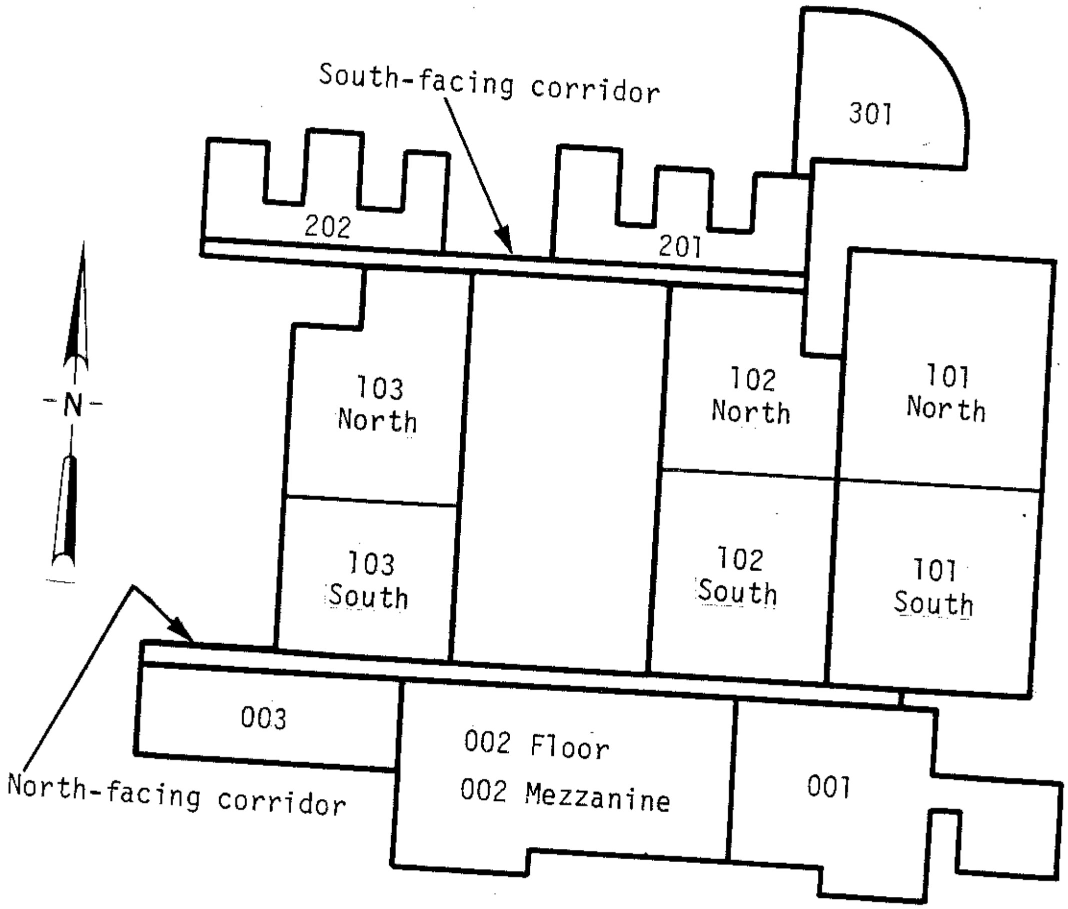



Figure 3.1 Plan View of the Site Showing Zone Breakdown

Each zone has scheduled inputs for lighting, people and miscellaneous electric loads. Weather data is also used as input to the building simulations and includes solar radiation, dry-bulb temperature, wet-bulb temperature, and wind speed. To meet the heating and cooling loads, each zone is coupled to an AHU with unique characteristics such as fan capacity, thermostat setpoints, outside air requirements and enthalpy economizer cycle. Internal mass is also uniquely defined for each zone based on usage and typical values.

Because of the sheer size of the TRNSYS simulation that would have been required to model all of the zones, AHUs and schedules, the site model was broken into four separate simulations. The zones modeled in each are:

1. 201, 202, 301, South-facing corridor
2. 101N, 101S, 102N, 102S
3. 103N, 103S, North-facing corridor
4. 001, 002 Floor, 002 Mezzanine, 003

For each of these simulations, pertinent load, electric, and weather data were written into an output file and after all four files were completed, another short program combined the information into one total file. This file was then used for input to the plant simulation model.

In the remaining part of this section, the zone and AHU models are described and then the predicted chilled water load is compared with the measured.

## 3.1 Components

### 3.1.1 Zone

The component used to model each zone was developed for version 12.1 of TRNSYS. It is a very detailed model which formulates and solves a set of heat transfer equations describing the zone at each simulation time-step. Specific inputs and parameters are used to describe the space, walls, floors, ceilings, windows, internal partitions, or walls separating zones at different temperatures.

In contrast to the common ASHRAE technique of lumping radiation and convection into a single constant coefficient, this model solves for radiative heat transfer to or from each surface. This should improve the accuracy of the model particularly for zones which can have significantly different surface temperatures. For example, a zone with large amounts of glazing, like the corridors, can have quite different temperatures on the interior glass surface and the floor. The main drawback to this technique is that a physically and geometrically correct model of each zone is required since the radiation heat transfer is dependent on surface characteristics and view factors.

The zone model is used in a temperature level control mode (mode 2) where the zone temperature and humidity are a balance between internal gains, ambient heat transfer, and cooling (or heating) equipment input. Heat is added or removed from the space by a ventilation flow stream. In this case, the ventilation flow stream comes from the air-handler component. Zone temperature controls are built into the air-handler model.

Rather than describe each zone in detail here, the major assumptions and considerations are discussed. Details of the zones can be determined from the listings in Appendix B.

First, and perhaps foremost among the assumptions, are the internal heat gains due to miscellaneous electrical equipment. This equipment includes such things as cathode-ray tubes for computer terminals, the computers themselves, manufacturing processes, environmental test chambers, material-handling machinery, and other office machines. Lights are handled separately and are generally easier to quantify because they are usually scheduled and installed wattage can be determined for each zone. On the other hand, the various equipment usage can vary from minute-to-minute and day-to-day. Further, the thermal distribution of the electrical heat generation in the zone is difficult to quantify.

Since the miscellaneous equipment heat gains are typically over half of the zone cooling loads, it is extremely difficult to predict cooling load with a high degree of certainty. For this study, equipment gains were assumed to be constant for each of three shifts during the day. The site personnel provided best estimates of these internal gains on a zone and shift basis. These estimates were essentially based on long-term electrical consumption data recorded by the minicomputer system.

A second, less important approximation is the lumping of smaller zones into large ones. There are two concerns with this approach. One involves the lumping of perimeter zones with interior zones. In warmer weather, this is not serious because both zones would require cooling.

However, in colder weather, exterior zones might require heating while interior zones would require cooling. By lumping the two zones together, the heat gains in the interior zone could offset the losses in the exterior zones. Consequently, both the estimated heating and cooling loads would be less than actual. A second concern is the internal radiation exchange. The actual radiation picture in a zone is quite complex given the many interior partitions and unique geometries. In the TRNSYS zone model, the mode is used in which all surfaces have a radiation view factor in proportion to their surface area relative to the total zone surface area. This is effectively modeling the zone as a sphere with all surfaces on the sphere.

A third assumption which can affect the estimated cooling loads is the ground floor heat transfer into (and out of) the earth. This factor is often insignificant for multi-story buildings, but in this case, many of the buildings are single-story with a large floor area in contact with the ground. The BLAST II manual (9) recommends that the earth temperature beneath the floor be determined by averaging the zone temperature and the undisturbed earth temperature which the manual lists for several locations. Earth temperature for climates similar to Charlotte is about 70 F in summer. During the major part of the cooling season, zone temperatures average about 80 F (due to AHU shut-down). Therefore, a constant ground temperature of 75 F was assumed to be present at the bottcm ot the slabs. The slabs are six inches thick, but were modeled as twelve inches thick to partly account for the additional mass of the earth immediately below the slabs.

### 3.1.2 Air-Handler

The air-handling unit model was developed specifically for this study. Included in this component are the supply fans, cooling coil, outside air interface, and all associated controls. Outside air flow can be controlled to be either constant, a constant fraction of the supply air flow, or dependent on enthalpy difference in an economizer mode. Nearly all of the zones but the computer area and 101North use the economizer mode when applicable. When economizer operation is not used or applicable, outside air flow is controlled to be a 10% fraction of the supply air flow rate.

All of the AHUs modeled have variable-volume fans which adjust flow by varying the pitch of the fan blades. In the actual system, a static pressure setpoint at the AHU outlet is the operative control that affects the flow. There are terminal units in the zones which have automatic dampers controlled by appropriate thermostats in the zones. In operation, as the zone temperature drops, the corresponding damper closes causing a rise in pressure at the fan. The fan control then adjusts the fan pitch and the total flow is reduced to maintain the set pressure. The overall relation between total fan flow and average zone temperature is assumed to be linear proportionality with a minimum and maximum flow as illustrated in Figure 3.2.

The systems normally operate in the cooling mode with a fixed supply air temperature setpoint, in this case 55 F. As the cooling load and zone temperature decrease, the supply air setpoint is raised as shown in Figure 3.3. The supply air setting is increased at these lower loads up to a maximum of 65 F. The result is that fan flow is

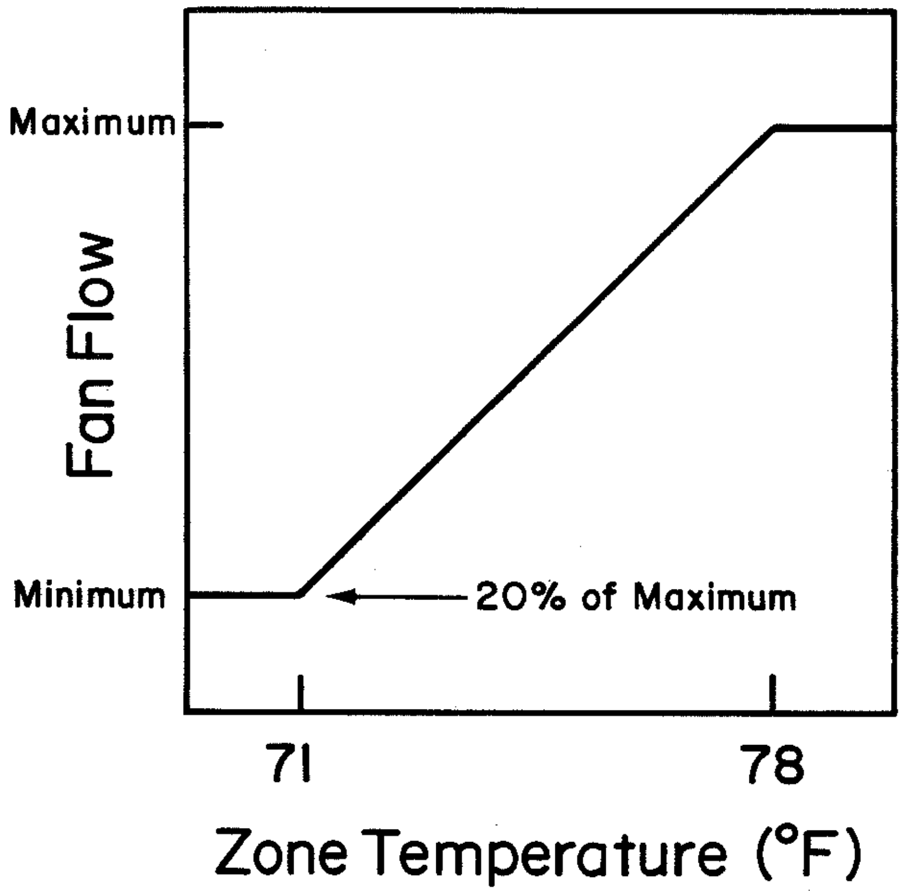



Figure 3.2 Relationship Between Total Fan Flow Rate and Average Zone Temperature

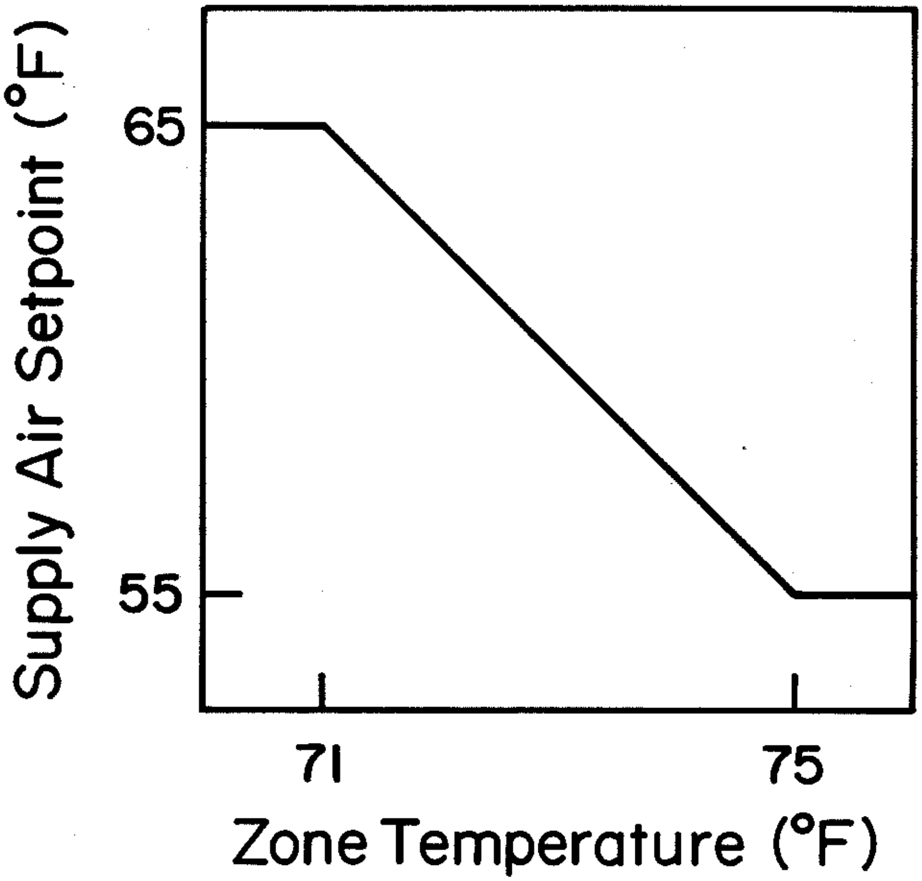



Figure 3.3 Relationship Between Supply Air Setpoint and Average Zone Temperature in Supply Air Reset Mode.

increased to meet the same load due to the smaller temperature difference. A disadvantage is that fan power consumption increases. One advantage is that if outside air dampers are at their minimum setting, more fresh outside air flow results. This can reduce complaints caused by very low air flows at low load conditions. In addition, the cooling coil can theoretically meet the same load with a higher water temperature. However, this effect was not modeled and is likely not a significant factor at this site because the computer area requires the same water temperature year round.

Reheat capability was also incorporated into the AHU model so that simulations could be carried out in cold weather. There is no humidity control in the model so the only time the reheat is activated is when the zone temperature is below 69 F. Heating coil output increases proportionally as zone temperature decreases up to its maximum at 67 F.

The combination of these control functions results in an AHU sensible load curve as shown in Figure 3.4. From 71 F and lower, the AHU fan flow rate is at its minimum. As the zone temperature rises above 71F, the air flow rate increases and the supply air setpoint decreases. At 75 F, the supply air setpoint is at its minimum of 55 F but the fan flow rate continues to increase. The maximum flow rate is reached at 78 F. Cooling rate continues to rise past 78 F because the temperature difference across the coil continues to rise.

The steep slope of the cooling curve between 71 and 78 F results in potential instabilities between the AHU and zone model during simulation. For this reason, a convergence component is inserted

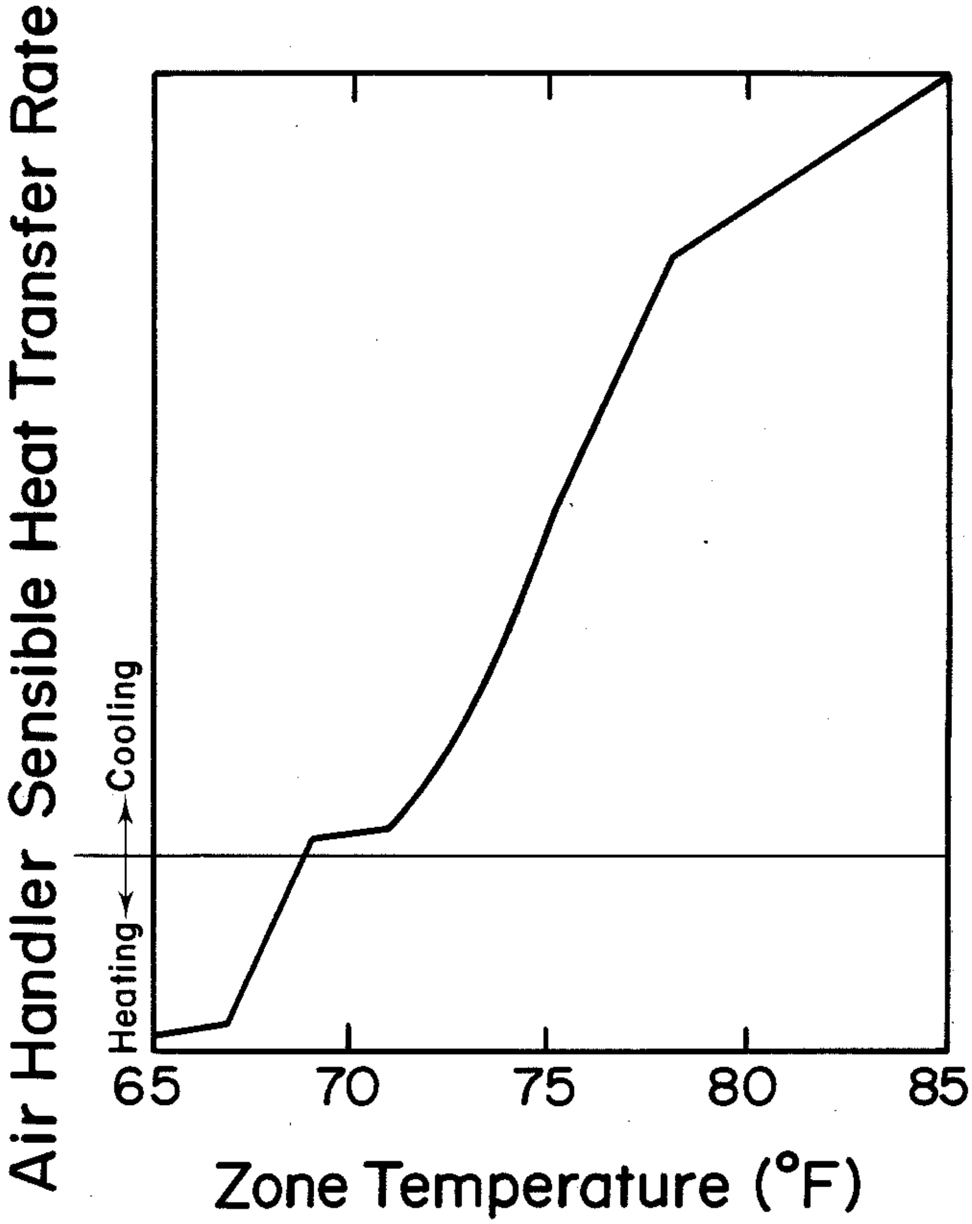



Figure 3.4 Typical Shape of the Air-Handler Heat Transfer Rate as a Function of Average Zone Temperature

between each zone component and its corresponding AHU.

If the zone requires cooling and outside air enthalpy is less than the return air enthalpy, an outside air economizer mode can be activated. This causes outside air to be used to the maximum extent in order to reduce the cooling coil load. However, the cooling coil load is eliminated only when the outside air dry-bulb temperature is less than the mixed air setpoint. To illustrate, outside air fraction is shown in Figure 3.5 as a function of the outside air temperature. For this example, return air is 80 F, mixed air setpoint is 55 F, and outside air enthalpy is less than the return air enthalpy when outside air temperature is less than 70 F. Once the outside air temperature is below the mixed air setpoint of 55 F, some return air is mixed with the outside air to achieve the setpoint, and the cooling coil has no load.

The cooling coil model is very simple and is based on recommendations by Stoecker (3). It is assumed that the coil can meet any load and that the air condition leaving the coil is 90% relative humidity at the setpoint temperature. If the air entering the coil has a lower humidity ratio than this, the humidity ratio leaving equals that entering.

Further explanation of the air-handler component is in Appendix A, along with a listing of the source code.

## 3.2 Comparison of Load Model with Measurements

In a manner similar to the plant model, the predicted loads from the building simulations were compared with actual measured chilled

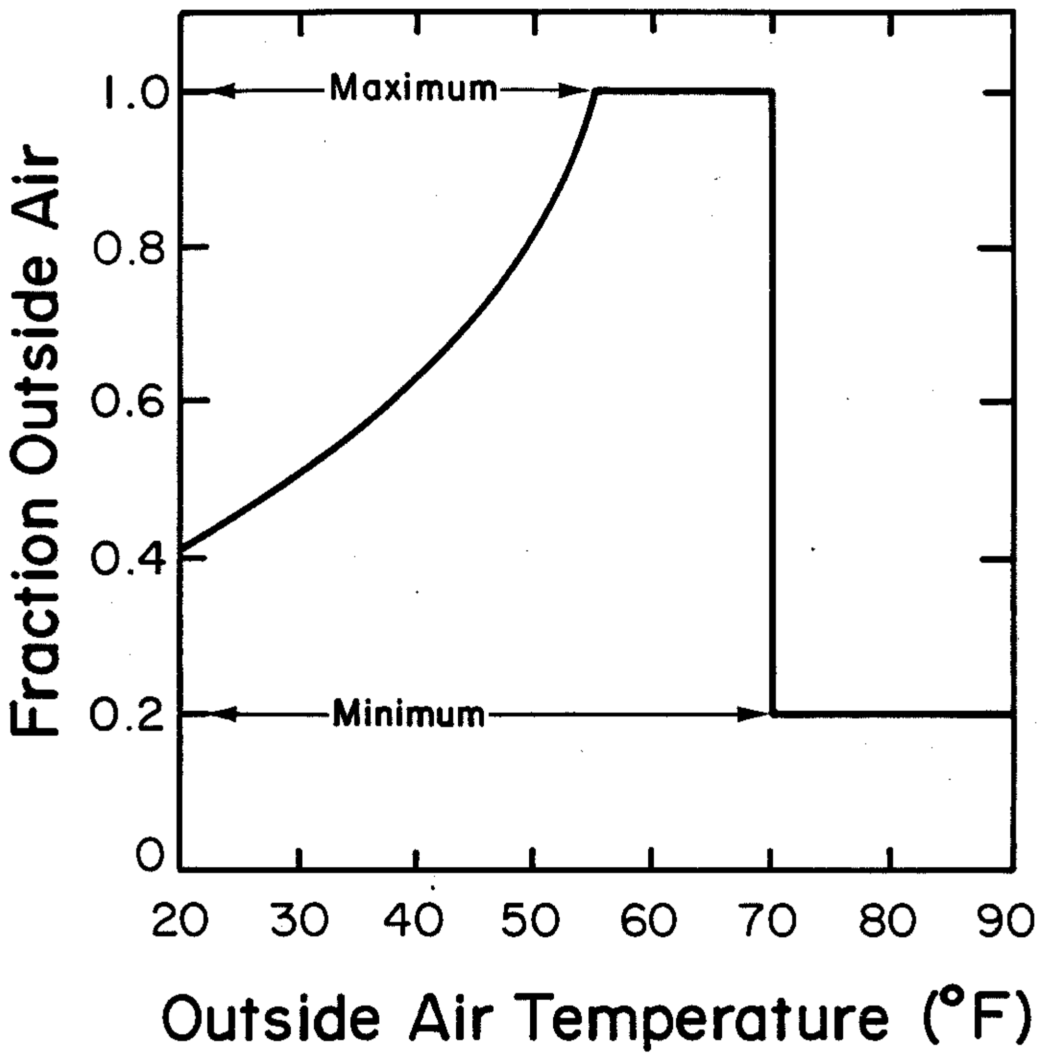



Figure 3.5 Example of the Relationship Between Outside Air Fraction and Outside Air Temperature in an Enthalpy Economizer Mode

water loads. It was desired to run the simulation with actual weather data and internal load data, but two basic problems were encountered. One, the solar radiation data was in error on the available data tapes. Two, the site electric loads were not available on a zone-by-zone basis.

Therefore, the following technique was used. Data were available for a three-day period in late July which included ambient dry-bulb and dewpoint, total chilled water load, and total site (excluding the plant) electric load. The simulation was run using TMY data for July and the assumed internal electric load schedules. Then, the TMY temperature data were compared with the measured data and a period with similar (generally within 10 F) temperatures was found. The predicted and measured cooling loads were then plotted for the second day which was the only complete 24-hour sequence of measured data. The result is shown in Figure 3.6.

On the positive side, the maximum and minimum loads compare quite well. The predicted total cooling load for the day is only 2.3% less than the measured. However, there are significant discrepancies between the shapes of the two curves. The predicted load shows sharp changes at morning start-up and at the end of first shift when several AHUs are supposedly turned on and shut down. The relative smoothness of the actual load cannot be explained if the AHUs are indeed turned on and off as assumed.

Part of the discrepancy can be explained by examination of Figure 3.7, which shows the total building electric demand profiles (excluding the plant demand). It is clear that the actual demand is not as smooth

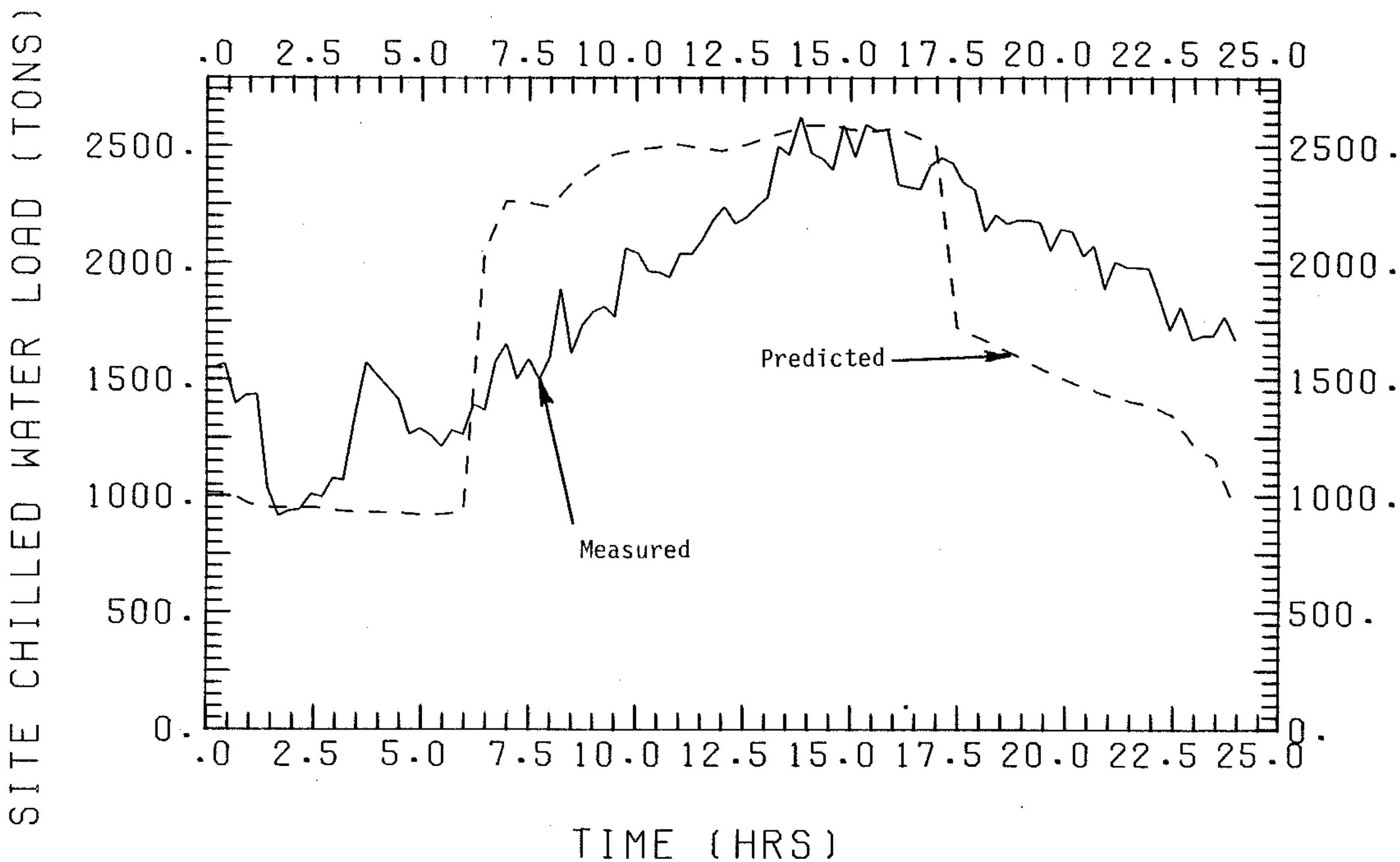



Figure 3.6 Predicted and Measured Site Chilled Water Load for a Mild July Day

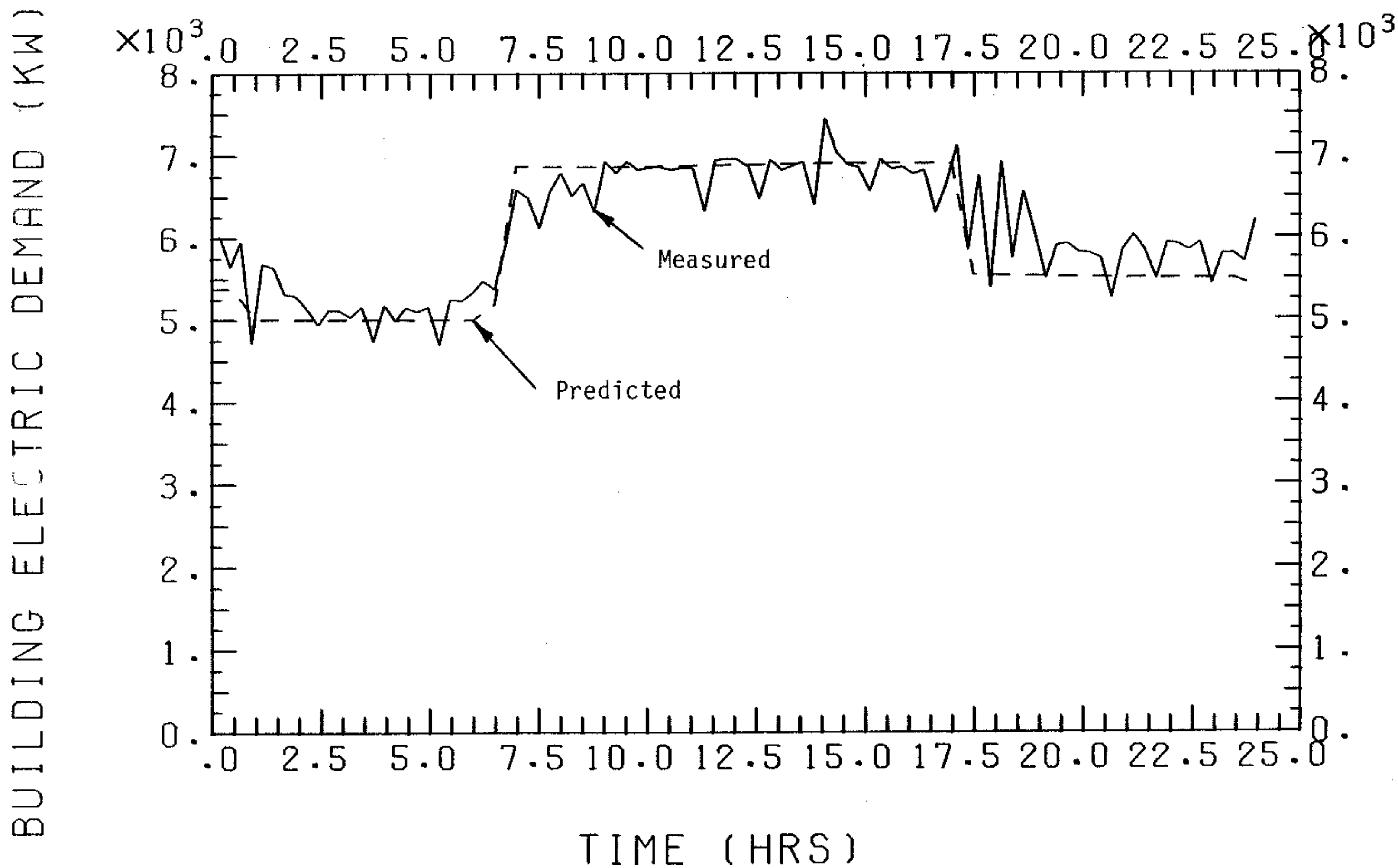



Figure 3.7 Predicted and Measured Buildings' Electrical Demand for a Mild July Day

and consistent as assumed. Though there is an abrupt increase in the morning about 6:30, the actual demand does not rise to the assumed level until about 9:00. A similar lag is evident at the end of first shift at 17:30. In fact, the actual demand during second shift never falls to the level assumed.

Another possible source of discrepancy during the morning start-up is the modeling of the zone heat transfer. When the AHUs are assumed to be off, there is still a considerable amount of heat generation that is absorbed by the internal mass, causing it to warm. During morning start-up, the absorbed heat is released into the zone air. The rate at which this heat is released can have a significant impact on the load profile. It may be that the wood walls used to model the internal mass release the stored heat too quickly.

There are potential problems with the plant simulation due to the differences between measured and predicted load profiles. Because the predicted profile is flatter during the peaking period from 6:30 to 17:30, the storage would generally have to last a longer time than in the actual system (assuming the peak day profile is similar to the measured day). This implies that the simulated demand reduction due to storage will likely be smaller than the actual potential. Another more subtle effect is likely because of the dependence of the plant efficiency on ambient wet-bulb temperature. Since the wet-bulb temperature changes during the day, the predicted energy consumption will likely differ from actual.

# 4. INVESTIGATION OF CONTROL STRATEGIES

This section describes the control strategies that were investigated. To assess the relative merits of the strategies, simulations were carried out using the simulated chilled water loads, described in section 3, as inputs to the plant model. Because of the expense associated with yearly simulations, the month of July was used as indicative of the peak cooling season. Examination of the yearly chilled water load file showed that the peak cooling load did indeed occur in July. A few of the strategies were simulated for an entire year to obtain a better estimate of the annual impact.

In all cases, the change in the electric utility bill was considered the measure of a strategy's merit. The effects on peak demand and consumption were distinguished due to the separate billing nature. The peak electric demand is paid for every month for 12 months and this should be considered when comparing the July results alone.

## 4.1 Deterministic Strategies

### 4.1.1 Strategy Development

Upon examination of the entire chilled water system, a subsystem was identified which could be separated from the larger system for control studies. By studying the interaction of the possible control settings and independent variables in this subsystem, the optimum control strategies were determined directly. Therefore, these strategies are referred to as deterministic.

The subsystem is shown in Figure 4.1 and includes the chiller, primary pumps, cooling tower, and condenser pumps. The figure shows that there are three controlled variables in this subsystem and two independent variables. The object was to find the combination of the three control states that results in minimum power consumption for each discrete combination of wet-bulb temperature and total chiller load.

When the plant is in storage modes 2 or 7, the number of chillers is dictated by the storage flow requirements. In these modes the number of chillers is not one of the control inputs to be optimized. Therefore, only two control inputs are needed. Only in mode 1 are all three control inputs optimized.

To determine the optimum settings, a TRNSYS steady-state model was developed which contained only the specified components. The sump volume was set to zero to eliminate the associated transient. Discrete input data were generated to cover the large number of combinations of wet-bulb temperature, chilled water load, cooling tower fan speeds, condenser pump flow and number of chillers. The values chosen for each input were:

1. Wet-bulb: 45 - 85 F in 5 F increments
2. Chiller load: 40 - 120% full load in 5% increments
3. Cooling tower fans: all cells on low up to all cells on high one cell at a time.
4. Condenser flow: 2000-3000 GPM in 100 GPM increments
5. Number of chillers: 1 - 4 in increments of 1

The total number of combinations is 27,846. Each combination was then input to the TRNSYS simulation to determine the steady-state system

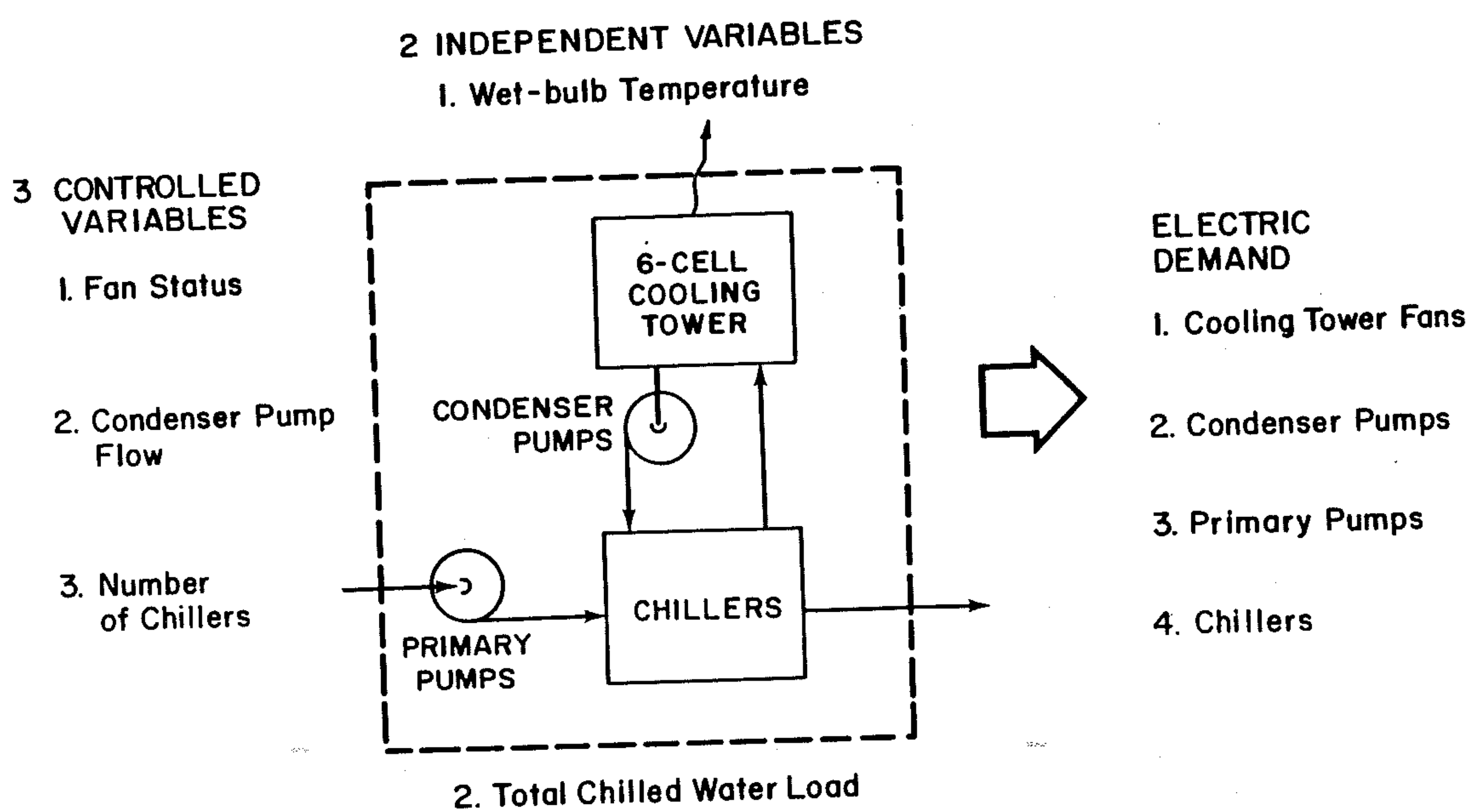



Figure 4.1 Subsystem for Optimization Studies

performance. The entire set of results was put into an output file and recorded on tape. Then, another program was executed which searched this file for the minimum power consumption condition for each discrete combination of the two independent variables and number of chillers. The results are presented next.

