# ASHRAE Technical Data Bulletin

## Energy Performance Analysis and Calculations

*A Collection of Papers from the ASHRAE Annual Meeting at Honolulu, Hawaii, June 1985*

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

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# Upgraded Documentation of the TC 4.7 Simplified Energy Analysis Procedure

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ABSTRACT

A manual entitled Simplified Energy Analysis Using the Modified Bin Method is currently available. All of the computational steps required to perform a complete energy analysis, from determining building space loads through calculation of central plant energy input, are developed in the manual. This paper provides an overview of the manual and highlights the appropriate applications of the modified bin method.

## INTRODUCTION

ASHRAE has been involved in the development of a simplified energy analysis procedure since 1975. The current Modified Bin Method represents several refinements to the original procedure developed by ASHRAE TC 4.7. Simplified Energy Analysis Using the Modified Bin Method was written to upgrade the documentation of this technique and to meet a three fold need in the field of energy analysis:

1. To fill the void between manual methods (degree-day equivalent full-load hours) and comprehensive hourly energy analysis methods. The design and operation of many buildings is too complex to rely on single-measure methods to predict energy consumption and does not warrant the time and cost required to perform an hourly computer simulation. For these applications, a method is needed that is both simple enough to perform manually and accounts for the most significant factors influencing energy consumption.

2. To make available an all-inclusive energy analysis procedure for space loads, HVAC system simulation, and central plant performance in one manual.

3. To illustrate through multiple examples the modifications to the procedure required to analyze different HVAC systems and control strategies. Five basic system types were considered - reheat, multizone, variable air volume, three-deck multizone, and dual-duct variable air volume. These systems were then modified to illustrate the capability of the Modified Bin Method to analyze control strategies such as set-back thermostats, economizer cycles, heating coil shutoff, and double-bundle chiller heat recovery.

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## OVERVIEW OF THE MANUAL

As shown in Figure 1, the simplified energy analysis procedure consists of four independent steps (similar to hourly computer simulations):

1. Calculation of space loads

2. Calculation of HVAC system coil loads necessary to meet the space loads

3. Calculation of primary equipment power fuel and power input required to supply hot and chilled water to the HVAC system

4. Calculation of annual energy consumption

### Loads Calculation

The loads equations are developed as extensions of the design load equations in Chapters 25 and 26 of the ASHRAE handbook 1981 Fundamentals. The difference is that averaging techniques are used to account for the time factor that converts a design condition load to an average load.

All loads are developed as linear functions of outside dry-bulb temperatures. Different load profiles are developed for different periods of the day - usually two periods, occupied and unoccupied, are sufficient. The result is a set of linear equations for each time period, which can be summed to obtain a total zone load profile as a function of outside temperature.

Solar Fenestration Loads. The design solar fenestration load is calculated using maximum solar heat gain factor (MSHGF) data. Tabulated values of cooling load factors (CLF) for various constructions account for the time lag between the introduction of the solar gain and the time when it actually becomes a load on the cooling system.

$$Q_{SOL} = A \times SC \times MSHGF \times CLF \qquad (1)$$

where: A = area of fenestration components
SC = shading coefficients of fenestration component

To convert this equation to one applicable to energy consumption calculations, the 24-hour sum of CLF is used with the fraction of possible sunshine (FPS) data to reduce the maximum solar heat gain to an average value. The resultant daily solar load is then divided by the run time of the aircondtioning system (t) to give an average hourly load.

$$Q_{SOL} = \frac{A \times SC \times MSHGF \times CLF_{TOT} \times FPS}{t} \qquad (2)$$

To establish the solar load profile, calculations are made for January and July values of the MSHGF and the results assigned to the peak heating and cooling temperatures ($T_{ph}$ and $T_{pc}$) respectively. A linear relationship between solar load and out-door temperature at intermediate points is assumed.

Figure 2 shows the two-zone plan for the example building. Figure 3 shows the solar load profile for the perimeter zone of the example building.

Solar Contribution Due to Transmission Loads. The cooling load temperature difference concept was developed to account for thermal storage in walls and roofs and for the increase in envelope heat gain when solar radiation is incident on exterior surfaces. CLTD values were computed based on sol-air temperatures and response factors for different constructions with corrections provided for latitude, month, and surface color (ASHRAE handbook 1981 Fundamentals).

To isolate the solar contribution to transmission gains, the manual uses a solar cooling load temperature difference value (CLTDS) obtained by summing the CLTD value for a given day and subtracting the average air-to-air temperature difference across the envelope components for that day.

$$QTS = A \times U \times CLTDS \times K \times FPS \quad (3)$$

<u>where</u>: A = area of envelope component
U = overall heat transmission coefficient of envelope components
K = color correction factor
FPS = Fraction of possible sunshine

The load profile is established as for the solar fenestration load profile as shown in Figures 4 and 5.

