SIMPLIFIED MODELS OF HVAC SYSTEM PERFORMANCE IN LARGE BUILDINGS

by

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This thesis examines a simplified energy analysis procedure. Steady state assumptions are used to develop expressions for cooling and heating energy consumption rates for terminal reheat, variable air volume, dual duct, three deck and dual fan/dual duct HVAC system types. Degree-day ideas are then developed and expanded into an equivalent degree-day method which is used to integrate consumption rates over a range of ambient temperatures and humidities to give total energy used. A correlation developed by D. Erbs' for ambient temperature and humidity distributions over a month is used to generate bin temperature and humidity data. The generated bin data are then used in equivalent degree-day calculations to evaluate HVAC cooling and heating energy consumption. Actual hourly data are used in the same calculations and the resulting heating and cooling energy consumptions compared with those found using bin data.

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NOMENCLATURE

Variable	Meaning
A	Area
A_o	Peak-to-peak amplitude of diurnal variation of monthly average hourly ambient temperature or relative humidity
a_n b_n	Coefficients in correlation for diurnal variation of monthly-average hourly ambient temperature or relative humidity in Eqs. (3.17) and (3.22) and Tables 3.1 and 3.2
c_p	Specific humidity of air
COP	Coefficient of performance of a chiller
C_f	Equivalent conductance factor
DD	Degree-days
e	Purchased energy rate
E	Total Equipment Energy
EDD	Equivalent degree-days
$F(T_A)$	Portion of a load expression varying with ambient temperature and summed in an EDD expression
h	Nondimensional temperature scale variable
h_{fg}	Heat of vaporization of water
h_o	Outside surface heat transfer coefficient
HL	Design zone heating load
I_T	Solar radiation incident on a surface
k	Fresh air fraction, ratio of outside air flow to total HVAC system air flow
K'	Cool air fraction, ratio of cool supply air flow to total HVAC system air flow

$\overline{K}_T$	Monthly-average clearness index
$\dot{m}$	Air mass flow rate
$\dot{m}_o$	Outside air mass flow rate
$\dot{m}_m$	Mimimum air mass flow rate in VAVR system
$\dot{m}_r$	Return air mass flow rate
$\dot{m}_t$	Induced air mass flow rate DFDD hot supply air mass flow rate
N_A	Number of hours at T_A or ω_A
N_m	Number of hours in a month
Q	Total coil energy
$Q(T_A)$	Cumulative distribution of hours lower than T_A
$\dot{q}$	Coil load
$\dot{q}_I$	Rate of internal gains
$\dot{q}_i$	Instantaneous rate of solar gain from hourly data
$\dot{q}_m$	Monthly-average rate of solar gain averaged from hourly data
$\dot{q}_{m,h}$	Monthly-average rate of solar gain for an individual hour of the day averaged from hourly data
$\dot{q}_s$	Rate of solar gains
$\dot{q}_L$	Rate of latent gains
$\dot{q}_G$	Total rate of sensible zone gains (internal plus solar)
t	Hour of the day, time
t^*	Nondimensional timescale variable
T	Temperature
T_A	Ambient temperature

T_{AC}	Ambient temperature below which zone cooling load is zero for a zone with dead band temperature control
T_{AH}	Ambient temperature above which zone heating load is zero for a zone with dead band temperature control
T_b	Base temperature
T_{bcs}	Sensible cooling base temperature
T_{bh}	Sensible heating base temperature
T_c	Cool supply duct set temperature
T_{chg}	Ambient temperature below which VAVR system supplies air at minimum air flow rate
T_{in}	Coil inlet temperature
T_m	Outside/return mixed air temperature
T_{out}	Coil outlet temperature
T_R	Zone set temperature Return air temperature
T_{RC}	Zone cooling set temperature for a zone with dead band temperature control
T_{RH}	Zone heating set temperature for a zone with dead band temperature control
T_{SA}	Sol-air temperature
$\overline{T}_m$	Monthly average temperature
$\overline{T}_{m,h}$	Monthly average temperature for an individual hour of the day
$\overline{T}_{m,p}$	Monthly average temperature for an individual time period of the day
U	Overall thermal conductance
U_f	Thermal conductance factor
V	Fuel heating value

α Surface absorptance

η Boiler efficiency
Furnace efficiency

σ_m Standard deviation of monthly-average temperature over a number of years for an individual month

σ_{yr} Standard deviation of 12 monthly-average temperatures from yearly-average temperature

ϕ Relative humidity

$\bar{\phi}_m$ Monthly-average relative humidity

$\bar{\phi}_{m,h}$ Monthly-average relative humidity for an individual hour of the day

$\bar{\phi}_{m,p}$ Monthly-average relative humidity for an individual time period of the day

ω Specific humidity

ω_A Ambient specific humidity

ω_b Base specific humidity

ω_{bcL} Latent cooling base specific humidity

ω_c Saturated specific humidity at T_c

ω_m Outside/return mixed air specific humidity

ω_L Zone generated specific humidity

ω_r Return air specific humidity

Other variables are defined locally.

Subscripts

c Cooling

cs Sensible cooling

cL Latent cooling

h	Heating
min	Minimum
ph	Preheating

HVAC System Abbreviations

DDM	Dual Duct
DDMD	Dual Duct with Dead band temperature control
DDME	Dual Duct with Economizer cycle control
TD	Three Deck
TRH	Terminal Reheat
TRHD	Terminal Reheat with Dead band temperature control
TRHE	Terminal Reheat with Economizer cycle control
VAV	Variable Air Volume
VAVD	Variable Air Volume with Dead band temperature control
VAVE	Variable Air Volume with Economizer cycle control

CHAPTER 1

INTRODUCTION

Humankind's ability to control the environment in which we work, live, and recreate has allowed us to be active in otherwise extreme climates, such as Minneapolis in January or Dallas in July. In the industrialized Western world, large buildings comprise the workplace for most people and, in urban areas, living and leisure areas as well. The impact of temperature, airflow, and fresh air supply in large buildings on human productivity levels and perception of surroundings is considerable and shows how crucial environmental control can be to how humans function. This is especially true in the workplace, where increasing emphasis is being placed on productivity and hence worker performance.

Environmental control in large commercial buildings is almost uniformly performed by heating, ventilation and air-conditioning (HVAC) equipment. HVAC systems consume large amounts of energy in order to provide necessary amounts of space heating or cooling. Recent rises in energy prices have spurred conservation measures aimed at reducing the energy used by these systems.

Thus, HVAC systems have great demands placed on them to deliver all important heating or cooling in the most energy efficient manner. To satisfy these demands, system designers and operators need to be able to calculate how much energy a given system is likely to use under certain conditions. Decisions may then be made as to what, if any, changes can be made to an existing or proposed system to enhance its energy performance without sacrificing comfort conditions.

This thesis examines a simplified energy analysis procedure. Steady state assumptions are used to develop expressions for cooling and heating energy consumption rates for terminal reheat, variable air volume, dual duct, three deck and dual fan/dual duct HVAC system types. Degree-day ideas are then developed and expanded into an equivalent degree-day method which is used to integrate consumption rates over a range of ambient temperatures and humidities to give total energy used. A correlation developed by D. Erbs' [10] for ambient temperature and humidity distributions over a month is used to generate bin temperature and humidity data. The generated bin data are then used in equivalent degree-day calculations to evaluate HVAC cooling and heating energy consumption. Actual hourly data are used in the same calculations and the resulting heating and cooling energy consumptions compared with those found using bin data.

CHAPTER 2

ASPECTS OF HVAC SYSTEMS IN LARGE BUILDINGS

In modeling HVAC systems in large buildings, three subsystems are generally partitioned and analyzed separately. As shown in Figure 2.1 these are: the building zone where energy is transferred to or from people, lights, etc.; the air (or secondary) system where heat is removed or added and air is circulated; and the plant (or primary) system where chilled water and steam or hot water are produced by heating and refrigeration equipment. A series of energy and mass balance relationships are written for each subsystem and between the three. Thus, the thermal requirements in the zone may be translated by a set of equations into the input energy required by the plant.

2.1 Zone Loads

A zone is a portion of a building assumed to have similar thermal characteristics throughout, such as temperature setting and usage. Energy transfers within a zone include envelope transmission losses or gains, solar gains, heat generation due to people, appliances, and lighting, latent inputs from people and appliances, and air infiltration generally all referred to as loads. The sum of these loads makes up the overall zone load or rate at which heat is to be removed (cooling) or supplied (heating) by the coil system.

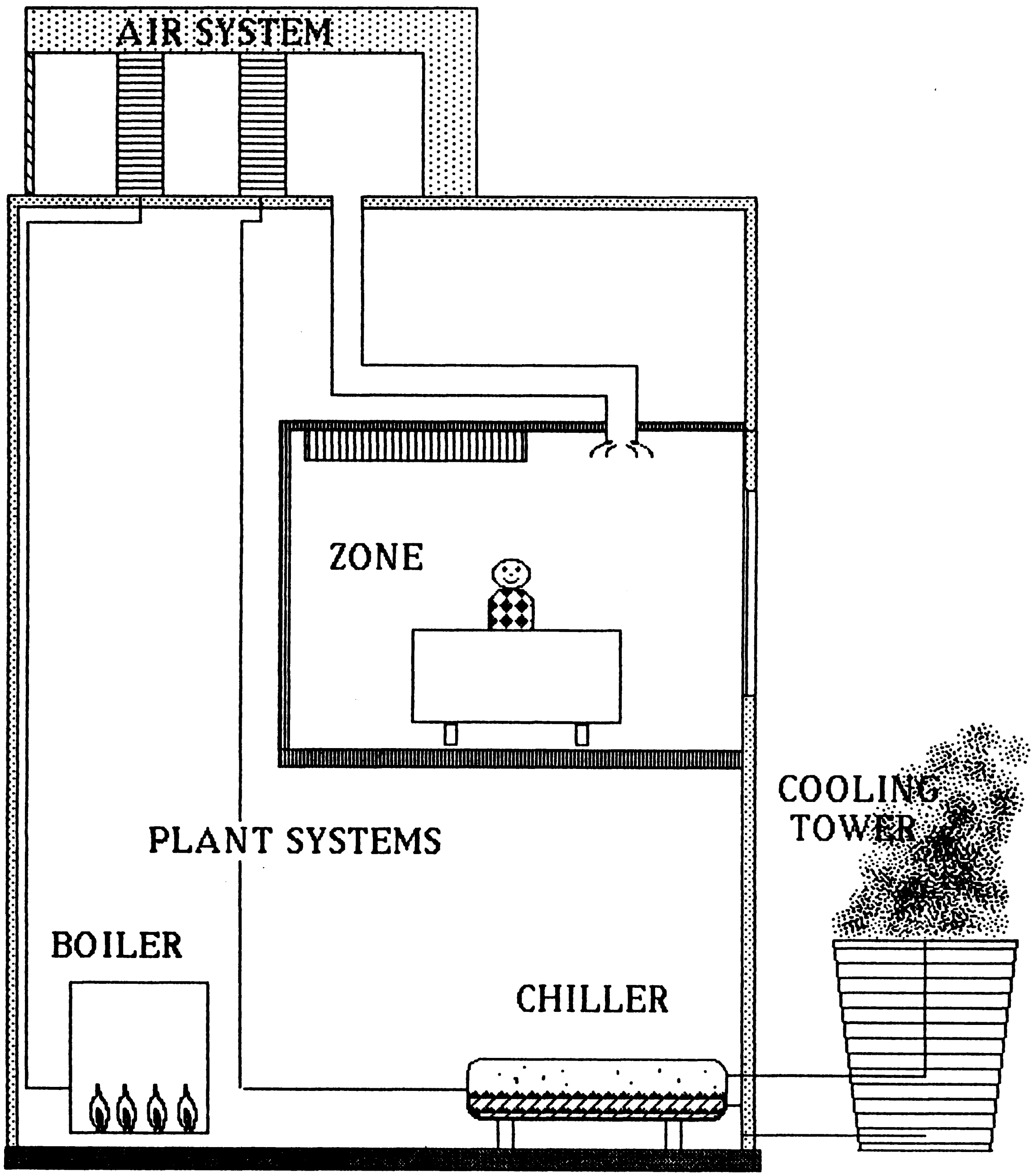


Fig. 2.1. Typical Large Building Zone Served By HVAC Coil and Plant System.

Envelope transmission arises from a combination of conductive, radiative and convective heat transfer between a zone at temperature T_R and the ambient at temperature T_A and impinging solar radiation, I_T. The composite heat transfer can be expressed as a linear temperature difference between room temperature and what is called sol-air temperature, T_{SA}:

$$T_{SA} = T_A + \frac{I_T \alpha}{h_o} \quad (2.1)$$

where α is the absorptance of the wall's outside surface and h_o is the convection heat transfer coefficient at the same surface. This envelope load can be written as a simple temperature difference of the form:

$$\dot{q} = UA(T_R - T_{SA}) \quad (2.2)$$

where U is the overall thermal conductance (a weighted average of all possible paths) and A, the overall area of the zone exposed to ambient temperatures.

Solar gains through windows will vary during the year and throughout the day. The exact amount through a particular type of window at a particular time on a particular day has been a topic of much study. Methods for calculating it are found in references such as [1] and will not be discussed in further detail here. Once the energy passes through the glass, it hits various interior surfaces, heating them and so causing a heat input to the zone.

People, the appliances they use, and the lighting they require all generate heat which results in positive input of energy to a zone called an internal gain. In totally internal zones where transmission and solar gains are not present, internal gains are the only inputs and cooling is required year round. Typical values for heat generated from people, lights, and machinery are available in reference [2]. Internal gains can be classified as sensible and latent (moisture). People and some appliances are chiefly responsible for the latter.

Infiltration of outside air through cracks and entries into the zone is another source of both sensible and latent load. However, in large buildings, an HVAC system usually provides enough positive pressure when operating to counteract infiltration. Thus, infiltration loads will be neglected.

Ventilation air, the amount of fresh air required for zone occupants, is considered as a zone load for design calculations. If it is centrally processed ventilation air in large HVAC systems passes into the zone indirectly, through the coil system. Thus, it is not considered a zone load here for energy analysis purposes but will be reintroduced in discussions later in Chapter 4.

2.2 Secondary System Components and Typical HVAC Systems

The amount of cooling or heating required for the coil system to meet a zone load depends heavily upon how the coils, fans and other components are arranged and operated. Energy balances on heating coils involve a simple enthalpy derived temperature difference equation

$$q_h = \dot{m}c_p(T_{out} - T_{in}) \tag{2.3}$$

where $\dot{m}$ is the mass flow of air through the coil, c_p is the specific heat of that air (assuming some constant level of moisture content), T_{out} is the air temperature leaving the coil, T_{in}, air temperature entering the coil ($T_{in} < T_{out}$), and $\dot{q}_h$ is the heating energy rate to be supplied to the coil. Sensible cooling required by a cooling coil, $\dot{q}_c$, has the same form as $\dot{q}_h$

$$\dot{q}_{cs} = \dot{m}c_p(T_{in} - T_{out}) \tag{2.4}$$

Latent loads ($\dot{q}_{cL}$), however, where moisture condenses because the air is cooled past saturation look like

$$q_L = \dot{m}h_{fg}(\omega_{in} - \omega_{out}) \tag{2.5}$$

where ω_{out} is the saturated specific humidity at the outcoming temperature, ω_{in} is the specific humidity into the coil, and h_{fg} is the heat of vaporization of water.

Fans add energy to the air flowing through them depending on fan and flow characteristics. This energy contribution is typically sufficient to raise the airstream temperature on the order of 2°F for most constant volume systems, a fairly small rise that will be neglected. More importantly, fans control air flow. They may be designed to operate at a constant volume or vary the volume supplied to the zone down to a minimum amount. The choice of fan operation will have a large impact on energy used.

Dampers have a similar importance. While they do not themselves have significant thermal effects on airstreams, they do regulate the mixing of different airstreams. Since mixing is a thermally important process, the relative amounts of each mixed stream are important. For two streams the energy and mass balance derived mixing equation is:

$$(\dot{m}_1 + \dot{m}_2)T_m = \dot{m}_1 T_1 + \dot{m}_2 T_2 \tag{2.6}$$

where c_p has been assumed constant and cancels out and T_m, generally the quantity of interest is the mixed temperature of streams 1 and 2.

Five system configurations (terminal reheat, variable air volume, dual duct, three-deck, and dual fan/dual duct) with several variations in operation (induction, economizer, and deadband set) are commonly used as designs for HVAC systems. A short description of each follows. Schematics are found in Figures 2.2-2.8.

Common to all systems is the mixing of outside and return airstreams. The outside air rate must be at least that required for ventilation, and may be more depending on controls. The rest of the air required by the system is supplied from the return air duct. The return air not used is exhausted to the environment.

Terminal Reheat. As shown in Figure 2.2, the mixed air at point m in this system passes through a central cooling coil which cools it to a set temperature (point c), usually on the order of 55°F, a minimum comfortable temperature to deliver air to zone occupants. The air is then drawn through a fan (not shown in the figure) and delivered at a constant rate to each of a number of zones. A heating coil, often called a reheat coil, at the entrance to each zone responds to a thermostat signal and adds heat to raise the entering cold stream temperature at point L as needed to meet the zone heating or cooling load. After flowing through the zone, the room temperature air is then returned to the central system in a return duct (point r) where it is mixed with all other zone return streams. The flow rate for each zone is fixed either by the design cooling load which is met by airflow at the cold duct temperature, design heating load at some maximum allowable entering air temperature, or airflow and ventilation requirements, whichever rate is highest.

Variable Air Volume. Figure 2.2 also represents a variable air volume system operated with reheat. Again, a central cooling coil

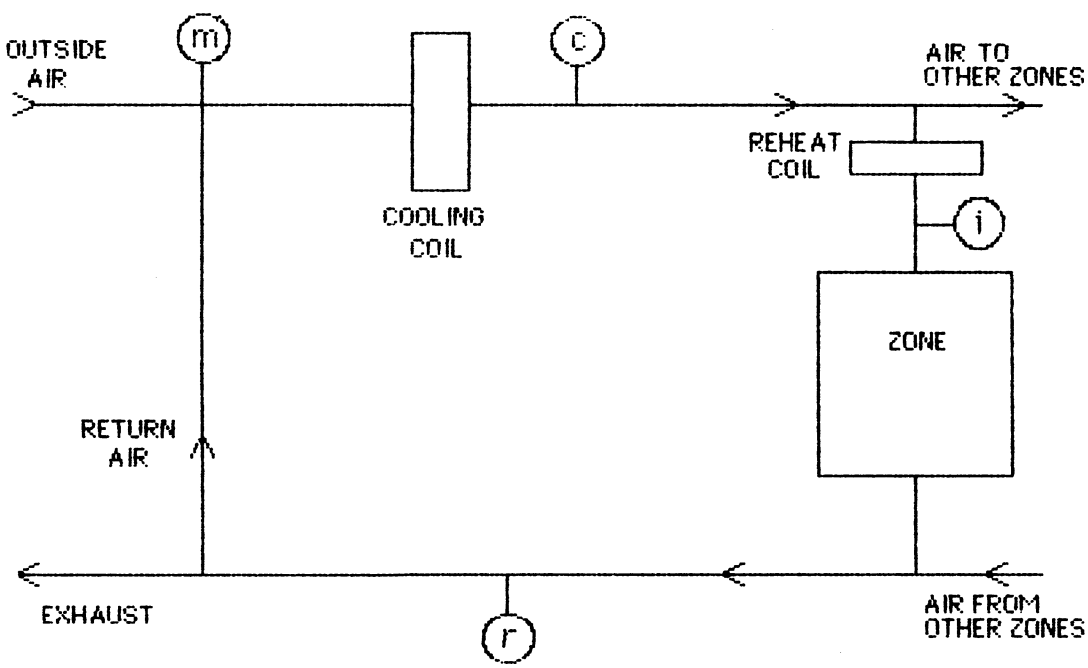


Fig. 2.2. Diagram of a Terminal Reheat and Variable Air Volume HVAC Systems.

cools the air to a set temperature (point c) and a fan delivers this to a number of zones. However, as zone cooling load decreases, the thermostat signals a decrease in the amount of airflow into the zone instead of raising the entering temperature as terminal reheat does. This is generally done by regulating zone dampers at point i which, as they close, raise duct pressure and cause the central variable speed fan to decrease the total mass flow rate. Once a minimum flow rate has been reached for a given zone or the zone has a heating load, the reheat coil operates as for the terminal reheat system with constant flow at the minimum level. This minimum flow rate is sized by either the heating or flow criteria mentioned above for terminal reheat.

Dual Duct. In this system, the outside/return air mixture passes through a fan and into one of two ducts, as shown in Figure 2.3. One duct contains a cooling coil (point c) as in the previous two systems. The other contains a heating coil which heats the air to a set temperature, generally around 95°F (point h). Air from these two ducts is then mixed for each zone separately (either near the central mechanical room or at each zone) to give a constant airflow rate at the temperature needed to meet that zone's load. The total flow rate remains constant but the rate through each coil varies as the overall need for heating and cooling fluctuates. Flow into each zone is sized as for terminal reheat, with the hot duct temperature taken as maximum allowable temperature.

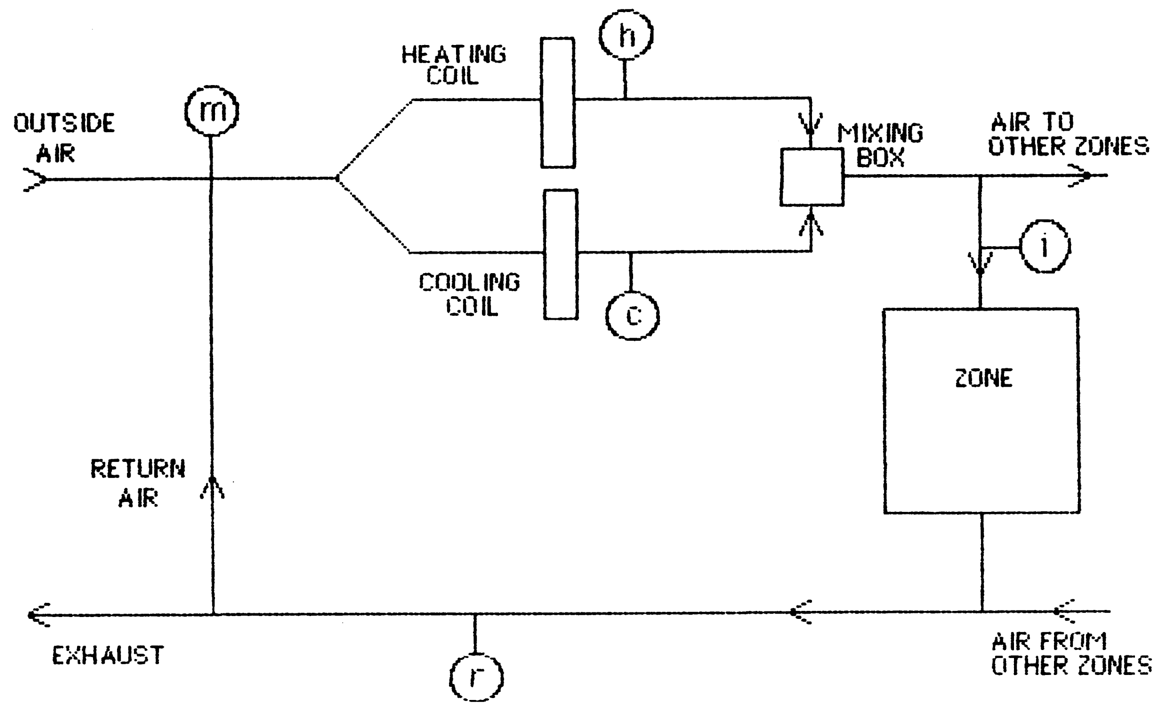


Fig. 2.3. Diagram of a Dual Duct HVAC System.

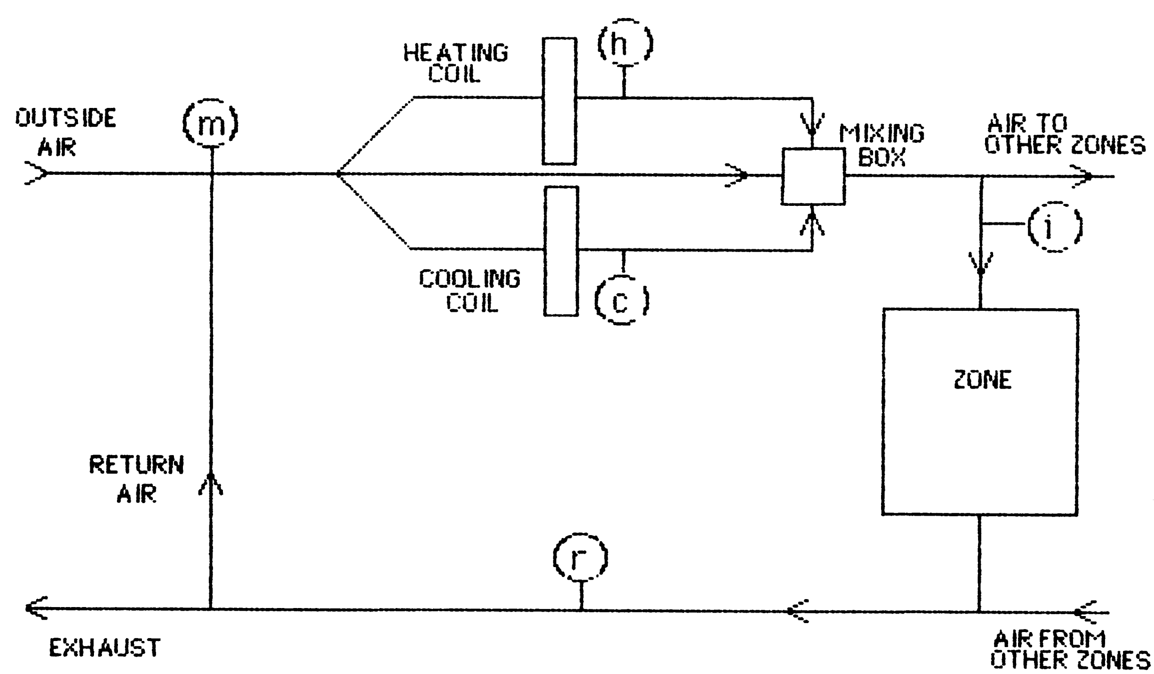


Fig. 2.4. Diagram of a Three Deck HVAC System.

Three Deck. This system, shown in Figure 2.4, is similar to the dual duct system in the mixing of air streams for each zone. However, a third, intermediate temperature stream is provided. The air in this stream (point m) passes directly from the fan to be mixed with either the cold or the hot stream (points c and h) to meet the zone cooling or heating load respectively. Thus, cold and hot streams are never mixed together.

Dual Fan/Dual Duct. Figure 2.5 shows this system. A central heating coil heats only return air and a central cooling coil cools a mixture of outside and remaining return air. Each stream has a separate variable speed fan to provide the required flow rate of each stream. Mixing of the two streams is as follows: Cooling is provided by varying the cool stream airflow (point c) as in the variable air volume system above. When the cool stream reaches minimum airflow an amount of the hot stream (point h) is added (at point i) to the cold to bring it up to the needed zone entering temperature. Minimum flow rates are determined by ventilation or heating criteria.

The following three items are variations which may be applied to any of the above system types.

Induction. Induction units such as the one in Figure 2.6 are air boxes added onto zone ducts which mix air from the zone (or return air) with supply air. Zone return is usually drawn (induced) by the pressure difference caused by the high velocity supply air. This is done for the purpose of moderating the supply temperature and/or increasing airflow rate into the zone for comfort reasons. A heating

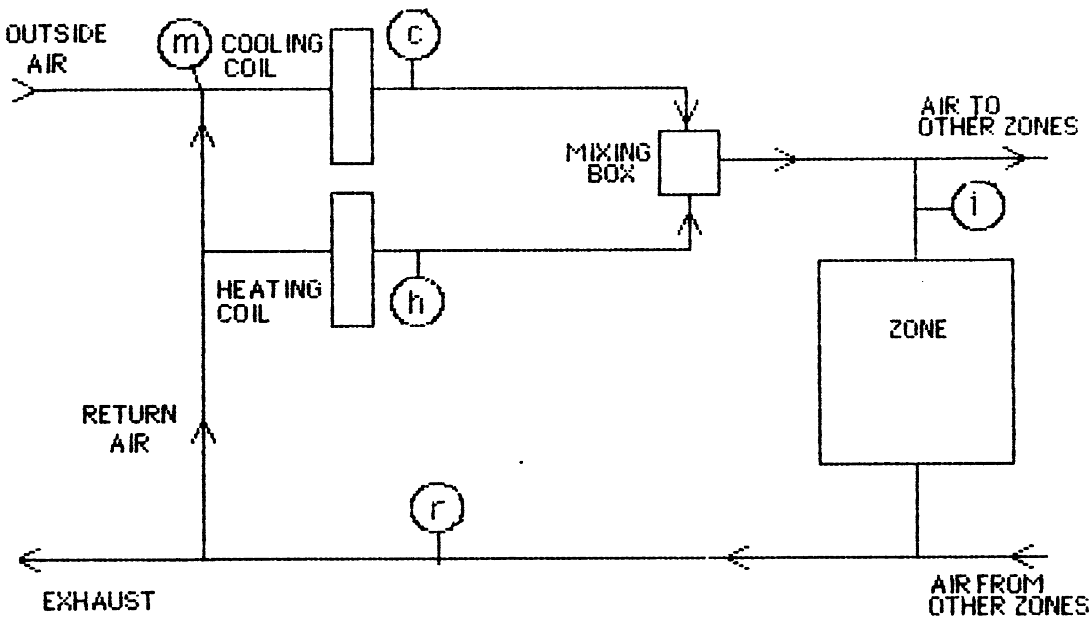


Fig. 2.5. Diagram of a Dual Fan/Dual Duct HVAC System.

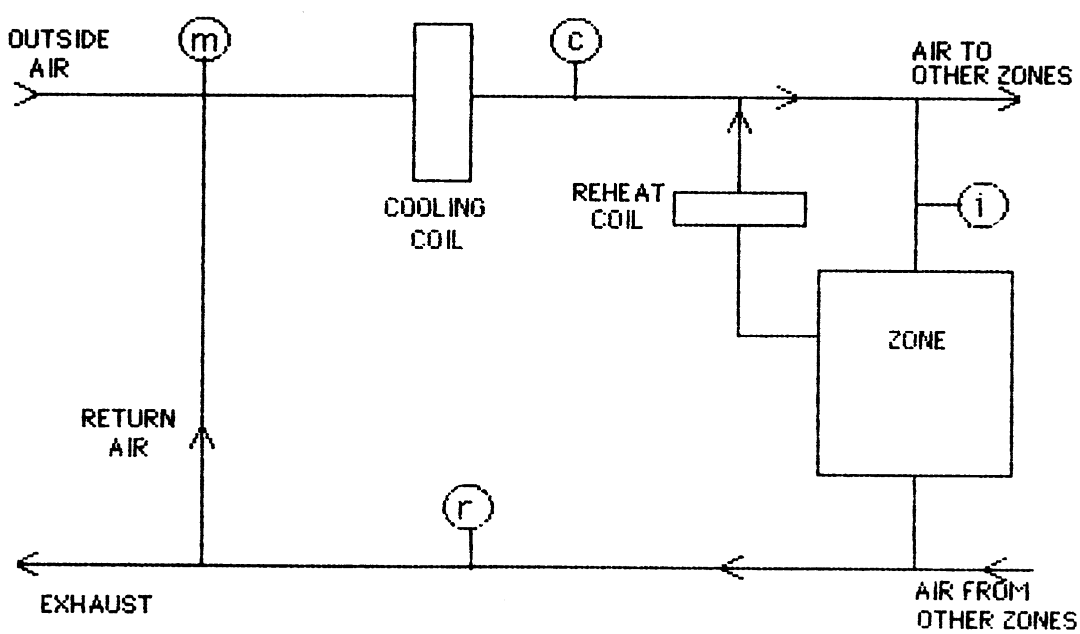


Fig. 2.6. Diagram of an HVAC System With an Attached Induction Unit.

coil is often included as shown in the figure. The unit then performs the same function as a reheat coil by adding heat to the incoming cold supply airstream to decrease its cooling effect. These units are most often attached to VAV systems to provide larger zone airflow rates although they can be attached to any system.

Economizer Cycle. This outside air control strategy is shown in Figure 2.7 as the variation of outside mass flow rate for any of the system types discussed above. In cold weather, the outside/return air mixture can often be combined in proportions which produce a mixed temperature equal to the cooling supply temperature, making cooling unnecessary or "free". In moderately cool weather, if the outside temperature is lower than the return temperature, taking the entire supply stream from outside air minimizes the mixed air temperature and thus, the cooling coil's load. At extremely high and low temperatures where the mixed air temperature falls below the cold supply temperature or above the return temperature, outside air use is minimized.

Dead Band Thermostat Setting. This control of room temperature is shown pictorially in Figure 2.8. The theory behind this control is to cool a zone to a certain room set temperature, heat to another, lower temperature and when the room is between the two temperatures, provide neither cooling nor heating.

2.3 Plant Equipment Operations

If a building owner simply buys chilled water and steam or hot water from some outside source, the total cooling and heating coil

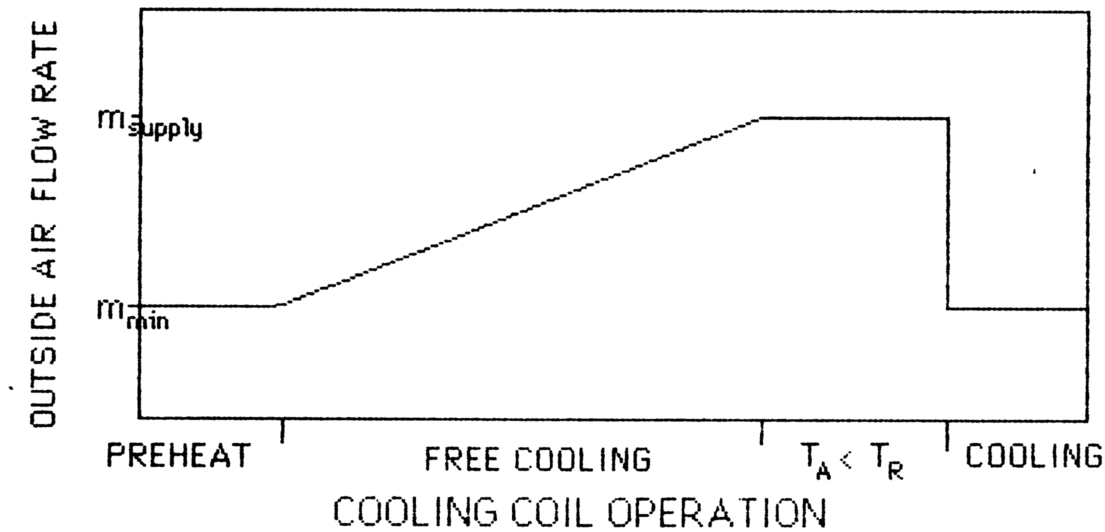


Fig. 2.7. Outside Air Flow Rate Variation With Cooling Coil Operation Over Ambient Temperature for Economizer Cycle Control.

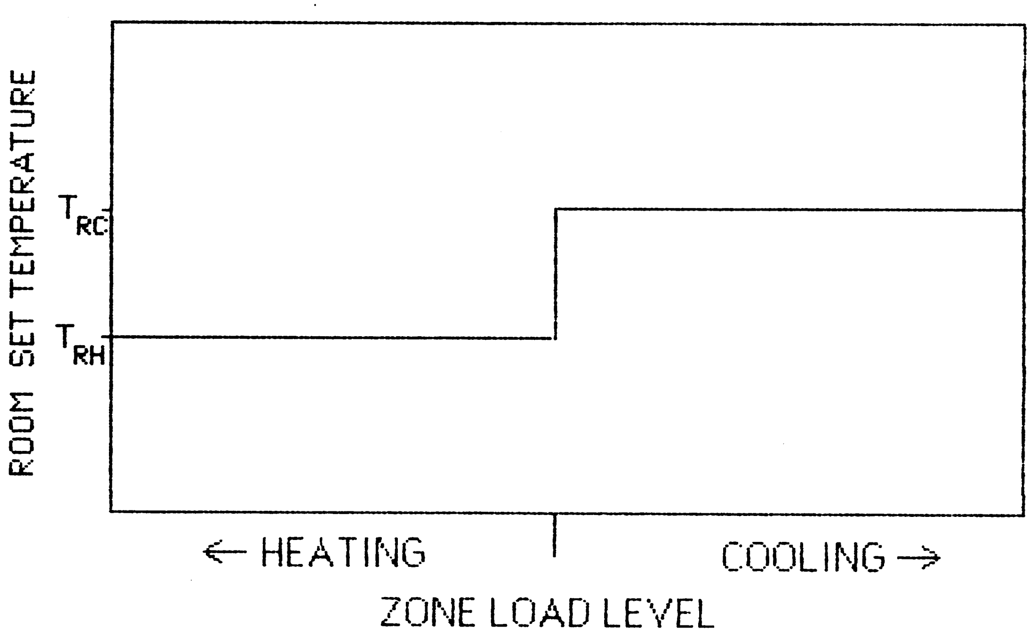


Fig. 2.8. Room Set Temperature Variation With Zone Load Level.

loads are the item of interest for any energy cost analyses. However, if the building owner pays for the energy used to make the chilled water and steam or hot water, the performance of plant equipment will have to be taken into account.

Several types of equipment are commonly used to provide the heating and cooling fluids needed by the system coils. The simplest and most common are chillers with either air cooled condensers or a cooling tower which chill water, and boilers which heat water or steam. These are generally found in a central location, serving all the HVAC systems in a building or often several buildings.

Boilers simply take in cool water and heat it to produce either hot water or steam at a certain temperature usually by combustion of some fossil fuel or electric resistance heating. The steam or hot water then flows through the HVAC system heating coils, gives up heat to the airstream and returns to the boiler as cooler water.

Compression chillers use a vapor compression cycle of some refrigerant to chill the incoming flow from the HVAC cooling coils and return a lower temperature stream back to the HVAC coils. This is accomplished in an evaporative heat exchange between the refrigerant and cooling coil stream. The liquid refrigerant evaporates removing heat from the cooling coil stream. The refrigerant vapor then condenses on another heat exchanger, giving up energy to some external stream and thus, completing the cycle. The external stream is often from a cooling tower which takes the warmer flow from the chiller, and cools it through a heat and mass transport process with the ambient air.

From zone, secondary, and plant system descriptions, it becomes obvious that energy use is affected by ambient temperature, building characteristics, occupancy requirements and equipment operating characteristics. How each fits into the final expression for energy use depends on how the systems are modeled.

CHAPTER 3

AN OVERVIEW OF SIMPLIFIED ENERGY CALCULATION METHODS

This chapter will examine the approaches that have already been taken to calculate total purchased energy use and total building loads. The distinction between the two is important. The latter tells only the energy rate demanded, the former, what was actually needed to meet the sum of all demands.

A distinction also exists between expressions which describe the rate of energy consumption or load and those that give the total consumption. Rate of energy use must be integrated over time of operation to give either a total building or equipment energy. Total heating or cooling loads are translated into purchased energy by boiler or chiller efficiencies only if those efficiencies are constant for all operating cases.

3.1 Residential Heat Pump Example

An example follows of the development of an energy calculation for a residence with a heat pump system whose COP varies with ambient temperature.

Figure 3.1 shows the schematic of a typical house connected to a heat pump which supplies heat at a rate of $\dot{q}_h$ to meet the house's heating load. Gains from solar and internal loads, $\dot{q}_S$ and $\dot{q}_I$ are shown. These gains are taken together as the sum of all zone gains:

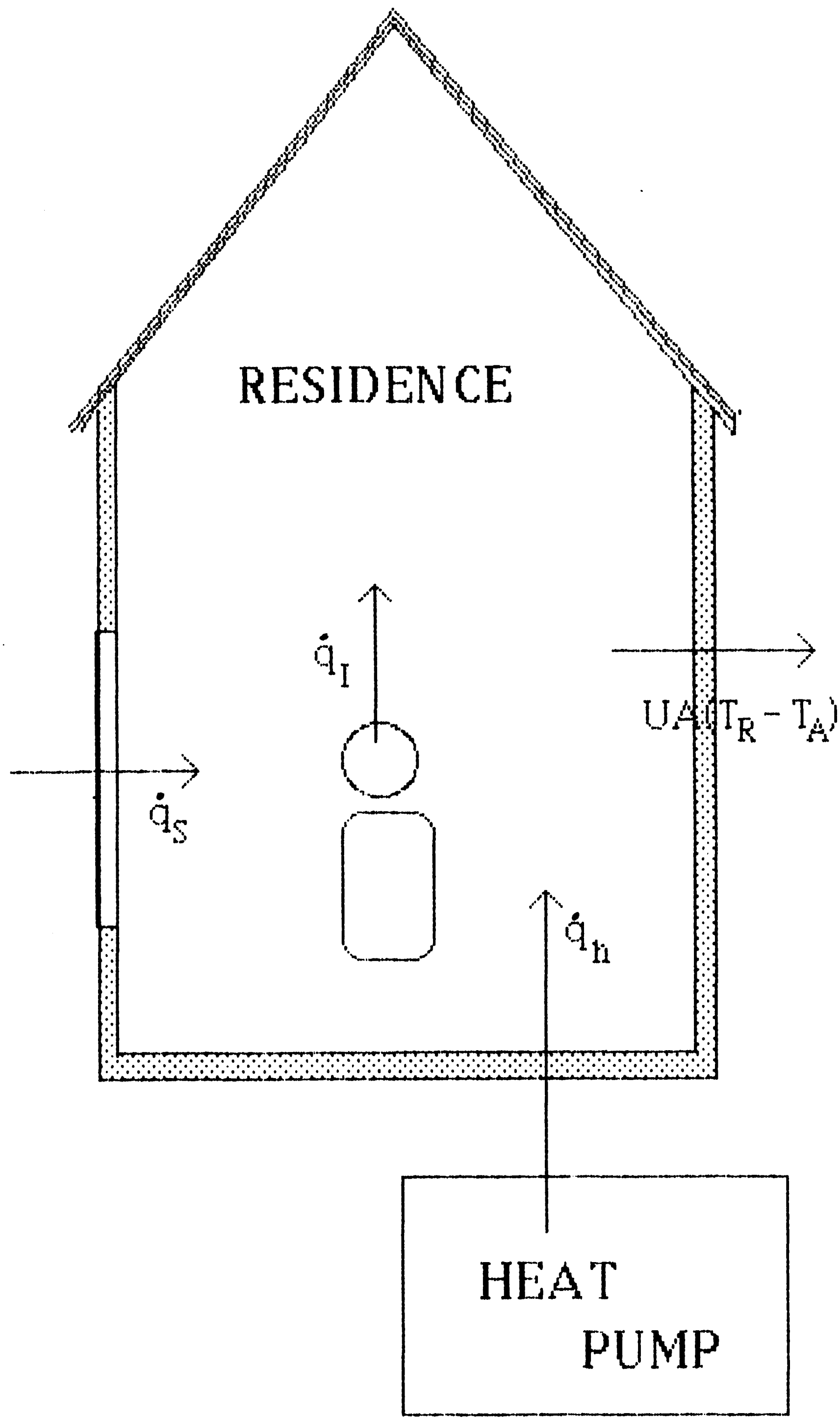


Fig. 3.1. Diagram of Heat Transfers in a Residence Where a Heat Pump Provides Heat.

$$\dot{q}_G = \dot{q}_I + \dot{q}_S \tag{3.1}$$

There also is exchange between inside and outside temperatures T_R and T_A through walls, windows, etc., all with an overall conductance of UA. The solar portion of the sol-air temperature difference (Eq. (2.1) is ignored here. An energy balance on the system gives:

$$q_h + q_G = UA(T_R - T_A) \tag{3.2}$$

solving for $\dot{q}_h$:

$$\dot{q}_h = UA\ [(T_R - \frac{q_G}{UA}) - T_A]^+ \tag{3.3}$$

A "+" sign on a quantity $[\Delta T]^+$, signifies that when ΔT is positive, $[\Delta T]^+ = \Delta T$ and when ΔT is negative $[\Delta T]^+$ has a value of zero.

When $\dot{q}_h$ in Eq. (3.3) is multiplied by the number of hours that ambient temperature was at T_A in a month, N_A, total heating energy used during those hours results. When this multiplication is done for all ambient temperatures occurring in the month, and the resulting energies are summed together, the total heating energy for the entire month, Q_h, is given:

$$Q_h = \sum_{T_A} \dot{q}_h N_A = UA \sum_{T_A} [(T_R - \frac{\dot{q}_G}{UA}) - T_A]^+ N_A \tag{3.4}$$

The result in Eq. (3.4) for the residence is a conductance factor, UA, multiplied by a summed quantity which is defined as a heating degree-day, DD_h. Defining a base temperature, T_b as all terms in the brackets other than T_A, the base temperature is:

$$T_b = T_R - \frac{\dot{q}_G}{UA} \tag{3.5}$$

and the expression for heating degree-day becomes:

$$DD_h = \sum_{T_A} \frac{[T_b - T_A]^+ N_A}{24} \tag{3.6}$$

with total heating energy, Q_h given as:

$$Q_h = UA\ DD_h \tag{3.7}$$

Assuming that the room set temperature is the same for cooling, $-\dot{q}_c$ replaces $\dot{q}_h$, in Eq. (3.2), the temperature difference in Eq. (3.2) is reversed, and the following expression results for cooling degree-day, DD_c:

$$DD_c = \sum_{T_A} \frac{[T_A - T_b]^+ N_A}{24} \tag{3.8}$$

The house in Figure 3.1 is supplied with heat at the rate of $\dot{q}_h$ by a heat pump. If the pump has a COP which varies with temperature, as in Figure 3.2, $\dot{q}_h$ at each T_A must be divided by the corresponding COP for that temperature to yield a heat pump purchased energy

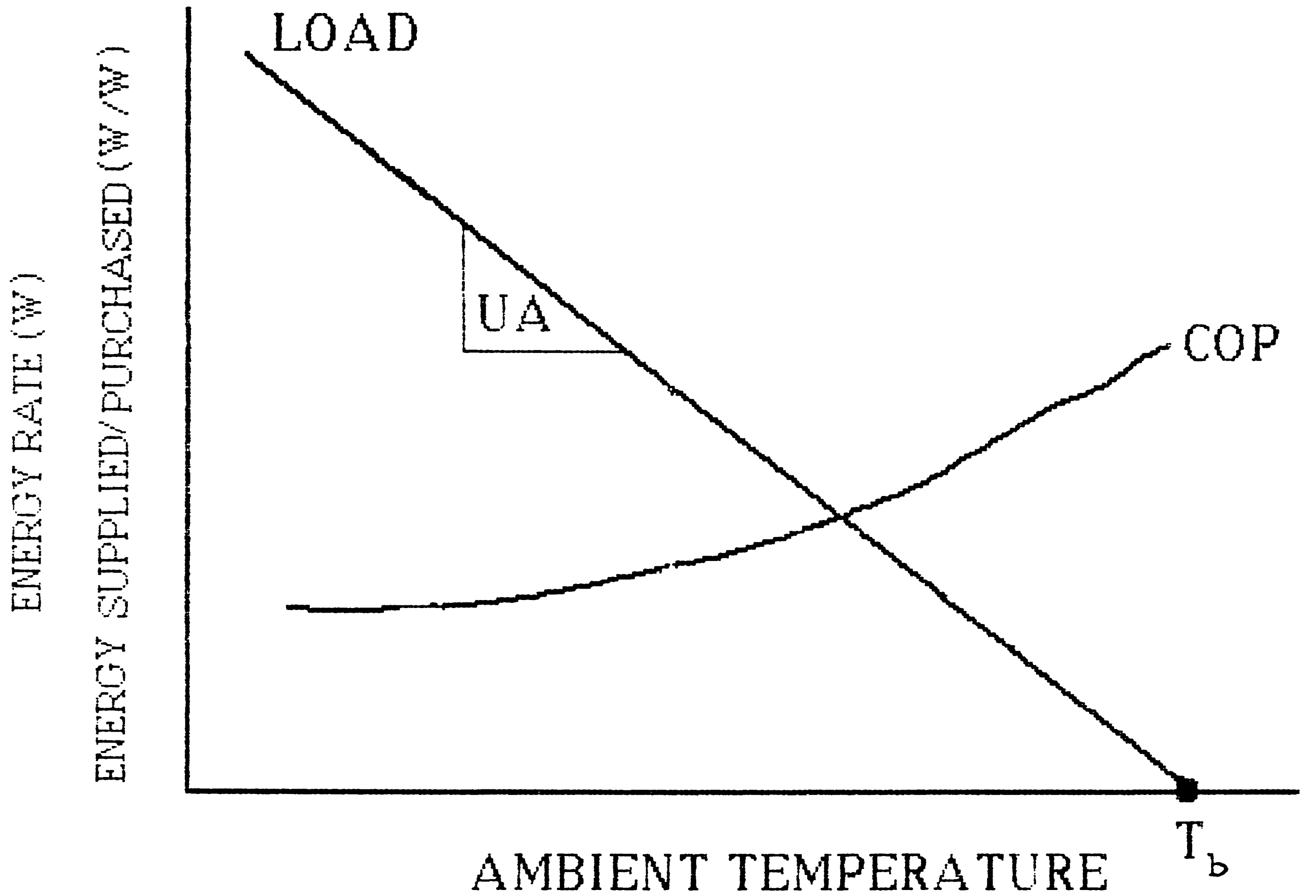


Fig. 3.2. Sample Heating Load and COP Variation With Ambient Temperature for the Residence and Heat Pump Shown in Fig. 3.1.

rate $\dot{e}_h$:

$$\dot{e}_h = \frac{UA[T_b - T_A]^+}{COP\ (T_A)} \tag{3.9}$$

which, when multiplied by the number of hours at T_A and integrated across temperatures, gives total purchased energy:

$$E_h = UA \sum_{T_A} \frac{(T_b - T_A)^+ N_A}{COP(T_A)} \tag{3.10}$$

DD_h cannot be used here to find total energy, because the COP varies with T_A, too.

3.2 Literature Review

ASHRAE TC4.7 Energy Calculations Committee has reviewed several simplified calculational procedures which employ expressions for both total building and total equipment loads. What follows is a summary of four methods applied to residential heating and cooling and compared to DOE-2 simulations by T. Ksuda et al. [4].

The first two methods use the following equation for purchased heating energy, E_h:

$$E_h = \frac{HL \cdot DD_{h,65} \cdot 24}{(T_{ODh} - T_{Rh})\ \eta V} \tag{3.11}$$

for a house with a design heating load of HL, standard heating degree-days based on 65°F $DD_{h,65}$, an outside design heating temperature of T_{ODh}, an indoor room design temperature of T_{Rh}, and furnace efficiency of η, and fuel heating value of V [4]. Comparing this to Eq. (3.10),

$$\frac{HL}{T_{ODh} - T_{Rh}} = UA$$

$$\eta V = COP(T_A)$$

The design load divided by the design temperature difference gives an effective UA conductance multiplier. The ηV quantity is constant with temperature, allowing it to be brought outside the summation sign in Eq. (3.10). The remaining expression in the summation is a degree-day equation, represented by DD_h in Eq. (3.6):

$$DD_{h,T_b} = \sum_{T_A} \frac{(T_b - T_A)^+ N_A}{24} \qquad (3.12)$$

The first method considered by Ksuda assumes a value of 10°F for the $\dot{q}_G/UA$ term and 75°F for the T_R term in Eq. (3.5). This gives T_b = 65°F. TRY hourly data were used by Ksuda to calculate degree-days as per Eqs. (3.6) and (3.8) where N_A = 1 hr for each value of T_A. Equation (3.11) with DD_h and DD_c calculated with a base temperature of 65°F tends to overestimate annual heating and cooling energy totals in modern residences [4]. Today 10°F for $\dot{q}_G/UA$ is not a good assumption because internal gains are larger and UA values smaller than in the past when 10°F was a good assumption.

The second method Ksuda used to calculate residential energy corrects for the 10°F assumption. When a base temperature which takes a particular structure's values for internal and solar gains and conductance factor, UA, into account, its value will vary from structure to structure and the degree-days are said to have a variable base. When DD's were calculated using the same hourly temperature data as above and variable base temperatures, comparison with DOE-2 for the residences was very good, within 10% for most cases [4].

Next, two methods which use bin temperature data were reviewed. A sample month of bin temperature data is shown pictorially in Figure 3.3. Each bar represents the hours that ambient temperature was between the upper and lower boundaries, N_A. The temperature assigned to that bin, T_A, is the temperature halfway between the boundary values. When Ksuda substituted 5°F bin values for N_A and T_A from the Air Force Manual 88-29 [8] in Eqs. (3.6) and (3.8) and calculated E_h, again using Eq. (3.11), the results were not as good relative to DOE-2 as the variable base degree-day calculation which used hourly data.

Another method considered by Ksuda and developed by the TC4.7 is called the Modified Bin Method (MBM). It is based heavily on Carrier's Rational Energy Analysis Procedure (REAP). This method calculates heating and cooling loads at four bin temperatures. All zone load heating components like solar gains and envelope loses are assumed linear with T_A. When zone load components are added together the resulting heating load is of the form $B_1 - B_2T_A$ where B_1 and B_2

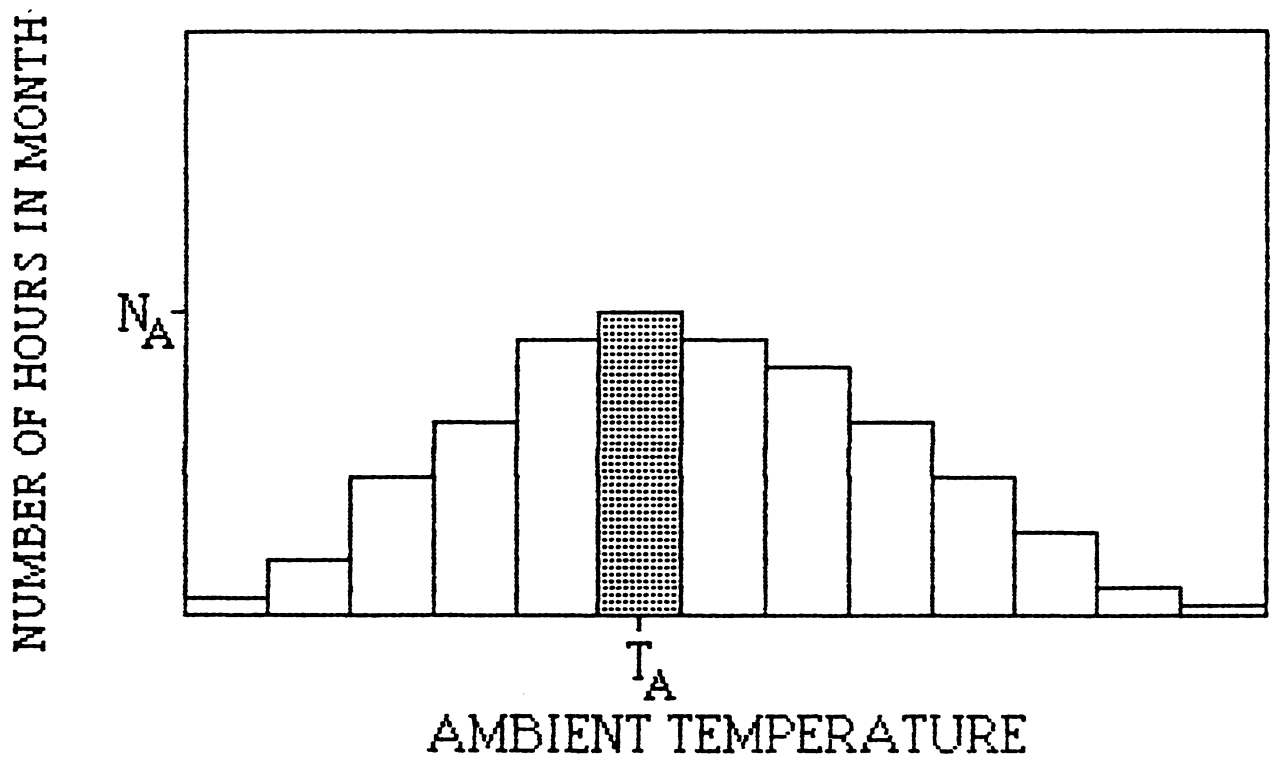


Fig. 3.3. Sample Set of Ambient Temperature Bins, Number of Hours in a Month at a Given Temperature.

are constants [5]. This may also be represented as $B_2[B_1/B_2 - T_A]$ in which B_2 acts like a conductance factor (UA in Eq. (3.3) for example) and B_1/B_2 acts like a base temperature. Operating and nonoperating time periods are evaluated separately. Equipment factors such as ηV and COP vary with ambient temperature and when multiplied by a bin building load rate, give purchased energy rate at each of the four original bin temperatures. For bins in between, interpolation is used to find an equipment energy rate for each bin which, multiplied by the hours in the bin and summed over all bins gives the total purchased heating energy:

$$E_n = B_2 \sum_{T_A} \frac{[B_1/B_2 - T_A]^+ N_A}{\eta V(T_A)} \tag{3.13}$$

The MBM was developed specifically to handle large building HVAC systems. Because zone loads are linked to equipment loads via the cooling and heating coils in large HVAC systems, energy and mass balance expressions for coils, mixed streams, etc. are applied to zone loads to get cooling and heating coil loads. The resulting cooling and heating coil loads at the four points are then applied to equipment performance equations which may vary with temperature or load/capacity ratios, yielding purchased energy rates at each point. Lines drawn between the points allow interpolation for the intermediate bin temperatures to give a purchased energy rate for each bin. Multiplying each bin rate by the hours of occurrence in the bin and summing over ambient temperature bins yields total energy used.

This method, when applied to energy used in residential systems, compared with DOE-2 as well as did the method which used variable base degree-days summed with hourly data [4]. When compared to the seven building simulation programs ACCESS, BLAST, BLDSIM, DOE-2, ECUBE, ESAS, and TRACE for various large buildings and systems, agreement was fairly good in most cases [6]. However, each program/ calculation comparison was done by a different operator, who was an expert in the simulation program used. All operators had to learn the TC4.7 MBM calculation procedure, indicating that a lack of familiarity with the procedure could have led to variability in results.

The relative merits of schemes which use hourly and bin weather data were noted in a paper by A. Black entitled "Is Bigger Really Better?" [7]. He tested a model for a terminal reheat system using hourly data with immediate loads, hourly data with time delayed loads and bin data with immediate loads all using monthly average solar gain levels. A 5% agreement between all schemes was the result, leading to the conclusion that as far as energy consumption goes, the weather data format will not have a significant effect on the determination.

Two general observations may be drawn from the results reviewed above. First, methods using bin data can be as accurate at predicting purchased energy as hourly simulations in systems where building capacitance is not a large factor. The major difference lies in type of data and number of calculations. If already tabulated degree-day totals are not available, hourly summations for them could become cumbersome.

3.3 Bin Weather Data

Given that bin methods are to be employed, bin data will be needed. These data could be derived from existing hourly data. Data published in Air Force Manual 88-29 (AFM) [8] which lists 5°F bins for three eight hour periods of a day for a number of locations in the US. For one year hourly data requires 8760 pieces of data. A year of bin data from the AFM entails as many as 60 or more pieces of data, a dramatic reduction.