First, the optimum number of chillers are considered. In order to find the optima, graphs were plotted for each wet-bulb temperature as shown in Figure 4.2. The coefficient of performance (COP) is based on the power consumption of the subsystem studied and does not include the secondary pump power. This power consumption is for the optimum combination of cooling tower fan speeds and condenser pump flow rate. The point where the curves cross dictates the load at which another chiller should be activated or deactivated. For example, when the load is less than 1370 Tons, the COP for one chiller operating is higher than for two. For the load range from 1370 to 2370 Tons, the combination of two chillers has the best COP. From 2370 to 3340 Tons, three chillers are the best and above 3340 Tons, four chillers are best.

Figure 4.3 shows the optimum number of chillers for three of the wet-bulbs studied and a total chiller load from 500 to 6000 Tons. One observation is that the wet-bulb temperature has a significant influence on the optimum number. Further, the effect of wet-bulb is more pronounced at higher loads. As an example of the potential impact of this strategy, consider the case where wet-bulb temperature is 60 F and the load is just under 2500 Tons. The optimum strategy dictates three chillers while the convention of running chillers to full load

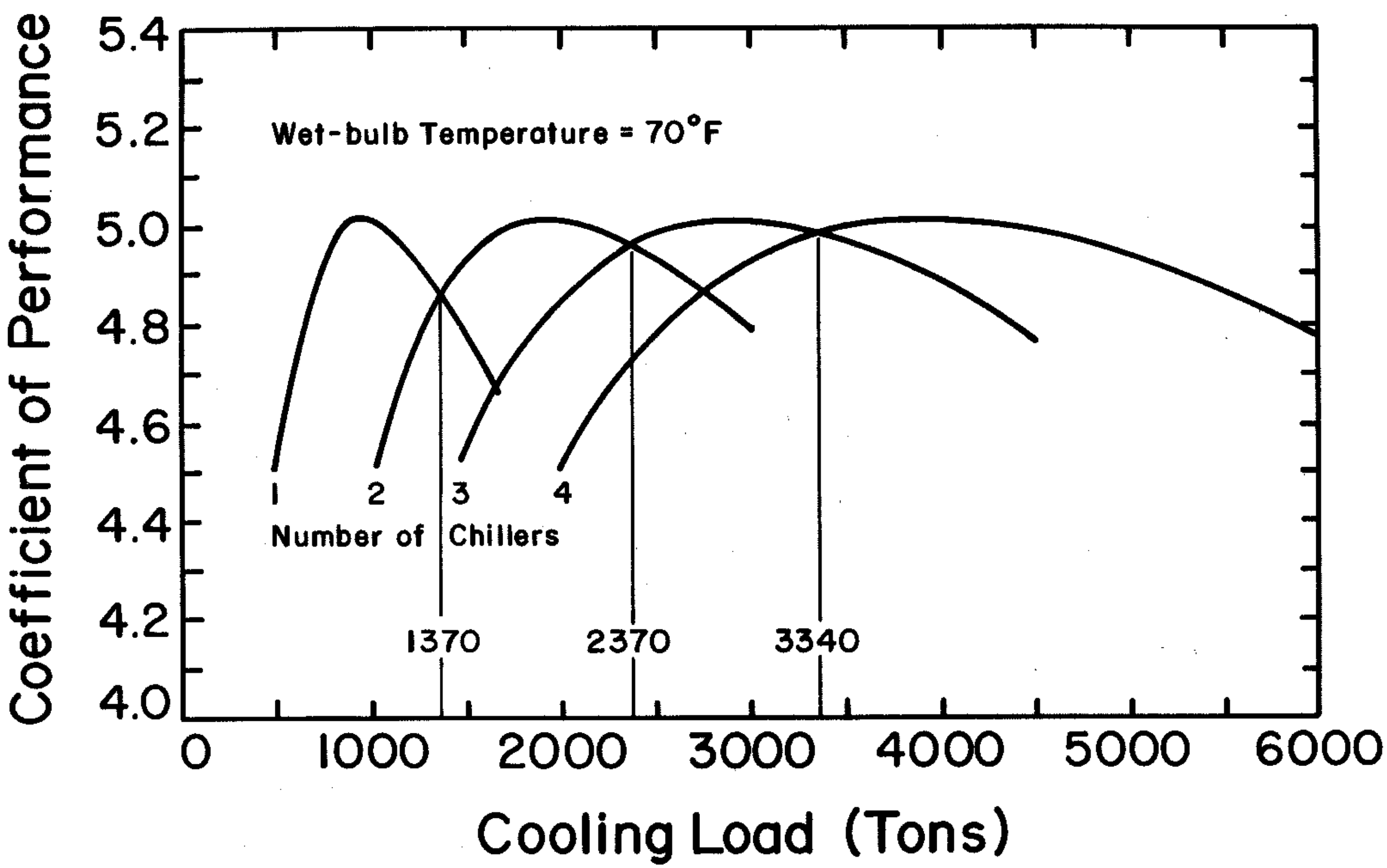



Figure 4.2 Example of the Determination of the Optimum Number of Chillers

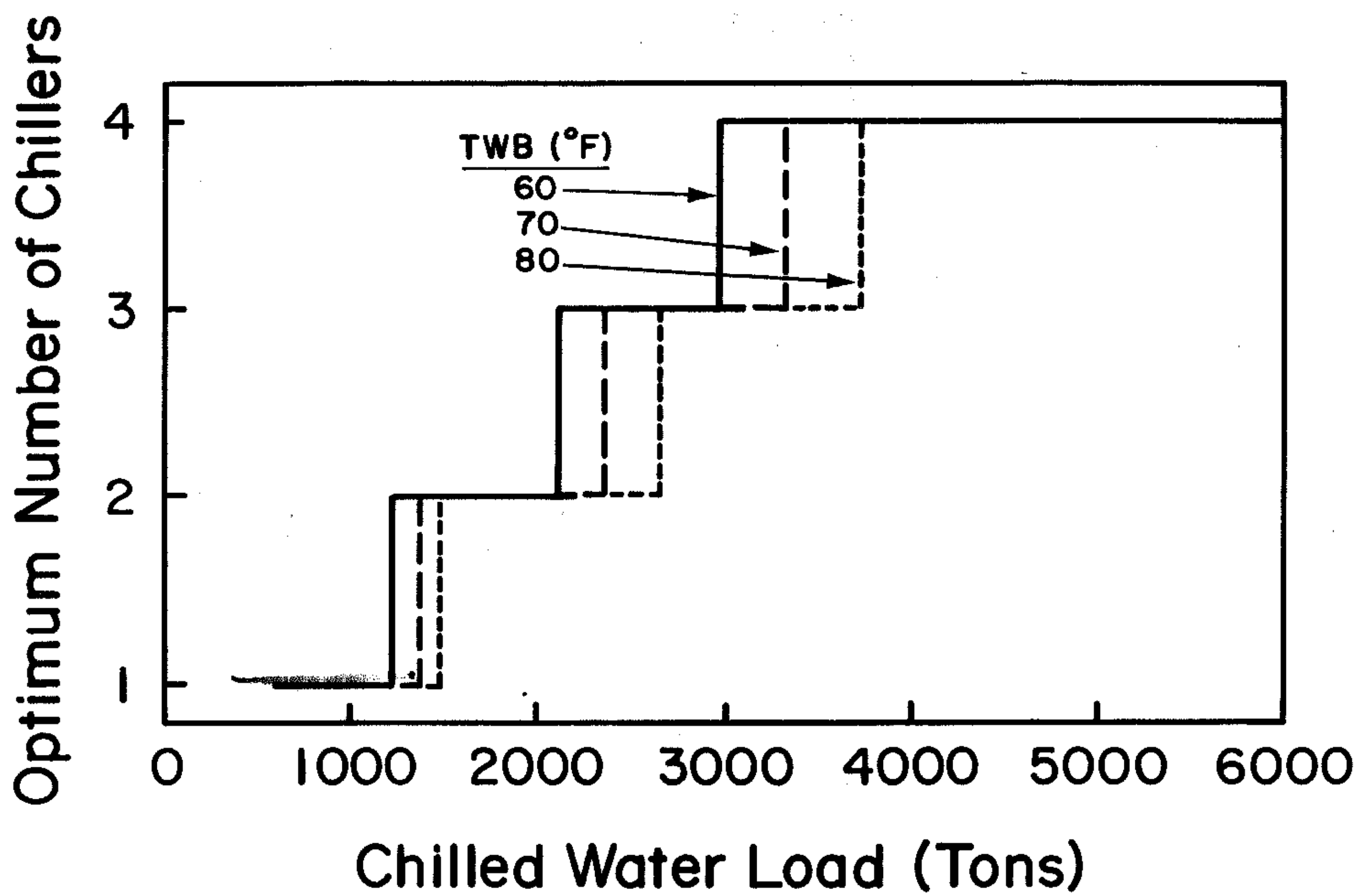



Figure 4.3 The Optimum Number of Chillers as a Function of Load and Wet-bulb Temperature

would dictate two (full load is 1250 Tons). The savings resulting from the optimum strategy is about 50 kw or 3% of the electric demand for the subsystem.

In order to implement this strategy in the simulation, the results were manipulated into the form shown in Figure 4.4. This figure shows the chiller part-load ratio (PLR) at which another chiller should be activated as a function of wet-bulb temperature. For example, suppose one chiller is operating and the ambient wet-bulb temperature is 65 F. When the PLR gets larger than 1.03, another chiller should be activated. Then, if the load continues to increase to a PLR of 0.90, three chillers should be activated. As wet-bulb temperature increases, the chillers should be run to a higher PLR before activating another chiller. A straight line was fit to the one chiller data while the two and three chiller data sets were adequately fit by a quadratic curve in each case. These relations were then programmed into the main control routine.

The second optimized controlled variable is the condenser flow rate. The discrete results were fit with a regression curve that describes the variation of optimum condenser flow as a function of wet-bulb temperature and chiller part-load ratio. The resulting curves are shown in Figure 4.5. The R-squared coefficient is 87% and the standard error of estimate is 48 GPM. One significant observation is that the optimum condenser flows are near the bottom of the operating range while actual operation has been near the upper range.

Sensitivity to condenser flow rate was studied for the case of three chillers operating and a wet-bulb temperature of 65 F. Three

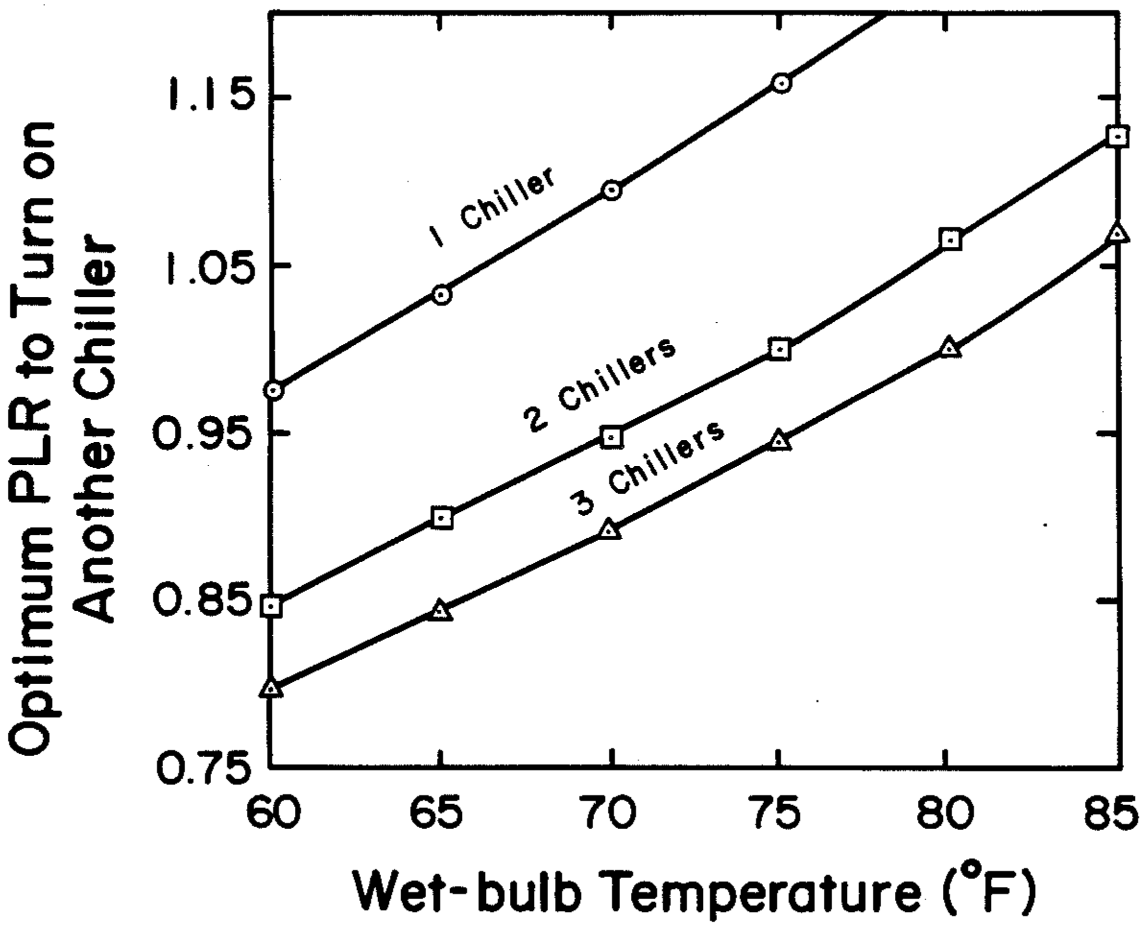



Figure 4.4 Optimum Number of Chiller Curves as Implemented in the Simulation

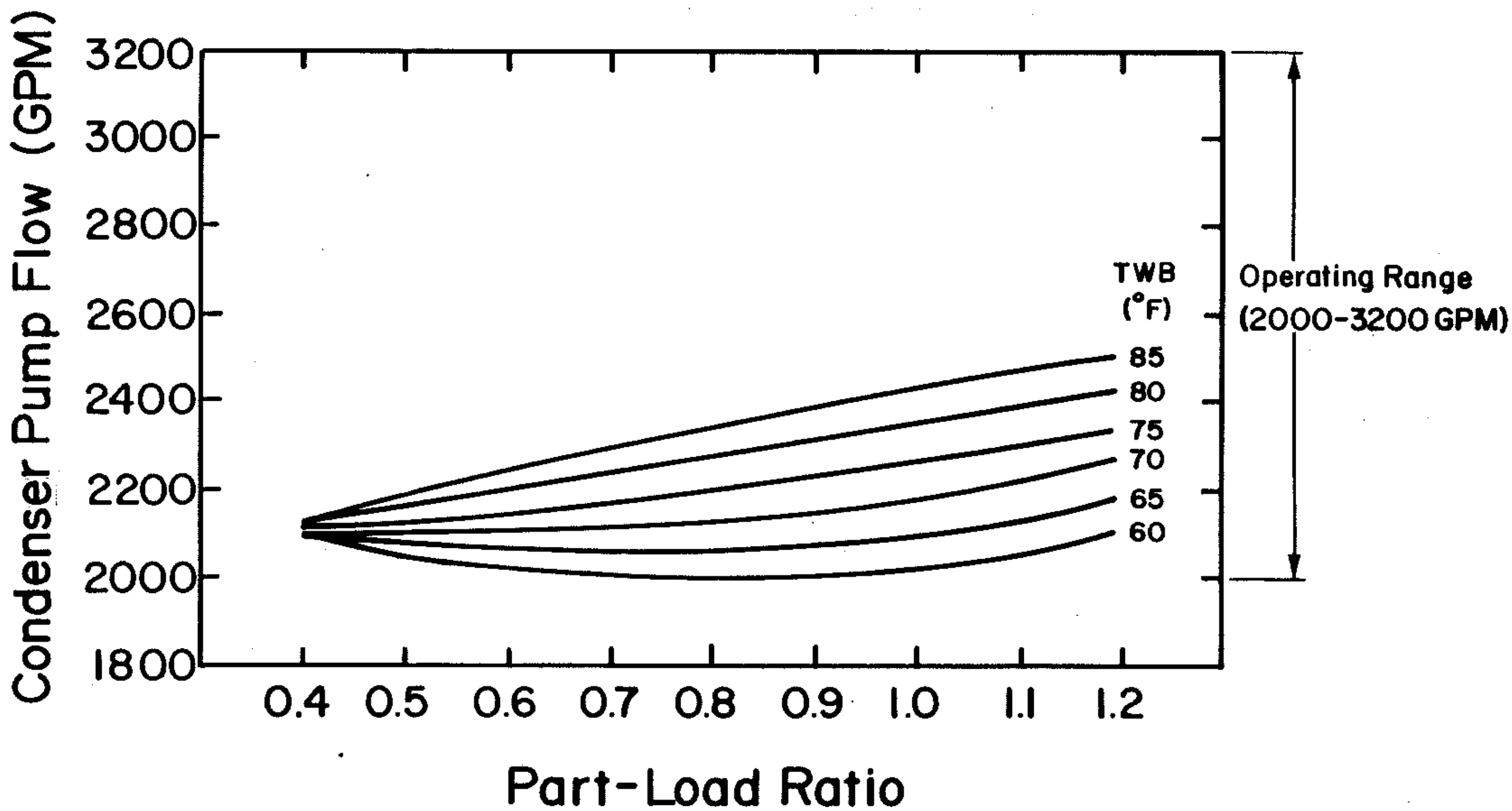



Figure 4.5 Optimum Condenser Pump Flow Rate as a Function of Chiller Part-load Ratio and Wet-bulb Temperature

part-load ratios were examined and the results are illustrated in Figure 4.6. The vertical scale is the relative increase in the subsystem power consumption relative to the optimum flow rate. Operation near the high end of the range can increase power consumption by up to 4%. On the other hand, a variation of plus or minus 200 GPM about the optimum causes less than 0.5% increase in power.

The third and final deterministic control studied is the cooling tower fan status. Because of the discrete nature of cooling tower fan control and the various different levels of operation, the results were used in their discrete form in the simulation. The entire set of results are listed in Appendix D. An example of the optimum tower control for three chiller operation is shown in Figure 4.7. For clarity, only three wet-bulb temperatures are shown. There are two consistent trends apparent in this figure. One, the optimum number of fans on high increases with increasing load. Two, as wet-bulb temperature increases, so does the optimum number of cells on high.

For example, assume that the ambient wet-bulb temperature is 70 F and three chillers were just activated. The three cooling tower fans should all be run on low speed until the chiller cooling load reaches about 1600 Tons. Then, one cell should be run on high up until the load reaches 2000 Tons. Two cells are run on high with one on low until the load passes 2300 Tons when all three cells are run on high. If the wet-bulb was cooler, the fans would be turned on high at higher loads.

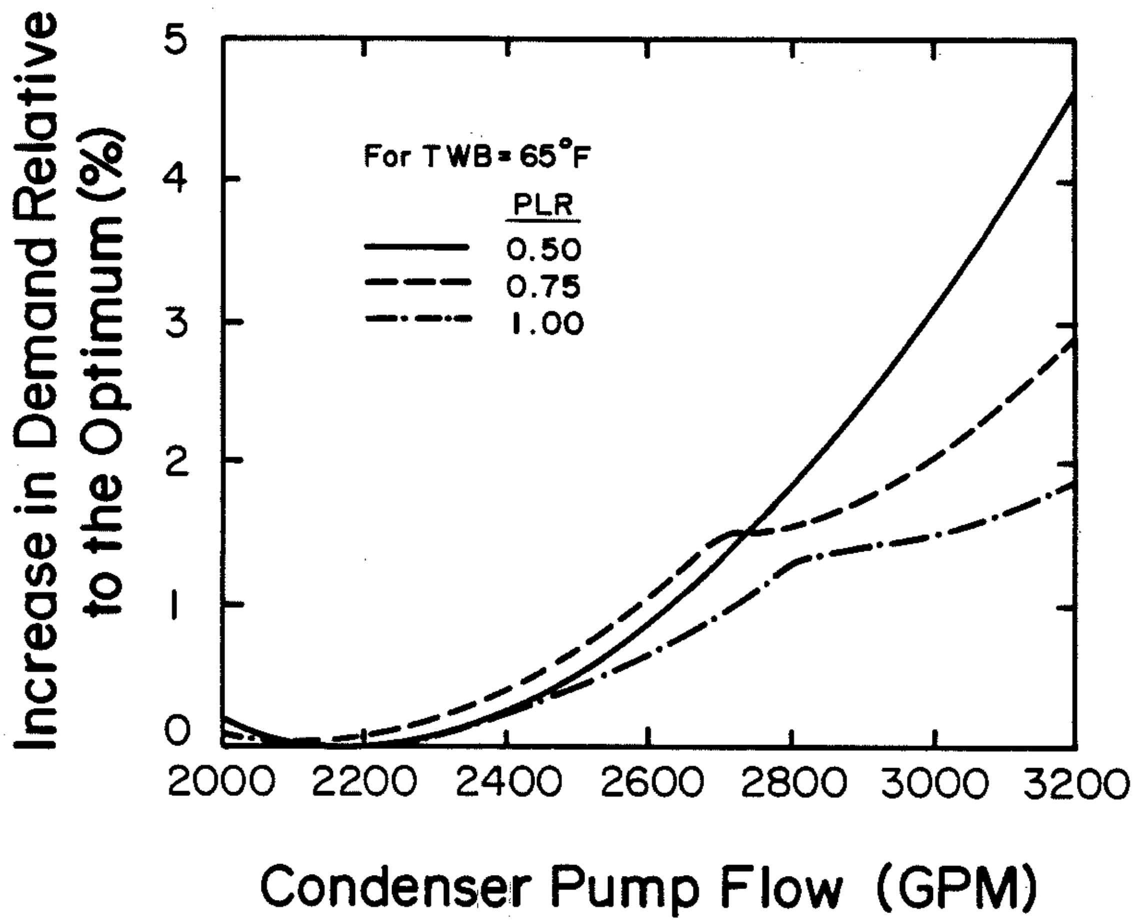



Figure 4.6 Sensitivity of the Subsystem Electric Demand to Condenser Pump Flow Rate

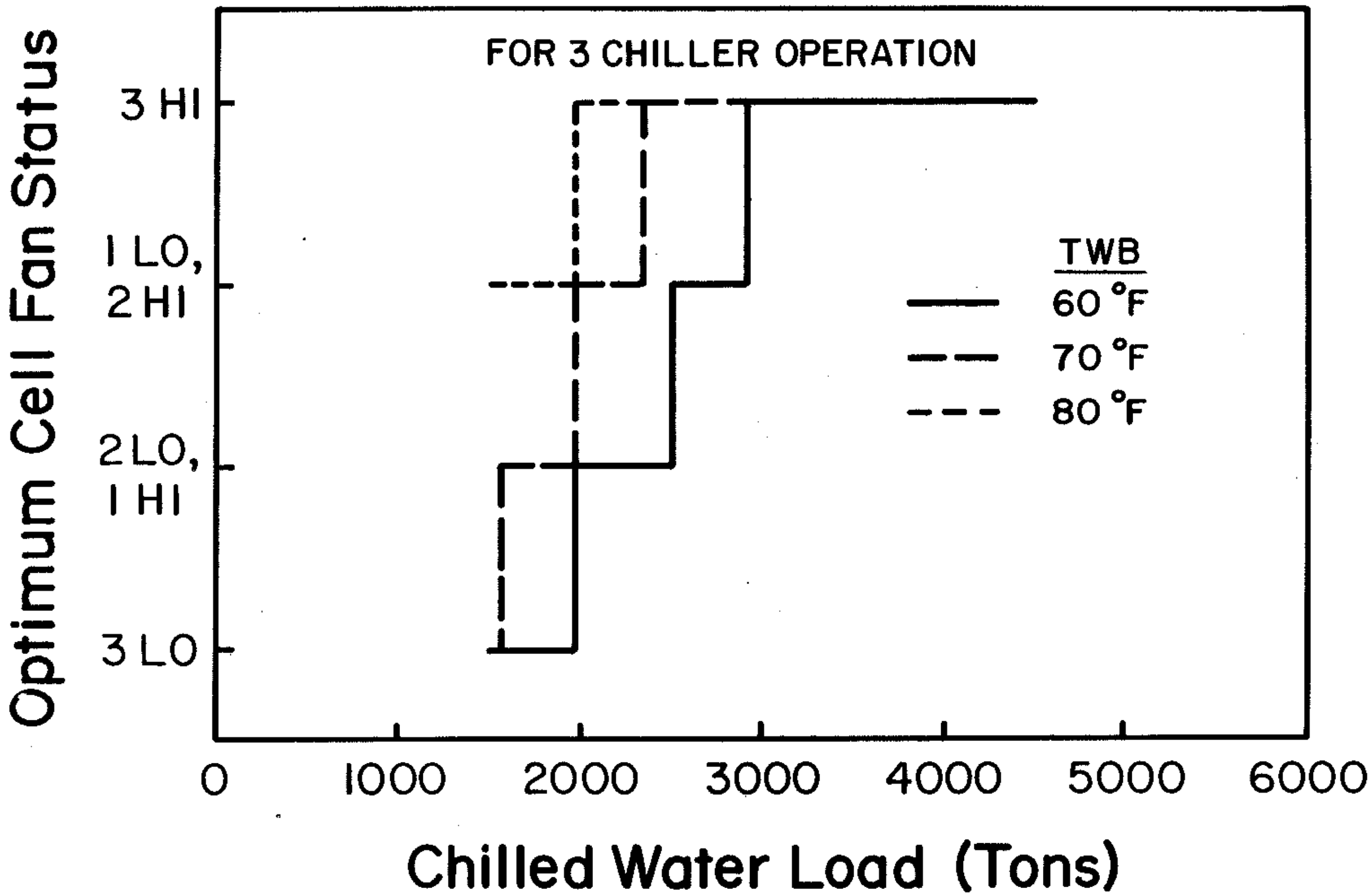



Figure 4.7 Optimum Cell Fan Control as a Function of Total Chilled Water Load and Wet-bulb Temperature

### 4.1.2 Simulation Results

As a basis for comparison for all of the strategies, a base case plant was defined which has the following characteristics. The storage tanks are not used which means the system operates in mode 1. Condenser pump flow rate is constant at 2800 GPM per pump, a value commonly observed from the four data tapes. Cooling tower fan status is controlled to maintain the approach temperature within 5 to 15 F of the wet-bulb, just as in the actual system. Number of chillers is based on operation up to 100% of design load if the site supply temperature is below 46 F.

The optimum strategies were simulated in various combinations and the results are summarized in Table 4.1. It is important to keep in mind that the three strategies were developed together and that the savings if implemented singly would likely be less than the combined savings. This is supported by the results in the table. Case 2 shows the savings from the combined strategies to be $495 for July. Both electrical consumption and demand are reduced by the more efficient plant operation. Cases 3a to 3c show the savings of each strategy by itself, the total being $336, less than the combined effect. These independent cases are useful in that they show that of the three strategies, condenser flow has the largest impact by an order of magnitude.

As a test of the significance of the variable condenser flow strategy versus a constant flow, cases 4a to 4c were simulated. Both of the other two optimum strategies were implemented. These cases show the benefit of reducing condenser flow from the typical value of 2800

Table 4.1 Optimized Strategies versus Base Case for July

| | Consumption (MWh) | Peak (kW) | Total Bill ($) | Savings ($) |
|---|---|---|---|---|
| 1. Base case | 5087.9 | 9766.7 | 186,433 | - |
| 2. All 3 optimized strategies | 5073.0 | 9747.2 | 185,938 | 495 |
| 3a. Optimum number of chillers | 5086.0 | 9766.7 | 186,404 | 29 |
| b. Optimum cooling tower level | 5086.2 | 9766.6 | 186,412 | 21 |
| c. Optimum condenser flow | 5078.4 | 9758.0 | 186,147 | 286 |
| 4a. Condenser flow constant @2800 GPM, 2 optimized strategies | 5085.4 | 9766.6 | 186,387 | 46 |
| b. 2500 GPM | 5077.2 | 9750.4 | 186,087 | 346 |
| c. 2200 GPM | 5072.9 | 9748.0 | 185,949 | 484 |

GPM per pump. Case 4c also shows that a constant flow of 2200 GPM results in savings ($484) very near that obtained with the optimum, variable flow control ($495).

For the base case, the plant power consumption is about 19% of the total consumption, or about 987 MWh. This fraction was applied to the monthly utility bill to obtain the plant portion, $35,400. The savings from the three optimized strategies of $495 is about 1.4% of the plant bill. An implication of this relatively minor savings is that the actual controls being used are not far from being optimum from the standpoint of overall plant efficiency and purchased energy.

## 4.2 Storage Mode Regulation

### 4.2.1 Strategy Development

The control of storage flow was discussed in section 2.1.6.3. The control investigated here is the time of activation of mode 2 during the day to limit the peak demand. In all storage cases considered, mode 7 was activated at midnight and was typically completed by 4-5 a.m.

This is one strategy where the shape of the load profile can have a significant effect on the results. The results presented here are not intended to be directly applicable to the actual system because of the load profile discrepancies discussed earlier in section 3.2. However, the methodology of studying different start times can be applied to actual load profiles when those data are available.

If mode 2 is activated too late in the day, chilled water will remain in the tanks when the peaking period ends in late afternoon. As a result, the peak demand limiting capability would not be fully utilized. Conversely, if mode 2 is activated too early in the day, the chilled water tanks would be depleted before the end of the peak period. This too would result in the demand limiting capability of storage being under-utilized.

### 4.2.2 Simulation Results

The results of the start-time simulations for July are summarized in Table 4.2. In these cases, all three of the optimized strategies were also activated so case 2 from Table 4.1 is used as the base case for comparison. Later times than 9:00 a.m. were studied, but peak demands were higher and savings were lower. The results in the table show that the best time for activating mode 2 is 8:00 a.m. which results in a savings of $711 for July, or about 2.0% of the base case plant bill. Peak demand was reduced by 257 kW.

More insight into this problem can be obtained by examining the electric demand profiles for the peak day, shown in Figure 4.8. The upper profile is for case 1 with the three optimized strategies activated but no storage use. The lower profile is case 2c with storage on at 8:00 a.m. The rise in the profile for case 2c at 16:30 indicates that stored chilled water was no longer available. This is further evidenced by the closeness of the two demand profiles at 17:00. The start time of 8:00 is a critical time because there is a jump in demand at 8:30 and if mode 2 were activated at 8:30, the profile for 2c would

Table 4.2 The Effect of Time of Activation of Mode 2 for July

| | Consumption (MWh) | Peak (kW) | Total Bill ($) | Savings ($) |
|---|---|---|---|---|
| 1. All 3 optimized strategies | 5073.0 | 9747.2 | 185,938 | - |
| 2a. Mode 2 on @9:00 a.m. | 5071.5 | 9574.4 | 185,432 | 506 |
| b. 8:30 a.m. | 5072.2 | 9566.3 | 185,433 | 505 |
| c. 8:00 a.m. | 5072.2 | 9490.3 | 185,227 | 711 |
| d. 7:30 a.m. | 5071.6 | 9734.0 | 185,870 | 68 |

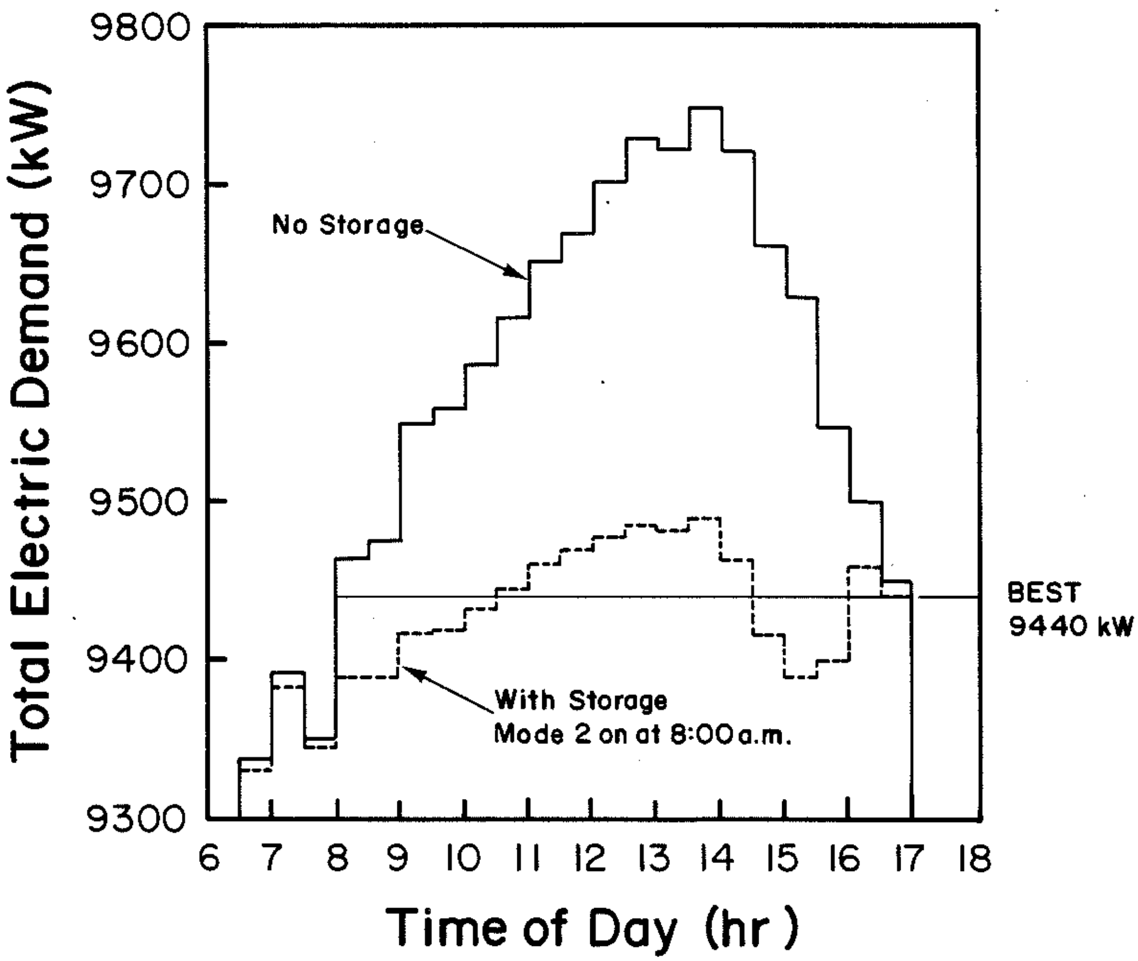



Figure 4.8 Electric Demand Profiles for the Peak Day in July

essentially shift upwards. In addition, there would be chilled water remaining in the tanks at 17:00.

This figure also shows that even though the chiller flow is held constant in mode 2, the total site demand still rises. There are several factors causing this rise. Because the site load increases toward mid-afternoon, both air-handler power and secondary pump power continue to rise. Another small factor is that ambient wet-bulb rises slightly causing an increase in condenser water temperature which causes a slight increase in chiller demand.

To test the maximum potential of the existing storage tanks on this peak day, the mode 2 profile was "levelized" to obtain the horizontal line shown in Figure 4.8. The levelized demand limit was estimated by averaging the mode 2 demand profile between 8:00 and 16:30. The resulting demand is 9440 kW, an additional reduction of 50 kW below case 2c. It is difficult to imagine a control strategy that could obtain a level demand without a prior knowledge of the shape of the demand profile. However, simulation studies such as these could be used to develop storage controls that anticipate the rise in demand shown for case 2c, thereby approaching a level demand.

The ultimate potential for chilled water storage (or thermal energy storage in any form) was examined for the peak day as shown in Figure 4.9. Here the total demand profile for the entire day was averaged to obtain the levelized demand of 7857 kW. The peak demand for the buildings plus the secondary pumps is 7250 kW. Therefore, it is feasible that thermal energy storage could limit the demand to 7857 kW. This is a reduction in peak demand of 1910 kw. At an approximate

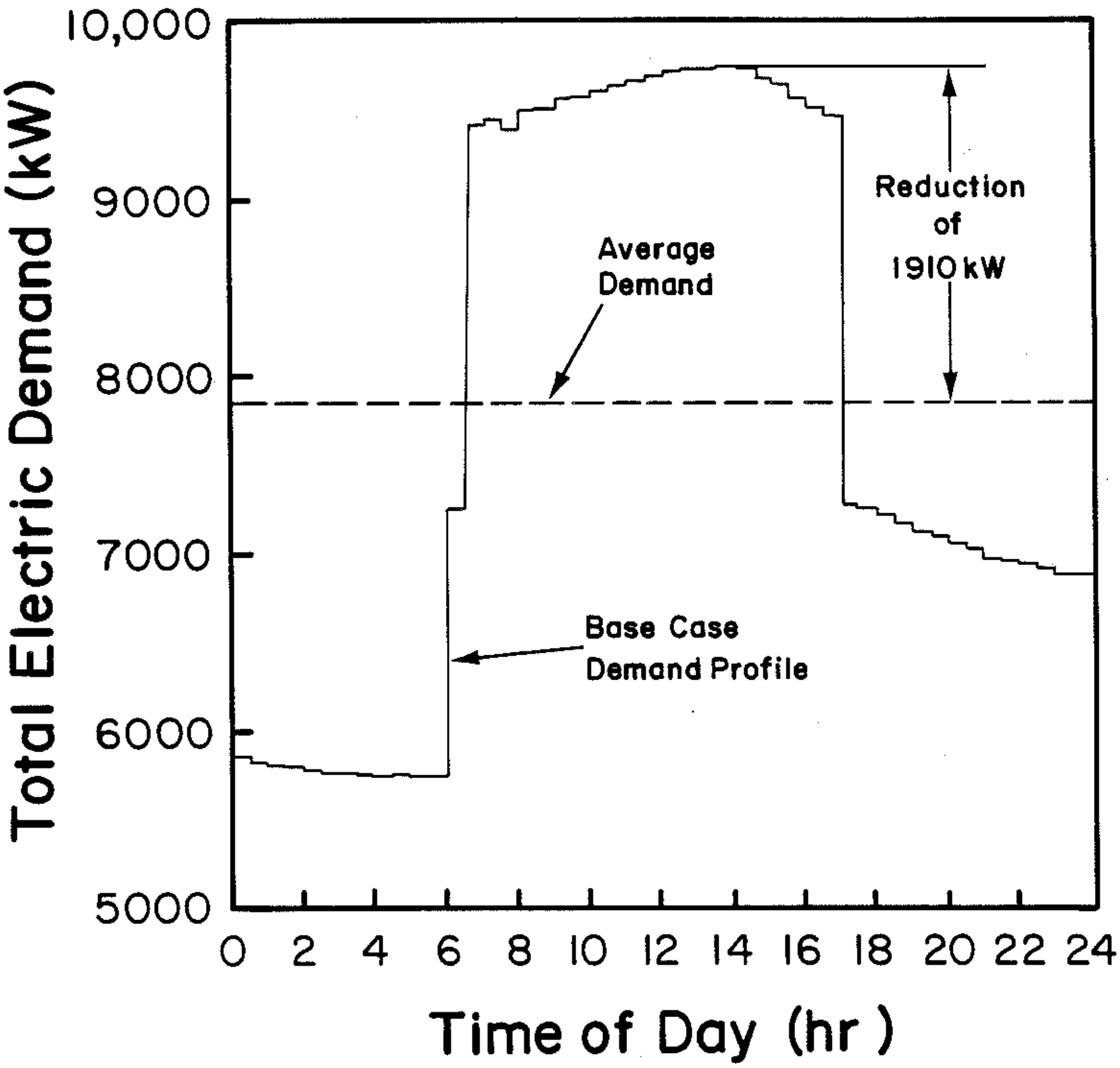



Figure 4.9 Electric Demand Profile for the Peak July Day Compared to the Average Demand

demand charge of $2.71/kW for 12 months, the savings would be $62,100 a year. With a three-year simple payback criterion, a maximum of $180,000 could be invested in a storage facility with this capacity.