<u>Transmission Loads - Walls, Roof, Windows</u>. The design transmission load is given by:

$$QT = A \times U \times CLTD \quad (4)$$

With the solar contribution isolated by Equation 3, this becomes:

$$QT = U \times A \times (T_o - T_i)$$

<u>where</u>: $T_o$ = outside temperature
$T_i$ = inside temperature

for energy calculations. Thus transmission loads are available as a direct function of outside air temperature. This function will be discontinuous if the inside temperature is allowed to vary.

<u>Internal Loads - Lights, People, Equipment</u>. Under design conditions the internal loads are calculated as:

$$QI = \text{Heat Gain} \times CLF \times UF \text{ (sensible gains)} \quad (5)$$
$$= \text{Heat Gain} \times UF \text{ (latent gains)} \quad (6)$$

<u>where</u>: UF = utilization factor

For energy-estimating purposes, an average usage factor converts maximum heat gain values to average values over a given time period. For people this would be the average percentage of occupancy; for lights, the average percent of peak lighting use; for equipment, the fraction of on-time. The cooling load factor is not used - it is assumed that all of these average loads are eventually felt by the HVAC system.

<u>Infiltration Loads</u>. The procedure uses the same equations as the design calculation for estimating loads due to outside air.

$$QV = 1.1 \times CFM \times (T_o - T_i) \text{ sensible load} \quad (7)$$

$$QV = 4840 \times CFM \times (W_o - W_i) \text{ latent load} \quad (8)$$

The difference is that $T_o$ and $W_o$ represent varying outdoor temperature and humidity ratios rather than design point values. The outside air loads are thus given as a direct function of outside air temperature, similar to the transmission loads.

<u>Total Loads</u>. With all load components established as linear functions of outside air temperature, the total load is simply the algebraic sum of the components. Separate load profiles established for occupied and unoccupied periods are summed to give separate total load profiles. Figures 3 through 11 illustrate these individual and total profile for the sample building analyzed in the manual, which was modeled with two zones - an interior zone and an exterior zone.

## HVAC System Simulation

In this step of the procedure, various air system components are configured to deliver the required heating or cooling effect to the zones. The system simulation involves performing mass and energy balances on each component to ultimately calculate coil loads. Fan power consumption is also determined in this step (ASHRAE handbook 1981 Fundamentals; ASHRAE handbook 1980 Systems; Energy Calculations 2, ASHRAE 1975).

The general simulation methodology is as follows:

1. Obtain zone loads and temperatures.

2. Compute cooling coil leaving air dry-bulb based on control strategy implemented.

3. Compute heating coil leaving air dry-bulb based on control strategy implemented for dual-path systems.

4a. For constant-volume systems, determine the zone supply air temperature.

4b. For variable-volume systems, determine the zone supply air volume.

5. Compute air volume through the cooling and heating coils.

6. Compute cooling coil entering conditions and leaving conditions. This involves calculation of changes in dry-bulb temperatures, humidity ratios, and heat and moisture gains throughout the air paths.

7. Compute coil loads, both sensible and latent.

8. Iterate if an assumed value changes during any calculation step above. step above.

Five specific system simulation examples were presented in the manual. The essential difference is the order in which the calculation steps are performed. The advantage of the modified bin method is that, once the load profiles are established in step A, the system simulation may be performed at any number of temperature bins. This is an essential feature of HVAC performance calculations and is particularly critical if control strategies based on outside air temperature are to be implemented.

The systems analyzed were:

Terminal reheat system (Figure 12)
Dual duct system (Figure 13)
Variable air-volume system (Figure 14)
Three-deck multizone system (Figure 15)
Dual fan/dual-duct variable-air-volume system (Figure 16)

The above systems were controlled with fixed amounts of outside air, fixed cooling coil leaving air temperature, and fixed heating coil leaving air temperature where applicable. Variation in the system and plant operation was made to demonstrate the computational technique. The variations demonstrated are:

Three-deck multizone with double-bundle chiller

Dual fan/dual duct variable-air-volume system with outside air dry-bulb temperature activated economizer cycle

Variable-air-volume system with dual set point thermostat

Dual duct system with hot water coil deenergized when the outdoor air temperature is above 60°F.

Variable-air-volume system with dual set point thermostat and outside air dry-bulb temperature activated economizer cycle

Variable-air-volume system with DX condensing unit

Selection of systems and variations was made to allow the reader to see the general approach of simulating single-path, dual-path, and tri-path systems with various operating strategies.

A chapter on component and control modeling is presented in the manual to allow the user to tailor these basic systems for specific use.

Figure 17 shows system coil loads and plant input for a dual duct system. Similar figures are developed in the manual for each of the basic systems.

Central Plant Performance

Models are developed in the manual for chillers, boilers, pumps, cooling towers, and direct expansion cooling coil units. These models account for the variation in equipment power consumption with load and, in the case of air-cooled condensers and cooling towers, with ambient dry-bulb and wet-bulb temperature. Manufacturers' data are required to establish the performance curves for plant equipment. Thus, accurate prediction of energy consumption again rests on the capability of the method to perform calculations at different outdoor temperatures. All models use the polynominal correction curve method. (ASHRAE handbook 1981; BLAST 2.0 Users Information Manual, U. S. Army Construction Engineering Research Laboratory 1979).