However, a method developed by Erbs et al. [9] describes a set of monthly temperature distributions which may be used either to generate bin data of any bin size or, to directly integrate variable base bin expressions rather than numerically summing over bins. The information needed to generate a distribution for a month N_m hours long is the long term monthly average temperature, $\bar{T}_m$ and the standard deviation over a period of years of that month's averages from the long term average, σ_m. The cumulative distribution Q, of hours at temperatures lower than a given temperature, T_A is given as:

$$Q(T_A) = \frac{1 + \tanh\,(1.698\ h)}{2} \qquad (3.14)$$

where

$$h = \frac{T_A - \bar{T}_m}{\sigma_m \sqrt{N_m/24}} \qquad (3.15)$$

The monthly standard deviation can be obtained from data or from a correlation which requires $\bar{T}_m$ and the standard deviation of twelve monthly average temperatures from the yearly average, σ_{yr}:

$$\sigma_m = 1.45 - 0.029\,\bar{T}_m + 0.0064\,\sigma_{yr} \qquad (3.16)$$

In addition, the correlation in Eq. (3.14) may be applied to any month long period. That is, a distribution may be found for each hour in a month or all hours in between say 9 a.m. and 5 p.m. An average temperature for each hour $\bar{T}_{m,h}$ and the number of days in the month or the average of the hourly temperatures in a period of interest (i.e., 9-5), $\bar{T}_{m,p}$ and the product of the number of hours in that period multiplied by the days in that month can be substituted for $\bar{T}_m$ and N_m respectively in Eq. (3.14) above. The twenty-four values of $\bar{T}_{m,h}$ can be obtained from the following expression for diurnal temperature variation:

$$\bar{T}_{m,h} = \bar{T}_m + A_o \sum_{n=1}^{4} a_n \cos\,(nt^* - b_n) \qquad (3.17)$$

where A_o is the amplitude of diurnal variation, $t^* = 2(t - 1)/24$ is based on time in hours, t (1 = 1a.m., ..., 24 =12 p.m.) and a_n and b_n are coefficients whose values are given in Table 3.1. A_o is not always a known quantity. It can be found from the following correlation [9]:

$$A_o = 25.8\ \overline{K}_T - 5.21 \quad (3.18)$$

where A_o is in degrees C and $\overline{K}_T$ is the monthly average clearness index. Thus, to replicate the AFM bin data, twelve values of $\overline{K}_T$ and $\overline{T}_m$ would be needed for a total of 24 values, almost a third that of AFM.

As mentioned before, the expression for Q in Eq. (3.14) was used to analytically integrate for the degree-days based on T_b. A detailed derivation of the resulting degree-day expression can be found in Ref. [9]:

$$DD_h = \sigma_m \left(\frac{N}{24}\right)^{3/2} \left[\frac{h}{2} + \frac{\ln\left(\cosh\left(1.698\ h\right)\right)}{3.396} + 0.2041\right] \quad (3.19)$$

where

$$h = \frac{T_b - \overline{T}_m}{\sigma_m \sqrt{N_m/24}} \quad (3.20)$$

For ease of calculation, degree-days are usually converted to degree-hours by multiplying DD_h above by 24. For cooling degree-hours, since the temperature difference is based on $(T_A - T_b)^+$, (see Eq. (3.8)) h becomes

Table 3.1. Coefficients for Diurnal Temperature Variation Expression in Eq. (3.17)

n	1	2	3	4
a_n	0.4632	0.0984	0.0168	0.0138
b_n	3.805	0.360	0.822	3.513

$$h = \frac{\bar{T}_m - T_b}{\sigma_m \sqrt{N_m/24}} \qquad (3.21)$$

Thus, a degree-day expression may be obtained from Eqs. (3.19) and (3.20) or (3.21) knowing only T_b, $\bar{T}_m$, and σ_m. This can afford a great reduction in calculational effort and input data. The method has been shown to match actual data for DD_h and DD_c using Eqs. (3.6) and (3.8) and hourly data for T_A over a 20°C range of base temperatures [9,10]. Using a summation of hourly values based on $\bar{T}_{m,h}$ was found to be more accurate than using one daily calculation based on $\bar{T}_m$ [9].

Latent loads require specific humidity data. Each AFM bin is accompanied by a coincident wet bulb temperature. Erbs investigated statistical representation of humidity data in depth [10]. Because of the high correlation between ambient temperature, relative humidity ϕ, and wet bulb temperature T_w, values of ϕ were used with both T_A

and T_W bin distributions. Both methods gave similar results although the humidity bins generated using a ϕ/T_W combination came a bit closer to actual data. However, when a ϕ/T_A combination is used, accuracy is not increased by distributing ω_A for each temperature bin. Calculations in chapters 5 and 7 of Ref. [10] determined both specific humidity bins and unitary air conditioner energy requirements. The results of both calculations indicate that using $\overline{T}_{m,h}$ and $\overline{\phi}_{m,h}$ in bin calculations gives results which are as good as the other methods tested when compared to actual data. Thus, the $\overline{\phi}_{m,h}$ $\overline{T}_{m,h}$ can be used to numerically generate a specific humidity distribution. This distribution will give one value of specific humidity for each temperature in a distribution.

Diurnal variation of relative humidity $\overline{\phi}_{m,h}$ is given in Ref. [10] as:

$$\overline{\phi}_{m,h} = \overline{\phi}_m + A_o \sum_{n=1}^{4} a_n \cos (nt^* - b_n) \qquad (3.22)$$

where t^* is as before, a_n and b_n are given in Table 3.2 and A_o the amplitude of diurnal variation of relative humidity is given by:

$$A_o = -0.516 + 0.1933\,\overline{K}_T - 1.663\,\overline{K}_T^3 + 0.00669\,\overline{T}_m - 1.933 \times 10^{-4}\,\overline{T}_m^2 \qquad (3.23)$$

Solar weather data will be discussed in depth in Chapter 5. Windspeed variations and their effect on energy consumption will not be considered.

Table 3.2. Coefficients for Diurnal Relative Humidity Variation Expression in Eq. (3.22)

n	1	2	3	4
a_n	0.4672	0.0958	0.0195	0.0147
b_n	0.666	2.3484	4.147	0.452

To summarize, this chapter has examined simplified modeling and looked at alternatives for generating bin weather and degree-day data. The possibility of using Erbs' analytic degree-day integration correlation and Erbs' techniques to generate bin data promises to allow reduction in computational time and the amount of input data required.

CHAPTER 4

APPLICATION OF VARIABLE BASE AND EQUIVALENT DEGREE-DAY IDEAS TO HVAC SYSTEM LOAD CALCULATIONS

Chapter 3 presented the idea of variable base degree-day summation of temperature differences as a means to obtaining total energy use. For the example of a residence, an energy balance on the residence gives a load expression. The load equation's temperature difference portion summed over ambient temperature gives degree-days which when multiplied by a conductance factor gives total energy. The same procedure will be followed in this chapter for the HVAC systems described in Chapter 2.

There is a distinction between zone load, coil load and equipment load. A zone load expression describes whether the zone is in need of cooling or heating. In a residence, this is the same as a coil load which describes the rate at which energy that must be supplied to the zone, by cooling or heating coils. In an HVAC system, the zone and coil loads are not necessarily the same because heating and cooling of the supply air stream are often done simultaneously to meet either zone heating or cooling loads. An equipment load is the energy needed by the heating or cooling equipment to meet the coil load.

In Section 4.1, coil load expressions are derived for each HVAC system mentioned in Chapter 2. Section 4.2 describes how these rate equations can be summed over ambient temperature to give expressions for total coil load. Equipment performance, which varies with ambient temperature is also discussed. Finally, Section 4.3 discusses the adding of coil loads for several zones served by the same system.

4.1 Derivation of Coil Load Rate Expressions

Table 4.1 shows generic heating, sensible cooling and latent cooling load expressions. These consist of a conductance factor, U_f multiplied by an expression describing the difference between some base condition, T_b or ω_b and ambient condition, T_A or ω_A. The subscripts h, cs, and cL indicate $\dot{q}$, U_f and T_b or ω_b values for heating, sensible cooling and latent cooling loads respectively.

4.1.1 Terminal Reheat Systems

Heating, sensible cooling, and latent cooling coil load expressions will be developed here for the terminal reheat system described in Chapter 2. Similar equations will be developed for economizer and dead band control as applied to terminal reheat.

Beginning in Fig. 4.1 at mixing point, m, with the outside air which enters at rate of $\dot{m}_o$, a fresh air fraction k is defined such that:

$$k = \frac{\dot{m}_o}{\dot{m}} \tag{4.1}$$

where m is the constant design system air flow. Outside air is then mixed with return air and substitution of $\dot{m}_o = \dot{m}$, $\dot{m}_r = \dot{m}_2$, $T_R = T_2$ and $T_A = T_1$ into the mixed air Eq. (2.6) gives:

Table 4.1. General Heating and Cooling Load Expressions

Name	Load	Expression
Heating	$\dot{q}_h$	$U_{fh}[T_{bh} - T_A]^+$
Sensible Cooling	$\dot{q}_{cs}$	$U_{fcs}[T_A - T_{bcs}]^+$
Latent Cooling	$\dot{q}_{cL}$	$U_{fcL}[\omega_A - \omega_{bcL}]^+$

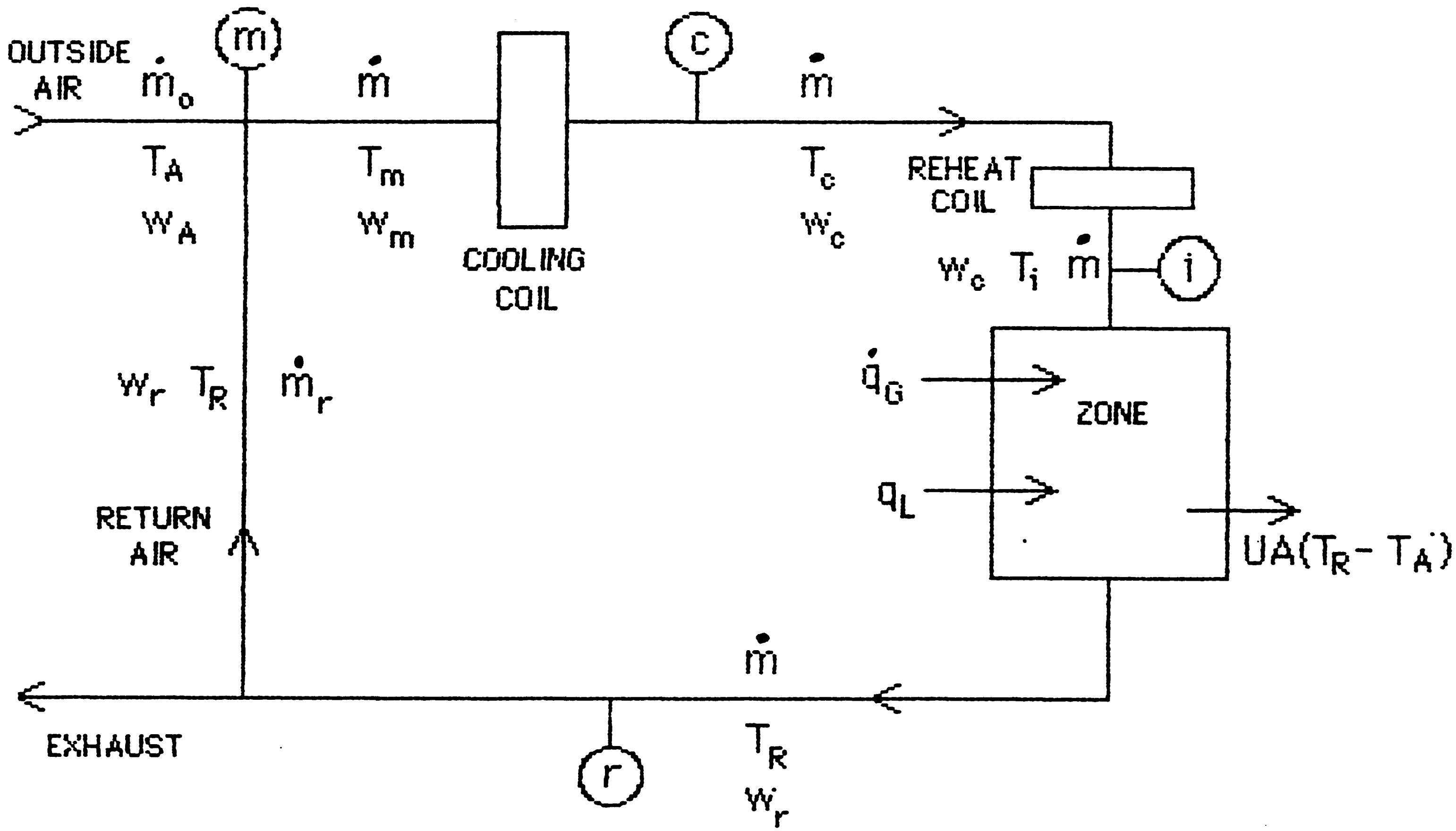


Fig. 4.1. Diagram of a Terminal Reheat and Variable Air Volume HVAC Systems.

$$T_m = \frac{\dot{m}_r T_R + \dot{m}_o T_A}{\dot{m}} \qquad (4.2)$$

Substitution of the expression for k into a mass balance on the mixing box gives $\dot{m}_r = (1 - k)\dot{m}$ and, thus:

$$T_m = (1 - k)T_R + kT_A \qquad (4.3)$$

The air stream then goes through a cooling coil and is cooled to a specified design supply temperature, T_c. Substituting $T_m = T_{in}$ and $T_c = T_{out}$ in Eq. (2.4), the following linear equation results for the required sensible cooling coil load at T_A:

$$\dot{q}_{cs} = \dot{m}c_p \, [(1 - k)T_R + kT_A - T_c]^+ = k\dot{m}c_p \, [T_A - \frac{T_c - T_R(1 - k)}{k}]^+ \qquad (4.4)$$

Equation (4.4) has values for conductance (also referered to as conductance factor) and base temperature of:

$$U_{fcs} = k\dot{m}c_p = \dot{m}_o c_p \qquad (4.4a)$$

$$T_{bcs} = \frac{T_c - (1 - k)T_R}{k} \qquad (4.4b)$$

The reheat coil occurs next on the system schematic at point i. Air at T_c enters and heat is added to bring the air to T_i, the supply air temperature into the zone. The latter temperature is fixed by the amount of heating or cooling needed in the zone to balance losses or gains. By taking the zone and reheat coil together, the following energy balance results:

$$\dot{q}_h - UA(T_R - T_A) + \dot{q}_G = \dot{m}c_p(T_R - T_c) \quad (4.5)$$

where $\dot{q}_G$ represents the gains in the zone (generated, solar, etc.), T_R is the room set temperature (also return air temperature), and $\dot{q}_h$ is the required reheat rate. Rearrangement of terms yields the following expression:

$$\dot{q}_h = UA \left[\frac{(\dot{m}c_p + UA)T_R - \dot{m}c_p T_c - \dot{q}_G}{UA} - T_A\right]^+ \quad (4.6)$$

which means that:

$$U_{fh} = UA \quad (4.6a)$$

$$T_{bh} = \frac{(\dot{m}c_p + UA)T_R - \dot{m}c_p T_c - \dot{q}_G}{UA} \quad (4.6b)$$

Important system parameters, then, appear in cooling and heating coil expressions, allowing the effect of each to be seen. For instance, because only the cooling coil "sees" the outside air as a load, outside air mass flow rate does not appear in the $\dot{q}_h$ equation but does appear in the $\dot{q}_{cs}$ Eq. (4.3). Similarly, the reheat coil expression Eq. (4.6), contains $\dot{q}_G$ and UA but $\dot{q}_{cs}$ does not because the cooling coil does not experience the zone load directly.

Consideration of the latent cooling load is also important because in some locations it can be large in comparison to sensible cooling load. If a latent cooling coil load exists, the exiting coil specific humidity at point c, will be ω_c as shown in Fig. 4.1, ideally the saturated value at T_c. Moisture is then input to the air stream in the zone by the latent load, $\dot{q}_{cL}$. This load may be translated into generated moisture rate by dividing by the heat of vaporization, h_{fg}, and into generated specific humidity, ω_L, by dividing by the air flow rate, $\dot{m}$:

$$\omega_L = \frac{\dot{q}_L}{\dot{m}h_{fg}} \tag{4.7}$$

Thus, the specific humidity of the return stream becomes $\omega_R = \omega_L + \omega_c$. Now, a mixing equation describes how much moisture is present after the return and outside air streams are mixed at point $\dot{m}$. Mass balance gives:

$$\begin{gathered} \dot{m}_o\omega_A + (\dot{m} - \dot{m}_o)\omega_R = \dot{m}\omega_m \\ \omega_m = k\omega_A + (1 - k)(\omega_L + \omega_c) \end{gathered} \tag{4.8}$$

Finally, the resulting latent load on the cooling coil, $\dot{q}_{c,L}$ is:

$$\dot{q}_{cL} = \dot{m}h_{fg}[\omega_m - \omega_c]^+ = k\dot{m}h_{fg}[\omega_A - (\omega_c - \frac{1-k}{k}\omega_L)]^+ \quad (4.9)$$

which is analogous to the generic expression for $\dot{q}_{cL}$ in Table 4.1. giving:

$$U_{fcL} = \dot{m}_o h_{fg} \quad (4.9a)$$

$$\omega_{bcL} = \frac{\omega_c - (1-k)\omega_L}{k} \quad (4.9b)$$

Table 4.2 summarizes all the U_f and T_b values presented above for terminal reheat systems. The system abbreviation TRH is in the left hand column, followed by the high and low values of temperature for the operating range. Here the range is $-\infty$ to ∞ which means that the equations derived hold for all values of ambient temperature. The number of the expression in the text which contains the base temperature, base humidity or conductance factor is listed in the appropriate column for heating and sensible and latent cooling. The equation numbers for T_b and U_f have the same number as the rate equation they fit in. For example, Eq. (4.6a) denotes the conductance factor and Eq. (4.6b) denotes the base temperature for the rate Eq. (4.6).

Figure 2.8 showed the operation of a deadband thermostat. Each system for which dead band control is used has a D added to the end of its abbreviation. Thus, terminal reheat with dead band control is TRHD. Heating is done to preserve a zone set temperature of T_{RH} and cooling, to preserve a zone set temperature of T_{RC}. Otherwise the zone temperature floats and no energy input is required. An energy balance on the zone determines the ambient temperature at which no heating or cooling is required. Thus, in Eq. (4.5) $\dot{q}_h = 0$ and $\dot{m}c_p\,(T_R - T_C) = 0$ giving:

$$\dot{q}_G = UA(T_R - T_A)$$

$$T_A = T_R - \frac{\dot{q}_G}{UA} \qquad (4.10)$$

The above expression is the same as the base temperature for the residence in Chapter 3. Cooling begins at $T_{AC} = T_{RC} - \dot{q}_G/UA$ and heating, at $T_{AH} = T_{RH} - \dot{q}_G/UA$.

Figure 4.2 shows T_R as a function of T_A. For the three ranges of operation labeled in the figure, the variation of room temperature settings and zone load are shown. As T_A increases toward T_{AH} in range 3, the zone heating load decreases to zero and the set temperature is maintained at T_{RH}. As T_A increases from T_{AC} in range 1, cooling increases and T_{RC} is maintained. In range 2, between T_{AH} and T_{AC}, the envelope load on the zone is not high enough to require either cooling or heating and the room set temperature floats between the two values.

To determine all coil loads in range 1 of operation, T_{RC} is substituted into Eqs. (4.4) and (4.6). The same procedure applies for range 3, substituting T_{RH}. For the middle operation temperature

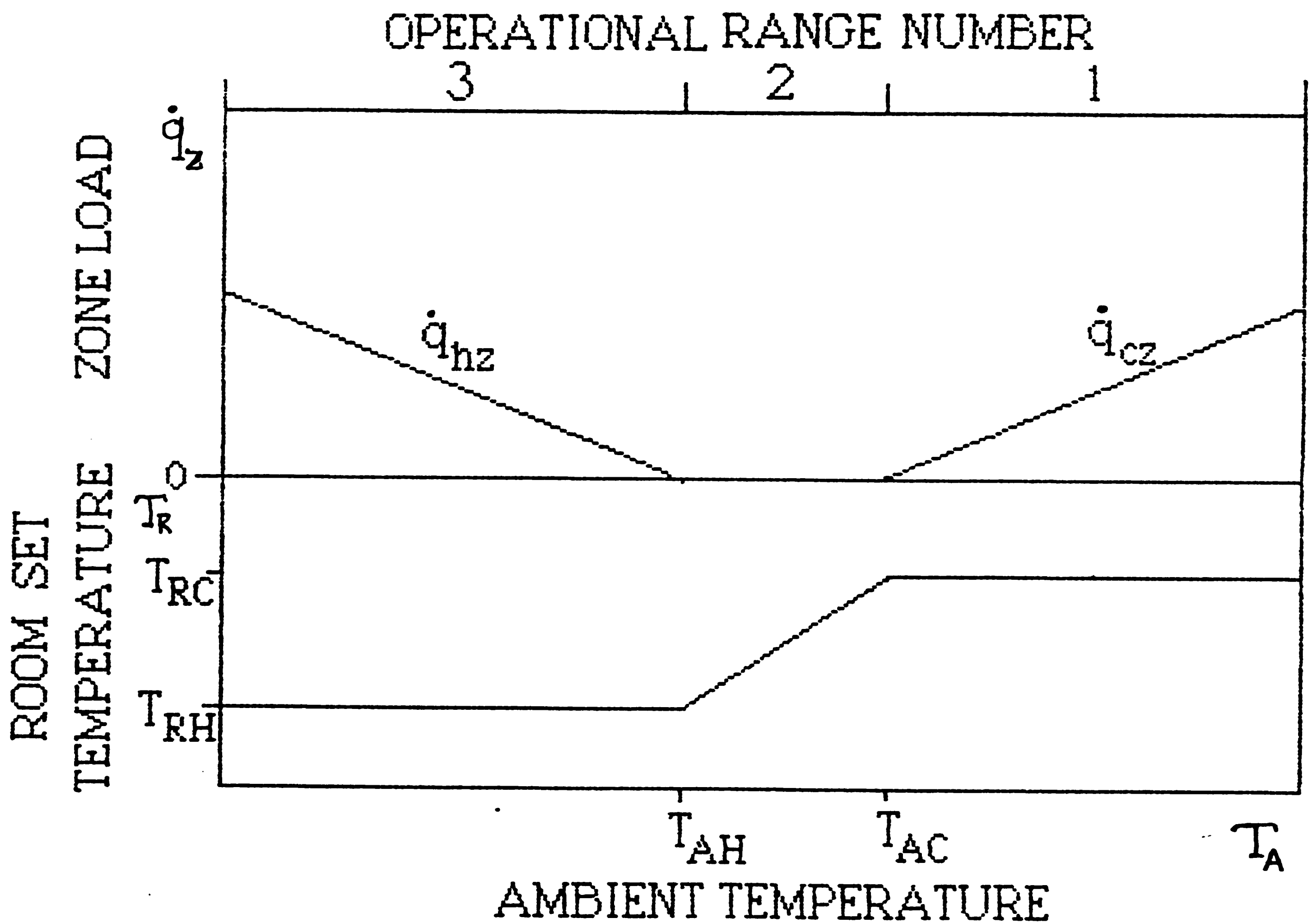


Fig. 4.2. Variation of Zone Heating and Cooling Loads and Room Set Temperature With Ambient Temperature for Dead Band Temperature Control.

range 2, $U_f = 0$ for all loads. U_f and T_b are summarized for TRHD as they were for TRH in Table 4.2. The substitution of T_{RH} and T_{RC} for T_R has been denoted by rating the value to be used for T_R in parentheses underneath number of the equation.

The use of an economizer cycle is denoted by adding an E to the end of a system's abbreviation. Terminal reheat with economizer is called TRHE. Economizer cycle control presents a similar situation to the dead band control. For dead band control, T_R varies with ambient temperature; for economizer control, outside air flow, $\dot{m}_o$, varies with temperature. As described in Chapter 2, the economizer varies the amount of outside air, as shown in Fig. 4.3. The variation of mixed air temperature, T_m is shown in the figure with the variation of outside air flow rate, $\dot{m}_o$ versus ambient temperature, T_A in four economizer operation temperature ranges. The idea is to minimize T_m so that sensible cooling will be minimized. Thus, if $T_A > T_R$ in range 1 of Fig. 4.3, T_m is minimized by as small an amount of outside air, $\dot{m}_o$ as is allowed to be supplied to the zone, $\dot{m}_{omin}$. When $T_A < T_R$ in range 2, using a maximum rate of outside air (equal to the rate of air supplied to the zone, $\dot{m}$) will minimize T_m making it equal to T_A and giving the line a slope of 1. For $T_A < T_C$ in range 3, heating would be needed to keep supply temperature at T_C if all outside air were to continue to be supplied. So, warm return air is mixed with outside air to keep $T_m = T_C$. As T_A decreases, so does $\dot{m}_o$, until the minimum flow rate has been reached and an auxili-

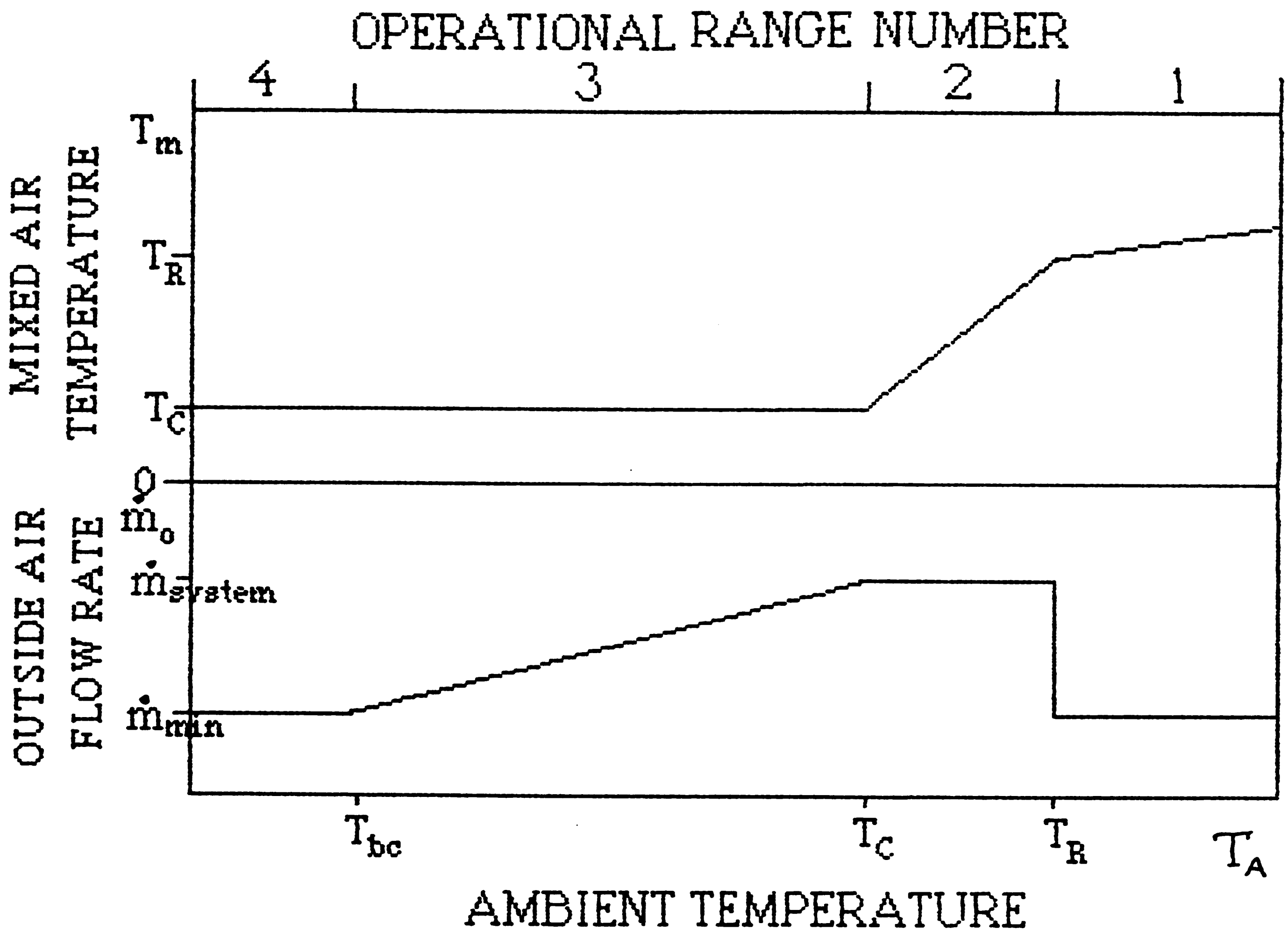


Fig. 4.3. Variation of Mixed Air Temperature and Outside Air Flow Rate With Ambient Temperature for Economizer Cycle Control.

ary preheater at point m in Fig. 4.1. must provide heat to keep the stream at T_c.

Doing an energy balance on the mixed air equation shows preheat rate, $\dot{q}_{ph}$:

$$\dot{q}_{ph} = k\dot{m}c_p \left[\frac{T_c - (1 - k)T_R}{k} - T_A\right]^+ \tag{4.11}$$

which is the reverse or "negative" of cooling load in Eq. (4.4). Preheating equations in general use the same base temperature and conductance factor as cooling in a heating rate equation.

The variable $\dot{m}_o$ varies in ranges as shown in Fig. 4.3 for all systems with economizer cycles. Economizer control affects only the cooling coil in the terminal reheat system because air is always supplied to the reheat unit whether by the cooling coil or free cooling at T_c. Below $T_A = T_c$ in range 3 of Fig. 4.3, cooling is free and U_{fcs} is effectively zero.

Thus, only two ranges result for positive cooling coil load, 2 and 1 in Fig. 4.3 with $\dot{m}_o = \dot{m}$ and $\dot{m}_{omin}$, respectively. Because supply mass flow, $\dot{m}$ is constant for the terminal reheat system, k, the ratio of $\dot{m}_o/\dot{m}$, is also constant in both ranges. Equations (4.4) and (4.9) for sensible and latent cooling loads both apply with values of k = 1 and k_{min} substituted in. However, when k = 1 in these equations, simplifications occur and equations reduce to:

$$\dot{q}_{cs} = \dot{m}c_p \left[T_A - T_c\right]^+ \tag{4.12}$$

Table 4.2. Numbers of Expressions in Chapter 4 Containing Conductance Factor, Base Temperatures and Base Humidity for Terminal Preheat Systems

System	Temperature Range		Heating		Sensible Cooling		Latent Cooling	
Abbr.	Low	High	U_{fh}	T_{bh}	U_{fcs}	T_{bcs}	U_{fcL}	ω_{bcL}
THR	$-\infty$	∞	4.6a	4.6b	4.4a	4.4b	4.9a	4.9b
TRHD	T_{AC}	∞	4.6a	4.6b (T_{RC})	4.4a	4.4b (T_{RH})	4.9a	4.9b
	T_{AH}	T_{AC}	0	---	0	---	0	--
	$-\infty$	T_{AH}	4.6a	4.6b (T_{RH})	4.4a	4.4b (T_{RH})	4.9a	4.9b
TRHE	T_R	∞	4.6a	4.6b	4.4a	4.4b	4.9a	4.9b
	T_c	T_R	4.6a	4.6b	4.12a	4.12b	4.13a	4.13b
	4.4b	T_c	4.6a	4.6b	0	---	0	---
	$-\infty$	4.4b	4.6a	4.6b	4.4a	4.4b	4.9a	4.9b

$$U_{fcs} = \dot{m}c_p \tag{4.12a}$$

$$T_{bcs} = T_c \tag{4.12b}$$

and
$$\dot{q}_{cL} = \dot{m}h_{fg}\,[\omega_A - \omega_c]^+ \tag{4.13}$$

$$U_{fCL} = \dot{m}h_{fg} \tag{4.13a}$$

$$\omega_{bCL} = \omega_c \tag{4.13b}$$

Table 4.2 summarizes the values of U_f and T_b and ω_b specific to the TRHE system covered above.

4.1.2 Variable Air Volume Systems

A variable air volume reheat (VAV) system can be represented by the schematic in Fig. 4.1 which described the TRH above. Since cooling is modulated by varying the air flow until a minimum, $\dot{m}_m$, is reached, the reheat coil will not be activated before minimum air flow is reached. The amount of air flow needed for cooling is found from an energy balance on the zone (essentially Eq. (4.5) with $\dot{q}_h$ = 0) with the result:

$$\dot{m}(T_A) = \frac{UA[T_A - (T_R - \frac{\dot{q}_G}{UA})]^+}{(T_R - T_c)c_p} \tag{4.14}$$

This fits the form of a cooling rate equation where conductance factor and base temperature are given by:

$$U_{fcs} = \frac{UA}{(T_R - T_c)c_p} \tag{4.14a}$$

$$T_{bcs} = T_R - \frac{\dot{q}_G}{UA} \tag{4.14b}$$

Substituting $\dot{m}_m = \dot{m}$ into Eq. (4.14) and solving for T_A, the following expression for the ambient temperature at which air flow reaches minimum flow rate and ceases to vary results in:

$$T_A = \frac{(\dot{m}_m c_p + UA)T_R - \dot{m}_m c_p T_c - \dot{q}_G}{UA} \tag{4.15}$$

This expression is also the base temperature for the terminal reheat coil (4.6b with $\dot{m} = \dot{m}_m$). Above this temperature, no reheat is necessary; below, reheat is necessary. Figure 4.4 shows the air flow and the resulting zone inlet temperature T_i as functions of ambient temperature T_A. Supply air into the zone is constant in temperature and decreasing in flow rate as T_A decreases towards T_{chg}, range 1 in the figure. As T_A decreases past T_{chg} into range 2, the minimum airflow is reached and maintained and the inlet temperature rises to meet decreased zone cooling and zone heating loads.

Substituting Eq. (4.14) for $\dot{m}$ and Eq. (4.3) for T_m into Eq. (2.4) and setting $T_{out} = T_c$, the following results for $\dot{q}_{cs}$:

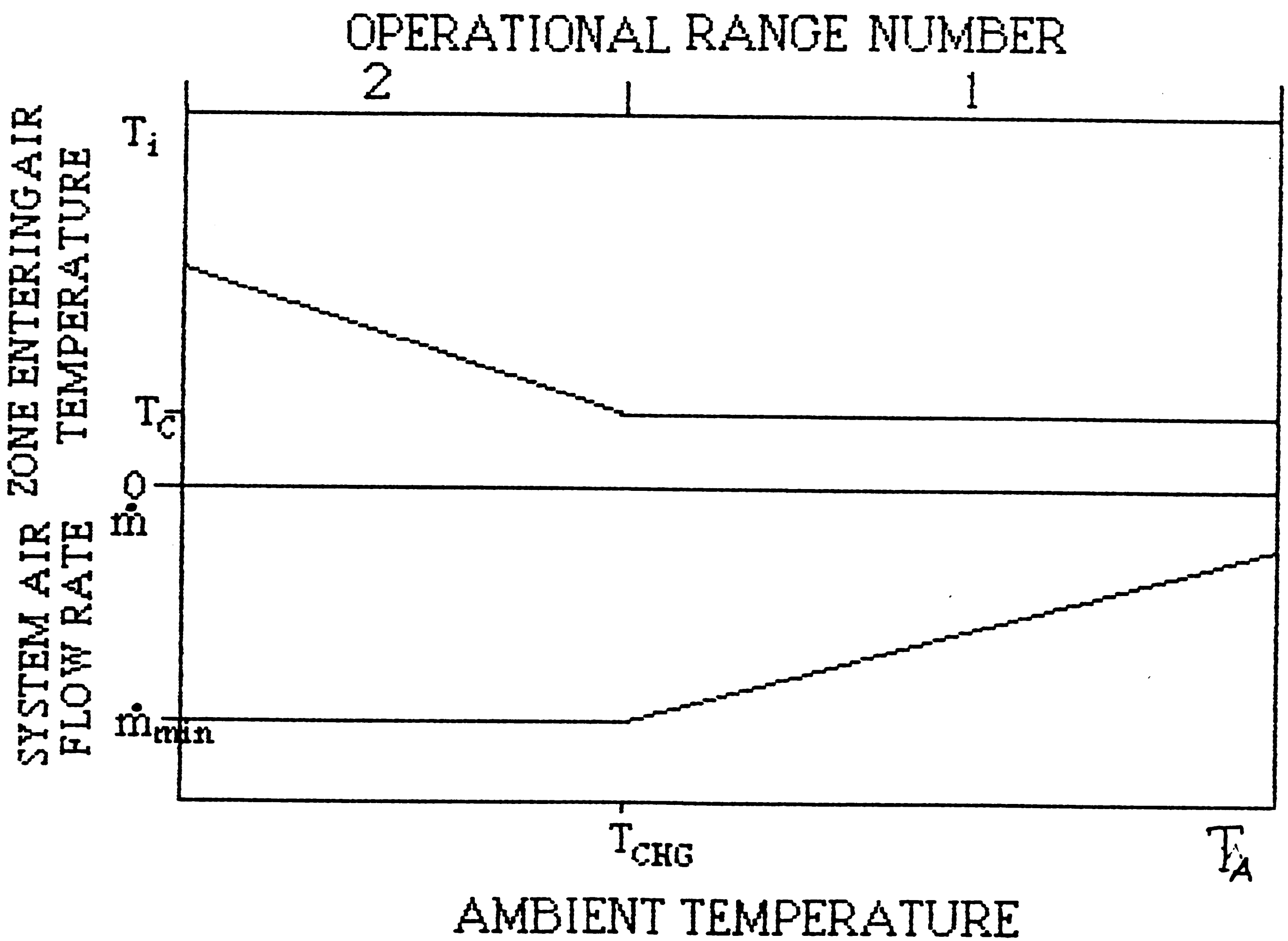


Fig. 4.4. Variation of Zone Entering Air Temperature and VAV Cooling Supply Air Flow Rate With Ambient Temperature for Variable Air Volume Reheat System Operation.

$$\dot{q}_{cs} = (\dot{m}_o c_p + UA)[T_A - (T_R - \frac{\dot{q}_G}{UA + \dot{m}_o c_p})]^+ \qquad (4.16)$$

with a base temperature and conductance factor equal to:

$$U_{fcs} = \dot{m}_o c_p + UA \qquad (4.16a)$$

$$T_{bcs} = T_R - \frac{\dot{q}_G}{UA + \dot{m}_o c_p} \qquad (4.16b)$$

Unlike reheat cooling, VAV cooling involves the cooling stream "seeing" both outside air and zone loads since zone gains and outside air flow rates both occur in the equations for T_{bcs} and U_{fcs} above.

Latent loads will vary with the varying mass flow . The expression for latent cooling $\dot{q}_{cL}$ is the same as for terminal reheat (Eq. 4.9). However, k is not a constant and when the ratio of outside to supply airflow, $\dot{m}_o/\dot{m}$ is substituted for k in Eq. (4.9):

$$\dot{q}_{cL} = \dot{m}_o h_{fg} [\omega_A - (\omega_c - \frac{\dot{m}(T_A) - \dot{m}_o}{\dot{m}_o} \omega_L)]^+ \qquad (4.17)$$

giving U_f and T_b equal to:

$$U_{fcL} = \dot{m}_o h_{fg} \qquad (4.17a)$$

$$\omega_{bcL} = \omega_c - \frac{\dot{m}(T_A) - \dot{m}_o}{\dot{m}_o} \omega_L \qquad (4.17b)$$

Equation (4.17a) is identical to Eq. (4.9a). In the expression Eq. (4.17b), $\dot{m}$ depends on T_A as given in Eq. (4.14).

The value for ambient specific humidity, ω_A corresponding to ambient temperature, T_A is used in Eq. (4.17) to evaluate $\dot{q}_{cL}$.

Induction units are often included in VAV systems (denoted as VAVI). Zone air flow, $\dot{m}_t$, at temperature T_R, as shown in Fig. 4.5, is mixed in an induction unit to give a mixed air flow at temperature, T_i, into the room. The flow consists of induced plus variable volume airflow $\dot{m}_t + \dot{m}(T_A)$ at a mixed temperature entering the zone, T_i:

$$T_i = \frac{\dot{m}T_c + \dot{m}_t T_R}{(\dot{m} + \dot{m}_t)} \qquad (4.18)$$

which will be higher than T_c. Substituting Eq. (4.18) into Eq. (4.5) with no reheat, $\dot{q}_h = 0$ and $\dot{m} = \dot{m}(T_A) + \dot{m}_t$ and $T_c = T_i$, the $\dot{m}_t$ terms drop out and Eq. (4.16) results, indicating that the induction unit has no thermal effect on the system. The zone needs the same amount of cooling whether an induction unit is included or not. When the heating coil is on and $\dot{m} = \dot{m}_m$ the unit has no effect either. Sensible heating and cooling coil loads are the same as for a VAV system.

The fact that inducing return air has no thermal effect on system performance is explained also by the fact that induced air is at zone conditions and the air flow into the zone ends up at those conditions. Thus, the induced part of the air stream goes from T_R to T_R whereas the supply stream goes from T_c to T_R, supplying the cool-

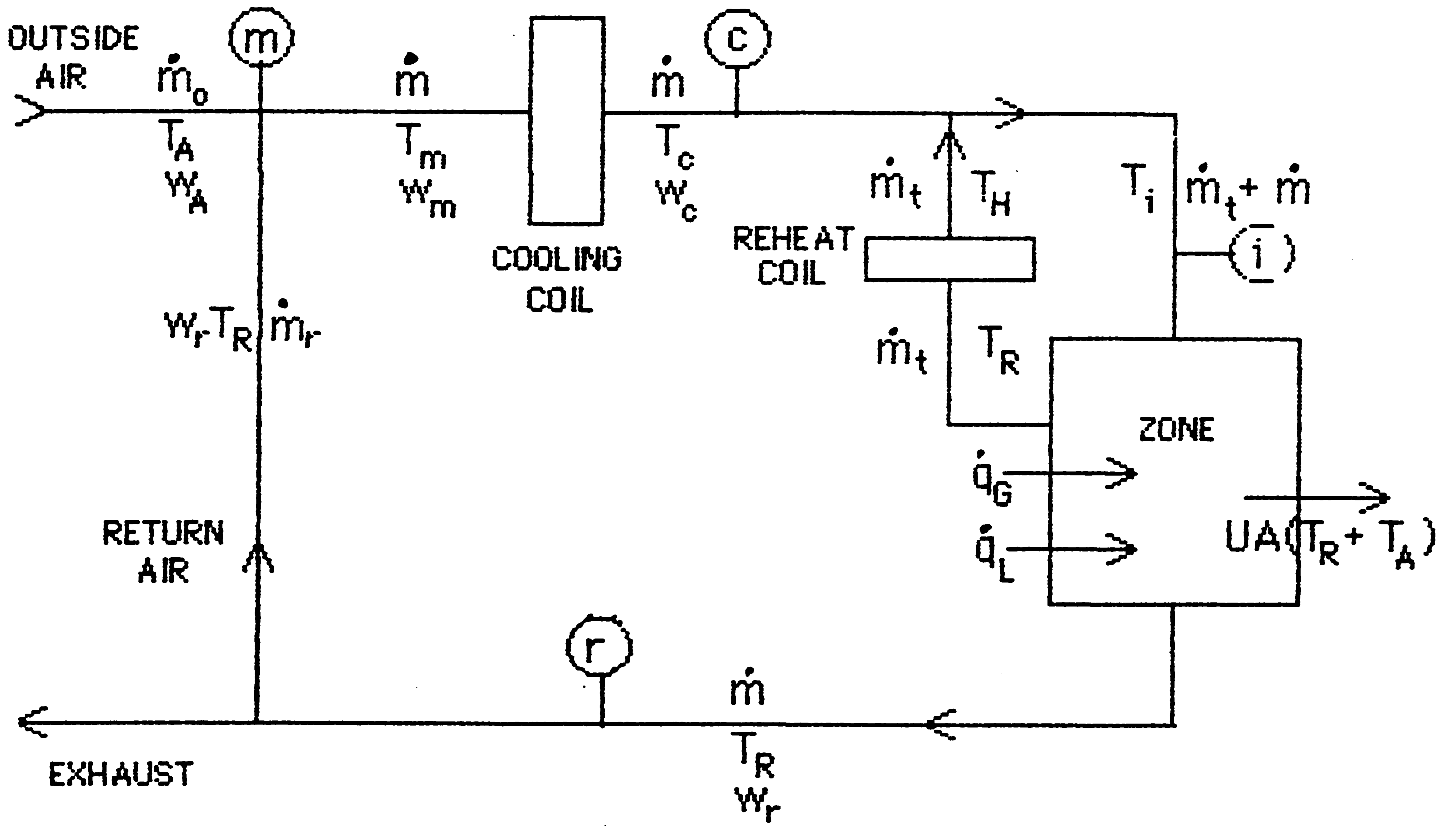


Fig. 4.5. Diagram of a VAV HVAC System With an Attached Induction Unit.

ing needed by the zone. The induced stream has no thermal effect on the cooling process.

From the dual fan/dual duct (DFDD) system shown in Fig. 4.6, it is apparent that for one zone or a group of zones all with return temperature T_R, the heating leg operates as an induction unit located in the central system rather than associated with a particular zone. The only major difference between VAVI and DFDD is that when cooling is being done by the cold leg at air flows greater than a minimum allowable air flow, $\dot{m}_m$, no air flows through the hot supply duct in DFDD whereas room temperature air flows through the induction unit in VAVI. Neither scenario has a thermal effect on coil energy demand. When the cool stream reaches a minimum air flow, the DFDD heating coil begins to provide reheat at the same rate as the VAVI heating coil does. Mass flows and temperatures labeled on the Fig. 4.6 reflect the parallel between the DFDD heating leg and VAVI induction unit operations. The equations describing heating and cooling loads are the same as VAV as a result. Thus, VAV, VAVI and DFDD systems are all represented by VAV in Table 4.3. Equation (4.6b) is subscripted with $\dot{m}_m$ in parentheses in the table to indicate that $\dot{m}$ in Eq. (4.6b) has been replaced with minimum flow rate $\dot{m}_m$ as in Eq. (4.15).

Use of an economizer cycle is a bit different from VAV than for TRH. Where T_{chg} in Fig. 4.4 falls in relation to the economizer settings in Fig. 4.3 determines how the economizer operates. If T_{chg} is below T_{bcs}, the economizer cycle operates entirely in the VAV portion

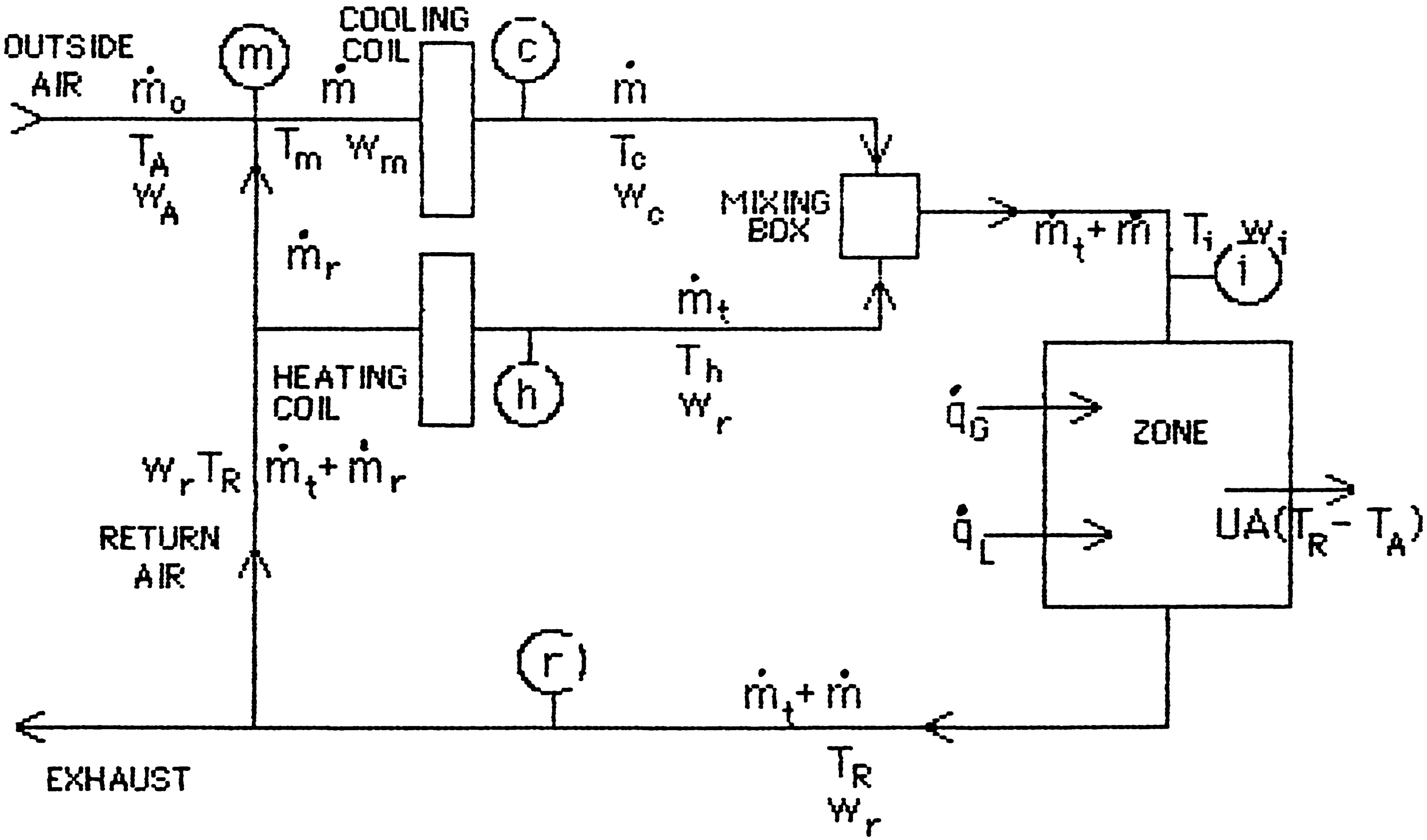


Fig. 4.6. Diagram of a Dual Fan/Dual Duct HVAC System.

(range 1 in Fig. 4.4), if above T_R, it operates entirely in the TRH portion (range 2 in Fig. 4.4), and if between, it operates in both ranges in Fig. 4.4. As the application of economizer to the reheat portion has already been derived for TRH, the application of economizer to the VAV portion (range 1 in Fig. 4.4) will be discussed. Free cooling between T_{bcs} and T_c in range 3 of Fig. 4.3 has no cooling coil load associated with it meaning that $U_{fcs} = 0$. Ranges 4 and 1 where $T_A < T_{bcs}$ and $T_A > T_R$ have a constant minimum setting on outside air flow rate, $\dot{m}_o$ and $\dot{q}_{cs}$ remains as derived for VAV in Eq. (4.16). Between T_c and T_R, however, $\dot{m}_o$ in Eq. (4.16) will be replaced by $\dot{m}(T_A)$ in Eq. (4.14) which gives the following for sensible cooling:

$$\dot{q}_{cs} = \frac{UA}{T_R - T_c}[T_A - T_R][T_A - (T_c - \frac{\dot{q}_G}{UA})] + \dot{q}_G \qquad (4.19)$$

The expression in Eq. (4.19) cannot be properly represented by a temperature difference equation. thus, the value of U_{fcs} on Table 4.3 is noted as the entire expression in Eq. (4.19).

$\dot{m}_o = \dot{m}(T_A)$substituted in Eq. (4.17) gives the same expression as Eq. (4.13) for latent load (with $\dot{m}$ given by Eq. 4.14). The VAVE expressions (just for the cooling portion of VAV) are listed in Table 4.3. An asterisk is placed by equation numbers which contain the expression for $\dot{m}$ which varies with temperature. The equation numbers of U_{fcs} and T_{bcs} for $\dot{m}(T_A)$ are also listed in Table 4.3.

Table 4.3. Equation Numbers of Expressions in Chapter 4 Containing Conductance Factors, Base Temperatures and Base Humidity for Variable Air Volume Systems

System	Temperature Range		Heating		Sensible Cooling		Latent Cooling	
Abbr.	Low	High	U_{fh}	T_{bh}	U_{fcs}	T_{bcs}	U_{fcL}	ω_{bcL}
VAVR	4.6b ($\dot{m}_m$)	∞	0	---	4.16a	4.16b	4.17a	4.17b*
	−∞	4.6b ($\dot{m}_m$)	4.6a	4.6b ($\dot{m}_m$)	4.4a ($\dot{m}_m$)	4.4b ($\dot{m}_m$)	4.9a ($\dot{m}_m$)	4.9b ($\dot{m}_m$)
VAVE	T_R	∞	0	---	4.16a	4.16b	4.17a	4.17b*
	T_c	T_R	0	---	4.19	---	4.13a	4.13b*
	4.16a	T_c	0	---	0	---	0	---
	−∞	4.16a	0	---	4.16a	4.16b	4.17a	4.17b*
VAVD	T_{AC}	∞	0	---	4.16a	4.16b (T_{RC})	4.17a	4.17b*
* $\dot{m}(T_A)$	−∞	∞	---	---	4.14a	4.14b	---	---

Application of a dead band temperature control in the VAV portion of VAV (abbreviated VAVD) has the same effect for VAV as it did for TRH. For ambient temperature in range 2 of Fig. 4.2, VAV provides cooling to the zone and T_{RC} is substituted for T_R in sensible cooling expressions and $\dot{m}(T_A)$ in latent cooling expressions. The resulting U_f and T_b values are summarized in Table 4.3.

4.1.3 Dual Duct and Three Deck Systems

The Dual Duct (DDM) system presents a different set of equations from VAV and TRH. Mixing takes place in two places, return and outside air at point m as for TRH and VAV systems and hot and cold streams at the mixing box at point i. In Fig. 4.7, the fraction of air through the cold duct at point c is $K' = \dot{m}_c/\dot{m}$ where $\dot{m}_c$ is the cold stream flow and $\dot{m}$, the constant total flow. K' varies from one to zero as cooling load in the zone is reduced. Since $\dot{m}$ must be constant, the fraction of air through the hot duct is given as $1 - K' = \dot{m}_h/\dot{m}$. From the mixing equation at the mixing box the following results:

$$K' = \frac{T_h - T_i}{T_h - T_c} \qquad (4.20)$$

From Eq. (4.5) where $\dot{q}_h = 0$ and $T_c = T_i$, T_i can be solved for and substituted in Eq. (4.20) to give an expression for K' as a function of T_A:

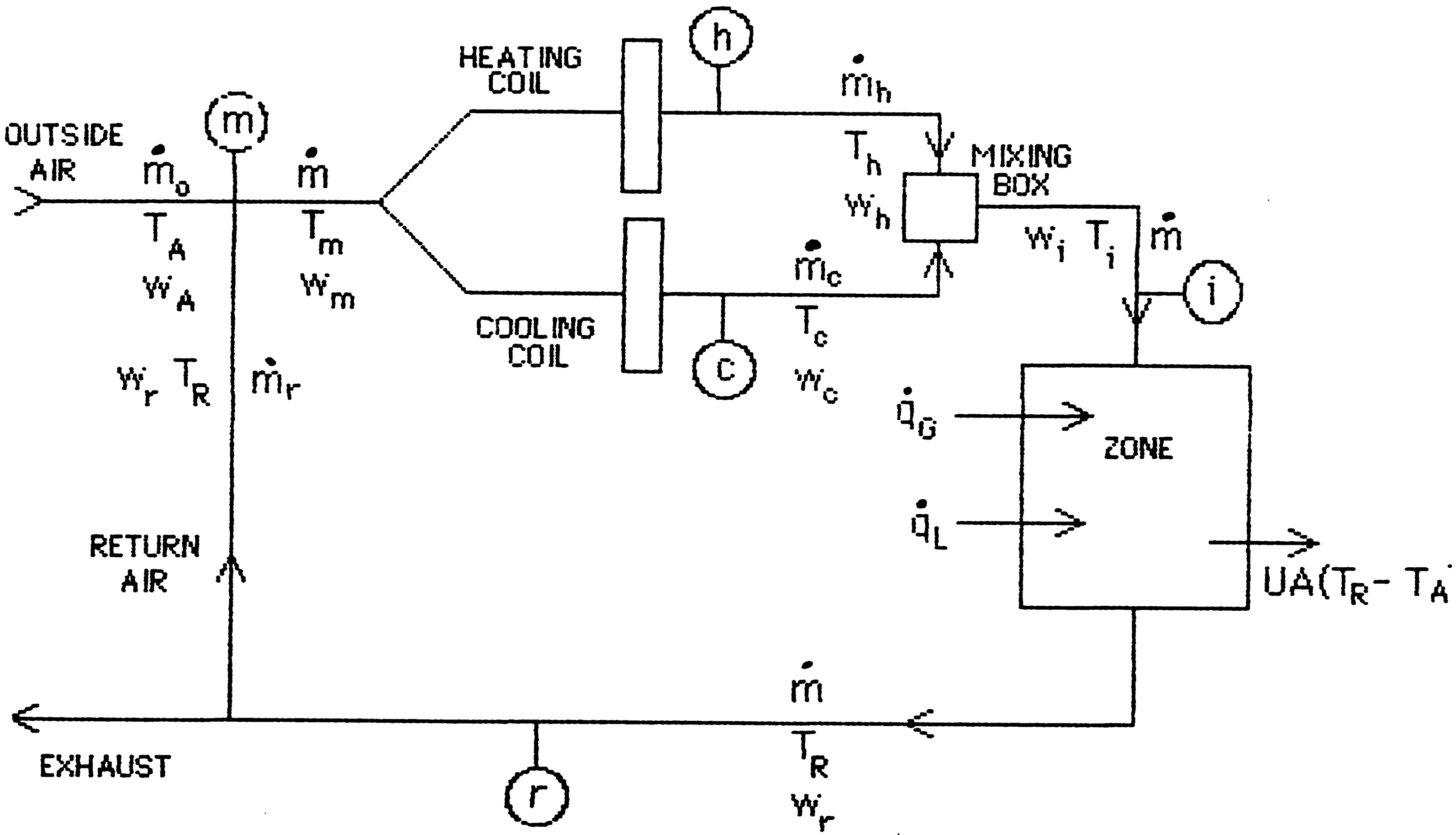


Fig. 4.7. Diagram of a Dual Duct HVAC System.

$$K'(T_A) = \frac{UA[T_A - \frac{(UA + \dot{m}c_p)T_R - \dot{m}c_pT_h - \dot{q}_G}{UA}]^+}{\dot{m}c_p\ [T_H - T_c]} \qquad (4.21)$$

which is essentially a cooling rate equation with U_{fcs} and T_{bcs} given by:

$$U_{fcs} = \frac{1}{\dot{m}c_p(T_h - T_c)} \qquad (4.21a)$$

$$T_{bcs} = \frac{(UA + \dot{m}c_p)T_R - \dot{m}c_pT_H - \dot{q}_G}{UA} \qquad (4.21b)$$

The sensible cooling coil load rate can be found from substituting $\dot{m} = \dot{m}K'$ in Eq. (4.4) giving:

$$\dot{q}_{cs} = K'\dot{m}c_p[T_m - T_c]^+ = K'(T_A)\ \dot{m}c_p\ [T_A - \frac{T_c - (1 - k)T_R}{k}]^+ \qquad (4.22)$$

where:

$$U_{fcs} = K'(T_A)\ \dot{m}c_p \qquad (4.22a)$$

$$T_{bcs} = \frac{T_c - (1 - k)T_R}{k} \qquad (4.22b)$$

Equation (4.22) is a nonlinear function of T_A because of the presence of $K'(T_A)$.

Similarly, heating load is found by substituting $\dot{m} = \dot{m}(1 - K')$ into Eq. (2.3):

$$\dot{q}_h = (1 - K'(T_A))\ \dot{m}c_p\ [T_A - \frac{T_H - (1 - k)T_R}{k}]^+ \qquad (4.23)$$

where: $$U_{fh} = (1 - K'(T_A))\,\dot{m}c_p \tag{4.23a}$$

$$T_{bh} = \frac{T_H - (1 - k)T_R}{k} \tag{4.23b}$$

Note that Eq. (4.22b) is the same as Eq. (4.4b).