## 4.3 Reset of the Chilled Water Setpoint

### 4.3.1 Strategy Development

The chilled water setpoint is controlled by the minicomputer system. There is also internal control built into each chiller as discussed in section 2.1.1.1. The result of the internal control is that the actual chilled water temperature deviates from the setpoint as shown previously in Figure 2.4. Because the actual temperature is typically below that required, the chiller power consumption is higher than necessary. This deviation from the setpoint can be greatly reduced by resetting the setpoint via the minicomputer system. For example, if chiller part-load ratio is 50% and the setpoint is 44 F, actual chilled water temperature would be about 42 F. If the minicomputer resets the setpoint to 46 F, then the actual temperature would be 44 F as desired. The reset frequency should be greater than the response time of the chiller to setpoint changes. Preliminary results from another project at the University of Wisconsin show that response time is typically less than two minutes.

### 4.3.2 Simulation Results

Without setpoint reset (SPR), the actual chilled water temperature varies 4 F from 100% to 0% load. It was assumed that with SPR, the temperature variation could be reduced to 0.5 F. The simulation was run for July and case 2c from Table 4.2. The results are 5056.9 MWh consumption, 9485.5 kW peak, and a bill of $184,739. This represents a reduction of $488 below case 2c, or about 1.4% of the base case plant bill. This savings is significant given the relative ease of resetting the setpoint with the minicomputer system.

It should be noted here that the three optimized strategies were defined without SPR. Use of SPR will alter the optimum control strategies. As an example, consider the optimum number of chillers in mode 1. When another chiller is activated without SPR, the PLR drops and so does the actual chilled water supply temperature. With SPR, the chiller power would be less in this condition and the optimum PLR at which to energize another chiller would also tend to be lower. The effect of SPR would be greater when going from one to two chillers than from two to three.

## 4.4 Storage Tank Subcooling

### 4.4.1 Strategy Development

The effective strorage capacity and cooling rate from storage can be increased by reducing the temperature of the chilled water stored in the tanks. However, running the chillers at a lower setpoint in mode 7 will also increase the chiller power consumption. The simulation was used to examine this tradeoff between reduced demand and increased consumption resulting from storage tank subcooling.

4.4.2 Simulation Results

The previous case with the three optimized strategies, mode 2 on at 8:00 a.m., and reset of chilled water setpoint was run with four levels of subcooling for July. The results are compared with the previous case in Table 4.3.

In all cases, the reduced demand charge is more than offset by the increase in the consumption charge. This can be misleading because the demand savings are effectively multiplied by twelve on an annual basis. On the other hand, subcooling is only required for those months that demand is near the peak. An examination of the annual simulations reported in the next section indicated that subcooling would be required for about four months, May through August. Therefore, in order to compare the annual impact of storage subcooling, the consumption charge increases for July were multiplied by four while the demand charge decreases were multiplied by twelve.

Even with these adjustments, the net effect of all the levels of subcooling on the annual utility bill was an increase as shown in the last column of Table 4.3. The utility bill increase is larger as the subcooling temperature is reduced. Therefore, subcooling of the storage tanks does not appear profitable with the current utility rate structure. Only if the demand charge was higher relative to the consumption charge could subcooling save money.

Table 4.3 Effects of Storage Tank Subcooling

| | July Results | | | | Annual Extrapolation | | |
|---|---|---|---|---|---|---|---|
| Subcooling Temperature (F) | Electric Consumption (MWh) | Increase in Consumption Charge ($) | Peak Demand (kW) | Reduction in Demand Charge ($) | Increase in Consumption Charge ($) | Reduction in Demand Charge ($) | Net Effect ($) |
| 44 | 5056.9 | - | 9485.5 | - | - | - | - |
| 43 | 5059.6 | 81 | 9476.3 | 23 | 324 | 276 | +48 |
| 42 | 5064.2 | 220 | 9465.1 | 51 | 880 | 612 | +268 |
| 41 | 5071.0 | 431 | 9463.9 | 54 | 1724 | 648 | +1076 |
| 40 | 5079.7 | 701 | 9451.0 | 85 | 2804 | 1020 | +1784 |

## 4.5 Annual Results

Selected strategies were simulated for an entire year and compared with the base case. Table 4.4 lists the results for the base case. The last column is the plant power consumption and includes the chillers, pumps, and cooling tower fans. For the year, plant power consumption is 13.3% of the total consumption. Using this proportion, the plant portion of the utility bill is $275,000.

The first strategy selected for comparison was the activation of mode 2 at 8:00 a.m. None of the three optimized strategies was activated. This case was not examined for July in the previous sections. The results are shown in Table 4.5. Use of storage results in a reduction in the annual utility bill of $5,449 or 2.0% of the base case plant bill. The savings are not as great as they could be because the peak demand occurs in June, not July as previously assumed. Note that in the base case, the peak demand does occur in July. This indicates that while 8:00 a.m. is the best time for July, it is not necessarily the best time for other months. The August demand in Table 4.5 is also higher than the July demand. The annual demand reduction is 161 kW compared to 249 kW for July. For greater demand reduction and more savings, the optimum start time for mode 2 should be studied for these other months. A start time dependent on the month could then be programmed into the minicomputer system.

The next case studied was the addition of the three optimized strategies to the previous case with storage activated at 8:00 a.m. These results are listed in Table 4.6. The annual utility bill is further reduced by $4,440 or 1.6% of the base case plant bill. The

Table 4.4 Annual Simulation Results for Base Case

| Month | Total Consumption (MWh) | Peak (kW) | Total Bill ($) | Plant Consumption (MWh) | Cooling Load (MBtu) |
|---|---|---|---|---|---|
| J | 4435.19 | 8083.7 | 166,167 | 336.7 | 5,528 |
| F | 4002.26 | 8344.0 | 152,702 | 323.9 | 5,392 |
| M | 4477.70 | 8539.1 | 167,489 | 403.8 | 6,762 |
| A | 4500.32 | 9227.9 | 168,192 | 560.2 | 9,158 |
| M | 4923.25 | 9475.7 | 181,345 | 793.5 | 12,620 |
| J | 4848.07 | 9614.6 | 179,007 | 894.2 | 14,070 |
| J | 5087.91 | 9766.7 | 186,466 | 986.7 | 15,310 |
| A | 5123.26 | 9665.4 | 187,566 | 985.2 | 15,330 |
| S | 4705.06 | 9435.6 | 174,560 | 796.8 | 12,570 |
| O | 4681.57 | 9261.9 | 173,829 | 561.9 | 9,189 |
| N | 4357.42 | 8383.3 | 163,748 | 389.2 | 6,509 |
| D | 4370.56 | 8383.7 | 164,157 | 342.7 | 5,727 |
| Total | 55,512.8 | | $ 2,065,228 | 7374.8 | 118,200 |

Table 4.5 Annual Simulation Results for
Mode 2 Activation at 8:00 a.m.

| Month | Total Consumption (MWh) | Peak (kW) | Total Bill ($) |
|---|---|---|---|
| J | 4428.17 | 8007.5 | 165,512 |
| F | 4000.63 | 8328.3 | 152,215 |
| M | 4479.17 | 8539.2 | 167,098 |
| A | 4499.48 | 9218.6 | 167,730 |
| M | 4922.73 | 9442.9 | 180,893 |
| J | 4850.08 | 9606.1 | 178,633 |
| J | 5086.81 | 9517.7 | 185,996 |
| A | 5124.71 | 9598.2 | 187,174 |
| S | 4703.44 | 9333.1 | 174,073 |
| O | 4680.52 | 9180.0 | 173,360 |
| N | 4359.11 | 8380.5 | 163,364 |
| D | 4370.92 | 8381.2 | 163,731 |
| Total | 55,505.8 | | $ 2,059,779 |

Table 4.6 Annual Simulation Results for Addition of Three Optimized Strategies

| Month | Total Consumption (MWh) | Peak (kW) | Total Bill ($) |
|---|---|---|---|
| J | 4425.14 | 7993.9 | 165,335 |
| F | 4000.92 | 8320.4 | 152,142 |
| M | 4472.12 | 8560.1 | 166,796 |
| A | 4490.16 | 9181.4 | 167,357 |
| M | 4910.14 | 9411.8 | 180,419 |
| J | 4835.10 | 9575.7 | 178,085 |
| J | 5072.64 | 9490.9 | 185,473 |
| A | 5109.47 | 9569.9 | 186,618 |
| S | 4690.43 | 9239.5 | 173,586 |
| O | 4671.16 | 8861.4 | 172,986 |
| N | 4353.43 | 8469.4 | 163,105 |
| D | 4364.11 | 8362.1 | 163,437 |
| Total | 55,394.8 | | $ 2,055,339 |

total reduction so far relative to the base case in $9889 or 3.6%. Most of the reduction in utility bill resulting from the three optimized strategies is due to reduced consumption and more efficient plant operation. The more efficient operation also reduces the peak demand by 30 kW.

The final case studied on an annual basis was the use of automatic reset of the chilled water setpoint. This feature was added to the previous case and the results are in Table 4.7. Reset results in an additional annual savings of $4,353, or 1.6% of the base case plant bill.

For all of the strategies simulated on an annual basis, the total reduction in utility bill is $14,242 or 5.2% of the annual plant portion of the electric bill. The total reduction in consumption is 252.2 MWh and the total reduction in peak demand is 197 kW. Though the savings are small on a relative basis, a telephone conversation with Duke Power, the local utility, indicated that 252.2 MWh would be enough to power 21 residential customers for a year (12,000 kWh per house per year).

Table 4.7 Annual Simulation Results for Addition of Reset of Chilled Water Supply Temperature

| Month | Total Consumption (MWh) | Peak (kW) | Total Bill ($) |
|---|---|---|---|
| J | 4416.57 | 7918.2 | 165,054 |
| F | 3994.12 | 8320.8 | 151,916 |
| M | 4463.16 | 8491.0 | 166,503 |
| A | 4479.75 | 9126.1 | 167,019 |
| M | 4896.88 | 9381.5 | 179,991 |
| J | 4820.08 | 9567.3 | 177,603 |
| J | 5057.89 | 9483.7 | 184,999 |
| A | 5093.12 | 9570.2 | 186,094 |
| S | 4677.87 | 9195.8 | 173,180 |
| O | 4661.00 | 8769.3 | 172,656 |
| N | 4343.33 | 8345.2 | 162,776 |
| D | 4356.79 | 8361.1 | 163,195 |
| Total | 55,260.6 | | $ 2,050,986 |

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Deterministic Strategies

The three optimized strategies in combination saved $495 in July and $4,440 for the annual simulation. The July savings resulting from the optimum condenser flow rate were an order of magnitude higher than the savings from either the optimum cooling tower fan control or the optimum number of chillers control. Simply reducing the constant condenser flow rate from 2800 to 2200 GPM resulted in savings nearly identical to the optimally controlled condenser flow rate for July.

Therefore, it is recommended that first priority be given to reducing the condenser flow rate and then implementing the optimum flow rate control. Because there is some complimentary effect of the three strategies, the other two should also be implemented.

If the automatic reset of chilled water setpoint is implemented, then the deterministic strategies should be reexamined. In particular, the optimum number of chillers is probably significantly affected by automatic reset.

## 5.2 Storage Mode Regulation

The optimum start-time for mode 2 was found to be 8:00 a.m. for July. However, the annual simulation showed that this is not necessarily the optimum time for the other summer months. For the annual simulation, a start-time of 8:00 a.m. resulted in a savings of $5,449. The peak demand for the year was reduced by 161 kW.

Because of the different shapes of the actual and simulated load profiles, the start-times studied do not translate directly to the actual system. It is recommended that the long-term recorded data be used to develop the necessary input data for the plant simulation in order to study mode 2 operation. The variation of the best start-time from month to month should also be investigated with the simulation and actual loads.

Further study of the actual load profile when in mode 2 can add to the demand-limiting capability through adjustment of chiller flow to reduce the small rise in demand due to the air-handler fans and secondary pumps. With these kinds of fine tuning, the storage tanks should be able to approach their maximum demand-limiting capability of 400 kW and annual utility bill savings of $13,000.

## 5.3 Reset of the Chilled Water Setpoint

Automatic reset of the chilled water setpoint saved $488 for July and $4,353 on an annual basis. These savings are significant given the simplicity of this control strategy. It is recommended that this strategy be implemented as soon as possible.

The use of automatic reset may have an additional benefit not studied. Because the chilled water supply temperature is allowed to get as high as 46 F, it seems that the actual chilled water temperature required at the air-handlers is 46 F. Unless there is warm return water bypassing the chillers, the chilled water setpoint could be raised from 44 F to 46 F which would reduce the chiller power consumption by about 4% (see Figure 2.3).

## 5.4 Storage Tank Subcooling

The estimated annual impact of storage tank subcooling showed that even a reduction in supply temperature of 1 F in mode 7 caused an increase in the annual utility bill. It appears that the only way subcooling might pay is if the peak days could be anticipated the night before and subcooling used only on these days.

## 5.5 Computer Simulation

The major part of this project was the development of the computer simulation. Much of the time was invested in the development of the new component models. Both the chiller and cooling tower models were designed to be general models which are made specific with manufacturer's data. For future projects, this part of the effort should be a minor task.

The other major part of the development effort was the modeling of the control functions. Most of the control strategies required for the simulation were performed manually in the actual system when this effort started. The operators were cooperative in relating their general control concepts, but many of the details required were not discussed. These details were discovered by implementing the general concepts in the simulation and then observing the system behavior.

The complexity and uniqueness of innovative heating and cooling systems would likely require a similar trial and error procedure for development of control strategies. This is a benefit of a detailed computer simulation tool like TRNSYS. Otherwise, the strategies would have to be tried in the actual system where an error or oversight could have disastrous consequences.

## 5.6 General Conclusions

Though the savings reported here are a minor portion of the total power bill, most of the strategies can be implemented on the minicomputer system with only a minor effort.

The utility rate schedule has a direct impact on the monetary savings accrued by these and any other conservation strategies. The Duke Power rates are relatively low compared to the rest of the country. Peak demand charge is about \$2.71/kW and the consumption charge is about \$0.031/kWh for typical summer conditions. Higher future rates and higher rates in other parts of the country would increase the savings substantially. The presence of time-of-day rates would also add to the benefit of the storage system on a year round basis.

An additional benefit of this project is the better understanding of the equipment and system operation by the plant personnel, both on a theoretical and practical basis. In one case in particular, this study pointed out that the actual outside air amounts were inconsistent with the supposed control strategies. An examination of the AHUs showed that many of the outside air dampers were out of adjustment causing excessive amounts of outside air during hot weather. The reduced cooling loads resulting from the proper adjustment likely result in as great or greater savings than all of the computer strategies.

The plant simulation model developed here will be transferred to the site. In this manner, new ideas for control strategies and equipment modifications can be checked out on the computer both to identify the energy impact and operational problems, if any.

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# APPENDIX A

## SUBROUTINE DOCUMENTATION

TYPE 1 Storage Tank Flow Control

TYPE 2 Mode Control

TYPE 5 Air-handling Unit

TYPE 6 Utility Bill

TYPE 7 Statistics

TYPE 10 Main Site Flow Routine

TYPE 13 Storage Outlet Mixer

TYPE 20 Condenser Pumps

TYPE 21 Chiller Model

TYPE 22 Cooling Tower

TYPE 23 Cooling Tower Control

TYPE 1 STORAGE TANK FLOW CONTROL

PARAMETERS

| | |
|---|---|
| 1 | TMFULL: maximum usable mass of water in each tank (lb) |
| 2 | TMIN: minimum mass of water in each storage tank (lb) |

INPUTS

| | |
|---|---|
| 1 | FLOW: flow rate to storage tanks (lb/hr) |
| 2-6 | TMASS: mass of water in tanks 1-5 (lb) |
| 7-11 | TT: temperature of water in tanks 1-5 (F) |
| 12 | MODE: system operating mode |

OUTPUTS

| | |
|---|---|
| 1-5 | Flow rate of water into tank 1-5 (lb/hr) |
| 6-10 | Flow rate of water out of tanks 1-5 (lb/hr) |

```
      SUBROUTINE TYPE1(TIME,XIN,OUT,T,DTDT,PAR,INFO)
C
C THIS SUBROUTINE CONTROLS THE FLOW TO AND FROM THE 5 STORAG
E TANKS
C WHEN THE TANKS COMPLETELY FILL OR EMPTY IN A GIVEN TIME ST
EP, THIS
C ROUTINE SETS OUTPUT(11) EQUAL TO THE MASS FLOW WHICH IS IN
 EXCESS OF
C THE CAPACITY SO THAT THE MAIN FLOW CONTROL CAN ADJUST THE
FLOWS
C ACCORDINGLY SO THAT THE TANKS JUST FILL THIS TIME STEP. WH
EN JUST
C FULL, OUTPUT(11) IS SET EQUAL TO 1 TO SIGNAL COMPLETION OF
 THE MODE.
C IF THE MODE IS NOT COMPLETE AND THERE IS CARRYOVER(TANKS S
WITCH),
C OUT(12) IS SET = TO 1 TO SIGNAL THE MODE CONTROLLER TO CON
TINUE SAME
C MODE FOR ANOTHER TIME STEP.
C
      DIMENSION TMASS(5),T(1),TT(5),XIN(12),OUT(12),PAR(2),I
NFO(10),
     1   TTP(5),TMASSP(5)
      COMMON /SIM/TIME0,TFINAL,DELT
      INTEGER SM
      REAL MIN,MTOT
      IF(INFO(7) .GT. -1)GO TO 1000
      CRYOVR = 0.
      MODE = -1
      NTNK = 1
      INFO(6)=12
      INFO(9)=1
C THE PARAMETERS TMFULL=THE MASS OF USABLE WATER IN EACH TAN
K
C                  TMIN=THE MINIMUM MASS OF WATER IN EACH TANK
C THEREFORE, THE MAXIMUM VOLUME IN EACH TANK=TMFULL+TMIN.
      TMFULL = PAR(1)
      TMIN = PAR(2)
1000  IF(INFO(7) .GT. 0)GO TO 1010
      PRNTNK = NTNK
      CRYVRP = CRYOVR
      MODEP = MODE
      DO 10 I=1,5
         TTP(I) = TT(I)
         TMASSP(I) = TMASS(I)
10       CONTINUE
1010  FLOW = XIN(1)
      DO 100 I=1,5
         TT(I) = XIN(6+I)
```

```
C SINCE TMASS IS THE USABLE TANK MASS, TMIN MUST BE SUBTRACT
ED FROM
C THE ACTUAL TANK MASS FROM TYPE 32.
         TMASS(I) = XIN(1+I) * 62.4 - TMIN
         IF(INFO(7).EQ.-1)THEN
            TTP(I) = TT(I)
            TMASSP(I) = TMASS(I)
         END IF
100   CONTINUE
      NTNK = PRNTNK
      CRYOVR = CRYVRP
      MIN = FLOW * DELT
      MTOT = 0.
      IF(FLOW .GT. 0.)GO TO 1100
      DO 200 I=1,12
200      OUT(I) = 0.
C
C IF FLOW TO STORAGE HAS STOPPED FOR SOME REASON BUT THERE W
AS
C CARRYOVER FLOW FROM THE PREVIOUS TIME STEP, THE PROGRAM SE
NDS
C THE CARRYOVER TO THE PROPER TANK.
C A SLIGHT ERROR IS INTRODUCED BECAUSE THE CURRENT FLOW TEMP
ERATURE
C IS USED AND THE LOSSES FROM THE CARRYOVER FLUID BEING IN T
HE TANK
C ARE IGNORED. THIS IS TRUE WHENEVER A TANK SWITCH OCCURS.
C
      IF(CRYOVR .EQ. 0.)GO TO 4000
      GO TO 1200
1100  MODE = XIN(12)
      IF(MODE.EQ.MODEP)GO TO 1300
C
C IF MODE HAS NOT CHANGED FROM 2 OR 3 TO 7 OR VICE VERSA,
C FOLLOWING CALCULATIONS CAN BE BYPASSED.
C THESE STATEMENTS FIND THE APPROPRIATE TANK TO SEND FLOW TO
C AND DETERMINE THE SUBMODE.
C
1400  DO 110 I=1,5
         IF(TMASSP(I) .GT. (TMFULL*.999))GO TO 110
         NTNK = I
         GO TO 1500
110      CONTINUE
1500  IF(NTNK .EQ. 5)GO TO 1600
      IF(NTNK .EQ. 1)GO TO 1700
      TL = 0.
      DO 120 I=1,NTNK-1
120      TL = TL + TTP(I)
      ICNT = NTNK - 1
      TLBAR = TL/ICNT
```

```
      GO TO 1750
1700  IF(TMASSP(1) .LT. 1.)SM = 0
      IF(TMASSP(1) .LT. 1.)GO TO 1300
      TLBAR = TTP(NTNK)
1750  TR = 0.
      DO 130 J=NTNK+1,5
130      TR = TR + TTP(J)
      JCNT = 5 - NTNK
      TRBAR = TR/JCNT
      SM = 0
      IF(TLBAR .LT. TRBAR)SM = 1
      IF(MODE .NE. 7)GO TO 1800
      IF(SM .EQ. 0)GO TO 1850
      SM = 0
      GO TO 1800
1850  SM = 1
1800  IF(SM .EQ. 1)NTNK = NTNK + 1
      GO TO 1300
1600  SM = 1
C
C RESET OUTPUTS
C
1300  DO 400 I=1,12
400      OUT(I) = 0.
C
C CHECK SUBMODE, 0 IS LEFT TO RIGHT, 1 IS OPPOSITE
C
1200  IF(SM .EQ. 1)GO TO 3000
C
C SUBMODE IS LEFT TO RIGHT
C CHECK FOR TANK OVERFLOW THIS TIME STEP
C
      MTOT=TMASSP(NTNK) + MIN
      IF(MTOT .LT. TMFULL*.999)GO TO 2000
C
C TANK(NTNK) WILL OVERFILL THIS TIME STEP, THE PROCEDURE IS
C TO PROVIDE ENOUGH TO FILL IT AND AT THE SAME TIME DRAIN
C THE ADJACENT TANK. THEN, NTNK IS INCREMENTED AND THE
C REMAINING FLOW IS DRAWN FROM THE NEXT TANK. THE INPUT TO
C THE NEW TANK FROM THIS TIMESTEP IS CARRIED OVER TO THE
C NEXT TIMESTEP TO PREVENT MIXING IN THE TANK WHICH WILL
C EMPTY THIS TIMESTEP.
C
      NTNK = NTNK + 1
      OUT(NTNK-1) = (TMFULL - TMASSP(NTNK-1))/DELT
      OUT(NTNK+5) = OUT(NTNK-1)
C
C CHECK NTNK=5 TO SEE IF MODE IS COMPLETE
C
      CRYOVR = FLOW - OUT(NTNK-1)
```

```
      IF(NTNK .LT. 5)GO TO 2100
C
C SET MODE COMPLETE FLAG AND CARRYOVER OUTPUT
C
3200  OUT(11) = CRYOVR + 1.
      CRYOVR = 0.
      GO TO 4000
C
C MODE IS NOT COMPLETE, DRAIN REMAINDER OUT OF NEXT TANK
C
2100  OUT(NTNK+6) = CRYOVR
      GO TO 4000
C
C TANK WILL NOT OVERFILL THIS TIME STEP
C
2000  OUT(NTNK) = FLOW + CRYOVR
      OUT(NTNK+6) = FLOW
      CRYOVR = 0.
      GO TO 4000
C
C SUBMODE IS RIGHT TO LEFT
C CHECK FOR OVERFLOW THIS TIME STEP
C
3000  MTOT = TMASSP(NTNK) + MIN
      IF(MTOT .LT. TMFULL*.999)GO TO 3100
C
C TANK WILL OVERFILL
C
      NTNK = NTNK - 1
      OUT(NTNK+1) = (TMFULL - TMASSP(NTNK+1))/DELT
      OUT(NTNK+5) = OUT(NTNK+1)
C
C CHECK IF NTNK=1 TO SEE IF MODE IS COMPLETE
C
      CRYOVR = FLOW - OUT(NTNK+1)
      IF(NTNK .EQ. 1)GO TO 3200
C
C MODE IS NOT COMPLETE, DRAIN REMAINDER OUT OF NEXT TANK
C
      OUT(NTNK+4) = CRYOVR
      GO TO 4000
C
C TANK WILL NOT OVERFILL THIS TIME STEP
C
3100  OUT(NTNK) = FLOW + CRYOVR
      OUT(NTNK+4) = FLOW
      CRYOVR = 0.
C
C FLOW CALCULATIONS ARE COMPLETE
C
```

```
4000  IF (CRYOVR .GT. 0.) OUT(12) = 1
      RETURN
      END
```

TYPE 2 MODE CONTROL

PARAMETERS

| | |
|---|---|
| 1 | TFRCL: ambient wet-bulb temperature below which free cooling is used (F) |
| 2 | TSTCL: desired cold water storage temperature (F) |
| 3 | TMFULL: maximum mass in each storage tank (lb) |
| 4 | STFLMX: maximum flow to or from storage in mode 2 and 3 (lb/hr) |
| 5 | STFMX7: Maximum flow to or from storage in mode 7 (lb/hr) |
| 6 | STFLMN: minimum flow to or from storage (lb/hr) |
| 7 | CHWSET: chilled water setpoint (F) |
| 8 | CHWMAX: maximum chilled water supply temperature (F) |
| 9 | CHWMIN: minimum chilled water supply temperature (F) |
| 10 | CHWSTM: chilled water setpoint during mode 7 (F) |
| 11 | LCHMX: maximum chiller loading (Btu/hr) |
| 12 | CP: specific heat of water (Btu/lb F) |
| 13 | FLOPMX: maximum primary pump flow (lb/hr) |
| 14 | FLRDMN: minimum fractional flow reduction on primary pumps |
| 15 | NSTK: number of controller oscillations allowed before output is fixed (not used) |
| 16 | BYFLO: maximum desired forward bypass flow in mode 1 (lb/hr) |
| 17 | M2ST: start time for mode 2 |
| 18 | M7ST: start time for mode 7 |
| 19 | M7DUR: allowable duration for mode 7 (hr) |
| 20 | TMIN: minimum mass of water in storage tanks (lb) |
| 21 | Not used |

22,23 C11,C12: coefficients of optimum PLR correlation for one chiller

24,25,26 C21,C22,C23: coefficients of optimum PLR correlation for two chillers

27,28,29 C31,C32,C33: coefficients of optimum PLR correlation for three chillers

INPUTS

1 CRYOVR: the flow rate in excess of the tank capacity at completion of a storage mode (lb/hr)

2-6 Volume of water in tanks 1-5 ($ft^3$)

7-11 TT(I): temperature of water in tanks 1-5 (F)

12 TWB: ambient wet-bulb temperature (F)

13 TCHWS: chilled water supply temperature (F)

14 FLOWS: secondary pump flow (lb/hr)

15 TCHWR: water temperature returning from site (F)

16 LATCH: digital signal from storage tank control which signals the mode control to continue with the same mode

17 PLR: chiller part-load ratio

18 CAP: chiller cooling capacity (Btu/hr)

19 LCHTOT: total chiller cooling load (Btu/hr)

20 KWFL: Chiller power consumption at full-load, per chiller (kW)

21 KWA: actual total chiller power consumption (kW)

22 FLOCH: water flow rate through chiller evaporators (lb/hr)

OUTPUTS

1 MODE: system operating mode

2-7 Control functions for flow diverters, T1-T6

8 FNCH: number of operating chillers

9 CHWSET: chilled water setpoint (F)

10 REDFLO: fractional amount of flow reduction using evaporator valves

11 LOAD: total chilled water load (Btu/hr)

```
      SUBROUTINE TYPE2(TIME,XIN,OUT,T,DTDT,PAR,INFO)
C THIS ROUTINE SELECTS THE OPTIMUM MODE FOR THE PLANT, SETS
THE
C VALVE POSITIONS, AND DETERMINES THE # OF CHILLERS.
C
      DIMENSION TMASS(5),TT(5),XIN(22),OUT(11),PAR(30),INFO(
10),CCST(5),
     1   TMASSP(5),TTP(5)
      REAL LOAD,LCHMX,LCHOP,LCHTOT,KWA,KWFL,M2ST,M7ST,M7DUR
      COMMON/SIM/TIME0,TFINAL,DELT
      IF (INFO(7) .GT. -1)GO TO 10
      INFO(6) = 11
      NCH = 0
      DT = 10.
      TFRCL = PAR(1)
      TSTCL = PAR(2)
      TMFULL = PAR(3)
      STFLMN = PAR(6)
      CHWSET = PAR(7)
      CHWMAX = PAR(8)
      CHWMIN = PAR(9)
      CHWSTM = PAR(10)
      LCHMX = PAR(11)
      CP = PAR(12)
      FLOPMX = PAR(13)
      FLRDMN = PAR(14)
      NSTK = PAR(15)
      BYFLO = PAR(16)
      M2ST = PAR(17)
      M7ST = PAR(18)
      M7DUR = PAR(19)
      TMIN = PAR(20)
      C11 = PAR(22)
      C12 = PAR(23)
      C21 = PAR(24)
      C22 = PAR(25)
      C23 = PAR(26)
      C31 = PAR(27)
      C32 = PAR(28)
      C33 = PAR(29)
      REDFLO = 1.
      TWBMIN = 100.
      PTWBMN = 100.
      PTTWBM = 4.
10    IF(INFO(7) .GT. 0)GO TO 15
      HOUR = (TIME/24.-INT(TIME/24.))*24.
      NOTM7 = 0
      NOTM2 = 0
      NCHP = NCH
```

```
      MPREV = IFIX(OUT(1))
      CRYVRP = CRYOVR
      LATCHP = LATCH
      RDFLP = REDFLO
      STFLMX = PAR(4)
      STFMX7 = PAR(5)
      DO 12 I=1,5
         TMASSP(I) = TMASS(I)
         TTP(I) = TT(I)
12       CONTINUE
15    CRYOVR = XIN(1)
      DO 20 I=1,5
         TMASS(I) = XIN(I+1)*62.4 - TMIN
20       TT(I) = XIN(I+6)
C THE PARAMETER CRYOVR IS SET BY THE STORAGE TANK CONTROLLER
 TO
C INDICATE THAT THE TANKS ARE COMPLETELY FULL OR EMPTY. CRYO
VR IS
C EQUAL TO THE FLOWRATE IN EXCESS OF THE TANK CAPACITY. IF T
HE TANK IS
C JUST FULL AND THE MODE IS COMPLETE, CRYOVR IS SET EQUAL TO
 1 TO
C SIGNAL MODE COMPLETION. IF CRYOVR > 1, THE MAXIMUM STORAGE
C FLOW IS REDUCED TO PREVENT OVERFILLING.
      IF(CRYOVR.GT.1. .AND. INFO(7).GT.0)THEN
         STFLMX = FLOWST - CRYOVR
         STFMX7 = STFLMX
      END IF
      TWB = XIN(12)
      TCHWS = XIN(13)
      FLOWS = XIN(14)
      TCHWR = XIN(15)
      LOAD = FLOWS*CP*(TCHWR-TCHWS)
      LATCH = XIN(16)
      PLR = XIN(17)
      CAP = XIN(18)
      LCHTOT = XIN(19)
      KWFL = XIN(20)
      KWA = XIN(21)
      FLOCH = XIN(22)
      MODEP = IFIX(OUT(1))
C RESET VALVE POSITIONS, ZERO IS DEFAULT
      DO 30 I=2,7
30       OUT(I) = 0.
C
C CHECK FOR STORAGE MODE LATCH, IT IS IMPORTANT TO CONTINUE
C THE SAME MODE BECAUSE THE STORAGE FLOW CONTROL IS HOLDING
SOME
C FLOW FOR THE PROPER TANK.
      IF (LATCHP .LT. 1)GO TO 35
```

```
      GO TO(35,300,300,35,35,35,700) MPREV
C
C FIND STORED COOLING CAPACITY (CCST).
35    IF(INFO(7).GT.0)GO TO 165
      QWARM = 0.
      WMASS = 0.
C FIND AVERAGE TEMPERATURE OF THE WARM TANKS.
      DO 150 I=1,5
         IF (TTP(I) .LT. (TSTCL+5.) .OR. TMASSP(I) .LT. 1.)G
O TO 150
         QWARM = QWARM + TMASSP(I) * TTP(I)
         WMASS = WMASS + TMASSP(I)
150      CONTINUE
      WTBAR = QWARM / (WMASS + .0001)
      IF (QWARM .EQ. 0.)WTBAR = TCHWR
C FIND COOLING CAPACITY OF THE TANKS WITH CHILLED WATER.
      DO 160 I=1,5
         IF (TMASSP(I) .LT. 1. .OR. TTP(I) .GE. (TSTCL + 5.)
)GO TO 170
         CCST(I) = TMASSP(I) * CP * (WTBAR - TTP(I))
         GO TO 160
170      CCST(I) = 0.
160      CONTINUE
C FIND TOTAL STORED COOLING CAPACITY (MILLION BTU).
      CCSTT = ( CCST(1) + CCST(2) + CCST(3) + CCST(4) + CCST
(5)) / 1.E6
C
C THIS NEXT SECTION STARTS THE MODE SELECTION PROCESS.
C
C THE FIRST MODE CHECKED FOR IS MODE 7, RECHARGING THE
C STORAGE TANKS.  THIS MODE IS ACTIVATED IF THE TANKS HAVE S
OME
C WARM WATER AND IF TIME IS WITHIN THE ALLOTED START AND
C STOP TIME.
C
165   IF (WMASS.GT.(TMFULL*.05).AND.HOUR.GT.M7ST.AND.HOUR.LT
.(M7ST+
     +   M7DUR))GO TO 700
C IF MODE 7 HAS NOT BEEN SELECTED, THE NEXT MODE CHECKED IS
C MODE 2 (OR MODE 3 IF FLOW IS LOW ENOUGH).
C MODES 2,3 ARE ACTIVATED IF THE TANKS HAVE SOME COLD
C WATER AND TIME IS WITHIN THE ALLOTED START AND STOP TIME.
      IF (WMASS.LT.(TMFULL*3.95).AND.HOUR.GT..99*M2ST)GO TO
300
C MODES 2,3,7 HAVE BEEN ELIMINATED FROM CONSIDERATION, ONLY
C MODE REMAINING IS MODE 1 - CHILLERS ONLY.
      GO TO 1000
700   OUT(1) = 7
      GO TO 670
C MODE 1
```

```
1000  OUT(1) = 1
      GO TO 610
C
C MODES 3 & 2 (IN ORDER OF PREFERENCE). USE STORAGE ONLY IF
FLOW IS LESS
C THAN STFLMX (INITIALLY 1500GPM) AND TANKS CAN HANDLE LOAD
FOR
C OVER AN HOUR (MODE=3). IF NOT, RUN CHILLERS AT OPTIMUM LOA
DING
C AND SUPPLEMENT WITH STORAGE(MODE=2).
300   IF (FLOWS .GT. STFLMX .OR. LOAD .GT. (CCSTT*1.E6))GO T
O 2000
C SET OUTPUTS FOR MODE 3
      OUT(1) = 3
      OUT(4) = 1.
      OUT(5) = 1.
      FNCH = 0.
      GO TO 9000
C SET OUTPUTS FOR MODE 2
2000  OUT(1) = 2
      GO TO 620
C
C THE FOLLOWING SECTION (LINE #S 600) DETERMINES THE # OF CH
ILLERS
C FOR MODES 1,2, OR 7.
C
C THIS ROUTINE DECIDES THE # OF CHILLERS  FOR MODE #1.
610   IF(INFO(7).GT.0.AND.MPREV.EQ.1)GO TO 618
      NCH = AINT(LOAD/LCHMX) + 1
      PLR = LOAD/(FLOAT(NCH)*CAP)
C CHILLER NUMBER OPTIMIZATION IN MODE 1
C BASED ON CORRELATIONS OF THE OPTIMUM PLR AT
C WHICH TO ACTIVATE ANOTHER CHILLER
      PLRO1 = C11 + C12*TWB
      IF(PLRO1.GT.1.)PLRO1=1.
      PLRO2 = C21 + C22*TWB + C23*TWB**2
      IF(PLRO2.GT.1.)PLRO2=1.
      PLRO3 = C31 + C32*TWB + C33*TWB**2
      IF(PLRO3.GT.1.)PLRO3=1.
      GO TO(611,612,613,614)NCH
611   IF(PLR.GT.PLRO1)NCH = NCH+1
      GO TO 617
612   IF(PLR.GT.PLRO2)THEN
         NCH = NCH+1
         PLR = LOAD/(FLOAT(NCH)*CAP)
         GO TO 613
      END IF
      NCH = NCH-1
      PLR = LOAD/(FLOAT(NCH)*CAP)
      GO TO 611
```

```
613    IF(PLR.GT.PLRO3)THEN
          NCH = NCH+1
          GO TO 617
       END IF
       PLRM1 = LOAD/(FLOAT(NCH-1)*CAP)
       IF(PLRM1.LT.PLRO2)THEN
          NCH = NCH-1
          PLR = PLRM1
          GO TO 612
       END IF
       GO TO 617
614    IF(PLR*4./3..LT.PLRO3)THEN
          PLR = PLR*4./3.
          NCH = NCH-1
          GO TO 613
       END IF
617    NCHO = NCH
618    IF(INFO(7).GT.0.AND.TCHWS.GT.CHWMAX)NCH=NCHO+1
       FNCH = FLOAT(NCH)
       REDFLO = 1.
       FLOWP = FNCH*FLOPMX*REDFLO
       BYPFLO = FLOWP - FLOWS
       IF(BYPFLO.LT.BYFLO)GO TO 410
       REDFLO = (FLOWS+BYFLO)/(FLOPMX*FNCH)
       IF(REDFLO.LT.FLRDMN)REDFLO = FLRDMN
       FLOWP = FNCH*FLOPMX*REDFLO
       GO TO 410
C
C THIS ROUTINE DECIDES THE # OF CHILLERS FOR MODE #2.
C
C IN MODE 2, CHILLERS ARE ALLOWED TO RUN AT THE SAME FLOW AN
D #
C UNLESS STORAGE FLOW IS OUT OF BOUNDS.
620    FLOWST = FLOWS-FLOWP
       IF(FLOWST.GT.STFLMN.AND.FLOWST.LT.STFLMX)GO TO 420
       IF(FLOWST.LT.STFLMN.AND.MPREV.NE.2)THEN
          REDFLO = (FLOWS-STFLMN)/(FLOPMX*FNCH)
          IF(REDFLO.LT.1..AND.REDFLO.GT.FLRDMN)THEN
             FLOWP = FNCH*REDFLO*FLOPMX
             GO TO 420
          END IF
       END IF
       IF(NCH .EQ. 0)NCH = 1
624    FNCH = FLOAT(NCH)
       RMIN = (FLOWS-STFLMX)/(FLOPMX*FNCH)
       RMAX = (FLOWS-STFLMN)/(FLOPMX*FNCH)
C IF RMIN IS LARGER THAN 1, ANOTHER CHILLER MUST BE ACTIVATE
D.
       IF(RMIN.GT.1.)GO TO 621
C SET FLOW TO MAKE STORAGE FLOW MAXIMUM.
```

```
      IF(RMIN.LT.FLRDMN)RMIN=FLRDMN
      REDFLO = RMIN
      FLOWP = FNCH*FLOPMX*REDFLO
      IF(REDFLO.LT.RMAX)GO TO 420
      OUT(1) = 1
      GO TO 610
621   IF(NCH.EQ.4)GO TO 1000
      NCH = NCH+1
      GO TO 624
C
C THIS ROUTINE DECIDES THE # OF CHILLERS FOR MODE 7.
C
670   ICNT = 0
      NCH = AINT(LOAD/CAP) + 2
675   IF(ICNT.LE.4)GO TO 671
      OUT(1) = 1
      GO TO 610
671   FNCH = FLOAT(NCH)
      RMAX = (STFMX7+FLOWS)/(FLOPMX*FNCH)
      RMIN = (STFLMN+FLOWS)/(FLOPMX*FNCH)
      IF(RMAX.LT.FLRDMN)GO TO 672
      IF(RMAX.GT.1.)GO TO 673
      REDFLO = RMAX
      GO TO 674
673   REDFLO = 1.
674   FLOWP = FNCH*REDFLO*FLOPMX
      IF(REDFLO.GT.RMIN)GO TO 470
      IF(NCH.EQ.4)GO TO 1000
      NCH = NCH+1
      ICNT = ICNT+1
      GO TO 675
672   IF(NCH.EQ.1)GO TO 1000
      NCH = NCH-1
      ICNT = ICNT+1
      GO TO 675
C
C THE FOLLOWING ROUTINES MODULATE THE APPROPRIATE VALVES IN
MODES 1,2,
C AND 7.
C
410   BYPFLO = FLOWP - FLOWS
      IF(BYPFLO .GT. 0.)GO TO 415
C BYPASS FLOW IS NEGATIVE.
      GAM6 = 0.
      GAM1 = 1. + BYPFLO/FLOWS
416   OUT(2) = GAM1
      OUT(3) = 1.
      OUT(7) = GAM6
      GO TO 430
C BYPASS FLOW IS POSITIVE.
```

```
415   GAM1 = 1.
      GAM6 = BYPFLO/FLOWP
      GO TO 416
C MODE IS 2, MODULATE VALVE 1.
420   GAM1 = FLOWP/FLOWS
      OUT(2) = GAM1
      OUT(3) = 1.
      OUT(4) = 1.
      OUT(5) = 1.
      FLOWST = FLOWS - FLOWP
      GO TO 430
C MODE IS 7, MODULATE VALVE 2.
470   GAM2 = FLOWS/FLOWP
      OUT(2) = 1.
      OUT(3) = GAM2
      OUT(6) = 1.
      FLOWST = FLOWP - FLOWS
430   CONTINUE
9000  FNCH = FLOAT(NCH)
      OUT(8) = FNCH
      OUT(9) = CHWSET
      IF(OUT(1).EQ.7.)OUT(9)=CHWSTM
      OUT(10) = REDFLO
      OUT(11) = LOAD
      RETURN
      END
```