Latent loads are complicated by the dual mixing of air. Untreated air at mixed specific humidity, ω_m flows through the heating coil and is mixed with cold air at ω_c. The mixed air enters the zone and picks up latent heat ω_L to give return specific humidity, ω_r:

$$\div_r = K'\omega_c + (1 - K')\,\omega_m + \omega_L \tag{4.24}$$

To solve for mixed specific humidity, ω_m, ω_r in Eq. (4.24) is substituted into Eq. (4.8) and gives ω_m. The expression for ω_m substituted into Eq. (2.5) where $\dot{m} = K'\dot{m}$, $\omega_{out} = \omega_c$ and $\omega_{in} = \omega_m$ gives:

$$\dot{q}_{cL} = \frac{k\dot{m}h_{fg}}{1 - (1 - k)(1 - K'(T_A))}\left[\omega_A - \left(\omega_c - \frac{1 - k}{k}\,\omega_L\right)\right]^+ \tag{4.25}$$

an expression in ω_A for which:

$$U_{fcL} = \frac{k\dot{m}h_{fg}}{1 - (1 - k)(1 - K'(T_A))} \tag{4.25a}$$

$$\omega_{bcL} = \omega_c - \frac{1 - k}{k}\,\omega_L \tag{4.25b}$$

Equation (4.25b) is identical to Eq. (4.9b). U_{fcL} is noted as the latter in Table 4.4 which summarizes the U_f's and T_b's. Two asterisks next to several equation numbers on the table denote the fact that those expressions contain $K'(T_A)$ whose U_f and T_b are also given on the table.

In a dual duct economizer cycle (DDME), k is simply set at k = 1 or k_{min} as terminal reheat economizer was. For k = 1, the latent expression in Eq. (4.25) simplifies and is equal to that for terminal reheat when k = 1 (Eq. 4.13.). The sensible loads in this range reduce when k = 1 is substituted to give the following expression for heating:

$$\dot{q}_h = U_{fh}[T_H - T_A]^+ \qquad (4.26)$$

where U_{fh} is as in Eq. (4.23a) and

$$T_{bh} = T_H \qquad (4.26b)$$

The following expression results for sensible cooling:

$$\dot{q}_{cs} = U_{fcs}[T_A - T_c]^+ \qquad (4.27)$$

where U_{fcs} is as in Eq. (4.22a) and T_{bc} is the same as Eq. (4.12b).

The heating coil load becomes linear in the free cooling range 3 in Fig. 4.3 because $T_m = T_c$ and system operation resembles that of terminal reheat where the hot stream is called upon to moderate an incoming stream at T_c. As a result, T_{bh} and U_{fh} reduce to the expressions for TRH. The U_f and T_b quantities for DDME can be found in Table 4.4.

Three Deck (TD) systems' mixing equations at point i in Fig. 4.8 are quite similar to those of the DDM. However, since only cooling or heating is ever done by the system, the two functions may be separated. Zone inlet temperature T_i is found as for DDM and K' is given by Eq. (4.21) where $T_H = T_m$. Substituting $K'\dot{m}$ into Eq. (2.4) for $\dot{m}$ and again solving for $\dot{q}_{cs}$ results in the following:

$$\dot{q}_{cs} = (\dot{m}_o c_p + UA)[T_A - (T_R - \frac{\dot{q}_G}{UA + \dot{m}_o c_p})]^+ \qquad (4.28)$$

Equation (4.28) is the same as for the cooling portion of VAV, Eq. (4.16). $\dot{q}_h$ is derived similarly to $\dot{q}_{cs}$ and results in an equation in which $U_{fh} = U_{fcs}$ and $T_{bh} = T_{bcs}$. The heating equation uses the cooling conductance factor and base temperature as preheating does in other HVAC systems.

The latent cooling load equation is a fairly complex one as derived in Appendix A. Because the sensible load expressions are the same as for the cooling portion of VAV which is the mode of operation at higher ambient temperatures where latent loads occur, it seems reasonable to expect that the TD latent load will be close to the VAV load. Thus, U_{fcL} and ω_{bcL} are taken the same as for VAV.

The TD system, then, operates essentially as a VAV system without the minimum air constraint because the air in the third untreated

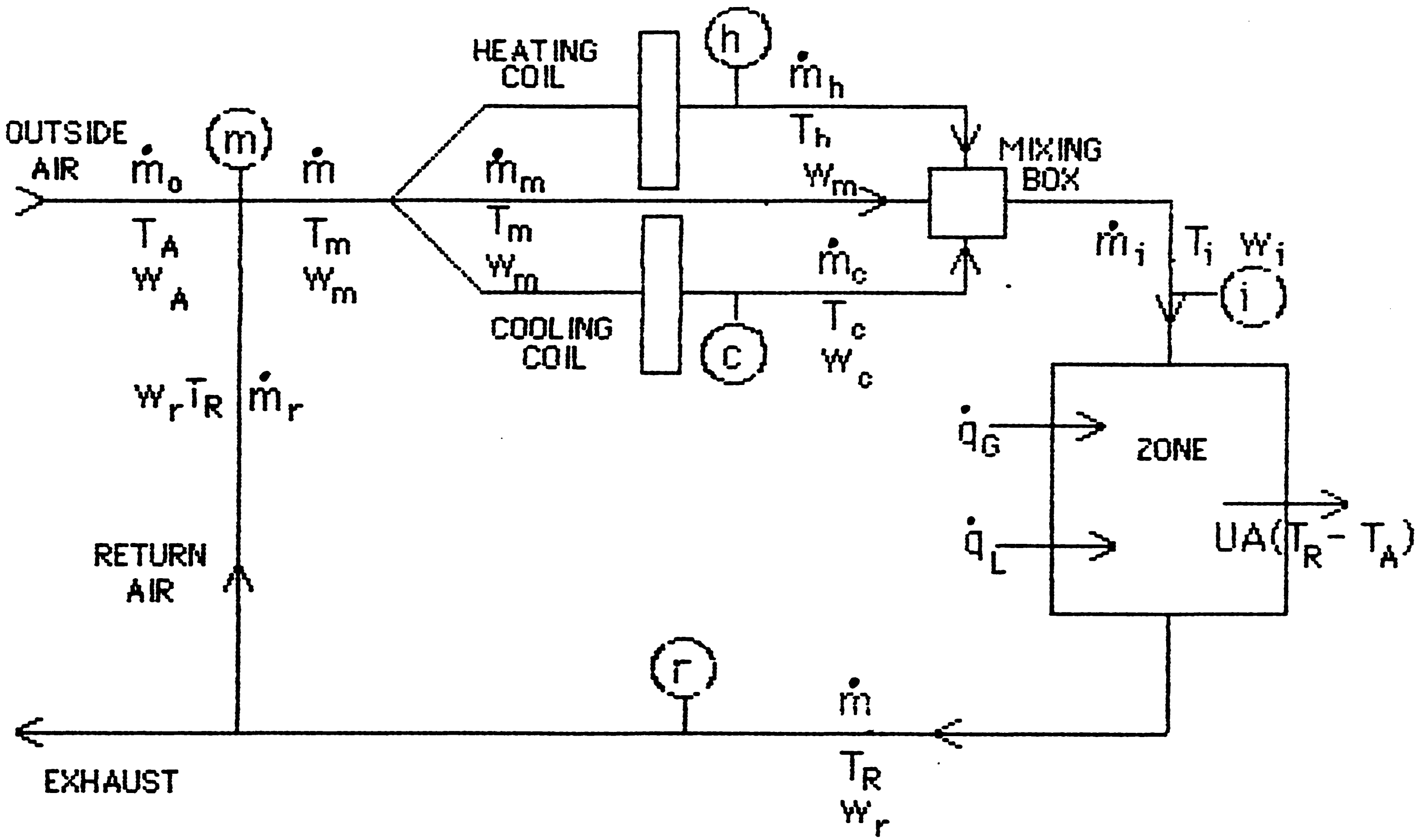


Fig. 4.8. Diagram of a Three Deck HVAC System.

Table 4.4. Equation Numbers of Expressions in Chapter 4 Containing Conductance Factors, Base Temperatures and Base Humidity for Dual Duct Systems

System	Temperature Range		Heating		Sensible Cooling		Latent Cooling	
Abbr.	Low	High	U_{fh}	T_{bh}	U_{fcs}	T_{bcs}	U_{fcL}	ω_{bcL}
DDM	$-\infty$	∞	4.23a**	4.23b	4.22a**	4.22b	4.25a**	4.9b
DDME	T_R	∞	4.23a**	4.23b	4.22a**	4.22b	4.25a**	4.9b
	T_c	T_R	4.23a**	4.26b	4.22a	4.12b	4.13a	4.13b
	4.4b	T_c	4.6a	4.6b	0	---	0	---
	$-\infty$	4.4b	4.23a**	4.23b	4.22a**	4.22b	4.25a	4.9b
DDMD	T_{AC}	$-\infty$	4.23a** (T_{RC})	4.23b (T_{RC})	4.22a** (T_{RC})	4.22b (T_{RC})	4.25a** (T_{RC})	4.9b
	T_{AH}	T_{AC}	0	---	0	---	0	---
	$-\infty$	T_{AH}	4.23a** (T_{RH})	4.23b (T_{RH})	4.22a** (T_{RH})	4.22b (T_{RH})	4.25a** (T_{RH})	4.9b
TD	$-\infty$	∞	4.16a	4.16b	4.16a	4.16b	4.17a	4.17b*
**$K'(T_A)$	$-\infty$	∞	---	---	4.21a	4.21b	---	---

duct is an extra source of ventilation. This conclusion is not a readily apparent one made simply by looking at system layouts. The method of combining all zone and air system energy and mass balances into one coil load expression gives valuable insights into system thermal operation.

An economizer cycle was not applied to this system. U_f and T_b values are listed in Table 4.4 along with the DDM systems.

4.2 Introduction of Equivalent Degree-Day Ideas

A degree-day (DD) as discussed in Chapter 3 is the summation of positive values of a temperature difference between ambient temperature and some base temperature (T_b). DD's are multiplied by conductance factor U_f, constant with ambient temperature T_A, resulting in total coil energy Q. Total coil energy multiplied by a fuel efficiency ηV, also constant with T_A, gives a total equipment energy, E. The base temperature and conductance factor originate from a coil load equation with one of the linear forms found in Table 4.1. Coil load equations originate from doing energy balances on the system under consideration. For a coil load expression which is a linear function of temperature and conductance factor, an equipment efficiency, and a set of bin or hourly data for a month, degree-days are used to calculate total coil energy and total equipment energy required in that month.

The process of going from coil rate equation to total equipment load using degree-day summations is shown in Table 4.5 for heating,

Table 4.5. Procedure for Obtaining Equipment Energy Using Degree-Days

Load	Load Equation $\dot{q}$	Degree-Day Equation (DD)	Coil Energy (Q)	Equipment Energy (E)
Heating	$U_{fh}[T_{bh} - T_A]^+$	$\sum_{T_A} [T_{bh} - T_A]^+ N_A$	$U_{fh}DD_h$	$\frac{Q_{Ph} + Q_h}{\eta V}$
Preheating	$U_{fcs}[T_{bcs} - T_A]^+$	$\sum_{T_A} [T_{bcs} - T_A]^+ N_A$	$U_{fcs}DD_{Ph}$	
Sensible Cooling	$U_{fcs}[T_A - T_{bcs}]^+$	$\sum_{T_A} [T_A - T_{bcs}]^+ N_A$	$U_{fc}DD_{cs}$	$\frac{Q_{cs} + Q_{cL}}{COP}$
Latent Cooling	$U_{fcL}[\omega_A - \omega_{bcL}]^+$	$\sum_{\omega_A} [\omega_A - \omega_{bcL}]^+ N_A$	$U_{fL}DD_{cL}$	

preheating, sensible cooling and latent cooling loads. In reality the quantity summed is the entire $U_f[T_A - T_b]$ expression but because U_f is constant with T_A, only the portion of the rate that varies with temperature is summed in the degree-day summation. The COP and ηV terms are cooling and heating equipment characteristics and are both constant values here but need not be so in general.

The HVAC systems in Section 4.1 which have coil load equations fitting the forms in Table 4.1 are the sensible coil loads for TRH, TRHE, TRHD, VAV, and TD, and the TRH latent load. Thus, DD_h for TRH is:

$$DD_h = \sum_{T_A} [T_A - T_b]^+ N_A \tag{4.29}$$

where T_b is the base temperature given in Eq. (4.6b). The resulting total heating coil load is:

$$Q_h = U_f \, DD_h \tag{4.30}$$

where U_f is the conductance factor in Eq. (4.6a).

The rest of the system load equations derived in Section 4.1 do not fit the form for either of two reasons. Some have a nonconstant U_f term (with respect to T_A) as in the case of all DDM, DDME, and DDMD loads and the cooling load for the second VAVE temperature range. For others, part of the base temperature or base humidity varies with T_A as is the case with all VAV and TD latent loads.

Either way, the load is expressed as some nonlinear function of T_A, $F(T_A)$ multiplied by some term that is constant with T_A termed C_f. Coil energies are obtained for these systems by summing the number of hours at T_A multiplied by the rate, $\dot{q}$ over all ambient temperatures. As was pointed out for degree-day sums, the whole coil rate equation is summed but because C_f is constant with ambient temperature, it is taken outside the summation sign and only the product of the function of temperature and number of hours at that temperature are summed. The summed quantity cannot properly be called a degree-day although it performs the same function, so it will be termed the equivalent degree-day (EDD) and the constant multiplying factor C_f, will be called the equivalent conductance factor (ECF). Thus, as is shown in Table 4.6, any load equation with a constant portion C_f and a portion $F(T_A)$ varying with respect to T_A may have the latter summed over T_A to give equivalent degree-days. EDD's multiplied by the equivalent conductance factor (constant portion) give coil load.

Sensible cooling load for DDM is taken as an example to illustrate how EDD's work. The expression for $\dot{q}_{cs}$ has the following form:

$$\dot{q}_{cs} = \frac{UA}{T_H - T_c} [T_A - T_{b4.21}][T_A - T_{b4.22}] \qquad (4.31)$$

Where the temperature difference equation for $K'(T_A)$ is represented by the second term in brackets and the composite is nonlinear in T_A. Thus:

$$C_{fcs} = \frac{UA}{T_H - T_c} \tag{4.31a}$$

$$F_{cs}(T_A) = [T_A - T_{b4.21}][T_A - T_{b4.22}] \tag{4.31b}$$

and EDD's, total coil load and total equipment loads may be found as per Table 4.6. Another example using DDM latent load recalls that Eq. (4.25) has the form:

$$\dot{q}_{cL} = \frac{k\dot{m}h_{fg}}{1 - (1 - K'(T_A))(1 - k)} [\omega_A - \omega_{bL}]^+ \tag{4.32}$$

Because K' varies with T_A, EDD must be used, giving F and C_f as:

$$F_{cL}(T_A) = \frac{[\omega_A - \omega_{bL}]^+}{1 - (1- K'(T_A))(1 - k)} \tag{4.32a}$$

$$C_{fcL} = k\dot{m}h_{fg} \tag{4.32b}$$

Now, when considering equipment energy totals, it is often necessary to be able to account for equipment performance which varies with T_A. This is certainly the case for chiller COP's. An equipment performance function of COP(T_A) must be divided into the $\dot{q}_{cs} + \dot{q}_{cL}$ cooling load sum and this entire expression summed as the EDD function. Expressions for EDD's when equipment performance is a function of T_A are shown in Table 4.7. Multiplying EDD by a C_f in this case is not necessary, because EDD gives total equipment load directly.

Table 4.6. Procedure for Obtaining Equipment Energy Using Equivalent Degree Days for Constant Equipment Performance

Load	Load Equation $\dot{q}$	Equivalent DD (EDD)	Coil Energy (Q)	Equipment Energy (E)
Heating	$C_{fh}F_h(T_A)^+$	$\sum_{T_A} F_h(T_A)^+ N_A$	$C_{fh}\ EDD_h$	$\frac{Q_{Ph} + Q_h}{nV}$
Preheating	$C_{fcs}(-F_{cs}(T_A)^-)$	$-\sum F_{cs}(T_A)^- N_A$	$C_{fcs}\ EDD_{Ph}$	
Sensible Cooling	$C_{fcs}F_{cs}(T_A)^+$	$\sum_{T_A} F_{cs}(T_A)^+ N_A$	$C_{fc}\ EDD_{cs}$	$\frac{Q_{cs} + Q_{cL}}{COP}$
Latent Cooling	$C_{vcL}F_{cL}(T_A,\omega_A)^+$	$\sum_{T_A,\omega_A} F_{cL}(T_A,\omega_A)^+ N_A$	$C_{fcL}\ EDD_{cL}$	

Table 4.7. Procedure for Obtaining Equipment Energy Using Equivalent Degree-Days and Equipment Performance that Varies With Temperature

Load	Coil Rate $\dot{q}$	Equipment Performance	Equivalent Degre-Day	Equipment Energy (E)
Heating	$C_{fh}F_h(T_A)^+$	$\eta V(T_A)$	$\sum_{T_A} \frac{C_{fh}F_h(T_A)^+ - C_{fcs}F_{cs}(T_A)^-}{\eta V(T_A)}$	EDD_h
Preheating	$C_{fcs}(-F_c(T_A)^-)$			
Sensible Cooling	$C_{fcs}F_c(T_A)^+$	$COP(T_A)$	$\sum_{T_A} \frac{C_{fcs}F_{cs}(T_A)^+ + C_{fcL}F_{cL}(T_A)^+}{COP(T_A)}$	EDD_c
Latent Cooling	$C_{fcL}F_{cL}(T_A,\omega_A)^+$			

Thus, any function of T_A can be summed using EDD's. Seen in this light, degree-day summations are a special subset of EDD summations for which $F(T_A) = [T_A - T_b]$. The same temperature and humidity data may be used for EDD's as was discussed in Chapter 3 for DD's. These are ambient temperature/specific humidity data in hourly or bin format. The option of using Erbs' correlation for direct integration of degree-days will not be extended to all EDD's, however, because an analytic solution to the integral involved has not been found for nonlinear functions of ambient temperature.

It should also be noted that, as with DD's, EDD's are summed separately over dead band or economizer operational temperature ranges. Expressions for $F(T_A)$ in each range are summed in EDD's and, multiplied by their respective C_f's then added together to give the total coil load over the entire ambient temperature range.

4.3 Rate Expressions For Systems Serving More Than One Zone

The rate equations in Section 4.1 were all derived for a single zone served by a single set of coils. In reality as many as ten or twenty zones are served by one central system. Single zone load expressions are added together to give an overall system load equation. How the addition of load expressions is done and the effect it has on the use of equivalent degree-day summation expressions developed in Section 4.2 is discussed in this section.

Modeling each zone with its own system is like modeling a piece of the larger system. The pieces added together make up the one, big central system. Air flows into (or from) each zone are additive. Supply temperatures T_H and T_C are uniform for all zones. The mixed return stream temperature is an air mass flow weighted average of all zone return temperatures. Heating, sensible cooling and latent cooling coil loads for all zones are also added together to give composite heating, sensible cooling, and latent cooling loads.

For instance, the sum of TRH cooling coil rates for two zones is:

$$\sum \dot{q}_{cs} = U_{fc1}[T_A - T_{bcs1}] + U_{fcs2}[T_A - T_{bcs2}] \tag{4.33}$$

The expressions in Eq. (4.33) are combined to give

$$\begin{aligned} \sum \dot{q}_{cs} &= (U_{fcs1} + U_{fcs2})T_A - (U_{fcs1}T_{bcs1} + U_{fcs2}T_{bcs2}) \\ &= (U_{fc1} + U_{fc2})[T_A - \frac{U_{fcs1}T_{bcs1} + U_{fcs2}T_{bcs2}}{U_{fcs1} + U_{fcs2}}]^{+} \end{aligned} \tag{4.34}$$

when one of two conditions exist:

1. Both cooling temperature differences are always positive or always negative.
2. Positive cooling energy in one stream compensates for negative cooling (or preheat) in the other when they occur together (at the same value of T_A).

If the base temperature of zone one is larger than the base temperature of zone two, both streams' cooling loads will be positive when T_A is greater than T_{bcs1} and negative when T_A is less than T_{bcs2}. When T_A is between the two base temperatures, the first half of Eq. (4.33) is negative and the second, positive.

As was discussed in Section 4.1, a negative cooling load is the same as a preheat load. Need for preheat load arises because the return stream no longer has enough heat to warm incoming outside air to give a mixed temperature of T_c or greater. Now, when the return streams from zones 1 and 2 are mixed together and then mixed with the outside air, the heat from zone 2's return stream which would otherwise be a positive load on the cooling coil is available to be used by stream 1 to heat up some of its outside air rather than using a preheater. Compensation of loads is made possible by the fact that the return streams from each zone are mixed and form one large stream that is cooled by one central coil. Thus, an average sensible cooling base temperature T_{BC} results in Eq. (4.34) which is lower than T_{bcs1} and higher than T_{bcs2}:

$$T_{BC} = \frac{U_{fcs1}T_{bcs1} + U_{fcs2}T_{bcs2}}{U_{fcs1} + U_{fcs2}} \tag{4.35}$$

Preheating load for the central system results at ambient temperatures less than T_{BC} in Eq. (4.35) above. A cooling load results for ambient temperatures greater than T_{BC}. The value of average sensible cooling base temperature, T_{BC}, can be used in degree-day summations for preheat and sensible cooling found in Table 4.5.

The same principles hold for adding nonlinear loads in dual duct systems as held for linear load in TRH:

$$\sum \dot{q}_{cs} = K_1'(T_A)^+ \dot{m}_1 c_p[T_A - T_{bcs1}]^+ + K_2'(T_A) \dot{m}_2 c_p[T_A - T_{bcs2}]^+ \quad (4.36)$$

Each $K'(T_A)^+$, the ratio of cold duct air to total system air flow, is always positive, or negative flow through the cold duct would result implying the system was designed improperly. As with TRH, the mixing of return streams will allow the temperature difference portions of the load equations for each zone in Eq. (4.36) to compensate for each other when one is positive and the other negative. Again, return streams mix together to form one large stream which is then cooled by one central cooling coil. Thus, for both linear and nonlinear cooling coil load expressions simple summing of loads is equivalent to applying mixing equations to the return streams, then doing coil calculations with the total stream.

Latent cooling loads can be added together like sensible cooling loads were. "Drier" return streams with a low ω_r mix with "wetter" streams and the sum of outside air streams at ω_A to give a mixed specific humidity. The mixed humidity compensates for differences in base humidities by giving an average base humidity for the whole stream.

Heating coil loads for dual duct and three deck systems can also be added because return streams are mixed together and go through one central heating coil, allowing compensation to occur when one zone's coil rate is positive and the other negative. Terminal reheat coils, however, because they serve only one zone, do not allow for the compensating effect of mixing zone air flows. However, all terminal reheat loads are positive for all ambient temperatures because a negative load indicates that more cooling than the central system was designed to provide is needed. Negative heating indicates a design error. Thus, zone heating coil loads are simply added to give an overall system heating coil load.

The method of addition of coil loads can be used when adding zone temperature limits for an economizer cycle. An average room temperature T_R should be taken for the upper control temperature and an overall cooling base temperature T_{BC} in Eq. (4.34) for the lowest.

Thus, all the systems whether they include one or more zones are modeled using a function of ambient temperature. Some have linear coil load functions and can make use of degree-day summations and Erbs' analytic integration technique to find coil load totals. Others are not and must use the equivalent degree-day (EDD) summations presented. The EDD summation is extremely flexible, allowing both linear and nonlinear rate equations to be summed into total loads. It also allows for equipment performance parameters to vary with ambient temperature.

CHAPTER 5

DISCUSSION OF WEATHER DATA USED IN DEGREE-DAY CALCULATIONS

How the parameters used in degree-day calculations are represented by data has an impact on cooling and heating calculation results. Two major parameters in degree-day calculations are gains (internal and solar) and ambient temperature. Accordingly, this chapter discusses representation of generated and solar loads and the format (size, range, etc) of the bin data generated from Erbs' correlation. The impact of both gains and temperature on degree-day and energy calculations is examined.

5.1 Representation of Solar and Internal Gains

The solar $\dot{q}_S$ and internal $\dot{q}_I$ gain compositely represented as gains, $\dot{q}_G$ in Chapters 3 and 4 appear in base temperature expressions in at least one coil load equation for each system. As such, gains are very important quantities. If large enough, they can affect the value of base temperatures which contain $\dot{q}_G$ and, thus, load totals drastically.

Internal gains from people, lights, etc. usually follow the occupancy schedule of a building. Figure 5.1 shows an example of how internal gains vary with time period for a typical office building. Peak gains occur during the period when most people work from 8 a.m.-4 p.m. Reduced gains occur during several hours when some people work late and janitors clean up. Minimal gains from security lights,

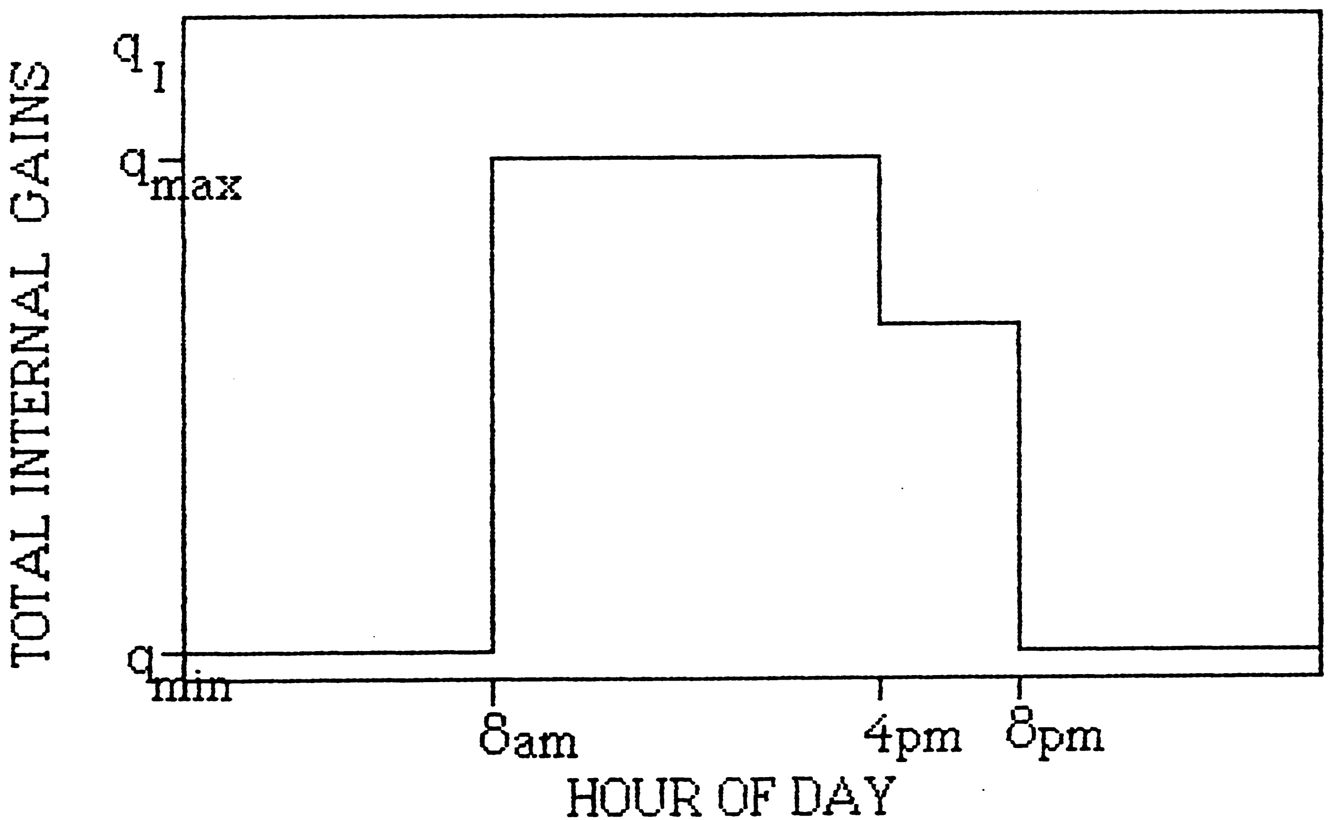


Fig. 5.1. Schedule of Internal Gains for a Typical Large Office Building.

etc. occur during the night when everyone goes home. Internal gains are fairly constant over each of the three time periods in the occupancy schedule and are represented by an average value for each period in coil load equations.

Solar loads, on the other hand, vary more sharply over the day as shown in Fig. 5.2. Three representations of monthly solar gain data for use with hourly temperature data in calculations of coil loads are possible. The first uses an hourly (or instantaneous) value of solar gain for each hour of the month. The second uses the monthly average value of solar gain in a given daylight hour to represent all values of solar gain in that hour during the month. The last uses the monthly average daily solar gain for the month for all daylight hours of the month. Thus, the three representations of solar gains each paired with hourly temperature data are decreasingly complex. For a month of hourly ambient temperature data, the first gives a separate solar gain for each hourly temperature in the daylight hours during the month. For 10 hours of daylight in a 30 day month, there are 300 solar gain, ambient temperature pairs. The second gives one hourly average solar gain in each of the 10 daylight hours. Each hourly average solar gain is matched with 30 ambient temperatures occurring for that hour in the month. The third provides only one average solar gain over all the daylight hours to be used for each of the 300 hourly ambient temperatures occuring in the daylight period.

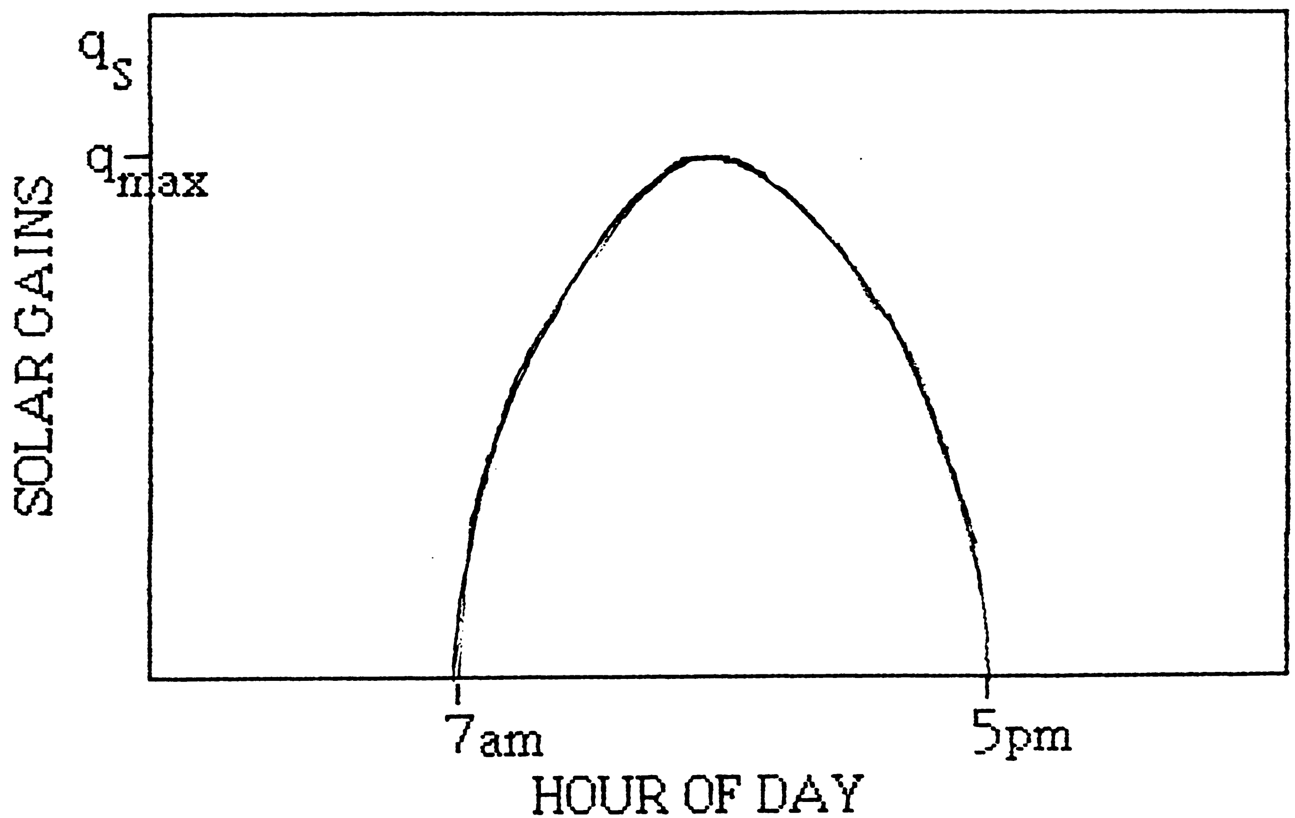


Fig. 5.2. Variation of Solar Gains for a South Facing Zone During One Day.

The use of the three different solar representations described above combined with hourly temperature data in a degree-day summation were considered. The south facing zone of an office building in Madison, Wisconsin whose important design parameters are listed in Table 6.1 was chosen to test the effect of solar load representation on zone cooling and heating load totals. The zone was modeled without internal gains in order to isolate the solar variation and it was assumed to face south to maximize the magnitude of insolation differences. The window module (TYPE 35) of TRNSYS [11], an hourly transient simulation program for calculating the performance of various building systems, was used to give hourly solar gains into the zone. This model calculates solar gain through a window of a specified type and orientation. The solar gain for each hour of each day in a month (or instantaneous solar gain $\dot{q}_i$), was calculated using TRNSYS. The instantaneous values were used to calculate both average gain for each hour in the daylight period in the month, $\dot{q}_{m,h}$ and average gain over all daylight hours in the month, $\dot{q}_m$. Each of the above values for solar gain were then substituted for $\dot{q}_G$ with corresponding hourly T_A values into the following zone heating degree-hour equation:

$$DD_h = \sum_{T_A} [T_R - \frac{\dot{q}_G}{UA} - T_A]^+ N_A \qquad (5.1)$$

The data for actual hourly insolation and ambient temperature were provided from TMY weather tapes for Madison. Assuming that T_R is the same for cooling and heating (no dead band control), the base temperature in Eq. (5.1) above is the same for sensible cooling as for heating, so negative values of the temperature difference expression were summed for cooling load.

The resulting yearly degree-hours are shown in Figs. 5.3 and 5.4. Hourly temperature data from TMY were used for all calculations. The totals labeled Q_i in the figures were found using hourly solar gains for $\dot{q}_s$; $Q_{m,h}$, using the monthly average solar gain for each daylight hour; and Q_m, the monthly average solar gain for all daylight hours. The summation of degree-hours using hourly average solar gains fell in between the summation using instantaneous and that using monthly average gains. The biggest difference in degree-hour totals is seen to occur in the winter months when solar gain variations over a day are highest for south facing zones. The smaller the variations over a day, the less difference there is between the methods of representing solar gains.

If the instantaneous solar degree-hour values are considered "correct", then it appears that using a monthly average solar value is not a good idea. However, solar energy which comes in through a window is not generally a direct load on a system. As mentioned in chapter 2, solar energy comes in windows, hits interior surfaces, raises the surface temperature and so adds heat to the zone. Such heat clearly involves the mechanism of energy storage in building elements. Storage tends to distribute the solar gain effects. The ASHRAE Design Cooling Load method in Ref [2] takes the effect of thermal storage of solar gains in building mass into account by the

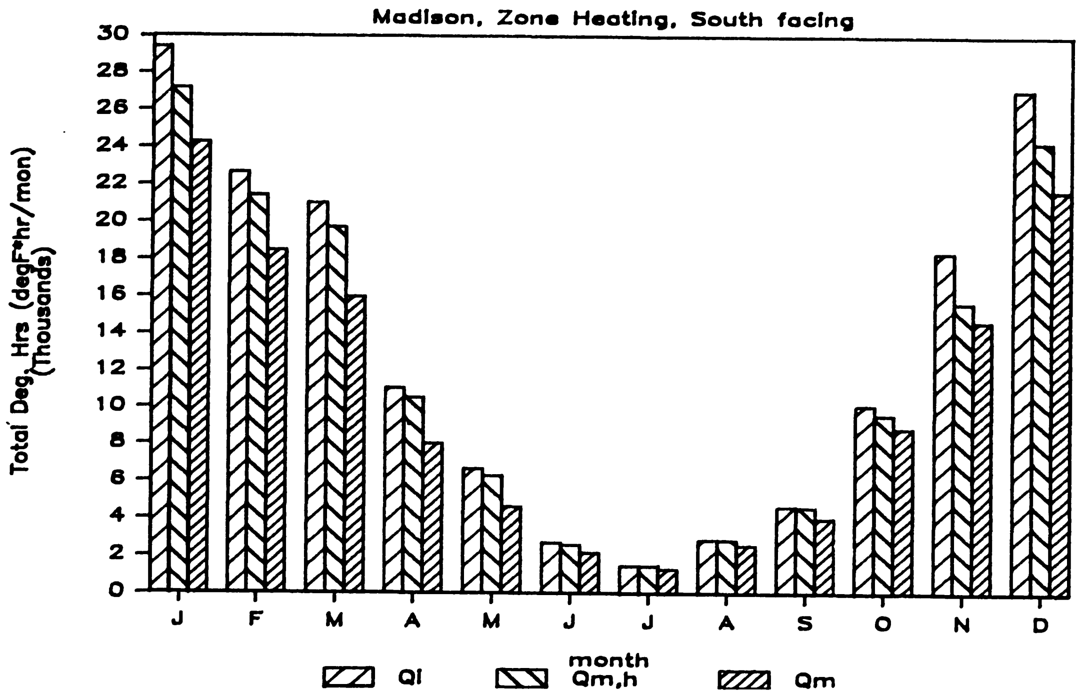


Fig. 5.3. Variation of Monthly Zone Heating Degree-Hours Over a Year in a South Facing Zone in Madison, WI Calculated Using the Three Methods Described in Section 5.1.

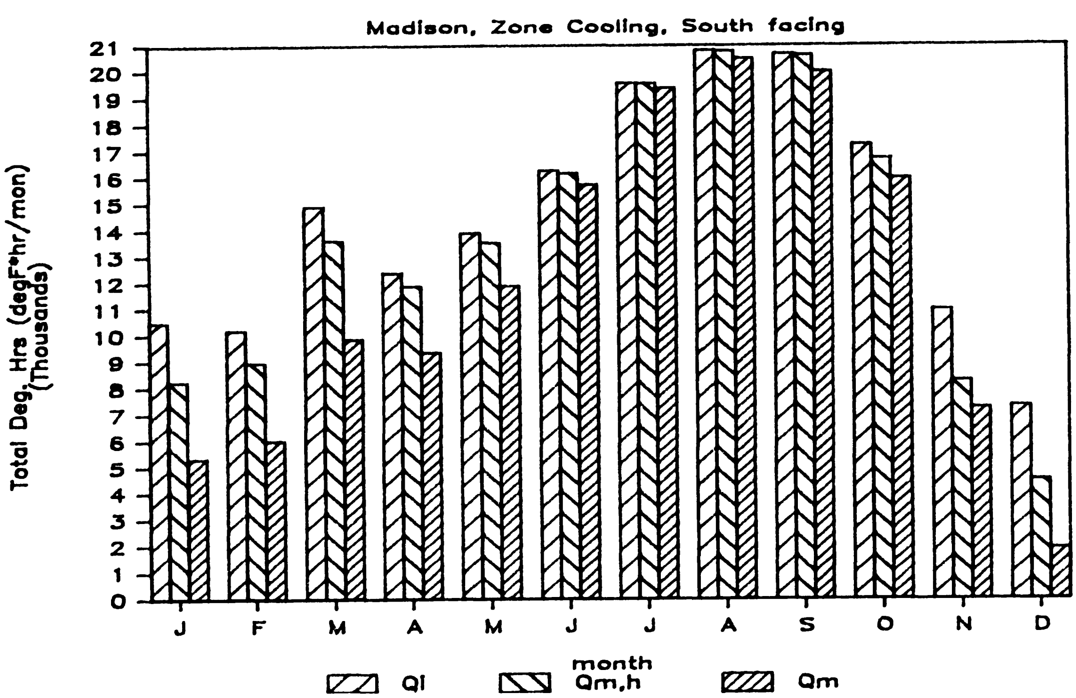


Fig. 5.4. Variation of Monthly Zone Cooling Degree-Hours Over a Year in a South Facing Zone in Madison, WI Calculated Using the Three Methods Described in Section 5.1.

use of a cooling load factor (CLF). The CLF is a number less than one which is multiplied by the incoming solar load through a window to give actual heat rate into the zone which requires cooling. Values for CLF were generated by ASHRAE using transfer function models [2]. Thus, using a daily average of solar gains for the month could be more "correct" than using the hourly instantaneous values.

In Figs. 5.3 and 5.4 both cooling and heating zone degree-hour totals are larger for instantaneous than average cases. Because the instantaneous solar loads vary so much, from zero to large values in the winter, the base temperature varies a great deal, too. Large variation in base temperatures gives larger extremes in overall temperature differences giving either large positive or large negative degree-hours. The $\dot{q}_{m,h}$ and $\dot{q}_m$ cause much less variation in $\dot{q}_G$ and thus, cause less extreme temperature differences.

A case can be made for using the average monthly gain values for both solar and internal gains over a time period larger than an hour. There is an advantage to using time periods greater than an hour in bin summations. Each time period requires its own set of bin temperature from period to period. This is so because a change in parameters gives a change in base temperature and conductance factor or in load function and equivalent conductance factor, necessitating a separate DD or EDD summation for each period in the month. Therefore, when one average solar gain over all daylight hours is used rather than 10 hourly values, one set of bin data rather than 10 is needed.

The percentage difference between Q_m and Q_i totals is as small as 2% and as large as 55%. Because using one monthly average daily solar gain averages solar input to a zone much the same as thermal capacitance does and because it lends itself to bin summation, it will be used in further summations. More study on the matter is recommended.

5.2 Examination of the Impact of the Format of Bin Temperature Data on Degree-Day Summation

This section examines those systems for which sensible load totals are summed from rate equations using degree-days as discussed in Chapter 4 (sensible loads for TRH, VAV, TRHE, and TRHD). Results using Erbs' correlation for degree-days and Erbs' correlation for temperature distribution from which bin data were obtained will be compared. The two should, ideally, give the same total energy because as bin size is made infinitely small, bin summations approach the analytically integrated quantity.

The smaller the size of the bins used to approximate the temperature distribution, the closer the bin summation will come to matching Erbs' analytic integration for DD's. However, smaller bins require more calculations. 5°C, 2°C, and 1°C bins were used to determine heating and cooling coil totals for the systems noted above. All compared well with the analytic degree-days. The 2°C bin totals matched the integrated totals to within +0.1% for TRH and VAV system equations tested. The 5°C bin totals were within +0.5%. 1°C bins, within +0.05% of integrated totals did not improve on the 2°C results significantly. So 2°C bins were deemed adequate to use for further bin summations.

Systems which have an economizer cycle or dead band control use DD's calculated in several operational temperature ranges as discussed in Chapter 4. Analytic and bin totals match better if the temperatures which define the operating ranges are moved to the edge of a bin (at most a move of 1°C here). For instance, in Fig. 5.5, the arrow at 22.2°C represents T_R the lower range temperature for TRHE's highest operating range. With T_R at 22.2°C as shown, all the hours in the 22°C bin are in the second operational temperature range of the economizer cycle. Only half or three quarters of those hours will be integrated in that range by analytic integration which essentially sums infinitely small bins. Thus, a difference between totals resulted when TRHE and TRHD totals were calculated. Two options exist to correct this difference. Both are aimed at including the same number of hours in operational temperature ranges in a bin summation as are included in an analytic integration. One option is to move the temperature defining the operating range to 23°C, the edge of the bin. The other option to correct that situation is to generate bins with edges that fall on the cutoff temperatures of the system in question. When the former was done, agreement between 2°C bin summations and integrated DD's for TRHE and TRHD were as good as for VAV and TRH (±0.05%).

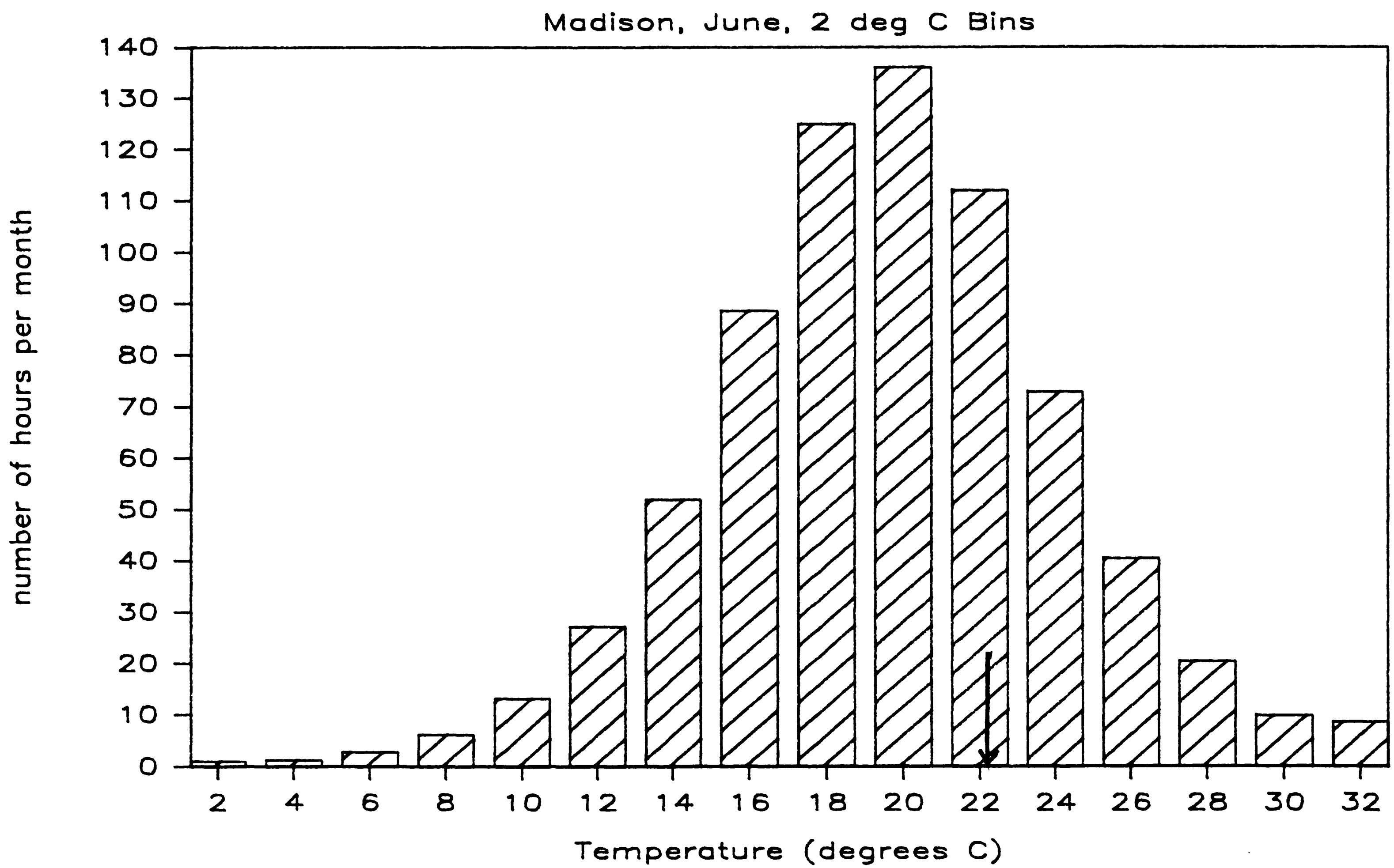


Fig. 5.5. Set of Ambient Temperature Bins for Madison, WI in June With Upper Limit Temperature for Economizer Cycle Control Noted by an Arrow on the Abscissa.

The range of temperatures included in bin distributions derived from Erbs' distribution correlation can be as large as from $-\infty$ to ∞ because of analytical routine of representation. The fewer bins in a distribution, the fewer the number of loads to sum will be. However, the number of hours at extreme temperatures (or tails) is very low. Actual bin distributions have a finite temperature range. Thus, three sets of finite limits were developed to define the range of temperatures included in Erbs' distributed bins. The first set of limits simply requires bins to contain at least 0.01 hours. The second requires that the bin hours from the first distribution be added together starting at each end of the distribution's tails and moving toward the distribution's center until the total hours reach at least 1. The total hours for each end are then assigned to the temperature of the last bin added in. This procedure of adding bin hours from extreme bins is also referred to as "rolling in the tails." The last set of limits rolls the tails into the bins containing high and low temperature for the month in TMY data. Three sets of bin data using these limits were used to find sensible coil energy totals for the TRH, VAV, TRHD, and TRHE systems. Agreement was very good for all system models. TRHE monthly sensible cooling totals are shown compared with the integrated totals as an example in Fig. 5.6. The notation h/l in the figure refers to summation using bins with finite ranges described above. TMY h/l refers to the third set of limits described; 1 hr h/l to the second; and 0.01 hr h/l to the first. ECDD refers to totals using Erbs' correlation for inte-

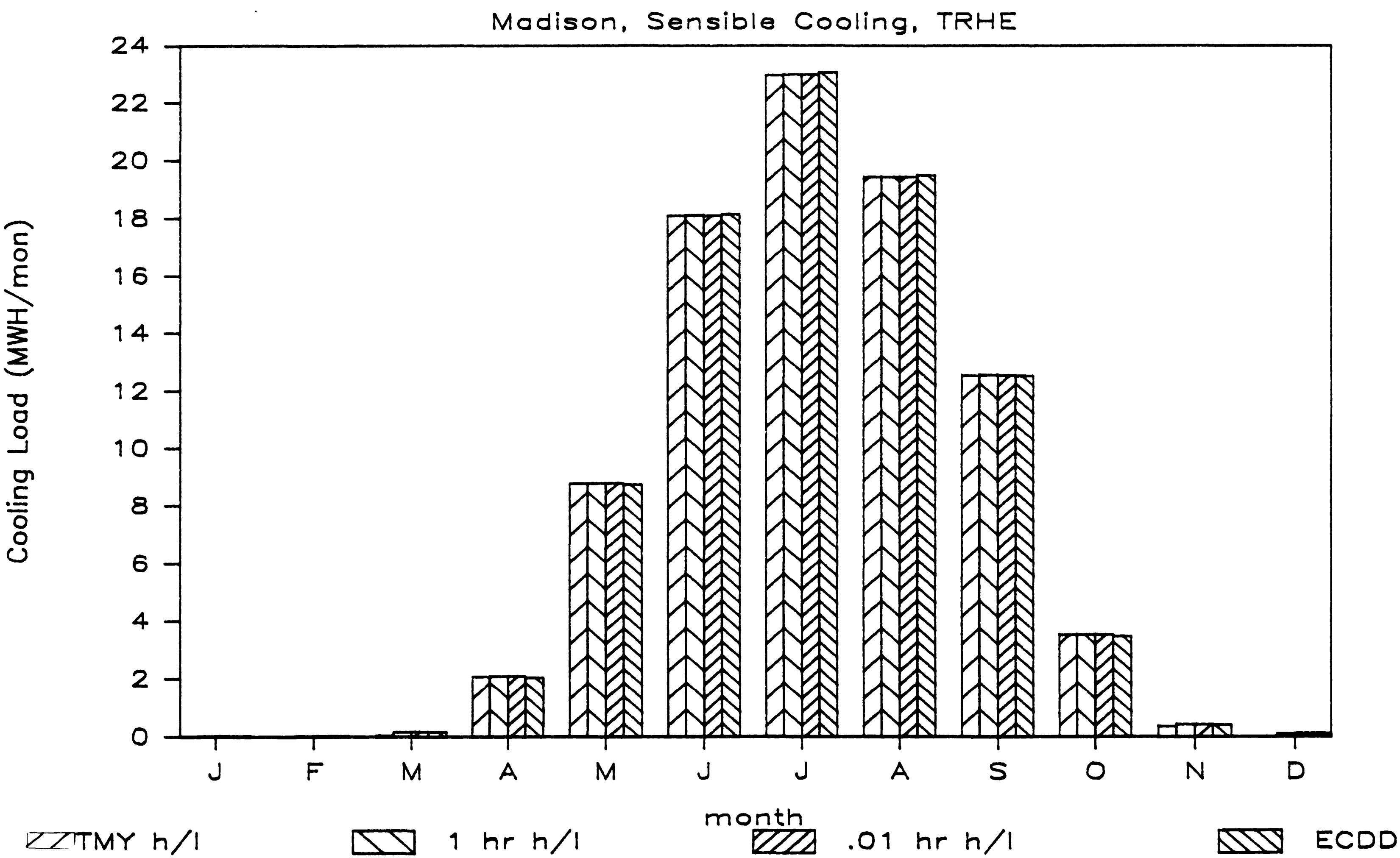


Fig. 5.6. Comparison of Sensible Cooling Coil Totals for a Terminal Reheat Economizer System in Madison, WI Calculated Using Erbs' Degree-Day Correlation and Bin Summations Using the Three Sets of Finite Bins Described in Section 5.2.

grated DD's. Comparison indicates that the ranges have no real impact on load totals. Lack of impact of ranges occurs because at most 10 or 20 hours out of over 700 in a month (the tail hours of the distribution) are altered by range differences. To save on computation, the number of bins should be minimized and to save on data input, the range to roll the tail bins into should not be specified externally to the distribution. Thus, the range specified by the second set of limits (rolling the tails into 1 hour bins) is used for all succeeding bin calculations.

A final point of comparison between analytically integrated and bin coil energy totals is the number of time periods used in the summation. A comparison was made of TRHE coil energy totals calculated using a full day as one period and a day split into the three time periods shown in Fig. 5.1. Bins were generated using Erbs' correlation for temperature distribution for the full day time period and each of three smaller periods shown in Fig. 5.1. When no gains of any sort are included for one and three period bin summations, the three period summations will all use the same base temperatures. When the sum of the three period bin distributions is the same as the one period distribution, total loads will be the same. This was not the case for a comparison of monthly TRHE cooling loads in Madison shown in Fig. 5.7. The agreement between analytic integration and bin totals for both distributions is very good. The difference between the totals calculated using the one period and three period distributions is significant in comparison. This latter difference

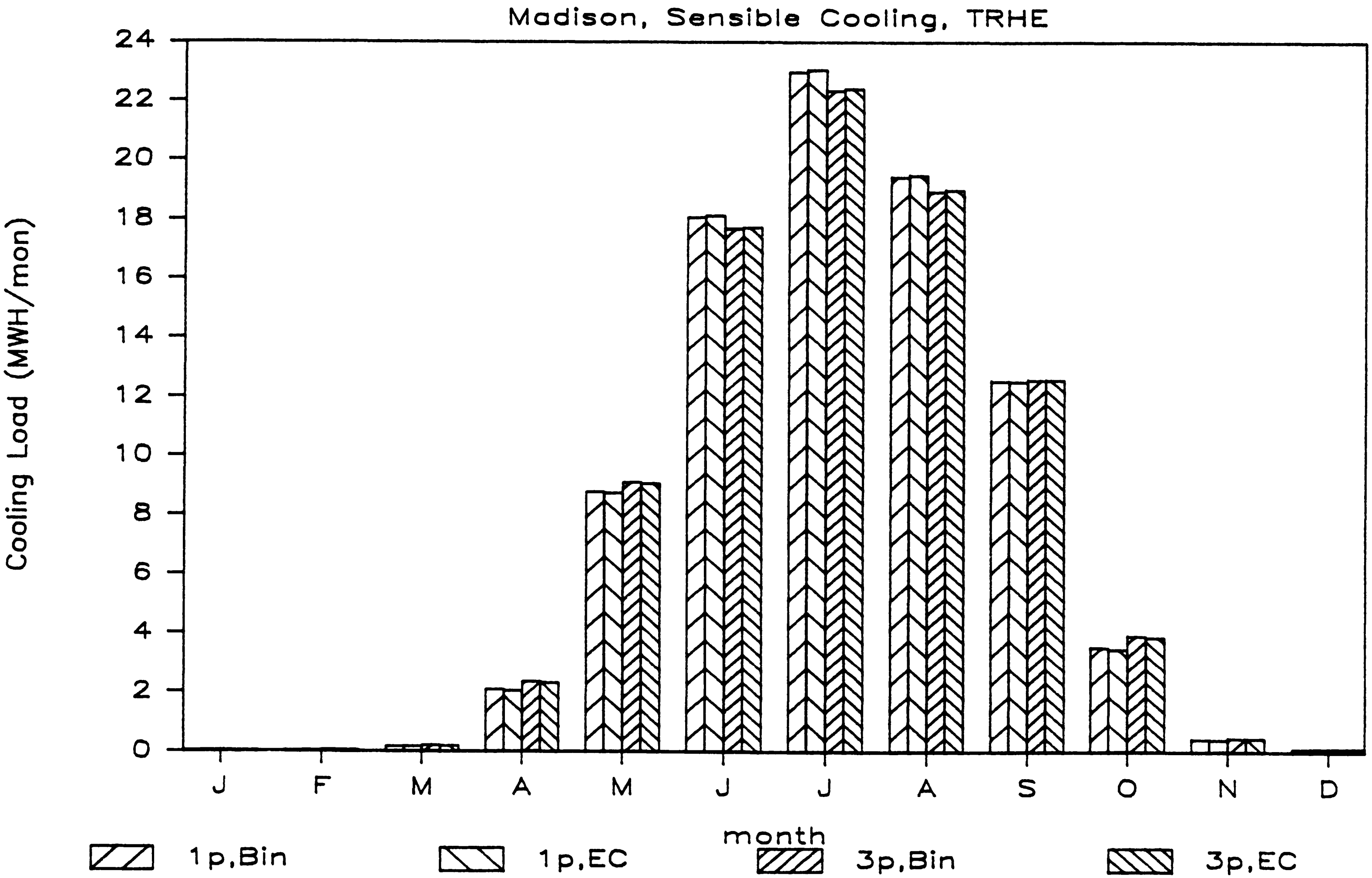


Fig. 5.7. Comparison of Sensible Cooling Coil Totals for a Terminal Reheat Economizer System in Madison, WI Calculated Using Erbs' Degree-Day Correlation and Bin Summations Using 2°C Bins for a Full Day and a Day Split Into Three Periods.

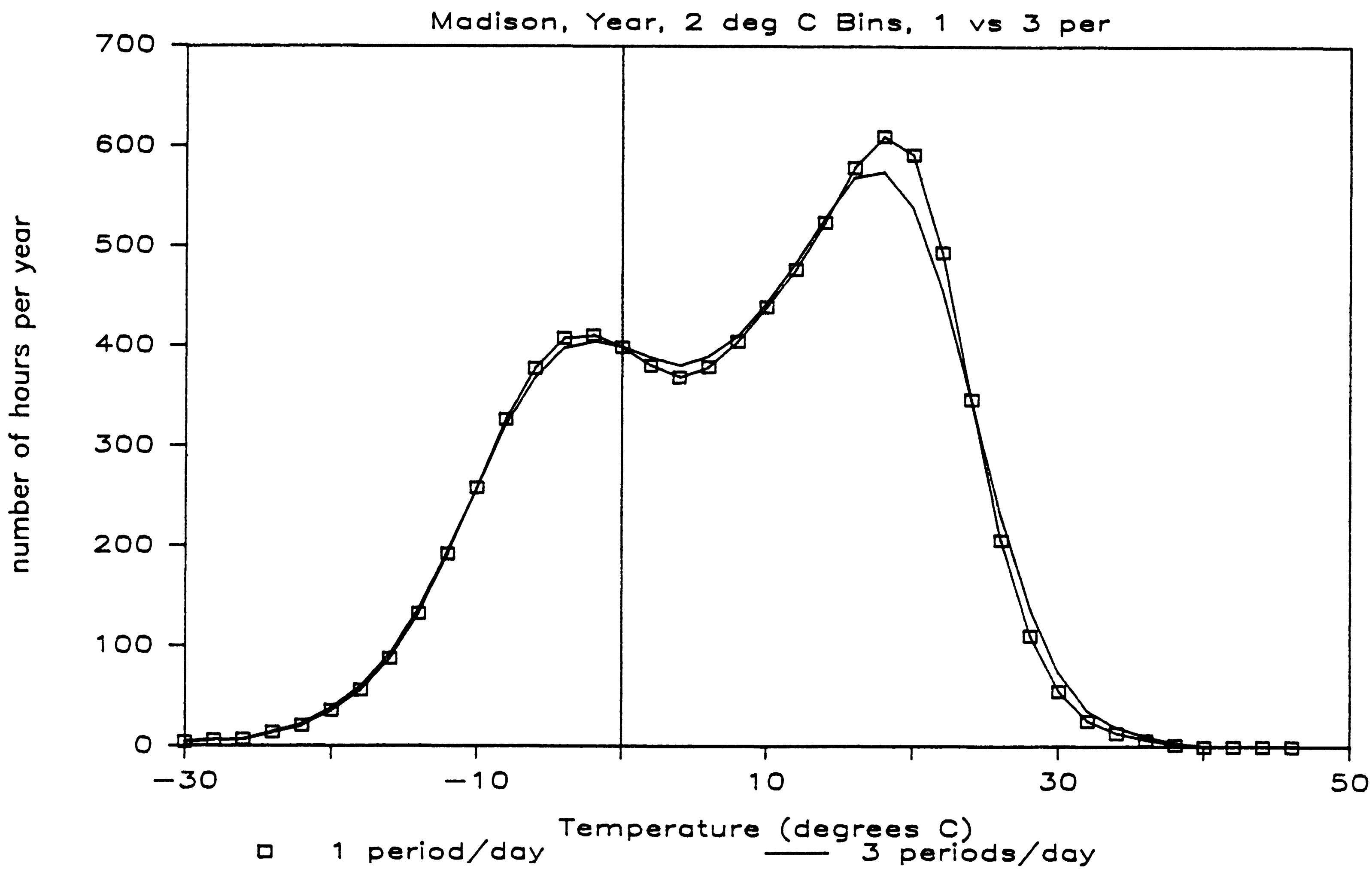


Fig. 5.8. Comparison of 2°C Bin Temperature Data for Madison, WI Generated Using Erbs' Temperature Distribution Correlation for One and Three Periods in a Day.

is explained by Fig. 5.8 which compares the yearly total of bin hours for 1 and 3 periods. The three period distribution is a bit smoother, lower in peaks and higher in tails than the one period distribution. The result is true for monthly distributions as well. The result makes sense because in the summer, peaks occur near higher temperatures and account for more of the cooling load. In the fall the peaks move away from the high temperatures and tails account for cooling loads. In the summer, then, the 1 period totals are larger because there are more hours compared to 3 periods and in the spring and in Fall the 3 period totals are higher, indicating that the tail hour differences dominate. The differences between the totals calculated using the two distributions effectively cancel each other in yearly totals which have difference on the order of less than 1%.

There is another effect of using daily bin distribution versus 3 or more period distributions. The latter allow zone loads to be averaged over occupancy periods rather than an entire 24 hour day. This leads to using more realistic values for $\dot{q}_G$ in each period and so to hopefully more accurate base temperatures. This is a real concern given the sensitivity of zone loads to solar modeling discussed earlier.

Thus, a bin summation scheme using 2°C bins with the tails rolled into one hour limits for a number of time periods which coincide with the occupancy schedule gave results which compared well with an analytic degree-day integration.

CHAPTER 6

COMPARISON OF HOURLY AND BIN DATA IN EQUIVALENT DEGREE-DAY SUMMATIONS FOR TOTAL LOADS IN HVAC SYSTEMS

This chapter will present comparisons between total system coil and equipment loads calculated with bin data and calculated with hourly data for temperature and specific humidity. The purpose is to determine how well the two types of data, used in equivalent degree-day summations, model expected system behavior and then how well the coil and equipment totals match. Agreement is good. Because the bin method requires fewer calculations and fewer input data it provides an efficient alternative to summing actual hourly data.

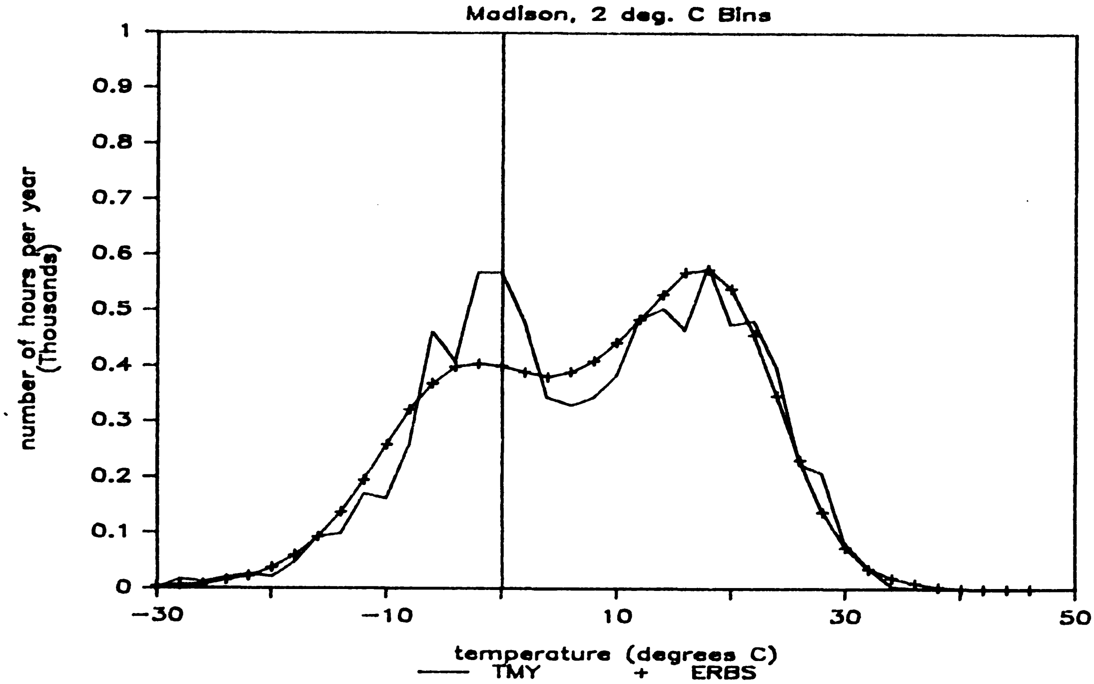
6.1 Discussion of Temperature Data and Building Model Used in Calculations

The hourly temperature and humidity data used in all calculations are taken from TMY weather tapes [12]. Each month represents a long term average set of hourly data. Average monthly temperature and relative humidity ($\bar{T}_m$ and $\bar{\phi}_m$) determined from these TMY hourly data were used to calculate $\bar{T}_{m,h}$ and $\bar{\phi}_{m,h}$ from Erbs' correlation, which in turn were used to find the average over three operating periods (8 a.m.-4 p.m., 4 p.m.-9 p.m., and the rest of the day), $\bar{T}_{m,p}$ and $\bar{\phi}_{m,p}$. The average temperatures for each period were then used in the Erbs temperature distribution equation to generate a set of 2°C bins within the tail bins rolled in to give at least one hour in high and low temperature bins as described in Chapter 5. An ambient specific humidity distribution was calculated using the average relative humidities for each period and the set of temperature bins in the same period to calculate a value for specific humidity (ω_A) for each bin. This procedure for generating temperature and humidity bin data was followed for four sites in the US: Madison, WI, Albuquerque, NM, Seattle, WA, and Miami, FL.

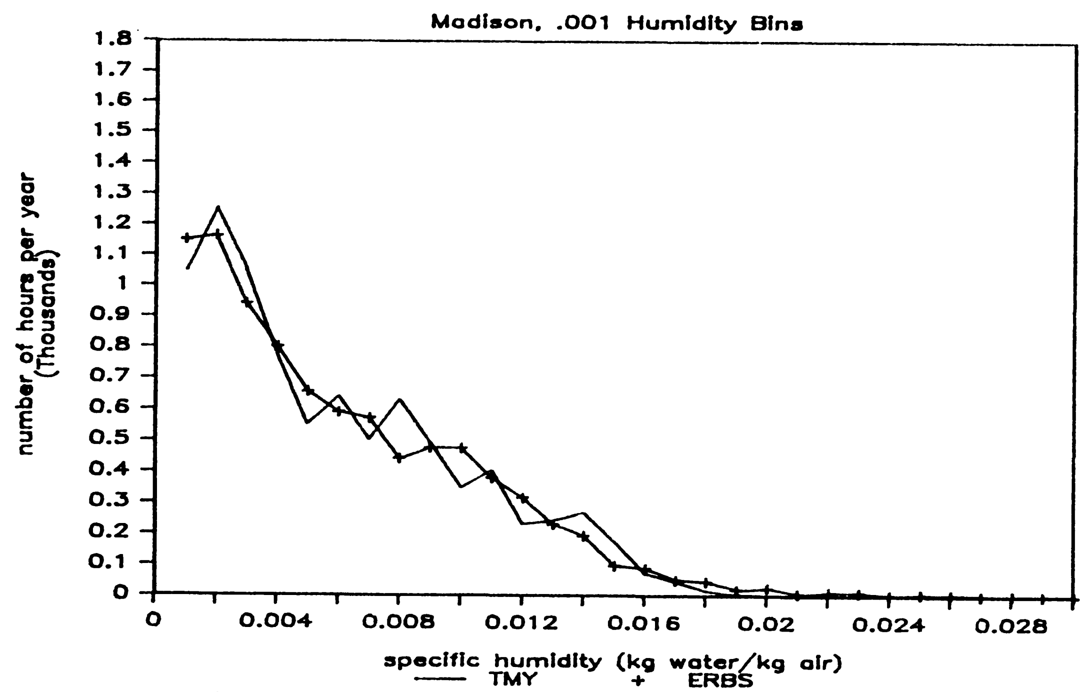
TMY temperature data were then placed in 2°C bins. TMY specific humidity data and the generated humidity distributions were placed in 0.001 kg water/kg air bins. The number of hours in each bin for the year was then determined by summing over 12 months. The yearly bin distributions are shown in Figs. 6.1-6.4. The bin distributions match the TMY distributions quite well for temperature and humidity. Further discussion of differences will take place after comparison of calculations in Section 6.3.

A building zone similar to a perimeter zone in Ref. [13] was chosen as a base case model for all calculations. Figure 6.6 shows the schedule of gains; Fig. 6.5, the floor plan. Table 6.1 gives the design parameter values such as number of people per square foot. Resulting calculation parameter values such as internal gains are listed in Table 6.2.

The primary goal of calculating coil energy totals in this chapter is to compare results using hourly data and results using bin data. The effect on calculations of varying solar gains from month to month would be confused with the effect of using hourly versus bin

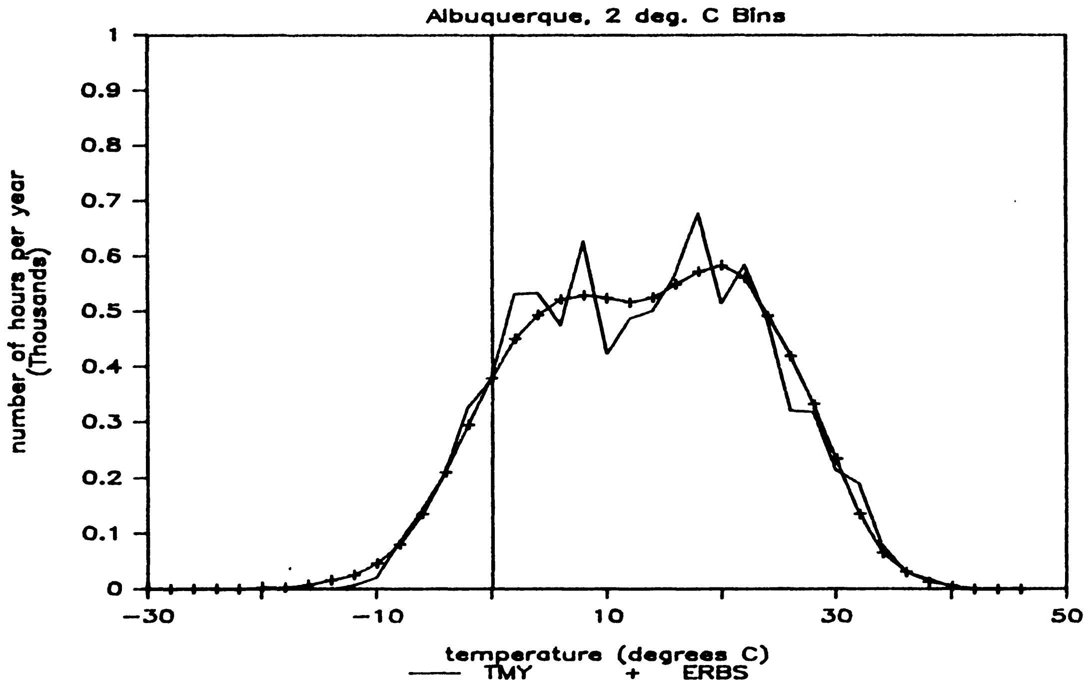


a) 2°C Temperature Bins.

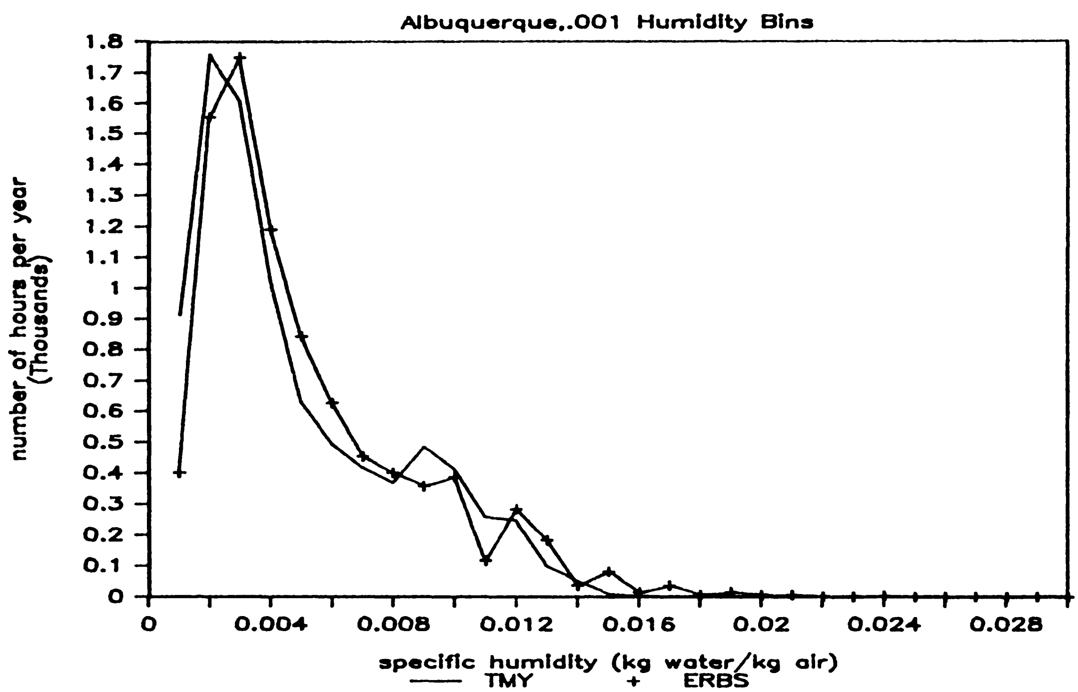


b) 0.001 kg Water/kg Air Humidity Bins.

Fig. 6.1. Comparison of Bin Weather Data Distributions Generated Using Erbs' Correlations for Three Periods in a Day and TMY Hourly Data for Madison, WI;

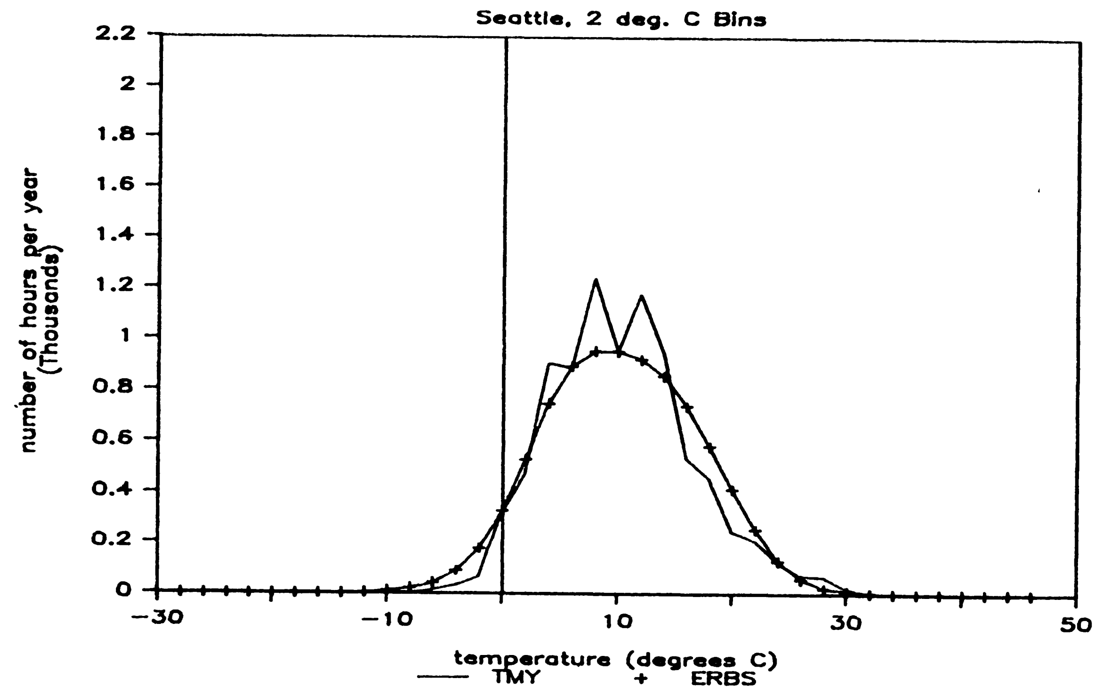


a) 2°C Temperature Bins.

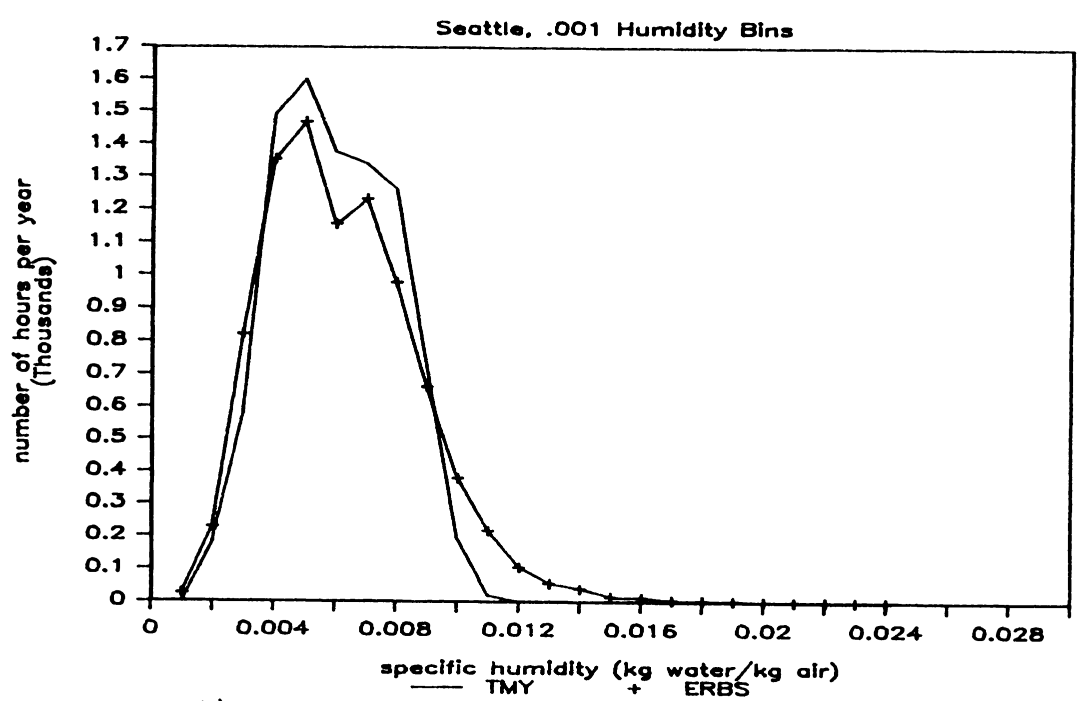


b) 0.001 kg Water/kg Air Humidity Bins.

Fig. 6.2. Comparison of Bin Weather Data Distributions Generated Using Erbs' Correlations for Three Periods in a Day and TMY Hourly Data for Albuquerque, NM.

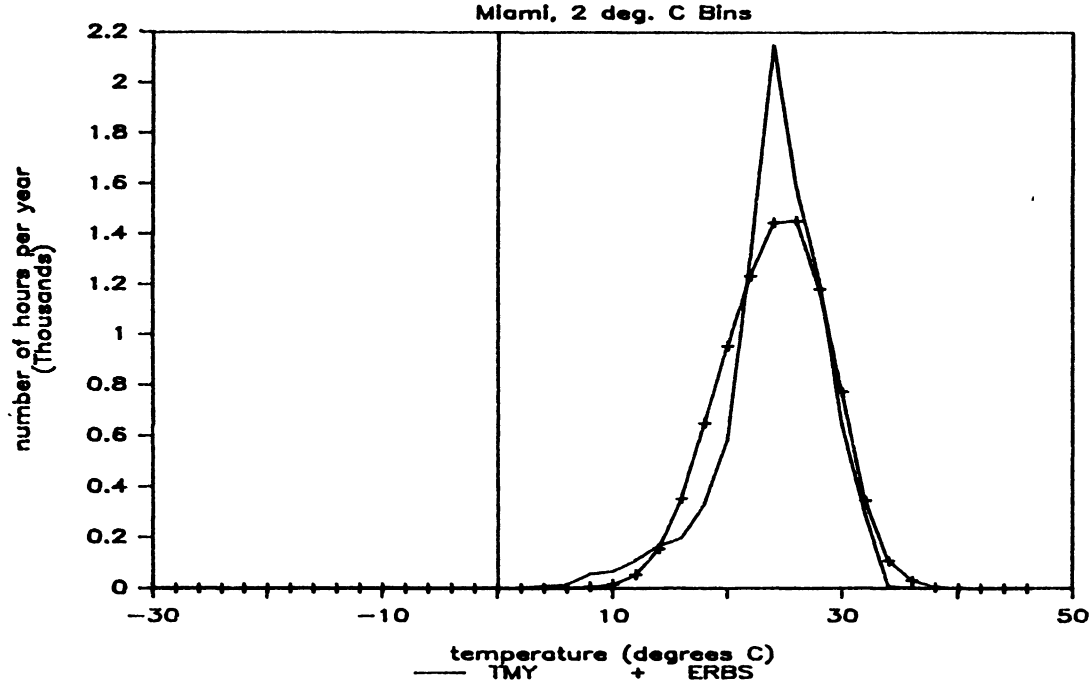


a) 2°C Temperature Bins.

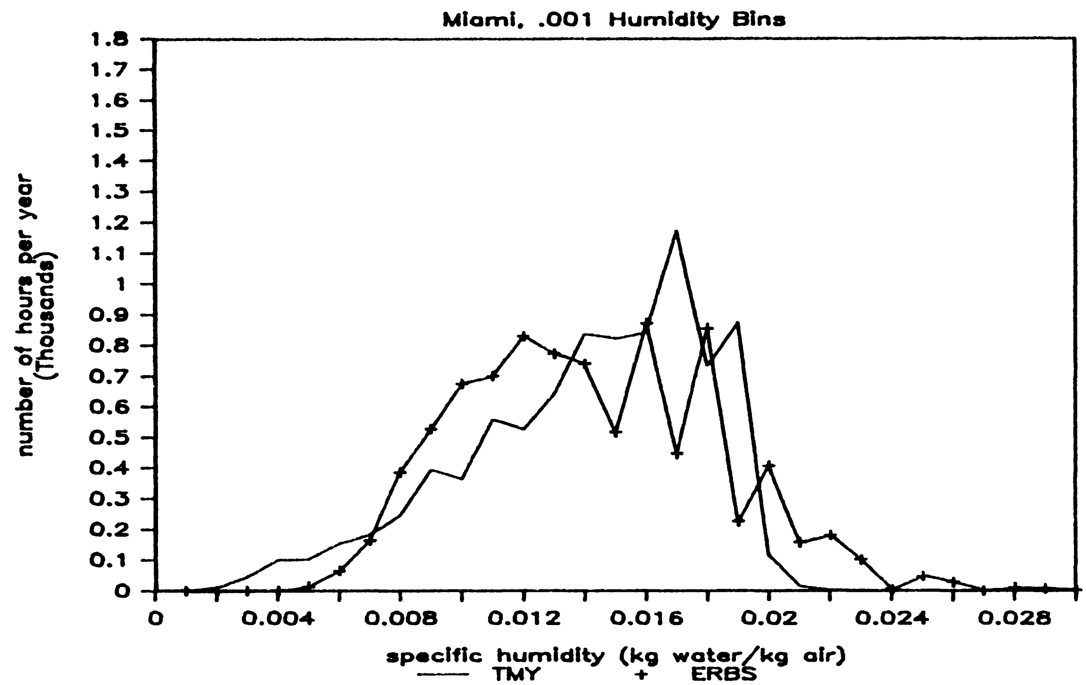


b) 0.001 kg Water/kg Air Humidity Bins.

Fig. 6.3. Comparison of Bin Weather Data Distributions Generated Using Erbs' Correlations for Three Periods in a Day and TMY Hourly Data for Seattle, WA.



a) 2°C Temperature Bins.



b) 0.001 kg Water/kg Air Humidity Bins.

Fig. 6.4. Comparison of Bin Weather Data Distributions Generated Using Erbs' Correlations for Three Periods in a Day and TMY Hourly Data for Miami, FL.

Table 6.1. Building Design Parameter Values Taken Largely from Ref. [3]

Building Design Parameter	Value
Wall U value	0.579 W/m^2-°C
Window U value	3.42 W/m^2-°C
Total wall area	330 m^2
Fraction of window area	0.2
Zone floor area	507 m^2
Heat input from lights	21.5 W/m^2
Occupant density	10 m^2/person
Sensible	140 W/person
Latent	55.6 W/person
Outside air flow per person	0.00849 kg/s person (15 cmf)

Table 6.2. Values of Base Case System Parameters Used in Calculations

Parameter	Base Case Value
Cold supply temperature, T_C	12.78°C (55°F)
Hot supply temperature, T_H	32.22°C (90°F)
Room set temperature, T_R	21.11°C (70°F)
Heating room set temperature, T_{RH}	18.33°C (65°F)
Cooling room set temperature, T_{RC}	23.89°C (75°F)
Outside air flow, $\dot{m}_o$	0.40 kg/s
Flow specific heat, C_p	1006.1 W/°C
Overall exterior U-value, U	1.15 W/m^2-°C
Exposed area, A	330 m^2
Daytime internal sensible gains, $\dot{q}_G$	18,000 W
Daytine internal latent gains, $\dot{q}_L$	3,000 W

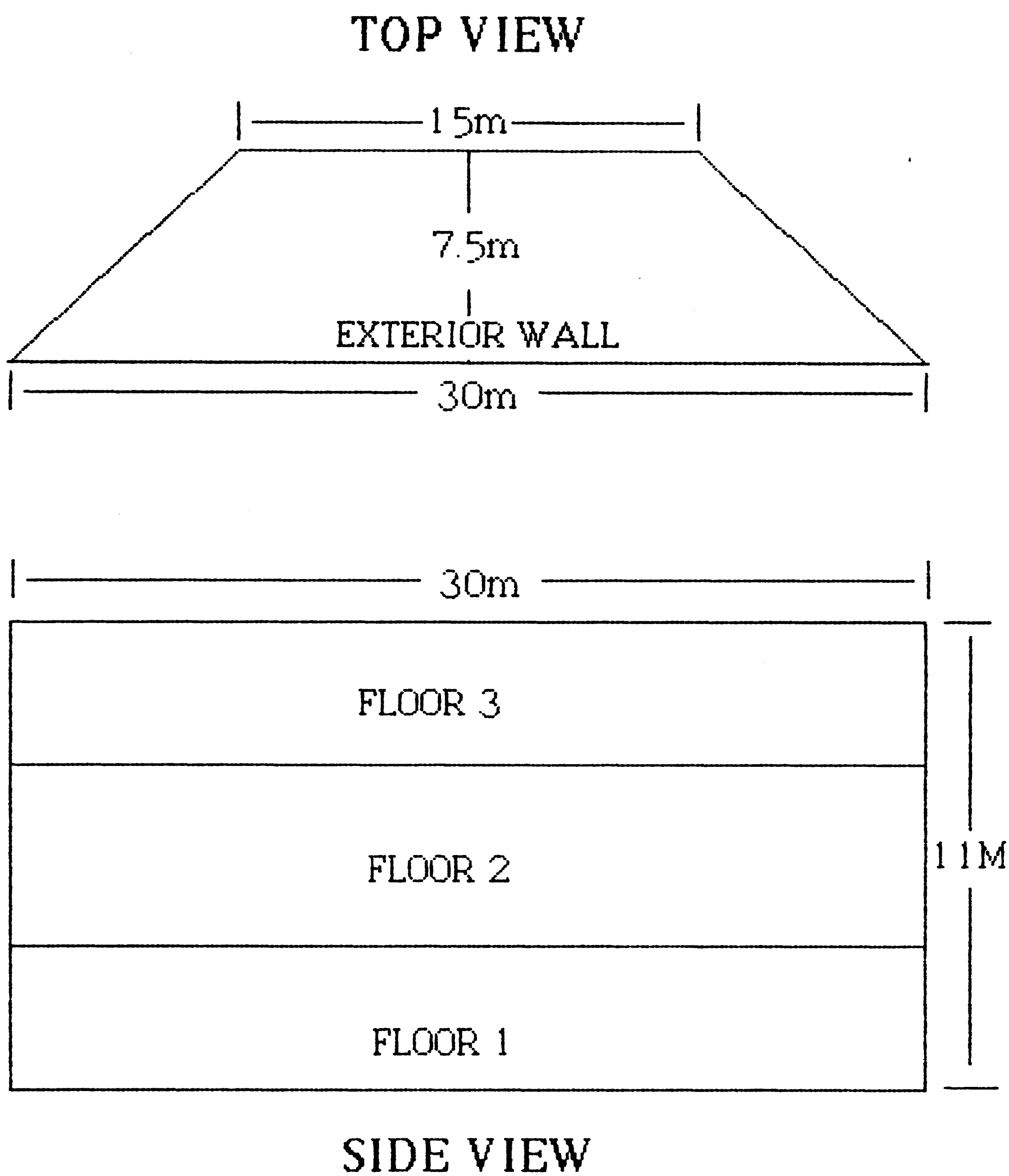


Fig. 6.5. Views of the Base Case Building Used in Section 6.1.

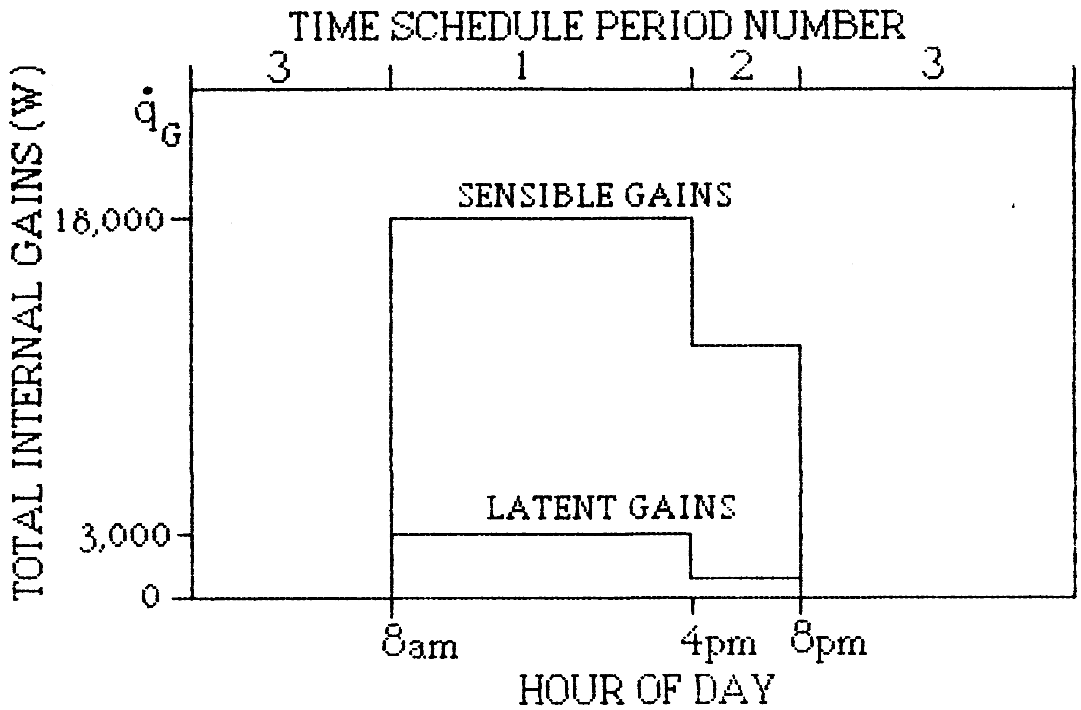


Fig. 6.6. Schedule of Internal Gains (Sensible and Latent) for The Base Case Building Described in Section 6.1.

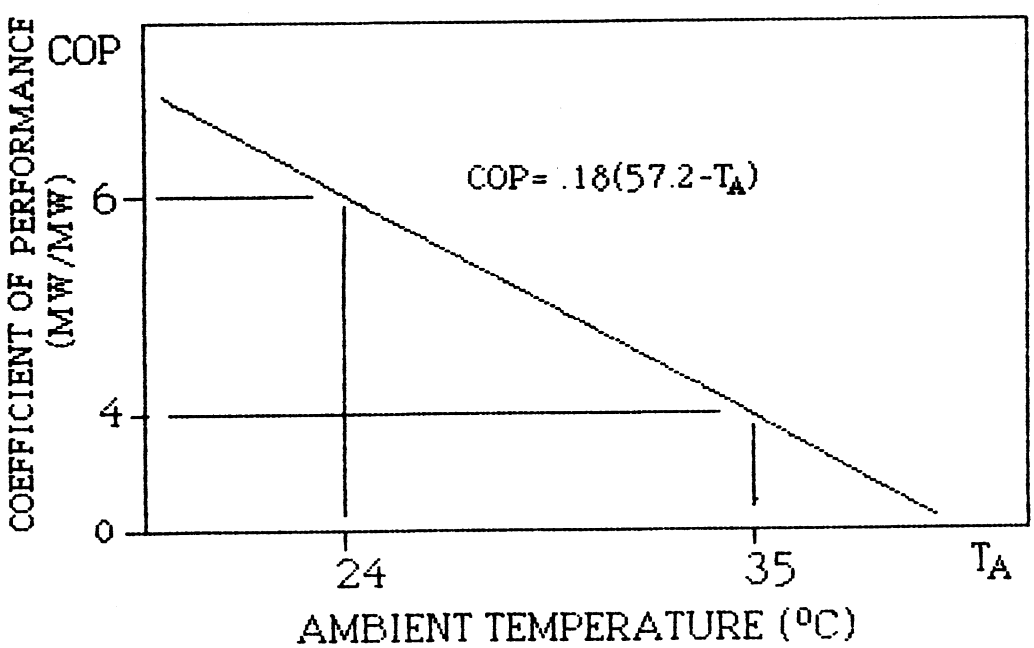


Fig. 6.7. Variation of Chiller COP Used for Chiller Energy Calculations in Sections 6.2 and 6.3.

data. In addition, when solar gains vary from month to month, coil load functions which contain gains will vary as well. Monthly variation in coil load functions makes yearly comparison of energy calculations that are done to assess the effect of using hourly and bin data more difficult. Thus, solar gains were set at zero for all periods and all months.

Values for air mass flow rates are set by one of the following design constraints. The first is the necessity that supply air be able to provide enough cooling at extremely hot ambient conditions and minimum allowable zone air entering temperature. The second is the necessity that supply air be able to provide enough heating at extremely cold ambient conditions and maximum allowable zone air entering temperature. The third constraint for variable volume systems only is that the rate of air supplied to a zone be at least the ventilation rate required by building codes.

An expression for mass flow to satisfy the first constraint is given by:

$$\dot{m}_C = \frac{UA(T_{Adc} - T_R) + \dot{q}_{Gmax}}{C_p(T_R - T_c)} \tag{6.1}$$

where $\dot{m}_C$ is the minimum mass flow required for cooling, T_{Adc} is the outside cooling design temperature, T_C is the cold supply temperature, T_R is the design room set temperature, and $\dot{q}_{Gmax}$ is the maximum expected rate of gains in the zone.

A similar expression describes the minimum mass flow rate to satisfy the second constraint $\dot{m}_H$:

$$\dot{m}_H = \frac{UA(T_R - T_{Adh})}{C_p(T_H - T_R)} \tag{6.2}$$

T_{Adh} is outside design heating temperature and T_H is maximum allowable heating supply temperature. Gains do not appear in this equation because the most extreme heating loads generally occur at night when internal gains are minimal or nonexistent.

An expression for the minimum allowable VAV air flow which will satisfy the third constraint is as follows:

$$\dot{m}_M = \frac{\dot{m}_o}{k_{min}} \tag{6.3}$$

where k_{min} is the lowest fraction of outdoor air flow desired at constant minimum volume, $\dot{m}_M$. If k_{min} is close to 1, $\dot{m}_M$ is minimized, which is desirable thing for VAV systems because the lower the volume of air delivered to the zone, the less energy will be expended by the VAV fan. However, heating of the zone is done by the reheat coil at minimum airflow rate. Heating is required when outside temperatures are low. Large fractions of cold outside air imply that not much warm return air is mixed with the outside air to raise mixed air temperature. Thus, preheating of the outside stream for large fractions of outside air is necessary to supply heat that the return air supplies at a lower fraction of outside air, k_{min}. The fraction k_{min} is set at 0.1 to 0.3 in general practice.

Air flows designed to satisfy cooling loads are generally higher than those designed to satisfy heating loads. This is because the difference between room set temperature and maximum allowable zone supply temperature, T_H, is larger than that between room and minimum allowable zone supply temperature, T_C. The difference in available zone/supply temperature differentials causes the denominator in Eq. (6.1) to be higher than the denominator in Eq. (6.2). Constant volume systems' supply flow, $\dot{m}$, is set equal to the largest of the three airflow rates calculated in Eq. (6.1)-(6.3). Variable volume systems' minimum supply flow rate, $\dot{m}_m$ is set equal to the largest of the rates in Eq. (6.2) or (6.3). In VAV systems, cooling flow constraints are automatically satisfied by the fact that air volume may vary to whatever level necessary.

Equipment to supply heating and cooling to the coils was chosen as a boiler with an efficiency constant with ambient temperature and a chiller with a of COP linear with ambient temperature. The variation of COP with temperature is shown in Fig. 6.7. The chiller COP function is applied to the sum of sensible and latent cooling rates at each T_A and then summed as an equivalent degree-day, EDD, as described in Chapter 5 to give total equipment load.

To obtain base temperatures and conductance factors for coil loads in each period, the base case parameter values can be substituted into the expressions listed for each system in Tables 4.2-4.4.

The resulting cooling load equations are then used in equivalent degree-hour summations to find the total coil energies for each period. Summing periods gives a monthly total load. Summing the loads for all months and dividing by 12 gives yearly average monthly energy.

Sample values for cooling and heating T_b and U_f for the TRH and VAV systems are listed in Table 6.3 for period 1 and period 3 (maximum and zero internal load respectively). There are no solar gains so the base temperature values will not vary from month to month. In Winter months, the large value of T_{bh} is larger than any bin temperature and lies entirely outside the bin distribution. When this is the case the temperature difference will be positive for every bin and the total coil load summation is transformed to:

$$Q_A = U_h \sum_{T_A} [T_{bh} - T_A] \; N_A = U_h[\sum T_{bh}N_A - \sum T_A N_A] \frac{\sum N_A}{\sum N_A} \qquad (6.4)$$

$$= U_h \; N_m \; [T_{bh} - \bar{T}_A]$$

A quick hand calculation using the number of hours and average temperature in January, gives the same answer as the degree-day summations using both bin and TMY data. Distribution is not important, then, if base temperatures lies outside the bin range. As a result, calculation using hourly and bin data with the same monthly average temperature give the same answer when base temperatures lie outside the bin range.

Table 6.3. Actual Values of Base Temperature for Terminal Reheat (TRH) and Variable Air Volume Reheat (VAV) Systems

(T_b in °C, U_f in W/°C, ω_{bcL} in kg-H_2O/kg-air and U_{fCL} in W kg-air/kg-H_2O)

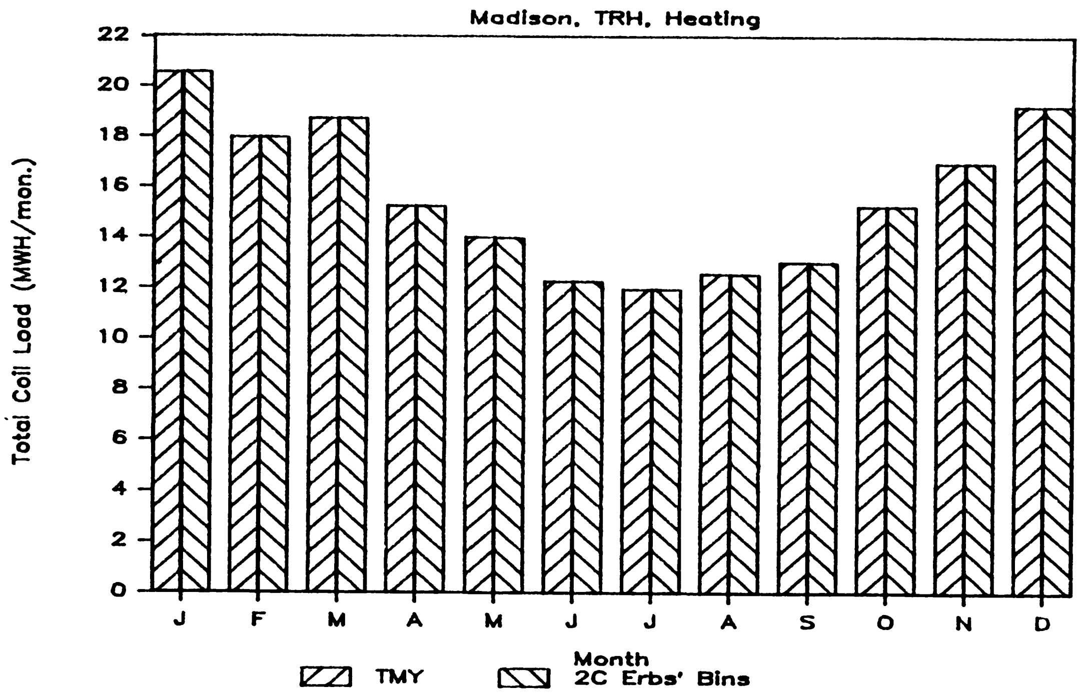
System Abbr.	Temperature Range Low	Temperature Range High	Heating U_{fh}	Heating T_{bh}	Sensible Cooling U_{fcs}	Sensible Cooling T_{bcs}	Latent Cooling U_{fcL}	Latent Cooling ω_{bcL}
(Zero Gains)								
TRH	$-\infty$	∞	379.5	86.26	402.4	-34.1	7.23×10^6	0.00670
VAV	64.2	∞	0	---	781.9	21.11	depends on T_A	depends on T_A
	$-\infty$	64.2	379.5	64.2	402.4	-19.5	4.66×10^6	0.00768
(Max. Gains)								
TRH	$-\infty$	∞	379.5	38.83	402.4	-34.1	7.23×10^6	0.00907
VAVR	15.6	∞	0	---	781.9	-1.91	depends on T_A	depends on T_A
	$-\infty$	15.6	379.5	15.6	402.4	-19.5	4.66×10^6	0.00768

6.2 Evaluation of Trends in HVAC Load Models

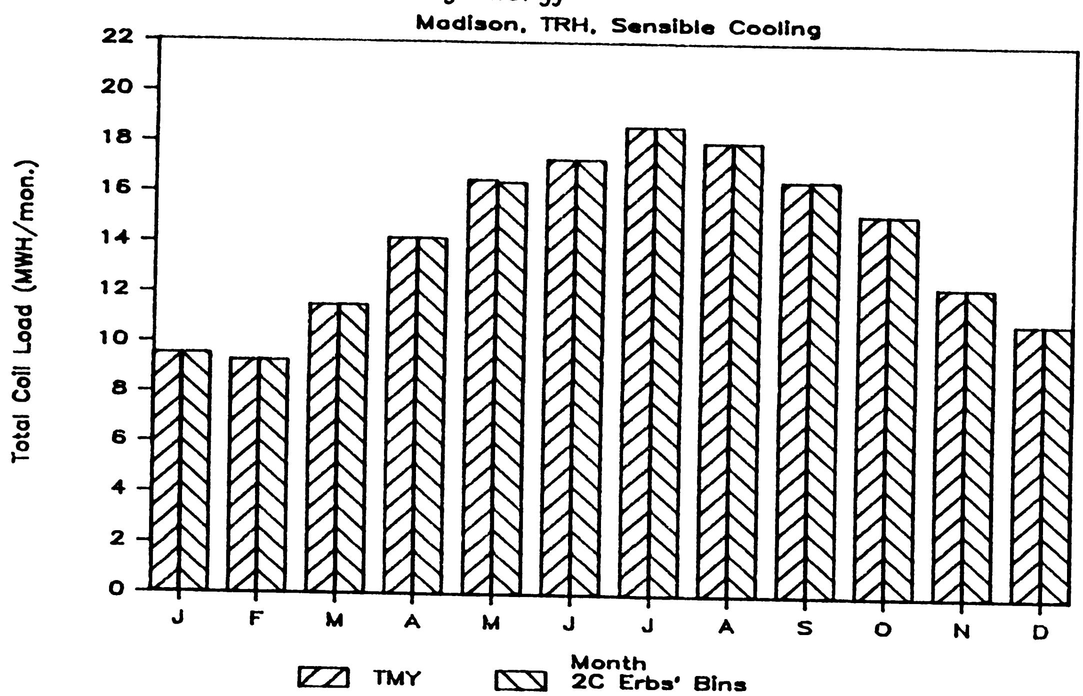
Both bin and TMY data for Madison, WI were used to calculate total heating, sensible and latent cooling as well as chiller equipment energy use for each month. All calculations in this section are done for the base design case in Madison. Figures 6.8-6.13 show heating, sensible cooling and latent cooling and chiller energies for each month and for TRH, VAV, DDM, TD, TRHE and TRHD systems.

For terminal reheat system calculations shown in Fig. 6.8a-d, heating totals in Fig. 6.8a decrease and cooling totals in Fig. 6.8b,c increase in the summer as expected. Latent cooling totals in Fig. 6.8c are very much smaller than sensible in Fig. 6.8b. The slight mismatch between summer latent cooling calculations in Fig. 6.8c shows up also in the chiller load in Fig. 6.8d.

Figure 6.9 shows the same information for the variable air volume (VAV) reheat system as was shown for terminal reheat. Both sensible cooling and reheat totals shown in Fig. 6.9b and 6.9a a respectively are noticeably smaller than for TRH. The reduction in coil energies is due to the fact that varying air volume reduces the amount of cool supply air which is reheated to meet zone loads in a constant volume system. Reheating occurs only when a minimum level of constant air flow is needed. Thus, less air is cooled and heated in VAV reheat systems than in constant volume TRH systems causing the VAV heating and cooling to be lower than TRH. The variation of all energies over the year in Figs. 6.9, however, is generally the same as TRH. Latent totals in Fig. 6.9c are virtually the same in magni-



a) Total Heating Energy



b) Sensible Cooling Energy.

Fig. 6.8. Variation of Monthly Coil and Chiller Energies Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day Over a Year for the Base Case Building Described in Section 6.1 Using a Terminal Reheat System.

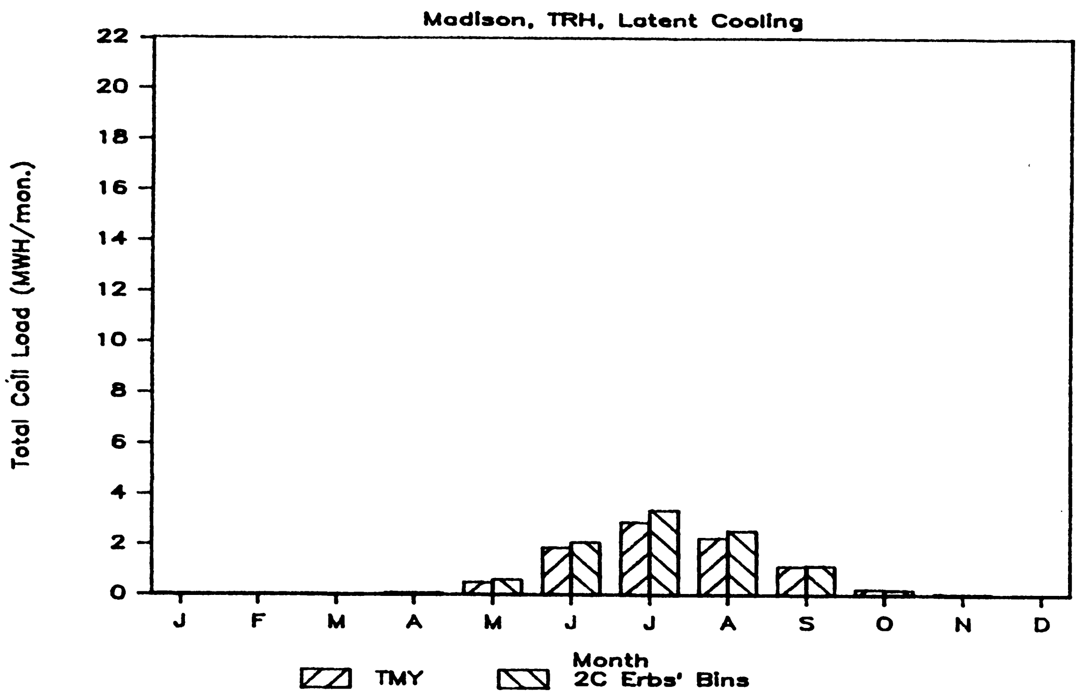


Fig. 6.8. c) Latent Cooling Energy.

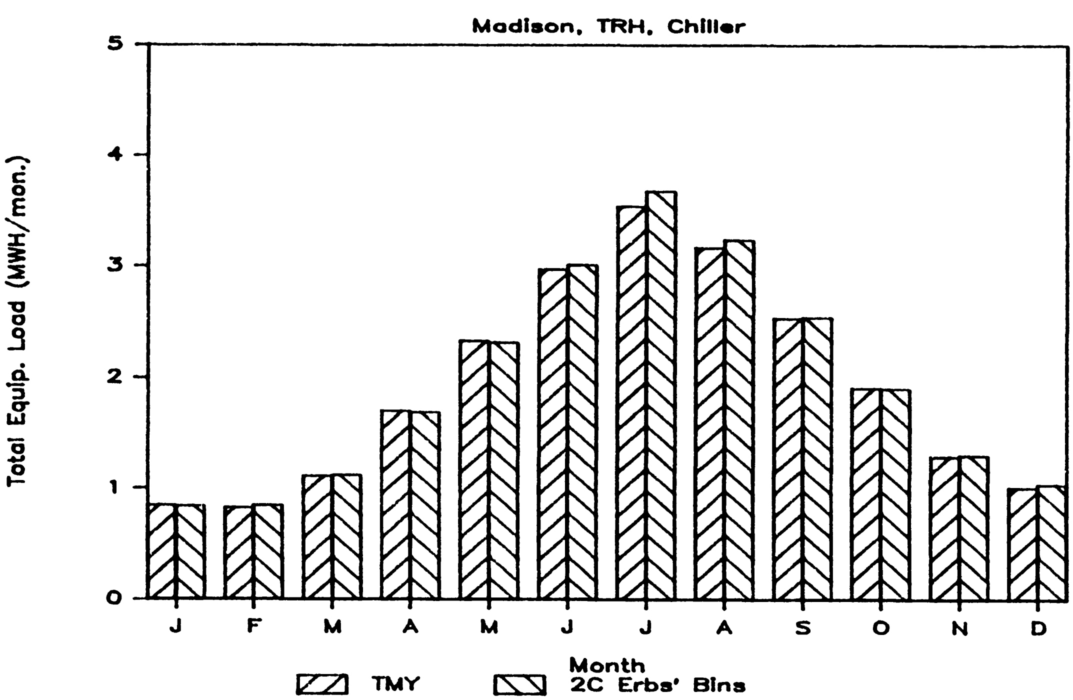
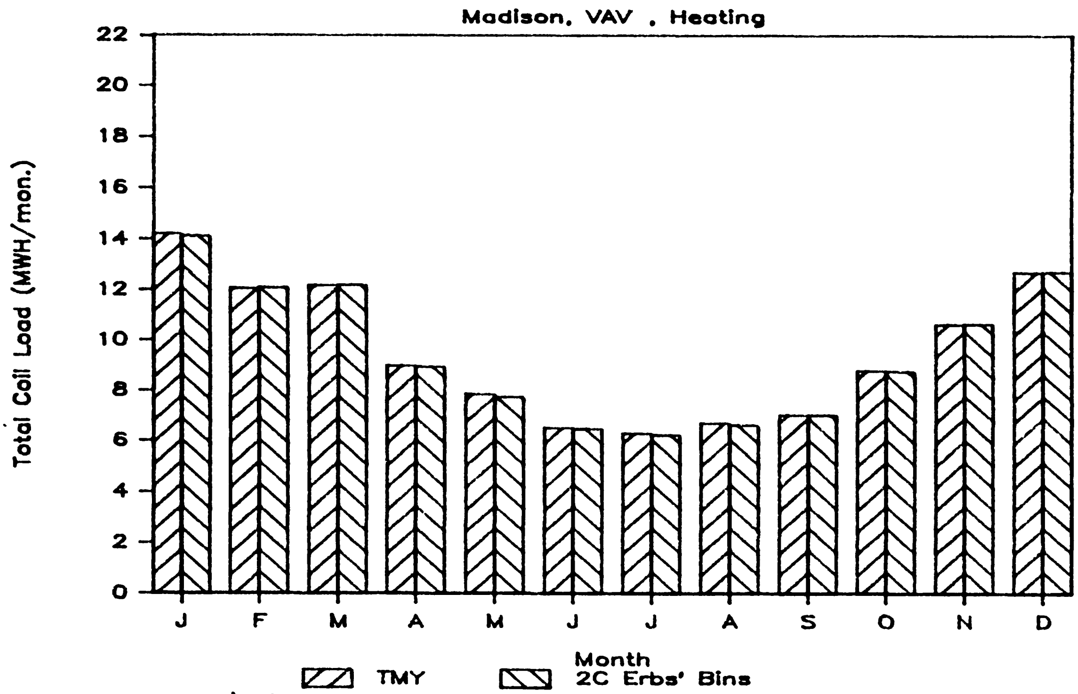
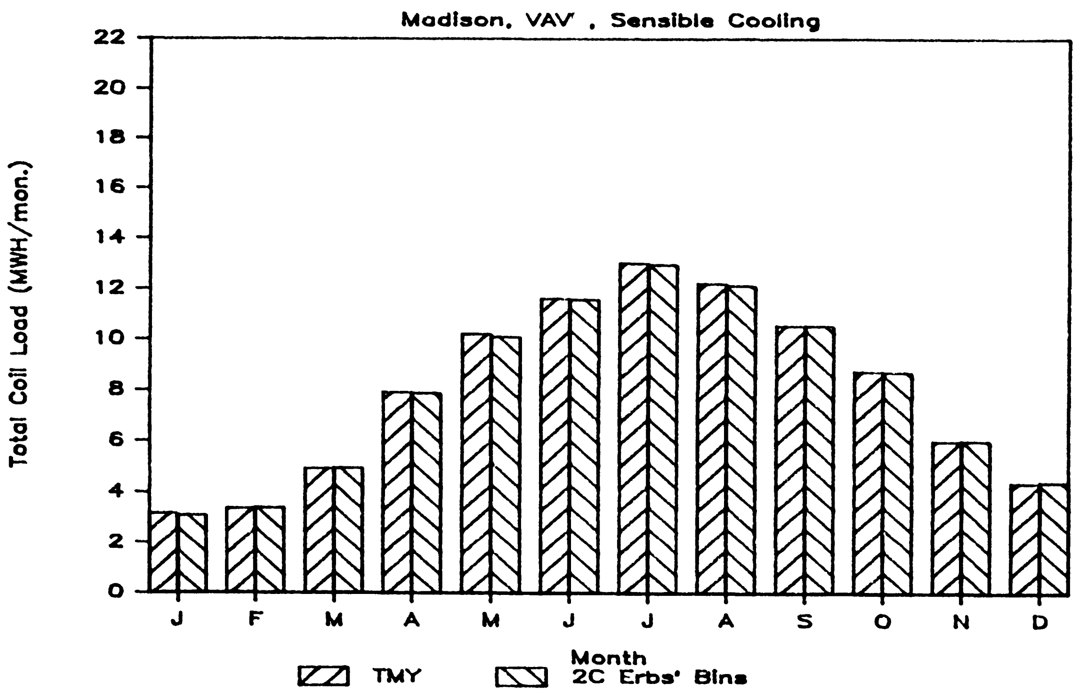


Fig. 6.8. d) Chiller Energy.



a) Total Heating Energy.



b) Sensible Cooling Energy.

Fig. 6.9 Variation of Monthly Coil and Chiller Energies Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day Over a Year for the Base Case Building Described in Section 6.1 Using a VAV Reheat System.

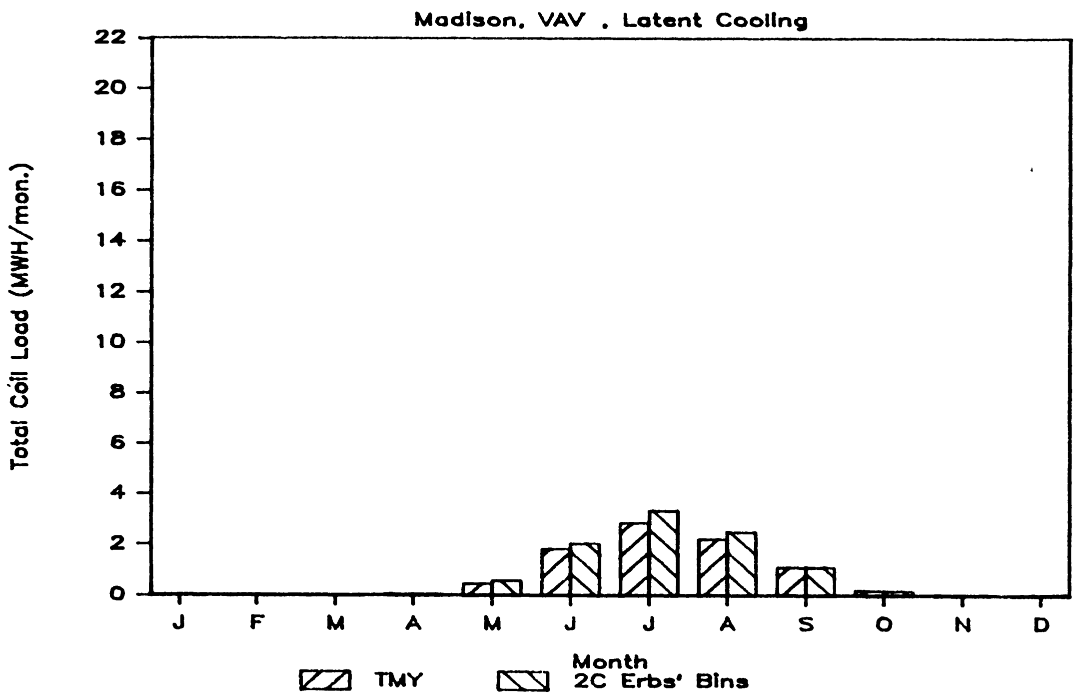


Fig. 6.9. c) Latent Cooling Energy.