TYPE 5 AIR-HANDLING UNIT

PARAMETERS

| | |
|---|---|
| 1 | TRACMX: return air temperature at which fan flow reaches it maximum (F) |
| 2 | TRACMN: return air temperature at which fan flow reaches it minimum (F) |
| 3 | CFMMX: maximum fan flow rate (CFM) |
| 4 | CFMMN: minimum fan flow rate (CFM) |
| 5 | TRARMX: return air temperature at which mixed air setpoint is at its lowest setting (F) |
| 6 | TRARMN: return air temperature at which mixed air setpoint is at its highest setting (F) |
| 7 | TMAMX: maximum mixed air setpoint (F) |
| 8 | TMAMN: minimum mixed air setpoint (F) |
| 9 | OACFM: outside air amount; if positive outside air flow rate is constant, if negative outside air is a constant fraction of the total fan flow rate |
| 10 | ECON: if greater than zero, enthalpy economizer is enabled |
| 11 | CCLAWD: cooling-coil leaving air humidity ratio at design conditions |
| 12 | DESPWR: fan power consumption at maximum flow rate (kW) |
| 13-16 | A1-A4: coefficients of a third-order fit of fan power ratio as a function of the flow ratio |
| 17 | THON: return air temperature at which heating coil starts (F) |
| 18 | THMAX: return air temperature at which heating coil output is at design (F) |
| 19 | QHEAT: design heating coil output (Btu/hr) |
| 20 | CFMINF: constant infiltration rate when air-handler is off (CFM) |

21 NSTK: used to stick the air flow rate and mixed air setpoint if the subroutine is called more than NSTK times each time-step

INPUTS

| | |
|---|---|
| 1 | TRA: return air temperature (F) |
| 2 | RAW: return air humidity ratio |
| 3 | TOA: outside air dry-bulb temperature (F) |
| 4 | OAW: outside air humidity ratio |
| 5 | ON: if greater than 0.5, the air-handler is on |

OUTPUTS

| | |
|---|---|
| 1 | CCL: total cooling coil load (Btu/hr) |
| 2 | CFM: total fan air flow rate (CFM) |
| 3 | CFMOA: outside air flow rate (CFM) |
| 4 | TSA: supply air temperature (F) |
| 5 | CCLAW: supply air humidity ratio |
| 6 | Total fan flow rate (lb/hr) |
| 7 | FPWR: fan power demand (kW) |
| 8 | OASENS: sensible cooling load due to outside air (Btu/hr) |
| 9 | OALAT: latent cooling load due to outside air (Btu/hr) |
| 10 | FANLD: cooling load due to fan power (Btu/hr) |
| 11 | QH: heating coil load (Btu/hr) |
| 12,13 | Not used |
| 14 | TMASET: mixed air setpoint (F) |
| 15 | TRAC: return air control temperature (F) |
| 16 | TRACP: return air control temperature from previous time-step (F) |

```
      SUBROUTINE TYPE5(TIME,XIN,OUT,T,DTDT,PAR,INFO)
      DIMENSION XIN(5),OUT(16),T(1),DTDT(1),PAR(21),INFO(10)
      REAL MAW,MADB
      INFO(6) = 16
      TRACMX = PAR(1)
      TRACMN = PAR(2)
      CFMMX = PAR(3)
      CFMMN = PAR(4)
      CFMSL = (CFMMX-CFMMN)/(TRACMX-TRACMN)
      TRARMX = PAR(5)
      TRARMN = PAR(6)
C SET TMAMX=TMAMN=(MIXED AIR SETPOINT) IF RETURN AIR RESET I
S NOT
C DESIRED.
      TMAMX = PAR(7)
      TMAMN = PAR(8)
      RSTSL = (TMAMX-TMAMN)/(TRARMN-TRARMX)
C IF OACFM IS POSITIVE, THE OUTSIDE AIR AMOUNT IS CONSTANT.
C IF OACFM IS NEGATIVE, OACFM IS THE CONSTANT FRACTION OF OU
TSIDE AIR.
C BOTH ARE OVERRIDDEN BY THE ENTHALPY ECONOMIZER IF PRESENT.
      OACFM = PAR(9)
C IF ECON>0, THEN ENTHALPY ECONOMIZER IS ENABLED.
      ECON = PAR(10)
      CCLAWD = PAR(11)
      CCLAW = CCLAWD
      DESPWR = PAR(12)
      A1 = PAR(13)
      A2 = PAR(14)
      A3 = PAR(15)
      A4 = PAR(16)
      THON = PAR(17)
      THMAX = PAR(18)
      QHEAT = PAR(19)
C IF CFMINF>0, THEN WHEN AHU IS OFF, NATURAL INFILTRATION CF
M TAKES OVER
      CFMINF = PAR(20)
C AFTER NSTK CALLS IN ONE TIME STEP, THE AIR QUANTITIES
C ARE STUCK IN ONE POSITION FOR STABILITY.
      NSTK = PAR(21)
      IF(INFO(7).EQ.0)TRACP=OUT(15)
      IF(INFO(7).GT.0)TRACP = OUT(16)
      TRA = XIN(1)
      IF(INFO(7).EQ.-1)TRACP=TRA
      RAW = XIN(2)
      TOA = XIN(3)
      OAW = XIN(4)
      ON = XIN(5)
C THE TEMPERATURE USED TO CONTROL THE SETPOINTS AND CFMS
```

```
C IS  THE TEMPERATURE AT THE END OF THE TIME STEP (THIS TIME
 STEP)
C IF THE PREVIOUS ZONE TEMPERATURE WAS ABOVE OR BELOW THE
C THERMOSTAT CONTROL RANGE.
      TRAC = 2.*TRA - TRACP
      IF(TRACP.LT.TRACMX.AND.TRACP.GT.THMAX)TRAC=TRA
      IF(ON.LT..5)THEN
         CCL = 0.
         CFM = CFMINF
         CFMOA = CFMINF
         FPWR = 0.
         OALAT = 0.
         OASENS = 0.
         FANLD = 0.
         QH = 0.
         TSA = TOA
         CCLAW = OAW
         GO TO 1000
      END IF
      HOA = .24*TOA + OAW*(1061.+.444*TOA)
      IF(INFO(7).GT.NSTK)THEN
         CFM = OUT(2)
         CFMOA = OUT(3)
         TMASET = OUT(14)
         GO TO 150
      END IF
C *************************
C   AIR HANDLER CALCULATIONS
C    USES ENTHALPY ECONOMIZER CYCLE
C    AND RETURN AIR RESET OF TMASET.
C *************************
C CALCULATE THE MIXED AIR SETPOINT
      IF(TMAMX.NE.TMAMN)THEN
         TMASET = RSTSL*(TRAC-TRARMN)+TMAMX
         IF(TMASET.GT.TMAMX)TMASET=TMAMX
         IF(TMASET.LT.TMAMN)TMASET=TMAMN
      ELSE
         TMASET = TMAMN
      END IF
C COMPUTE TOTAL CFM
      CFM = CFMSL*(TRAC-TRACMN)+CFMMN
      IF(CFM.GT.CFMMX)CFM=CFMMX
      IF(CFM.LT.CFMMN)CFM=CFMMN
C COMPUTE RETURN AIR ENTHALPY
      HRA = .24*TRA + RAW*(1061.+.444*TRA)
C USE ENTHALPY ECONOMIZER IF ENABLED
      IF(ECON.GT.0)THEN
C USE MINIMUM OUTSIDE AIR IF HOA>HRA.
         IF(HOA.GT.HRA)THEN
            CFMOA = OACFM
```

```
            IF(OACFM.LT.0.)CFMOA=ABS(OACFM)*CFM
         ELSE
C USE 100% OA IN ECONOMIZER MODE IF TOA>TMASET
            IF(TOA.GT.TMASET)THEN
               CFMOA = CFM
C ELSE MIX OUTSIDE AIR TO ACIEVE DESIRED TMA
            ELSE
               CFMOA = ((TMASET-TRA)/(TOA-TRA))*CFM
               OAMIN = OACFM
               IF(OACFM.LT.0.)OAMIN=ABS(OACFM)*CFM
               IF(CFMOA.LT.OAMIN)CFMOA=OAMIN
            END IF
         END IF
C ELSE ENTHALPY ECONOMIZER IS DISABLED, USE SPECIFIED OUTSID
E AIR.
      ELSE
         CFMOA = OACFM
         IF(OACFM.LT.0.)CFMOA=ABS(OACFM)*CFM
      END IF
C COMPUTE MIXED AIR CONDITIONS
150   MADB = TRA + (CFMOA/CFM)*(TOA-TRA)
      MAW = RAW + (CFMOA/CFM)*(OAW-RAW)
C FIND FAN POWER
      PLR = CFM/CFMMX
      FFLP = A1 + A2*PLR + A3*PLR**2 + A4*PLR**3
      FPWR = DESPWR*FFLP
C FIND FAN TEMPERATURE RISE
      DTF = FPWR*3413./(1.08*CFM)
C COMPUTE COOLING COIL LOADS, CHECK FOR CONDENSATION.
      IF(MADB.GT.TRACMX)THEN
         TMASET = TMASET + MADB - TRACMX
      END IF
C FIND COIL LEAVING HUMIDITY RATIO, ASSUMED TO BE 90%RH
C AT TMASET.
      CCLAW = .0198 - 6.72E-4*TMASET + 8.45E-6*TMASET**2
      IF(MAW.LT.CCLAW)CCLAW=MAW
      CCEADB = MADB + DTF
      OASENS = 1.08*CFM*(MADB-TRA)
      OALAT = 4840.*CFM*(MAW-RAW)
      FANLD = FPWR*3413.
      CCL = 1.08*CFM*(CCEADB-TMASET) + 4840.*CFM*(MAW-CCLAW)
C
C FIND HEATING NEEDS IF ANY.
      IF(TRAC.LT.THON)THEN
         QH = ((THON-TRAC)/(THON-THMAX))*QHEAT
         IF(QH.GT.QHEAT)QH=QHEAT
         TSA = QH/(1.08*CFM) + TMASET
      ELSE
         QH = 0.
         TSA = TMASET
```

```
      END IF
1000  OUT(1) = CCL
      OUT(2) = CFM
      OUT(3) = CFMOA
      OUT(4) = TSA
      OUT(5) = CCLAW
      OUT(6) = CFM*4.5
      OUT(7) = FPWR
      OUT(8) = OASENS
      OUT(9) = OALAT
      OUT(10) = FANLD
      OUT(11) = QH
      OUT(14) = TMASET
      OUT(15) = TRAC
      OUT(16) = TRACP
      RETURN
      END
```

TYPE 6 UTILITY BILL

PARAMETERS

| | |
|---|---|
| 1 | FAC: basic facilities charge ($) |
| 2 | PKWBR: demand above which demand charge applies (kW) |
| 3 | DEMCHG: demand charge ($/kW) |
| 4 | ENDBR1: first break point in energy charge (kWh/kW) |
| 5 | ENDBR2: second break point in energy charge (kWh/kW) |
| 6 | ENDBR3: third break point in energy charge (kWh/kW) |
| 7 | ENBR11: first energy break point (kWh) |
| 8 | ENBR12: second energy break point (KWH) |
| 9 | ENBR2: last energy break point (kWh) |
| 10 | RBR11: energy rate for first interval ($/kWh) |
| 11 | RBR12: energy rate for second interval ($/kWh) |
| 12 | RBR13: energy rate for third interval ($/kWh) |
| 13 | RBR21: energy rate for fourth interval ($/kWH) |
| 14 | RBR22: energy rate for fifth interval ($/kWh) |
| 15 | RBR3: energy rate for last interval ($/kWh) |
| 16 | BILLD: billing demand (kW) |

INPUTS

| | |
|---|---|
| 1 | TOTEL: total electrical consumption for the month (kW) |
| 2 | PEAK: peak 30-minute electrical demand for the month (kW) |

OUTPUTS - None

This subroutine prints the billing information each month.

```
      SUBROUTINE TYPE6(TIME,XIN,OUT,T,DTDT,PAR,INFO)
      DIMENSION XIN(2),OUT(1),T(1),DTDT(1),PAR(16),INFO(10)
      IF(INFO(7).EQ.-1)THEN
      INFO(9) = 0
      FAC = PAR(1)
      PKWBR = PAR(2)
      DEMCHG = PAR(3)
      ENDBR1 = PAR(4)
      ENDBR2 = PAR(5)
      ENDBR3 = PAR(6)
      ENBR11 = PAR(7)
      ENBR12 = PAR(8)
      ENBR2 = PAR(9)
      RBR11 = PAR(10)
      RBR12 = PAR(11)
      RBR13 = PAR(12)
      RBR21 = PAR(13)
      RBR22 = PAR(14)
      RBR3 = PAR(15)
      BILLD = PAR(16)
      GO TO 1000
      END IF
      TOTEL = XIN(1)
      PEAK = XIN(2)
C FIND DEMAND CHARGE AND RESET BILLING DEMAND IF REQUIRED.
      IF(PEAK.GT.BILLD)BILLD=PEAK
      DEM = (BILLD-PKWBR)*DEMCHG
C FIND ENERGY CONSUMPTION CHARGES.
      B1 = ENDBR1*BILLD
      ECH1 = RBR11*ENBR11 + RBR12*ENBR12 + RBR13*(B1-ENBR11-
ENBR12)
      B2 = ENDBR2*BILLD
      ECH3 = RBR3*(TOTEL-B2-B1)
      IF(ECH3.LT.0.)ECH3=0.
      IF(B2.GT.ENBR2.AND.TOTEL.GT.(B2+B1))ECH2=RBR21*ENBR2 +
     +   RBR22*(B2-ENBR2)
      IF(B2.GT.ENBR2.AND.TOTEL.LT.(B2+B1))ECH2=RBR21*ENBR2 +
     +   RBR22*(TOTEL-ENBR2)
      IF(B2.LT.ENBR2.AND.TOTEL.GT.(B2+B1))ECH2=RBR21*B2
      IF(B2.LT.ENBR2.AND.TOTEL.LT.(B2+B1))ECH2=RBR21*(TOTEL-
B1)
      ENER = ECH1 + ECH2 + ECH3
C ADD ALL CHARGES INCLUDING FACILITIES CHARGE.
      TOTCH = DEM + ENER + FAC
      WRITE(*,1)TOTEL/1000.,PEAK,BILLD,DEM,ENER,TOTCH
1     FORMAT(' ','****************************** ELECTRIC COS
TS',
     +   /,' CONS. (MWH)',T15,'PEAK (KW) BILLDEM (KW)',T40,
     +   'DEMCH ($)  ENERCH ($) TOTAL ($)',/,F9.2,3X,F10.1,
```

```
     +    F12.1,F13.0,F13.0,F10.0,/,'*********************',
     +    '*************************************************'
)
1000  RETURN
      END
```

TYPE 7 STATISTICS

PARAMETERS

| | |
|---|---|
| 1 | NMO: number of month at start of simulation |

INPUTS

| | |
|---|---|
| 1 | A: any input, typically total site electric demand |

OUTPUTS

| | |
|---|---|
| 1 | TOTEL: total integrated value of the input for the month |
| 2 | AMXMX: maximum value of the input for the month |

This subroutine also has written output.

```
      SUBROUTINE TYPE7(TIME,XIN,OUT,T,DTDT,PAR,INFO)
      DIMENSION NDAYS(12),XIN(1),OUT(2),AMIN(48),AMAX(48),
     +   JDAYMN(48),JDAYMX(48),XTOT(48),XSQTOT(48),
     +   XMN(48),VAR(48),SDEV(48),HR(48),A(48,31),T(1),DTDT(
1),PAR(1),
     +   INFO(10)
      COMMON/SIM/TIME0,TFINAL,DELT
      INTEGER DAYMOS
      DATA NDAYS/31,28,31,30,31,30,31,31,30,31,30,31/
      IF(INFO(7).EQ.-1)THEN
         INFO(6) = 2
         NHR = INT(24./(DELT*.9999))
         NMO = INT(PAR(1))
         DAYMOS = 0
         DO 7 I=1,NHR
7           AMIN(I) = 1.E12
      END IF
      IF(TIME.EQ.TIME0)GO TO 1000
      IF(INFO(7).EQ.0.AND.TIME.GT.(TIME0+DELT))THEN
         IF(A(IHR,JDAY) .LT. AMIN(IHR))THEN
            AMIN(IHR) = A(IHR,JDAY)
            JDAYMN(IHR) = JDAY
         END IF
         IF(A(IHR,JDAY) .GT. AMAX(IHR))THEN
            AMAX(IHR) = A(IHR,JDAY)
            JDAYMX(IHR) = JDAY
         END IF
      END IF
      IF(INFO(7).EQ.0)THEN
         TD = TIME/23.9999
         REM = TD - INT(TD)
         HOUR = REM*24.0001
         IHR = INT(FLOAT(NHR/24)*HOUR)
         JDAY = INT(TD) + 1 - DAYMOS
         IF(IHR.EQ.0)THEN
            IHR = NHR
            JDAY = JDAY - 1
         END IF
      END IF
      A(IHR,JDAY) = XIN(1)
      IF(JDAY.EQ.NDAYS(NMO).AND.IHR.EQ.NHR.AND.INFO(7).EQ.0)
THEN
      DO 10 I=1,NHR
         XTOT(I)=0.
         XSQTOT(I) = 0.
10    CONTINUE
      DO 50 I=1,NHR
      DO 100 J=1,NDAYS(NMO)
            XTOT(I) = XTOT(I)+A(I,J)
```

```
            XSQTOT(I) = XSQTOT(I) + A(I,J)**2
100       CONTINUE
50      CONTINUE
        FDAYS = FLOAT(NDAYS(NMO))
        WRITE(*,1)NMO
1       FORMAT('0',' STATISTICS FOR MONTH #',I3,/,T8,'HOUR',T1
7,
     +    'MEAN',T28,'MIN',T43,'MAX',T57,'VAR',T66,'SDEV')
        DO 150 I=1,NHR
          XMN(I) = XTOT(I)/FDAYS
          VAR(I) = (XSQTOT(I) - XMN(I)*XTOT(I))/(FDAYS-1.)
          SDEV(I) = VAR(I)**.5
          HR(I) = FLOAT(I)*24./FLOAT(NHR)
          WRITE(*,2)HR(I),XMN(I),AMIN(I),JDAYMN(I),AMAX(I),JD
AYMX(I),
     +      VAR(I),SDEV(I)
2         FORMAT(' ',F10.1,2F10.0,I5,F10.0,I5,2F10.0)
          IF(AMAX(I).GT.AMXMX)THEN
          AMXMX = AMAX(I)
          JDMXMX = JDAYMX(I)
          END IF
150     CONTINUE
        WRITE(*,4)JDMXMX
4       FORMAT('1','****** VALUES FOR THE PEAK DAY OF THE MONT
H, DAY',I3,
     +    ' ******')
        DO 170 I=1,NHR
          WRITE(*,3)HR(I),A(I,JDMXMX)
3         FORMAT(' ',F5.1,F10.0)
     .    WRITE(15,5)HR(I),A(I,JDMXMX)
5         FORMAT(F5.1,F10.0)
170       CONTINUE
        DAYMOS = DAYMOS + NDAYS(NMO)
        NMO = NMO+1
        IF(NMO.EQ.13)NMO=1
        DO 200 I=1,NHR
          XTOTT = XTOTT + XTOT(I)
          AMIN(I) = 1.E12
          AMAX(I) = 0.
200     CONTINUE
        TOTEL = XTOTT*DELT
        OUT(1) = TOTEL
        OUT(2) = AMXMX
        XTOTT = 0.
        AMXMX = 0.
        END IF
1000    RETURN
        END
```

TYPE 10 MAIN SITE FLOW ROUTINE

PARAMETERS

| | |
|---|---|
| 1,2 | F1,F2: coefficients of linear fit of site chilled water temperature rise as a function of the chilled water supply temperature |
| 3-5 | C1-C3: coefficients of quadratic fit of secondary pump power demand as a function of flow rate |

INPUTS

| | |
|---|---|
| 1 | LOAD: total cooling load (Btu/hr) |
| 2 | TCHWS: chilled water supply temperature (F) |

OUTPUTS

| | |
|---|---|
| 1 | FLOWS: total secondary pump flow rate (lb/hr) |
| 2 | TCHWR: chilled water return temperature (F) |
| 3 | PMPPWR: total secondary pump power demand (kW) |

```
      SUBROUTINE TYPE10(TIME,XIN,OUT,T,DTDT,PAR,INFO)
C
C MAIN SITE FLOW ROUTINE - DETERMINES THE SITE FLOW BASED ON
C THE SITE CHILLED WATER LOAD AND THE CHILLED WATER SUPPLY
C TEMPERATURE, ALSO DETERMINES THE PUMPING POWER.
C A RELATION FOR THE CHILLED WATER TEMPERATURE RISE ACROSS
C THE SITE AS A FUNCTION OF TCHWS IS DERIVED FROM THE IBM
C PERFORMANCE DATA: DT = F1+F2*TCHWS. THIS IS THE EFFECTIVE
C MODEL OF THE WATER SIDE OF ALL THE AHU COILS.
C PUMPING POWER IS ALSO DETERMINED FROM A CORRELATION OF
C OPERATING DATA. BOTH OF THESE CORRELATIONS SHOULD BE
C UPDATED PERIODICALLY AND WHENEVER CONTROL IS CHANGED.
C
      DIMENSION XIN(2),OUT(3),T(1),DTDT(1),PAR(6),INFO(10)
      REAL LOAD
      IF(INFO(7) .GT. -1)GO TO 15
      INFO(6) = 3
      F1 = PAR(1)
      F2 = PAR(2)
      C1 = PAR(3)
      C2 = PAR(4)
      C3 = PAR(5)
C FLOMAX IS THE MAXIMUM FLOW PER PUMP IN GPM
      FLOMAX = PAR(6)
15    LOAD = XIN(1)
      TCHWS = XIN(2)
      DELTT = F1 + F2*TCHWS
      FLOWS = LOAD/(1.003*DELTT)
      TCHWR = TCHWS + DELTT
C PUMP POWER IS BASED ON A CURVE FIT FROM IBM DATA
C WATER FLOW UNITS ARE GPM.
      NPMP = INT(FLOWS/(500.4*FLOMAX)) + 1
      FLOWSP = FLOWS/FLOAT(NPMP)
      PMPPWR = (C1 + C2*FLOWSP/500.4 + C3*(FLOWSP/500.4)**2)
*FLOAT(NPMP)
      OUT(1) = FLOWS
      OUT(2) = TCHWR
      OUT(3) = PMPPWR
      RETURN
      END
```

TYPE 13 STORAGE OUTLET MIXER

PARAMETERS - None

INPUTS

| | |
|---|---|
| 1,3,5,7,9 | M1-M5: mass flow rate of water from tanks 1 to 5 (lb/hr) |
| 2,4,6,8,10 | T1-T5: average water temperature leaving tanks 1-5 (F) |

OUTPUTS

| | |
|---|---|
| 1 | Total mass flow rate (lb/hr) |
| 2 | Mass flow average temperature (F) |

```
      SUBROUTINE TYPE13(TIME,XIN,OUT,TT,DTDT,PAR,INFO)
C
C THIS ROUTINE MIXES 5 INLET FLOW STREAMS COMING FROM THE ST
ORAGE TANKS.
C
      DIMENSION XIN(10),OUT(2),TT(1),DTDT(1),PAR(1),INFO(10)
      REAL M1,M2,M3,M4,M5,M
      INFO(6) = 2
      M1 = XIN(1)
      T1 = XIN(2)
      M2 = XIN(3)
      T2 = XIN(4)
      M3 = XIN(5)
      T3 = XIN(6)
      M4 = XIN(7)
      T4 = XIN(8)
      M5 = XIN(9)
      T5 = XIN(10)
      M = M1 + M2 + M3 + M4 + M5
      T = (M1*T1 + M2*T2 + M3*T3 + M4*T4 + M5*T5) / M
      OUT(1) = M
      OUT(2) = T
      RETURN
      END
```

TYPE 20 CONDENSER PUMPS

PARAMETERS

| | |
|---|---|
| 1 | FLOWCD: condenser pump flow per pump (GPM) |
| 2-4 | C1-C3: coefficients of quadratic curve fit of pump power demand as a function of flow rate |
| 5-10 | A1-A6: coefficients of curve fit of optimum pump flow as a function of wet-bulb temperature and part-load ratio |
| 11 | OPTON: flag to activate flow optimization, if greater than zero, optimization is activated. |

INPUTS

| | |
|---|---|
| 1 | FNCH: number of operating chillers |
| 2 | PLR: chiller part-load ratio |
| 3 | TWB: wet-bulb temperature (F) |

OUTPUTS

| | |
|---|---|
| 1 | FLOWC: total condenser pump flow rate (lb/hr) |
| 2 | PMPPWR: total condenser pump power demand (kW) |

```
      SUBROUTINE TYPE20(TIME,XIN,OUT,T,DTDT,PAR,INFO)
      DIMENSION XIN(3),OUT(2),T(1),DTDT(1),PAR(11),INFO(10)
C
C THIS SUBROUTINE MODELS THE CONDENSOR PUMPS WHICH ARE
C ASSUMED TO RUN AT CONSTANT SPEED. THE # OF PUMPS EQUALS TH
E
C NUMBER OF CHILLERS. FLOW IS EITHER PROPORTINAL TO THE
C NUMBER OF CHILLERS OR A FUNCTION OF TWB AND PLR BASED
C ON OPTIMIZATION STUDIES
C
      IF(INFO(7).GT.-1)GO TO 10
C
C PARAMETER DEFINITIONS:
C        FLOWCD = CONDENSOR PUMP FLOW PER CHILLER (GPM)
C        PUMPP = CONDENSOR PUMP POWER CONSUMPTION AT DESIGN
(KW)
C        C1,C2,C3 = COEFFICIENTS OF QUADRATIC FIT OF PUMP
C                   POWER DEMAND VS. FLOW.
C        A1-A6 = COEFFICIENTS OF CURVE DESCRIBING OPTIMUM PU
MP
C                FLOW AS A FUNCTION OF TWB AND CHILLER PLR
C        OPTON = SIGNAL TO TURN ON THE FLOW OPTIMIZATION,
C                IF ZERO OR LESS, PUMP FLOW IS CONSTANT
C                AND EQUAL TO PAR(1).
C
      INFO(6) = 2
      FLOWCD = PAR(1)
      C1 = PAR(2)
      C2 = PAR(3)
      C3 = PAR(4)
      A1 = PAR(5)
      A2 = PAR(6)
      A3 = PAR(7)
      A4 = PAR(8)
      A5 = PAR(9)
      A6 = PAR(10)
      OPTON = PAR(11)
C
C INPUT AND OUTPUT DEFINITIONS:
C        NCH = NUMBER OF CHILLERS
C        FLOWC = TOTAL CONDENSOR LOOP FLOW RATE (LB/HR)
C        PMPFLO = FLOW RATE PER PUMP (GPM)
C        PMPPWR = TOTAL CONDENSOR PUMP POWER CONSUMPTION (KW
)
C
10    FNCH = XIN(1)
      PLR = XIN(2)
      TWB = XIN(3)
      IF(OPTON.GT.0.)THEN
```

```
          FLOWCD = A1+A2*TWB+A3*PLR+A4*TWB*PLR+A5*TWB*PLR**2+
     +             A6*PLR**2
      END IF
      FLOWC = FLOWCD*500.*FNCH
C PUMP POWER IS COMPUTED USING A CURVE FIT BASED ON IBM DATA
C THE FORM IS PUMPKW=F(FLOW IN GPM,# OF PUMPS).
      PMPFLO = FLOWCD
      PMPPWR = (C1 + C2*PMPFLO + C3*PMPFLO**2)*FNCH
      OUT(1) = FLOWC
      OUT(2) = PMPPWR
      RETURN
      END
```

TYPE 21 CHILLER MODEL

PARAMETERS

| | |
|---|---|
| 1-9 | C1-C9: coefficients of bi-quadratic curve fit of chiller kilowatt ratio as a function of part-load ratio and condenser water return temperature. |
| 10 | CAP: design cooling capacity of chiller (Btu/hr) |
| 11 | KWFL: chiller power at full-load (kW) |
| 12 | PWPKW: primary pump power consumption at design (kW) |
| 13 | PMPFLO: primary pump flow rate at design (lb/hr) |
| 14 | CP: specific heat of water (Btu/lb F) |
| 15 | KWTOEN: conversion factor from kW to energy units, this case to Btu/hr |
| 17-19 | F1-F3 from curve fit of percentage change in chiller electrical demand relative to 44 as a function of chilled water supply temperature |
| 20 | TR: TCHWS throttling range (F) |

INPUTS

| | |
|---|---|
| 1 | NCH: number of chillers |
| 2 | TCHIN: chilled water temperature entering evaporator (F) |
| 3 | FLOWP: total chilled water flow (lb/hr) |
| 4 | TCHWS: condenser water supply temperature (F) |
| 5 | CHWSET: chilled water supply temperature setpoint (F) |
| 6 | FLOWC: condenser water flow rate (lb/hr) |

OUTPUTS

| | |
|---|---|
| 1 | KWFL: full-load chiller power consumption, per chiller (kW) |
| 2 | KWA: actual total chiller power consumption (kW) |

| | |
|---|---|
| 3 | CAP: design cooling capacity of chiller (Btu/hr) |
| 4 | PLR: actual part-load ratio |
| 5 | FLOWP: chilled water flow rate (lb/hr) |
| 6 | TCHWS: actual chilled water supply temperature (F) |
| 7 | TCWR: condenser water return temperature (F) |
| 8 | LCOND: total condenser heat rejection rate (Btu/hr) |
| 9 | LTOT: total cooling load on chiller (Btu/hr) |
| 10 | PKWA: total primary pump power consumption (kW) |

```
      SUBROUTINE TYPE21(TIME,XIN,OUT,TT,DTDT,PAR,INFO)
C
C THIS ROUTINE MODELS THE CHILLER PERFORMANCE OF 5 1250TON C
HILLERS.
C
      DIMENSION XIN(6),OUT(10),TT(1),DTDT(1),PAR(20),INFO(10
)
      REAL LCH,LCHMX,MODE,KWA,KWFL,KWR,LTOT,LCOND,KWTOEN
      IF(INFO(7) .GT. -1)GO TO 10
      INFO(6) = 10
      C1 = PAR(1)
      C2 = PAR(2)
      C3 = PAR(3)
      C4 = PAR(4)
      C5 = PAR(5)
      C6 = PAR(6)
      C7 = PAR(7)
      C8 = PAR(8)
      C9 = PAR(9)
      CAP = PAR(10)
      KWFL = PAR(11)
      PMPKW = PAR(12)
      PMPFLO = PAR(13)
      CP = PAR(14)
      KWTOEN = PAR(15)
      TOL = PAR(16)
      F1 = PAR(17)/100.
      F2 = PAR(18)/100.
      F3 = PAR(19)/100.
      TR = PAR(20)
10    FNCH = XIN(1)
      NCH = INT(FNCH)
      TCHIN = XIN(2)
      FLOWP = XIN(3)
      TCWS = XIN(4)
      CHWSET = XIN(5)
      FLOWC = XIN(6)
      PKWA = 0.
      KWA = 0.
      PLR = 0.
      LCOND = 0.
      LTOT = 0.
      IF(FLOWP .LT. 1. .OR. NCH .LT. 1 .OR. FLOWC .LT. 1.)GO
 TO 100
C FIND PUMPING POWER, ASSUME ONLY DEPENDENT ON THE NUMBER OF
 CHILLERS,
C NOT ON THE ACTUAL FLOW PER PUMP
      PKWA = PMPKW*FNCH
C NEXT LOOP FINDS THE CHILLED WATER SUPPLY TEMPERATURE FOR
C THE CURRENT LOADING.
```

```
      DO 25 I=1,25
C DETERMINE CHILLER LOADING.
         LCH = (FLOWP/FNCH) * CP * (TCHIN-TCHWS)
         LTOT = LCH * FNCH
         PLR = LCH/CAP
         TCHWSN = CHWSET + (PLR-1.)*TR
         IF(ABS(TCHWSN-TCHWS).LT.TOL)GO TO 30
         TCHWS = TCHWSN
25    CONTINUE
C
C FIND CHILLER FULL-LOAD CHARACTERISTICS.
C
30    DO 50 I=1,50
      T = TCWS + 1.18*LTOT/(FLOWC*CP)
      KWR = C1 + C2*T + C3*T**2 + C4*PLR + C5*PLR**2 + C6*T*
PLR +
     1       C7*T**2*PLR + C8*T*PLR**2 + C9*T**2*PLR**2
      KWA = KWR * KWFL * FNCH
      KWA = KWA*(1.+F1+F2*TCHWS+F3*TCHWS**2)
      LCOND = LTOT + KWA*KWTOEN
      TCWR = TCWS + LCOND/(FLOWC*CP)
      IF(ABS(T-TCWR).LT.TOL)GO TO 100
      T = TCWR
50    CONTINUE
100   OUT(1) = KWFL
      OUT(2) = KWA
      OUT(3) = CAP
      OUT(4) = PLR
      OUT(5) = FLOWP
      OUT(6) = TCHWS
      OUT(7) = TCWR
      OUT(8) = LCOND
      OUT(9) = LTOT
      OUT(10) = PKWA
      RETURN
      END
```

TYPE 22 COOLING TOWER

PARAMETERS

| | |
|---|---|
| 1,2 | AA,BB: coefficients of linear regression of effectiveness data, E=AA(R)+BB |
| 3 | FANOF: air flow rate per cell with fan off (CFM) |
| 4 | FANHI: air flow rate per cell with fan on high speed (CFM) |
| 5 | FANLO: air flow rate per cell with fan on low speed (CFM) |
| 6 | HIFANP: fan power on high speed (kW) |
| 7 | LOFANP: fan power on low speed (kW) |
| 8 | NCELLS: number of cells in tower |
| 9 | MC: mass of water in each cell's basin (lb) |
| 10 | MSUMP: mass of water in tower sump (lb) |
| 11 | TCWMIN: minimum allow condenser water supply temperature (leaving tower) (F) |
| 12 | CP: specific heat of water (Btu/lb F) |

INPUTS

| | |
|---|---|
| 1 | TCWR: condenser water return temperature (entering tower) (F) |
| 2 | LTOWER: total tower heat rejection rate (Btu/hr) |
| 3 | TWB: ambient wet-bulb temperature (F) |
| 4 | TDB: ambient dry-bulb temperature (F) |
| 5 | P: ambient barometric pressure (psia) |
| 6 | FLOWC: total condenser water flow rate (lb/hr) |
| 7-16 | NFS: fan status in cells 1-10:<br>2 = fan on high<br>1 = fan on low<br>0 = fan off<br>-1 = cell off (no water flow) |