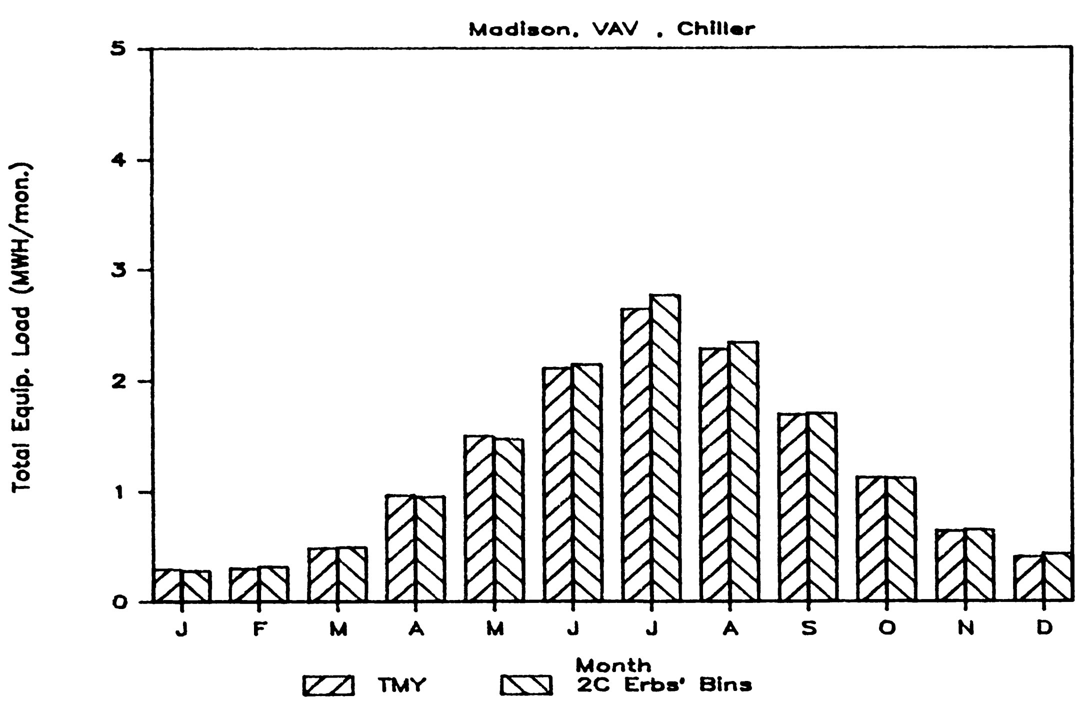
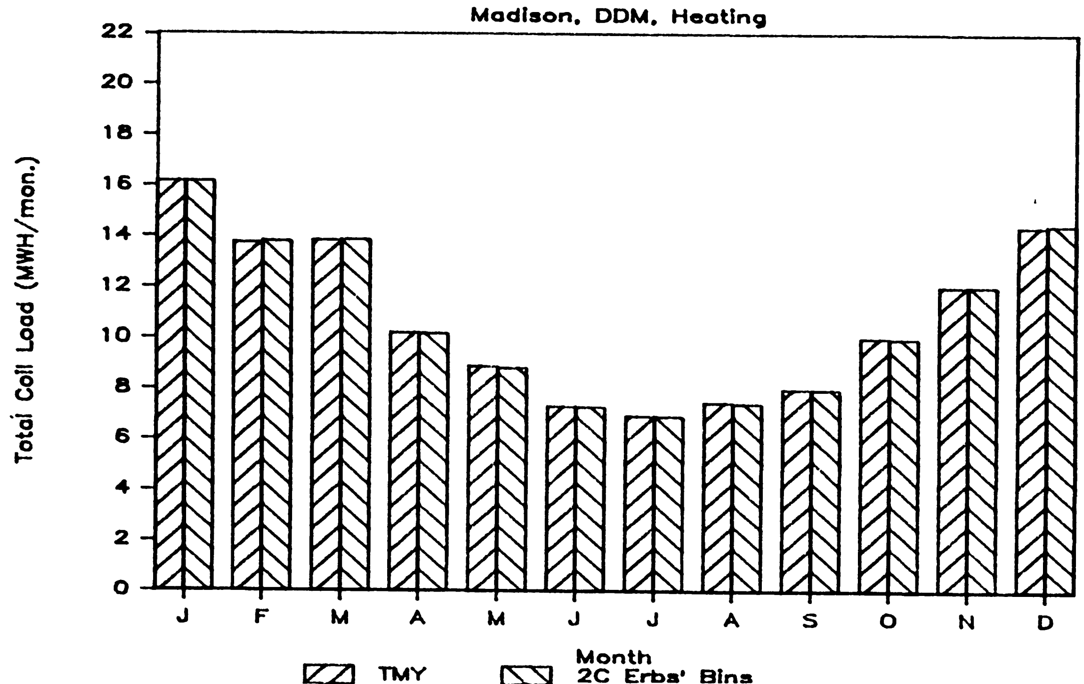


Fig. 6.9. d) Chiller Energy.

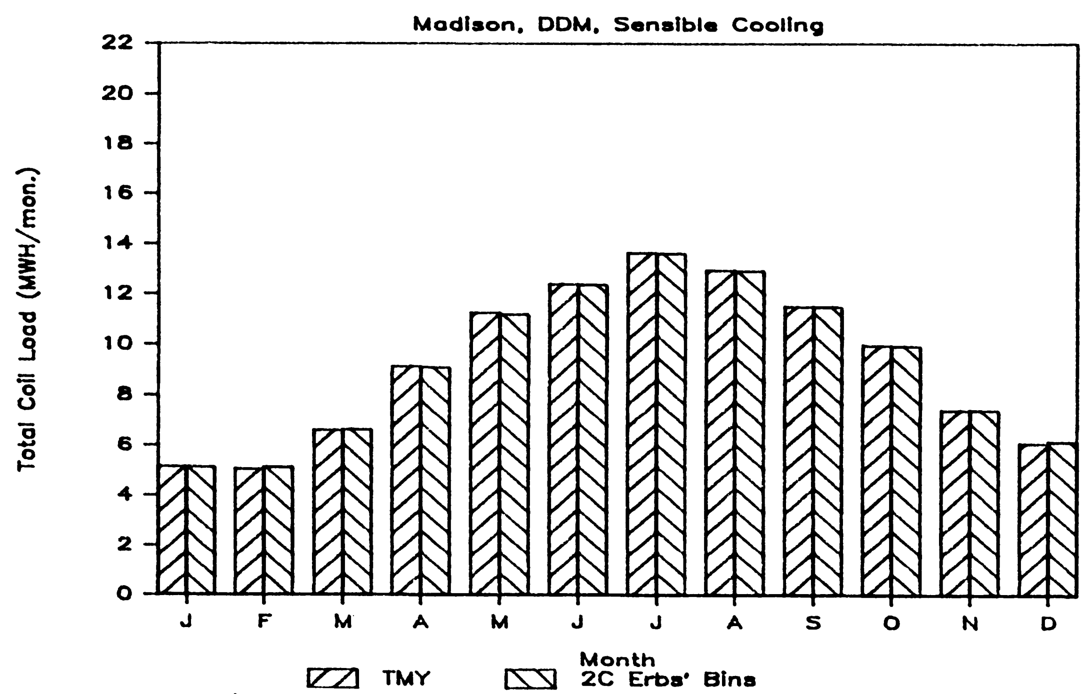
tude as TRH latent totals but because of lower sensible loads, have a larger percentage impact on total cooling coil energy. VAV chiller energy shown in Fig. 6.9d is lower than for TRH chiller energy, as would be expected with lower VAV cooling totals.

The dual duct system totals (DDM) loads in Figs. 6.10a-d have the same variation over the year and latent cooling totals shown in Fig. 6.10c as TRH and VAV systems do. The annual sensible heating and cooling totals shown in Fig. 6.10a and 6.10b, and chiller energy in Fig. 6.10d lie in between the TRH and VAV annual total levels.

Figure 6.11 summarizes three deck (TD) system energies. Figures 6.11a and 6.11b show by far the lowest sensible cooling and heating totals of the four systems compared so far. Because the other systems had almost identical latent totals and quite different sensible totals, it appears that system type has little impact on latent loads. Thus, the assumption made in Section 4.1.3 that VAV latent load is a good approximation for TD latent load is justified. Chiller energies, not shown for the TD system, are lower than for the other systems, and have peak totals in July as the other three systems do. Moreover, the expression for zone heating and cooling load, taking both envelope and ventilation loads into account, exactly corresponds to the U_f and T_b values for TD. In other words, the TD system does not supply extra heating and cooling in order to meet zone loads. The fact that total loads go to near zero for winter cooling and summer heating as zone loads do illustrates the close association between zone and TD loads.



a) Total Heating Energy.



b) Sensible Cooling Energy.

Fig. 6.10. Variation of Monthly Coil and Chiller Energies Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day Over a Year for the Base Case Building Described in Section 6.1 Using a Dual Duct System.

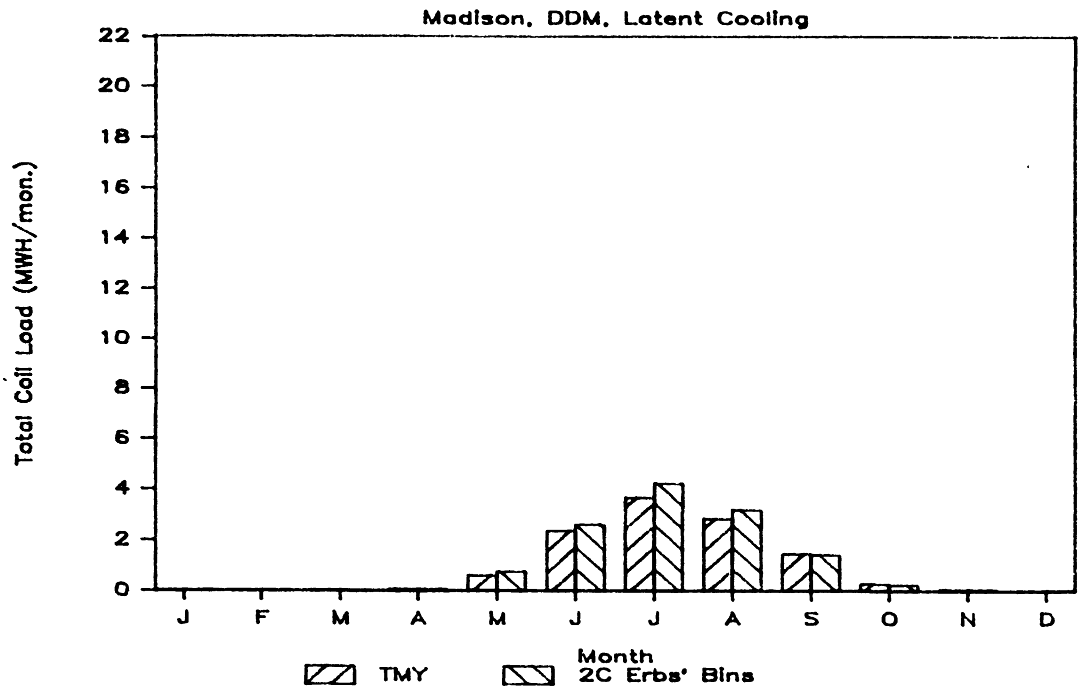


Fig. 6.10. c) Latent Cooling Energy.

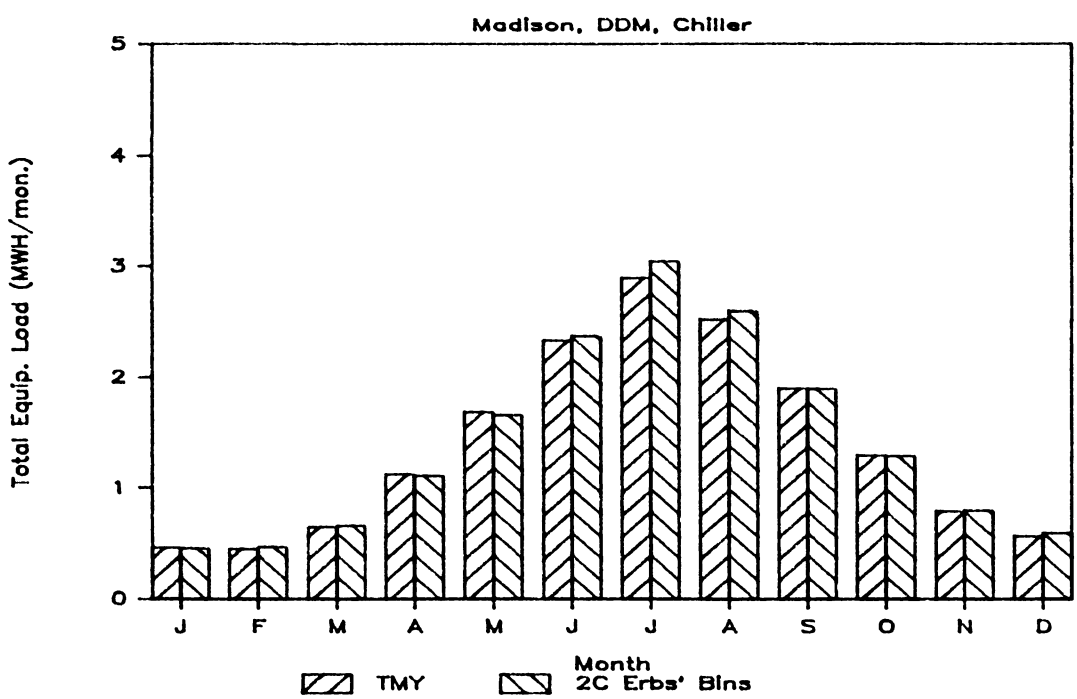
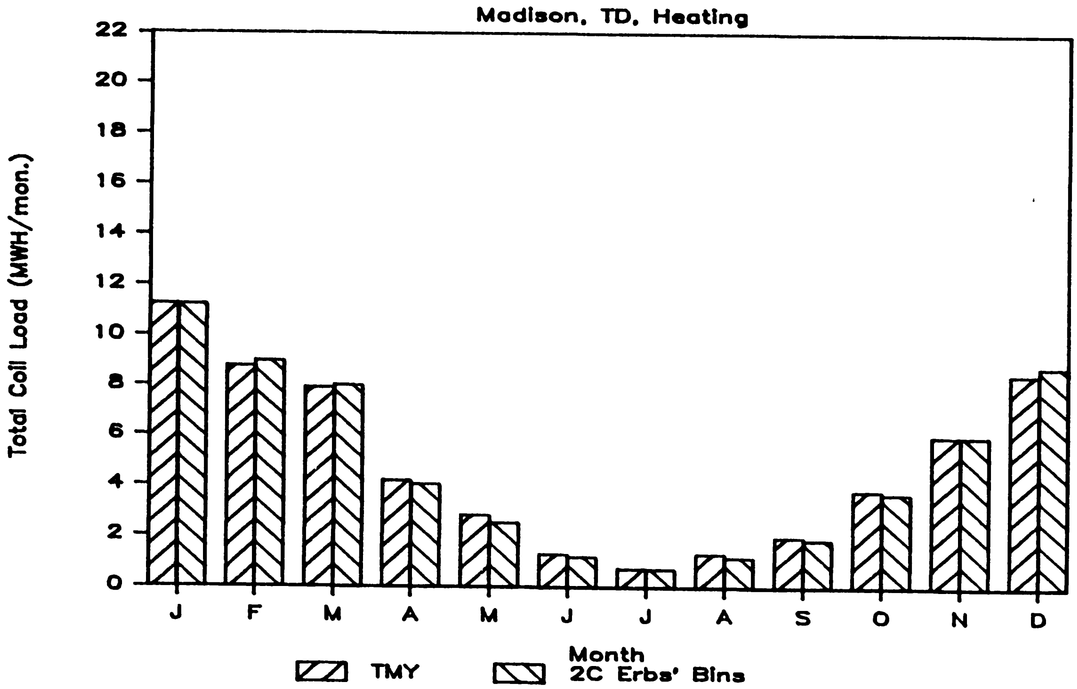
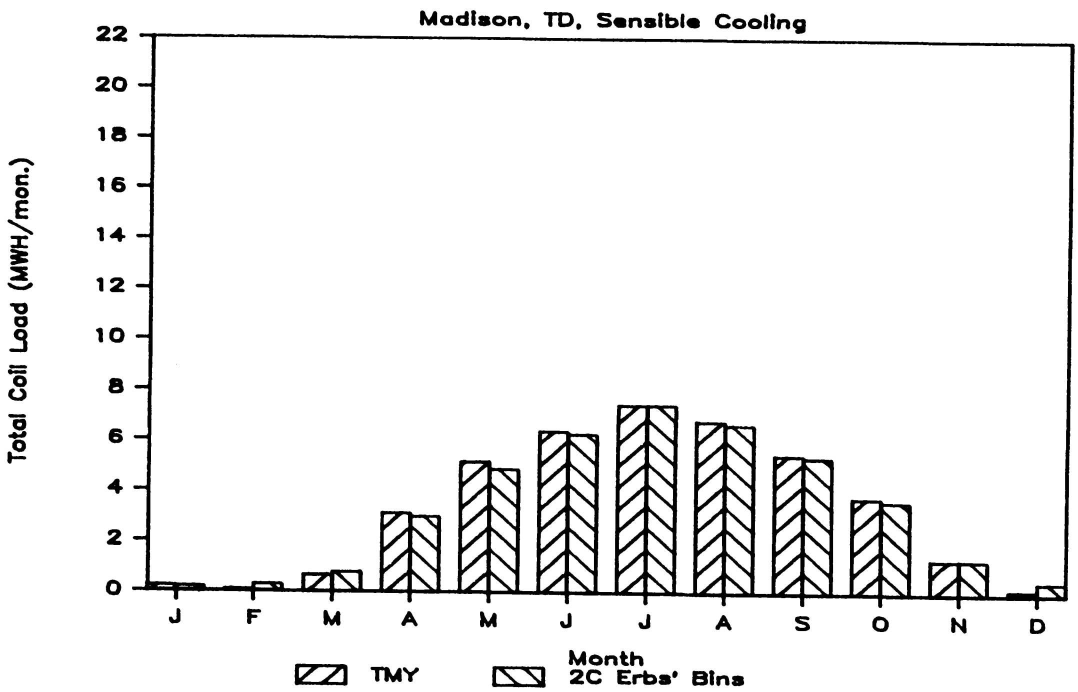


Fig. 6.10. d) Chiller Energy.



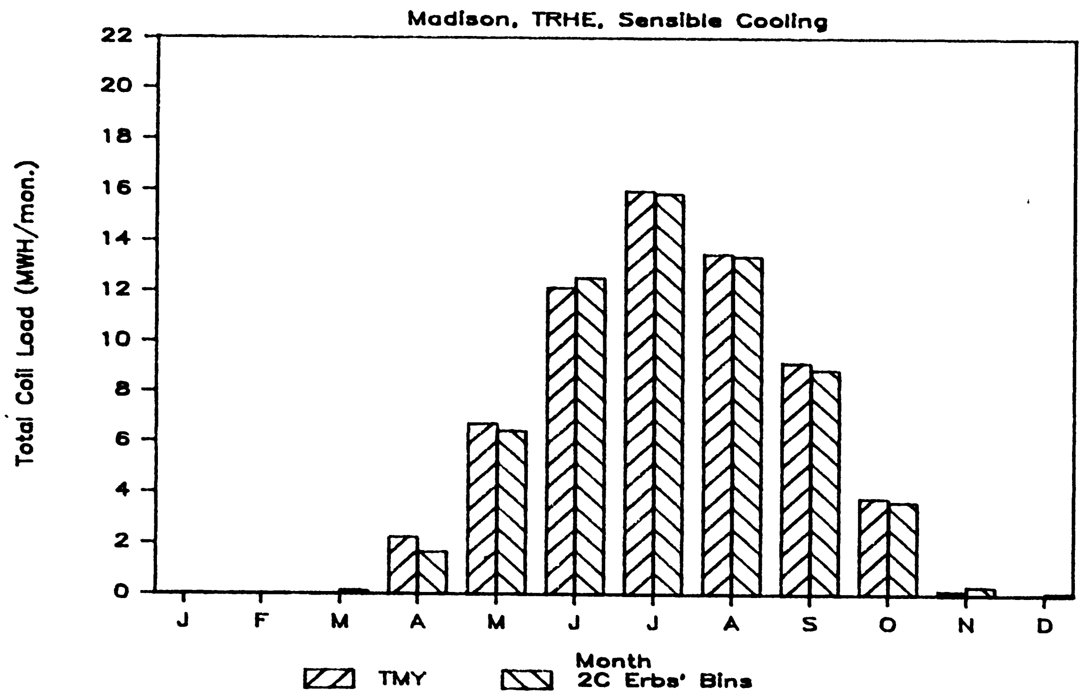
a) Total Heating Energy.



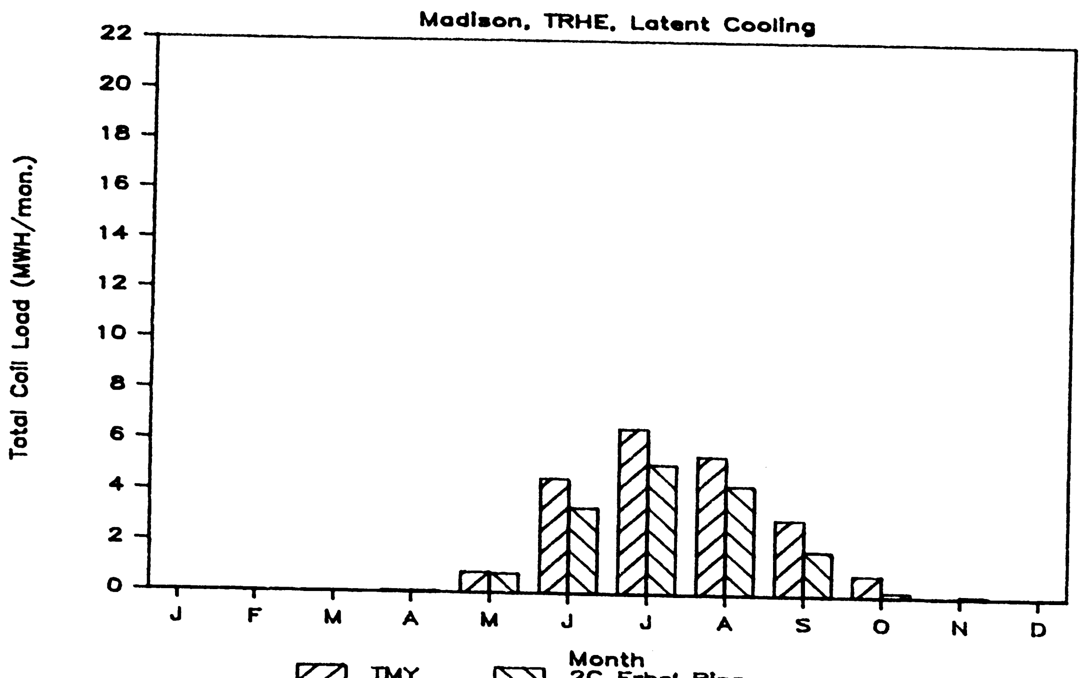
b) Sensible Cooling Energy.

Fig. 6.11. Variation of Monthly Coil Energies Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day Over a Year for the Base Case Building Described in Section 6.1 Using a Three Deck System.

The effect of an economizer cycle on terminal reheat performance can be seen in the sensible and latent cooling coil totals and total chiller energy profiles in Fig. 6.12a-c. The heating loads (not shown) are the same as for TRH in Fig. 6.8a. The sensible cooling coil loads are negligible in the winter months when free cooling is available. Peak summer sensible loads are slightly reduced from TRH totals shown in Fig. 6.8b as well. Latent loads, however, are up from TRH levels in Fig 6.8c because 100% outside air is used when T_A is between T_C and T_R, Noticeable differences between TMY and bin latent loads occur in all months. The differences are due to the fact that ω_A and T_A are linked differently in TMY and bin data. The former has a distribution of ω_A with ambient temperature whereas in the bin representations there is only one associated ω_A value. Because the economizer cycle operates only according to temperature levels, the link between T_A and ω_A becomes important. More will be said on this matter later in Section 6.3. Economizer cycles applied to VAV and DDM exhibited the same type of behavior and are not shown. The only exception is that DDM heating totals go up with the application of the economizer control. With mixed air temperature minimized, the heating coil adds a larger amount of heat into the hot supply air stream than it would if a constant minimum amount of outside air were used for all ambient temperatures. Thus, minimizing mixed temperature maximizes required heating. An economizer cycle is not applied to dual duct systems in actual practice.



a) Sensible Cooling Energy.



b) Latent Cooling Energy.

Fig. 6.12. Variation of Monthly Coil and Chiller Energies Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day Over a Year for the Base Case Building Described in Section 6.1 Using a Terminal Reheat System With Economizer Control.

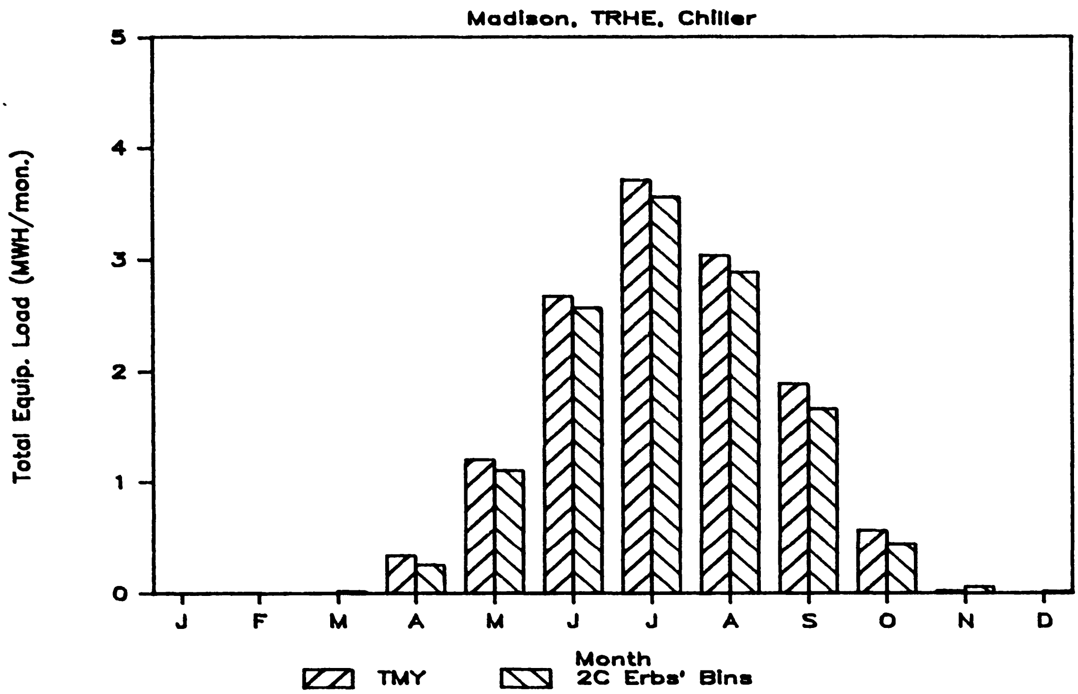
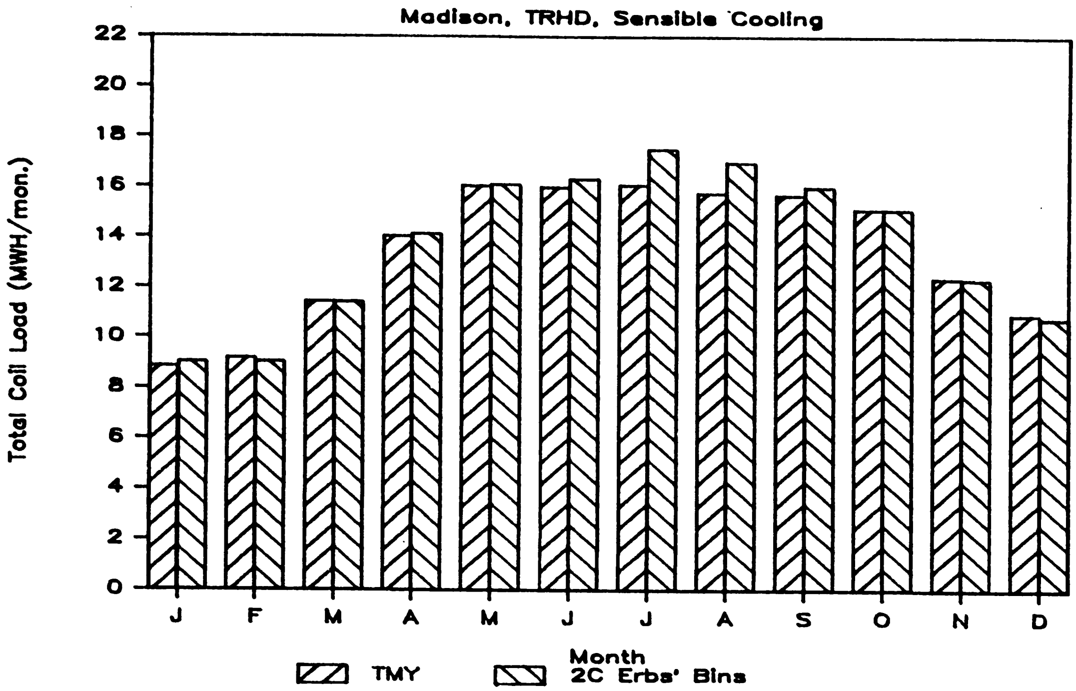


Fig. 6.12. c) Chiller Energy.

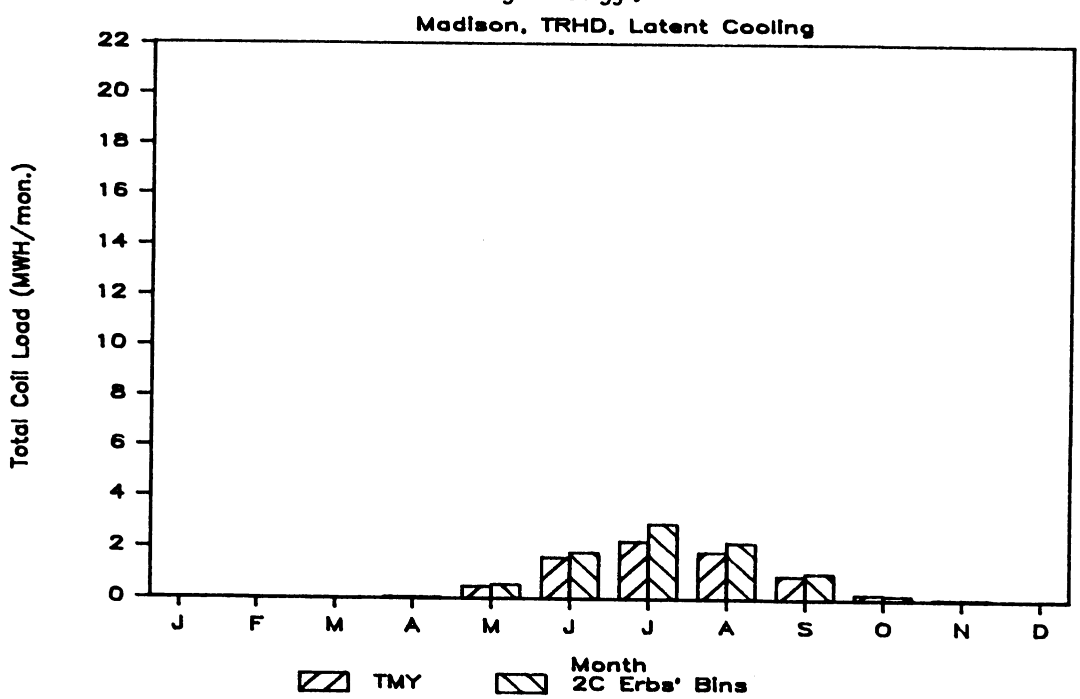
The sensible and latent cooling and chiller totals for dead band set control applied to TRH are shown in Figure 6.13a-c. The sensible totals shown in Fig. 6.13a are somewhat lower overall than for regular terminal reheat in the summer. Large differences occur in the summer between hourly and bin data summations for sensible cooling. The cause of differences is that in the summer months, T_{AH} and T_{AC}, which define the range of T_A where loads are taken to be zero, tend to fall near the middle of the bin temperature distribution where the majority of hours are located. Because TMY and Erbs' distributions do not match exactly in the middle of the distributions, a significant difference in the number of hours at zero load could easily result. The latent loads are smaller than for the other systems also because a significant number of hours have been eliminated from the summation. As with the economizer control, the effect of dead band control on VAV and DDM energy totals display similar trends to totals for TRHD in Fig. 6.13 and are not presented here.

6.3 Comparison of Average Monthly Energy Totals Calculated Using Hourly and Bin Data

The question, "Do the differences between TMY and bin summations observed in some months make a difference on an annual basis?" will be considered next. Figure 6.14 shows the comparison of yearly average cooling and heating coil loads, with cooling on the top and heating, inverted on the bottom. Totals shown on the Fig. 6.14 are coded as follows: T indicates terminal reheat systems, ηV indicates vari-



a) Sensible Cooling Energy.



b) Latent Cooling Energy.

Fig. 6.13. Variation of Monthly Coil and Chiller Energies Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day Over a Year for the Base Case Building Described in Section 6.1 Using a Terminal Reheat System With Dead Band Temperature Control.

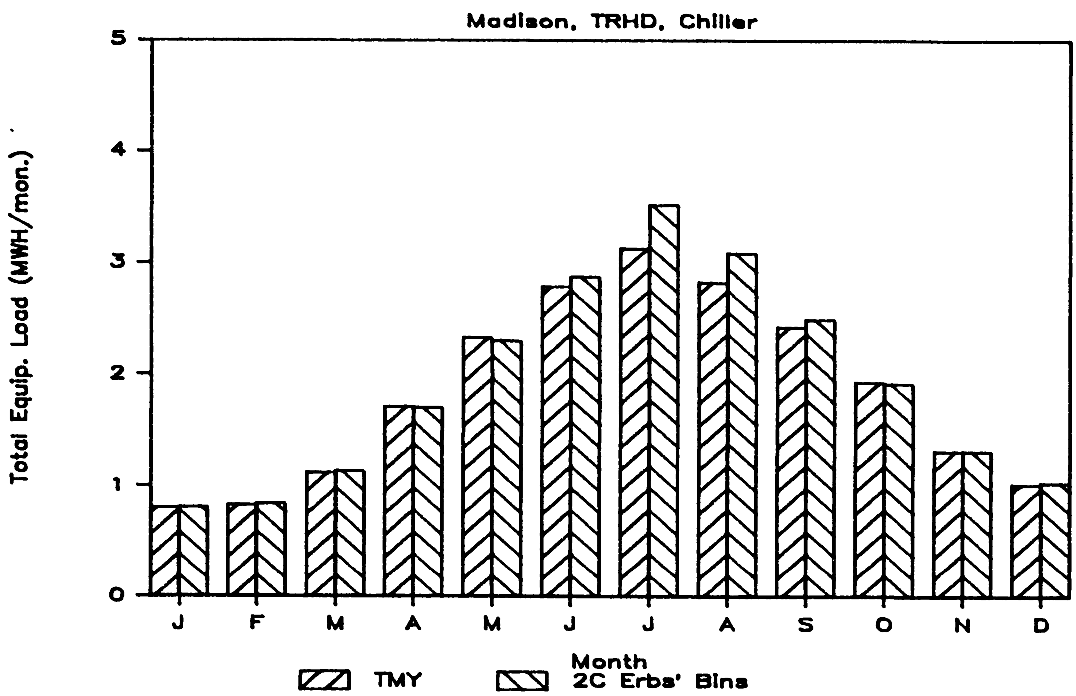


Fig. 6.13. c) Chiller Energy.

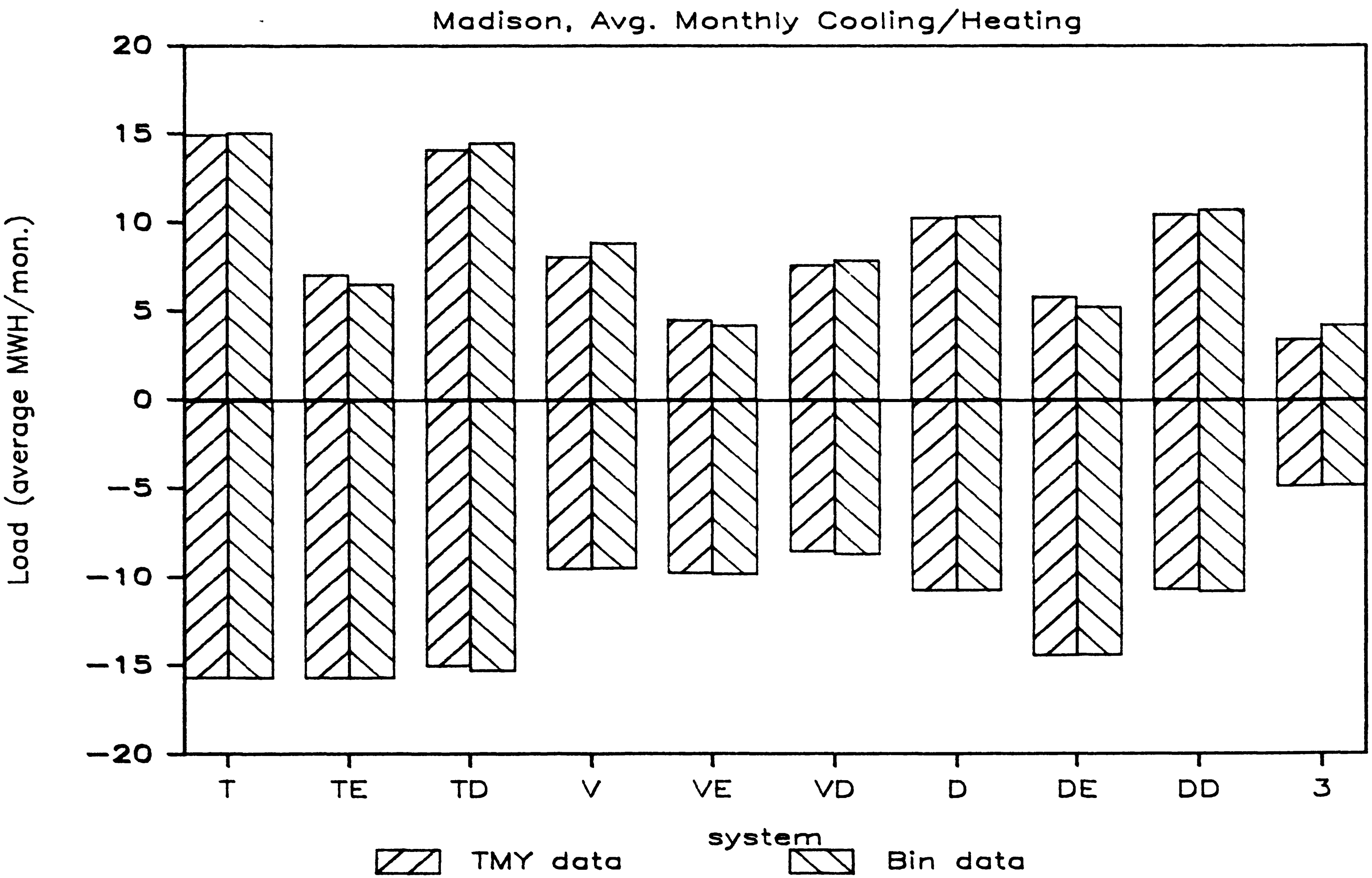


Fig. 6.14 Comparison of Average Monthly Heating and Cooling Coil Energy Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day Over a Year for the 13 Combinations of Parameters Described in Section 6.3 and All 10 Systems Described in Chapter 4.

able air volume, D indicates dual duct, 3 indicates three deck, E signifies use of an economizer cycle and D signifies the use of dead band control. There are some differences in cooling coil totals between TMY and bin summations. Cooling coil differences are due largely to latent total differences and are less than 9% for all systems using economizer cycle, less than 4% for all systems using dead band control, less than 11% for variable air volume and three deck systems and less than 0.5% for a terminal reheat system. Heating coil totals are virtually identical for all systems. These are good matches.

The next issue addressed is whether the magnitude of difference between results using TMY vs. bin data in coil and chiller totals is dependent on either location or building. Three variables, outside air flow rate, m_o, internal gains, $\dot{q}_G$, and external wall area, A, were chosen to be varied. Two values on either side of each variable's base case settings were taken while the other two were held constant. Thus, 13 combinations of the three parameters resulted. Each parameter combination constitutes a set of design conditions for which constant and minimum air flows must be calculated to satisfy the constraints described in Section 4.1. Design levels for m_d and m_m computed for Madison, Albuquerque, Seattle, and Miami. The 13 levels for the varied parameters are given in Table 6.4.

Only TRH, VAV, DDM, TD, TRHE and VAVE will be considered. The dead band control applied to TRH, VAV and DDM gives very similar results to those systems with out dead band control. The economizer

Table 6.4. Levels for Variation of Outside Airflow $\dot{m}_o$, Exposed Area A, and Internal Gains $\dot{q}_G$ Base Design Case

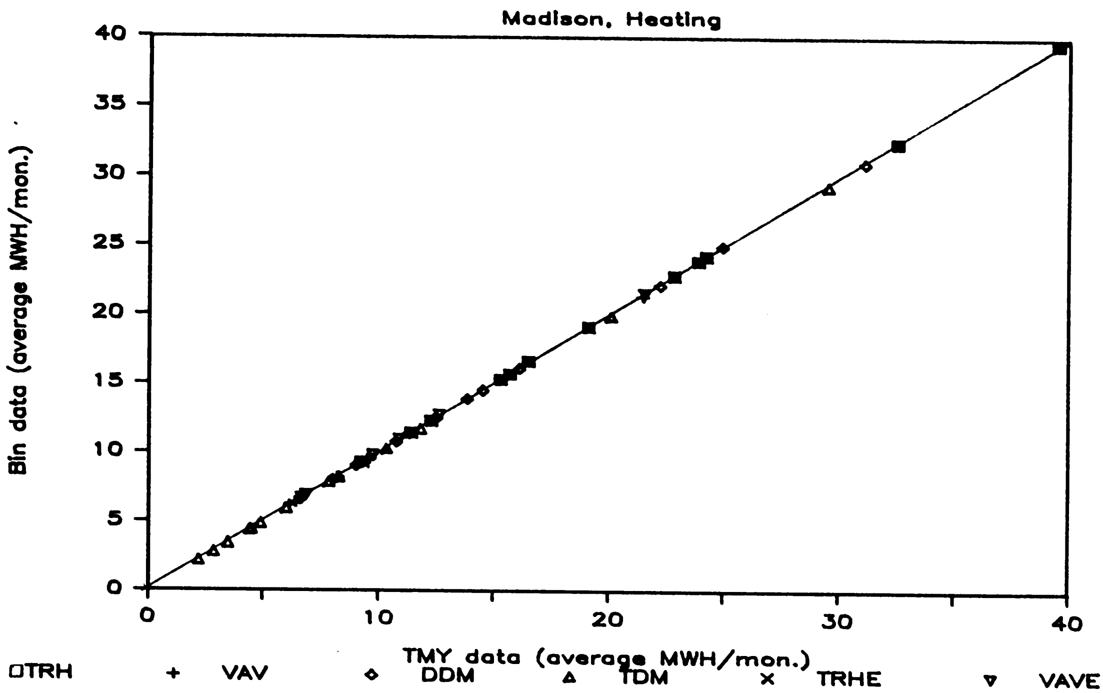
Variation #	$\dot{m}_o$ (kg/s)	A (m^2)	$\dot{q}_G$ (W)
1 (base)	0.40	330	18,000
2	0.01	330	18,000
3	1.00	330	18,000
4	2.00	330	18,000
5	2.95	330	18,000
6	0.40	330	36,000
7	0.40	330	27,000
8	0.40	330	9,000
9	0.40	330	0
10	0.40	990	18,000
11	0.40	660	18,000
12	0.40	165	18,000
13	0.40	82.5	18,000

cycle applied to DDM as stated in Section 6.2 is not a practical option. Therefore consideration of any of the dead band controlled systems or DDME would not add to the discussion.

Calculation of average monthly total loads over a year using bin data and TMY data were made for heating, sensible cooling, latent cooling, total cooling and chiller energy. A full set of these plots is shown in Fig. 6.15a-e for Madison. All thirteen design points are plotted for each system which is represented by a different symbol. The line with a slope of one represents a perfect fit.

The sensible cooling (Fig. 6.15b) and heating (Fig. 6.15a) loads fall very close to the agreement line for all systems and all configurations with no noticeable bias. This indicates good overall agreement for a number of cases. The latent cooling loads (Fig. 6.15c), however, show noticeable deviation. The total cooling load (Fig. 6.15d) is really unaffected by this deviation because, in general, latent loads are much smaller than sensible loads for Madison. Chiller loads (Fig. 6.15e), too are fairly comparable as a result.

For the other three locations, sensible cooling and heating loads agreed as well as did the Madison ones. These results are not shown. A comparison of the yearly bin distributions in Fig. 6.1-6.4a shows very good agreement between the TMY and Erbs' distributed 2°C temperature bins. Shape and range match fairly well. As a result, it is expected that sensible totals agree for most every situation, as they do.



a) Total Heating.

Fig. 6.15. Comparison of Average Monthly Energies Over a Year Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day Year for the 13 Combinations of Parameters and 6 Systems Described in Section 6.3 in Madison, WI.

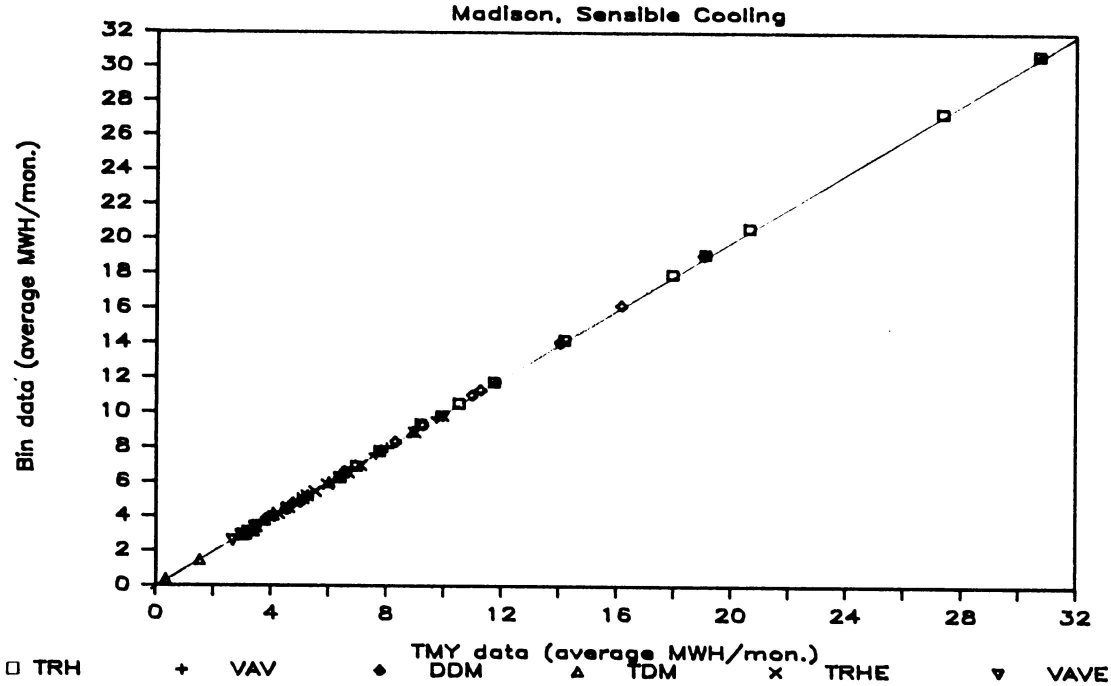


Fig. 6.15. b) Sensible Cooling.

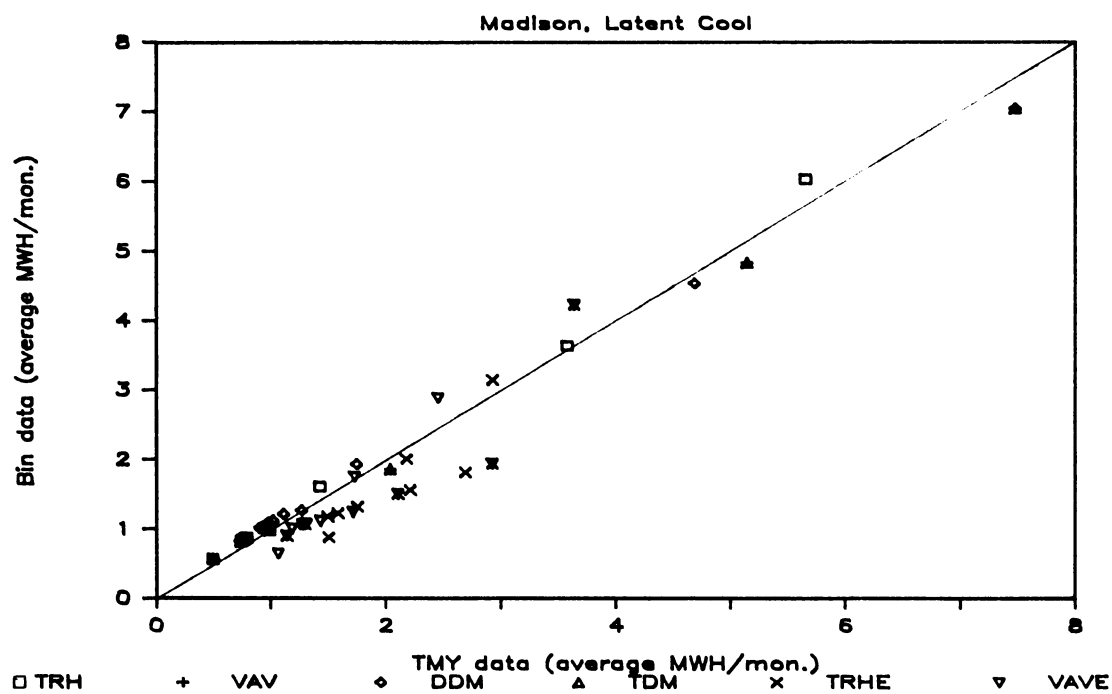


Fig. 6.15. c) Latent Cooling.

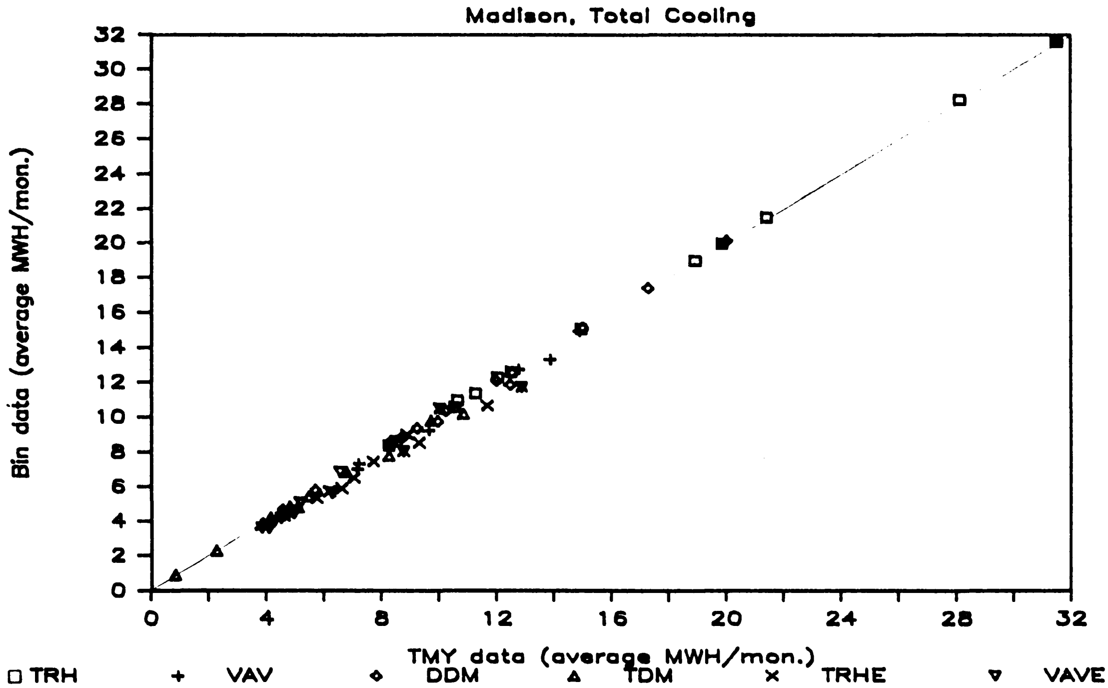


Fig. 6.15. d) Total Cooling.

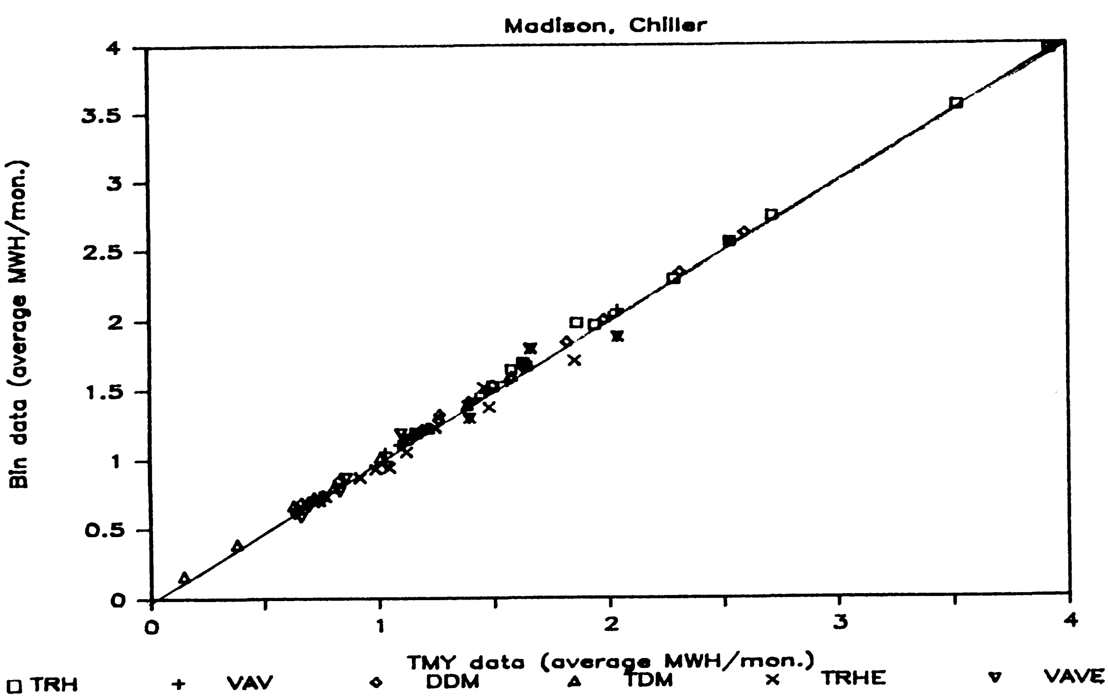
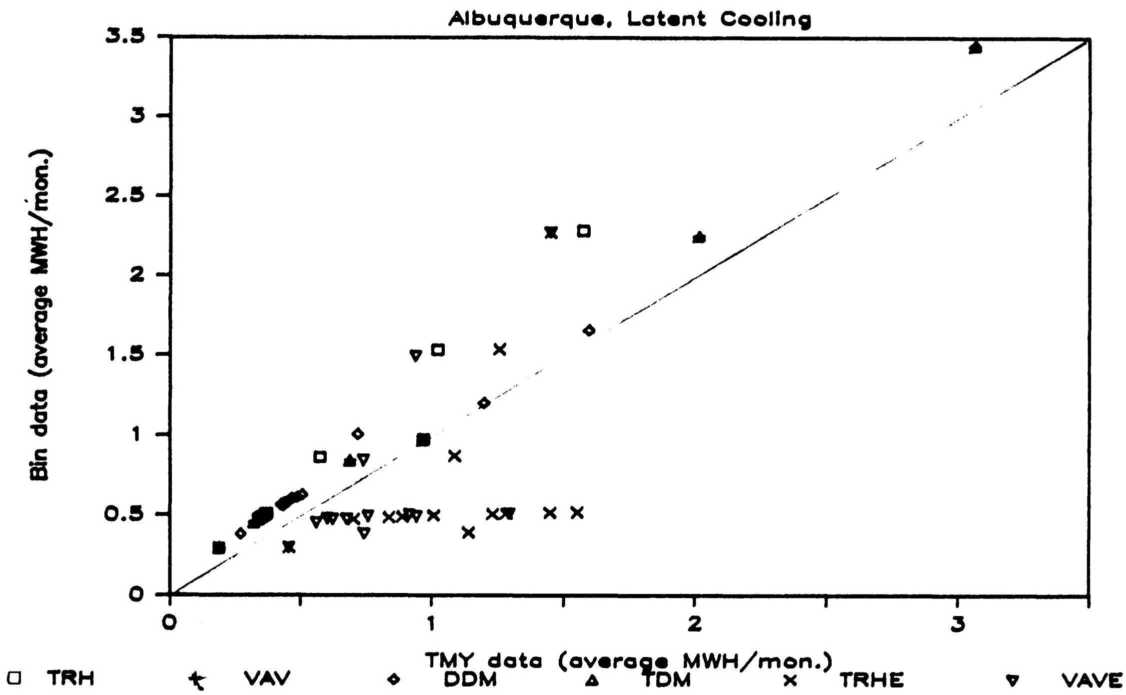


Fig. 6.15. e) Chiller Energy.

A comparison of Figs. 6.16-6.18a-c with Figures 6.15c-e shows definite differences in latent cooling load agreement but minimal impact on total and chiller loads.

The trends in Albuquerque's set (Fig. 6.16) are similar to those in Madison's. The economizer cycles are fairly consistently underpredicted, but the latent loads are so much smaller than the sensible that total cooling loads lie fairly well along the line. From Figs. 6.1b and 6.2b it becomes apparent that the two locations have similar ω_A distributions both of which compare fairly well between TMY and bin data. The reason for the deviation of the economizer cycle latent loads lies in the link between T_A and ω_A discussed earlier in Section 6.2. As noted there, the bin T_A's have only one average ω_A associated with them whereas they are distributed with T_A in TMY data. ω_A must be greater than an ω_{bc} for a latent cooling load to exist. While the average values may not give a positive latent load rate, the distributed ones do, making TMY summed economizer latent loads larger than bin summed ones. This arises only when the operating ranges are defined by values of temperature which have an impact on air flow and thus latent load rates, making the relationship between ω_A an T_A crucial.

In Fig. 6.17, the trends in Seattle's latent loads go fairly sharply from underprediction of TMY totals by bins at large loads to consistent overprediction at small loads. No trends caused by economizer control are apparent even when the small loads are examined up close. This time, an examination of the ω_A distributions in Fig.



a) Latent Cooling.

Fig. 6.16. Comparison of Average Monthly Energies Over a Year Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day for the 13 Combinations of Parameters and 6 Systems Described in Section 6.3 in Albuquerque, NM.