OUTPUTS

| | |
|---|---|
| 1 | TCWS: average condenser water supply temperature (F) |
| 2 | FANPWR: total fan power consumption (kW) |
| 3 | MAKEUP: total makeup water flow rate (GPM) |
| 4 | TSF: condenser water supply temperature at end of time-step (F) |
| 5 | LIMIT: flag signalling tower control that the leaving water temperature is being limited to its minimum value:<br>1 = limiting situation<br>0 = no limit |
| 6-15 | TF: temperature of water leaving the basins of cells 1-10 at end of time-step |

```
      SUBROUTINE TYPE22(TIME,XIN,OUT,T,DTDT,PAR,INFO)
      DIMENSION XIN(16),OUT(15),PAR(12),INFO(10),T(1),DTDT(1
),
     +   NFS(10),TT(10),TTI(10),TW(10),TF(10)
      COMMON /A/F,FLOW,TWB,TDB,TCWR,P,RNGE,AA,BB
      REAL LTOWER,MAKEUP,MAKUPH,MAKUPL,MAKUPO,LOFANP,MC,MSUM
P
      IF(INFO(7).GT.-1) GO TO 10
C
C DEFINITION OF INPUT PARAMETERS:
C        AA,BB = COEFFICIENTS OF LINEAR FIT OF EFFECTIVENESS
,
C                E = AA*R + BB
C        FANOF = FAN FLOW PER CELL WITH FAN OFF (CFM)
C        FANHI = FAN FLOW PER CELL ON HIGH SPEED (CFM)
C        FANLO = FAN FLOW PER CELL ON LOW SPEED (CFM)
C        HIFANP = FAN POWER ON HIGH (KW)
C        LOFANP = FAN POWER ON LOW (KW)
C        NCELLS = TOTAL NUMBER OF CELLS IN TOWER
C        MC = MASS OF WATER IN CELL SUMP
C        MSUMP = MASS OF WATER IN COMMON SUMP
C        TCWMIN = MINIMUM ALLOWABLE CONDENSOR WATER SUPPLY T
EMPERATURE
C        CP = SPECIFIC HEAT OF WATER (BTU/LBM-F)
C
      AA = PAR(1)
      BB = PAR(2)
      FANOF = PAR(3)*60.
      FANHI = PAR(4)*60.
      FANLO = PAR(5)*60.
      HIFANP = PAR(6)
      LOFANP = PAR(7)
      NCELLS = INT(PAR(8))
      MC = PAR(9)
      MSUMP = PAR(10)
      TCWMIN = PAR(11)
      CP = PAR(12)
      INFO(9) = 0
      INFO(6) = 15
C
C INPUT DEFINITIONS:
C        TCWR = CONDENSOR WATER RETURN TEMPERATURE
C        LTOWER = TOTAL TOWER HEAT REJECTION RATE
C        TWB = AMBIENT WET-BULB TEMPERATURE
C        TDB = AMBIENT DRY-BULB TEMPERATURE
C        P = AMBIENT BAROMETRIC PRESSURE (PSIA ABSOLUTE)
C        FLOWC = TOTAL CONDENSOR WATER FLOW (LB/HR)
C        NFS = CELL FAN STATUS
C
```

```
C EXPLANATION OF OTHER VARIABLES:
C        NCELL = NUMBER OF CELLS WITH WATER FLOW, ASSUMED TH
AT
C                FLOW IS EQUALLY DISTRIBUTED AMONG CELLS.
C        NFANHI = NUMBER OF CELLS ON HIGH FAN SPEED
C        NFANLO = NUMBER OF CELLS ON LOW FAN SPEED
C        FLOW  = PER CELL CONDENSOR WATER FLOW (LB/HR)
C        RNGE = CONDENSOR WATER RANGE (TIN - TOUT)
C        FANPWR = TOTAL FAN POWER DEMAND (KW)
C        MAKEUP = TOTAL MAKEUP WATER FLOW (GPM)
C
10    IF(INFO(7).NE.0)GO TO 15
      LIMIT = 0
      TSI = OUT(1)
      DO 12 I=1,NCELLS
12       TTI(I) = OUT(5+I)
15    TCWR = XIN(1)
      LTOWER = XIN(2)
      TWB = XIN(3)
      TDB = XIN(4)
      P    = XIN(5)
      FLOWC = XIN(6)
      IF(INFO(7).EQ.-1)THEN
         TSI = TDB
         DO 18 I=1,NCELLS
18          TTI(I) = TDB
      END IF
      NFANHI = 0
      NFANLO = 0
      NFANOF = 0
C POSSIBLE CONTROL INPUTS FOR EACH CELL:
C     -1 = NO FLOW
C      0 = FLOW, FAN OFF
C      1 = FLOW, LO FAN
C      2 = FLOW, HI FAN
C
      DO 20 I=1,NCELLS
         NFS(I) = INT(XIN(6+I))
         IF(NFS(I).EQ.2)NFANHI = NFANHI+1
         IF(NFS(I).EQ.1)NFANLO = NFANLO+1
         IF(NFS(I).EQ.0)NFANOF = NFANOF+1
20    CONTINUE
      NCELL = NFANHI+NFANLO+NFANOF
      FNC = FLOAT(NCELL)
      FLOW = FLOWC/FNC
      RNGE = LTOWER/(FLOWC*CP)
C
C FIND CURRENT TOWER WATER TEMPERATURES BASED ON CURRENT TCW
R
C
```

```
50    IF(NFANOF.GT.0)CALL TOWER(FANOF,TW(1),MAKUPO)
      IF(NFANLO.GT.0)CALL TOWER(FANLO,TW(2),MAKUPL)
      IF(NFANHI.GT.0)CALL TOWER(FANHI,TW(3),MAKUPH)
C FIND THE STEADY-STATE SUPPLY TEMPERATURE FOR LIMIT CHECK.
      TCWSSS = (FLOAT(NFANLO)*TW(2)+FLOAT(NFANHI)*TW(3)+
     +       FLOAT(NFANOF)*TW(1))/FNC
C IF MINIMUM TEMPERATURE LIMIT HAS NOT BEEN HIT, GO ON
C TO THE SUMP CALCULATIONS
      IF(TCWSSS.GT.TCWMIN.AND.LIMIT.EQ.0)GO TO 300
C IF MINIMUM IS HIT THE FIRST TIME, ALL CELLS ARE STARTED
C WITH FAN OFF (LOWEST LEVEL).  THEN LEVEL IS INCREASED STEP
C BY STEP UNTIL THE TCWS AGAIN DROPS BELOW THE MINIMUM.
C THIS INDICATES THAT THE TOWER SHOULD CYCLE BETWEEN THE
C CURRENT LEVEL AND THE PREVIOUS ONE.
      IF(TCWSSS.LT.TCWMIN.AND.LIMIT.EQ.0)THEN
         LIMIT = 1
         NFANOF = NCELL
         NFANLO = 0
         NFANHI = 0
         GO TO 50
      END IF
C CHECK TO SEE IF LATEST LEVEL IS BELOW MINIMUM - BRANCH
C TO CYCLING CALCULATIONS IF SO.
      IF(TCWSSS.LT.TCWMIN.AND.LIMIT.EQ.1)GO TO 150
C OTHERWISE, RAISE LEVEL A STEP AND CONTINUE.
      MKUPOP = MAKUPO
      MKUPLP = MAKUPL
      MKUPHP = MAKUPH
      NFANOP = NFANOF
      NFANLP = NFANLO
      NFANHP = NFANHI
      TCWSP = TCWSSS
      IF(NFANOF.GT.0)THEN
      NFANOF = NFANOF-1
      NFANLO = NFANLO+1
      GO TO 50
      ELSE
      IF(NFANHI.EQ.NCELL)GO TO 300
      NFANLO = NFANLO-1
      NFANHI = NFANHI+1
      END IF
      GO TO 50
C CURRENT LEVEL IS TOO COLD, PREVIOUS LEVEL WAS NOT: MIX
C THE TWO TO OBTAIN THE DESIRED TEMPERATURE.
150   RUNL = (TCWMIN-TCWSP)/(TCWSSS-TCWSP)
      FANPL = FLOAT(NFANHI)*HIFANP+FLOAT(NFANLO)*LOFANP
      MAKEL = FLOAT(NFANHI)*MAKUPH+FLOAT(NFANLO)*MAKUPL+FLOA
T(NFANOF)*
     +        MAKUPO
      FANPL1 = FLOAT(NFANHP)*HIFANP+FLOAT(NFANLP)*LOFANP
```

```
      MAKEL1 = FLOAT(NFANHP)*MKUPHP+FLOAT(NFANLP)*MKUPLP+
     +         FLOAT(NFANOP)*MKUPOP
      FANPWR = RUNL*FANPL + (1.-RUNL)*FANPL1
      MAKEUP = RUNL*MAKEL + (1.-RUNL)*MAKEL1
      DO 170 K=1,3
170      TW(K) = TCWMIN
300   IF(MC.GT.0.)THEN
         A = -FLOW/MC
         DO 310 I=1,NCELLS
            IF(NFS(I).GE.0)THEN
               B = (FLOW/MC)*TW(NFS(I)+1)
               CALL DIFFEQ(TIME,A,B,TTI(I),TF(I),TT(I))
            ELSE
               TT(I) = TTI(I)
            END IF
310      CONTINUE
      ELSE
         DO 320 I=1,NCELLS
            IF(NFS(I).GE.0)THEN
               TT(I) = TW(NFS(I)+1)
               TF(I) = TT(I)
            ELSE
               TT(I) = TTI(I)
               TF(I) = TT(I)
            END IF
320      CONTINUE
      END IF
C
C FIND AVERAGE WATER TEMP LEAVING THE CELLS
      TTA = 0.
      DO 330 I=1,NCELLS
         IF(NFS(I).EQ.-1)GO TO 330
         TTA = TTA + (TT(I)/FNC)
330   CONTINUE
      IF(MSUMP.GT.0.)THEN
         A = -FLOWC/MSUMP
         B = (FLOWC/MSUMP)*TTA
         CALL DIFFEQ(TIME,A,B,TSI,TSF,TCWS)
      ELSE
         TCWS = TTA
         TSF = TCWS
      END IF
      IF(LIMIT.EQ.0)THEN
         FANPWR = FLOAT(NFANHI)*HIFANP + FLOAT(NFANLO)*LOFAN
P
         MAKEUP = FLOAT(NFANHI)*MAKUPH + FLOAT(NFANLO)*MAKUP
L +
     +             FLOAT(NFANOF)*MAKUPO
      END IF
      OUT(1) = TCWS
```

```
      OUT(2) = FANPWR
      OUT(3) = MAKEUP
      OUT(4) = TSF
      OUT(5) = LIMIT
      DO 450 I=1,NCELLS
450      OUT(5+I) = TF(I)
      END
      SUBROUTINE TOWER(FAN,TCWS,MAKEUP)
      COMMON /A/F,FLOW,TWB,TDB,TCWR,P,RNGEC,A,B
C
C     THIS PROGRAM CALCULATES THE PERFORMANCE OF A
C     COOLING TOWER(INLET AND OUTLET WATER TEMPERATURES)
C     USING A METHOD DEVELOPED BY AUSTIN WHILLIER. THE METHOD
C     WAS PRESENTED IN AN ARTICLE ENTITLED "A FRESH LOOK AT T
HE
C     CALCULATION OF PERFORMANCE OF COOLING TOWERS", ASHRAE
C     TRANSACTIONS, V.82, PART 1, 1967.
C
C EXPLANATION OF PARAMETERS:
C         A,B = COEFFICIENTS OF EFFECTIVENESS CORRELATION
C         FLOW = WATER FLOW (LB/HR)
C         FAN = AIR FLOW (CU FT/HR)
C         MAKEUP = MAKEUP WATER FLOW (GPM)
C         WARA = ACTUAL RATIO OF WATER FLOW TO AIR FLOW
C         WARR = REFERENCE WATER TO AIR RATIO
C         ETAW = TOWER WATER EFFICIENCY
C
      REAL MAKEUP
      RNGE = RNGEC
      CALL  SIG(TWB,TDB,P,SI,VI,WI)
      DO 50 I=1,100
      T0= TCWR
      DO 40 M=1,100
C
C     LOOP FOR DETERMINING THE STATE OF THE OUTLET AIR.
C     USED TO DETERMINE THE MASS FLOW OF AIR.
C
         CALL SIG(T0,T0,P,S0,V0,W0)
         FUN = FAN*(S0-SI)/V0-FLOW*1.003*RNGE
         CALL SIG(T0+.1,T0+.1,P,SH,VH,WH)
         CALL SIG(T0-.1,T0-.1,P,SL,VL,WL)
         FH = FAN*(SH-SI)/VH-FLOW*1.003*RNGE
         FL = FAN*(SL-SI)/VL-FLOW*1.003*RNGE
         DFDT= (FH-FL)/.2
         TN = T0 - FUN/DFDT
         IF(ABS(TN-T0).LT..01) GO TO 500
         IF(M.EQ.100)WRITE(*,1)
1        FORMAT('0','*** COOLING TOWER AIR LOOP DID NOT CONV
ERGE ***')
         T0= TN
```

```
40        CONTINUE
500     G = FAN/V0
        WARA= FLOW/G
C
C    ACTUAL WATER-TO-AIR RATIO.
C
C LOOP FOR DETERMINING THE ACTUAL TOWER WATER TEMPERATURES
C
          CALL SIG(TCWR,TCWR,P,S3,V3,W3)
          WARR= (S3-SI)/(TCWR-TWB)
          R   = WARA/WARR
          RR  = R
          IF(RR.LT.1.) GO TO 520
          RR  = 1./RR
520       E = A*RR + B
          IF(E.GT.1.)E=1.
          IF(R.LE.1.) GO TO 530
C WATER EFFICIENCY IS "ETAW".
          ETAW= E/R
          GO TO 540
530       ETAW=E
540     RNGEN = ETAW*(TCWR-TWB)
          IF(ABS(RNGEN-RNGE).LT..01) GO TO 550
           RNGE = RNGEN
          IF(I.EQ.100)WRITE(*,2)
2         FORMAT('0','*** COOLING TOWER WATER LOOP DID NOT CON
VERGE ***')
50        CONTINUE
550     MAKEUP = G/500.*(W0-WI)
        TCWS = TCWR - RNGE
        RETURN
        END
        SUBROUTINE SIG(TWB,TDB,P,S,V,W)
        T = (TWB-32.)/1.8 + 273.15
        PWS= EXP(-5800.2206/T + 1.3914993 - .04860239*T +
       +     .41764768E-4*T**2 - .14452093E-7*T**3 +
       +     6.545967*LOG(T))
        PWS  = PWS*.000145
        WSST= .62198*PWS/(P-PWS)
        IF(ABS(TDB-TWB).LT..01)GO TO 10
        W = ((1093.-.556*TWB)*WSST - .24*(TDB-TWB))/
       +   (1093.+.444*TDB-TWB)
        V = .3705*(TDB+460.)*(1.+1.6078*W)/P
        H = .24*TDB + W*(1061.+.444*TDB)
        S = H - W*1.003*TWB
        GO TO 20
10      V = .3705*(TWB+460.)*(1.+1.6078*WSST)/P
        H = .24*TWB + WSST*(1061. + .444*TWB)
        S = H - WSST*1.003*TWB
        W = WSST
```

```
20    RETURN
      END
```

TYPE 23 COOLING TOWER CONTROL

PARAMETERS

| | |
|---|---|
| 1 | APPHI: high approach limit (F) |
| 2 | APPLO: low approach limit (F) |
| 3 | NCELLS: number of cells in tower (10 maximum) |
| 4 | TCWMX: maximum desired condenser water supply temperature (F) |
| 5 | OPTON: flag activating optimum control strategy; if greater than 0, strategy is activated |

INPUTS

| | |
|---|---|
| 1 | TWB: ambient wet-bulb temperature (F) |
| 2 | TCWS: condenser water supply temperature (leaving tower) (F) |
| 3 | NCH: number of chillers |
| 4 | TLIMIT: flag from cooling tower indicating minimum water temperature condition |
| 5 | LCHTOT: total chilled water load (Btu/hr) |

OUTPUTS

| | |
|---|---|
| 1 | NCELL: number of cells with water flow |
| 2 | NFANHI: number of cells with fan on high speed |
| 3 | NFANLO: number of cells with fan on low speed |
| 4 | APP: approach (F) |
| 5-14 | NFS: cell fan status (see TYPE 22) |

```
      SUBROUTINE TYPE23(TIME,XIN,OUT,T,DTDT,PAR,INFO)
      DIMENSION XIN(5),OUT(14),T(1),DTDT(1),PAR(5),INFO(10),
     +   X(2),NX(2),NY(3),Y(3)
      REAL LCHTOT
      DATA NX/17,8/
      IF(INFO(7).GT.-1)GO TO 10
C
C        APPHI = HIGH APPROACH LIMIT
C        APPLO = LOW APPROACH LIMIT
C        NCELLS = NUMBER OF CELLS IN TOWER (MAX 10)
C        TCWMX = MAXIMUM ALLOWABLE TEMPERATURE LEAVING TOWER
C        TCWMN = MINIMUM ALLOWABLE TEMPERATURE LEAVING TOWER
C
      INFO(6) = 14
      APPHI = PAR(1)
      APPLO = PAR(2)
      NCELLS = PAR(3)
      TCWMX = PAR(4)
      OPTON = PAR(5)
C
C        TWB = AMBIENT WET-BULB TEMPERATURE
C        TCWS = CONDENSOR WATER SUPPLY TEMPERATURE AT END OF
 TIMESTEP
C        TCWSF = TCWS AT END OF PREVIOUS TIMESTEP
C        NCH = NUMBER OF OPERATING CHILLERS
C        NCELL = NUMBER OF COOLING TOWER CELLS WITH WATER FL
OW
C        NFANHI = NUMBER OF CELLS ON HIGH FAN SPEED
C        NFANLO = NUMBER OF CELLS ON LOW FAN SPEED
C        APP = COOLING TOWER APPROACH (TCWS - TWB)
C
10    IF(INFO(7).GT.0)GO TO 15
      TCWSF = TCWS
      LIMP = LIMIT
      LIMIT = 0
      APP = 0
15    TWB = XIN(1)
      TCWS = XIN(2)
      NCH = INT(XIN(3))
      NCELL = NCH
      IF(INFO(7).GT.0)LIMIT = INT(XIN(4))
      LCHTOT = XIN(5)/12000.
      IF(INFO(7).EQ.0)THEN
C
C DETERMINE CORRECT OPERATING LEVEL.
C USE PREVIOUS LEVEL AS FIRST CHOICE IF NCH HASN'T CHANGED
C
         NFHP = INT(OUT(2))
         NFLP = INT(OUT(3))
```

```
            NFOP = INT(OUT(1))-NFHP-NFLP
            NCHPR = NCHP
         END IF
         IF(LIMIT.EQ.1)GO TO 400
C
C USE OPTIMUM CONTROL IF ACTIVATED.
         IF(OPTON.GT.0.)THEN
            APP = TCWS-TWB
            X(1) = LCHTOT
            X(2) = TWB
            NX(2) = 8
            IF(INFO(7).EQ.-1)THEN
               CALL DATA(13,2,NX,3,X,Y,INFO)
               CALL DATA(14,2,NX,3,X,Y,INFO)
               NX(2) = 6
               CALL DATA(15,2,NX,3,X,Y,INFO)
               CALL DATA(16,2,NX,3,X,Y,INFO)
               NX(2) = 8
            END IF
            GO TO(310,320,330,340)NCH
310         CALL DATA(13,2,NX,3,X,Y,INFO)
            GO TO 350
320         CALL DATA(14,2,NX,3,X,Y,INFO)
            GO TO 350
330         NX(2) = 6
            CALL DATA(15,2,NX,3,X,Y,INFO)
            GO TO 350
340         NX(2) = 6
            CALL DATA(16,2,NX,3,X,Y,INFO)
350         DO 355 II=2,3
               REM = Y(II)-INT(Y(II))
               IF(REM.GT..5)Y(II)=AINT(Y(II))+1
               IF(REM.LE..5)Y(II)=AINT(Y(II))
355            CONTINUE
            NFANHI = INT(Y(2))
            NFANLO = INT(Y(3))
            IF((NFANLO+NFANHI).GT.NCELL)NFANLO=NCELL-NFANHI
            GO TO 400
         END IF
         IF(NCH.EQ.NCHPR)THEN
            NFANHI = NFHP
            NFANLO = NFLP
            NFANOF = NFOP
            GO TO 100
         END IF
C IF NCH HAS INCREASED OR IF PREVIOUS TIME CALLED FOR
C TEMPERATURE LIMITING, START WITH LOWEST LEVEL ( ALL CELLS
C    ON LOW SPEED SINCE PART LOAD IS LOW)
         IF(NCH.GT.NCHPR.OR.LIMP.EQ.1)THEN
            NFANHI = 0
```

```
          NFANLO = NCH
          GO TO 399
C IF NCH HAS DECREASED, START WITH HIGHEST LEVEL IN REMAININ
G
C    CELLS SINCE PART LOAD WILL BE HIGH.
       ELSE
          NFANHI = NCH
          NFANLO = 0
          GO TO 399
       END IF
C
C CHECK IF TCWS AT END OF TIMESTEP IS WITHIN DESIRED LIMITS
C
100    APP = TCWSF-TWB
       IF(APP.LT.APPHI.AND.APP.GT.APPLO.AND.TCWSF.LT.TCWMX)GO
 TO 400
C IF APPROACH IS TOO LOW, DECREASE TOWER LEVEL ONE NOTCH.
C IF AT LOWEST LEVEL, STAY THERE.
       IF(APP.GT.APPHI.OR.TCWSF.GT.TCWMX)GO TO 260
C APPROACH IS TOO LOW.
105    IF(NFANHI.EQ.0)GO TO 120
       NFANHI = NFANHI - 1
       NFANLO = NFANLO + 1
       GO TO 400
120    IF(NFANLO.EQ.0)GO TO 400
       NFANLO = NFANLO - 1
       GO TO 400
C APPROACH IS TOO HIGH OR WATER IS TOO HOT, INCREASE TOWER L
EVEL.
C IF AT HIGHEST LEVEL, STAY THERE.
260    IF(NFANHI.EQ.NCELL)GO TO 400
       IF(NFANOF.EQ.0)THEN
          NFANHI = NFANHI + 1
          NFANLO = NFANLO - 1
       ELSE
          NFANOF = NFANOF - 1
          NFANLO = NFANLO + 1
          NFANHI = 0
       END IF
399    APP = TCWSF - TWB
400    OUT(1) = FLOAT(NCELL)
       OUT(2) = FLOAT(NFANHI)
       OUT(3) = FLOAT(NFANLO)
       OUT(4) = APP
       NFANOF = NCELL - NFANHI - NFANLO
       DO 410 I=1,NFANHI
410       OUT(4+I) = 2.
       DO 420 I=NFANHI+1,NFANLO+NFANHI
420       OUT(4+I) = 1.
       DO 430 I=NFANLO+NFANHI+1,NFANLO+NFANHI+NFANOF
```

```
430      OUT(4+I) = 0.
      DO 440 I=NFANHI+NFANLO+NFANOF+1,NCELLS
440      OUT(4+I) = -1.
      NCHP = NCH
      RETURN
      END
```

# APPENDIX B

# TRNSYS DECKS

Plant Simulation

Zones 201,202,301,Corridor

Zones 101N,101S,102N,102S

Zones 103N,103S,Corridor

Zones 001/501,002-Floor,
002-Mezzanine,003

```
************************************************************
********
*
*          IBM CHARLOTTE: CHILLER OPTIMIZATION STUDY
*
*            ALL OPTIMIZED STRATEGIES ON - WITH STORAGE
*            MODE 7 ON AT 0 HRS AND 44F,  MODE 2 ON AT 800 H
RS,
*            STORAGE FLOW MAX = 1500 GPM, MIN = 0 GPM
*            BUILDING LOADS: BDL75 - 50% CONV.
*            ALL 3 OPTIMIZED STRATEGIES ON
*            CHILLER TR=0.5
*
************************************************************
********
 NOLIST
 CONSTANTS TAMB=70. VTANK=13369. MINVT=2003. MAXVT=11303. CP
=1.003
 SIMULATION 1 8760 .5
 TOLERANCES .01 .0001
 LIMITS 40 10
 UNIT 7 TYPE 9 BUILDING LOAD READER
      PARAMETERS 31
      9 .5 -1 1 0 -2 1 0 -3 1 0 -4 1 0 -5 1 0
      -6 1 0 -7 1 0 -8 1 0 -9 1 0 11 -1
*OUTPUTS: 1=TIME, 2=CCL(BTUH), 3=QHEAT(BTUH), 4=LITES(KW),
*        5=MISC.ELEC.(KW), 6=AHUFANS(KW), 7=TOTAL NON-PLANT
 ELEC.(KW)
*        8=TDB(F), 9=TWB(F)
*********************************************
*  SYSTEM MODEL OF CHILLER PLANT
*********************************************
 UNIT 8 TYPE 38 PLUG FLOW SUPPLY PIPE
      PAR 8
      1 24100 2000 2000 CP 62.4 0 42
      INP 5
      30,1 30,2 0,0 0,0 0,0
      44   9.6E5 0    0   70
 UNIT 12 TYPE 10 SEC. PUMP
      PARAMETERS 6
      34 -.538 -10.7 .0195 5.22E-6 3300
      INPUTS 2
      7,2 8,1
      8.4E6 45
 UNIT 9 TYPE 39 PLUG FLOW RETURN PIPE
      PAR 8
      1 24100 2000 2000 CP 62.4 0 53
      INP 5
      12,2 12,1 0,0 0,0 0,0
      55  9.6E5 0    0   70
```

```
 UNIT 11 TYPE 2 MODE CONTROL
      PARAMETERS 29
      0 45 567216 750600 750600 0 44 46 44 44 15.E6
      CP 1.251E6 .72 5 250200
* THE NEXT 3 INPUTS ARE 1)TIME ON FOR MODE 2, 2)TIME ON FOR
MODE 7,
*     AND 3)DURATION OF MODE 7
      8.0 0 6   112072 0
* THE NEXT PARAMETERS ARE COEFFICIENTS DEFINING THE OPTIMUM
PLR AT
* WHICH TO ACTIVATE ANOTHER CHILLER.
* FOR NO OPTIMIZATION, THEY SHOULD BE:
*       1 0 1 0 0 1 0 0
* OR IF GREATER THAN RATED CAPACITY OPERATION IS DESIRED, SU
BSTITUTE
* THE FULL LOAD RATIO AT WHICH ANOTHER CHILLER IS ACTIVATED
FOR 1.
      .234 .0123 .635 -.00173 .0000866 .683 -.00429 .000104
      INPUTS 22
      10,11 1,11 2,11 3,11 4,11 5,11 1,10 2,10 3,10 4,10 5,1
0
      7,9 30,1 12,1 9,1 10,12 14,4 14,3 14,9 14,1 14,2 14,5
      0 MINVT MAXVT MAXVT MAXVT MAXVT 45 45 45 45 45 70 44 8
37487 55 0 .6
      15.E6 9.78E6 815 460 784474
 UNIT 21 TYPE 11 FLOW DIVERTER
      PARAMETERS 1
      2
      INPUTS 3
      9,1 9,2 11,2
      55 837487 .9367
 UNIT 23 TYPE 11 VALVE 3
      PARAMETERS 1
      2
      INPUTS 3
      21,1 21,2 11,4
      55 53001 1
 UNIT 24 TYPE 11 VALVE 4
      PARAMETERS 1
      2
      INPUTS 3
      23,3 23,4 11,5
      55 53001 1
 UNIT 27 TYPE 11 TEE 7
      PARAMETERS 1
      1
      INPUTS 4
      22,1 22,2 24,3 24,4
      55 0 55 53001
 UNIT 10 TYPE 1 STORAGE FLOW CONTROL
      PARAMETERS 2
```

```
     580320 124987
     INPUTS 12
     27,2 1,11 2,11 3,11 4,11 5,11 1,10 2,10 3,10 4,10 5,10
11,1
     53001 MINVT MAXVT MAXVT MAXVT MAXVT 45 45 45 45 45 2
UNIT 1 TYPE 32 VARIABLE VOLUME TANK #1
     PARAMETERS 11
     VTANK MINVT MAXVT 84.8 572.3 .05 .05 CP 62.4 45 MINVT
     INPUTS 4
     27,1 10,1 10,6 7,8
     55 53001 0 50
UNIT 2 TYPE 32 TANK #2
     PARAMETERS 11
     VTANK MINVT MAXVT 84.8 572.3 .05 .05 CP 62.4 45 MAXVT
     INPUTS 4
     27,1 10,2 10,7 7,8
     55 0 53001 50
UNIT 3 TYPE 32 TANK #3
     PARAMETERS 11
     VTANK MINVT MAXVT 84.8 572.3 .05 .05 CP 62.4 45 MAXVT
     INPUTS 4
     27,1 10,3 10,8 7,8
     55 0 0 50
UNIT 4 TYPE 32 TANK #4
     PARAMETERS 11
     VTANK MINVT MAXVT 84.8 572.3 .05 .05 CP 62.4 45 MAXVT
     INPUTS 4
     27,1 10,4 10,9 7,8
     55 0 0 50
UNIT 5 TYPE 32 TANK #5
     PARAMETERS 11
     VTANK MINVT MAXVT 84.8 572.3 .05 .05 CP 62.4 45 MAXVT
     INPUTS 4
     27,1 10,5 10,10 7,8
     55 0 0 50
UNIT 13 TYPE 13 STORAGE OUTLET MIXER
     INPUTS 10
     1,2 1,1 2,2 2,1 3,2 3,1 4,2 4,1 5,2 5,1
     0 45 53001 45 0 45 0 45 0 45
UNIT 25 TYPE 11 VALVE 5
     PARAMETERS 1
     2
     INPUTS 3
     13,2 13,1 11,6
     45 53001 0
UNIT 32 TYPE 11 TEE 12
     PARAMETERS 1
     1
     INPUTS 4
     21,3 21,4 26,3 26,4
     55 837487 45 0
```

```
 UNIT 31 TYPE 11 TEE 11
      PARAMETERS 1
      1
      INPUTS 4
      25,3 25,4 32,1 32,2
      45 0 55 784474
 UNIT 14 TYPE 21  CHILLERS
      PARAMETERS 20
      .46808975 -.012024672 .10199244E-3 .16306156 .59740695
      .0035330505 -.24342423E-4 -.0018921433 .63541157E-5
      15.E6 803 26 1.251E6 CP 3413. .05
      288.7 -10.55 .09076
* THE NEXT PARAMETER IS THE CHILLED WATER SUPPLY TEMPERATURE
* THROTTLING RANGE - NORMAL IS 4 F.
      0.5
      INPUTS 6
      11,8 31,1 31,2 15,1 11,9 17,1
      1 55 784474 75 45 1.5E6
 UNIT 17 TYPE 20 CONDENSOR PUMPS
      PARAMETERS 11
      2800 74.5 -.0463 1.38E-5
      3687 -21.13 -5246 69.27 -32.36 2645
* THE NEXT PARAMETER ACTIVATES THE OPTIMUM CONDENSOR
* PUMP FLOW RATE STRATEGY. 0 = OFF, 1 = ON
      1
      INPUTS 3
      11,8 14,4 7,9
      1   .8   60
 UNIT 16 TYPE 23 TOWER CONTROL
      PARAMETERS 5
      15 5 6 85
* THE NEXT PARAMETER ACTIVATES THE OPTIMUM TOWER
* CONTROL STRATEGY. 0 = OFF, 1 = ON
      1
      INPUTS 5
      7,9  15,4 11,8 15,5 14,9
      70  85    1     0  9.6E6
 UNIT 15 TYPE 22 COOLING TOWERS
      PARAMETERS 12
      -.5614 1.068 34641 346410 173205 24 3 6 67390 199700 6
5 CP
      INPUTS 12
      14,7 14,8 7,9 7,8 0,0 17,1 16,5 16,6 16,7 16,8 16,9 16
,10
      85  1.12E7  70  80 14.696  1.5E6  2   -1   -1   -1   -
1  -1
 UNIT 26 TYPE 11 VALVE 6
      PARAMETERS 1
      2
      INPUTS 3
      14,6 14,5 11,7
```

```
      45 784474 0
 UNIT 22 TYPE 11 VALVE 2
      PARAMETERS 1
      2
      INPUTS 3
      26,1 26,2 11,3
      45 837487 1
 UNIT 28 TYPE 11 TEE 8
      PARAMETERS 1
      1
      INPUTS 4
      25,1 25,2 22,3 22,4
      45 53001 45 784474
 UNIT 29 TYPE 11 TEE 9
      PARAMETERS 1
      1
      INPUTS 4
      15,1 0,0 28,1 28,2
      45 0 45 837487
 UNIT 30 TYPE 11 TEE 10
      PARAMETERS 1
      1
      INPUTS 4
      23,1 23,2 29,1 29,2
      45 0 45 837487
*********************************************
*   OUTPUT
*********************************************
 UNIT 35 TYPE 7 STATISTICS
      PARAMETERS 1
*     PAR(1) = MONTH AT START OF SIMULATION.
      1
      INPUTS 1
      47,1
      5000
 UNIT 36 TYPE 6 ELECTRIC BILL
      PARAMETERS 16
      11.16 30 2.46 125 275 400 3000 87000 140000
      .0776 .0403 .0307 .0381 .0322 .0311
* THE NEXT PARAMETER IS THE BILLING DEMAND.
      9000
      INPUTS 2
      35,1 35,2
      1.E6 8000
 UNIT 47 TYPE 15 ALG. OPERATOR
* THIS UNIT ADDS ALL THE ELECTRIC LOADS TOGETHER TO GET THE
SITE DEMAND
      PARAMETERS 36
      0 0 3 0 3 0 3 0 3 0 3 0 3 0 3 -4 -11 -12 3 -4
      -14 -15 3 -18 3 -3 -13 3 -16 3 -17 3 -3 -17 4 -4
```

```
       INPUTS 8
       7,4 7,5 15,2 17,2 14,10 14,2 7,6 12,3
*      LITE ELEC CTFAN CPMP PPMP CHIL  AHU SPMP
       0    0    0     0    0     0     0   0
*OUTPUTS:1=TOTAL, 2=LITES+ELEC, 3=PUMPS, 4=HVAC(1-2-COMP),
*          5 = PLANT(4-AHU).
 UNIT 48 TYPE 27 HISTOGRAM
       PARAMETERS 8
       2 -1 -1 1 8760 0 24 24
       INPUTS 3
       47,1 14,2 7,9
       TOTPWR CHILER TWB
 UNIT 42 TYPE 27 HISTOGRAM PLOTTER
       PARAMETERS 20
       1 -1 -1 1 8760 0 12000 24 0 24 24 0 1.1 22 60 100 20 3
8 48 20
       INPUTS 5
       47,1 16,4 14,4 15,1 30,1
       TOTPWR APPRCH PLR TCWS TCHWS
 UNIT 43 TYPE 28 SIMULATION SUMMARY
       PARAMETERS 27
       -1 1 8760 -1 2
       0 -4 0 -4 0 -4 0 -4 0 -4 0 -2 2 -4 0 -2 2 -4 0 -4 0 -4
       INPUTS 9
        15,2 15,3 14,10 12,3 17,2 7,9 7,8 47,5 7,6
       LABELS 9
       CTFPWR MAKEUP PPUMP SPMP CPMP TWBAVG TDBAVG PLANTE AHU
EL
 UNIT 44 TYPE 26 PLOTTER
       PARAMETERS 4
       .5 4344 5088 1
       INPUTS 3
       47,1 47,2 47,4
       ETOTAL LI+EL HVAC
 UNIT 46 TYPE 15 ALGEBRAIC OPERATOR
       PARAMETERS 20
       0 0 3 0 3 0 3 0 3 -4 0 0 3 0 3 0 3 0 3 -4
       INPUTS 10
       1,7 2,7 3,7 4,7 5,7 1,8 2,8 3,8 4,8 5,8
       0  0  0  0  0  0  0  0  0  0
 UNIT 45 TYPE 28 SIMSUM
       PARAMETERS 29
       -1 1 8760 -1 2
       1 0 -4  0 -4 0 -4 0 -4 0 -1 3413. 1 -4 0 -4
       0 -4 0 -4 0 -4 0 -4
       INPUTS 10
       46,2 7,2 14,9 46,1 14,2 14,8 47,1 47,2 47,3 47,4
       LABELS 10
       TENERG LOAD CHLOAD TLOSS CHPWR LCOND TOTPWR LI+EL TOTP
MP HVACEL
       CHECK 1.5 2,-3,-4,-1
```

```
     CHECK 1.5 6,-5,-3
UNIT 41 TYPE 25 PRINTER 1
     PARAMETERS 4
     276 1 8760 -1
     INPUTS 10
     11,1 14,4 15,1 7,9 27,2 7,2  11,11 14,2 7,7 47,1
     MODE PLR TCWS TWB FLOWST CCL  LOAD KWA ELEC TOTEL
UNIT 40 TYPE 25 PRINTER 2
     PARAMETERS 4
     276 1 8760 -1
     INPUTS 10
     1,11 2,11 3,11 4,11 5,11 1,10 2,10 3,10 4,10 5,10
     V1  V2  V3  V4 V5  T1  T2  T3  T4  T5
UNIT 37 TYPE 25 PRINTER 3
     PAR 4
     276 1 8760 -1
     INP 3
     12,2 14,5 12,1
     P2TIN FLOWP FLOWS
UNIT 50 TYPE 8 APPROACH PRINT
     PARAMETERS 0
     INPUTS 1
     16,4
     10
END
```

```
***********************************************************
* IBM CHARLOTTE - BUILDING LOAD SIMULATIONS
*    BUILDINGS 201,202 AND 301
*    AIR CAPACITANCE BASED ON VOLUME
*    GROUND TEMPERATURE AT 75F
*    CONVECTION FRACTION OF 0.5
*    AREA WEIGHTED VIEW FACTORS
***********************************************************
NOLIST
SIMULATION 6552 8760 .5
TOLERANCES .01 .001
LIMITS 50 5
UNIT 1 TYPE 9 DATA READER
      PARAMETERS 5
      14 1 -8 1 0
*********************************************
*   SITE LOAD DESCRIPTION
*********************************************
UNIT 2 TYPE 16 RADIATION PROCESSOR
      PARAMETERS 7
      3 1 274 35 428.9 0 -1
      INPUTS 12
      1,8 1,19 1,20  0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0
       0  0    1   .25 90  180  90 270  90  0   90  90
*OUTS: 1=NV, 2=EV, 3=SV, 4=WV
UNIT 3 TYPE 16 RADIATION PROCESSOR
      PARAMETERS 7
      3 1 274 35 428.9 0 -1
      INPUTS 10
      1,8 1,19 1,20 0,0 0,0 0,0 0,0 0,0 0,0 0,0
      0   0    1  .25  60  180 60  0   30  270
*OUTS: 1=N60, 2=S60, 3=E30
UNIT 4 TYPE 33 PSYCH CALCS.
      PARAMETERS 2
      3 2
      INPUTS 2
      1,11 1,12
      70   50
* OUT(1)=W, OUT(2)=TWB
*****************************************************
* SCHEDULES BDLG 201
*****************************************************
UNIT 6 TYPE 14 PEOPLE SCHEDULE - WD
      PARAMETERS 20
      0 0 7 0 7 400 8 400 8 800 16 800 16 400 17 400 17 0 24
 0
UNIT 7 TYPE 14 LIGHT SCHEDULE - WD
      PARAMETERS 12
      0 1.41E5 6.5 1.41E5 6.5 1.41E6 17.25 1.41E6 17.25 1.41
```

```
E5 24 1.41E5
UNIT 8 TYPE 14 ELECTRIC SCHEDULE - WD
      PARAMETERS 12
      0 1.3E6 6.5 1.3E6 6.5 1.3E6 17.25 1.3E6 17.25 1.3E6 24
 1.3E6
UNIT 9 TYPE 14 AHU SCHEDULE - WD
      PARAMETERS 12
      0 0 6 0 6 1 17.25 1 17.25 0 24 0
UNIT 10 TYPE 14 PEOPLE SCHEDULE - WE
      PARAMETERS 4
      0 0 24 0
UNIT 11 TYPE 14 LIGHT SCHEDULE - WE
      PARAMETERS 4
      0 1.41E5 24 1.41E5
UNIT 12 TYPE 14 ELECTRIC SCHEDULE - WE
      PARAMETERS 4
      0 .95E6 24 .95E6
UNIT 13 TYPE 14 AHU SCHEDULE - WE
      PARAMETERS 4
      0 0 24 0
******************************************
* SCHEDULES BDLG 202
******************************************
UNIT 16 TYPE 14 PEOPLE SCHEDULE - WD
      PARAMETERS 20
      0 0 7 0 7 350 8 350 8 700 16 700 16 350 17 350 17 0 24
 0
UNIT 17 TYPE 14 LIGHT SCHEDULE - WD
      PARAMETERS 12
      0 4.9E5 6.5 4.9E5 6.5 1.49E6 17.25 1.49E6 17.25 4.9E5
24 4.9E5
UNIT 18 TYPE 14 ELECTRIC SCHEDULE - WD
      PARAMETERS 12
      0 2.3E6 6.5 2.3E6 6.5 2.3E6 17.25 2.3E6 17.25 2.3E6 24
 2.3E6
UNIT 19 TYPE 14 AHU SCHEDULE - WD
      PARAMETERS 12
      0 1 6 1 6 1 17.25 1 17.25 1 24 1
UNIT 20 TYPE 14 PEOPLE SCHEDULE - WE
      PARAMETERS 4
      0 0 24 0
UNIT 21 TYPE 14 LIGHT SCHEDULE - WE
      PARAMETERS 4
      0 1.49E5 24 1.49E5
UNIT 22 TYPE 14 ELECTRIC SCHEDULE - WE
      PARAMETERS 4
      0 1.90E6 24 1.90E6
UNIT 23 TYPE 14 AHU SCHEDULE - WE
      PARAMETERS 4
      0 1 24 1
```

```
*******************************************
* SCHEDULES BDLG 301-CAF
*******************************************
UNIT 26 TYPE 14 LIGHT SCHEDULE - WD
      PARAMETERS 12
      0 2.76E4 6.5 2.76E4 6.5 2.76E5 17.25 2.76E5 17.25 2.76
E4 24 2.76E4
UNIT 27 TYPE 14 ELECTRIC SCHEDULE - WD
      PARAMETERS 12
      0 0 6.5 0 6.5 5.E5 17.25 5.E5 17.25 0 24 0
UNIT 28 TYPE 14 AHU SCHEDULE - WD
      PARAMETERS 12
      0 0 6 0 6 1 17.25 1 17.25 0 24 0
UNIT 29 TYPE 14 LIGHT SCHEDULE - WE
      PARAMETERS 4
      0 2.76E4 24 2.76E4
UNIT 30 TYPE 14 ELECTRIC SCHEDULE - WE
      PARAMETERS 4
      0 0 24 0
UNIT 31 TYPE 14 AHU SCHEDULE - WE
      PARAMETERS 4
      0 0 24 0
**********************************************
* LOAD SEQUENCER FOR WEEKLY SCHEDULING - ALL ZONES
**********************************************
UNIT 32 TYPE 41 LOAD SEQUENCER
      PARAMETERS 8
      11 1 1 1 1 1 2 2
      INPUTS 22
       6,1  7,1  8,1  9,1  16,1 17,1 18,1 19,1  26,1 27,1 28
,1
      10,1 11,1 12,1 13,1  20,1 21,1 22,1 23,1  29,1 30,1 31
,1
      0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
*OUTPUTS: 1,2,3,4=P,L,E,AHU-201  5,6,7,8=P,L,E,AHU-202
*         9,10,11=L,E,AHU-301(NO PEOPLE)
**********************************************
* BLDG 201 LAB/ADMIN
**********************************************
UNIT 40 TYPE 19 BLDG 201
      PARAMETERS 11
      2 2 2.065E6 0 0 0 37200 11 .5 73 .009
      INPUTS 11
      1,11 4,1 42,4 42,6 42,5 0,0 32,1 0,0 32,2 32,3 1,14
      75   .01 55  8.E5  .0083 0  0    4   1.4E5 0   7.5
*NORTH WALL
      PARAMETERS 7
      1 1 9760 .4 .6 2 27
      INPUTS 1
      2,6
```

```
      0
*EAST WALL
      PARAMETERS 3
      2 -1 4120
      INPUTS 1
      2,11
      0
*SOUTH WALL - EXTERIOR TO ACCOUNT FOR REDUCED E/W AREAS OF W
ALL
      PAR 7
      3 1 14640 .6 .2 2 27
      INPUTS 1
      2,14
      0
*WEST WALL
      PARAMETERS 3
      4 -1 2158
      INPUTS 1
      2,14
      0
*ROOF
      PARAMETERS 7
      5 1 60870 .2 .6 1 17
      INPUTS 1
      2,4
      0
*NORTH GLAZING
      PARAMETERS 8
      6 5 4880 1 .4 1.0 1 9
      INPUTS 5
      2,6 2,7 0,0 0,0 0,0
      0   0    .4 .56 1
*EAST GLAZING
      PARAMETERS 8
      7 5 2520 1 .4 1.0 1 9
      INPUTS 5
      2,11 2,12 0,0 0,0 0,0
      0    0    .4 .55 1
*WEST GLAZING
      PARAMETERS 8
      8 5 4480 1 .4 1.0 1 9
      INPUTS 5
      2,17 2,18 0,0 0,0 0,0
      0    0    .4 .56 1
*GROUND FLOOR - 12 IN HW CONCRETE
      PAR 7
      9 3 60870 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
```

```
*INTERIOR FLOORS - 4 IN HW CONCRETE WITH PLENUM
      PARAMETERS 7
      10 2 183000 .2 .8 3 39
*INTERIOR FURNITURE MASS AT 3BTU/(SF-F)
      PARAMETERS 7
      11 2 113000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
***********************************************
* BLDG 202 LAB/ADMIN
***********************************************
UNIT 41 TYPE 19 BLDG 202
      PARAMETERS 11
      2 2 2.19E6 0 0 0 39400 11 .5 73 .009
      INPUTS 11
      1,11 4,1 43,4 43,6 43,5 0,0 32,5 0,0 32,6 32,7 1,14
      75   .01 55   8.E5 .008  0    0     4  1.5E5 0   7.5
*NORTH WALL
      PARAMETERS 7
      1 1 9480 .4 .6 2 27
      INPUTS 1
      2,6
      0
*EAST WALL
      PARAMETERS 3
      2 -1 1942
      INPUTS 1
      2,11
      0
*SOUTH WALL
      PAR 3
      3 -1 14640
      INPUTS 1
      2,14
      0
*WEST WALL
      PARAMETERS 3
      4 -1 1942
      INPUTS 1
      2,14
      0
*ROOF
      PARAMETERS 7
      5 1 60870 .2 .6 1 17
      INPUTS 1
      2,4
      0
*NORTH GLAZING
      PARAMETERS 8
```

```
      6 5 5160 1 .4 1.0 1 9
      INPUTS 5
      2,6 2,7 0,0 0,0 0,0
      0   0   .4 .56 1
*EAST GLAZING
      PARAMETERS 8
      7 5 4690 1 .4 1.0 1 9
      INPUTS 5
      2,11 2,12 0,0 0,0 0,0
      0    0   .4 .56 1
*WEST GLAZING
      PARAMETERS 8
      8 5 4690 1 .4 1.0 1 9
      INPUTS 5
      2,17 2,18 0,0 0,0 0,0
      0     0  .4 .56 1
*GROUND FLOOR - 12 IN HW CONCRETE
      PAR 7
      9 3 60870 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*INTERIOR FLOORS - 4 IN HW CONCRETE WITH PLENUM
      PARAMETERS 7
      10 2 183000 .2 .8 3 31
*INTERIOR FURNITURE MASS AT 3 BTU/(SF-F)
      PARAMETERS 7
      11 2 120000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
*********************************************
* BLDG 301 CAFETERIA
*********************************************
UNIT 39 TYPE 19 BLDG 301
      PARAMETERS 11
      2 2 898000 0 0 0 16200 11 .5 73 .009
      INPUTS 11
      1,11 4,1 38,4 38,6 38,5 0,0 0,0 0,0 32,9 32,10 1,14
      75   .01 55   4.E5 .0083 0   0    4   2.E4 0    7.5
*NORTH WALL
      PARAMETERS 7
      1 1 2000 .4 .6 2 27
      INPUTS 1
      2,6
      0
*EAST WALL
      PARAMETERS 3
      2 -1 1680
      INPUTS 1
```

```
      2,11
      0
*SOUTH WALL
      PARAMETERS 3
      3 -1 2975
      INPUTS 1
      2,14
      0
*WEST WALL
      PARAMETERS 3
      4 -1 1080
      INPUTS 1
      2,17
      0
*ROOF
      PARAMETERS 7
      5 1 44900 .2 .6 1 17
      INPUTS 1
      2,4
      0
*INTERIOR FURNITURE MASS - 2 IN AT 1BTU/(SF-F)
      PARAMETERS 7
      6 2 12200 .2 .8 3 29
*NORTH GLAZING
      PARAMETERS 8
      7 5 2400 1 .4 1.0 1 11
      INPUTS 5
      2,6 2,7 0,0 0,0 0,0
      0   0    .4 .56 1
*EAST GLAZING
      PARAMETERS 8
      8 5 2400 1 .4 1.0 1 11
      INPUTS 5
      2,11 2,12 0,0 0,0 0,0
      0    0    .4  .56 1
*SOUTH GLAZING
      PARAMETERS 8
      9 5 1425 1 .4 1.0 1 11
      INPUTS 5
      2,14 2,15 0,0 0,0 0,0
      0    0    .4  .56 1
*WEST GLAZING
      PARAMETERS 8
      10 5 3000 1 .4 1.0 1 11
      INPUTS 5
      2,17 2,18 0,0 0,0 0,0
      0    0    .4  .56 1
*GROUND FLOORS - 12 IN HW CONCRETE
      PARAMETERS 7
      11 3 44900 .8 .2 3 22
```

```
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*VIEW FACTORS
      PAR 1
      0
****************************************
* SOUTH FACING CORRIDOR
****************************************
UNIT 14 TYPE 19 SOUTH CORRIDOR
      PAR 11
      2 2 174000 0 0 0 9000 7 0 73 .009
      INPUTS 11
      1,11 4,1 15,4 15,6 0,0 0,0 0,0 0,0 0,0 0,0 0,0
      75   .01 55   0    .0083 0  0   4   0   0  7.5
*SOUTH WALL - ALL GLASS
      PAR 8
      1 5 8730 1 .4 1.0 1 7
      INPUTS 5
      2,6 2,7 0,0 0,0 0,0
      0    0  .4  .56  1
*EAST WALL
      PAR 7
      2 1 199 .4 .6 2 27
      INPUTS 1
      2,11
      0
*NORTH WALL - ADIABATIC
      PAR 7
      3 2 8730 .6 .2 3 23
*WEST WALL
      PAR 3
      4 -2 199
      INPUTS 1
      2,17
      0
*ROOF - GLASS AT 60 DEG TO SOUTH
      PAR 8
      5 5  17400 1 .4 1.0 1 7
      INPUTS 5
      3,11 3,12 0,0 0,0 0,0
      0    0    .55 .56  1
*NORTH GLAZING
      PAR 8
      6 5 1110 1 .4 1.0 1 7
      INPUTS 5
      2,6 2,7 0,0 0,0 0,0
      0   0   .4  .56  1
*FLOOR - 12 IN HW CONCRETE
      PAR 7
```

```
       7 3 17400 .5 .5 3 22
       INPUTS 3
       0,0 0,0 0,0
       75  75  0
*VIEW FACTORS
       PAR 1
       0
**********************************
* SOUTH CORRIDOR - AIR HANDLER
**********************************
UNIT 24 TYPE 44 CONVERGER
       PAR 1
       1
       INPUTS 1
       14,1
       73
UNIT 15 TYPE 5 CORRIDOR AHU
       PARAMETERS 21
       78 71 50000 10000 75 71 65 55 -.1 1 .0083
       25 .35071 .3085 -.54137 .87199
       69 67 4.5E5 0 50
       INPUTS 5
       24,1 14,2 1,11 4,1 32,4
       75   .009 78   .01 1
**************************************
* BLDG 201 - AIR HANDLER
**************************************
UNIT 25 TYPE 44 CONVERGER
       PAR 1
       1
       INPUTS 1
       40,1
       73
UNIT 42 TYPE 5 AHU-BLDG 201
       PARAMETERS 21
       78 71 244000 49000 75 71 65 55 -.1 1 .0083
       85 .35071 .3085 -.54137 .87199
       69 67 3.2E6 0 50
       INPUTS 5
       25,1 40,2 1,11 4,1 32,4
       75   .009 78  .01  0
***********************************************
* BLDG 202 - AIR HANDLER
***********************************************
UNIT 33 TYPE 44 CONVERGER
       PAR 1
       1
       INPUTS 1
       41,1
       73
```

```
UNIT 43 TYPE 5 AHU-BDLG 202
      PARAMETERS 21
      78 71 157500 31500 75 71 65 55 -.1 1 .0083
      64 .35071 .3085 -.54137 .87199
      69 67 3.4E6 0 50
      INPUTS 5
      33,1 41,2 1,11 4,1 32,8
      75   .009 78   .01 1
****************************************
* BDLG 301 - AIR HANDLER
****************************************
UNIT 37 TYPE 44 CONVERGER
      PAR 1
      1
      INPUTS 1
      39,1
      73
UNIT 38 TYPE 5 AHU-BDLG 301
      PARAMETERS 21
      78 71 60000 12000 75 71 65 55 -.1 1 .0083
      20 .35071 .3085 -.54137 .87199
      69 67 7.6E5 0 50
      INPUTS 5
      37,1 39,2 1,11 4,1 32,11
      75   .009 78   .01 0
******************************************
* OUTPUTS
******************************************
 UNIT 44 TYPE 25 PRINTER 1
       PARAMETERS 4
      .5 6552 6600 -1
      INPUTS 10
      1,11 40,1 42,1 49,4 14,1 15,1 49,8 39,1 38,1 50,5
      TOA TRA201 CCL201 SOL201 TRAC CCLC SOLC TRA301  CCL301
 SOL301
*     1,11 14,1 49,8 14,11 14,12 14,13 14,14 14,15 40,1 39,1
*     TOA  TRAC SOLC TSURF TEQ QSOLI QCONV QIR TRA201 TRA301
*UNIT 45 TYPE 25 PRINTER 2
*     PARAMETERS 4
*     .5 4344 4392 -1
*     INPUTS 9
*     32,9 32,10 39,1 1,11 39,3 39,6 38,1 39,5 50,5
*     LIT301 ELEC TRA TOA QCONV ZSENS QCCL QINF QSOL
UNIT 35 TYPE 15 ALG. OP. FOR OUTPUTS
      PARAMETERS 28
      0 0 3 0 3 0 3 -4 0 0 3 0 3 -1 3413 2 -3
      0 0 3 0 3 -1 3413 2 -3 3 -4
      INPUTS 10
      42,1 43,1 15,1 38,1 32,2 32,6 32,9 32,3 32,7 32,10
      0    1.E6   0   0  1.E5   1.E5   1.E4 2.E5 2.E5 2.E4
```

```
*OUT: 1=CCLTOT, 2=LITES, 3=MISC.ELEC., 4=LITES+ELEC.
UNIT 36 TYPE 15 ALG.OP. FOR OUTPUTS
      PARAMETERS 19
      0 0 3 0 3 0 3 -3 0 3 -4
      0 0 3 0 3 0 3 -4
      INPUTS 9
      42,7 43,7 38,7 15,7 35,4 42,11 43,11 38,11 15,11
      0    0    0    0    0    0     0     0     0
*OUTS: 1=AHUELEC, 2=LITES+ELEC.+AHUELEC, 3=QHEATING
UNIT 46 TYPE 28 SIMSUM 202
      PARAMETERS 29
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4  0 -4 0 -4 0 -4 0 -
4 0 -4
      INPUTS 10
      41,1 41,2 43,1 41,6 32,6 32,7 43,9 43,8 43,11 49,7
      LABELS 10
      TRA202 RAW202 CCL202 ZS202 LITE02 ELEC02 OAL02 OAS02 Q
H02 SOL02
UNIT 47 TYPE 28 SIMSUM 301
      PARAMETERS 29
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4 0 -4 0 -4 0 -4 0 -4
 0 -4
      INPUTS 10
      39,1 39,2 38,1 39,6 32,9 32,10 38,9 38,8 38,11 50,5
      LABELS 10
      TRA301 RAW301 CCL301 ZS301 LIT301 EL301 OAL301 OAS301
QH301 SOL301
UNIT 50 TYPE 15 ALG. OP. FOR 301 SOLAR GAINS
      PARAMETERS 24
      0 -1 960 1 -3 0 -1 960 1 -3
      0 -1 570 1 -3 0 -1 1200 1 -3
      3 3 3 -4
      INPUTS 4
      2,6 2,11 2,14 2,17
      0    0    0    0
*OUTPUTS: 1=N, 2=E, 3=S, 4=W, 5=TOTAL
UNIT 49 TYPE 15 ALG.OP. FOR 201 AND CORRIDOR SOLAR GAINS
      PARAMETERS 36
      0 -1 1952 1 -3  0 -1 1008 1 -3
      0 -1 1792 1 -3 3 3 -4
      -11 -1 444 1 -3 -13 -1 3492 1 -3
      -15 -1 9570 1 -3 3 3 -4
      INPUTS 5
      2,6 2,11 2,14 2,17 3,11
      0   0    0    0    0
*OUTPUTS: 1=N, 2=E, 3=W, 4=TOTAL, CORR: 5=N, 6=S, 7=S60, 8=T
OT
UNIT 48 TYPE 28 SIMSUM 201
```

```
      PARAMETERS 29
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4 0 -4 0 -4 0 -4 0 -4
 0 -4
      INPUTS 10
      40,1 40,2 42,1 40,6 32,2 32,3 42,9 42,8 42,11 49,4
      LABELS 10
      TRA201 RAW201 CCL201 ZS201 LIT201 EL201 OAL201 OAS201
QH201 SOL201
UNIT 5 TYPE 28 SIMSUM CORRIDOR
      PAR 25
       -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4 0 -4 0 -4 0 -4
      INPUTS 8
      14,1 14,2 15,1 14,6 15,9 15,8 15,11 49,8
      LABELS 8
      TRAC RAWC CCLC ZSC OALC OASC QHC SOLC
UNIT 34 TYPE 25 FILE PRINTER
      PARAMETERS 4
      .5 1 8760 10
      INPUTS 8
      35,1 36,3 35,2 35,3 36,1 36,2 1,11 4,2
      CCLTOT QHEAT LITES ELEC AHUFAN TOTEL TDB TWB
END
```

```
***********************************************************
* IBM CHARLOTTE - BUILDING LOAD SIMULATIONS
*    BUILDINGS 101NZ AND SZ,102NZ AND SZ
*    AIR CAPACITANCE BASED ON VOLUME
*    INFILTRATION AT 0.0 ACH WHEN AHU IS OFF
*    GROUND TEMPERATURE AT 75F
*    CONVECTION FRACTION OF .5
*    AREA WEIGHTED VIEW FACTORS
***********************************************************
NOLIST
SIMULATION 6552 8760 .5
TOLERANCES .01 .001
LIMITS 50 5
UNIT 1 TYPE 9 DATA READER
      PARAMETERS 5
      14 1 -8 1 0
*********************************************
*   SITE LOAD DESCRIPTION
*********************************************
UNIT 2 TYPE 16 RADIATION PROCESSOR
      PARAMETERS 7
      3 1 274 35 428.9 0 -1
      INPUTS 12
      1,8 1,19 1,20  0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0
       0  0     1   .25 90  180  90 270  90  0   90  90
*OUTS: 1=NV, 2=EV, 3=SV, 4=WV
UNIT 3 TYPE 16 RADIATION PROCESSOR
      PARAMETERS 7
      3 1 274 35 428.9 0 -1
      INPUTS 10
      1,8 1,19 1,20 0,0 0,0 0,0 0,0 0,0 0,0 0,0
      0   0     1  .25  60  180 60  0   30  270
*OUTS: 1=N60, 2=S60, 3=E30
UNIT 4 TYPE 33 PSYCH CALCS.
      PARAMETERS 2
      3 2
      INPUTS 2
      1,11 1,12
      70   50
* OUT(1)=W, OUT(2)=TWB
*****************************************************
* SCHEDULES
*****************************************************
UNIT 6 TYPE 14 PEOPLE SCHEDULE, 101 NZ, 2 SHIFT- WD
      PARAMETERS 14
      0 0 7.5 0 7.5 150 17 150 17 100 24 100 24 0
UNIT 7 TYPE 14 GENERIC LIGHT SCHEDULE,2 SHIFT - WD
      PARAMETERS 12
      0 1 .5 1 .5 .1  6.5 .1 6.5 1 24 1
```

```
UNIT 8 TYPE 14 GENERIC AHU SCHEDULE, 2 SHIFT - WD
      PARAMETERS 12
      0 0 6 0 6 1 23.5 1 23.5 0 24 0
UNIT 9 TYPE 30 GENERIC LOAD SEQUENCER - PEOPLE,LIGHTS,&AHUS
* 2 SHIFTS WD, OFF WE
      PARAMETERS 7
      1 1 1 1 1 2 2
      INPUTS 6
      6,1 7,1 8,1 0,0 0,0 0,0
      0 .1 0  0  .1  0
UNIT 10 TYPE 15 ALG. OP. TO SCALE LIGHTING LEVELS
      PARAMETERS 10
      0 -1 618000 1 -4 -11 -1 546000 1 -4
      INPUTS 2
      9,2 9,3
      1    1
*OUT: 1=101SZ, 2=102SZ
UNIT 11 TYPE 14 PEOPLE SCHEDULE, 101 SZ, WD
      PARAMETERS 12
      0 0 7.5 0 7.5 550 17 550 17 0 24 0
UNIT 12 TYPE 14 PEOPLE SCHEDULE, 102NZ, WD
      PARAMETERS 12
      0 15 7.5 15 7.5 70 17 70 17 15 24 15
UNIT 13 TYPE 14 PEOPLE SCHEDULE, 102SZ, WD
      PARAMETERS 14
      0 0 7.5 0 7.5 80 17 80 17 20 24 20 24 0
UNIT 14 TYPE 30 PEOPLE LOAD SEQUENCER, 101SZ, 102NZ, 102SZ
      PARAMETERS 7
      1 1 1 1 1 2 2
      INPUTS 6
      11,1 12,1 13,1 0,0 0,0 0,0
      0     15  0     0    15  0
UNIT 15 TYPE 14 ELEC, 101NZ
      PARAMETERS 12
      0 3.21E6 .5 3.21E6 .5 2.53E6 6.5 2.53E6 6.5 3.21E6 24
3.21E6
UNIT 16 TYPE 14 ELEC, 101SZ
      PARAMETERS 16
      0 0 .5 0 .5 5.5E5 6.5 5.5E5 6.5 6.8E4 17 6.8E4 17 0 24
 0
UNIT 17 TYPE 14 ELEC, 102SZ
      PARAMETERS 16
      0 1.4E5 .5 1.4E5 .5 6.5E5  6.5 6.5E5 6.5 3.1E5 17 3.1E
5
      17 1.4E5 24 1.4E5
UNIT 18 TYPE 30 ELEC LOAD SEQUENCER, 101NZ, 101SZ, 102SZ
      PARAMETERS 7
      1 1 1 1 1 2 2
      INPUTS 6
      15,1 16,1 17,1 0,0 0,0 0,0
```

```
      3.2E6 0  1.4E5 2.4E6 3.4E5 4.1E5
********************************************
* BDLG 101 NZ
**********************************************
UNIT 31 TYPE 19 BLDG 101 NZ
      PARAMETERS 11
      2 2 2.3E6 0 0 0 41400 11 .5 73 .009
      INPUTS 11
      1,11 4,1 32,4 32,6 32,5 0,0 9,1 0,0 0,0 18,1 1,14
      75   .01 55  8.E5  .0083 0  0    4   7.1E5 3.2E6   7.5
*NORTH WALL
      PARAMETERS 7
      1 1 5440 .4 .6 2 27
      INPUTS 1
      2,6
      0
*EAST WALL
      PARAMETERS 3
      2 -1 6120
      INPUTS 1
      2,11
      0
*WEST WALL EXT
      PARAMETERS 3
      3 -1 2535
      INPUTS 1
      2,17
      0
*ROOF
      PARAMETERS 7
      4 1 115200 .2 .6 1 17
      INPUTS 1
      2,4
      0
*SOUTH WALL NEXT TO 101SZ
      PARAMETERS 7
      5 3 6400 .2 .8 3 23
      INPUTS 3
      0,0 33,1 0,0
      73  73   0
*WEST WALL NEXT TO 102NZ
      PARAMETERS 7
      6 3 3100 .2 .8 3 23
      INPUTS 3
      0,0 35,1 0,0
      73  73   0
*NORTH GLAZING
      PARAMETERS 8
      7 5 960 1 .4 1.0 1 10
      INPUTS 5
```

```
      2,6 2,7 0,0 0,0 0,0
      0   0    .4 1.19 1
*EAST GLAZING
      PARAMETERS 8
      8 5 1080 1 .4 1.0 1 10
      INPUTS 5
      2,11 2,12 0,0 0,0 0,0
      0    0    .4 1.0 .55 1
*WEST GLAZING
      PARAMETERS 8
      9 5 1565 1 .4 1.0 1 10
      INPUTS 5
      2,17 2,18 0,0 0,0 0,0
      0    0    .4 1.19 1
*FLOOR - 12 IN HW CONCRETE
      PARAMETERS 7
      10 3 115200 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*INTERIOR FURNITURE MASS AT 7.5 BTU/(SF-F)
      PARAMETERS 7
      11 2 158000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
***********************************************
* BDLG 101 SOUTH ZONE
***********************************************
UNIT 33 TYPE 19 BLDG 101SZ
      PARAMETERS 11
      2 2 2.02E6 0 0 0 36400 9 .5 73 .009
      INPUTS 11
      1,11 4,1 34,4 34,6 34,5 0,0 14,1 0,0 10,1 18,2 1,14
      75   .01 55   8.E5 .008  0    0    4   1.5E5 0   7.5
*EAST WALL
      PARAMETERS 7
      1 1 5450 .4 1.0 .6 2 27
      INPUTS 1
      2,11
      0
*SOUTH WALL
      PARAMETERS 3
      2 -1 3000
      INPUTS 1
      2,14
      0
*ROOF
      PARAMETERS 7
      3 1 99200 .2 .6 1 17
```

```
      INPUTS 1
      2,4
      0
*NORTH WALL NEXT TO NZ101
      PARAMETERS 7
      4 3 6400 .2 .8 3 23
      INPUTS 3
      0,0 31,1 0,0
      73  73   0
*SOUTH WALL NEXT TO CORRIDOR - ADIABATIC
      PAR 7
      5 2 3400 .2 .8 3 23
*WEST WALL NEXT TO SZ102
      PARAMETERS 7
      6 3 6200 .2 .8 3 23
      INPUTS 3
      0,0 37,1 0,0
      73   73  0
*EAST GLAZING
      PARAMETERS 8
      7 5 750 1 .4 1.0 1 9
      INPUTS 5
      2,11 2,12 0,0 0,0 0,0
      0    0   .4 1.19 1
*FLOOR - 12 IN HW CONCRETE
      PARAMETERS 7
      8 3 99200 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*INTERIOR FURNITURE MASS AT 12 BTU/(SF-F)
      PARAMETERS 7
      9 2 217000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
********************************************
* BLDG 102 NORTH ZONE
********************************************
UNIT 35 TYPE 19 BLDG 301
      PARAMETERS 11
      2 2 1.34E6 0 0 0 24100 12 .5 73 .009
      INPUTS 11
      1,11 4,1 36,4 36,6 36,5 0,0 14,2 0,0 0,0 0,0 1,14
      75   .01 55   4.E5 .0083 0  0    4   4.1E5 4.74E6    7
.5
*NORTH WALL
      PARAMETERS 7
      1 1 650 .4 1.0 .6 2 27
      INPUTS 1
```

```
      2,6
      0
*WEST WALL
      PAR 3
      2 -1 940
      INPUTS 1
      2,11
      0
*WEST WALL
      PARAMETERS 3
      3 -1 4370
      INPUTS 1
      2,17
      0
*ROOF
      PARAMETERS 7
      4 1 66800 .2 .6 1 17
      INPUTS 1
      2,4
      0
*NORTH WALL NEXT TO CORRIDOR - ADIABATIC
      PAR 7
      5 2 4100 .2 .8 3 23
*EAST WALL NEXT TO 101NZ
      PARAMETERS 7
      6 3 3100 .2 .8 3 23
      INPUTS 3
      0,0 31,1 0,0
      73   73  0
*SOUTH WALL NEXT TO 102SZ
      PARAMETERS 7
      7 3 5400 .2 .8 3 23
      INPUTS 3
      0,0 37,1 0,0
      73   73  0
*NORTH GLAZING
      PARAMETERS 8
      8 5 650 1 .4 1.0 1 11
      INPUTS 5
      2,6 2,7 0,0 0,0 0,0
      0   0    .4 1.19 1
*EAST GLAZING
      PARAMETERS 8
      9 5 900 1 .4 1.0 1 11
      INPUTS 5
      2,11 2,12 0,0 0,0 0,0
      0    0   .4  1.19 1
*WEST GLAZING
      PARAMETERS 8
      10 5 570 1 .4 1.0 1 11
```

```
      INPUTS 5
      2,17 2,18 0,0 0,0 0,0
      0    0   .4  1.19 1
*FLOOR - 12 IN HW CONCRETE
      PARAMETERS 7
      11 3 66800 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*INTERIOR FURNITURE MASS AT 12 BTU/(SF-F)
      PARAMETERS 7
      12 2 146000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
********************************************
* BDLG 102 SOUTH ZONE
********************************************
UNIT 37 TYPE 19 BLDG 102 SZ
      PARAMETERS 11
      2 2 1.67E6 0 0 0 30100 8 .5 73 .009
      INPUTS 11
      1,11 4,1 38,4 38,6 38,5 0,0 14,3 0,0 10,2 18,3 1,14
      75   .01 55  8.E5  .0083 0  0    4   5.46E5 3.1E5   7.
5
*WEST WALL EXT
      PARAMETERS 7
      1 1 5740 .2 .6 2 27
      INPUTS 1
      2,17
      0
*ROOF
      PARAMETERS 7
      2 1 83700 .2 .6 1 17
      INPUTS 1
      2,4
      0
*NORTH WALL NEXT TO NORTH ZONE
      PARAMETERS 7
      3 3 5400 .2 .8 3 23
      INPUTS 3
      0,0 33,1 0,0
      73  73   0
*EAST WALL NEXT TO 101SZ
      PARAMETERS 7
      4 3 6200 .2 .8 3 23
      INPUTS 3
      0,0 35,1 0,0
      73  73   0
*SOUTH WALL NEXT TO CORRIDOR - ADIABATIC
```

```
      PAR 7
      5 2 5400 .2 .8 3 23
*WEST GLAZING
      PARAMETERS 8
      6 5 660 1 .4 1.0 1 7
      INPUTS 5
      2,17 2,18 0,0 0,0 0,0
      0    0    .4 1.19 1
*FLOOR - 12 IN HW CONCRETE
      PARAMETERS 7
      7 3 83700 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*INTERIOR FURNITURE MASS AT 12 BTU/(SF-F)
      PARAMETERS 7
      8 2 183000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
**************************************
* BLDG 101NZ - AIR HANDLER
* NO ECONOMIZER, 10% OA
**************************************
UNIT 21 TYPE 44 CONVERGER
      PAR 1
      1
      INPUTS 1
      31,1
      73
UNIT 32 TYPE 5 AHU-BLDG 101NZ
      PARAMETERS 21
      78 71 181000 36000 75 71 55 55 -.1 0 .0083
      60 .35071 .3085 -.54137 .87199
      69 67 1.8E6 0 50
      INPUTS 5
      21,1 31,2 1,11 4,1 0,0
      75   .009 78  .01  1
***********************************************
* BLDG 101SZ - AIR HANDLER
***********************************************
UNIT 22 TYPE 44 CONVERGER
      PAR 1
      1
      INPUTS 1
      33,1
      73
UNIT 34 TYPE 5 AHU-BDLG 101SZ
      PARAMETFRS 21
      78 71 60000 12000 75 71 65 55 -.1 1 .0083
```

```
      25 .35071 .3085 -.54137 .87199
      69 67 1.6E6 0 50
      INPUTS 5
      22,1 33,2 1,11 4,1 9,3
      75   .009 78   .01 1
*****************************************
* BDLG 102NZ - AIR HANDLER
* NO ECONOMIZER, 5% OA
*****************************************
UNIT 23 TYPE 44 CONVERGER
      PAR 1
      1
      INPUTS 1
      35,1
      73
UNIT 36 TYPE 5 AHU-BDLG 102NZ
      PARAMETERS 21
      78 71 236000 47000 75 71 55 55 -.05 0 .0083
      60 .35071 .3085 -.54137 .87199
      69 67 1.2E6 0 50
      INPUTS 5
      23,1 35,2 1,11 4,1 0,0
      75   .009 78   .01 1
********************************************
* BLDG 102SZ - AIR HANDLER
********************************************
UNIT 24 TYPE 44 CONVERGER
      PAR 1
      1
      INPUTS 1
      37,1
      73
UNIT 38 TYPE 5 AHU-BLDG 102SZ
      PARAMETERS 21
      78 71 70000 14000 75 71 65 55 -.1 1 .0083
      35 .35071 .3085 -.54137 .87199
      69 67 1.2E6 0 50
      INPUTS 5
      24,1 37,2 1,11 4,1 9,3
      75   .009 78   .01 1
*******************************************
* OUTPUTS
*******************************************
UNIT 40 TYPE 15 ALG. OP. FOR OUTPUTS
      PARAMETERS 32
      0 0 3 0 3 0 3 -4
      0 0 3 -1 1.12E6 3 -1 3413 2 -3
      0 0 3 0 3 -1 4.74E6 3 -1 3413 2 -3 3 -4
      INPUTS 9
      32,1 34,1 36,1 38,1 10,1 10,2 18,1 18,2 18,3
```

```
      0    1.E6   0   1.E5  1.E5  1.E4 2.E5 2.E5 2.E4
*OUT: 1=CCLTOT, 2=LITES, 3=MISC.ELEC., 4=LITES+ELEC.
UNIT 41 TYPE 15 ALG.OP. FOR OUTPUTS
      PARAMETERS 19
      0 0 3 0 3 0 3 -3 0 3 -4
      0 0 3 0 3 0 3 -4
      INPUTS 9
      32,7 34,7 36,7 38,7 40,4 32,11 34,11 36,11 38,11
      0    0    0    0  0    0     0     0     0
*OUTS: 1=AHUELEC, 2=LITES+ELEC.+AHUELEC., 3=QHEATING
UNIT 42 TYPE 28 SIMSUM 101NZ
      PARAMETERS 28
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4
      -1 7.1E5 -4 0 -4 0 -4 0 -4 0 -4
      INPUTS 8
      31,1 31,2 32,1 31,6 18,1 32,9 32,8 32,11
      LABELS 9
      TRA01N RAW01N CCL01N ZS01N LITE1N ELEC1N OAL1N OAS1N Q
H01N
UNIT 43 TYPE 28 SIMSUM 101SZ
      PARAMETERS 27
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4  0 -4 0 -4 0 -4 0 -
4
      INPUTS 9
      33,1 33,2 34,1 33,6 10,1 18,2 34,9 34,8 34,11
      LABELS 9
      TRA01S RAW01S CCL01S ZS01S LIT01S EL01S OAL01S OAS01S
QH01S
UNIT 44 TYPE 28 SIMSUM 102NZ
      PARAMETERS 29
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4  0 -4 0 -4 -1 4.1E5 -4 -1 4.74E6 -
4 0 -4
      0 -4 0 -4
      INPUTS 7
      35,1 35,2 36,1 35,6 36,9 36,8 36,11
      LABELS 9
      TRA02N RAW02N CCL02N ZS02N LIT02N EL02N OAL02N OAS02N
QH02N
UNIT 45 TYPE 28 SIMSUM 102SZ
      PARAMETERS 27
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4  0 -4 0 -4 0 -4 0 -
4
      INPUTS 9
      37,1 37,2 38,1 37,6 10,2 18,3 38,9 38,8 38,11
      LABELS 9
      TRA02S RAW02S CCL02S ZS02S LIT02S EL02S OAL02S OAS02S
```

```
QH02S
UNIT 46 TYPE 25 FILE PRINTER
      PARAMETERS 4
      .5 1 8760 10
      INPUTS 6
      40,1 41,3 40,2 40,3 41,1 41,2
      CCLTOT QHEAT  LITES ELEC AHUFAN TOTEL
UNIT 47 TYPE 25 PRINTER
      PARAMETERS 4
      .5 6552 6600 -1
      INPUTS 9
      1,11 31,1 32,1 33,1 34,1 35,1 36,1 37,1 38,1
      TOA TRA01N CCL01N TRA01S CCL01S TRA02N CCL02N TRA02S C
CL02S
END
```

```
************************************************************
* IBM CHARLOTTE - BUILDING LOAD SIMULATIONS
*    BUILDING 103 N AND S, CORRIDOR
*    AIR CAPACITANCE BASED ON VOLUME
*    INFILTRATION AT 0.0 ACH WHEN AHU IS OFF
*    GROUND TEMPERATURE AT 70F
*    CONVECTION FRACTION OF .5
*    AREA WEIGHTED VIEW FACTORS
************************************************************
NOLIST
SIMULATION 6552 8760 .5
TOLERANCES .01 .001
LIMITS 50 5
UNIT 1 TYPE 9 DATA READER
      PARAMETERS 5
      14 1 -8 1 0
********************************************
*   SITE LOAD DESCRIPTION
********************************************
UNIT 2 TYPE 16 RADIATION PROCESSOR
      PARAMETERS 7
      3 1 274 35 428.9 0 -1
      INPUTS 12
      1,8 1,19 1,20  0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0
       0  0     1   .25 90   180  90 270  90  0   90  90
*OUTS: 1=NV, 2=EV, 3=SV, 4=WV
UNIT 3 TYPE 16 RADIATION PROCESSOR
      PARAMETERS 7
      3 1 274 35 428.9 0 -1
      INPUTS 10
      1,8 1,19 1,20 0,0 0,0 0,0 0,0 0,0 0,0 0,0
      0   0     1  .25  60   180 60  0   30  270
*OUTS: 1=N60, 2=S60, 3=E30
UNIT 4 TYPE 33 PSYCH CALCS.
      PARAMETERS 2
      3 2
      INPUTS 2
      1,11 1,12
      70   50
* OUT(1)=W, OUT(2)=TWB
****************************************************
* SCHEDULES
****************************************************
UNIT 6 TYPE 14 PEOPLE SCHEDULE, 103 NZ, 1 SHIFT- WD
      PARAMETERS 12
      0 0 7 0 8 250 16 250 17 0 24 0
UNIT 7 TYPE 14 PEOPLE SCHEDULE, 103 SZ, 1 SHIFT - WD
      PARAMETERS 12
      0 0 7 0 8 50 16 50 17 0 24 0
```

```
UNIT 8 TYPE 30 PEOPLE LOAD SEQUENCER
      PARAMETERS 7
      1 1 1 1 1 2 2
      INPUTS 6
      6,1 7,1 0,0 0,0 0,0 0,0
      0   0   0   0   0   0
UNIT 9 TYPE 14 LIGHT SCHEDULE, 103 NZ, WD
      PARAMETERS 12
      0 5.39E4 6.5 5.39E4 6.5 5.39E5 17.25 5.39E5 17.25 5.39
E4 24 5.39E4
UNIT 10 TYPE 14 LIGHT SCHEDULE, 103 SZ, WD
      PARAMETERS 12
      0 4.13E4 6.5 4.13E4 6.5 4.13E5 17.25 4.13E5 17.25 4.13
E4 24 4.13E4
UNIT 11 TYPE 30 LIGHT SEQUENCER, 103NZ, 103SZ
      PARAMETERS 7
      1 1 1 1 1 2 2
      INPUTS 6
      9,1 10,1 0,0 0,0 0,0 0,0
      5.4E4 4.1E4 0   5.4E4 4.1E4  0
UNIT 12 TYPE 14 ELECTRIC SCHEDULE, 103NZ, WD
      PARAMETERS 12
      0 5.26E5 6.5 5.26E5 6.5 3.41E5 17.25 3.41E5 17.25 5.26
E5 24 5.26E5
UNIT 13 TYPE 14 ELECTRIC SCHEDULE, 103SZ, WD
      PARAMETERS 12
      0 1.91E5 6.5 1.91E5 6.5 1.36E5 17.25 1.36E5 17.25 1.91
E5 24 1.91E5
UNIT 14 TYPE 30 ELECTRIC SEQUENCER, 103NZ, 103SZ
      PARAMETERS 7
      1 1 1 1 1 2 2
      INPUTS 6
      12,1 13,1 0,0 0,0 0,0 0,0
      5.26E5 1.91E5 0 0 7.8E4 0
UNIT 15 TYPE 14 AHU SCHEDULE - 1ST SHIFT
      PARAMETERS 12
      0 0 6 0 6 1 17.25 1 17.25 0 24 0
UNIT 16 TYPE 14 AHU SCHEDULE - 2 SHIFTS
      PARAMETERS 12
      0 0 6 0 6 1 23.5 1 23.5 0 24 0
UNIT 17 TYPE 30 AHU SEQUENCER, 103NX, 103SZ, WE-OFF
      PARAMETERS 7
      1 1 1 1 1 2 2
      INPUTS 6
      15,1 16,1 0,0 0,0 0,0 0,0
      0    1    0    0    0    0
*********************************************
* BDLG 103 NZ
*********************************************
UNIT 31 TYPE 19 BLDG 103 NZ
```

```
        PARAMETERS 11
        2 2 1.75E6 0 0 0 31500 11 .5 73 .009
        INPUTS 11
        1,11 4,1 32,4 32,6 32,5 0,0 8,1 0,0 11,1 14,1 1,14
        75   .01 55  8.E5  .0083 0  0    4   5.4E4 5.3E5   7.5
*NORTH WALL
        PARAMETERS 7
        1 1 700 .4 .6 2 27
        INPUTS 1
        2,6
        0
*EAST WALL
        PARAMETERS 3
        2 -1 6030
        INPUTS 1
        2,11
        0
*WEST WALL
        PARAMETERS 3
        3 -1 5380
        INPUTS 1
        2,17
        0
*ROOF
        PARAMETERS 7
        4 1 87500 .2 .6 1 17
        INPUTS 1
        2,4
        0
*NORTH INTERIOR WALL NEXT TO 202 CORRIDOR - ADIABATIC
        PAR 7
        5 2 3680 .2 .8 3 23
*SOUTH WALL NEXT TO 103SZ
        PARAMETERS 7
        6 3 5080 .2 .8 3 23
        INPUTS 3
        0,0 33,1 0,0
        73  73   0
*NORTH GLAZING
        PARAMETERS 8
        7 5 700 1 .4 1.0 1 10
        INPUTS 5
        2,6 2,7 0,0 0,0 0,0
        0   0    .4 1.19 1
*EAST GLAZING
        PARAMETERS 8
        8 5 870 1 .4 1.0 1 10
        INPUTS 5
        2,11 2,12 0,0 0,0 0,0
        0    0    .4 1.0 .55 1
```

```
*WEST GLAZING
      PARAMETERS 8
      9 5 1520 1 .4 1.0 1 10
      INPUTS 5
      2,17 2,18 0,0 0,0 0,0
      0    0    .4 1.19 1
*FLOOR - 12 IN CONCRETE
      PARAMETERS 7
      10 3 87500 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*INTERIOR FURNITURE MASS AT 7.5 BTU/(SF-F)
      PARAMETERS 7
      11 2 120000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
***********************************************
* BDLG 103 SOUTH ZONE
***********************************************
UNIT 33 TYPE 19 BLDG 103SZ
      PARAMETERS 11
      2 2 1.34E6 0 0 0 24000 9 .5 73 .009
      INPUTS 11
      1,11 4,1 34,4 34,6 34,5 0,0 8,2 0,0 11,2 14,2 1,14
      75   .01 55   8.E5 .008  0   0    4  4.1E4 1.9E5   7.5
*EAST WALL
      PARAMETERS 7
      1 1 4260 .4 .6 2 27
      INPUTS 1
      2,11
      0
*WEST WALL
      PARAMETERS 3
      2 -1 4380
      INPUTS 1
      2,17
      0
*ROOF
      PARAMETERS 7
      3 1 67200 .2 .6 1 17
      INPUTS 1
      2,4
      0
*NORTH WALL NEXT TO NZ301
      PARAMETERS 7
      4 3 5600 .2 .8 3 23
      INPUTS 3
      0,0 31,1 0,0
```

```
      73  73   0
*SOUTH WALL NEXT TO CORRIDOR - ADIABATIC
      PAR 7
      5 2 5600 .2 .8 3 23
*EAST GLAZING
      PARAMETERS 8
      6 5 540 1 .4 1.0 1 8
      INPUTS 5
      2,11 2,12 0,0 0,0 0,0
      0    0    .4  1.19 1
*WEST GLAZING
      PARAMETERS 8
      7 5 420 1 .4 1.0 1 8
      INPUTS 5
      2,17 2,18 0,0 0,0 0,0
      0    0    .4  1.19 1
*FLOORS - 12 IN CONCRETE
      PARAMETERS 7
      8 3 67200 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*INTERIOR FURNITURE MASS AT 12BTU/(SF-F)
      PARAMETERS 7
      9 2 146000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
***********************************
* NORTH CORRIDOR
***********************************
UNIT 35 TYPE 19 NORTH CORRIDOR
      PAR 11
      2 2 1.54E5 0 0 0 7700 7 .5 73 .009
      INPUTS 11
      1,11 4,1 36,4 36,6 36,5 0,0 0,0 0,0 0,0 0,0 1,14
      75   .01 55   3.E5 .008 0   0   4   0   0   7.5
*NORTH WALL - ADIABATIC
      PAR 7
      1 2 5650 .2 .8 3 23
*EAST WALL
      PAR 7
      2 1 121 .4 .6 2 27
      INPUTS 1
      2,11
      0
*SOUTH WALL - ADIABATIC
      PAR 3
      3 -1 12700
*WEST WALL
```

```
      PAR 3
      4 -2 121
      INPUTS 1
      2,17
      0
*NORTH GLAZING
      PAR 8
      5 5 7050 1 .4 1.0 1 7
      INPUTS 5
      2,6 2,7 0,0 0,0 0,0
      0   0   .4  1.19  1
*NORTH SLOPED GLAZING - ROOF
      PAR 8
      6 5 15400 1 .50 1.0 1 7
      INPUTS 5
      3,6 3,7 0,0 0,0 0,0
      0   0   .5  1.19 1
*FLOOR - 12 IN HW CONCRETE
      PAR 7
      7 3 15400 .5 .5 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*VIEW FACTORS
      PAR 1
      0
***************************************
* BLDG 103NZ - AIR HANDLER
***************************************
UNIT 37 TYPE 44 CONVERGRNCE PROMOTOR
      PAR 1
      1
      INPUTS 1
      31,1
      73
UNIT 32 TYPE 5 AHU-BLDG 103NZ
      PARAMETERS 21
      78 71 75000 15000 75 71 65 55 -.1 1 .0083
      40 .35071 .3085 -.54137 .87199
      69 67 6.1E6 0 50
      INPUTS 5
      37,1 31,2 1,11 4,1 17,1
      75   .009 78  .01  0
************************************************
* BLDG 103SZ - AIR HANDLER
************************************************
UNIT 38 TYPE 44 CONVERGENCE PROMOTOR
      PAR 1
      1
      INPUTS 1
```

```
      33,1
      73
UNIT 34 TYPE 5 AHU-BDLG 103SZ
      PARAMETERS 21
      78 71 38000 18000 75 71 65 55 -.1 1 .0083
      15 .35071 .3085 -.54137 .87199
      69 67 6.1E6 0 50
      INPUTS 5
      38,1 33,2 1,11 4,1 17,2
      75   .009 78   .01 0
***************************************
* NORTH CORRIDOR - AIR HANDLER
***************************************
UNIT 29 TYPE 44 CONVERGENCE PROMOTOR
      PAR 1
      1
      INPUTS 1
      35,1
      73
UNIT 36 TYPE 5 AHU-N. COORRIDOR
      PARAMETERS 21
      78 71 37500 7500 75 71 65 55 -.1 1 .0083
      20 .35071 .3085 -.54137 .87199
      69 67 5.9E5 0 50
      INPUTS 5
      29,1 35,2 1,11 4,1 17,2
      75   .009 78   .01 0
******************************************
* OUTPUTS
******************************************
UNIT 40 TYPE 15 ALG. OP. FOR OUTPUTS
      PARAMETERS 29
      0 0 3 0 3 -4  0 0 3 -1 3413 2 -3
      0 0 3 -1 3413 2 -3  0 0 3 0 3 -3  3 3 -4
      INPUTS 10
      32,1 34,1 36,1 11,1 11,2 14,1 14,2 32,7 34,7 36,7
      0  0   0  0   0   0   0   0   0   0
*OUT: 1=CCLTOT, 2=LITES, 3=MISC.ELEC., 4=AHUELEC, 5=TOTEL
UNIT 39 TYPE 15 ALG. OP. FOR HEAT
      PAR 6
      0 0 3 0 3 -4
      INPUTS 3
      32,11 34,11 36,11
      0     0     0
UNIT 41 TYPE 15 ALG.OP. FOR SOLAR GAINS
      PARAMETERS 40
      0 -1 280 1 -3  0 -1 348 1 -3
      0 -1 608 1 -3 3 3 -4
      -12 -1 216 1 -3 -13 -1 168 1 -3  3 -4
      -11 -1 2820 1 -14 -1 7700 1  3 -4
```

```
      INPUTS 4
      2,6 2,11 2,17 3,6
      0    0    0    0
*OUTS:103NZ 1=N,2=E,3=W,4=TOT  103SZ 5=E,6=W,7=TOT
*    CORR 8=TOT
UNIT 42 TYPE 28 SIMSUM 103NZ
      PARAMETERS 29
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4
      0 -4 0 -4 0 -4 0 -4 0 -4 0 -4
      INPUTS 10
      31,1 31,2 32,1 31,6 11,1 14,1 32,9 32,8 32,11 41,4
      LABELS 10
      TRA01N RAW01N CCL01N ZS01N LITE1N ELEC1N OAL1N OAS1N Q
H01N SOL01N
UNIT 43 TYPE 28 SIMSUM 103SZ
      PARAMETERS 29
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4  0 -4 0 -4 0 -4 0 -
4 0 -4
      INPUTS 10
      33,1 33,2 34,1 33,6 11,2 14,2 34,9 34,8 34,11 41,8
      LABELS 10
      TRA01S RAW01S CCL01S ZS01S LIT01S EL01S OAL01S OAS01S
QH01S SOL01S
UNIT 44 TYPE 28 SIMSUM CORRIDOR
      PAR 25
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4  0 -4  0 -4 0 -4 0 -4 0 -4 0 -4
      INPUTS 8
      35,1 35,2 36,1 35,6 36,9 36,8 36,11 41,8
      LABELS 8
      TRACOR RAWCOR CCLCOR ZSCOR OALCOR OASCOR QHCOR SOLCOR
UNIT 45 TYPE 25 FILE PRINTER
      PARAMETERS 4
      .5 1 8760 10
      INPUTS 6
      40,1 39,1 40,2 40,3 40,4 40,5
      CCLTOT QHEAT  LITES ELEC AHUFAN TOTEL
 UNIT 46 TYPE 25 PRINTER
      PARAMETERS 4
      .5 6552 6600 -1
      INPUTS 10
      31,1 32,1 41,4 33,1 34,1 33,6 41,7 35,1 36,1 41,8
      TRAN CCLN SOLN TRAS CCLS ZSS SOLS TRAC CCLC SOLC
END
```

```
***********************************************************
* IBM CHARLOTTE - BUILDING LOAD SIMULATIONS
*    BUILDINGS 001,002FLOOR,002MEZZANINE, AND ASRS(003)
*    AIR CAPACITANCE BASED ON VOLUME
*    INFILTRATION AT 0.0 ACH WHEN AHU IS OFF
*    GROUND TEMPERATURE AT 75F
*    CONVECTION FRACTION OF .5
*    AREA WEIGHTED VIEW FACTORS
***********************************************************
NOLIST
SIMULATION 6552 8760 .5
TOLERANCES .01 .001
LIMITS 50 5
UNIT 1 TYPE 9 DATA READER
      PAR 5
      14 1 -8 1 0
********************************************
*   SITE LOAD DESCRIPTION
********************************************
UNIT 2 TYPE 16 RADIATION PROCESSOR
      PAR 7
      3 1 274 35 428.9 0 -1
      INPUTS 12
      1,8 1,19 1,20  0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0
       0  0     1   .25 90  180  90 270 . 90  0   90  90
*OUTS: 1=NV, 2=EV, 3=SV, 4=WV
UNIT 3 TYPE 16 RADIATION PROCESSOR
      PAR 7
      3 1 274 35 428.9 0 -1
      INPUTS 10
      1,8 1,19 1,20 0,0 0,0 0,0 0,0 0,0 0,0 0,0
      0   0     1  .25  60  180 60  0   30  270
*OUTS: 1=N60, 2=S60, 3=E30
UNIT 4 TYPE 33 PSYCH CALCS.
      PAR 2
      3 2
      INPUTS 2
      1,11 1,12
      70  50
* OUT(1)=W, OUT(2)=TWB
***************************************************
* SCHEDULES
***************************************************
UNIT 6 TYPE 14 PEOPLE SCHEDULE - 001 WD
      PAR 16
      0 35 .5 35 .5 0 7 0 8 40 16 40 17 35 24 35
UNIT 7 TYPE 14 PEOPLE SCHEDULE - 002 FLOOR
      PAR 12
      0 20 .5 20 .5 0 7 0 8 20 24 20
```

```
UNIT 8 TYPE 14 PEOPLE SCHEDULE - 002 MEZZ.
      PAR 12
      0 0 7 0 8 50 16 50 17 0 24 0
UNIT 9 TYPE 30 LOAD SEQUENCER - PEOPLE 001,002FL,002MEZ
      PAR 7
      1 1 1 1 1 2 2
      INPUTS 6
      6,1 7,1 8,1 0,0 0,0 0,0
      35  20  0   0   0   0
UNIT 10 TYPE 14 LIGHTS - 001 WD
      PAR 12
      0 1.98E5 .5 1.98E5 .5 1.98E4 6.5 1.98E4 6.5 1.98E5 24
1.98E5
UNIT 11 TYPE 14 LIGHTS - 002FL WD
      PAR 12
      0 2.90E5 .5 2.90E5 .5 2.90E4 6.5 2.90E4 6.5 2.90E5 24
2.90E5
UNIT 12 TYPE 14 LIGHTS - 002M WD
      PAR 12
      0 4.10E4 6.5 4.10E4 6.5 4.10E5 17.25 4.10E5 17.25 4.10
E4 24 4.10E4
UNIT 13 TYPE 30 LOAD SEQUENCER - LIGHTS 001,002FL,002MEZ
      PAR 7
      1 1 1 1 1 2 2
      INPUTS 6
      10,1 11,1 12,1 0,0 0,0 0,0
      1.98E5 2.9E5 4.1E4 1.98E4 2.9E4 1.98E4
UNIT 14 TYPE 14 ELECTRIC - 001 WD
      PAR 12
      0 2.3E5 .5 2.3E5 .5 2.1E5 6.5 2.1E5 6.5 2.3E5 24 2.3E5
UNIT 15 TYPE 14 ELECTRIC - 002FL WD
      PAR 12
      0 1.4E6 .5 1.4E6 .5 1.2E6 6.5 1.2E6 6.5 1.4E6 24 1.4E6
UNIT 16 TYPE 14 ELECTRIC - 002MEZ
      PAR 12
      0 3.0E5 6.5 3.0E5 6.5 2.5E5 17.25 2.5E5 17.25 3.0E5 24
 3.0E5
UNIT 17 TYPE 30 LOAD SEQUENCER - ELECTRIC 001,002FL,002MEZ
      PAR 7
      1 1 1 1 1 2 2
      INPUTS 6
      14,1 15,1 16,1 0,0 0,0 0,0
      2.3E5 1.4E6 3.0E5 2.1E5 1.2E6 3.0E5
UNIT 18 TYPE 14 GENERIC AHU SCHEDULE - 1 SHIFT
      PAR 12
      0 0 6 0 6 1 17.25 1 17.25 0 24 0
UNIT 19 TYPE 14 GENERIC AHU SCHEDULE - 2 SHIFT
      PAR 12
      0 0 6 0 6 1 23.5 1 23.5 0 24 0
UNIT 20 TYPE 30 LOAD SEQUENCER AHUS, 1SH,2SH, WE-OFF
```

```
        PAR 7
        1 1 1 1 1 2 2
        INPUTS 6
        18,1 19,1 0,0 0,0 0,0 0,0
        0    1    0    0    0    0
**********************************************
* BLDG 001/501
**********************************************
UNIT 31 TYPE 19 BLDG 001/501
        PAR 11
        2 2 2.9E6 0 0 0 52000 8 .5 73 .009
        INPUTS 11
        1,11 4,1 32,4 32,6 32,5 0,0 9,1 0,0 13,1 17,1 1,14
        75   .01 55   8.E5  .0083 0   0    4    1.4E5 0   7.5
*NORTH WALL NEXT TO 101 CORRIDOR - ADIABATIC
        PAR 7
        1 2 9600 .2 .8 3 23
*EAST WALL
        PAR 7
        2 1 9000 .4 .6 2 27
        INPUTS 1
        2,11
        0
*SOUTH WALL
        PAR 3
        3 -2 9600
        INPUTS 1
        2,14
        0
*WEST WALL
        PAR 3
        4 -2 3000
        INPUTS 1
        2,17
        0
*ROOF
        PAR 7
        5 1 96000 .2 .6 1 17
        INPUTS 1
        2,4
        0
*INT WALL NEXT TO 002
        PAR 7
        6 3 6000 .2 .8 3 23
        INPUTS 3
        0,0 33,1 0,0
        73   73   0
*INTERIOR FLOOR - 12 IN HW CONCRETE
        PAR 7
        7 3 96000 .8 .2 3 22
```

```
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*INTERIOR FURNITURE MASS AT 20BTU/(SF-F)
      PAR 7
      8 2 349000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
***********************************************
* BLDG 002 FLOOR
***********************************************
UNIT 33 TYPE 19 BLDG 002 FLOOR
      PAR 11
      2 2 3.6E6 0 0 0 64800 10 .5 73 .009
      INPUTS 11
      1,11 4,1 34,4 34,6 34,5 0,0 8,2 0,0 13,2 17,2 1,14
      75   .01 55   8.E5 .008  0    0    4  1.5E5 0   7.5
*NORTH WALL NEXT TO 102-103 CORRIDOR - ADIABATIC
      PAR 7
      1 2 14400 .2 .8 3 23
*EAST EXTERIOR WALL
      PAR 7
      2 1 1500 .4 .6 2 27
      INPUTS 1
      2,11
      0
*SOUTH WALL
      PAR 3
      3 -2 10000
      INPUTS 1
      2,14
      0
*WEST WALL
      PAR 3
      4 -2 4800
      INPUTS 1
      2,17
      0
*ROOF
      PAR 7
      5 1 148800 .2 .6 1 17
      INPUTS 1
      2,4
      0
*EAST INTERIOR WALL NEXT TO 001
      PAR 7
      6 3 7800 .2 .8 3 23
      INPUTS 3
      0,0 31,1 0,0
```

```
      73  73   0
*SOUTH INTERIOR WALL NEXT TO 002MEZZ
      PAR 7
      7 3 4400 .2 .8 3 23
      INPUTS 3
      0,0 35,1 0,0
      73  73   0
*WEST INTERIOR WALL NEXT TO ASRS
      PAR 7
      8 3 4500 .2 .8 3 23
      INPUTS 3
      0,0 37,1 0,0
      73  73   0
* FLOOR - 12 IN HW CONCRETE
      PAR 7
      9 3 148800 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*INTERIOR FURNITURE MASS AT 12BTU/(SF-F)
      PAR 7
      10 2 324000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
********************************************
* BLDG 002 MEZZANINE
********************************************
UNIT 35 TYPE 19 BLDG 002 MEZZ.
      PAR 11
      2 2 6.7E5 0 0 0 12100 9 .5 73 .009
      INPUTS 11
      1,11 4,1 36,4 36,6 36,5 0,0 8,3 0,0 13,3 17,3 1,14
      75   .01 55   4.E5 .0083 0  0    4   2.E4 0    7.5
*SOUTH WALL
      PAR 7
      1 1 3945 .4 .6 2 27
      INPUTS 1
      2,14
      0
*ROOF (DUE TO RADIATION BOX, THE ROOF IS MODELED IN 002 FLOO
R,
*   THIS SURFACE IS FOR THE RADIATION BOX ONLY)
      PAR 7
      2 2 67000 .2 .8 3 23
*INTERIOR PARTITION FOR QUICK RADIATION RESPONSE
      PAR 7
      3 2 67000 .2 .8 3 23
*NORTH INTERIOR WALL NEXT TO 002 FLOOR
      PAR 7
```

```
      4 3 4400 .2 .8 3 23
      INPUTS 3
      0,0 33,1 0,0
      73  73   0
*EAST INTERIOR WALL - ADIABATIC
      PAR 7
      5 2 1523 .2 .8 3 23
*WEST INTERIOR WALL - ADIABATIC
      PAR 7
      6 2 1523 .2 .8 3 23
*SOUTH GLAZING
      PAR 8
      7 5 455 1 .4 1.0 1 3
      INPUTS 5
      2,14 2,17 0,0 0,0 0,0
      0    0   .4  1.19 1
*INTERIOR FLOOR - 4 IN HW CONCRETE WITH FALSE CEILING
      PAR 7
      8 2 67000 .8 .2 3 39
*INTERIOR FURNITURE MASS AT 3BTU/(SF-F)
      PAR 7
      9 2 37000 .2 .8 3 30
*VIEW FACTORS
      PAR 1
      0
********************************************
* BDLG ASRS/003
********************************************
UNIT 37 TYPE 19 BDLG ASRS/003
      PAR 11
      2 2 2.2E6 0 0 0 39600 7 .5 73 .009
      INPUTS 11
      1,11 4,1 38,4 38,6 38,5 0,0 0,0 0,0 0,0 0,0 1,14
      75  .01  55   6.E5 .0083 0  0   4   0   3.4E4 7.5
*SOUTH WALL
      PAR 7
      1 1 14700 .4 .6 2 27
      INPUTS 1
      2,14
      0
*WEST WALL
      PAR 3
      2 -1 4500
      INPUTS 1
      2,17
      0
*ROOF
      PAR 7
      3 1 73500 .2 .6 1 17
      INPUTS 1
```

```
      2,4
      0
*INTERIOR FURNITURE MASS AT 36BTU/(SF-F)
      PAR 7
      4 2 482000 .2 .8 3 30
*EAST INTERIOR WALL NEXT TO 002 FLOOR
      PAR 7
      5 3 4500 .2 .8 3 23
      INPUTS 3
      0,0 33,1 0,0
      73  73   0
*NORTH INTERIOR WALL - ADIABATIC
      PAR 7
      6 2 14700 .2 .8 3 23
*FLOOR - 12 IN HW CONCRETE
      PAR 7
      7 3 73500 .8 .2 3 22
      INPUTS 3
      0,0 0,0 0,0
      75  75  0
*VIEW FACTORS
      PAR 1
      0
**************************************
* BLDG 001 - AIR HANDLER
**************************************
UNIT 21 TYPE 44 CONVERGER
      PAR 1
      1
      INPUTS 1
      31,1
      73
UNIT 32 TYPE 5 AHU-BLDG 001
      PAR 21
      78 71 28000 5600 75 71 65 55 -.1 1 .0083
      18 .35071 .3085 -.54137 .87199
      69 67 5.0E5 0 50
      INPUTS 5
      21,1 31,2 1,11 4,1 20,2
      75   .009 78  .01  1
***********************************************
* BLDG 002 FLOOR - AIR HANDLER
***********************************************
UNIT 22 TYPE 44 CONVERGER
      PAR 1
      1
      INPUTS 1
      33,1
      73
UNIT 34 TYPE 5 AHU-BDLG 002 FL
```

```
      PAR 21
      78 71 176000 35200 75 71 65 55 -.1 1 .0083
      76 .35071 .3085 -.54137 .87199
      69 67 6.6E5 0 50
      INPUTS 5
      22,1 33,2 1,11 4,1 20,2
      75   .009 78   .01 1
****************************************
* BDLG 002 MEZZANINE - AIR HANDLER
****************************************
UNIT 23 TYPE 44 CONVERGER
      PAR 1
      1
      INPUTS 1
      35,1
      73
UNIT 36 TYPE 5 AHU-BDLG 002 MEZZ
      PAR 21
      78 71 70000 14000 75 71 65 55 -.1 1 .0083
      35 .35071 .3085 -.54137 .87199
      69 67 4.1E5 0 50
      INPUTS 5
      23,1 35,2 1,11 4,1 20,1
      75   .009 78   .01 0
********************************************
* BDLG ASRS - AIR HANDLER
********************************************
UNIT 24 TYPE 44 CONVERGER
      PAR 1
      1
      INPUTS 1
      37,1
      73
UNIT 38 TYPE 5 AHU - BDLG ASRS
      PAR 21
      78 71 15000 3000 75 71 65 55 -.1 1 .0083
      10 .35071 .3085 -.54137 .87199
      69 67 3.3E6 0 50
      INPUTS 5
      24,1 37,2 1,11 4,1 0,0
      75   .009 78   .01 1
******************************************
* OUTPUTS
******************************************
UNIT 40 TYPE 15 ALG. OP. FOR OUTPUTS
      PAR 34
      0 0 3 0 3 0 3 -4  0 0 3 0 3 -1 23900 3 -1 3413 2 -3
      0 0 3 0 3 -1 10200 3 -1 3413 2 -3 3 -4
      INPUTS 10
      32,1 34,1 36,1 38,1 13,1 13,2 13,3 17,1 17,2 17,3
```

```
      0    0     0    0    0    0     0    0   0     0
*OUT: 1=CCLTOT, 2=LITES, 3=MISC.ELEC., 4=LITES+ELEC.
UNIT 41 TYPE 15 ALG.OP. FOR OUTPUTS
      PAR 19
      0 0 3 0 3 0 3 -3 0 3 -4
      0 0 3 0 3 0 3 -4
      INPUTS 9
      32,7 34,7 36,7 38,7 40,4 32,11 34,11 36,11 38,11
      0    0    0    0    0    0     0     0     0
*OUTS: 1=AHUELEC, 2=LITES+ELEC.+AHUELEC, 3=QHEATING
UNIT 42 TYPE 28 SIMSUM 001
      PAR 27
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4  0 -4 0 -4 0 -4 0 -
4
      INPUTS 9
      31,1 31,2 32,1 31,6 13,1 17,1 32,9 32,8 32,11
      LABELS 9
      TRA001 RAW001 CCL001 ZS001 LITE01 ELEC01 OAL01 OAS01 Q
H01
UNIT 43 TYPE 28 SIMSUM 002 FLOOR
      PAR 27
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4 0 -4 0 -4 0 -4 0 -4
      INPUTS 9
      33,1 33,2 34,1 33,6 13,2 17,2 34,9 34,8 34,11
      LABELS 9
      TRA02F RAW02F CCL02F ZS02F LIT02F EL02F OAL02F OAS02F
QH02F
UNIT 44 TYPE 28 SIMSUM 002 MEZ
      PAR 27
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 0 -4 0 -4 0 -4 0 -4 0 -4
      INPUTS 9
      35,1 35,2 36,1 35,6 13,3 17,3 36,9 36,8 36,11
      LABELS 9
      TRA02M RAW02M CCL02M ZS02M LIT02M EL02M OAL02M OAS02M
QH02M
UNIT 45 TYPE 28 SIMSUM ASRS
      PAR 30
      -1 1 8760 -1 2
      0 -2 2 -4 0 -2 2 -4 0 -4 0 -4 -1 3.4E4 -4
      0 -4 0 -4 0 -4 0 -2 2 -4
      INPUTS 8
      37,1 37,2 38,1 37,6 38,9 38,8 38,11 1,11
      LABELS 9
      TRA03 RAW03 CCL03 ZS03 LI+EL OAL03 OAS03 QH03 TOA
UNIT 46 TYPE 25 FILE PRINTER
      PAR 4
      .5 1 8760 10
```

```
      INPUTS 6
      40,1 41,3 40,2 40,3 41,1 41,2
      CCLTOT QHEAT LITES ELEC AHUFAN TOTEL
UNIT 47 TYPE 25 PRINTER
      PAR 4
      .5 6552 6600 -1
      INPUTS 9
      1,11 31,1 32,1 33,1 34,1 35,1 36,1 37,1 38,1
      TOA TRA01 CCL01 TRA02F CCL02F TRA02M CCL02M TRA03 CCL0
3
END
```