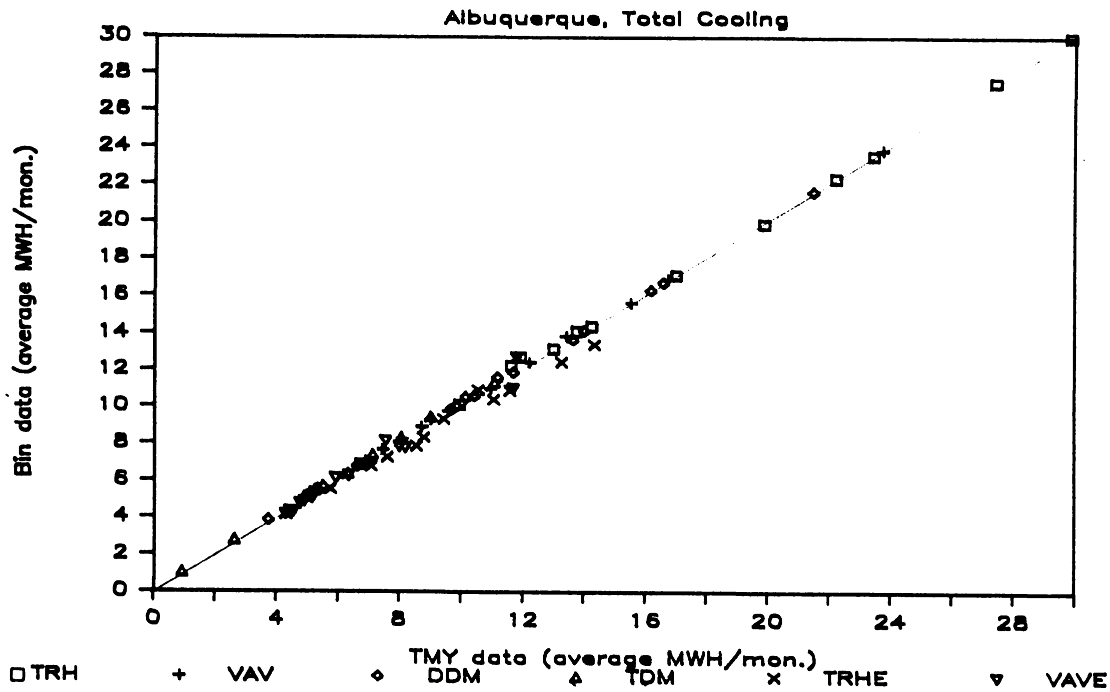


Fig. 6.16. b) Total Cooling.

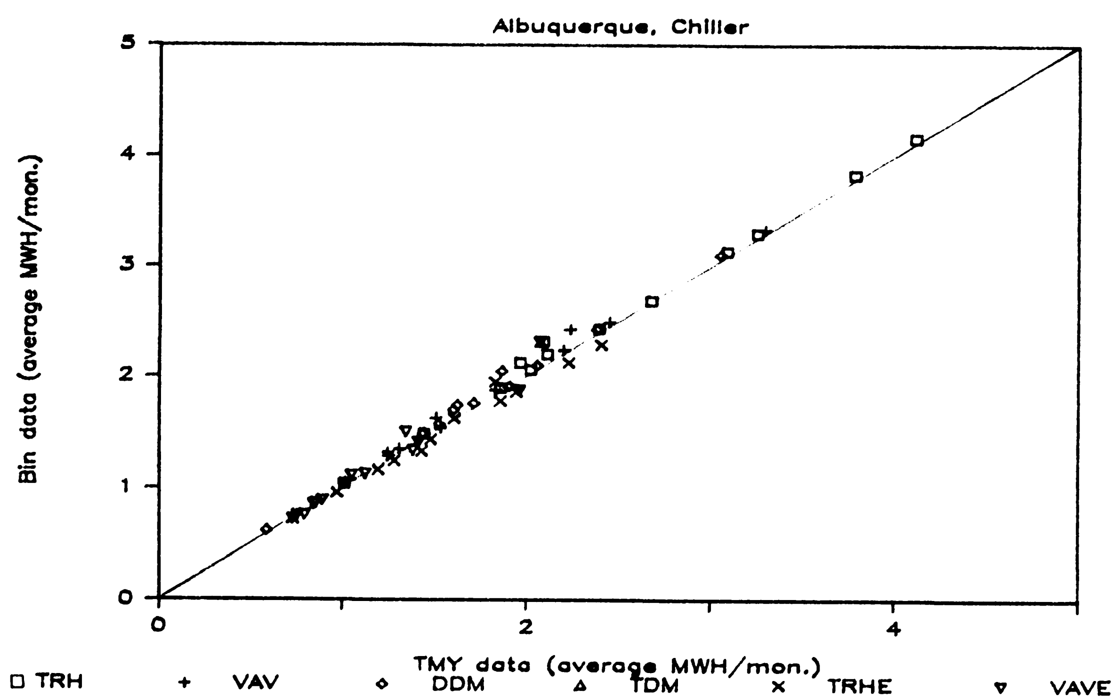
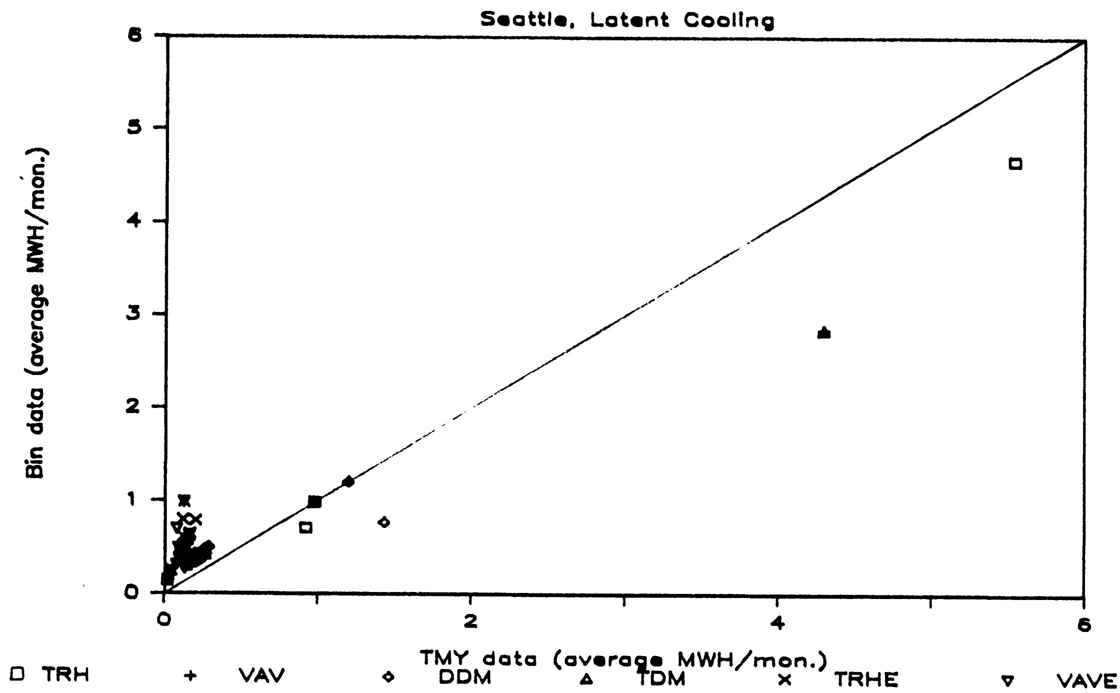


Fig. 6.16. c) Chiller Energy.



a) Latent Cooling.

Fig. 6.17. Comparison of Average Monthly Energies Over a Year Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day for the 13 Combinations of Parameters and 6 Systems Described in Section 6.3 in Seattle, WA.

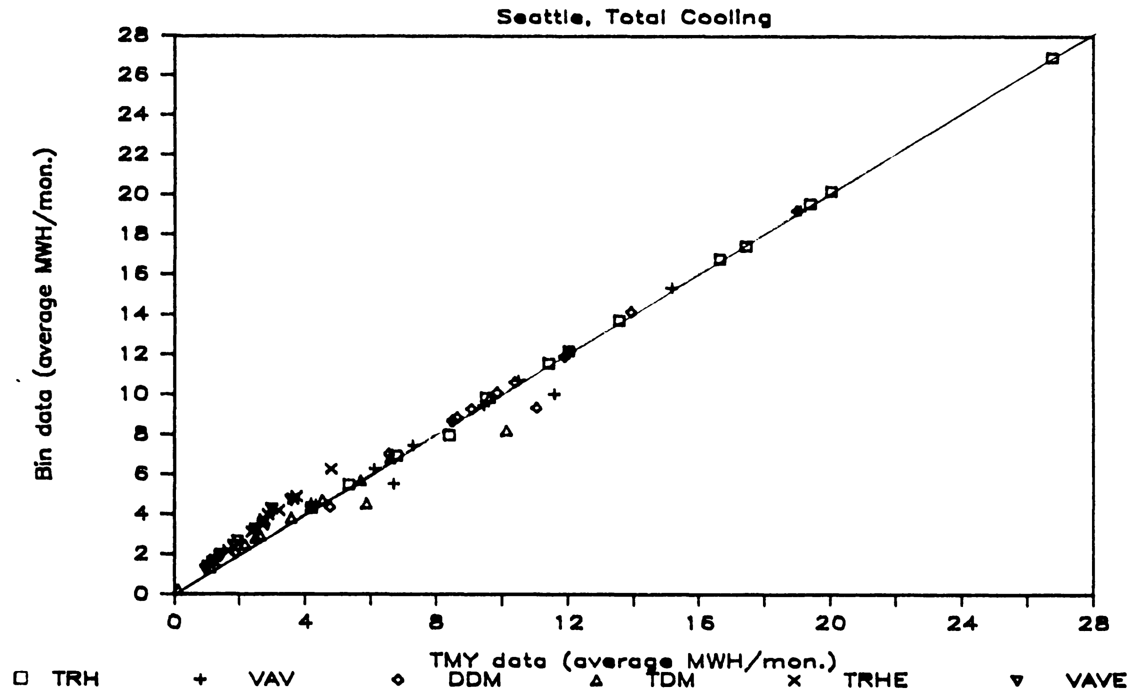


Fig. 6.17. b) Total Cooling.

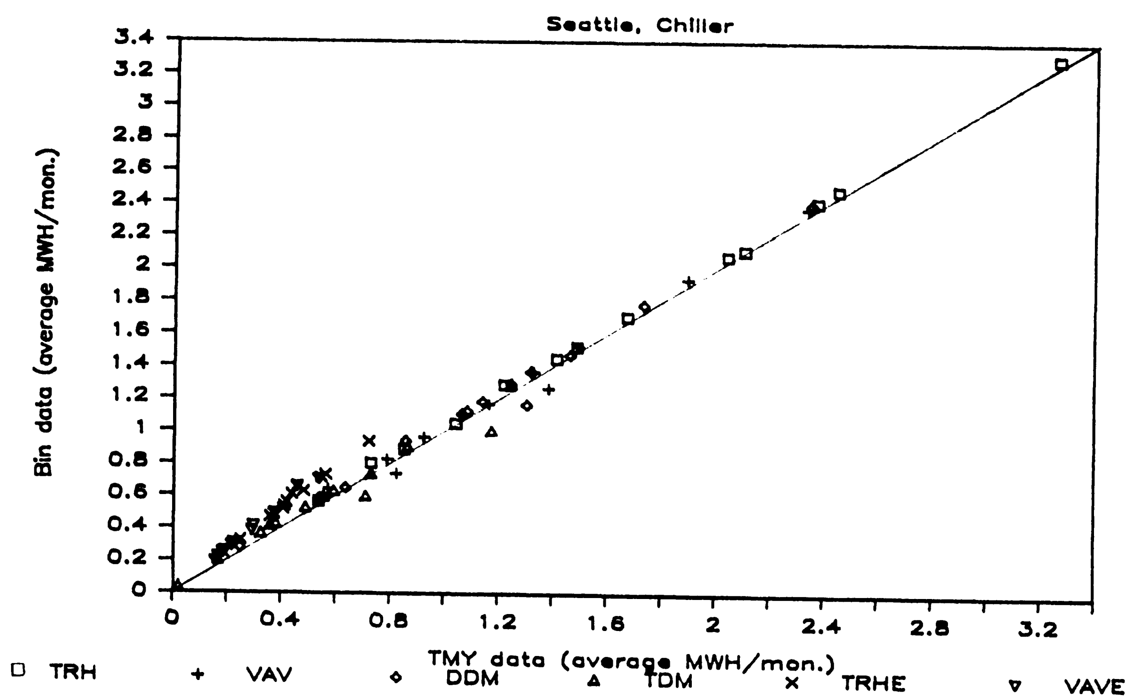
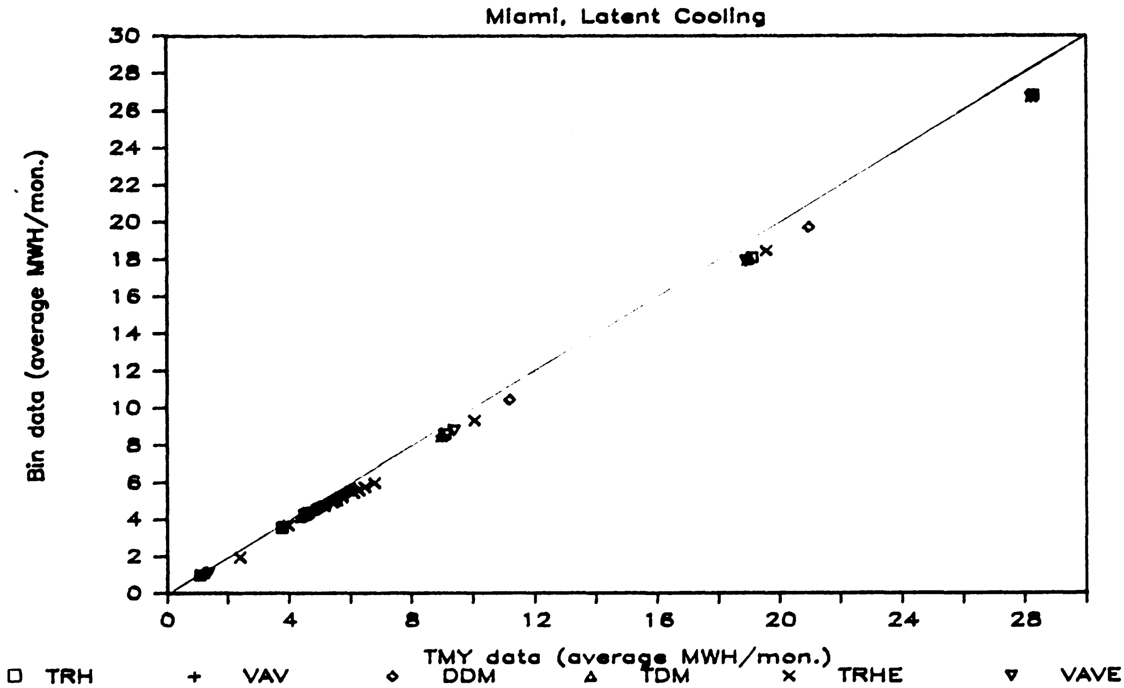


Fig. 6.17. c) Chiller Energy.

6.3b supplies the reason for these striking differences between low and high latent totals. Above ω_A = 0.009 the Erbs' distribution is consistently higher than TMY and extends to higher ω_A's. Below that point, the reverse is true. The larger the base humidity, the smaller the latent load total is. Thus, only higher values of ω_A which have a bias in hours towards bin totals are included in smaller latent load totals. Thus, the higher bin totals result for small loads. The reverse is true for smaller base humidities and larger latent totals. The trend in the ω_A distributions is slanted towards the large hour dominance of the TMY distribution. However, the bin dominated tail region is still included in these totals, and so the deviation from the line with a slope of one is more gradual for large load deviations than small.

Seattle's latent loads are smaller than sensible cooling loads and, as for Madison and Albuquerque, total cooling and chiller loads shown in Fig. 6.17b&c show good agreement between TMY and bin methods. The economizer cycles tend to overpredict chiller because the ratio of latent to sensible totals goes down as free cooling reduces sensible and maximum outside air increases latent. Thus, the latent bin overprediction dominates economizer cycle cooling and chiller totals in Seattle.

Finally, a look at Miami's latent load totals in Fig. 6.18a shows a different picture. Latent totals are large, as expected, of the same order of magnitude as sensible cooling totals. Agreement between bin and TMY totals is good for systems with smaller latent



a) Latent Cooling.

Fig. 6.18. Comparison of Average Monthly Energies Over a Year Calculated Using TMY and Bin Data Generated Using Erbs' Correlations for a Three Period Day for the 13 Combinations of Parameters and 6 Systems Described in Section 6.3 in Miami, FL.

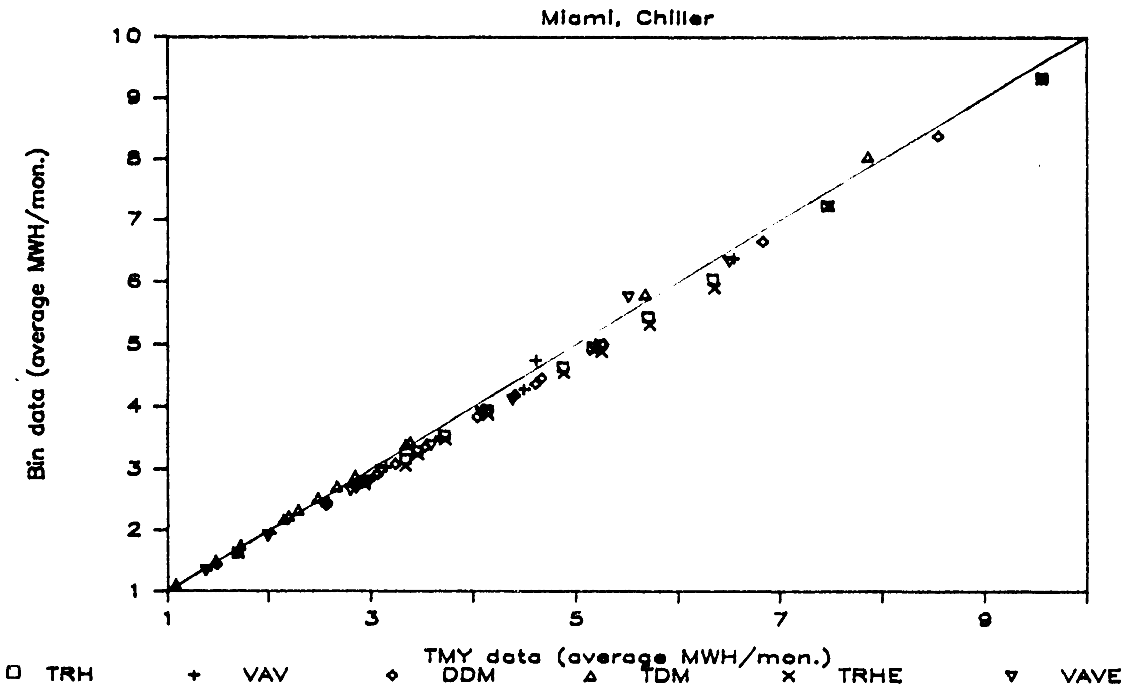


Fig. 6.18. c) Chiller Energy.

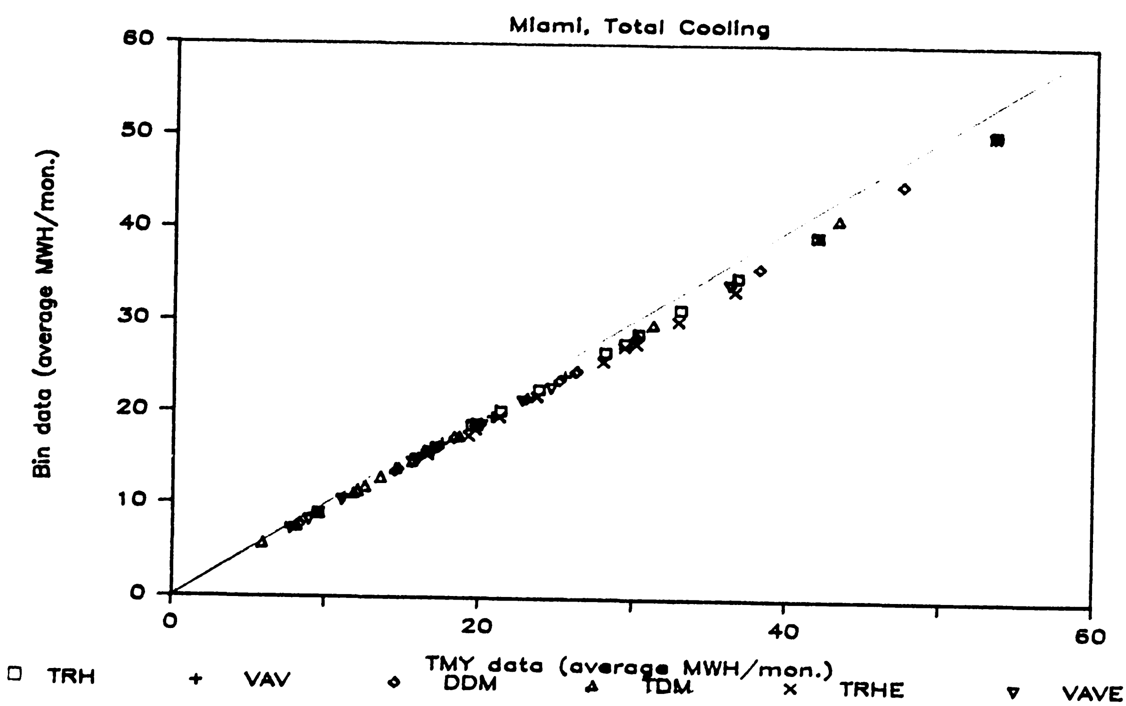


Fig. 6.18. b) Total Cooling.

loads. However, bin summation tends to underpredict slightly for large latent loads. Again, the ω_A distributions afford an answer (Fig. 6.4b). ω_{bcL} is generally in the vicinity of 0.006 to 0.012, a range which for Miami's distribution lies far to the left. This means that the majority of hours are above ω_{bc} and distributional differences hold less meaning just as in the case of the TRH T_{bh} in winter (Section 6.1). The TMY distribution has a fairly pronounced peak around 0.010 whereas the Erbs distribution has no pronounced peak and is centered more on 0.014. Thus latent cooling totals for values of small ω_{bcL} tend not to agree because the averages of the TMY and Erbs specific humidity distributions are different. The latter average is smaller and consequently gives smaller latent totals.

Because latent loads are of the same order as sensible loads in Miami, they have a noticeable effect on total cooling energy shown in Fig. 6.18b. The figure shows that bin total cooling energy underpredicts TMY slightly at large total cooling loads. The chiller totals shown in Fig. 6.18c display good agreement between bin and TMY summations. The latent load differences are less than 5% and do not affect chiller energy totals.

Thus, for all the systems observed in all locations, the equivalent degree-day models match expected trends, validating the use of temperature difference rate expressions. Furthermore, 2°C bins generated using Erbs' correlation gave sensible load totals which compared well with TMY summed load totals over a wide range of system configurations. Latent calculations, however, were affected by both overall ω_A distributional differences and concurrent T_A/ω_A distributional differences between TMY and bin data but the total cooling loads agreed. Chiller totals which represent purchased energy showed good agreement between methods.

The results discussed in this chapter show that equivalent degree-day calculations for purchased energy requirements using bin data generated using Erbs' correlations give good results when compared to the same calculations using actual hourly data. Differences are less than 5% for all system types and all locations. The implication of this conclusion is that Erbs' correlations, which require fewer actual data than hourly data, can be used in place of hourly data to calculate purchased energy.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

Several important topics have been discussed the preceding chapters. HVAC systems were discussed and their operations described. Energy and mass balances on the various systems allowed the derivation of expressions for heating, preheating, sensible cooling and latent cooling coil loads which depend on ambient temperature. Equivalent degree-day expressions were developed from degree-day ideas. Coil and equipment energies were calculated using both hourly weather data and bin weather data derived from Erbs' correlations and the results were compared. The conclusions to be drawn from the topics discussed and recommendations for work that will expand on what has been done here follow.

7.1 Conclusions

The equivalent degree-day (EDD) ideas presented in Chapter 4 allow extension of degree-day concepts to HVAC systems and components. Conventionally defined degree-days (DD) are commonly used to find energy totals for systems whose coil load expressions are a linear function of temperature; equivalent degree-days are used for coil load expressions that are any function of temperature. EDD's are also used to find equipment energy totals for plant equipment like chillers whose COP varies with temperature. The use of EDD's simplifies calculations by allowing the summation of one load equation over ambient temperature ranges to give equipment load directly.

Both hourly and bin weather data were used in EDD and DD summations. Results using bin data calculated from Erbs' correlation for the distribution of hours with ambient temperature were shown to compare well to actual hourly data when the two were used to calculate total heating and cooling coil energy with EDD's for a wide range of systems and locations. This is an extremely useful result because Erbs' correlation requires only monthly average temperature and humidity values for input data and is used to generate bins of any size for any time period of the day. Standard bin data sets involve large amounts of actual data. They are restricted to one standard bin size and three standard daily time periods. Thus, Erbs' distribution correlation provides a reliable and flexible source of bin weather data which is able to be used in EDD summations.

Erbs' degree-day correlation is very useful for system loads which are linear functions of temperature. The same actual data is required for Erbs' correlation for degree-days as was required for Erbs' distribution correlation. However, the correlation is done in one calculation, whereas bin summations must be done for each ambient temperature bin.

The procedure of calculating loads for an entire HVAC system rather than separating the zone loads from the air system loads is also useful. Calculations done for an entire HVAC system allow the interaction between the variables in coil load expressions to be seen immediately. Adding together coil load expressions for different zones served by the same system to form one system coil load expression shows how individual zones influence system energy.

The idea of EDD summations of the portions of load expressions which are a function of temperature gives insight into how energy calculations may be performed for loads which vary with temperature. Energy calculations reviewed in the literature were as complex as the Modified Bin Method [5], where coil and equipment loads are implicit functions of ambient temperature, or as simple as a degree-day method where coil and equipment loads are both linear functions of ambient temperature [4]. Complex and simple calculations have in common that loads are expressed as some function of temperature, a distribution of hours with weather data is represented by use of actual data or correlated functions, and load expressions multiplied by the number of hours at a given ambient temperature are summed over all ambient temperatures to find total energy use. The way in which loads are expressed as a function of temperature and the way in which hours are distributed with weather variables varies from energy calculation procedure to energy calculation procedure. The element of summing loads over ambient temperature distributions is common to all procedures.

7.2 Recommendations for Further Work

The HVAC system load equations examined in this thesis consider only the energy required for heating and cooling. There will also be energy involved in running fans, pumps, and other peripheral equipment. These peripheral energies may be on the order of the thermal energy requirement. If so, models for major peripheral equipment loads should be developed. If the performance of these components is a function of ambient temperature, the EDD and weather distribution ideas developed in this thesis can be applied.

Energy calculations comparing bin and hourly temperature data results should be done with different levels of solar gains each month to check the impact on the two methods. The solar portion of sol-air temperatures should also be taken into account when varying monthly solar loads over the year.

Another area to explore is how the bin size affects energy calculation results. One critical area in which bin size may be important includes temperatures which separate operational ranges of economizer and dead band controls. As mentioned in Chapter 5, it is helpful if the edge of a bin coincides with the temperatures which separate operational temperature ranges. Bins towards the middle of monthly distributions have many hours in them. These bins constitute a critical area in a temperature distribution. The assumption in bin data is that the average temperature represents all temperatures in the bin. There is a distribution of hours with temperature across single bins, and a large number of hours will magnify the error in assuming one average temperature for all hours in each bin. Thus, the effect of making bin size smaller near the middle of distribution curves should be examined.

The disagreement in latent loads calculated using hourly data and Erbs' correlation bin data for economizer cycles in Albuquerque and Madison was due to the fact that specific humidity is distributed with ambient temperature in the hourly data but not in the Erbs' correlation. Erbs did investigate distributions of specific humidity with ambient temperature and found they do not significantly enhance either yearly specific humidity bin distributions or results of load calculations for a room air conditioner. However, both these quantities are summed over all values of specific humidity, independent of what bin temperature the humidity is associated with. Summing of latent loads in economizer cycles is done over specific humidities which depend on what temperature range the temperature bin associated with the humidity is in. How humidity is distributed with temperature is important. Clearly, associating only one average specific humidity with each temperature bin does not give good results for an economizer cycle latent load calculation. Thus, Erbs' humidity distributions applied to the latent economizer load summations might improve agreement between latent loads calculated using hourly and bin data and should be developed further.

The ability to accurately model building energy use as efficiently as possible with a minimum of actual input data and computations needed is very important. As energy prices rise and supplies become scarce, good models will be even more important. The work in this thesis is an attempt to further the ability of simplified calculations to model energy use.

APPENDIX A

DERIVATION OF COIL LOAD EQUATIONS

Detailed derivations of all the HVAC system coil loads discussed in Chapter 4 are done in this appendix. The derivation for each system will give:

1. The figure number(s) containing a schematic diagram of the system and/or control strategy involved as shown in Chapter 4.
2. List of quantities constant with temperature.
3. List of fundamental equations from mass and energy balances on various portions of the system.
4. Major step in combining the fundamental quantities to obtain heating, sensible cooling and latent cooling load rate equations ($\dot{q}_h$, $\dot{q}_c$, $\dot{q}_L$).
5. Any additional comments.

It should be noted that:

$$X = [T_1 - T_2]^+$$

means that when $[T_1 - T_2] > 0$, $X = T_1 - T_2$ and when $[T_1 - T_2] < 0$, $X = 0$. Similarly, for:

$$Y = [T_1 - T_2]^-$$

$[T_1 - T_2] < 0$, gives $Y = T_1 - T_2$ and when $[T_1 - T_2] > 0$, $Y = 0$. So,

$Y = -X$. If

$$R = \sum_{T_1} X \qquad \text{and} \qquad S = \sum_{T_1} Y$$

the result $R = -S$ occurs only if every $X > 0$ and every $Y < 0$. The "+" picks only positive values and the "-", only negative.

Terminal Reheat (TRH)

Figure: 4.1

Constant: $\dot{m}_o$, $\dot{m}$, $\dot{m}_r$, T_c, ω_c, T_R, $\dot{q}_G$, $\dot{q}_L$, U, A, c_p

Equations:

Definition, moisture mass flow at any point x

$$\dot{m}_{h_2ox} = \omega_x \dot{m}_{air_x} \tag{A.1}$$

Definition, fresh air fraction

$$k = \frac{\dot{m}_o}{\dot{m}} \tag{A.2}$$

Air mass balance at m

$$\dot{m}_o + \dot{m}_r = \dot{m} \tag{A.3}$$

Moisture mass balance at m

$$\omega_A \dot{m}_o + \omega_r \dot{m}_r = \omega_m \dot{m} \tag{A.4}$$

Energy mass balance at m

$$\dot{m}_o c_p T_A + \dot{m}_r c_p T_R = \dot{m} c_p T_m \tag{A.5}$$

Sensible energy balance at c

$$\dot{q}_{cs} = \dot{m}c_p(T_m - T_c) \tag{A.6}$$

Latent energy balance at c

$$\dot{q}_{cL} = h_{fg}(\dot{m}\omega_m - \dot{m}\omega_c) \tag{A.7}$$

Definition, envelope loss

$$\dot{q}_o = UA(T_R - T_A) \tag{A.8}$$

Definition, moisture from zone latent input

$$\dot{m}\omega_L = \frac{\dot{q}_L}{h_{fg}} \tag{A.9}$$

Energy balance on zone and reheat coil

$$\dot{q}_h + \dot{q}_G - \dot{q}_o = \dot{m}c_p(T_R - T_C) \tag{A.10}$$

Moisture balance on zone

$$\dot{m}\omega_c - \dot{m}\omega_L = \dot{m}\omega_T \tag{A.11}$$

Derivation:

1. Heating

Combine Eqs. (A.8) and (A.10), solve for $\dot{q}_h$

$$\dot{q}_h = \dot{m}c_p\ (T_R - T_C) + UA(T_R - T_A) - \dot{q}_G$$

$$= -\ UAT_A + T_R(\dot{m}c_p + UA) - \dot{m}c_pT_c - \dot{q}_G$$

$$\dot{q}_h = UA\ [\frac{T_R(\dot{m}c_p + UA) - \dot{m}c_pT_c - \dot{q}_G}{UA} - T_A]^+ \qquad (A.12)$$

2. Sensible Cooling

Combine Eqs. (A.2), (A.3) and (A.5), solve for T_m

$$\dot{m}_oT_A + (\dot{m} - \dot{m}_o)T_R = \dot{m}T_m$$

$$T_m = \frac{\dot{m}_o}{\dot{m}}\ T_A + \frac{\dot{m} - \dot{m}_o}{\dot{m}}\ T_R \qquad (A.13)$$

$$T_m = kT_A + (1 - k)T_R \qquad (A.14)$$

Use Eqs. (A.14) and (A.6) to find $\dot{q}_{cs}$

$$\dot{q}_{cs} = \dot{m}c_p\ (kT_A + (1 - k)T_R - T_c)$$

$$\dot{q}_{cs} = \frac{k\dot{m}c_p}{\dot{m}_oc_p}\ [T_A - \frac{T_C - (1 - k)T_R}{k}]^+ \qquad (A.15)$$

Latent Cooling

Use Eqs. (A.9) and (A.11) to find ω_r

$$\omega_r = \frac{\dot{m}\omega_c}{\dot{m}} + \frac{\dot{m}}{\dot{m}}\frac{\dot{q}_L}{\dot{m}h_{fg}}$$

$$\omega_r = \omega_c + \omega_L , \qquad \omega_L = \frac{\dot{q}_L}{\dot{m}h_{fg}} \tag{A.16}$$

Substitute Eq. (A.16) in Eq. (A.4), solve for ω_m

$$\dot{m}\omega_m = \omega_A\dot{m}_o + (\dot{m} - \dot{m}_o)(\omega_c + \omega_L) \tag{A.17a}$$

$$\omega_m = k\omega_A + (1 - k)(\omega_c + \omega_L) \tag{A.17b}$$

Substitute Eq. (A.17) into Eq. (A.7) for $\dot{q}_{cL}$

$$\dot{q}_{cL} = h_{fg}\dot{m}(k\omega_A + (1 - k)(\omega_c + \omega_L) - \omega_c)$$

$$= k\dot{m}h_{fg}(\omega_A + \frac{(1 - k - 1)\omega_c + (1 - k)\omega_L}{k})$$

$$\dot{q}_{cL} = \dot{m}_o h_{fg}[\omega_A - (\omega_c - \frac{1 - k}{k}\omega_L)]^+ \tag{A.18}$$

Comments

If $T_m < T_c$, add heat (preheating) instead of cooling at point c, $\dot{q}_{ph} = \dot{m}c_p[T_c - T_m]$. Substituting Eq. (A.14) for T_m

$$\dot{q}_{ph} = \dot{m}c_p[T_c - (kT_A + (1 - k)T_R)]^+$$

$$\dot{q}_{ph} = \dot{m}_o c_p \left[\frac{T_c - (1 - k)T_R}{k} - T_A\right]^+ = - \dot{m}_o c_p\left[T_A - T_c - \frac{(1 - k)T_R}{k}\right] = -\dot{q}_c \tag{A.19}$$

$\dot{q}_{ph}^+ = -\dot{q}_c^-$ is true for all systems that preheat is $\dot{q}_c$ when a "-" is put on the temperature difference portion. In terms of base temperature and conductance factor, $\dot{q}_{ph}$ has T_{bc} and U_{fc} but the form of the equation is $\dot{q}_h$.

Terminal Reheat With Economizer (TRHE)

Figures: 4.1 and 4.3

Constant: $\dot{m}$, T_c, ω_c, T_R, $\dot{q}_G$, $\dot{q}_c$, U, A, c_p

$\dot{m}_{om}$ = minimum necessary outise air level

$k_m = \dot{m}_{om}/\dot{m}$

Equations:

k and T_m piecewise continuous function of T_A in Fig. 4.3.

Derivation:

Heating

k and T_m do not appear in Eq. (A.12)

$$\dot{q}_h = \dot{q}_{hA.12}$$

Sensible Cooling

Range 1; $T_A > T_R$ substitute $k = k_m$ into Eq. (A.15)

$$\dot{q}_{cs} = [T_A - \frac{T_c - (1 - k_m)T_R}{k_m}]^+$$

Range 4; $T_A < T_{bc} \rightarrow [T_A - T_{bc}] < 0 \rightarrow \dot{q}_{ph} > 0$, $\dot{q}_{cs} = 0$ Range 3; substituting $T_m = T_c$ in Eq. (A.6)

$$\dot{q}_{cs} = \dot{m}c_p[T_C - T_c] = 0 \qquad \text{(A.20)}$$

Range 2; substituting k = 1 in Eq. (A.15)

$$\dot{q}_{cs} = \dot{m}c_p[T_A - \frac{T_c(1 - 1)T_R}{1}]^+$$

$$\dot{q}_{cs} = \dot{m}c_p[T_A - T_c]^+ \qquad (A.21)$$

<u>Latent Cooling</u>

Range 1 and 4; substitute $k = k_m$ into Eq. (A.18)

$$\dot{q}_{cL} = \dot{m}_{om}h_{fg}[\omega_A - (\omega_c - \frac{1 - k_m}{k_m}\omega_L)]^+$$

Range 3; free cooling, no cooling is done

$$\dot{q}_{cL} = 0$$

Range 2; substitute $k = 1$ in Eq. (A.18)

$$\dot{q}_{cL} = \dot{m}h_{fg}[\omega_A - (\omega_c - \frac{1 - 1}{1}\omega_L)]^+$$

$$\dot{q}_{cL} = \dot{m}h_{fg}[\omega_A - \omega_c]^+ \qquad (A.22)$$

Terminal Reheat with Deadband Control (TRHD)

Figures: 4.1 and 4.2

Constants: $\dot{m}_o$, $\dot{m}$, $\dot{m}_r$, T_{RC}, T_{RH}, T_C, ω_ε, $\dot{q}_G$, $\dot{q}_L$, U, A, c_p

Equations: no additional ones

T_R is a piecewise continuous function of T_A in Fig. 4.2.

Derivation

In Range 2 no heating or cooling is needed, so substitute $\dot{q}_h = 0$ and $\dot{m}c_p(T_R - T_c) = 0$ in Eq. (A.10) and solve for T_A at limits of Range 2.

1. $T_R = T_{RH}$, substitute $\dot{q}_o$ in Eq. (A.8) to give $T_A = T_{AH}$

$$\dot{q}_G - UA(T_{RH} - T_A) = 0$$

$$T_A - T_{RH} = \frac{\dot{q}_G}{UA}$$

$$T_{AH} = T_{RH} + \frac{\dot{q}_G}{UA}$$

2. $T_R = T_{RC}$, substitute $\dot{q}_o$ in Eq. (A.24) to give $T_A = T_{AC}$

$$\dot{q}_G + UA(T_{AC} - T_{RC}) = 0$$

$$T_{AC} - T_{RC} = \frac{\dot{q}_G}{UA}$$

$$T_{AC} = T_{RC} + \frac{\dot{q}_G}{UA}$$

Heating

Range 1; substitute $T_R = T_{RC}$ in Eq. (A.12)

$$\dot{q}_h = UA\left[\frac{T_{RC}(\dot{m}c_p + UA) - \dot{m}c_p T_{RC} - \dot{q}_G}{UA} - T_A\right]^+$$

Range 3; substitute $T_R = T_{RH}$ into Eq. (A.12). Range 2; no zone load, no need for heating

$$\dot{q}_h = 0$$

Sensible and Latent Cooling

Range 1, 3; as above, substitute $T_R = T_{RC}$ and T_{RH} into Eqs. (A.15) and (A.18). Range 2; as for heating, no zone load implies no need for cooling

$$\dot{q}_{cs} = \dot{q}_{cL} = 0$$

Comments

No change in the form of Eqs. (A.12), (A.15) and (A.15) results because T_{RH} and T_{RC} are constants as T_R is. This will be the case no matter what system is involved. Thus, the deadband control will not be derived for the others, but the rates equations ($\dot{q}_h$, $\dot{q}_{cs}$ and $\dot{q}_{cL}$) affected by deadband control (containing T_R) will be noted in Comments.

Variable Air Volume With Reheat (VAV)

Figures: 4.1 and 4.4

Constants: $\dot{m}_o$, T_c, ω_c, T_R, $\dot{q}_G$, $\dot{q}_L$, U, A, c_p

$\dot{m}_m$ - minimum acceptable airflow into zone

Equations:

Cooling energy balance on zone ($\dot{q}_h = 0$)

$$\dot{q}_G + \dot{q}_o + \dot{m}c_p(T_R - T_c) \tag{A.23}$$

Definition, envelope gain

$$\dot{q}_o = UA(T_A - T_R) \tag{A.24}$$

Derivations:

Heating

Range 1; $\dot{m} > \dot{m}_m$, no heating called for

$$\dot{q}_h = 0$$

Range 2; substitute $\dot{m} = \dot{m}_m$ into Eq. (A.12)

$$\dot{q}_h = UA\left[\frac{T_R(\dot{m}_m c_p + UA) - \dot{m}_m c_p T_c - \dot{q}_G}{UA} - T_A\right]^+ \tag{A.25}$$

which has the same form as Eq. (A.12).

Sensible Cooling

Range 1; solve for mass flow, $\dot{m}$ using Eqs. (A.23) and (A.8)

$$\dot{m}c_p(T_R - T_c) = \dot{q}_G + UA(T_A - T_R)$$

$$\dot{m} = \frac{UA[T_A - (T_R - \frac{\dot{q}_G}{UA})]}{c_p(T_R - T_c)} \qquad (A.26)$$

Find substitute $T_A = T_{chg}$ and $\dot{m} = \dot{m}_m$ in Eq. (A.24) to solve for T_{chg}

$$\dot{m}_m = UA\,\frac{[T_{chg} - (T_R - \frac{\dot{q}_G}{UA})]^+}{c_p(T_R - T_c)}$$

$$\frac{\dot{m}_m c_p(T_R - T_c)}{UA} + (T_R - \frac{\dot{q}_G}{UA})\,\frac{UA}{UA} = T_{chg}$$

$$T_{chg} = \frac{(UA + \dot{m}_m c_p)T_R - \dot{m}_m c_p T_c - \dot{q}_G}{UA} \qquad (A.27)$$

This is also the reheat coil base temperature in Eq. (A.25). Range 1; solve for $\dot{q}_{cs}$ using Eq. (A.6), T_m from Eq. (A.13) and $\dot{m}$ from Eq. (A.26)

$$\dot{q}_{cs} = \dot{m}c_p(\frac{\dot{m}_o}{\dot{m}}\,T_A + \frac{\dot{m} - \dot{m}_o}{\dot{m}}\,T_R - T_c)$$

$$= \dot{m}_o c_p(T_A - T_R) + \dot{m}c_p(T_R - T_C)$$

$$= \dot{m}_o c_p(T_A - T_R) + UA(T_A - T_R + \frac{\dot{q}_G}{UA})$$

$$= (\dot{m}_o c_p + UA)(T_A - T_R) + \dot{q}_G$$

$$\dot{q}_{cs} = (\dot{m}_o c_p + UA)[T_A - (T_R - \frac{\dot{q}_G}{\dot{m}_o c_p + UA})]^+ \tag{A.28}$$

Define: Range 2; substitute $\dot{m} = \dot{m}_m$ in Eq. (A.2)

$$k_m = \dot{m}_o/\dot{m}_m \tag{A.29}$$

substitute $k = k_m$ in Eq. (A.15).

Latent Cooling

Range 1; $\dot{m} = \dot{m}(T_A)$ or given in Eq. (A.26). Redefine ω_L using Eq. (A.9):

$$\omega_L(T_A) = \frac{\dot{q}_L}{\dot{m}(T_A)h_{fg}} \qquad \text{(varies with } T_A\text{)}$$

Equations (A.16) and (A.17a) remain the same, substitute Eq. (A.17) into Eq. (A.7) and solve for $\dot{q}_{cL}$:

$$\dot{q}_{cL} = h_{fg}(\omega_A \dot{m}_o + (\dot{m}(T_A) - \dot{m}_o)(\omega_c - \omega_L(T_A) - \dot{m}(T_A)\omega_c)$$

$$= \dot{m}_o h_{fg}(\omega_A + \frac{(\dot{m}(T_A) - \dot{m}_o - \dot{m}(T_A))\omega_c - (\dot{m}(T_A) - \dot{m}_o)\omega_L}{\dot{m}_o})$$

$$\dot{q}_{cL} = \dot{m}_o h_{fg}[\omega_A + \omega_c - \frac{\dot{m}(T_A) - \dot{m}_o}{\dot{m}_o}\omega_L(T_A)]^+ \tag{A.30}$$

Comment

Note that $\dot{q}_{cL}$ depends on concomitant values for T_A and ω_A.

VAV With Economizer (VAVE)

Figures: 4.1, 4.3, 4.4

Constants: $\dot{m}_{om}$, T_c, ω_c, T_R, $\dot{q}_G$, $\dot{q}_L$, U, A, c_p

Equations:

$\dot{m}_o$ and T_m piecewise continuous function of T_A in Fig. 4.4. For Range 1 in Fig. 4.3, mass flow $\dot{m} = \dot{m}(T_A)$ in Eq. (A.26) (assumes $T_{chg} < T_{bc}$ in Figs. 4.3 and 4.4).

Derivation:

"Range" below = Range on Fig. 4.4.

Heating

For Range 1-4; there is no heating, $\dot{q}_h = 0$.

Sensible Cooling

Range 1,4; substitute $\dot{m}_o = \dot{m}_{om}$ in Eq. (A.28)

$$\dot{q}_{cs} = (\dot{m}_{om}c_p + UA)[T_A - (T_R - \frac{UA}{(\dot{m}_{om} + UA)})]^+$$

has the same form as Eq. (A.28). Range 2; free cooling

$$\dot{q}_{cs} = 0$$

Range 3; substitute $\dot{m}_o = \dot{m}(T_A)$ into Eqs. (A.26) and (A.28)

$$\dot{q}_{cs} = (\dot{m}(T_A)c_p + UA)[T_A - (T_R - \frac{\dot{q}_G}{\dot{m}(T_A)c_p + UA})]^+$$

$$\dot{q}_{cs} = (UA + \dot{m}(T_A)c_p)[\frac{(T_A - T_R)(UA + \dot{m}(T_A))c_p + \dot{q}_G}{UA + \dot{m}(T_A)c_p}]$$

$$= (T_A - T_R)[\frac{UA(T_R - T_c)}{(T_R - T_c)} + \frac{UA(T_A - (T_R - \frac{\dot{q}_G}{UA}))}{(T_R - T_c)}] + \dot{q}_G$$

$$= \frac{(T_A - T_R)UA}{T_R - T_c}[T_R - T_c + T_A - T_R - \frac{\dot{q}_G}{UA}] + \dot{q}_G$$

$$\dot{q}_{cs} = \frac{UA}{T_R - T_c}[T_A - T_R]^+[T_A - T_c - \frac{\dot{q}_G}{UA}] + \dot{q}_G \qquad (A.31)$$

Latent Cooling

Range 1, 4; substitute $\dot{m} = \dot{m}_{om}$ into Eq. (A.30). Range 3; also as for sensible, free cooling means:

$$\dot{q}_{cL} = 0$$

Range 2; substituting $\dot{m}_o = \dot{m}(T_A)$ into Eq. (A.30)

$$\dot{q}_{cc} = \dot{m}(T_A)h_{fg}[\omega_A - \omega_c - \frac{\dot{m}(T_A) - \dot{m}(T_A)}{\dot{m}(T_A)}\omega_L(T_A)]^+$$

$$\dot{q}_{cL} = \dot{m}(T_A)h_{fg}[\omega_A - \omega_c]^+ \qquad (A.32)$$

Variable Air Volume With Deadband Control (VAVD)

Figures: 4.3 and 4.4

Comments:

In Range 1 of Fig. 4.4 where $\dot{m} > \dot{m}_m$, the system provides only cooling thus $T_R = T_{RC}$ for the entire range ($T_A > T_{chg}$).

In Range 2 for Fig. 4.4 where $\dot{m} = \dot{m}_m$, both T_{RC} and T_{RH} used for T_R as in TRHD.

VAV With Induction Unit (VAVI)

Figure: 4.5

Constants: $\dot{m}_m$, $\dot{m}_o$, $\dot{m}_\varepsilon$, T_c, ω_c, T_R, $\dot{q}_c$, $\dot{q}_L$, U, A, c_p

Equations:

Mass balance at i

$$\dot{m}_i = \dot{m} + \dot{m}_t \tag{A.33}$$

Energy balance at i

$$T_c\dot{m} + \dot{m}_t T_H = (\dot{m} + \dot{m}_c)T_i \tag{A.34}$$

Energy balance on reheat

$$\dot{q}_h = \dot{m}_t c_p (T_H - T_R) \tag{A.35}$$

Zone energy balance

$$\dot{q}_G + \dot{q}_o = (\dot{m} + \dot{m}_t) c_p \; (T_R - T_i) \tag{A.36}$$

Derivation

For $\dot{m} > \dot{m}_m$ (operation for VAV cooling)

$$\dot{q}_h = 0$$

Using Eqs. (A.33) and (A.35), find T_i

$$T_i = \frac{T_c\dot{m} + \dot{m}_t T_R}{(\dot{m} + \dot{m}_t)} \qquad (A.37)$$

Substitute Eq. (A.37) into Eq. (A.36)

$$\dot{q}_G + \dot{q}_o = (\dot{m} + \dot{m}_t)\, c_p \frac{(T_R(\dot{m} + \dot{m}_t) - \dot{m}T_c - \dot{m}_t T_R)}{\dot{m}_t + \dot{m}}$$

$$\dot{q}_G + \dot{q}_o = c_p(\dot{m}T_R - \dot{m}T_c + \dot{m}_t T_R - \dot{m}_t T_R)$$

which is the same as Eq. (A.23) used to find $\dot{q}_{cs}$ for VAVR.

For $\dot{m} = \dot{m}_m$ (reheat operation) $T_H > T_R$ $\dot{q}_{cs}$ is given by expressions in Eqs. (A.15) and (A.29). Using Eqs. (A.33) and (A.35), T_i is now

$$T_i = \frac{T_c\dot{m}_m + \dot{m}_t T_H}{(\dot{m}_m + \dot{m}_t)} \qquad (A.38)$$

Using Eq. (A.35) solve for T_H

$$T_H - T_R = \frac{\dot{q}_h}{\dot{m}_t c_p} + T_R \qquad (A.39)$$

Combine Eqs. (A.39), (A.38) and (A.36) to solve for $\dot{q}_h$

$$\dot{q}_G + \dot{q}_o = (\dot{m}_m + \dot{m}_t)\,c_p\left(\frac{T_p(\dot{m}_m + \dot{m}_t) - T_c\dot{m}_m - \dot{m}_t\left(\frac{\dot{q}_h}{\dot{m}_t c_p} + T_R\right)}{(\dot{m}_m + \dot{m}_t)}\right)$$

$$\dot{q}_G + \dot{q}_o = c_p\left(T_R\dot{m}_m + \dot{m}_t T_R - \dot{m}_m T_c - \dot{m}_t T_R - \frac{\dot{q}_h}{c_p}\right)$$

$$\dot{q}_G + \dot{q}_o = \dot{m}_m c_p(T_R - T_C) - \dot{q}_h$$

$$\dot{q}_h + \dot{q}_G + \dot{q}_o = \dot{m}_m c_p(T_R - T_C)$$

which is the same as Eq. (A.10) with $\dot{m} = \dot{m}_m$ which gives reheat load $\dot{q}_h$ in Eq. (A.25).

Comments

The sensible heating and cooling loads are the same for VAVI as for VAV.

Dual Duct (DDM)

Figure: 4.7

Constants: T_R, T_c, T_H, $\dot{m}$, $\dot{m}_o$, ω_c, $\dot{q}_G$, $\dot{q}_L$, U, A, c_p

Equations:

Definition, fraction cool duct flow

$$K' = \dot{m}_c/\dot{m} \tag{A.40}$$

Latent energy balance at c

$$\dot{q}_{cL} = \dot{m}_o h_{fg}(\omega_m - \omega_c) \tag{A.41}$$

Sensible energy balance at c

$$\dot{q}_{cs} = \dot{m}_c c_p(T_m - T_c) \tag{A.42}$$

Sensible energy balance at h

$$\dot{q}_h = \dot{m}_h c_p(T_H - T_m) \tag{A.43}$$

Sensible energy balance at i

$$\dot{m}_h c_p T_H + \dot{m}_c c_p T_c = \dot{m}T_i \tag{A.44}$$

Mass energy balance at i

$$\dot{m}_h + \dot{m}_c = \dot{m} \tag{A.45}$$

Energy balance on zone (with envelope gains, $\dot{q}_o$)

$$\dot{q}_G + \dot{q}_o = \dot{m}c_p(T_R - T_i) \tag{A.46}$$

Derivation

Use Eqs. (A.46) and (A.24) to solve for T_i:

$$\dot{m}c_p(T_R - T_i) = UA(T_A - T_R) + \dot{q}_G$$

$$+T_i = + \frac{(UA + \dot{m}c_p) - UAT_A - \dot{q}_G}{\dot{m}c_p} \tag{A.49}$$

Combine Eqs. (A.40), (A.44) and (A.45) to find K':

$$(\dot{m} - \dot{m}_c)T_H + \dot{m}_c T_i = \dot{m}T_i$$

$$(-1)\ \dot{m}_c(T_c - T_H) = \dot{m}(T_i - T_H)(-1)$$

$$K' = \frac{\dot{m}_c}{\dot{m}} = \frac{T_H - T_i}{T_H - T_c} \tag{A.50}$$

Substitute Eq. (A.49) into Eq. (A.50)

$$K' = \frac{T_H(\dot{m}c_p) - (UA + \dot{m}c_p) + UAT_A + \dot{q}_G}{\dot{m}c_p(T_H - T_c)}$$

$$K'(T_A) = \frac{UA[T_A - \frac{(UA + \dot{m}c_p)T_R - \dot{m}c_pT_H - \dot{q}_G}{\dot{m}c_p(T_H - T_c)}]^+}{\dot{m}c_p(T_H - T_c)} \qquad (A.51)$$

Heating

Using $K'(T_A)$ in Eqs. (A.51), (A.45) and (A.14), solve for $\dot{q}_h$

$$\dot{q}_h = \frac{\dot{m} - \dot{m}_c}{\dot{m}} \dot{m}c_p(T_H - KT_A + (1 - k)T_R)$$

$$\dot{q}_h = (1 - K'(T_A))\ k\dot{m}c_p[\frac{T_H - (1 - k)T_R}{k} - T_A]^+ \qquad (A.52)$$

Sensible Cooling

Using $K'(T_A)$ in Eq. (A.51) with Eqs. (A.42) and (A.14), solve for $\dot{q}_{cs}$

$$\dot{q}_{cs} = K'(T_A)\ \dot{m}c_p(kT_A + (1 - k)T_R - T_c)$$

$$\dot{q}_{cs} = K'(T_A)\ k\dot{m}c_p(T_A - \frac{T_c - (1 - k)T_R}{k}) \qquad (A.53)$$

Latent

Using Eqs. (A.48), (A.47) and (A.41) find ω_r

$$\dot{m}\omega_r = \dot{m}_h\omega_m + \omega_c\dot{m}_c + \dot{m}\omega_L$$

$$\omega_r = (1 - K')\omega_m + K'\omega_c + \omega_L \tag{A.54}$$

Using Eqs. (A.2) and (A.54) in Eq. (A.4) find ω_m

$$k\omega_A + \left((1 - K')\omega_m + K'\omega_c + \omega_L\right)(1 - k) = \omega_m$$

$$\omega_m\left(1 - (1 - K')\right)(1 - k) = k\omega_A - (1 - k)\ K'\omega_c - (1 - K')$$

$$\omega_m = \frac{k\omega_A + (1 - k)\ K'(T_A)\omega_c + (1 - k)\omega_L}{1 - \left(1 - K'(T_A)\right)(1 - k)}$$

Substitute ω_m in Eq. (A.55) into Eq. (A.41) to find $\dot{q}_{cL}$

$$\dot{q}_{cL} = \frac{K'\dot{m}h_{fg}(k\omega_A + (1 - k)K'\omega_c - (1 - k)\omega_L - \left(1 - (1 - K')(1 - k)\right)\omega_c}{1 - (1 - k)(1 - K')}$$

$$\dot{q}_{cL} = \frac{K'k\dot{m}h_{fg}\left[\omega_A - \left(\omega_c - \frac{1 - k}{k}\omega_L\right)\right]^+}{1 - (1 - k)(1 - K')} \tag{A.56}$$

Dual Duct With Economizer (DDME)

Figure: 4.3 and 4.7

Constants: T_R, T_c, T_C, $\dot{m}$, ω_c, $\dot{q}_G$, $\dot{q}_c$, U, A, c_p

Equations:

k and T_m piecewise continuous functions of T_A in Fig. 4.7.

Derivation:

Heating

Range 1 and 4, substitute $k = k_m$ in Eq. (A.52). Range 2 substitute $T_m = T_A$ substituted in Eq. (A.43) with $\dot{m}_h = (1 - K'(T_A))\dot{m}$ where $K'(T_A)$ is given in Eq. (A.51) to solve for $\dot{q}_h$.

$$\dot{q}_h = \dot{m}_h c_p (T_H - T_A)$$

$$\dot{q}_h = (1 - K'(T_A))\ \dot{m}c_p(T_H - T_A) \qquad \text{(A.57)}$$

Range 3, substitute $T_m = T_c$ into Eq. (A.43)

$$\dot{q}_h = (1 - K'(T_A))\ \dot{m}c_p(T_H - T_c) \qquad \text{(A.58)}$$

Substitute $K'(T_A)$ in Eq. (A.51) into Eq. (A.58) to find $\dot{q}_h$

$$\dot{q}_h = \frac{[\dot{m}c_p(T_H - T_c) - UAT_A + (UA + \dot{m}c_p)T_R - \dot{m}c_pT_H - \dot{q}_G]\ \dot{m}c_p(T_H - T_c)}{\dot{m}c_p(T_H - T_c)}$$

$$\dot{q}_h = [-\dot{m}c_pT_c - UAT_A + (UA + \dot{m}c_p)T_R - \dot{q}_G]$$

$$= UA[\frac{(UA + \dot{m}c_p)T_R - \dot{m}c_pT_c - \dot{q}_G}{UA} - T_A]^+$$

which is the same expression as Eq. (A.12)

Sensible Cooling

Range 1 and 4 substitute $k = k_m$ in Eq. (A.53). Range 3 substitute $T_m = T_c \rightarrow$ free cooling,

$$\dot{q}_{cs} = 0$$

Range 2 substitute $T_m = T_A$ substituted into Eq. (A.42) with $\dot{m}_c = K'(T_A)\dot{m}$ to solve for $\dot{q}_{cs}$

$$\dot{q}_{cs} = K'(T_A)\dot{m}c_p [T_A - T_c]^+ \qquad (A.58)$$

Latent Cooling

Range 1 and 4 substitute $k = k_m$ in Eq. (A.56). Range 3, free cooling,

$$\dot{q}_{cL} = 0$$

Range 2, $\dot{m}_o = \dot{m}$ implies $k = 1$. Substitute $k = 1$ in Eq. (A.56):

$$\dot{q}_{cL} = \frac{K'(T_A)\ \dot{m}h_{fg}(\omega_A - (\omega_c - \frac{1 - 1}{1}\omega_c))}{1 - (1 - 1)(1 - K')}$$

$$\dot{q}_{cL} = K'(T_A)\ \dot{m}h_{fg}(\omega_A - \omega_c)^+$$

Dual Duct with Deadband Control (DDMD)

Figure: 4.2 and 4.7

Comments

In Range 1, substitute $T_R = T_{RC}$ in Eqs. (A.52), (A.53) and (A.51). In Range 3, substitute $T_R = T_{RH}$ in the same equations. In Range 2

$$\dot{q}_h = \dot{q}_{cs} - \dot{q}_{cL} = 0$$

Three Deck (TD)

Figure: 4.8

Constants: $\dot{m}$, T_R, T_H, T_c, $\dot{q}_c$, $\dot{q}_G$, U, A, c_p

Equations:

(Note: $\dot{m}_m$ here denotes mass flow in third, mixed air duct not minimum airflow for VAV.)