# APPENDIX C

## CORRELATION EQUATIONS

Chiller

Cooling Tower

Pumps

Site Chilled Water Circuit

Optimized Strategies

Pumps - continued

2. Quadratic fit of condenser pump electric demand as a function of water flow rate per pump:

$$KW = 74.5 - 0.0463(GPM) + 1.38x10^{-5}(GPM)^2.$$

Site Chilled Water Circuit

Linear fit of chilled water temperature rise (DT) as a function of chilled water supply temperature:

$$DT = 34.0 - 0.538(TCHWS).$$

Optimized Strategies

1. Optimum PLR at which to activate another chiller as a function of wet-bulb temperature:

   1 Chiller

   $$PLROPT = 0.234 + 0.0123(TWB)$$

   2 Chillers

   $$PLROPT = 0.635 - 0.00173(TWB) + 8.86x10^{-5}(TWB)^2$$

   3 Chillers

   $$PLROPT = 0.683 - 0.00429(TWB) + 1.04x10^{-4}(TWB)^2.$$

2. Linear-quadratic fit of the optimum condensor pump flow rate as a function of wet-bulb temperature and chiller part-load ratio:

$$GPM = 3687 - 21.13(TWB) - 5246(PLR) + 69.27(TWB)(PLR) - 32.36(TWB)(PLR)^2 + 2645(PLR)^2.$$

CORRELATION EQUATIONS (BY LEAST-SQUARES)

Chiller

1. Biquadratic fit of kilowatt-ratio (KWR) as a function of part-load ratio (PLR) and condensor water return temperature (TCWR):

$$KWR = 0.4681 - 0.01202(TCWR) + 1.020\times10^{-4}(TCWR)^2 + 0.1631(PLR) + 0.5974(PLR)^2 + 0.003533(TCWR)(PLR) - 2.434\times10^{-5}(TCWR)^2(PLR) - 0.001892(TCWR)(PLR)^2 + 6.354\times10^{-5}(TCWR)^2(PLR)^2.$$

2. Quadratic fit of percent change in chiller power demand relative to 44 F setpoint as a function of other setpoints from 40 to 50 F:

$$\% = 288.7 - 10.55(TCHWS) + 0.09076(TCHWS)^2.$$

Cooling Tower

Linear fit of effectiveness, E, as a function of tower capacity factor, R:

$$E = 1.068 - 0.5614(R).$$

Pumps

1. Quadratic fit of secondary pump electric demand as a function of water flow rate per pump:

$$KW = -10.7 + 0.0195(GPM) + 5.22\times10^{-6}(GPM)^2.$$

# APPENDIX D

# OPTIMUM COOLING TOWER CONTROL DATA

| Subsystem Electric Demand (kW) | Optimum Condenser Flow (GPM) | Optimum Cell Fan Speeds Hi | Lo | Wet-bulb (F) | Total Chiller Load (Tons) |
|---|---|---|---|---|---|
| 346.6 | 2000.0 | 0 | 1 | 45.0 | 500.0 |
| 377.3 | 2000.0 | 0 | 1 | 45.0 | 562.0 |
| 410.2 | 2000.0 | 0 | 1 | 45.0 | 625.0 |
| 444.3 | 2100.0 | 0 | 1 | 45.0 | 687.0 |
| 480.6 | 2100.0 | 0 | 1 | 45.0 | 750.0 |
| 518.0 | 2100.0 | 0 | 1 | 45.0 | 812.0 |
| 557.6 | 2100.0 | 0 | 1 | 45.0 | 875.0 |
| 598.0 | 2200.0 | 0 | 1 | 45.0 | 936.7 |
| 642.2 | 2200.0 | 0 | 1 | 45.0 | 1000.0 |
| 688.2 | 2200.0 | 1 | 0 | 45.0 | 1061.7 |
| 735.9 | 2200.0 | 1 | 0 | 45.0 | 1125.0 |
| 784.0 | 2300.0 | 1 | 0 | 45.0 | 1186.7 |
| 834.2 | 2300.0 | 1 | 0 | 45.0 | 1250.0 |
| 884.9 | 2300.0 | 1 | 0 | 45.0 | 1311.7 |
| 937.6 | 2400.0 | 1 | 0 | 45.0 | 1375.0 |
| 990.8 | 2400.0 | 1 | 0 | 45.0 | 1436.7 |
| 1046.0 | 2400.0 | 1 | 0 | 45.0 | 1500.0 |
| 691.8 | 2000.0 | 0 | 2 | 45.0 | 1000.0 |
| 753.9 | 2000.0 | 0 | 2 | 45.0 | 1125.0 |
| 819.6 | 2000.0 | 0 | 2 | 45.0 | 1250.0 |
| 888.5 | 2100.0 | 0 | 2 | 45.0 | 1375.0 |
| 960.7 | 2100.0 | 0 | 2 | 45.0 | 1500.0 |
| 1036.0 | 2100.0 | 0 | 2 | 45.0 | 1625.0 |
| 1115.0 | 2100.0 | 0 | 2 | 45.0 | 1750.0 |
| 1197.0 | 2100.0 | 0 | 2 | 45.0 | 1875.0 |
| 1284.0 | 2200.0 | 0 | 2 | 45.0 | 2000.0 |
| 1377.0 | 2100.0 | 1 | 1 | 45.0 | 2125.0 |
| 1471.0 | 2200.0 | 1 | 1 | 45.0 | 2250.0 |
| 1568.0 | 2300.0 | 1 | 1 | 45.0 | 2375.0 |
| 1667.0 | 2300.0 | 1 | 1 | 45.0 | 2500.0 |
| 1770.0 | 2300.0 | 2 | 0 | 45.0 | 2625.0 |
| 1874.0 | 2400.0 | 2 | 0 | 45.0 | 2750.0 |
| 1982.0 | 2400.0 | 2 | 0 | 45.0 | 2875.0 |
| 2092.0 | 2400.0 | 2 | 0 | 45.0 | 3000.0 |
| 347.1 | 2000.0 | 0 | 1 | 50.0 | 500.0 |
| 377.7 | 2000.0 | 0 | 1 | 50.0 | 562.0 |
| 410.6 | 2000.0 | 0 | 1 | 50.0 | 625.0 |
| 444.7 | 2000.0 | 0 | 1 | 50.0 | 687.0 |
| 481.6 | 2100.0 | 0 | 1 | 50.0 | 750.0 |
| 520.9 | 2100.0 | 0 | 1 | 50.0 | 812.0 |
| 563.3 | 2100.0 | 0 | 1 | 50.0 | 875.0 |
| 606.5 | 2100.0 | 0 | 1 | 50.0 | 936.7 |
| 652.0 | 2200.0 | 0 | 1 | 50.0 | 1000.0 |
| 697.7 | 2000.0 | 1 | 0 | 50.0 | 1061.7 |

| | | | | | |
|---|---|---|---|---|---|
| 745.0 | 2000.0 | 1 | 0 | 50.0 | 1125.0 |
| 792.8 | 2000.0 | 1 | 0 | 50.0 | 1186.7 |
| 842.7 | 2000.0 | 1 | 0 | 50.0 | 1250.0 |
| 893.1 | 2000.0 | 1 | 0 | 50.0 | 1311.7 |
| 945.5 | 2100.0 | 1 | 0 | 50.0 | 1375.0 |
| 998.3 | 2100.0 | 1 | 0 | 50.0 | 1436.7 |
| 1053.0 | 2000.0 | 1 | 0 | 50.0 | 1500.0 |
| 693.3 | 2000.0 | 0 | 2 | 50.0 | 1000.0 |
| 755.3 | 2000.0 | 0 | 2 | 50.0 | 1125.0 |
| 820.9 | 2000.0 | 0 | 2 | 50.0 | 1250.0 |
| 889.8 | 2100.0 | 0 | 2 | 50.0 | 1375.0 |
| 963.2 | 2000.0 | 0 | 2 | 50.0 | 1500.0 |
| 1043.0 | 2000.0 | 0 | 2 | 50.0 | 1625.0 |
| 1127.0 | 2000.0 | 0 | 2 | 50.0 | 1750.0 |
| 1213.0 | 2000.0 | 1 | 1 | 50.0 | 1875.0 |
| 1302.0 | 2000.0 | 1 | 1 | 50.0 | 2000.0 |
| 1393.0 | 2000.0 | 1 | 1 | 50.0 | 2125.0 |
| 1487.0 | 2000.0 | 1 | 1 | 50.0 | 2250.0 |
| 1584.0 | 2000.0 | 2 | 0 | 50.0 | 2375.0 |
| 1684.0 | 2000.0 | 2 | 0 | 50.0 | 2500.0 |
| 1786.0 | 2000.0 | 2 | 0 | 50.0 | 2625.0 |
| 1890.0 | 2000.0 | 2 | 0 | 50.0 | 2750.0 |
| 1997.0 | 2000.0 | 2 | 0 | 50.0 | 2875.0 |
| 2106.0 | 2000.0 | 2 | 0 | 50.0 | 3000.0 |
| 347.9 | 2000.0 | 0 | 1 | 55.0 | 500.0 |
| 380.0 | 2000.0 | 0 | 1 | 55.0 | 562.0 |
| 415.5 | 2000.0 | 0 | 1 | 55.0 | 625.0 |
| 452.2 | 2100.0 | 0 | 1 | 55.0 | 687.0 |
| 491.5 | 2100.0 | 0 | 1 | 55.0 | 750.0 |
| 531.8 | 2100.0 | 0 | 1 | 55.0 | 812.0 |
| 574.4 | 2200.0 | 0 | 1 | 55.0 | 875.0 |
| 617.5 | 2000.0 | 1 | 0 | 55.0 | 936.7 |
| 661.5 | 2000.0 | 1 | 0 | 55.0 | 1000.0 |
| 706.4 | 2000.0 | 1 | 0 | 55.0 | 1061.7 |
| 753.3 | 2000.0 | 1 | 0 | 55.0 | 1125.0 |
| 801.0 | 2000.0 | 1 | 0 | 55.0 | 1186.7 |
| 850.9 | 2000.0 | 1 | 0 | 55.0 | 1250.0 |
| 901.3 | 2000.0 | 1 | 0 | 55.0 | 1311.7 |
| 953.8 | 2000.0 | 1 | 0 | 55.0 | 1375.0 |
| 1007.0 | 2000.0 | 1 | 0 | 55.0 | 1436.7 |
| 1062.0 | 2000.0 | 1 | 0 | 55.0 | 1500.0 |
| 695.3 | 2000.0 | 0 | 2 | 55.0 | 1000.0 |
| 760.6 | 2000.0 | 0 | 2 | 55.0 | 1125.0 |
| 831.0 | 2000.0 | 0 | 2 | 55.0 | 1250.0 |
| 905.0 | 2100.0 | 0 | 2 | 55.0 | 1375.0 |
| 983.0 | 2100.0 | 0 | 2 | 55.0 | 1500.0 |
| 1064.0 | 2100.0 | 0 | 2 | 55.0 | 1625.0 |
| 1147.0 | 2000.0 | 1 | 1 | 55.0 | 1750.0 |
| 1233.0 | 2000.0 | 1 | 1 | 55.0 | 1875.0 |
| 1322.0 | 2000.0 | 1 | 1 | 55.0 | 2000.0 |

| | | | | | |
|---|---|---|---|---|---|
| 1413.0 | 2000.0 | 2 | 0 | 55.0 | 2125.0 |
| 1507.0 | 2000.0 | 2 | 0 | 55.0 | 2250.0 |
| 1603.0 | 2000.0 | 2 | 0 | 55.0 | 2375.0 |
| 1702.0 | 2000.0 | 2 | 0 | 55.0 | 2500.0 |
| 1803.0 | 2000.0 | 2 | 0 | 55.0 | 2625.0 |
| 1907.0 | 2000.0 | 2 | 0 | 55.0 | 2750.0 |
| 2014.0 | 2000.0 | 2 | 0 | 55.0 | 2875.0 |
| 2124.0 | 2000.0 | 2 | 0 | 55.0 | 3000.0 |
| 357.8 | 2000.0 | 0 | 1 | 60.0 | 500.0 |
| 391.4 | 2000.0 | 0 | 1 | 60.0 | 562.0 |
| 427.4 | 2100.0 | 0 | 1 | 60.0 | 625.0 |
| 464.8 | 2100.0 | 0 | 1 | 60.0 | 687.0 |
| 504.3 | 2200.0 | 0 | 1 | 60.0 | 750.0 |
| 544.8 | 2200.0 | 0 | 1 | 60.0 | 812.0 |
| 586.2 | 2000.0 | 1 | 0 | 60.0 | 875.0 |
| 628.2 | 2000.0 | 1 | 0 | 60.0 | 936.7 |
| 672.3 | 2000.0 | 1 | 0 | 60.0 | 1000.0 |
| 717.2 | 2000.0 | 1 | 0 | 60.0 | 1061.7 |
| 764.3 | 2000.0 | 1 | 0 | 60.0 | 1125.0 |
| 812.0 | 2000.0 | 1 | 0 | 60.0 | 1186.7 |
| 861.8 | 2100.0 | 1 | 0 | 60.0 | 1250.0 |
| 912.2 | 2100.0 | 1 | 0 | 60.0 | 1311.7 |
| 964.7 | 2100.0 | 1 | 0 | 60.0 | 1375.0 |
| 1018.0 | 2000.0 | 1 | 0 | 60.0 | 1436.7 |
| 1073.0 | 2000.0 | 1 | 0 | 60.0 | 1500.0 |
| 715.9 | 2100.0 | 0 | 2 | 60.0 | 1000.0 |
| 783.4 | 2000.0 | 0 | 2 | 60.0 | 1125.0 |
| 854.9 | 2100.0 | 0 | 2 | 60.0 | 1250.0 |
| 930.1 | 2100.0 | 0 | 2 | 60.0 | 1375.0 |
| 1007.8 | 2000.0 | 1 | 1 | 60.0 | 1500.0 |
| 1088.0 | 2000.0 | 1 | 1 | 60.0 | 1625.0 |
| 1171.0 | 2000.0 | 1 | 1 | 60.0 | 1750.0 |
| 1257.0 | 2000.0 | 1 | 1 | 60.0 | 1875.0 |
| 1344.0 | 2000.0 | 2 | 0 | 60.0 | 2000.0 |
| 1435.0 | 2000.0 | 2 | 0 | 60.0 | 2125.0 |
| 1528.0 | 2000.0 | 2 | 0 | 60.0 | 2250.0 |
| 1625.0 | 2000.0 | 2 | 0 | 60.0 | 2375.0 |
| 1723.0 | 2100.0 | 2 | 0 | 60.0 | 2500.0 |
| 1825.0 | 2000.0 | 2 | 0 | 60.0 | 2625.0 |
| 1929.0 | 2100.0 | 2 | 0 | 60.0 | 2750.0 |
| 2036.0 | 2100.0 | 2 | 0 | 60.0 | 2875.0 |
| 2145.0 | 2100.0 | 2 | 0 | 60.0 | 3000.0 |
| 1074.0 | 2100.0 | 0 | 3 | 60.0 | 1500.0 |
| 1175.0 | 2000.0 | 0 | 3 | 60.0 | 1686.7 |
| 1282.0 | 2100.0 | 0 | 3 | 60.0 | 1875.0 |
| 1395.0 | 2000.0 | 1 | 2 | 60.0 | 2061.7 |
| 1511.0 | 2000.0 | 1 | 2 | 60.0 | 2250.0 |
| 1631.0 | 2100.0 | 1 | 2 | 60.0 | 2436.7 |
| 1755.0 | 2000.0 | 2 | 1 | 60.0 | 2625.0 |
| 1883.0 | 2000.0 | 2 | 1 | 60.0 | 2811.7 |

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|---|---|---|---|---|---|
| 2016.0 | 2000.0 | 3 | 0 | 60.0 | 3000.0 |
| 2152.0 | 2000.0 | 3 | 0 | 60.0 | 3186.7 |
| 2292.0 | 2000.0 | 3 | 0 | 60.0 | 3375.0 |
| 2436.0 | 2000.0 | 3 | 0 | 60.0 | 3561.7 |
| 2585.0 | 2100.0 | 3 | 0 | 60.0 | 3750.0 |
| 2737.0 | 2100.0 | 3 | 0 | 60.0 | 3936.7 |
| 2894.0 | 2100.0 | 3 | 0 | 60.0 | 4125.0 |
| 3054.0 | 2100.0 | 3 | 0 | 60.0 | 4311.7 |
| 3218.0 | 2100.0 | 3 | 0 | 60.0 | 4500.0 |
| 1432.0 | 2100.0 | 0 | 4 | 60.0 | 2000.0 |
| 1567.0 | 2000.0 | 0 | 4 | 60.0 | 2250.0 |
| 1710.0 | 2100.0 | 0 | 4 | 60.0 | 2500.0 |
| 1860.0 | 2100.0 | 0 | 4 | 60.0 | 2750.0 |
| 2015.0 | 2000.0 | 2 | 2 | 60.0 | 3000.0 |
| 2175.0 | 2000.0 | 2 | 2 | 60.0 | 3250.0 |
| 2341.0 | 2000.0 | 2 | 2 | 60.0 | 3500.0 |
| 2511.0 | 2000.0 | 3 | 1 | 60.0 | 3750.0 |
| 2688.0 | 2000.0 | 3 | 1 | 60.0 | 4000.0 |
| 2870.0 | 2000.0 | 4 | 0 | 60.0 | 4250.0 |
| 3057.0 | 2000.0 | 4 | 0 | 60.0 | 4500.0 |
| 3249.0 | 2000.0 | 4 | 0 | 60.0 | 4750.0 |
| 3447.0 | 2000.0 | 4 | 0 | 60.0 | 5000.0 |
| 3650.0 | 2100.0 | 4 | 0 | 60.0 | 5250.0 |
| 3858.0 | 2100.0 | 4 | 0 | 60.0 | 5500.0 |
| 4072.0 | 2100.0 | 4 | 0 | 60.0 | 5750.0 |
| 4290.0 | 2100.0 | 4 | 0 | 60.0 | 6000.0 |
| 371.3 | 2100.0 | 0 | 1 | 65.0 | 500.0 |
| 405.5 | 2100.0 | 0 | 1 | 65.0 | 562.0 |
| 442.0 | 2200.0 | 0 | 1 | 65.0 | 625.0 |
| 479.7 | 2200.0 | 0 | 1 | 65.0 | 687.0 |
| 518.9 | 2000.0 | 1 | 0 | 65.0 | 750.0 |
| 557.9 | 2000.0 | 1 | 0 | 65.0 | 812.0 |
| 599.1 | 2000.0 | 1 | 0 | 65.0 | 875.0 |
| 641.1 | 2000.0 | 1 | 0 | 65.0 | 936.7 |
| 685.3 | 2100.0 | 1 | 0 | 65.0 | 1000.0 |
| 730.2 | 2100.0 | 1 | 0 | 65.0 | 1061.7 |
| 777.2 | 2100.0 | 1 | 0 | 65.0 | 1125.0 |
| 824.9 | 2100.0 | 1 | 0 | 65.0 | 1186.7 |
| 874.8 | 2100.0 | 1 | 0 | 65.0 | 1250.0 |
| 925.0 | 2200.0 | 1 | 0 | 65.0 | 1311.7 |
| 977.4 | 2200.0 | 1 | 0 | 65.0 | 1375.0 |
| 1030.0 | 2200.0 | 1 | 0 | 65.0 | 1436.7 |
| 1085.0 | 2200.0 | 1 | 0 | 65.0 | 1500.0 |
| 742.7 | 2100.0 | 0 | 2 | 65.0 | 1000.0 |
| 811.6 | 2100.0 | 0 | 2 | 65.0 | 1125.0 |
| 884.0 | 2200.0 | 0 | 2 | 65.0 | 1250.0 |
| 958.3 | 2000.0 | 1 | 1 | 65.0 | 1375.0 |
| 1035.0 | 2100.0 | 1 | 1 | 65.0 | 1500.0 |
| 1115.0 | 2100.0 | 1 | 1 | 65.0 | 1625.0 |
| 1198.0 | 2000.0 | 2 | 0 | 65.0 | 1750.0 |

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|---|---|---|---|---|---|
| 1283.0 | 2000.0 | 2 | 0 | 65.0 | 1875.0 |
| 1370.0 | 2100.0 | 2 | 0 | 65.0 | 2000.0 |
| 1461.0 | 2000.0 | 2 | 0 | 65.0 | 2125.0 |
| 1554.0 | 2100.0 | 2 | 0 | 65.0 | 2250.0 |
| 1650.0 | 2100.0 | 2 | 0 | 65.0 | 2375.0 |
| 1749.0 | 2100.0 | 2 | 0 | 65.0 | 2500.0 |
| 1851.0 | 2100.0 | 2 | 0 | 65.0 | 2625.0 |
| 1955.0 | 2100.0 | 2 | 0 | 65.0 | 2750.0 |
| 2061.0 | 2200.0 | 2 | 0 | 65.0 | 2875.0 |
| 2170.0 | 2200.0 | 2 | 0 | 65.0 | 3000.0 |
| 1114.0 | 2100.0 | 0 | 3 | 65.0 | 1500.0 |
| 1217.0 | 2100.0 | 0 | 3 | 65.0 | 1686.7 |
| 1326.0 | 2000.0 | 1 | 2 | 65.0 | 1875.0 |
| 1437.0 | 2100.0 | 1 | 2 | 65.0 | 2061.7 |
| 1553.0 | 2000.0 | 2 | 1 | 65.0 | 2250.0 |
| 1672.0 | 2000.0 | 2 | 1 | 65.0 | 2436.7 |
| 1796.0 | 2100.0 | 2 | 1 | 65.0 | 2625.0 |
| 1924.0 | 2000.0 | 3 | 0 | 65.0 | 2811.7 |
| 2056.0 | 2000.0 | 3 | 0 | 65.0 | 3000.0 |
| 2191.0 | 2100.0 | 3 | 0 | 65.0 | 3186.7 |
| 2331.0 | 2100.0 | 3 | 0 | 65.0 | 3375.0 |
| 2475.0 | 2100.0 | 3 | 0 | 65.0 | 3561.7 |
| 2624.0 | 2100.0 | 3 | 0 | 65.0 | 3750.0 |
| 2776.0 | 2100.0 | 3 | 0 | 65.0 | 3936.7 |
| 2932.0 | 2200.0 | 3 | 0 | 65.0 | 4125.0 |
| 3091.0 | 2200.0 | 3 | 0 | 65.0 | 4311.7 |
| 3255.0 | 2200.0 | 3 | 0 | 65.0 | 4500.0 |
| 1485.0 | 2100.0 | 0 | 4 | 65.0 | 2000.0 |
| 1623.0 | 2100.0 | 0 | 4 | 65.0 | 2250.0 |
| 1768.0 | 2100.0 | 1 | 3 | 65.0 | 2500.0 |
| 1916.0 | 2100.0 | 2 | 2 | 65.0 | 2750.0 |
| 2070.0 | 2100.0 | 2 | 2 | 65.0 | 3000.0 |
| 2230.0 | 2000.0 | 3 | 1 | 65.0 | 3250.0 |
| 2394.0 | 2100.0 | 3 | 1 | 65.0 | 3500.0 |
| 2565.0 | 2000.0 | 4 | 0 | 65.0 | 3750.0 |
| 2741.0 | 2000.0 | 4 | 0 | 65.0 | 4000.0 |
| 2922.0 | 2100.0 | 4 | 0 | 65.0 | 4250.0 |
| 3108.0 | 2100.0 | 4 | 0 | 65.0 | 4500.0 |
| 3301.0 | 2100.0 | 4 | 0 | 65.0 | 4750.0 |
| 3499.0 | 2100.0 | 4 | 0 | 65.0 | 5000.0 |
| 3701.0 | 2200.0 | 4 | 0 | 65.0 | 5250.0 |
| 3909.0 | 2200.0 | 4 | 0 | 65.0 | 5500.0 |
| 4122.0 | 2200.0 | 4 | 0 | 65.0 | 5750.0 |
| 4340.0 | 2200.0 | 4 | 0 | 65.0 | 6000.0 |
| 388.0 | 2200.0 | 0 | 1 | 70.0 | 500.0 |
| 422.6 | 2200.0 | 0 | 1 | 70.0 | 562.0 |
| 459.5 | 2200.0 | 0 | 1 | 70.0 | 625.0 |
| 496.0 | 2000.0 | 1 | 0 | 70.0 | 687.0 |
| 534.2 | 2000.0 | 1 | 0 | 70.0 | 750.0 |
| 573.2 | 2100.0 | 1 | 0 | 70.0 | 812.0 |

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|---|---|---|---|---|---|
| 614.4 | 2100.0 | 1 | 0 | 70.0 | 875.0 |
| 656.5 | 2100.0 | 1 | 0 | 70.0 | 936.7 |
| 700.7 | 2100.0 | 1 | 0 | 70.0 | 1000.0 |
| 745.5 | 2200.0 | 1 | 0 | 70.0 | 1061.7 |
| 792.5 | 2200.0 | 1 | 0 | 70.0 | 1125.0 |
| 840.1 | 2200.0 | 1 | 0 | 70.0 | 1186.7 |
| 889.8 | 2200.0 | 1 | 0 | 70.0 | 1250.0 |
| 940.0 | 2200.0 | 1 | 0 | 70.0 | 1311.7 |
| 992.2 | 2300.0 | 1 | 0 | 70.0 | 1375.0 |
| 1045.0 | 2200.0 | 1 | 0 | 70.0 | 1436.7 |
| 1100.0 | 2200.0 | 1 | 0 | 70.0 | 1500.0 |
| 776.0 | 2200.0 | 0 | 2 | 70.0 | 1000.0 |
| 845.6 | 2100.0 | 1 | 1 | 70.0 | 1125.0 |
| 916.4 | 2100.0 | 1 | 1 | 70.0 | 1250.0 |
| 990.6 | 2100.0 | 1 | 1 | 70.0 | 1375.0 |
| 1068.0 | 2000.0 | 2 | 0 | 70.0 | 1500.0 |
| 1147.0 | 2000.0 | 2 | 0 | 70.0 | 1625.0 |
| 1229.0 | 2000.0 | 2 | 0 | 70.0 | 1750.0 |
| 1313.0 | 2100.0 | 2 | 0 | 70.0 | 1875.0 |
| 1401.0 | 2100.0 | 2 | 0 | 70.0 | 2000.0 |
| 1491.0 | 2200.0 | 2 | 0 | 70.0 | 2125.0 |
| 1585.0 | 2100.0 | 2 | 0 | 70.0 | 2250.0 |
| 1681.0 | 2100.0 | 2 | 0 | 70.0 | 2375.0 |
| 1779.0 | 2200.0 | 2 | 0 | 70.0 | 2500.0 |
| 1881.0 | 2200.0 | 2 | 0 | 70.0 | 2625.0 |
| 1984.0 | 2200.0 | 2 | 0 | 70.0 | 2750.0 |
| 2090.0 | 2300.0 | 2 | 0 | 70.0 | 2875.0 |
| 2199.0 | 2300.0 | 2 | 0 | 70.0 | 3000.0 |
| 1164.0 | 2100.0 | 0 | 3 | 70.0 | 1500.0 |
| 1267.0 | 2100.0 | 1 | 2 | 70.0 | 1686.7 |
| 1375.0 | 2100.0 | 1 | 2 | 70.0 | 1875.0 |
| 1485.0 | 2100.0 | 2 | 1 | 70.0 | 2061.7 |
| 1601.0 | 2100.0 | 2 | 1 | 70.0 | 2250.0 |
| 1720.0 | 2000.0 | 3 | 0 | 70.0 | 2436.7 |
| 1843.0 | 2100.0 | 3 | 0 | 70.0 | 2625.0 |
| 1970.0 | 2100.0 | 3 | 0 | 70.0 | 2811.7 |
| 2102.0 | 2100.0 | 3 | 0 | 70.0 | 3000.0 |
| 2237.0 | 2100.0 | 3 | 0 | 70.0 | 3186.7 |
| 2377.0 | 2200.0 | 3 | 0 | 70.0 | 3375.0 |
| 2521.0 | 2200.0 | 3 | 0 | 70.0 | 3561.7 |
| 2669.0 | 2200.0 | 3 | 0 | 70.0 | 3750.0 |
| 2820.0 | 2200.0 | 3 | 0 | 70.0 | 3936.7 |
| 2976.0 | 2300.0 | 3 | 0 | 70.0 | 4125.0 |
| 3135.0 | 2300.0 | 3 | 0 | 70.0 | 4311.7 |
| 3298.0 | 2300.0 | 3 | 0 | 70.0 | 4500.0 |
| 1552.0 | 2100.0 | 0 | 4 | 70.0 | 2000.0 |
| 1691.0 | 2000.0 | 2 | 2 | 70.0 | 2250.0 |
| 1833.0 | 2100.0 | 2 | 2 | 70.0 | 2500.0 |
| 1981.0 | 2100.0 | 2 | 2 | 70.0 | 2750.0 |
| 2134.0 | 2100.0 | 3 | 1 | 70.0 | 3000.0 |

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|---|---|---|---|---|---|
| 2293.0 | 2100.0 | 3 | 1 | 70.0 | 3250.0 |
| 2457.0 | 2100.0 | 4 | 0 | 70.0 | 3500.0 |
| 2627.0 | 2100.0 | 4 | 0 | 70.0 | 3750.0 |
| 2802.0 | 2100.0 | 4 | 0 | 70.0 | 4000.0 |
| 2983.0 | 2100.0 | 4 | 0 | 70.0 | 4250.0 |
| 3169.0 | 2200.0 | 4 | 0 | 70.0 | 4500.0 |
| 3361.0 | 2200.0 | 4 | 0 | 70.0 | 4750.0 |
| 3559.0 | 2200.0 | 4 | 0 | 70.0 | 5000.0 |
| 3761.0 | 2200.0 | 4 | 0 | 70.0 | 5250.0 |
| 3968.0 | 2300.0 | 4 | 0 | 70.0 | 5500.0 |
| 4181.0 | 2200.0 | 4 | 0 | 70.0 | 5750.0 |
| 4398.0 | 2300.0 | 4 | 0 | 70.0 | 6000.0 |
| 407.9 | 2200.0 | 0 | 1 | 75.0 | 500.0 |
| 442.8 | 2300.0 | 0 | 1 | 75.0 | 562.0 |
| 478.0 | 2100.0 | 1 | 0 | 75.0 | 625.0 |
| 514.0 | 2100.0 | 1 | 0 | 75.0 | 687.0 |
| 552.2 | 2100.0 | 1 | 0 | 75.0 | 750.0 |
| 591.3 | 2100.0 | 1 | 0 | 75.0 | 812.0 |
| 632.5 | 2200.0 | 1 | 0 | 75.0 | 875.0 |
| 674.5 | 2200.0 | 1 | 0 | 75.0 | 936.7 |
| 718.6 | 2200.0 | 1 | 0 | 75.0 | 1000.0 |
| 763.4 | 2200.0 | 1 | 0 | 75.0 | 1061.7 |
| 810.2 | 2300.0 | 1 | 0 | 75.0 | 1125.0 |
| 857.6 | 2300.0 | 1 | 0 | 75.0 | 1186.7 |
| 907.1 | 2300.0 | 1 | 0 | 75.0 | 1250.0 |
| 957.1 | 2300.0 | 1 | 0 | 75.0 | 1311.7 |
| 1009.0 | 2300.0 | 1 | 0 | 75.0 | 1375.0 |
| 1062.0 | 2200.0 | 1 | 0 | 75.0 | 1436.7 |
| 1116.0 | 2300.0 | 1 | 0 | 75.0 | 1500.0 |
| 815.2 | 2100.0 | 1 | 1 | 75.0 | 1000.0 |
| 883.1 | 2100.0 | 1 | 1 | 75.0 | 1125.0 |
| 954.2 | 2200.0 | 1 | 1 | 75.0 | 1250.0 |
| 1028.0 | 2100.0 | 2 | 0 | 75.0 | 1375.0 |
| 1104.0 | 2100.0 | 2 | 0 | 75.0 | 1500.0 |
| 1183.0 | 2100.0 | 2 | 0 | 75.0 | 1625.0 |
| 1265.0 | 2100.0 | 2 | 0 | 75.0 | 1750.0 |
| 1349.0 | 2200.0 | 2 | 0 | 75.0 | 1875.0 |
| 1437.0 | 2200.0 | 2 | 0 | 75.0 | 2000.0 |
| 1527.0 | 2200.0 | 2 | 0 | 75.0 | 2125.0 |
| 1620.0 | 2200.0 | 2 | 0 | 75.0 | 2250.0 |
| 1716.0 | 2200.0 | 2 | 0 | 75.0 | 2375.0 |
| 1814.0 | 2300.0 | 2 | 0 | 75.0 | 2500.0 |
| 1915.0 | 2300.0 | 2 | 0 | 75.0 | 2625.0 |
| 2018.0 | 2300.0 | 2 | 0 | 75.0 | 2750.0 |
| 2124.0 | 2300.0 | 2 | 0 | 75.0 | 2875.0 |
| 2232.0 | 2300.0 | 2 | 0 | 75.0 | 3000.0 |
| 1223.0 | 2100.0 | 1 | 2 | 75.0 | 1500.0 |
| 1325.0 | 2100.0 | 1 | 2 | 75.0 | 1686.7 |
| 1431.0 | 2100.0 | 2 | 1 | 75.0 | 1875.0 |
| 1541.0 | 2200.0 | 2 | 1 | 75.0 | 2061.7 |

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| 1656.0 | 2100.0 | 3 | 0 | 75.0 | 2250.0 |
| 1774.0 | 2100.0 | 3 | 0 | 75.0 | 2436.7 |
| 1897.0 | 2200.0 | 3 | 0 | 75.0 | 2625.0 |
| 2024.0 | 2200.0 | 3 | 0 | 75.0 | 2811.7 |
| 2155.0 | 2200.0 | 3 | 0 | 75.0 | 3000.0 |
| 2291.0 | 2200.0 | 3 | 0 | 75.0 | 3186.7 |
| 2430.0 | 2300.0 | 3 | 0 | 75.0 | 3375.0 |
| 2573.0 | 2300.0 | 3 | 0 | 75.0 | 3561.7 |
| 2721.0 | 2300.0 | 3 | 0 | 75.0 | 3750.0 |
| 2872.0 | 2300.0 | 3 | 0 | 75.0 | 3936.7 |
| 3027.0 | 2300.0 | 3 | 0 | 75.0 | 4125.0 |
| 3186.0 | 2300.0 | 3 | 0 | 75.0 | 4311.7 |
| 3348.0 | 2400.0 | 3 | 0 | 75.0 | 4500.0 |
| 1630.0 | 2100.0 | 2 | 2 | 75.0 | 2000.0 |
| 1766.0 | 2100.0 | 2 | 2 | 75.0 | 2250.0 |
| 1909.0 | 2100.0 | 2 | 2 | 75.0 | 2500.0 |
| 2056.0 | 2100.0 | 3 | 1 | 75.0 | 2750.0 |
| 2208.0 | 2100.0 | 4 | 0 | 75.0 | 3000.0 |
| 2366.0 | 2100.0 | 4 | 0 | 75.0 | 3250.0 |
| 2529.0 | 2200.0 | 4 | 0 | 75.0 | 3500.0 |
| 2699.0 | 2200.0 | 4 | 0 | 75.0 | 3750.0 |
| 2874.0 | 2200.0 | 4 | 0 | 75.0 | 4000.0 |
| 3054.0 | 2200.0 | 4 | 0 | 75.0 | 4250.0 |
| 3240.0 | 2300.0 | 4 | 0 | 75.0 | 4500.0 |
| 3431.0 | 2300.0 | 4 | 0 | 75.0 | 4750.0 |
| 3628.0 | 2300.0 | 4 | 0 | 75.0 | 5000.0 |
| 3830.0 | 2300.0 | 4 | 0 | 75.0 | 5250.0 |
| 4036.0 | 2300.0 | 4 | 0 | 75.0 | 5500.0 |
| 4248.0 | 2300.0 | 4 | 0 | 75.0 | 5750.0 |
| 4464.0 | 2400.0 | 4 | 0 | 75.0 | 6000.0 |
| 431.2 | 2100.0 | 1 | 0 | 80.0 | 500.0 |
| 464.0 | 2100.0 | 1 | 0 | 80.0 | 562.0 |
| 499.1 | 2100.0 | 1 | 0 | 80.0 | 625.0 |
| 535.1 | 2200.0 | 1 | 0 | 80.0 | 687.0 |
| 573.3 | 2200.0 | 1 | 0 | 80.0 | 750.0 |
| 612.3 | 2200.0 | 1 | 0 | 80.0 | 812.0 |
| 653.5 | 2200.0 | 1 | 0 | 80.0 | 875.0 |
| 695.3 | 2300.0 | 1 | 0 | 80.0 | 936.7 |
| 739.2 | 2300.0 | 1 | 0 | 80.0 | 1000.0 |
| 783.8 | 2300.0 | 1 | 0 | 80.0 | 1061.7 |
| 830.6 | 2300.0 | 1 | 0 | 80.0 | 1125.0 |
| 877.7 | 2400.0 | 1 | 0 | 80.0 | 1186.7 |
| 927.0 | 2400.0 | 1 | 0 | 80.0 | 1250.0 |
| 976.8 | 2400.0 | 1 | 0 | 80.0 | 1311.7 |
| 1029.0 | 2300.0 | 1 | 0 | 80.0 | 1375.0 |
| 1081.0 | 2300.0 | 1 | 0 | 80.0 | 1436.7 |
| 1135.0 | 2400.0 | 1 | 0 | 80.0 | 1500.0 |
| 859.6 | 2200.0 | 1 | 1 | 80.0 | 1000.0 |
| 927.3 | 2200.0 | 1 | 1 | 80.0 | 1125.0 |
| 998.2 | 2100.0 | 2 | 0 | 80.0 | 1250.0 |

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| 1071.0 | 2100.0 | 2 | 0 | 80.0 | 1375.0 |
| 1146.0 | 2200.0 | 2 | 0 | 80.0 | 1500.0 |
| 1225.0 | 2200.0 | 2 | 0 | 80.0 | 1625.0 |
| 1307.0 | 2200.0 | 2 | 0 | 80.0 | 1750.0 |
| 1391.0 | 2200.0 | 2 | 0 | 80.0 | 1875.0 |
| 1478.0 | 2300.0 | 2 | 0 | 80.0 | 2000.0 |
| 1568.0 | 2300.0 | 2 | 0 | 80.0 | 2125.0 |
| 1661.0 | 2300.0 | 2 | 0 | 80.0 | 2250.0 |
| 1756.0 | 2300.0 | 2 | 0 | 80.0 | 2375.0 |
| 1854.0 | 2300.0 | 2 | 0 | 80.0 | 2500.0 |
| 1954.0 | 2400.0 | 2 | 0 | 80.0 | 2625.0 |
| 2057.0 | 2400.0 | 2 | 0 | 80.0 | 2750.0 |
| 2162.0 | 2400.0 | 2 | 0 | 80.0 | 2875.0 |
| 2270.0 | 2400.0 | 2 | 0 | 80.0 | 3000.0 |
| 1289.0 | 2100.0 | 2 | 1 | 80.0 | 1500.0 |
| 1390.0 | 2100.0 | 2 | 1 | 80.0 | 1686.7 |
| 1496.0 | 2200.0 | 2 | 1 | 80.0 | 1875.0 |
| 1606.0 | 2100.0 | 3 | 0 | 80.0 | 2061.7 |
| 1719.0 | 2200.0 | 3 | 0 | 80.0 | 2250.0 |
| 1837.0 | 2200.0 | 3 | 0 | 80.0 | 2436.7 |
| 1960.0 | 2200.0 | 3 | 0 | 80.0 | 2625.0 |
| 2086.0 | 2300.0 | 3 | 0 | 80.0 | 2811.7 |
| 2217.0 | 2300.0 | 3 | 0 | 80.0 | 3000.0 |
| 2352.0 | 2300.0 | 3 | 0 | 80.0 | 3186.7 |
| 2491.0 | 2300.0 | 3 | 0 | 80.0 | 3375.0 |
| 2634.0 | 2300.0 | 3 | 0 | 80.0 | 3561.7 |
| 2781.0 | 2300.0 | 3 | 0 | 80.0 | 3750.0 |
| 2931.0 | 2400.0 | 3 | 0 | 80.0 | 3936.7 |
| 3085.0 | 2400.0 | 3 | 0 | 80.0 | 4125.0 |
| 3243.0 | 2400.0 | 3 | 0 | 80.0 | 4311.7 |
| 3405.0 | 2400.0 | 3 | 0 | 80.0 | 4500.0 |
| 1719.0 | 2200.0 | 2 | 2 | 80.0 | 2000.0 |
| 1854.0 | 2200.0 | 3 | 1 | 80.0 | 2250.0 |
| 1995.0 | 2200.0 | 3 | 1 | 80.0 | 2500.0 |
| 2141.0 | 2200.0 | 4 | 0 | 80.0 | 2750.0 |
| 2292.0 | 2200.0 | 4 | 0 | 80.0 | 3000.0 |
| 2450.0 | 2200.0 | 4 | 0 | 80.0 | 3250.0 |
| 2613.0 | 2200.0 | 4 | 0 | 80.0 | 3500.0 |
| 2782.0 | 2300.0 | 4 | 0 | 80.0 | 3750.0 |
| 2956.0 | 2300.0 | 4 | 0 | 80.0 | 4000.0 |
| 3136.0 | 2300.0 | 4 | 0 | 80.0 | 4250.0 |
| 3322.0 | 2300.0 | 4 | 0 | 80.0 | 4500.0 |
| 3512.0 | 2300.0 | 4 | 0 | 80.0 | 4750.0 |
| 3707.0 | 2400.0 | 4 | 0 | 80.0 | 5000.0 |
| 3908.0 | 2400.0 | 4 | 0 | 80.0 | 5250.0 |
| 4114.0 | 2400.0 | 4 | 0 | 80.0 | 5500.0 |
| 4324.0 | 2400.0 | 4 | 0 | 80.0 | 5750.0 |
| 4540.0 | 2400.0 | 4 | 0 | 80.0 | 6000.0 |
| 455.6 | 2100.0 | 1 | 0 | 85.0 | 500.0 |
| 488.5 | 2200.0 | 1 | 0 | 85.0 | 562.0 |

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|---|---|---|---|---|---|
| 523.5 | 2200.0 | 1 | 0 | 85.0 | 625.0 |
| 559.5 | 2200.0 | 1 | 0 | 85.0 | 687.0 |
| 597.5 | 2300.0 | 1 | 0 | 85.0 | 750.0 |
| 636.4 | 2300.0 | 1 | 0 | 85.0 | 812.0 |
| 677.4 | 2300.0 | 1 | 0 | 85.0 | 875.0 |
| 719.1 | 2300.0 | 1 | 0 | 85.0 | 936.7 |
| 762.8 | 2400.0 | 1 | 0 | 85.0 | 1000.0 |
| 807.1 | 2400.0 | 1 | 0 | 85.0 | 1061.7 |
| 853.6 | 2400.0 | 1 | 0 | 85.0 | 1125.0 |
| 900.6 | 2400.0 | 1 | 0 | 85.0 | 1186.7 |
| 949.5 | 2500.0 | 1 | 0 | 85.0 | 1250.0 |
| 999.0 | 2500.0 | 1 | 0 | 85.0 | 1311.7 |
| 1050.0 | 2500.0 | 1 | 0 | 85.0 | 1375.0 |
| 1102.0 | 2500.0 | 1 | 0 | 85.0 | 1436.7 |
| 1156.0 | 2500.0 | 1 | 0 | 85.0 | 1500.0 |
| 910.2 | 2200.0 | 1 | 1 | 85.0 | 1000.0 |
| 977.5 | 2200.0 | 2 | 0 | 85.0 | 1125.0 |
| 1047.0 | 2100.0 | 2 | 0 | 85.0 | 1250.0 |
| 1120.0 | 2100.0 | 2 | 0 | 85.0 | 1375.0 |
| 1195.0 | 2200.0 | 2 | 0 | 85.0 | 1500.0 |
| 1273.0 | 2300.0 | 2 | 0 | 85.0 | 1625.0 |
| 1355.0 | 2200.0 | 2 | 0 | 85.0 | 1750.0 |
| 1439.0 | 2300.0 | 2 | 0 | 85.0 | 1875.0 |
| 1525.0 | 2400.0 | 2 | 0 | 85.0 | 2000.0 |
| 1615.0 | 2300.0 | 2 | 0 | 85.0 | 2125.0 |
| 1707.0 | 2400.0 | 2 | 0 | 85.0 | 2250.0 |
| 1802.0 | 2400.0 | 2 | 0 | 85.0 | 2375.0 |
| 1899.0 | 2400.0 | 2 | 0 | 85.0 | 2500.0 |
| 1999.0 | 2400.0 | 2 | 0 | 85.0 | 2625.0 |
| 2101.0 | 2400.0 | 2 | 0 | 85.0 | 2750.0 |
| 2205.0 | 2500.0 | 2 | 0 | 85.0 | 2875.0 |
| 2312.0 | 2500.0 | 2 | 0 | 85.0 | 3000.0 |
| 1365.0 | 2200.0 | 2 | 1 | 85.0 | 1500.0 |
| 1466.0 | 2100.0 | 3 | 0 | 85.0 | 1686.7 |
| 1570.0 | 2200.0 | 3 | 0 | 85.0 | 1875.0 |
| 1679.0 | 2200.0 | 3 | 0 | 85.0 | 2061.7 |
| 1792.0 | 2300.0 | 3 | 0 | 85.0 | 2250.0 |
| 1909.0 | 2300.0 | 3 | 0 | 85.0 | 2436.7 |
| 2032.0 | 2300.0 | 3 | 0 | 85.0 | 2625.0 |
| 2158.0 | 2300.0 | 3 | 0 | 85.0 | 2811.7 |
| 2288.0 | 2300.0 | 3 | 0 | 85.0 | 3000.0 |
| 2422.0 | 2400.0 | 3 | 0 | 85.0 | 3186.7 |
| 2560.0 | 2400.0 | 3 | 0 | 85.0 | 3375.0 |
| 2702.0 | 2400.0 | 3 | 0 | 85.0 | 3561.7 |
| 2848.0 | 2400.0 | 3 | 0 | 85.0 | 3750.0 |
| 2997.0 | 2500.0 | 3 | 0 | 85.0 | 3936.7 |
| 3151.0 | 2500.0 | 3 | 0 | 85.0 | 4125.0 |
| 3308.0 | 2500.0 | 3 | 0 | 85.0 | 4311.7 |
| 3469.0 | 2500.0 | 3 | 0 | 85.0 | 4500.0 |
| 1820.0 | 2100.0 | 3 | 1 | 85.0 | 2000.0 |

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|---|---|---|---|---|---|
| 1954.0 | 2200.0 | 3 | 1 | 85.0 | 2250.0 |
| 2093.0 | 2200.0 | 4 | 0 | 85.0 | 2500.0 |
| 2239.0 | 2200.0 | 4 | 0 | 85.0 | 2750.0 |
| 2390.0 | 2200.0 | 4 | 0 | 85.0 | 3000.0 |
| 2546.0 | 2300.0 | 4 | 0 | 85.0 | 3250.0 |
| 2709.0 | 2300.0 | 4 | 0 | 85.0 | 3500.0 |
| 2877.0 | 2300.0 | 4 | 0 | 85.0 | 3750.0 |
| 3050.0 | 2400.0 | 4 | 0 | 85.0 | 4000.0 |
| 3229.0 | 2400.0 | 4 | 0 | 85.0 | 4250.0 |
| 3414.0 | 2400.0 | 4 | 0 | 85.0 | 4500.0 |
| 3603.0 | 2400.0 | 4 | 0 | 85.0 | 4750.0 |
| 3797.0 | 2500.0 | 4 | 0 | 85.0 | 5000.0 |
| 3997.0 | 2500.0 | 4 | 0 | 85.0 | 5250.0 |
| 4201.0 | 2500.0 | 4 | 0 | 85.0 | 5500.0 |
| 4410.0 | 2500.0 | 4 | 0 | 85.0 | 5750.0 |
| 4625.0 | 2500.0 | 4 | 0 | 85.0 | 6000.0 |