Heating mass balance at i

$$\dot{m}_h + \dot{m}_m = \dot{m} \tag{A.59}$$

Cooling mass balance at i

$$\dot{m}_c + \dot{m}_m = \dot{m} \tag{A.60}$$

Heating energy balance at i

$$\dot{m}_h c_p T_H + \dot{m}_m c_p T_m = \dot{m} c_p T_i \tag{A.61}$$

Cooling energy balance at i

$$\dot{m}_c c_p T_c + \dot{m}_m c_p T_m = \dot{m} c_p T_i \tag{A.62}$$

Define

$$K'' = \dot{m}_h / \dot{m} \tag{A.63}$$

Derivation:

Heating

Using Eqs. (A.59) and (A.61), find K"

$$\dot{m}_h T_H + (\dot{m} - \dot{m}_h) T_m = \dot{m} T_c$$

$$\dot{m}_h (T_H - T_m) = \dot{m}(T_i - T_m)$$

$$K'' = \frac{\dot{m}_h}{\dot{m}} = \frac{T_i - T_m}{T_H - T_m} \qquad \text{(A.64)}$$

Substitute $\dot{m}_h = K''\dot{m}$ where K" is given in Eq. (A.64), T_i in Eq. (A.49) and T_m in Eq. (A.13) into Eq. (A.43) to solve for $\dot{q}_h$

$$\dot{q}_h = \frac{T_i - T_m}{T_H - T_m} \dot{m}c_p \, [\overline{T}_H - T_m] = \dot{m}c_p[T_i - T_m] \qquad \text{(A.64)}$$

$$\dot{q}_h = \dot{m}c_p[\frac{T_R(UA + \dot{m}c_p) - T_A UA - \dot{q}_G}{\dot{m}c_p} - \frac{\dot{m}_o}{\dot{m}} T_A - \frac{\dot{m} - \dot{m}_o}{\dot{m}} T_R]$$

$$= [\, T_R(UA + \dot{m}c_p - \dot{m}c_p + \dot{m}_o c_p) - T_A(UA + \dot{m}_o c_p) - \dot{q}_G]$$

$$\dot{q}_h = (UA + \dot{m}_o c_p)[(T_R - \frac{\dot{q}_G}{UA + \dot{m}_o c_p}) - T_A]^+ \qquad \text{(A.65)}$$

Sensible Cooling:

Using Eqs. (A.40), (A.60) and (A.62), solve for K'

$$K' = \frac{\dot{m}_c}{\dot{m}} = \frac{T_i - T_m}{T_c - T_m} \qquad (A.66)$$

Substitute $\dot{m}_c = K'\dot{m}$ where K' is given in Eq. (A.66), T_i in Eq. (A.49), and T_m in Eq. (A.13) into Eq. (A.42), solve for $\dot{q}_{cs}$

$$\dot{q}_{cs} = \frac{T_i - T_m}{T_c - T_m} \dot{m}c_p(T_m - T_c)$$

$\dot{q}_{cs} = \dot{m}c_p[T_m - T_i] = - \dot{q}_h$ in Eq. (A.64)

$$\dot{q}_{cs} = (UA + \dot{m}_o c_p)[T_A - (T_R - \frac{\dot{q}_G}{UA + \dot{m}_o c_p})]^+$$

which is the same expression for VAV cooling in Eq. (A.28).

Latent Cooling:

Substitute K' in Eq. (A.66) into Eq. (A.56), solve for $\dot{q}_{cL}$

$$\dot{q}_{cL} = \frac{\frac{T_i - T_m}{T_c - T_m} k\dot{m}h_{fg}(\omega_A - (\omega_c - \frac{1 - k}{k}\omega_L))}{1 - (1 - k)(\frac{T_c - T_m - T_i - T_m}{T_c - T_m})} \qquad (A.67)$$

$$= \frac{T_i - T_m}{T_c - T_i}[\frac{k\dot{m}h_{fg}}{1 - (1 - k)}(\omega_A - (\omega_c - \frac{1 - k}{k}\omega_L))]^+$$

Substitute T_m in Eqs. (A.13) and (A.14) and T_i in Eq. (A.49) in Eq. (A.67)

$$\dot{q}_{cs} = \frac{((T_R - \frac{\dot{q}_G}{UA + \dot{m}_o c_p}) - T_A)\ UA + \dot{m}_o c_p}{\dot{m}c_p(\dot{m}c_p T_c - T_R(UA + \dot{m}c_p) - T_A UA - \dot{q}_G)\ /\ \dot{m}c_p}\ [\ \dots\ ]^+$$

$$\dot{q}_{cs} = [\frac{(UA + \dot{m}_o c_p)[T_A - (T_R - \frac{\dot{q}_G}{UA + \dot{m}_o c_p})]^+}{UA[T_A - \frac{T_R(UA + \dot{m}c_p) - \dot{m}c_p T_c - \dot{q}_G}{UA}]}]^+\ [\ \dots\ ]^+ \qquad (A.68)$$

Comment:

Equation (A.68) contains a terribly complicated expression in T_A the whole of which must be positive. Since $\dot{q}_{cs}$ in TD is the same as $\dot{q}_{cs}$ for VAV, it is recommended that $\dot{q}_{cL}$ for VAV (Eq. (A.32)) be used instead of Eq. (A.68) for $\dot{q}_{cL}$ in TD. The assumption is that latent loads vary more with ambient and zone specific humidity than with system type than two different systems given the same ω_A and ω_{cL} will have similar latent loads.

Dual Fan Dual Duct (DFDD)

Figure: 4.4 and 4.6

Constants: $\dot{m}_o$, $\dot{m}_m$, T_c, T_H, T_R, U, A, c_p

Equations:

Airflow through the cooling coil is piecewise continuous in Fig. 4.4 as for VAV.

Derivation:

Heating

Range 1 cooling only, no hot stream needed

$$\dot{m}_t = 0 \qquad \dot{q}_h = 0$$

Range 2, $\dot{m} = \dot{m}_m$ minimum cooling airflow, Eqs. (A.33) and (A.34) combine to give T_i in Eq. (A.38).

Using Eq. (A.35) due for $\dot{m}_t$ in terms of $\dot{q}_h$

$$\dot{m}_t = \frac{\dot{q}_h}{c_p(T_H - T_R)} \tag{A.69}$$

Combine Eqs. (A.69), (A.38) and (A.36) to solve for $\dot{q}_h$

$$\dot{q}_G + \dot{q}_o = (\dot{m}_h + \dot{m}_t)\; c_p\left(\frac{T_R(\dot{m}_m + \dot{m}_t) - \dot{m}_m T_c - \dot{m}_t T_H}{\dot{m}_m + \dot{m}_t}\right)$$

$$\dot{q}_G + \dot{q}_o = \dot{m}_m c_p (T_R - T_c) + \frac{\dot{q}_h}{c_p(T_H - T_R)}\, c_p (T_R - T_H)$$

$$\dot{q}_G + \dot{q}_o = \dot{m}_m c_p (T_R - T_c) - \dot{q}_h$$

$$\dot{q}_G + \dot{q}_o + \dot{q}_h = \dot{m}_m c_p (T_R - T_C)$$

which is the same as Eq. (A.10) with $\dot{m}_m$ and the same result as for VAVI which gives $\dot{q}_h$ in Eq. (A.25).

Cooling

It is obvious that cooling is done with variable air volume control and reheat heating are exactly the same as for VAV with reheat.

APPENDIX B

DEGREE DAYS WITH LIMIT TEMPERATURE RANGES

In this Appendix, expressions are derived for heating and cooling degree-days with base temperature T_b and temperature limits, T_x and T_y on ambient temperature, T_A. Heating and cooling calculations are separated. Roman numerals signify a temperature constraint on T_A with respect to T_X and/or T_y. Capital letters signify the relationship of T_b to T_x and or T_y. Figures whose numbers are noted next to each constraint, show the range contraints on T_A pictorially. The resulting expressions are summarized on a summary sheet at the back along with the names the quantities in this appendix appear under in the subroutine DDX listed in Appendix C.

<u>Define</u>

$$DD_{HT_b} = \sum_{-\infty}^{T} N_A(T - T_A)$$

$$DD_{CT_b} = \sum_{T}^{\infty} N_A(T_A - T)$$

$$Q + T = \sum_{T}^{\infty} N_A$$

$$Q - T = \sum_{-\infty}^{T} N_A$$

(Q is cumulative number of hours, not total energy here.) Therefore

$$\sum_{T}^{\infty} N_A(T - T_A) = - DD_{CT}$$

$$\sum_{-\infty}^{T} N_A(T_A - T) = - DD_{HT}$$

Heating DD Calculations

$$T_{base} = T_b$$
$$T_{ambient} = T_A$$
$$\text{extra condition} = T_x$$

I. $T_A > T_x$ (Fig. B.1a)

A. $T_b \leq T_x$ (Fig. B.1b)

$$DD_H = 0 \qquad \text{(B.1)}$$

(no overlap of Range I and Range A).

B. $T_b > T_x$ (Fig. B.1c)

$$D_H = \sum_{T_x}^{T_b} N_A(T_b - T_A) = \sum_{-\infty}^{T_b} N_A(T_b - T_A) - \sum_{-\infty}^{T_x} N_A\ (T_b - T_A)$$

$$DD_H = DD_{HT_b} - \sum_{-\infty}^{T_x} N_A[(T_b - T_x) + (T_x - T_A)]$$

$$= DD_{HT_b} - (T_b - T_x) \sum_{-\infty}^{T_x} N_A - \sum_{-\infty}^{T_x} N_A(T_x - T_A)$$

$$DD_H = DD_{HT_b} - (T_b - T_x)\ Q_{-T_x} - DD_{HT_x} \tag{B.2}$$

II. $T_A < T_x$ (Fig. B.2a)

A. $T_b \leq T_x$ (Fig. B.2b)

$$DD_H = DD_{HT_b} \tag{B.3}$$

B. $T_b > T_x$ (Fig. B.2c)

$$DD_H = \sum_{-\infty}^{T_x} N_A(T_b - T_A) = \sum_{-\infty}^{T_x} N_i[(T_b - T_x) + (T_x - T_A)]$$

$$= (T_b - T_x) \sum_{-\infty}^{T_x} N_A + \sum_{-\infty}^{T_x} N_A(T_x - T_A)$$

$$DD_H = (T_b - T_x)Q_{-T_x} + DD_{HT_x} \tag{B.4}$$

III. $T_y < T_A < T_x$ (Fig. B.3a)

A. $T_y < T_x < T_b$ (Fig. B.3b)

$$DD_H = \sum_{T_y}^{T_x} N_i(T_b - T_A) = \sum_{-\infty}^{T_x} N_A(T_b - T_A) - \sum_{-\infty}^{T_x} N_A(T_b - T_A)$$

using II.B:

$$DD_H = (T_b - T_x)Q_{-T_x} + DD_{HT_x} - [(T_b - T_y)Q_{-T_y} + DD_{HT_y}] \tag{B.5}$$

As a check, if $T_x = T_b$

$$DD_H = 0 + DD_{HT_b} - (T_b - T_y)Q_{-T_y} - DD_{HT_y}$$

should be the same as $T_A > T_y$, $T_y < T_b$, it is.

B. $T_y < T_b < T_x$ (Fig. B.3c)

Same as $T_A > T_y$, $T_y < T_b$

$$DD_H = DD_{HT_b} - (T_b - T_y)Q_{-T_y} - DD_{HT_y} \qquad (B.6)$$

C. $T_b < T_y < T_x$ (Fig. B.3d)

$$DD_H = 0$$

<u>Cooling DD Calculations</u>

$$T_{base} = T_b$$
$$T_{ambient} = T_A$$
$$\text{condition} = T_x$$

I. $T_A > T_x$ (Fig. B.4a)

A. $T_b \leq T_x$ (Fig. B.4b)

$$DD_C = \sum_{T_x}^{\infty} N_A(T_A - T_b) = \sum_{T_x}^{\infty} N_A[(T_A - T_x) + (T_x - T_b)$$

$$= \sum_{T_x}^{\infty} N_A(T_A - T_x) + (T_x - T_b) \sum_{T_x} N_A$$

$$DD_C = DD_{CT_x} + (T_x - T_b)Q_{+T_x} \tag{B.7}$$

B. $T_b > T_x$ (Fig. B.4c)

$$DD_C = \sum_{T_b}^{\infty} N_A(T_A - T_b) = DD_{CT_b} \tag{B.8}$$

II. $T_A < T_x$ (Fig. B.5a)

A. $T_b \leq T_x$ (Fig. B.5b)

$$DD_C = \sum_{T_b}^{T_x} N_A(T_A - T_b) = \sum_{T_b}^{\infty} N_A(T_A - T_b) - \sum_{T_x}^{\infty} N_A(T_A - T_b)$$

$$= DD_{CT_b} - \sum_{T_x}^{\infty} N_A(T_A - T_x) + (T_x - T_b)\sum_{T_x}^{\infty} N_A$$

$$DD_C = DD_{CT_b} - (T_x - T_b)Q_{+T_x} - DD_{CT_x} \tag{B.9}$$

B. $T_b > T_x$ (Fig. B.5c)

$$DD_C = 0 \tag{B.10}$$

III. $T_y < T_A < T_x$ (Fig. B.6a)

A. $T_y < T_x < T_b$ (Fig. B.6b)

$$DD_C = 0 \tag{B.11}$$

B. $T_y < T_b < T_x$ (Fig. B.6c)

Same as $T_A < T_x$, $T_b \leq T_x$

$$DD_C = DD_{CT_b} - (T_x - T_b)Q_{+T_x} - DD_{CT_x} \tag{B.12}$$

C. $T_b < T_y < T_x$ (Fig. B.6d)

$$DD_C = \sum_{T_y}^{T_x} N_A(T_A - T_b) = \sum_{T_y}^{\infty} N_A(T_A - T_b) - \sum_{T_x}^{\infty} N_A(T_A - T_b)$$

from I.A

$$DD_C = DD_{CT_y} + (T_y - T_b)Q_{+T_y} - \left(DD_{CT_x} + (T_x - T_b)Q_{+T_x}\right) \tag{B.13}$$

As a check let $T_b = T_y$

$$DD_C = DD_{CT_b} + 0 - DD_{CT_x} - (T_x - T_b)Q_{+T_x}$$

Should be the same as $T_A < T_x$, $T_b < T_x$.

Summary Sheet

Range Type	Qualifier	Heating (DD_H)	Cooling (DD_C)
I. $T_A > T_x$	$T_x \geq T_b$	0	$DD_{CT_x} + (T_x - T_b)Q_{+T_x}$
	$T_x < T_b$	$DD_{HT_b} - DD_{HT_x} - (T_b - T_x)Q_{-T_x}$	DD_{CT_b}
II. $T_A < T_x$	$T_x \geq T_b$	DD_{HT_b}	$DD_{CT_b} - DD_{CT_x} - (T_x - T_b)Q_{+T_x}$
	$T_x < T_b$	$DD_{HT_x} + (T_b - T_x)Q_{-T_x}$	0
III. $T_y < T_A < T_x$ DD_y	$T_y < T_x < T_b$	$[(T_b - T_x)Q_{-T_x} - (T_b - T_y)Q_{-T_y}] + [DD_{HT_x} - DD_{HT_y}]$	0
	$T_y < T_b < T_x$	$[DD_{HT_b} - DD_{HT_y}] - (T_b - T_y)Q_{-T_y}$	$[DD_{CT_b} - DD_{CT_x}] - (T_x - T_b)Q_{+T_x}$
	$T_y < T_x < T_b$	0	$[DD_{CT_y} - DD_{CT_x}] + [(T_y - T_b)Q_{+T_y} - (T_x - T_b)Q_{+T_x}]$

Quantity in DDX.SUB = Quantity in Appendix B

$DD1 = DD_{H,CT_b}$ $DD2 = DD_{H,CT_x}$ $DD3 = DD_{H,CT_y}$ $Q1 = Q_{+,-T_x}$ $Q2 = Q_{+,-T_y}$

Variable NUM in DDX.SUB = Condition in Appendix B

$1 = T_A < T_x$ $2 = T_A > T_x$

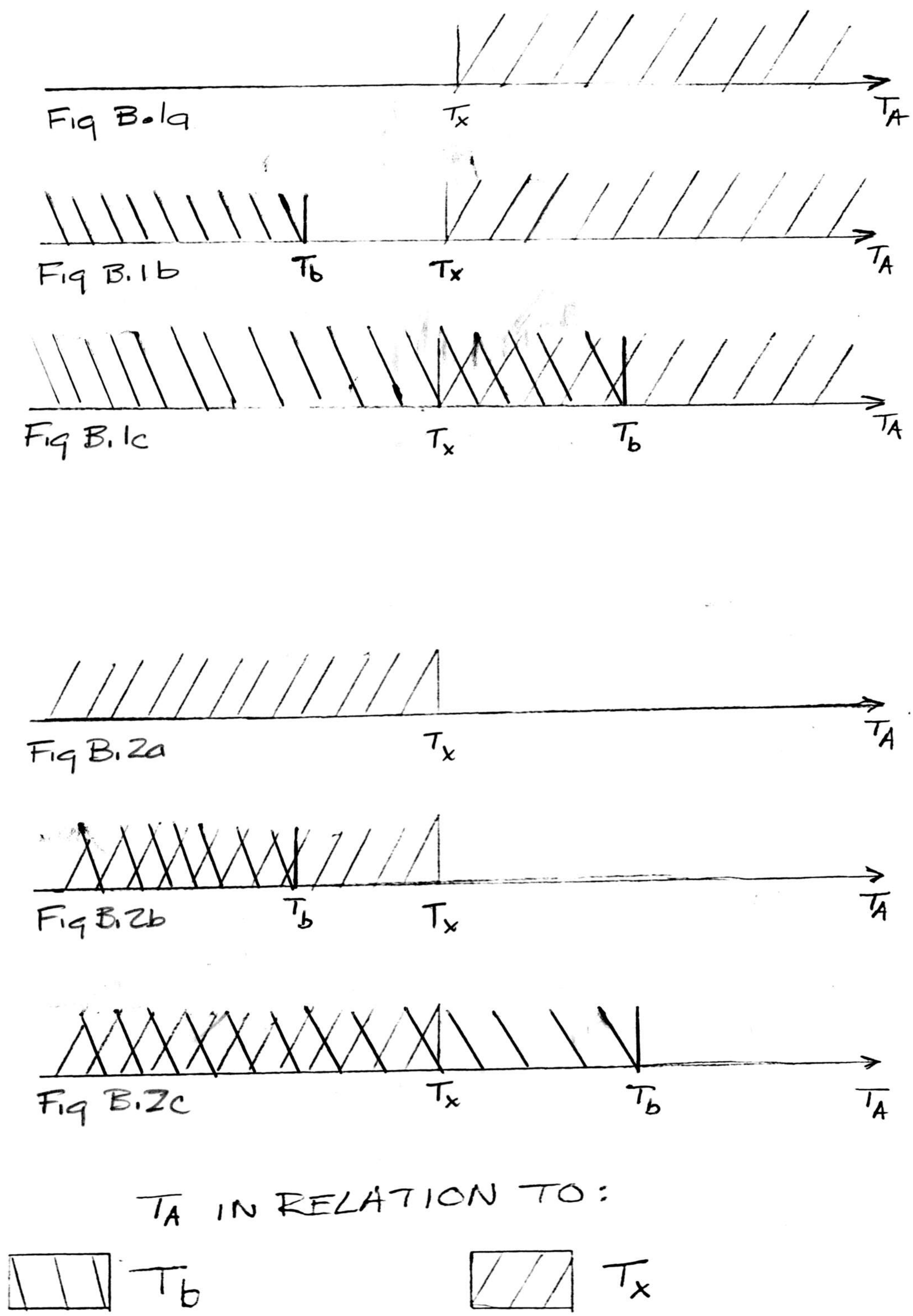


Fig B.1a
Tx
TA
Fig B.1b
Tb
Tx
TA
Fig B.1c
Tx
Tb
TA
Fig B.2a
Tx
TA
Fig B.2b
Tb
Tx
TA
Fig B.2c
Tx
Tb
TA
TA IN RELATION TO:
Tb
Tx

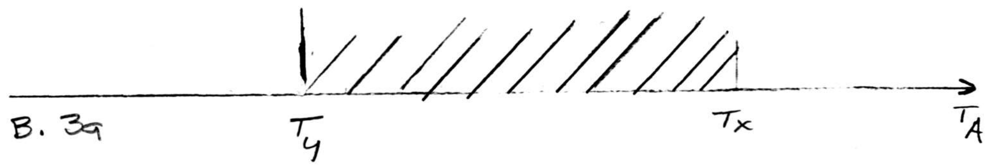


Fig B. 3a

Fig B. 3b

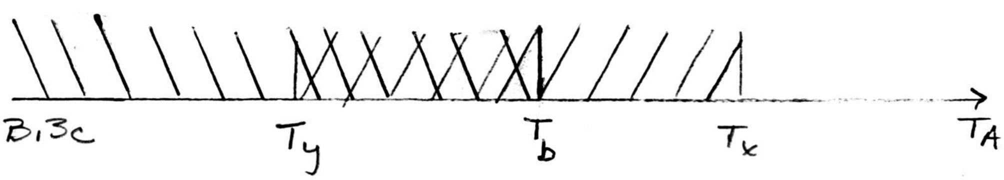


Fig B. 3c

Fig B. 3d

T_A IN RELATION TO

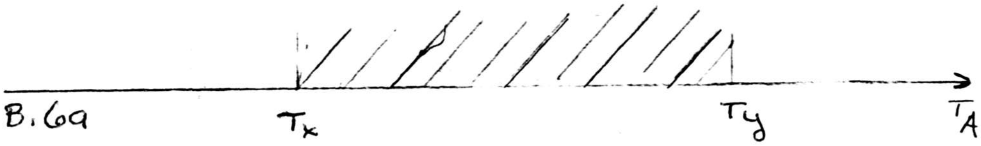


Fig. B.6a

Fig. B.6b

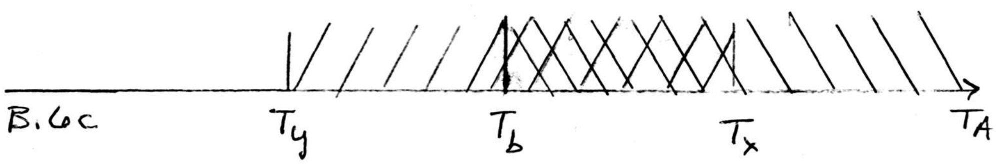


Fig. B.6c

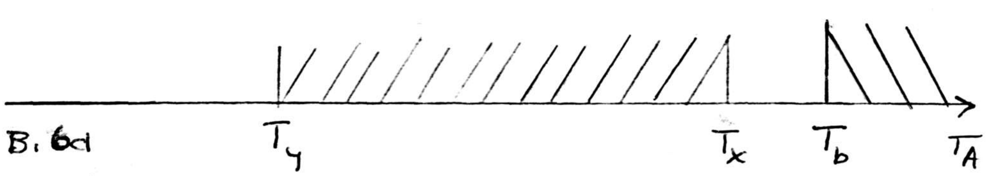


Fig. B.6d

T_A IN RELATION TO

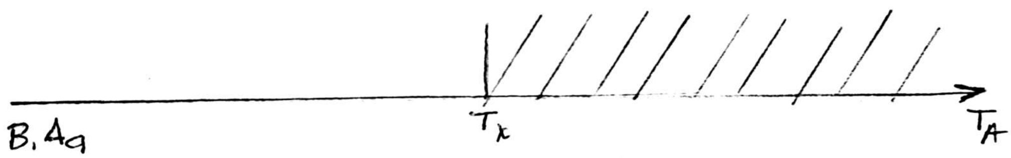


Fig. B.4a

Fig. B.4b

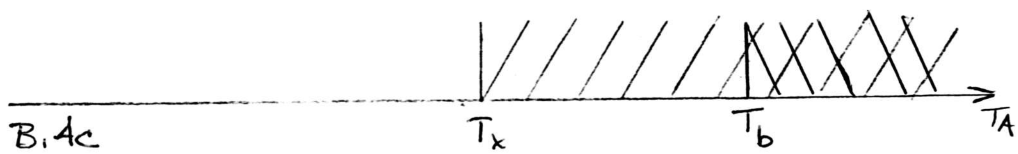


Fig. B.4c

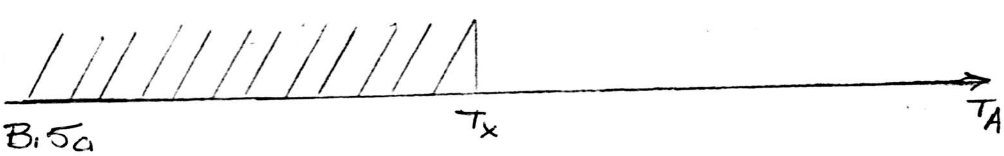


Fig. B.5a

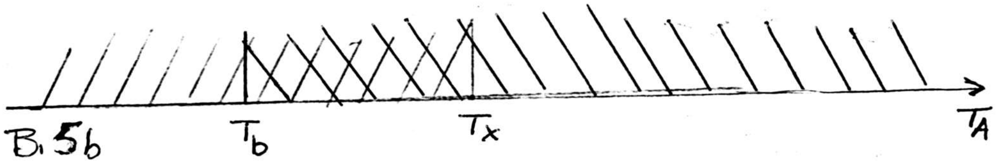


Fig. B.5b

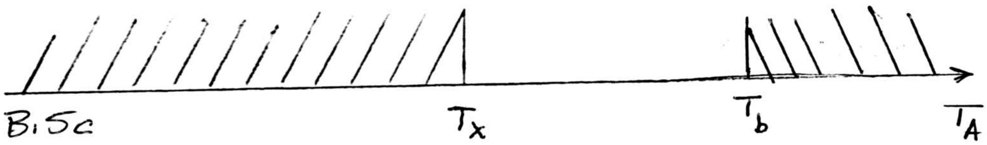


Fig. B.5c

T_A IN RELATION TO:

APPENDIX C

PROGRAM LISTINGS

```
C PROGRAM CALCULATES MONTHLY HEATING AND SENSIBLE AND
C LATENT COOLING AND CHILLER ENERGIES COILS FOR
C TRH, VAV, DDM, TD, AND ECONOMIZER AND DEAD BAND
C CONTROL APPLIED TO THE FIRST THREE
C ONE ZONE SERVED
C FOR ONE YEAR
C WITH EQUIVALENT DEGREE-DAY SUMMATIONS
C USING BIN DATA GENERATED FROM ERBS' CORREALATION
C AND HOURLY DATA READ FROM TMY TAPES AND DEGREE-DAY
C INTEGRATION WHERE POSSIBLE USING ERBS' DD
C CORRELATION.
C
C LOGICAL UNITS USED:
C  30= 8707SOLR*MAD, TMY HOURLY AMBIENT WEATHER FILE
C  CONTAINS: TA(I) FOR EADH HOUR OF A MONTH IN
C            FORMAT: T30,F4.1 (71)
C
C  40= CREAD.M1, AVERAGE AND BIN TEMPERATURE DATA
C  CONTAINS: NSYS-  NUMBER INDICATING KIND OF
C             HVAC SYS.  TO BE TESTED; T5, I2 (89)
C            BINDT- TEMPERATURE BIN SIZE;T5,F5.2 (75)
C            NPOINT- NUMBER OF BASE TEMPERATURES
C             DESIRED; T5,I2 (89)
C            NTAIL- # > 0 INDICATES TAILS ARE TO BE
C             ROLLED INTO LIMITS SPECIFIED BY TUP AND
C             TBOT (READ IN BELOW FOR EACH MONTH)
C            SIGYR - STANDARD DEVIATION OF MONTHLY
C             AVERAGE TEMPS ABOUT YEARLY
C             AVERAGE; T25,F8.2 (74)
C  THE FOLLOWING VARIABLES ARE READ IN FOR EACH MONTH
C            TBAR- MONTH'S AVG.  TEMP ; T25, F8.2(74)
C            SIGMA- STD.  DEV.  OF A PARTICULAR AVERAGE
C             MONTHLY TEMP ABOUT LONG TERM AVERGE
C             TEMPERATURE FOR THAT MONTH ;T25,F8.2
C             (74)
C            KTBAR-MONTH'S VALUE OF Kt;T25, F8.2 (74)
C            RHBAR-AVERAGE MONTHLY RELATIVE HUMIDITY
C            QSBAR-AVERAGE MONTHLY SOLAR GAINS
C            NSUP, NSDN-TIME OF SUNRISE AND SUNSET
C            TUP, TBOT- UPPER AND LOWER TEMPERATURE
```

```
C              LIMITS TO ROLL BIN DISTRIBUT'N TAILS TO
C  45= INREAD, OPERATING SCHEDULE INFORMATION
C  CONTAINS:
C                 NPER- NUMBER OF PERIODS IN SCHEDULE;
C                  T5, I2 (89)
C                 NSTART(I)- STARTING TIME ON 24 HR.
C                  CLOCK FOR EACH
C                  PERIOD;T5,I2 (89)
C                  (IF NPER= 1 OR 24, NSTART NEED
C                  NOT BE ENTERED)
C  31= COUT, OUTPUT FILE LISTING COIL ENERGY USAGE.
C
C  THE FOLLOWING ARRAYS NEED EXPLANATION:
C  PXY       P SIGNIFIES COIL TOTALS FOR A SINGLE
C  QXY         PERIOD
C  ENRGY     Q SIGNIFIES COIL TOTALS FOR AN ENTIRE
C  SQXY        MONTH, THE SUM OF
C  SENRGY      ALL PERIODS IN THAT MONTH
C            ENERG SIGNIFIES CHILLER TOTALS FOR AN
C              ENTIRE MONTH
C            S SIGNIFIES AN AVERAGE SUM OVER THE YEAR.
C              THE AVERAGE OVER ALL MONTHS
C            X SIGNIFIES THE COIL WHOSE LOAD IS
C              REPRESENTED BY
C              C= SENSIBLE COOLING, H= HEATING,
C              PH= PREHEATING L=LATENT COOLING
C            Y SIGNIFIES THE METHOD USED TO GET THE
C              COIL LOAD
C              H= HOURLY, B= BIN, E= ERB'S CORRELATION
C
C  THE FOLLOWING SUBROUTINES NEED TO BE ADDED:
C    WRITE2- WRITES FINAL OUTPUT INTO OUTPUT FILE
C    PERERR- CALCULATES PERCENTAGE ERROR BETWEEN TWO
C            QUANTITIES
C    HRTEMP- CALCULATES AVERAGE TEMPERATURE AND
C            RELATIVE HUMIDITY FOR EACH
C            HOUR OF THE DAY AND AVERAGES THESE
C            W/IN GIVEN PERIODS FOR AVG TEMP,
C            RELATIVE HUMIDITY, AND
C            NUMBER OF HOURS IN THAT PERIOD.
C    BINCALC- USES D ERB'S EQUATIONS TO CALCULATE
C             BINS FOR GIVEN AV TEMP AND REL HUMIDITY
C             AND NUMBER OF HOURS IN EITHER
C             PERIOD OR MONTH.
C    HBQCALC- CALCULATES DEGREE HOUR DIFFERENCES FOR
C             GIVEN BASE TEMPERATURE
C             AND NUMBER OF HOURS AT THAT TEMPERATURE
C    DDX- DOES ERB'S CORRELATION FOR DEGREE HOURS
C         W/IN A GIVEN RANGE
```

```
C    SYSORT- ASSIGNS NON-TEMPERATURE-DEPENDENT
C            (PRIMARY) CONDUCTANCE FACTORS AND
C            BASE TEMPS FOR ALL SYSTEM TYPES INTO
C            3-D ARRAY
C    TRH- ASSIGNS M'S AND TB'S FOR ALL TERMINAL
C         REHEAT RELATED SYSTEMS
C    VAV- ASSIGNS M'S AND TB'S FOR ALL VAV RELATED
C         SYSTEMS
C    DDM- ASSIGNS M'S AND TB'S FOR ALL DUAL DUCT
C         RELATED SYSTEMS
C    CALC- ASSIGNS TEMPERATURE DEPENDENT (SECONDARY)
C          CONDUCTANCE FACTORS AND BASE
C          TEMPS FOR CERTAIN TEMPERATURE AND SYSTEM
C          WHICH TO GETHER MAKE UP THE SYTSTEM'S LOAD
C          FUNCTIONS
C    HUMID- CALCULATES LATENT LOAD; FOR HUMIDITY
C           CALCULATIONS, THE FORM U[WA - Wb] IS NOT
C           USED, RATHER THE ENTIRE LATENT LOAD IS
C           ASSIGNED TO A LOAD FACTOR, QL WHICH WHEN
C           MULTIPLIED BY NO.  OF HR.S AND SUMMED
C           GIVES LATENT EDD'S
C    OMEGA- USES ERB'S CORRELATIONS TO GET HUMIDITY
C           RATIO GIVEN TEMP AND RH.
C
C
C  THE FOLLOWING FUNCTIONS NEED TO BE ADDED:
C    DD- CALCULATES ERB'S CORRELATION DEGREE HOURS
C        W/O ANY RANGE SPECS
C    QN- CALCULATES ERB'S CORRELATION CUMULATIVE
C        HOUR DISTRIBUTION
C
C-----------------------------------------------------
C
      COMMON /BYRNE/ NHR(24), NSTART(26), NHOUR(12),
     &NUM(800), NBIN(24),
     &NR(16), NF(3)
      COMMON /ALONE/ PCB(24),PHB(24),PPHB(24),
     &PEB(24),PLH(24),PCH(24),PHH(24),PPHH(24),
     &QCB(10,32),QHB(10,32),ENRGB(10,32),QLB(10,32),
     &QPB(10,32),PEH(24),PLB(24)
     &QCH(10,32),QHH(10,32),ENRGH(10,32),QLH(10,32),
     &QPH(10,32),
     &SQCB(10,32),SQHB(10,32),SENRGB(10,32),
     &SQLB(10,32),SQPB(10,32),
     &SQCH(10,32),SQHH(10,32),SENRGH(10,32),
     &SQLH(10,32),SQPH(10,32)
      COMMON /CRIPES/ HF(16,6), TBH(16,6), CF(16,6),
     &TBC(16,6), TLO(16,6), THI(16,6),
     &TA(800,24), WA(800,24), TBIN(240,24),
```

```
     &HBIN(240,24), WBIN(240,24),
     &TBARP(24), RHBARP(24), QSBARP(24)
      COMMON /DAPPER/ TC(32),TH(32),TR(32),TRH(32),
     &TRC(32),QL(24,32), QG(24,32), QD(24,32), U(32),
     &A(32)
      CHARACTER *4 COIL(5)
      CHARACTER S(20)*4 , SWRITE*4
      REAL KTBAR,MDOT(32),MMIN(32),MOUT(32)
C
C-----------------------------------------------------
C THIS SECTION SETS CALENDAR DATA, READS
C SCHEDULE DATA, SETS UP VARIABLES BASED
C ON SCHEDULE DATA, AND
C SETS BUILDING AND DESIGNED SYSTEM CONSTANTS
C-----------------------------------------------------
C
5     FORMAT(//'AMBIENT TEMP=',F7.2)
19    FORMAT(T3,A4,T11,F6.2,T21,F6.2,T31,F7.2,T40,
     &F7.2,T51,F7.2,
     &T60,F7.2,T70,E10.4)
27    FORMAT(/,1X,'SYS TYPE',T12,'TLO<',T18,'TA',T22,
     &'<THI',T34,'MH',
     &T43,'TBH',T54,'MC',T63,'TBC',T73,'QLC')
26    FORMAT(/'PERIOD=',I3)
28    FORMAT(' ')
C
74    FORMAT(T25,F15.4)
75    FORMAT(T5,F5.2)
89    FORMAT(T5,I2)
92    FORMAT(' NSYS= ',T15,I3)
93    FORMAT(' NPOINT=',T15,I3)
15    FORMAT(' BIN SIZE=',T15,F8.2,' C')
315   FORMAT('NUMBER OF PERIODS=',I5)
C
C   SET NUMBER OF DAYS IN EACH MONTH
C
      DATA NHOUR/744,672,744,720,744,720,744,744,720,
     &744,720,744/
C
C   ASSIGN SYSTEM NAMES FOR PRINT OUT
C
      DATA S/'TRH ','VAVR','DDM ','TDM ','TRHE',
     &'VARE','DDME','TRHD',
     &'VARD','DDMD','1-k ','MVAV','MVVE','    ',
     &'    ','    ','    ',
     &'    ','    ','    '/
C
C  ASSIGN COIL ABREVIATIONS FOR PRINT OUT
C
```

```
      DATA COIL/'COOL','HEAT','CHIL','LATE','PREH'/
C
C
C   SET MEGA DIVISOR=> DIVISION BY THIS CONVERTS
C   UNITS X TO MEGAX(MX)
C
      CM=1E+06
C
C READ SYSTEM NUMBER, BINSIZE (DEG C), WHETHER
C BIN RANGE TAILS ARE TO BE ROLLED IN AND NUMBER OF
C POINTS TO BE READ
C
      READ(40,89) NSYSTM
      READ(40,75) BINDT
      READ(40,89) NTAIL
      READ(45,89) NPOINT
C
C READ STANDARD DEVIATION OF MONTHLY AVERAGE TEMPS
C ABOUT YEARLY
C AVERAGE FOR THE SITE IN QUESTION.
C
      READ(40,74)SIGYR
C
C   ECHO CHECK
C
C      WRITE(31,74)SIGYR
      WRITE(31,92) NSYS
      WRITE(31,15) BINDT
      WRITE(31,788) NTAIL
788   FORMAT('NTAIL=',I4)
      WRITE(31,93) NPOINT
C
C   READ OCCUPANCY SCHEDULE DATA FOR THE BUILDING,
C   ASSUMES SAME
C   SCHEDULE FOR ALL MONTHS.
C
      READ(45,89)NPER
      WRITE(31,315) NPER
C
      IF(NPER .LE. 1) THEN
        NSTART(1)= 1
        GO TO 80
      ENDIF
      IF(NPER .EQ. 24) THEN
        DO 70 I=1,24
70         NSTART(I)= I
      ELSE
        DO 472 I=1,NPER
472         READ(45,89)NSTART(I)
```

```
      ENDIF
C
80    NSTART(NPER+1)= 25
C
C CALL ROUTINE THAT READS SYS PARAMETER MATRIX OF
C VARIABLES NOT DEPENDENT ON TA OR MONTH.
C
      CALL READER(TC,TH,TR,TRH,TRC,MDOT,MOUT,MMIN,CP,
     &U,A,QG,QL,NPER,
     &NSTART,NPOINT)
C
C
C-----------------------------------------------------
C   SET YEARLY AVERAGE SUMMATIONS TO ZERO
C-----------------------------------------------------
      DO 30 I= 1,NPOINT
      DO 30 K=1,10
         SQCB(K,I)= 0.
         SQHB(K,I)= 0.
         SQLB(K,I)= 0.
         SQPB(K,I)= 0.
         SENRGB(K,I)= 0.
         SQCH(K,I)= 0.
         SQHH(K,I)= 0.
         SQLH(K,I)= 0.
         SQPH(K,I)= 0.
         SENRGH(K,I)= 0.
30    CONTINUE
C
C
C-------------------------------------------------------
C THIS SECTION IS DEVOTED TO READING SITE DATA AND C
CALCULATING ANY
C DATA DEEMED NECESSARY TO SET UP FOR CALCULATIONS
C-------------------------------------------------------
C
      DO 1000 IMON= 1,12
C
71    FORMAT(T30,F4.1,T53,F4.4)
72    FORMAT(T25,I3)
73    FORMAT(T10,F7.2,T25,F7.2,T40,F7.4)
164   FORMAT(T25,I4,T30,I4)
165   FORMAT(T25,F7.2,T35,F7.2)
C
C READ HOURLY TEMPERATURE DATA INTO AN ARRAY
C DIVIDED INTO OPERATING PERIODS (J)
C FOR INPUT TO THE FIRST DEGREE DAY CALCULATIONS.
C
      DO 37 J=1,NPER
```

```
37        NUM(J)= 0
C
      DO 40 I=1,NHOUR(IMON)
         K= MOD(I,24)
         IF(K .EQ. 0) K=24
         DO 45 J=1,NPER
            IF(K .GE.  NSTART(J) .AND.
  &                   K .LT.  NSTART(J+1)) THEN
              NUM(J)= NUM(J) + 1
              READ(30,71) TA(NUM(J),J), WA(NUM(J),J)
            ENDIF
45       CONTINUE
         IF(K .LT.  NSTART(1)) THEN
           NUM(NPER)= NUM(NPER) + 1
           READ(30,71) TA(NUM(NPER),NPER),
     &                 WA(NUM(NPER),NPER)
         ENDIF
40    CONTINUE
C
C READ AVERAGE MONTHLY DATA
C CALCULATE MONTHLY STANDARD DEVIATION, SIGMA,
C FOR EACH MONTH
C USING ERB'S CORRELATION,IF NO POSITIVE VALUE READ
C FOR IT.  THEN CALL
C HRTEMP TO CALCULATE HOURLY TEMPERATURE AND RELATIVE
C HUMIDITIES AND AVERAGE TEMP'S AND REL HUMIDITIES
C OVER SPECIFIED OPERATING PERIODS, TBARP(I)'S.
C
      READ(40,74) TBAR
      READ(40,74) SIGMA
      READ(40,74) KTBAR
      READ(40,74) RHBAR
      READ(40,74) QSBAR
      READ(40,164) NSUP,NSDN
      READ(40,165) TUP,TBOT
C
      IF(SIGMA .LE. 0.) THEN
        SIGMA= 1.45 - (.029 * TBAR) + (.0664 * SIGYR)
      ENDIF
C
      IF(NPER .GT. 1) THEN
         CALL HRTEMP(SIGMA,TBAR,RHBAR,KTBAR,TBARP,
     &RHBARP,NPER,NSTART,
     &NHOUR(IMON),NHR,IMON)
C
      ELSE
         TBARP(1)= TBAR
         RHBARP(1)= RHBAR
         QSBARP(1)= QSBAR
```

```
            NHR(1)= NHOUR(IMON)
         ENDIF
C
C CALCULATE TEMPERATURE AND SPECIFIC HUMIDITIY BIN
C DATA FOR EACH OPERATING PERIOD TBIN WBIN AND
C HBIN= NO.  HRS IN EACH BIN
C
           DO 102 J=1,NPER
102         CALL BINCALC(SIGMA,BINDT,TBARP(J),RHBARP(J),
     &                   NHR(J),NHOUR(IMON),
     &                   NBIN(J),TBIN,HBIN,WBIN,J,TBOT,
     &                   TUP,NTAIL)
C
C   SET MONTHLY SUMMATIONS TO ZERO
C
         DO 35 K=1,10
           DO 35 I=1,NPOINT
             QCB(K,I)= 0.
             QHB(K,I)= 0.
             QLB(K,I)= 0.
             QPB(K,I)= 0.
             ENRGB(K,I)= 0.
             QCH(K,I)= 0.
             QHH(K,I)= 0.
             QLH(K,I)= 0.
             QPH(K,I)= 0.
             ENRGH(K,I)= 0.
35       CONTINUE
C
C ----------------------------------------------------
C THIS SECTION OVERSEES MONTH/VARIABLE PARAMETER
C DEPENDENT INFORMATION IN SETTING UP
C DAILY LOADS TO GO INTO TB AND UF CALCULATIONS.
C ----------------------------------------------------
C
22       FORMAT('SCHEDULE INFORMATION'/T5,'PERIOD',T13,
     &'START',T20,'HRS',T25,'SOL+INT GAINS',
     &T40,'LATENT GAINS',T54,'AVG TEMP')
23       FORMAT('DAILY')
24       FORMAT('HOURLY')
25       FORMAT(T5,I3,T15,I3,T20,I3,T25,F10.2,T40,
     &F10.2,T54,F10.2)
326       FORMAT('IPOINT=',I5)
C
C SET UP DO LOOP FOR CALCULATIONS FOR EACH
C PARAMETER VARIATION
C
C=======
         DO 140 IPOINT= 1,NPOINT
```

```
      I= IPOINT
C=======
C
C ADD EACH MONTH'S SOLAR TERM INTO
C THE TOTAL ZONE INPUT LOAD, QD FOR EACH TIME PERIOD
C
      IF(NPER .EQ. 1) THEN
         QD(1,I)= QG(1,I) +
     &(QSBAR * FLOAT(NSDN - NSUP) / 24.)
      ELSE
      DO 100 J=1,NPER
         IF(NSTART(J) .GE.  NSUP .AND.
     &NSTART(J+1) .LE.  NSDN) THEN
           QD(J,I)= QG(J,I) + QSBAR
         ELSE
           IF(NSTART(J+1) .GE.  NSUP) THEN
             QD(J,I)=QG(J,I) +
     &(QSBAR * (NSTART(J+1)-NSUP) /
     &(NSTART(J+1)-NSTART(J)))
           ENDIF
           IF(NSTART(J) .LE.  NSDN)THEN
             QD(J,I)= QG(J,I) +
     &(QSBAR * (NSDN-NSTART(J)) /
     &(NSTART(J+1)-NSTART(J)))
           ENDIF
           IF(NSTART(J) .LT.  NSUP .OR.
     &NSTART(J) .GT.  NSDN)THEN
             QD(J,I)= QG(J,I) + 0.
           ENDIF
         ENDIF
100   CONTINUE
      ENDIF
C
C  WRITE SCHEDULE OF LOADING ON ZONE
C
      WRITE(31,326) IPOINT
C      WRITE(31,22)
C      IF(NPER .NE. 24) THEN
C        DO 982 J=1,NPER
C982       WRITE(31,25) J,NSTART(J),NHR(J),QD(J,I),
     &QL(J,I),TBARP(J)
C      ELSE
C        WRITE(31,24)
C      ENDIF
C
C-----------------------------------------------------
C THIS SECTION OVERSEES COIL LOAD CALCULATIONS AND
C PRINTING OF COIL ENERGY TOTALS
C-----------------------------------------------------
```

```
C
82     FORMAT(/' TOTAL OVER OPERATING PERIODS,
      &IPOINT=',I5)
83     FORMAT(/T7,'SYS',T20,'HRLY',T30,'BIN',T38,
      &'% ERR',T50,'HRLY',
      &T60,'BIN',T68,'%ERR'/T20,'MWH',T30,'MWH',T50,
      &'MWH',T60,'MWH')
84     FORMAT(/' PERIOD OF OPERATION=', I3)
85     FORMAT(//' YEARLY AVERAGE SUMMATION SUMMARY')
86     FORMAT(/'TOTALS FOR = ',T20,A4,T50,A4)
91     FORMAT(/'MONTH= ',I3)
190    FORMAT(' MAIN',2X,'NR=',I2,3X,'NF=',I2,3X,
      &'MDOT=',F7.2,3X,'MOUT=',
      &F7.2/' MMIN=',F7.2,3X,'WA=',F7.4,3X,'TC=',
      &F7.2,3X,'TR=',F7.2/
      &' QL=',F10.2,3X,'NS=',I3,3X,'J=',I3)
438    FORMAT('IMON=',I4)
184    FORMAT(T7,A4,T18,F6.3,T28,F6.3)
C
C   SET UP TIME PERIOD DO LOOP, J
C
C======
       DO 160 J= 1,NPER
C======
C
C CALCULATE MATRIX OF UF'S AND TB'S FOR THE GIVEN
C COMBINATION OF VARYING PARAMETERS
C AND TIME PERIOD.
C
          CALL SYSORT(U(I),A(I),MOUT(I),MMIN(I),
      &MDOT(I),CP,TR(I),TC(I),
      &TH(I),TRC(I),TRH(I),QD(J,I),HF,TBH,CF,TBC,
      &TLO,THI,NR,NF)
C
C   PRINT MATRIX OF UF'S AND TB'S
C
        IF(IMON .EQ. 1) THEN
          WRITE(32,438) IMON
          WRITE(32,26) J
          WRITE(32,27)
          DO 210 INS= 1,13
          DO 200 NP= 1,NR(INS)
             IF(NP .EQ. 1)THEN
               SWRITE=S(INS)
             ELSE
               SWRITE= S(20)
             ENDIF
       DO 436 NFG= 1,NBIN(J)
          IF(TLO(INS,NP) .LE.  TBIN(NFG,J) .AND.
```

```
     &TLO(INS,NP) .GT.  (TBIN(NFG,J)-(BINDT/2.)))THEN
           TLO(INS,NP)= TBIN(NFG,J) - (BINDT/2.)
           THI(INS,NP+1)= TBIN(NFG,J) - (BINDT/2.)
           GO TO 437
         ENDIF
         IF(TLO(INS,NP) .GT.  TBIN(NFG,J) .AND.
     &TLO(INS,NP) .LT.  (TBIN(NFG,J)+(BINDT/2.))) THEN
           TLO(INS,NP)= TBIN(NFG,J) + (BINDT/2.)
           THI(INS,NP+1)= TBIN(NFG,J) + (BINDT/2.)
           GO TO 437
         ENDIF
436    CONTINUE
437    THI(13,1)=THI(5,2)
       WRITE(32,19) SWRITE,TLO(INS,NP),THI(INS,NP),
     & HF(INS,NP),TBH(INS,NP),CF(INS,NP),TBC(INS,NP),
     &1.0
200       CONTINUE
          WRITE(32,28)
210       CONTINUE
        ENDIF
C
C SET LOOP FOR EACH SYSTEM, NSYS/K
C ZERO OUT MONTHLY TIME PERIOD SUM ARRAYS
C
C=========
          DO 160 NSYS= 1,NSYSTM
C          NSYS= NSYSTM
          K= NSYS
C=========
C
             PCB(J)= 0.
             PLB(J)= 0.
             PHB(J)= 0.
             PPHB(J)= 0.
             PEB(J)= 0.
             PCH(J)= 0.
             PLH(J)= 0.
             PHH(J)= 0.
             PPHH(J)= 0.
             PEH(J)= 0.
C
C CALCULATE HOURLY TOTALS FOR EACH PERIOD; SELECT
C PARTICULAR UF'S AND TB'S
C  WITH CALC AND SEND THESE TO HBQCALC TO GET LOADS
C
             DO 130 L= 1,NUM(J)
C
C CALL ROUTINE CALC TO CALCULATE UF'S AND TB'S AT
C EACH TA
```

```
C
      CALL CALC(TA(L,J),TBH,TBC,CF,HF,TLO,THI,NR,NF,
     &MDOT(I),MOUT(I),
     &MMIN(I),WA(L,J),TC(I),TR(I),QL(J,I),NSYS,TBHA,
     &TBCA,CFA,HFA,
     &QLC,IR)
C
C CALL ROUTINE HBQCALC TO CALCULATE LOAD AT EACH TA
C SET THREE DECK LATENT LOAD EQUAL TO VAV
C LATENT LOAD AND THREE DECK PREHEAT EQUAL TO ZERO
C
      CALL HBQCALC(CFA,TBCA,HFA,TBHA,QLC,PCX,PHX,
     &PPHX,PLX,TA(L,J),1.)
      IF(K .EQ. 2) SOH(L,J)= PLX
      IF(K .EQ. 4) PLX= SOH(L,J)
      IF(K .EQ. 4) PPHX=0
C
C CALCULATE COP AND EACH TA
C
      COP= .180 * (57.22 - TA(L,J))
C
C CONVERT TO DESIRED UNITS AND SUM ALL LOAD*TIME
C PRODUCTS OVER TIME PERIOD TO GIVE ENERGY TOTALS
C FOR THAT TIME PERIOD
C
      PCH(J)= PCH(J) + PCX/CM
      PPHH(J)= PPHH(J) + PPHX/CM
      PHH(J)= PHH(J) + PHX/CM
      PLH(J)= PLH(J) + PLX/CM
      PEH(J)= PEH(J) + ((PCX + PLX) / (COP * CM))
C      PEH(J)= PEH(J) + (PCX / (COP * CM))
C
130         CONTINUE
C
C SUM TOTAL COIL EHERGIES OVER PERIODS FOR MONTH.
C
C         QCH(K,I)= QCH(K,I) + PCH(J) + PLH(J)
         QCH(K,I)= QCH(K,I) + PCH(J)
C         QPHH(K,I)= QPHH(K,I) + PPHH(J)
         QHH(K,I)= QHH(K,I) + PHH(J) + PPHH(J)
         QLH(K,I)= QLH(K,I) + PLH(J)
         ENRGH(K,I)= PEH(J) + ENRGH(K,I)
C
C CALCULATE BIN TOTALS, DO SAME AS ABOVE FOR PERIOD
C AND MONTH TOTALS.
C
            DO 135 L= 1,NBIN(J)
C
C CALL ROUTINE CALC TO CALCULATE UF'S AND TB'S AT
```

```
C EACH TA
C
      CALL CALC(TBIN(L,J),TBH,TBC,CF,HF,TLO,THI,NR,
     &NF,MDOT(I),MOUT(I),
     &MMIN(I),WBIN(L,J),TC(I),TR(I),QL(J,I),NSYS,
     &TBHA,TBCA,CFA,HFA,
     &QLC,IR)
C
C CALL ROUTINE HBQCALC TO CALCULATE LOAD AT EACH TA
C SET THREE DECK LATENT LOAD EQUAL TO VAV
C LATENT LOAD AND THREE DECK PREHEAT EQUAL TO ZERO
C
      CALL HBQCALC(CFA,TBCA,HFA,TBHA,QLC,PCX,PHX,
     &PPHX,PLX,
     &TBIN(L,J),HBIN(L,J))
       IF(K .EQ. 2) SOB(L,J)= PLX
       IF(K .EQ. 4) PLX= SOB(L,J)
       IF(K .EQ. 4) PPHX=0
C
C CALCULATE COP AT EACH TA
C
      COP= .180 * (57.22 - TBIN(L,J))
C
C
C CONVERT TO DESIRED UNITS AND SUM ALL LOAD*TIME
C PRODUCTS OVER TIME PERIOD TO GIVE ENERGY TOTALS
C FOR THAT TIME PERIOD
C
      PCB(J)= PCB(J) + PCX/CM
      PPHB(J)= PPHB(J) + PPHX/CM
      PHB(J)= PHB(J) + PHX/CM
      PLB(J)= PLB(J) + PLX/CM
      PEB(J)= PEB(J) + ((PCX + PLX) / (COP * CM))
C      PEB(J)= PEB(J) + (PCX  / (COP * CM))
C
135         CONTINUE
C
C
C SUM TOTAL COIL ENERGIES OVER PERIODS FOR MONTH.
C
C          QCB(K,I)= QCB(K,I) + PCB(J) + PLB(J)
         QCB(K,I)= QCB(K,I) + PCB(J)
C          QPB(K,I)= QPB(K,I) + PPHB(J)
         QHB(K,I)= QHB(K,I) + PHB(J) + PPHB(J)
         QLB(K,I)= QLB(K,I) + PLB(J)
         ENRGB(K,I)= PEB(J) + ENRGB(K,I)
160   CONTINUE
C
C DO SUMS FOR AVERAGE MONTHLY COIL AND CHILLER
```

```
C ENERGY OVER A YEAR
C
         DO 140 K= 1,NSYSTM
C          K= NSYSTM
            SQCB(K,I)= SQCB(K,I) + (QCB(K,I)/12.)
            SQHB(K,I)= SQHB(K,I) + (QHB(K,I)/12.)
            SENRGH(K,I)= SENRGH(K,I)+(ENRGH(K,I)/12.)
C            SQPB(K,I)= SQPB(K,I) + (QPB(K,I)/12.)
            SQLB(K,I)= SQLB(K,I) + (QLB(K,I)/12.)
            SQCH(K,I)= SQCH(K,I) + (QCH(K,I)/12.)
            SQHH(K,I)= SQHH(K,I) + (QHH(K,I)/12.)
            SENRGB(K,I)= SENRGB(K,I)+(ENRGB(K,I)/12.)
C            SQPH(K,I)= SQPH(K,I) + (QPH(K,I)/12.)
            SQLH(K,I)= SQLH(K,I) + (QLH(K,I)/12.)
140      CONTINUE
C
C WRITE MONTHLY TOTAL VALUES OF COIL LOADS FOR EACH
C COMBINATION OF VARIABLE PARAMETERS
C
C        WRITE(31,91) IMON
C      DO 179 I=1,NPOINT
C        WRITE(31,82)
C
C        WRITE(31,86) COIL(1),COIL(4)
C        WRITE(31,83)
C        DO 175 K=1,NSYSTM
C       K=NSYSTM
C175        CALL WRITE2(S(K),QCH(K,I),QCB(K,I),
C     &QLH(K,I),QLB(K,I))
C
C        WRITE(31,86) COIL(2),COIL(3)
C        WRITE(31,83)
C        DO 177 K=1,NSYSTM
C       K=NSYSTM
C177        CALL WRITE2(S(K),QHH(K,I),QHB(K,I),
C     &ENRGH(K,I),ENRGB(K,I))
C
C179   CONTINUE
C
C WRITE AVERAGE MONTHLY TOTAL VALUES FOR EACH
C COMBINATION OF VARIABLE PARAMETERS
C
      IF(IMON .EQ. 12) THEN
      WRITE(31,85)
      DO 189 I=1,NPOINT
        WRITE(31,82) I
C
        WRITE(31,86) COIL(1),COIL(4)
        WRITE(31,83)
```

```
        DO 185 K=1,NSYSTM
C       K=NSYSTM
185        CALL WRITE2(S(K),SQCH(K,I),SQCB(K,I),
     &SQLH(K,I),SQLB(K,I))
C
        WRITE(31,86) COIL(2),COIL(3)
        WRITE(31,83)
        DO 187 K=1,NSYSTM
C       K=NSYSTM
187        CALL WRITE2(S(K),SQHH(K,I),SQHB(K,I),
     &SENRGH(K,I),SENRGB(K,I))
C
189   CONTINUE
      ENDIF
C
C-----------------------------------------------------
C
1000  CONTINUE
      STOP
      END
C
C
C-----------------------------------------------------
C NOTE THE ABOVE PROGRAM DOES NOT USE THE ERBS' CORR-
C ELATION DD'S CALCULATED BELOW, BUT IT COULD WITH
C MINOR CHANGES.  THE SUFFIX "E" DENOTES ERBS' DD
C HEATING AND SENSIBLE COOLING TOTALS
C-----------------------------------------------------
C
C CALCULATE ERB'S CORRELATION DD TOTALS, FOR SENSIBLE
C HEATING AND COOLING USING CONSTANT
C UF'S AND TB'S FROM SYSORT FOR THE SYSTEMS THAT HAVE
C THEM: TRH, VAV, TRHE, TRHD
C
      PCE(J)=(HF(1,1)/CM)*DD(TBC(12,1),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),1)
      PHE(J)=(HF(1,1)/CM)*DD(TBC(12,1),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),0)
      GO TO 874
            IF(NSYS .EQ. 1) THEN
      PHE(J)= (HF(1,1)/CM) * DD(TBH(1,1),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),0)
      PCE(J)= (CF(1,1)/CM) * DD(TBC(1,1),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),1)
      PPHE(J)= (CF(1,1)/CM) * DD(TBC(1,1),TBARP(J),
```

```
     &SIGMA,NHR(J),
     &NHOUR(IMON),0)
            ENDIF
C
            IF(NSYS .EQ. 2) THEN
      PHE(J)= HF(2,2) * (DD(TBH(2,2),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),0) / CM)
      PPHE(J)= CF(2,2) * (DD(TBC(2,2),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),0) / CM)
      CALL DDX(NHOUR(IMON),NHR(J),TBC(2,1),
     &TBARP(J),SIGMA,1,2,
     &TLO(2,1),DDE)
      PCE(J)= CF(2,1) * DDE / CM
      CALL DDX(NHOUR(IMON),NHR(J),TBC(2,2),
     &TBARP(J),SIGMA,1,1,
     &THI(2,2),DDE)
      PCE(J)= PCE(J) + (CF(2,2) * DDE / CM)
            ENDIF
C
            IF(NSYS .EQ. 4) THEN
      PHE(J)= HF(4,1) * (DD(TBH(4,1),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),0) / CM)
      PCE(J)= CF(4,1) * (DD(TBC(4,1),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),1) / CM)
      PPHE(J)= 0.
            ENDIF
C
            IF(NSYS .EQ. 5) THEN
      PHE(J)= HF(5,1) * (DD(TBH(5,1),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),0) / CM)
      PPHE(J)= CF(5,4) * (DD(TBC(5,4),TBARP(J),
     &SIGMA,NHR(J),
     &NHOUR(IMON),0) / CM)
      CALL DDX(NHOUR(IMON),NHR(J),TBC(5,1),TBARP(J),
     &SIGMA,1,2,
     &TLO(5,1),DDE)
      PCE(J)= CF(5,1) * DDE / CM
      CALL DDX(NHOUR(IMON),NHR(J),TBC(5,2),TBARP(J),
     &SIGMA,1,1,
     &THI(5,2),DDE)
      PCE(J)= PCE(J) + (CF(5,2) * DDE / CM)
            ENDIF
C
            IF(NSYS .EQ. 8) THEN
```

```
       CALL DDX(NHOUR(IMON),NHR(J),TBH(8,1),TBARP(J),
      &SIGMA,0,2,
      &TLO(8,1),DDE)
       PHE(J)= HF(8,1) * DDE / CM
       CALL DDX(NHOUR(IMON),NHR(J),TBH(8,3),TBARP(J),
      &SIGMA,0,1,
      &THI(8,3),DDE)
       PHE(J)= PHE(J) + (HF(8,3) * DDE / CM)
       CALL DDX(NHOUR(IMON),NHR(J),TBC(8,1),TBARP(J),
      &SIGMA,0,2,
      &TLO(8,1),DDE)
       PPHE(J)= CF(8,1) * DDE / CM
       CALL DDX(NHOUR(IMON),NHR(J),TBC(8,3),TBARP(J),
      &SIGMA,0,1,
      &THI(8,3),DDE)
       PPHE(J)= PCE(J) + (CF(8,3) * DDE / CM)
       CALL DDX(NHOUR(IMON),NHR(J),TBC(8,1),TBARP(J),
      &SIGMA,1,2,
      &TLO(8,1),DDE)
       PCE(J)= CF(8,1) * DDE / CM
       CALL DDX(NHOUR(IMON),NHR(J),TBC(8,3),TBARP(J),
      &SIGMA,1,1,
      &THI(8,3),DDE)
       PCE(J)= PCE(J) + (CF(8,3) * DDE / CM)
             ENDIF
C
             IF(NSYS .EQ. 3 .OR.  NSYS .EQ. 6
      &.OR.  NSYS .EQ. 7 .OR.  NSYS .GE. 9)THEN
       PHE(J)= 0.
       PPHE(J)= 0.
       PCE(J)= 0.
             ENDIF
C
874    CONTINUE
       QCE(K,I)= QCE(K,I) + PCE(J)
       QPHE(K,I)= QPHE(K,I) + PPHE(J)
       QHE(K,I)= QHE(K,I) + PHE(J)
C-----------------------------------------------------
C THE FOLLOWING ARE SUBPROGRAMS CALLED IN THE MAIN]
C PROGRAM ABOVE
C-----------------------------------------------------
C READING SUBROUTINE, READS PARAMRETER VALUES FROM
C 45= MATRIX, MATRIX OF INPUT INFORMATION ALL READ
C      IN WITH FORMAT 90,
C      TC,TH,TR,DBT,MDOT,MMIN,MOUT,U,A,QI,QLDAY
C      AS DESCRIBED BELOW IN FORMAT STATEMENTS
C
C-----------------------------------------------------
C
```

```
      SUBROUTINE READER(TC,TH,TR,TRH,TRC,MDOT,MOUT,
     &MMIN,CP,U,A,QG,QL,
     &NPER,NSTART,NPOINT)
      INTEGER NSTART(26)
      REAL MMIN(32),MDOT(32),MOUT(32),QG(24,32),
     &TC(32),TH(32),QL(24,32)
      REAL U(32), A(32),TR(32), TRH(32), TRC(32)
C
      X(Y)= (Y - 32.) / 1.8
C
C-----------------------------------------------------
C THIS SECTION READS PARAMETERS
C-----------------------------------------------------
C
C
90    FORMAT(T5,F11.5)
15    FORMAT(//'SPECD QUANTITIES, DESIGNED FROM THE
     &OTTENSTEIN BLDG.')
1     FORMAT(' TC(COLD SUPPLY TEMP)=',T50,F8.2,' C')
2     FORMAT(' TH(HOT SUPPLY TEMP)=',T50,F8.2,' C')
3     FORMAT(' TR(ROOM SET TEMP)=',T50,F8.2,' C')
80    FORMAT(' DBT(DEADBAND +/- SET)=',T50,F8.2,' C')
4     FORMAT(' TRH(HEATING ROOM SET)=',T50,F8.2,' C')
5     FORMAT(' TRC(COOLING ROOM SET)=',T50,F8.2,' C')
7     FORMAT(' MDOT(CAV DESIGN AIRFLOW RATE)=',T50,
     &F8.2,' KG/SEC')
8     FORMAT(' MMIN(VAV MINIMUM AIRFLOW RATE)=',T50,
     &F8.2,' KG/SEC')
9     FORMAT(' MOUT(LOWER LIMIT ON OUTSIDE AIR)=',
     &T50,F8.2,' KG/SEC')
10    FORMAT(' CP(FLOW SPECIFIC HEAT)=',T50,F8.2,
     &' W/DEGC')
11    FORMAT(' U(U-VALUE)=',T50,F8.2,' W/M C')
12    FORMAT(' A(EXPOSED AREA)=',T50,F8.2,' M ')
14    FORMAT(' QI(DAYTIME INTERNAL GAINS)=',T50,F8.2,
     &' W')
6     FORMAT(' QL(DAYTIME LATENT GAINS)=',T50,F8.2,
     &' W')
101   FORMAT(I3,T4,F6.2,T11,F6.2,T18,F6.2,T25,F6.2,
     &T32,F6.2,T39,F6.2,
     &T45,F6.2,T52,F6.2,T59,F7.2,T67,F8.2,T76,F8.2)
102   FORMAT('RUN',T7,'TC',T14,'TH',T21,'TR',T28,
     &'DBT',T35,'MDOT',T43,
     &'MMIN',T49,'MOUT',T56,'U',T63,'A',T71,'QI',T80,
     &'QLDAY')
C
C  READ SYSTEM PARAMETERS, SET CP FOR DRY AIR
C
      CP= 1006.10
```

```
      DO 200 K=1,NPOINT
       READ(45,90) TC(K)
       READ(45,90) TH(K)
       READ(45,90) TR(K)
       READ(45,90) DBT
       READ(45,90) MDOT(K)
       READ(45,90) MMIN(K)
       READ(45,90) MOUT(K)
       READ(45,90) U(K)
       READ(45,90) A(K)
       READ(45,90) QI
       READ(45,90) QLDAY
C
C CONVERT F TEMPERATURES TO C
C
       DBT= DBT/1.8
       TR(K)= X(TR(K))
       TRC(K)= TR(K) + DBT
       TRH(K)= TR(K) - DBT
       TC(K)= X(TC(K))
       TH(K)= X(TH(K))
       QGDAY= QI
C
C ASSIGN LEVELS OF LATENT AND SENSIBLE INTERNAL GAINS
C FOR EACH TIME PERIOD ASSUMING MAXIMUM GAINS OCCUR
C BETWEEN 7 AM AND 7 PM ALL TIME PERIODS OVERLAPPING
C THIS TIME PERIOD USE WEIGHTED AVERAGE OF MAXIMUM
      IF(NPER .EQ. 1)
        QG(1,K)= QGDAY / 2.
        QL(1,K)= QLDAY / 2.
      ELSE
       DO 100 I=1,NPER
          IF(NSTART(I) .GE. 7 .AND.
     &NSTART(I+1) .LE. 19)THEN
            QG(I,K)= QGDAY
            QL(I,K)= QLDAY
          ELSE
            IF(NSTART(I+1) .GE. 7) THEN
              QG(I,K)=QGDAY*(NSTART(I+1)-7) /
     &(NSTART(I+1)-NSTART(I))
              QL(I,K)=QLDAY*(NSTART(I+1)-7) /
     &(NSTART(I+1)-NSTART(I))
            ENDIF
            IF(NSTART(I) .LE. 19)
              QL(I,K)= QLDAY*(19-NSTART(I)) /
     &(NSTART(I+1)-NSTART(I))
              QG(I,K)= QGDAY*(19-NSTART(I)) /
     &(NSTART(I+1)-NSTART(I))
            ENDIF
```

```
            IF(NSTART(I) .LT. 7 .OR.
     &NSTART(I) .GT. 19) THEN
               QG(I,K)= 0.
               QL(I,K)= 0.
            ENDIF
          ENDIF
100     CONTINUE
        ENDIF
C
C   ECHO CHECK
C
         IF(K .EQ. 1)  THEN
          WRITE(31,15)
          WRITE(31,1) TC(K)
          WRITE(31,2) TH(K)
          WRITE(31,3) TR(K)
          WRITE(31,80) DBT
          WRITE(31,4) TRH(K)
          WRITE(31,5) TRC(K)
          WRITE(31,7) MDOT(K)
          WRITE(31,8) MMIN(K)
          WRITE(31,9) MOUT(K)
          WRITE(31,10) CP
          WRITE(31,11) U(K)
          WRITE(31,12) A(K)
          WRITE(31,14) QI
          WRITE(31,6) QLDAY
          WRITE(31,102)
         ENDIF
C
         WRITE(31,101) K,TC(K),TH(K),TR(K),DBT,MDOT(K),
     &MMIN(K),
     &MOUT(K),U(K),A(K),QI,QLDAY
C
200     CONTINUE
C
        RETURN
        END
C
C=====================================================
C
C SUBROUTINE CALLS PERCENTAGE ERROR ROUTINE AND
C WRITES RESULTS LOAD TOTALS AND % ERR
C
C-----------------------------------------------------
C
        SUBROUTINE WRITE2(CHAR,X1,X2,X3,X4)
        CHARACTER *4 CHAR
C
```

```
184   FORMAT(T7,A4,T18,F6.3,T28,F6.3,T38,F6.3,T48,
     .F6.3,T58,F6.3,
     .T68,F6.3)
C
      CALL PERERR(X1,X2,P1)
      CALL PERERR(X3,X4,P2)
C
      WRITE(31,184) CHAR,X1,X2,P1,X3,X4,P2
C
      RETURN
      END
C=====================================================
C
C SUBROUTINE CALCULATES PERCENTAGE ERROR OF THE
C SECOND NUMBER, X
C FROM THE FIRST, Y.
C
C-----------------------------------------------------
      SUBROUTINE PERERR(X,Y,P)
C
         IF(X .GE. .001) THEN
           DIF= X - Y
           P= 100.*(DIF/X)
         ELSE
           P= 333.333
         ENDIF
C
      RETURN
      END
C=====================================================
C
C SUBROUTINE ASSIGNS CONDUCTANCE FACTORS (CF,HF),
C BASE TEMPERATURES
C (TBH,TBC), AND RANGE TEMPERATURES(TLO,THI),
C FOR ALL SYSTEM TYPES:
C 1= TRH TERMINAL REHEAT, 2=VAV VAV WITH REHEAT
C 3= DDM DUAL DUCT 4= 3DM THREE DECK
C 5= 1W/ECONOMISER 6=2W/ECONOMISER 7=3W/ECONOMISER
C 8= 1W/DEAD BAND ROOM CONTROL 9=2W/DEAD BAND
C 10=3W/DEAD BAND
C AS PER DERIVATRIONS DONE IN JUNE AND AUG '85.
C NOTE: CF(I,K)=> I=SYSTEM NUMBER
C                 J=OPERATIONAL PERIOD
C                  K=TEMPERATURE RANGE NUMBER
C
C-----------------------------------------------------
C
      SUBROUTINE SYSORT(U,A,MOUT,MMIN,MDOT,CP,TR,TC,
     &TH,TRC,TRH,QG,
```

```
     &HF,TBH,CF,TBC,TLO,THI,NR,NF)
      REAL HF(16,6),TBH(16,6),CF(16,6),TBC(16,6),
     &TLO(16,6),THI(16,6), MDOT,MMIN,MOUT
      INTEGER NR(16),NF(3)
C
C   TRH ASSIGNMENTS
C
      CALL TRHT(U,A,MDOT,MOUT,CP,TC,TR,QG,0,
     &HF(1,1),TBH(1,1),
     &CF(1,1),TBC(1,1))
      TLO(1,1)=-1000.
      THI(1,1)= 1000.
      NR(1)=1
C
C VAV ASSIGNMENTS, TWO RANGES OF OPERATION-
C VAV AND REHEAT- INDICATED
C
      CALL VAV(U,A,MOUT,CP,TR,TC,QG,0,HF(2,1),
     &TBH(2,1),CF(2,1),
     &TBC(2,1))
      CALL TRHT(U,A,MMIN,MOUT,CP,TC,TR,QG,0,HF(2,2),
     &TBH(2,2),
     &CF(2,2),TBC(2,2))
      TLO(2,1)= TBH(2,2)
      THI(2,1)= 1000.
      TLO(2,2)=-1000.
      THI(2,2)= TBH(2,2)
      NR(2)= 2
      IF(TLO(2,1) .LT.  TBC(2,1)) WRITE(31,19)
19    FORMAT(' THERE IS A VAV DESIGN PROBLEM')
C
C  DDM ASSIGNMENTS
C
      CALL DDM(U,A,MDOT,MOUT,CP,TH,TR,TC,QG,0,
     &HF(3,1),TBH(3,1),
     &CF(3,1),TBC(3,1))
      TLO(3,1)= -1000.
      THI(3,1)= 1000.
      NR(3)= 1
C
C  3DM ASSIGNMENTS
C
      CALL VAV(U,A,MOUT,CP,TR,TC,QG,-1,HF(4,1),
     &TBH(4,1),CF(4,1),
     &TBC(4,1))
      TLO(4,1)= -1000.
      THI(4,1)= 1000.
      NR(4)= 1
C
```

```
C THRE ASSIGNMENTS, 4 ECONOMISER RANGES
C
       CALL TRHT(U,A,MDOT,MOUT,CP,TC,TR,QG,0,HF(5,1),
      &TBH(5,1),
      &CF(5,1),TBC(5,1))
       TLO(5,1)= TR
       THI(5,1)= 1000.
       CALL TRHT(U,A,MDOT,MOUT,CP,TC,TR,QG,1,HF(5,2),
      &TBH(5,2),
      &CF(5,2),TBC(5,2))
       TLO(5,2)= TC
       THI(5,2)= TR
       CALL TRHT(U,A,MDOT,MOUT,CP,TC,TR,QG,2,HF(5,3),
      &TBH(5,3),
      &CF(5,3),TBC(5,3))
       TLO(5,3)= TBC(5,1)
       THI(5,3)= TC
       CALL TRHT(U,A,MDOT,MOUT,CP,TC,TR,QG,0,HF(5,4),
      &TBH(5,4),
      &CF(5,4),TBC(5,4))
       TLO(5,4)= -1000.
       THI(5,4)= TBC(5,1)
       NR(5)= 4
C
C VAVE ASSIGNMENTS, 4 ECONOMISER RANGES WITH 5th FOR
C VAV/REHEAT SPLIT NF KEEPS TRACK OF WHERE TCHG FALLS
C W/R TO FOUR ECONOMIZER RANGE TEMPERATURES
C
       TCHG= TLO(2,1)
       TLO(6,1)= TR
       THI(6,1)= 1000.
       TLO(6,2)= TC
       THI(6,2)= TR
       TLO(6,3)= TBC(2,1)
       THI(6,3)= TC
       TLO(6,4)= -1000.
       THI(6,4)= TBC(2,1)
       DO 100 K=1,4
         CALL VAV(U,A,MOUT,CP,TR,TC,QG,K-1,HF(6,K),
      &TBH(6,K),CF(6,K)
      &,TBC(6,K))
         IF(TCHG .GT.  TLO(6,K)) GO TO 160
100    CONTINUE
160    DO 200 M=4,K,-1
          TLO(6,M+1)= TLO(6,M)
200       THI(6,M+1)= THI(6,M)
       THI(6,K+1)= TCHG
       TLO(6,K)= TCHG
C
```

```
      NK= K+1
      DO 250 N= NK,5
         CALL TRHT(U,A,MMIN,MOUT,CP,TC,TR,QG,N-2,
     &HF(6,N),TBH(6,N),
     &CF(6,N),TBC(6,N))
250   CONTINUE
      IF(TCHG .GT.  THI(6,5)) THEN
        THI(6,5)= TBC(2,2)
        TLO(6,4)= TBC(2,2)
      ENDIF
      IF(THI(6,2) .EQ.  TR) NF(1)= 1
      IF(THI(6,2) .EQ.  TCHG) NF(1)= 2
      NR(6)= 5
C
C  DDME ASSIGNMENTS 4 ECONOMISER RANGES AS WITH TRHE
C
      CALL DDM(U,A,MDOT,MOUT,CP,TH,TR,TC,QG,0,
     &HF(7,1),TBH(7,1),
     &CF(7,1),TBC(7,1))
      TLO(7,1)= TR
      THI(7,1)= 1000.
      CALL DDM(U,A,MDOT,MOUT,CP,TH,TR,TC,QG,1,
     &HF(7,2),TBH(7,2),
     &CF(7,2) ,TBC(7,2))
      TLO(7,2)= TC
      THI(7,2)= TR
      CALL DDM(U,A,MDOT,MOUT,CP,TH,TR,TC,QG,2,
     &HF(7,3),TBH(7,3),
     &CF(7,3),TBC(7,3))
      TLO(7,3)= TBC(5,1)
      THI(7,3)= TC
      CALL DDM(U,A,MDOT,MOUT,CP,TH,TR,TC,QG,0,
     &HF(7,4),TBH(7,4),
     &CF(7,4),TBC(7,4))
      TLO(7,4)= -1000.
      THI(7,4)= TBC(5,1)
      NR(7)= 4
C
C TRHD ASSIGNMENTS, 3 RANGES REFLECT DIFFERENT SET
C TEMPS FOR HEATING
C AND COOLING IN ZONE
C
      CALL TRHT(U,A,MDOT,MOUT,CP,TC,TRC,QG,0,HF(8,1),
     &TBH(8,1),
     &CF(8,1),TBC(8,1))
      TLO(8,1)= TRC - (QG/(U*A))
      THI(8,1)= 1000.
        HF(8,2)=  0.
        TBH(8,2)= 0.
```

```
        CF(8,2)=  0.
        TBC(8,2)= 0.
      TLO(8,2)= TRH - (QG/(U*A))
      THI(8,2)= TLO(8,1)
      CALL TRHT(U,A,MDOT,MOUT,CP,TC,TRH,QG,0,HF(8,3),
     &TBH(8,3),
     &CF(8,3),TBC(8,3))
      TLO(8,3)= -1000.
      THI(8,3)= TLO(8,2)
      NR(8)= 3
C
C VAVD ASSIGNMENTS, NF KEEPS TRACK ON WHERE TAH
C AND TAC FALL W/R TCHG
C
      THI(9,1)= 1000.
      TDB2= TLO(8,2)
      TDB1= THI(8,2)
      CALL VAV(U,A,MOUT,CP,TRC,TC,QG,0,HF(9,1),
     &TBH(9,1),CF(9,1)
     &,TBC(9,1))
      IF(TDB1 .GT.  TLO(2,1))THEN
        TLO(9,1)= TDB1
        THI(9,2)= TDB1
        TLO(9,2)= TLO(2,1)
        THI(9,3)= TLO(2,1)
        HF(9,2)=  0.
        TBH(9,2)= 0.
        CF(9,2)=  0.
        TBC(9,2)= 0.
      ELSE
        NF(2)= 1
        TLO(9,2)= TDB1
        THI(9,3)= TDB1
        TLO(9,1)= TLO(2,1)
        THI(9,2)= TLO(2,1)
        CALL TRHT(U,A,MMIN,MOUT,CP,TC,TRC,QG,0,
     &HF(9,2),TBH(9,2),
     &           CF(9,2),TBC(9,2))
      ENDIF
C
      IF(TDB2 .LE.  TLO(2,1))THEN
        IF(NF(2) .NE. 1) NF(2)= 2
        TLO(9,3)= TDB2
        THI(9,4)= TDB2
        HF(9,3)=  0.
        TBH(9,3)= 0.
        CF(9,3)=  0.
        TBC(9,3)= 0.
      ELSE
```

```
          NF(2)= 3
          TLO(9,2)= TDB2
          THI(9,3)= TDB2
          TLO(9,3)= TLO(2,1)
          THI(9,4)= TLO(2,1)
          CALL VAV(U,A,MOUT,CP,TRH,TC,QG,0,HF(9,3),
     &TBH(9,3),CF(9,3)
     &,TBC(9,3))
        ENDIF
        CALL TRHT(U,A,MMIN,MOUT,CP,TC,TRH,QG,0,HF(9,4),
     &TBH(9,4),
     &CF(9,4),TBC(9,4))
        TLO(9,4)= -1000.
        NR(9)=4
C
C DDMD ASSIGNMENTS
C
        CALL DDM(U,A,MDOT,MOUT,CP,TH,TRC,TC,QG,0,
     &HF(10,1),TBH(10,1),
     &CF(10,1),TBC(10,1))
          HF(10,2)=  0.
          TBH(10,2)= 0.
          CF(10,2)=  0.
          TBC(10,2)= 0.
        DO 350 I=1,3
           TLO(10,I)= TLO(8,I)
350        THI(10,I)= THI(8,I)
        CALL DDM(U,A,MDOT,MOUT,CP,TH,TRH,TC,QG,0,
     &HF(10,3),TBH(10,3),
     &CF(10,3),TBC(10,3))
        NR(10)= 3
C
C ASSIGNMENTS FOR 1-K',mVAV,AND MVAVE
C (THE LATTER IS A PORTION OF THE VAV
C ECONOIZER EXPRESSION FOR RANGE 2-
C TA BETS'WEEN TC AND TR
C
        DO 400 I= 11,13
           TLO(I,1)= -1000.
           THI(I,1)= 1000.
           TBH(I,1)= 0.
           TBC(I,1)= 0.
           CF(I,1)= 0.
           HF(I,1)= 0.
400     CONTINUE
        HF(11,1)= (U*A) /((TH - TC) * MDOT * CP)
        TBH(11,1)= TBH(1,1)
        NR(11)= 1
        CF(12,1)= (U*A) /((TR - TC) * CP)
```

```
      TBC(12,1)= TR - (QG / (U*A))
      NR(12)= 1
      CF(13,1)= (U*A) /(TR - TC)
      TBC(13,1)= TR
      TLO(13,1)= TC
      THI(13,1)= TR
      NR(13)= 1
C
      RETURN
      END
C
C
C=====================================================
C SUBROUTINE ASSIGNS CONDUCTANCE FACTORS AND BASE
C TEMPS FOR TERMINAL REHEAT TYPE SYSTEMS
C-----------------------------------------------------
C
      SUBROUTINE TRHT(U,A,MDOT,MOUT,CP,TC,TR,QG,
     &NECON,HF,TBH,CF,TBC)
      REAL MDOT,MOUT,K
C
C TBH AND UFH ARE THE SAME FOR ALL SYSTEMS
C
      K=MOUT/MDOT
      HF= U * A
      TBH= ((((U*A) +(MDOT*CP)) * TR) -
     &(MDOT*CP * TC) - QG) / (U*A)
C
C REGULAR TRH COOLING
C
      IF(NECON .EQ. 0 .OR.  NECON .EQ. 3) THEN
        CF= MOUT * CP
        TBC= (TC - ((1-K) * TR)) / K
      ELSE
C
C ECONOMIZER RANGE 2 TRH COOLING
C
        IF(NECON .EQ. 1) THEN
          CF= MDOT * CP
          TBC=TC
        ENDIF
C
C ECONOMIZER FREE COOLING
C
        IF(NECON .EQ. 2) THEN
          CF= 0.
          TBC= 0.
        ENDIF
      ENDIF
```

```
C
      RETURN
      END
C
C=====================================================
C ROUTINE ASSIGNS CONDUCTANCE FACTOR AND BASE TEMPS
C VARIABLE AIR VOLUME TYPE SYSTEMS.
C-----------------------------------------------------
C
      SUBROUTINE VAV(U,A,MOUT,CP,TR,TC,QG,NECON,HF,
     &TBH,CF,TBC)
      REAL MOUT
C
      HF= 0.
      TBH= 0.
C
C REGULAR VAV
C
      IF(NECON .LE. 0 .OR.  NECON .EQ. 3) THEN
        CF= (U * A) + (MOUT * CP)
        TBC= TR - (QG / CF)
      ELSE
C
C ECONOMIZER RANGE 2
C
        IF(NECON .EQ. 1) THEN
          CF= 1.
          TBC= TC - (QG / (U*A))
        ENDIF
C
C FREE COOLING
C
        IF(NECON .EQ. 2)
          CF= 0.
          TBC= 0.
        ENDIF
      ENDIF
C
C THREE DECK
C
      IF(NECON .EQ. -1) THEN
        HF= CF
        TBH= TBC
      ENDIF
C
      RETURN
      END
C
C
```

```
C=====================================================
C ROUTINE ASSIGNS CONDUCTANCE FACTORS AND BASE TEMPS
C FOR DUAL DUCT TYPE SYSTEMS.
C-----------------------------------------------------
C
      SUBROUTINE DDM(U,A,MDOT,MOUT,CP,TH,TR,TC,QG,
     &NECON,HF,TBH,CF,TBC)
      REAL MDOT,MOUT,K
C
      K=MOUT/MDOT
C
C REGULAR DDM
C
      IF(NECON .EQ. 0) THEN
        HF= MOUT * CP
        TBH= (TH - ((1.- K) * TR)) / K
        CF= MOUT * CP
        TBC= (TC - ((1.- K) * TR)) / K
      ELSE
C
C ECONOMIZER RANGE 2
C
        IF(NECON .EQ. 1) THEN
          HF= MDOT * CP
          TBH= TH
          CF= HF
          TBC= TC
        ENDIF
        IF(NECON .EQ. 2) THEN
          HF= U * A
          TBH= ((((U*A) +(MDOT*CP)) * TR) -
     &(MDOT*CP * TC) - QG)/(U*A)
          CF= 0.
          TBC= 0.
        ENDIF
      ENDIF
C
      RETURN
      END
C
C-----------------------------------------------------
C ROUTINE CALCULATES SPECIFIC MULTIPLIERS AND BASE
C TEMPS
C GIVEN AN AMBIENT TEMP AND MATRIX OF PRELIMINARY
C UF'S AND TB'S FROM READER.
C-----------------------------------------------------
C
      SUBROUTINE CALC(TA,TBH,TBC,CF,HF,TLO,THI,NR,NF,
     &MDOT,MOUT,MMIN,WA,
```

```
     &TC,TR,QL,NS,TBHA,TBCA,CFA,HFA,QLC,IR)
      REAL MVAV,MVAVE,MOUT,MMIN,MDOT,TBH(16,6),
     &TBC(16,6),
     &HF(16,6),CF(16,6),THI(16,6),TLO(16,6)
      INTEGER NR(16),NF(3)
19    FORMAT(1X,F7.2,4(5X,F7.2),5X,E10.4)
20    FORMAT('NR=',I2,3X,'NF=',I2,3X,'MDOT=',F7.2,3X,
     &'MOUT=',F7.2/
     &' MMIN=',F7.2,3X,'WA=',F7.4,3X,'TC=',F7.2,3X,
     &'TR=',F7.2,/
     &' QL=',F10.2,3X,'NS=',I3,3X,'J=',I3)
C
C FUNCTION FOR LATENT HEAT OF VAPORIZATION AT TEMP T
C
      HFG(T)= 1000. * (2500.81 -
     &(T * (2500.81 - 2357.63) / 60.))
C
C CALCULATE VARIABLES NEEDED TO CORRECT UF AND TB
C VALUES FOR VAV AND DDM SYSTEM CALCULATIONS
C AND ALL LATENT LOAD CALCULATIONS
C
      D1KP= (TBH(11,1) - TA) * HF(11,1)
      IF(D1KP .LT. 0. .OR.  D1KP .GT. 1.) WRITE(31,29)
     &TA, D1KP
29    FORMAT('A DESIGN PROBLEM EXISTS,
     &TA='F6.2,'D1KP=',F8.4)
      MVAV= CF(12,1) * (TA - TBC(12,1))
      MVAVE= CF(13,1) * (TA - TBC(13,1))
      HFGR= HFG(TR)
      HFGA= HFG(TA)
      CALL OMEGA(TC,1.,WC)
C
      DO 100 IR = 1,NR(NS)
      IF(TA .GE.  TLO(NS,IR) .AND.  TA .LE.
THI(NS,IR))
           HFA= HF(NS,IR)
           TBHA= TBH(NS,IR)
           CFA= CF(NS,IR)
           TBCA= TBC(NS,IR)
           GO TO 110
         ENDIF
100   CONTINUE
C
110   IF(NS .EQ. 1) THEN
        CALL HUMID(WA,MOUT,MDOT,TA,WC,QL,D1KP,1,TBCA,
     &QLC,HFGR,HFGA)
      ENDIF
C
      IF(NS .EQ. 2) THEN
```

```
      IF(IR .EQ. 1) CALL HUMID(WA,MOUT,MVAV,TA,WC,QL,
     &D1KP,1,TBCA,QLC,HFGR,HFGA)
      IF(IR .EQ. 2) CALL HUMID(WA,MOUT,MMIN,TA,WC,QL,
     &D1KP,1,TBCA,QLC,HFGR,HFGA)
      ENDIF
C
      IF(NS .EQ. 3) THEN
        HFA= D1KP * HFA
        CFA= (1 - D1KP) * CFA
        CALL HUMID(WA,MOUT,MDOT,TA,WC,QL,D1KP,2,TBCA,
     &QLC,HFGR,HFGA)
      ENDIF
C
      IF(NS .EQ. 4) THEN
        CALL HUMID(WA,MOUT,MVAV,TA,WC,QL,D1KP,1,TBCA,
     &QLC,HFGR,HFGA)
      ENDIF
C
      IF(NS .EQ. 5) THEN
        QLC= 0.
        IF(IR .EQ. 1) THEN
        CALL HUMID(WA,MOUT,MDOT,TA,WC,QL,D1KP,1,TBCA,
     &QLC,HFGR,HFGA)
        ENDIF
        IF(IR .EQ. 2) THEN
        CALL HUMID(WA,MDOT,MDOT,TA,WC,QL,D1KP,3,TBCA,
     &QLC,HFGR,HFGA)
        ENDIF
      ENDIF
C
      IF(NS .EQ. 6) THEN
       QLC= 0.
       IF(IR .EQ. 1)CALL HUMID(WA,MOUT,MVAV,TA,WC,QL,
     &D1KP,1,TBCA,QLC,HFGR,HFGA)
       IF(NF(1) .EQ. 1 .AND.  IR .EQ.2) THEN
        CFA= CFA * MVAVE
        CALL HUMID(WA,MVAV,MVAV,TA,WC,QL,D1KP,3,TBCA,
     &QLC,HFGR,HFGA)
       ENDIF
       IF(NF(1) .EQ. 2) THEN
       IF(IR .EQ. 2)CALL HUMID(WA,MOUT,MMIN,TA,WC,QL,
     &D1KP,1,TBCA,QLC,HFGR,HFGA)
     & HFGR,HFGA)
       IF(IR .EQ. 3)CALL HUMID(WA,MMIN,MMIN,TA,WC,QL,
     &D1KP,1,TBCA,QLC,HFGR,HFGA)
        ENDIF
      ENDIF
C
      IF(NS .EQ. 7) THEN
```

```
      IF(IR .NE. 3) THEN
        HFA= D1KP * HFA
        CFA= (1 - D1KP) * CFA
      ENDIF
      IF(IR .GT. 2) THEN
        QLC= 0.
      ELSE
     IF(IR .EQ. 1)CALL HUMID(WA,MOUT,MDOT,TA,WC,QL,
     &D1KP,1,TBCA,QLC,HFGR,HFGA)
     IF(IR .EQ. 2)CALL HUMID(WA,MDOT,MDOT,TA,WC,QL,
     &D1KP,1,TBCA,QLC,HFGR,HFGA)
      ENDIF
    ENDIF
C
    IF(NS .EQ. 8) THEN
      IF(IR .EQ. 1 .OR.  IR .EQ. 3)
      CALL HUMID(WA,MOUT,MDOT,TA,WC,QL,D1KP,1,TBCA,
     &QLC, HFGR,HFGA)
      ELSE
        QLC= 0.
      ENDIF
    ENDIF
C
    IF(NS .EQ. 9) THEN
     QLC= 0.
     IF(IR .EQ. 1)CALL HUMID(WA,MOUT,MVAV,TA,WC,QL,
     &D1KP,1,TBCA,QLC,HFGR,HFGA)
     IF(IR .EQ. 4)CALL HUMID(WA,MOUT,MMIN,TA,WC,QL,
     &D1KP,1,TBCA,QLC,HFGR,HFGA)
     IF(NF(2) .EQ. 1 .AND.  IR .EQ. 2) THEN
     CALL HUMID(WA,MOUT,MMIN,TA,WC,QL,D1KP,1,TBCA,
     &QLC, HFGR,HFGA)
     ENDIF
     IF(NF(2) .EQ. 3 .AND.  IR .EQ. 3) THEN
     CALL HUMID(WA,MOUT,MVAV,TA,WC,QL,D1KP,1,TBCA,
     &QLC, HFGR,HFGA)
     ENDIF
    ENDIF
C
    IF(NS .EQ. 10) THEN
      HFA= D1KP * HFA
      CFA= (1 - D1KP) * CFA
      IF(IR .EQ. 1 .OR.  IR .EQ. 3)
      CALL HUMID(WA,MOUT,MDOT,TA,WC,QL,D1KP,2,TBCA,
     &QLC, HFGR,HFGA)
      ELSE
        QLC= 0.
      ENDIF
    ENDIF
```

```
C
C       DO 950 I=1,10
C       DO 950 K=1,5
C950       WRITE(32,900)I,K,HF(I,K)
C900    FORMAT(T3,I2,T7,I2,T11,I2,T15,F7.2)
C
C       WRITE(32,19) TA,HFA,TBHA,CFA,TBCA,QLC
C
      RETURN
      END
C-----------------------------------------------------------
C ROUTINE CALCULATES LATENT COOLING GIVEN MASS FLOW,
C TEMPERATURE,
C RELATIVE HUMIDITY AND LATENT SPACE INPUT.
C-----------------------------------------------------------
C
      SUBROUTINE HUMID(WA,MO,MD,T,WC,QL,D1KP,N,TBC,
     &QLC,HFGR,HFGA)
      REAL MO,MD,K
C
C SET FRESH AIR FRACTION
C
      K= MO / MD
C
C IF NO SENSIBLE COOLING CONE THERE WILL BE NO LATENT
C
      IF(T .LE.  TBC) THEN
        WF=0.
        GO TO 1000
      ENDIF
C
C CALCULATE WL AND WM
C
      WL= QL / (MD * HFGR)
      WM= ((MO * WA) + ((MD - MO) * WL)) / MO
C
C LATENT LOAD EXISTS IF WM>WC, OTHERWISE LOAD= 0,
C WF IS HUMIDITY FACTOR MULTIPLIED BY HFG TO GIVE
C LATENT LOAD QLC
C
      IF(WM .GE.  WC) THEN
        IF(N .EQ. 1) THEN
          WF= (MO * (WA - WC - WL)) + (MD * WL)
        ENDIF
        IF(N .EQ. 2) THEN
        BOTTOM= 1 - ((1-K) * D1KP)
          WF= ((K * (WA - WC)) + ((1-K) * WL)) * MD /
     &BOTTOM
C          WRITE(32,902) K,BOTTOM
```

```
C902     FORMAT(' K=',F4.3,T15,'BOTTOM=',F7.3)
        ENDIF
        IF(N .EQ. 3) THEN
          WF= MO * (WA - WC)
        ENDIF
      ELSE
       WF= 0.
      ENDIF
C
      QLC= WF * HFGA
C
1000  RETURN
      END
C=====================================================
C THIS SUBROUTINE
C CALCULATES AVERAGE TEMP. & REL.  HUMIDITY FOR EACH
C HOUR OF THE DAY FOR ANY GIVEN MONTH AND
C FOR N SPECIFIED PERIODS DURING THE DAY,
C EACH OF A DIFFERENT LENGTH,
C NHR(I), BEGINNING AT SPECIFIED TIMES, NSTART(I).
C IN UNITS OF HOURS AND DEGREES CENTIGRADE.
C-----------------------------------------------------
      SUBROUTINE HRTEMP(SIGMA,TBAR,RHBAR,KTBAR,TBARP,
     &RHBARP,NPER,NSTART,
     &NH,NHR,KMON)
      INTEGER NSTART(26), NHR(24)
      REAL KTBAR, TBARH(24), RHBARH(24)
      REAL TBARP(24), TSUM(24), RHBARP(24), RHSUM(24)
C
C
83    FORMAT(' AVG.  TEMP.=',T25,F8.2,
     &/'STD.  DEV.  OF TEMP.=',T25,F8.2)
88    FORMAT(' ', T5, I3, T10, F7.2, T20, F7.2,T35,
     &I3,T40,F7.2,T50,F7.2)
87    FORMAT(T5,F7.2)
90    FORMAT(' AVERAGE TEMPERATURES FOR EACH
     &HOUR OF THE DAY')
192   FORMAT('MON=',I3)
92    FORMAT(T5' PER#',T14,'NO HRS',T22,'BEGIN',
     &T30,'AVG TEMP')
91    FORMAT(T5,I3,T14,I5,T22,I3,T30,F7.2,T40,F7.2)
C
      PI= 3.1416
C
      DO 14 J= 1,NPER
         TSUM(J)= 0.
         RHSUM(J)= 0.
14         NHR(J)= 0
C
```

```
C CALCULATE AVERAGE TEMPERATURE FOR EACH
C HOUR OF THE MONTH
C
      A= (25.8 * KTBAR) - 5.21
      DO 24 I=1,24
         TSTAR= 2 * PI * (I-1)/24.
C
         PPARTS= .4632*COS(TSTAR - 3.805)
         PPARTS= .0984*COS(2.*TSTAR - .36) + PPARTS
         PPARTS= .0168*COS(3.*TSTAR - .0822) + PPARTS
         PPARTS= .0138*COS(4.*TSTAR - 3.513) + PPARTS
         TBARH(I)= (A * PPARTS) + TBAR
C
         B= -.516 + (1.933*KTBAR)-(1.663*(KTBAR**3))+
     &(.00669*TBAR) - (1.993E-04 * (TBAR**2))
         PIECES= .4672*COS(TSTAR - .666)
         PIECES= .0958*COS(2.*TSTAR - .3484) + PIECES
         PIECES= .0195*COS(3.*TSTAR - 4.147) + PIECES
         PIECES= .0147*COS(4.*TSTAR - .452) + PIECES
         RHBARH(I)= (B * PIECES) + RHBAR
C
C TAKE AVERAGE OF HOURLY VALUES FOR EACH PERIOD OF
C MONTH BY SUMMING OVER PERIOD, TSUM AND RHSUM,
C COUNTING NO.  OF HOURS IN PERIOD, NHR, AND DIVIDING
C SUM PERIOD, TSUM AND RHSUM, COUNTING NO.  OF HOURS
C IN PERIOD, NHR, AND DIVIDING SUM BY NUMBER OF HRS
C FOR EACH PERIOD, TBARP AND RHBARP
C
      IF(NPER .EQ. 24) THEN
        TSUM(I)= TBARH(I)
        RHSUM(I)= RHBARH(I)
        NHR(I)= 1
      ELSE
       DO 21 J=1,NPER
         IF(I .GE.  NSTART(J) .AND.
     &I .LT.  NSTART(J+1))THEN
          TSUM(J)= TSUM(J) + TBARH(I)
          RHSUM(J)= RHSUM(J) + RHBARH(I)
          NHR(J)= NHR(J) + 1
         ENDIF
21    CONTINUE
           IF(I .LT.  NSTART(1)) THEN
              TSUM(NPER)= TSUM(NPER) + TBARH(I)
              RHSUM(NPER)= RHSUM(NPER) + RHBARH(I)
              NHR(NPER)= NHR(NPER) + 1
           ENDIF
         ENDIF
24    CONTINUE
C
```

```
C       WRITE(33,90)
C       DO 99 I= 1,12
C          K= I + 12
C99         WRITE(33,88) I, TBARH(I),RHBARH(I), K,
     &TBARH(K),RHBARH(K)
C100    CONTINUE
C
      IF(KMON .EQ. 3) THEN
C         WRITE(33,92)
C         WRITE(33,192) KMON
      ENDIF
      DO 25 J= 1,NPER
         TBARP(J)= TSUM(J)/(NHR(J) * 1.)
         RHBARP(J)= RHSUM(J)/(NHR(J) * 1.)
         NHR(J)= NHR(J) * (NH/24)
         IF (KMON .EQ. 3) THEN
C           WRITE(33,91) J,NHR(J),NSTART(J),TBARP(J),
     &RHBARP(J)
         ENDIF
25    CONTINUE
C
      RETURN
      END
C
C=====================================================
CTHIS ROUTINE CALCULATES NUMBER OF HOURS (HBIN(I)) AT
C EACH AMBIENT TEMP BIN (TBIN(I)) ,AND THE SPECIFIC
C HUMIDITY (WBIN(I)) FOR EACH BIN TEMPERATURE
C IN UNITS OF HOURS AND DEGREES CENTIGRADE.
C-----------------------------------------------------
C
      SUBROUTINE BINCALC(SIGMA,BINDT,TBAR,RHBAR,NH1,
     &NH2,NB,TBIN,
     &HBIN,WBIN,IPER,TB1,TB2)
      REAL TBIN(240,24),HBIN(240,24),WBIN(240,24)
C
84    FORMAT(' ', T10, F7.2, T25, F7.2, T35, F7.4)
85    FORMAT(' KOUNT= ', I4,T25,' KEND= ',I4)
86    FORMAT(' NUMBER OF BINS=', T25, I3)
87    FORMAT('TOTAL BIN HRS= ',T25,F7.2)
C
      PI= 3.1416
C
C SET LARGE HI AN LOW TEMPERATURES
30    TLOW= -60.
      THI= 60.
C
C CALCULATE NO, OF BINS
      NBIN= ((THI - TLOW) / BINDT)  + 1
```

```
      KBIN= NBIN + 1
C
      HBIN(KBIN,IPER)= 0.
      NB=0.
C
C DO FOR EACH BIN: STARTING FROM LOWEST BIN, ASSIGN
C UPPER AND LOWER TEMPERATURES OF EACH BIN.
C CALCULATE CUMULATIVE HOURS LOWER THAN UPPER AND
C LOWER TEMPERATURES USING ERGS' CORRELATION FOR Q
C SUBTRACT LATTER FROM FORMER FOR # HOURS AT EACH
C BIN.  ASSIGN # HRS IN BINS ONLY IF # HRS>.01
C
      KOUNT= NBIN
      DO 60 I= 1,NBIN
         TBIN(I,IPER)= TLOW + (I-1)*BINDT
         T= TBIN(I,IPER) + (BINDT/2.)
         QNUP= QN(T,TBAR,SIGMA,NH1,NH2,0)
         T= TBIN(I,IPER) - (BINDT/2.)
         QNLO= QN(T,TBAR,SIGMA,NH1,NH2,0)
         HBIN(I,IPER)= QNUP - QNLO
         IF(HBIN(I,IPER) .  GT. .005)THEN
           NB = NB + 1
           KOUNT= MIN0(KOUNT,I)
         ENDIF
      HBIN(KBIN,IPER)= HBIN(KBIN,IPER) + HBIN(I,IPER)
60    CONTINUE
C
C CALCULATE SPEC HUM AT EACH TEMP BIN KNOWING BIN
C TEMP AND AVG REL.  HUM.  CHANGE COUNTER VALUES ON
BINS
C TO START AT 1 FOR LOWEST TEMP BIN
C
      DO 80 J= KOUNT, KEND
         KDUM=J-KOUNT+1
         TBIN(KDUM,IPER)= TBIN(J,IPER)
         HBIN(KDUM,IPER)= HBIN(J,IPER)
C         CALL OMEGA(TBIN(KDUM,IPER),RHBAR,WBIN(KDUM,
     &IPER))
80    CONTINUE
C
C REASSIGN TAIL TEMP BIN VALUES, SUMMED TO HIGH AND
C LOW BINS DESIGNATED FOR THAT MONTH, TB2, AND TB1
C RESPECTIVELY.  TO DEACTIVATE THIS, COMMENT FOLLOWING
C SECTION DOWN TO RETURN STATEMENT AND DECOMMENT
C THE CALL AND WRITE STATEMENTS IMMEDIATELY ABOVE.
C
      NB1 = 0.
      NB2= NB
      HB1= 0.
```

```
      HB2= 0.
      DO 90 J=1,NB
          IF(TBIN(J,IPER) .LE.  TB1) THEN
           HB1= HBIN(J,IPER) + HB1
           NB1= J
         ENDIF
         IF(TBIN(J,IPER) .GE.  TB2) THEN
          HB2= HBIN(J,IPER) + HB2
           NB2= MIN0(J,NB2)
         ENDIF
90    CONTINUE
      HBIN(NB1,IPER)= HB1
      HBIN(NB2,IPER)= HB2
C
C CALCULATE SPEC HUM AT EACH TEMP BIN KNOWING BIN
C TEMP AND AVG REL.  HUM.  CHANGE COUNTER VALUES ONBINS
C TO START AT 1 FOR LOWEST TEMP BIN
C
      DO 100 J= NB1,NB2
         KDUM=J-NB1+1
         TBIN(KDUM,IPER)= TBIN(J,IPER)
         HBIN(KDUM,IPER)= HBIN(J,IPER)
         CALL OMEGA(TBIN(KDUM,IPER),RHBAR,WBIN(KDUM,
     &IPER))
C         WRITE(35,84) TBIN(KDUM,IPER),
     &HBIN(KDUM,IPER), WBIN(KDUM,IPER)
100   CONTINUE
C
      NB= NB2 - NB1 + 1
C     WRITE(35,86) NB
C
      RETURN
      END
C
C
C
C=======================================================
C SUBROUTINE CALCULATES ERB'S CORRELATION FOR DEGREE
C HOURS(DDBAK) NUM: GREATER(1) OR LESS(20 THAN A
C GIVEN TEMPERATURE(TX) WHICH IS EITHER GREATER OR
C LESS THAN THE BASE TEMPCERATURE USED(TB) FOR
C NHEAT: HEATING(0) OR COOLING(1) DEGREE HOURS.
C ALL AS PER DERIVATIONS MADE IN AUG '85.
C-------------------------------------------------------
C
      SUBROUTINE DDX(NHM,NHP,TB,TBAR,SIGMA,NHEAT,NUM,
     &TX,DDBAK)
C
C CALC QUANTITIES NEEDED IN SUBSEQUENT OPERATIONS
```

```
C
      DD1= DD(TB,TBAR,SIGMA,NHP,NHM,NHEAT)
      DD2= DD(TX,TBAR,SIGMA,NHP,NHM,NHEAT)
      Q1= QN(TX,TBAR,SIGMA,NHP,NHM,NHEAT)
C
C DECISIONS FOR HEATING CALCULATIONS:
C OPTION 1; TX>TB, TX<TB; OPITION 2; TX>TB, TX<TB
C SEE APPENDIX B FOR DERIVATION
C
      IF(NHEAT .EQ. 0) THEN
C
        IF(NUM .EQ. 1) THEN
C
          IF(TX .GE.  TB) THEN
            DDBAK= DD1
          ELSE
            DDBAK= DD2 + ((TB - TX) * Q1)
          ENDIF
C
        ELSE
C
         IF(TX .GE.  TB) THEN
            DDBAK= 0.
          ELSE
            DDBAK= DD1 - DD2 - ((TB - TX) * Q1)
          ENDIF
C
        ENDIF
C
      ELSE
C
        IF(NUM .EQ. 1) THEN
C
          IF(TX .GE.  TB) THEN
            DDBAK= DD1 - DD2 -((TX - TB) * Q1)
          ELSE
            DDBAK= 0.
          ENDIF
C
        ELSE
C
         IF(TX .GE.  TB) THEN
            DDBAK= DD2 + ((TX - TB) * Q1)
          ELSE
            DDBAK= DD1
          ENDIF
C
        ENDIF
C
```

```
      ENDIF
C
      RETURN
      END
C
C=====================================================
C FUNCTION CALCULATES:
C DEGREE HOURS(DD), NHEAT: 0=HEATING DD 1=COOLING DD
C SEE COMPANION FUNCTION, QN
C-----------------------------------------------------
C
      FUNCTION DD(T,TAV,SIGM,NHPER,NHMON,NHEAT)
C
C AS PER D EBB'S PAPER, H IS CALCULATED AS h FOR
C HEATING AND AS h*
C FOR COOLING ACCORDING TO THE CODE VARIABLE NHEAT
C
      HRTODY= (FLOAT(NHMON))/24.
      IF(NHEAT .EQ. 0) THEN
         H= (T - TAV)/ (SQRT(HRTODY) * SIGM)
      ELSE
         H= (TAV - T)/ (SQRT(HRTODY) * SIGM)
      ENDIF
C
C DEGREE DAY CALCULATION IS PERFORMED WITH PART
C GIVEN VALUE OF H CALCULATED.
C
      PIECE= (H/2) + (ALOG(COSH(1.698*H)) / 3.396) +
     &.2041
C
      DD= (SIGM * (SQRT(HRTODY) * NHPER) * PIECE)
C
      RETURN
      END
C
C=====================================================
C FUNCTION FIGURES NUMBER OF HOURS(QN), NHEAT:
C ABOVE(1) OR BALOW(0) GIVEN TEMP(T) IN A PERIOD OF
C NHPER HOURS IN A MONTH OF NHMON HOURS
C-----------------------------------------------------
C
      FUNCTION QN(T,TAV,SIGM,NHPER,NHMON,NHEAT)
C
C AS PER D EBB'S PAPER, H IS CALCULATED AS h FOR
C HEATING AND AS h*
C FOR COOLING ACCORDING TO THE CODE VARIABLE NHEAT
C
      HRTODY= (FLOAT(NHMON))/24.
      IF(NHEAT .EQ. 0) THEN
```

```
            H= (T - TAV)/ (SQRT(HRTODY) * SIGM)
         ELSE
            H= (TAV - T)/ (SQRT(HRTODY) * SIGM)
         ENDIF
C
C NUMBER OF HRS ABOVE OR BELOW (SEE TOP DESCRIPTION)
C ARE CALCULATED.
C
         QN= (FLOAT(NHPER)) / (1. + EXP(-3.396*H))
C
C
         RETURN
         END
C
CYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYY
C
C THE FOLLOWING ARE SAMPLE INPUT FILES:
C  MATRIX CONTAINS BUILDING PARAMETER VALUES
C SCHEDULE TIMES WERE SET BY DESIGN,
C PARAMETERS WERE SET BY BUILDING DESIGN, &
C AIR MASS FLOWS WERE CALCULATED USING
C EQ.S IN SECTION 6.1 (MMIN AND MDOT)
C  CREAD.M1 CONTAINS MONTHLY-AVERAGE DATA
C TEMP AND REL HUMIDITY AND STD.  DEV OF TEMP
C WERE CALCULATED USING
C THE ROUTINES THAT FOLLOW CREAD.M1
C KTBAR VALUES ARE FROM REF. 1
C SUNRISE AND SUNSET ARE SET FROM REF. 2
C HI/LO TEMP BINS TO ROLL TAILS INTO ARE SET
C TO GIVE LIMITS DESCRIBED IN SECTION 5.2
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C MATRIX
    1 = NUMBER OF PARAMETER COMBINATIONS TO READ IN
    3 = NUMBER OF PERIODS IN OPERATING SCHEDULE
    8 >
   16 > STARTING TIMES FOR EACH PERIOD
   20 >
      55.        TC
      90.        TH
      70.        TR
       5.        DBT
       2.95      MDOT
       1.90      MMIN
        .40      MOUT
       1.15      U
     330.        A
   15000.        QI
    3000.        QL
CREAD.M1
```

```
10      > PROGRAM DOES 1 THRU THIS SYSTEM #
 2.00   > BIN SIZE
 1      > IF >0, ROLL TAILS INTO HI/LO BINS
                                11.0200 YR SD   MONTH
                                -8.41   TEMP      1
                                 2.43   STD DEV
                                  .45   KTBAR
                                  .7453 RHBAR
                                 0.0000 QSBAR
                          8   16        SUNUP/SUNDN
                         16.       -34. HI/LO T BINS
                                -5.98             2
                                 2.36
                                  .49
                                  .7433
                                 0.0000
                          7   17
                         16.       -28.
                                -1.87             3
                                 2.24
                                  .50
                                  .7023
                                 0.0000
                          7   17
                         22.       -24.
                                 8.66             4
                                 1.93
                                  .48
                                  .6169
                                 0.0000
                          6   18
                         28.       -12.
                                14.59             5
                                 1.76
                                  .51
                                  .6814
                                 0.0000
                          6   20
                         34.        -4.
                                19.60             6
                                 1.61
                                  .53
                                  .7231
                                 0.0000
                          5   21
                         36.         2.
                                22.11             7
                                 1.54
                                  .55
```

```
                               .7301
                              0.0000
                        6   20
                       38.         6.
                             20.01              8
                              1.60
                               .55
                               .7435
                              0.0000
                        6   19
                       36.         2.
                             16.80              9
                              1.69
                               .52
                               .7129
                              0.0000
                        7   18
                       34.         0.
                             10.49              10
                              1.88
                               .50
                               .6724
                              0.0000
                        7   17
                       30.        -8.
                              2.36              11
                              2.11
                               .40
                               .8016
                              0.0000
                        8   16
                       24.       -20.
                             -3.72              12
                              2.29
                               .38
                               .7908
                              0.0000
                        8   16
                       20.       -28.
C=====================================================
C THIS PROGRAM CALCULATES MONTHLY AND ANNUAL AVERAGE
C TEMPERATURES AND THE STANDARD DEVIATION OF MONTHLY
C AVG.  TEMPERATURES FROM
C THE ANNUAL.  (TABAR, TYRBAR, AND SIGYR RESPECTIVELY)
C----------------------------------------------------
C
      REAL TABAR(12)
      INTEGER NHOUR (12)
80    FORMAT(/'FROM PROGRAM TBAR, WHEN READING FROM
```

```
     &TMY UNITS= DEG C')
81     FORMAT(T30,F4.1)
82     FORMAT(/'MONTH ',T15,'AV TEMP')
83     FORMAT(T2,I2,T13,F8.3)
84     FORMAT(' ANNUAL' ,T13,F8.3,/' ANNUAL STD.DEV.,
     &SIGYR=',F8.3)
C
C INITIALIZE SUMS TO ZERO, SET NO.  OF DAYS IN MON.
C
       TYRSUM=0.
       WRITE(35,80)
       DATA NHOUR/744,672,744,720,744,720,744,744,720,
     &744,720,744/
       DO 30 IMON=1,12
          TASUM=0.
C
C READ TEMPERATURE FROM TMY DATA. AND SUM OVER WHOLE
C MONTH (TASUM),
C
          DO 20 I= 1,NHOUR(IMON)
                READ(30,81) TAMB
                TASUM= TASUM + TAMB
20        CONTINUE
          TABAR(IMON)= TASUM / NHOUR(IMON)
          TYRSUM=TABAR(IMON) + TYRSUM
30     CONTINUE
          TYRBAR= TYRSUM / 12.
C
C CALCULATE THE STANDARD DEVIATION OF THE MONTHLY
C AVERAGES FROM THE ANNUAL AVERAGE.
C
       DO 40 IMON=1,12
          SIGSUM= SIGSUM + (TYRBAR - TABAR(IMON))**2
C
40     CONTINUE
       SIGYR= SQRT(SIGSUM / 11.)
C
C WRITES ALL MONTHLY AVERAGE TEMPERATURES
C THEN ANNUAL AVERAGE AND STANDARD DEVIATION.
C
       WRITE(35,82)
       DO 50 IMON= 1,12
          WRITE(35,83) IMON,TABAR(IMON)
50     CONTINUE
       WRITE(35,84)TYRBAR, SIGYR
C
       STOP
       END
C
```

```
C-----------------------------------------------------
C THIS PROGRAM GENERATES RHBAR BY TMY DATA EVALUATION
C AND SIGMA FOR A MONTH FROM ERB'S CORR.
C MUST CALL OME.SUB(OMEGA)
C-----------------------------------------------------
C
C
      REAL KTBAR
      INTEGER NHOUR(12)
C
71    FORMAT(T30,F4.1,T53,F4.4)
72    FORMAT(T25,I3)
73    FORMAT(T10,F7.2,T25,F7.2,T40,F7.4)
74    FORMAT(T25,F8.2)
76    FORMAT(/'IMON=',I3/'RHBAR FROM TMY=',F8.4)
C
C READ HOURLY TEMPERATURE DATA INTO AN ARRAY DIVIDED
C BY PERIODS FOR INPUT TO THE FIRST DEG-DAY CALCS.
C
      READ(40,74) SIGYR
      DATA NHOUR/744,672,744,720,744,720,744,744,720,
     &744,720,744/
C
      DO 1000 IMON= 1,12
C
      RHSUM= 0.
      DO 40 I=1,NHOUR(IMON)
         READ(30,71) TA, WA
         CALL OMEGA(TA,1.,WSA)
         RHSUM= RHSUM + (WA/WSA)
40    CONTINUE
         RH = RHSUM / (NHOUR(IMON) * 1.)
C
C   READ AVERAGE MONTHLY DATA NEEDED FOR INPUT
C   TO THE THIRD DEGREE DAY CALCULATION.
C   CALCULATE MONTHLY STANDARD DEVIATION, SIGMA
C   USING ERB'S CORRELATION
C
      READ(40,74) TBAR
      READ(40,74) KTBAR
C
      IF(SIGMA .LE. 0.) THEN
        SIGMA= 1.45 - (.029 * TBAR) + (.0664 * SIGYR)
      ENDIF
C
      WRITE(31,76) IMON, RH
C
1000  CONTINUE
      STOP
```

```
C---------------------------------------------------------
C ROUTINE CALCULATES SPECIFIC HUMIDITY GIVEN AMBIENT
C TEMPERATURE AND RELATIVE HUMIDITY AS PER
C CORRELATION IN ERBS' THESIS APP.  A.
C---------------------------------------------------------
C
      SUBROUTINE OMEGA(T,RH,W)
C
      R= (T + 273.15) * 1.8
      IF(T .GE. 0.) THEN
        PWS= 2.4074E+07 * EXP(-9548/R)
      ELSE
        PWS= 4.933E+08 * EXP(-11040/R)
      ENDIF
C
      WS= (.622 * PWS) / (14.7 - PWS)
      W= WS * RH
C
      RETURN
      END
C =========================================================
C SUBROUTINE CALCULATES COOLING, LATENT, HEATING,
C AND PREHEAT COIL LOADS AT GIVEN TEMP, BASE TEMPS,
C COND FACTORS AND NUMBER OF HOURS.
C---------------------------------------------------------
C
      SUBROUTINE HBQCALC(CFACT,TBC,HFACT,TBH,QLF,QC,
     &QH,QPH,QL,T,HOURS)
C
C CALC FOR TEMP,T: LATE&SENS COOL AND HEAT QL,QC,QH
C
      QL= QLF * HOURS
      QC= CFACT * (T - TBC) * HOURS
      QH= HFACT * (TBH - T) * HOURS
C
C  PROCESS THE COIL LOADS AS FOLLOWS:
C   (1) COOL AND HEAT HAVE ONLY POSITIVE VALUES
C   (2) ANY NEGATIVE HEATING VALUE IS ZERO
C   (3) ANY NEGATIVE COOLING VALUE IS PREHEATING
C
      IF(QH .LE. 0.) QH= 0.
      IF(QC .LE. 0.) THEN
        QPH= ABS(QC)
        QC= 0.
      ELSE
        QPH= 0.
      ENDIF
C
      RETURN
      END
```

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