Energy Calculation

The modified bin method involves performing average or "diversified" calculations at four outdoor temperature conditions. These temperatures represent the mid-points of bins that are judged to be of some significance for the location and operation of a particular building and represent the following conditions:

Peak Cooling ($T_{pc}$). This is usually the midpoint of the highest temperature bin occuring at the location.

Intermediate Cooling ($T_{ic}$). This represents the lowest temperature bin in which the envelope transmission and outdoor air sensible loads impose cooling loads on the building. For buildings with occupied cooling thermostat settings between 74°F and 80°F, this is normally the 77°F or 72°F bin.

Intermediate Heating ($T_{ih}$). This represents the midpoint of a temperature bin where the net building loads change from heating to cooling loads. It is near the balance point for exterior zones, and it is also the temperature where the economizer cycle is adequate for meeting any building cooling loads. This is generally taken to be between 52°F and 42°F. When dual set point thermostats are used, the room temperature changes from cooling to heating at this point.

Peak Heating ($T_{ph}$). This is usually the midpoint of the lowest temperature bin occuring at the location.

System loads and plant power input are computed at these four temperature bins. Plant power at intermediate points is obtained by linear interpolation. Energy consumption is computed at each bin by multiplying the plant power by the annual hours if occurance of that bin. Bin frequency data are available for most cities for eight-hour time periods. These data must be modified to accomodate a dual time period situation. For each time period, the annual energy consumption is simply the sum of all the bin energy consumption values.

Figure 18 shows the calculation of chiller energy for the loads shown in Figure 17.

When more detailed analysis is required, an equation for the load profile is used to allow system calculations at each bin. Plant calculations may also be accomplished at each bin. This technique is demonstrated in the manual.

## CONCLUSIONS

As stated above, the modified bin method allows for simulation of different HVAC systems. Table 1 is a comparison of energy consumption of the five HVAC systems discussed in the manual. Results were obtained both manually (using the four-point method) and by computer (calculating consumptions at each bin individually). The results from these methods differ by less than 12% for all systems. The discrepancies are mostly in distribution energy - fan and pump energy. Perhaps more significant is the time required to perform the calculations manually. Computer programs are presented in the manual for all of the systems studied, which take the total building load profile as input and simulate system and plant performance at each tem-perature bin for occupied and unoccupied time periods. These programs are easily modified for other system configurations and significantly reduce computational time. The programs are not generalized and are represented only to show the basis of the example problem.

Table 1 also indicates that the method does provide an adequate basis for a comparative analysis of different HVAC systems. The relative energy consumption of the different systems is what one would expect for a given building with given environmental conditions; the reheat system is the most inefficient energy delivery system, while the VAV system is most efficient.

The validity of the method to analyze different system control options was tested by making modifications to the programs and re-running them with the same loads and bin data. Table 2 shows the results of these simulations. No claim is made as to the accuracy of the percent savings, only that the method allows for comparisons to be made.

The accuracy of the modified bin method in predicting energy consumption has been tested against hourly computer simulations, and results show agreement to within approximately 10% (T. Kusuda, "A comparison of energy calculation procedures," ASHRAE Journal 1981). The sample building used in the manual was simulated using the BLAST computer program and agreement to within 7% was achieved (BLAST 2.0 Users Information Manual, U.S. Army Construction Engineering Research Laboratory 1979).

The energy consumption of a building depends on many factors, some of which the modified bin method does not account for. Therefore, to understand the applicability and usefullness of this technique, the following strengths and weaknesses should be recognized.

The procedure is based on time averaging techniques, and as such, has limited capability in accurately dealing with highly time dependent problems. The major premise is that the net time dependent energy rate, added to or removed from the space during a given computational period, is equivalent to the average energy rate added or removed from the space times the duration of the computational period. The weakness in this premise is the approximation used in developing the average rates of energy gains or losses from the space. The thermal capacitance of the space will induce a time lag before the thermal load to the space actually becomes a load on the HVAC system. Thus, the load computed by averaging may not become the actual load on the HVAC system. Furthermore, the variation of space temperatures characteristic of any control system, which causes heat storage and release, is not accurately represented. This issue may also be argued in hourly simulation programs, since the space temperature variation may occur within the hourly time step. Large space temperature variations associated with deadband controls and night setback and setup conditions may show significant variation with hourly simulators.

The strengths of the method lie in the nature of the energy analysis problem to be solved. The method is generally useful when the building mass (thermal capacitance) is not a primary issue in the analysis. In buildings dominated by internal loads or in low mass structures, the method provides reasonable results. The method should be used with considerable judgment when the primary analysis deals with thermal capacitance dominated problems such as wide deadband thermostats, setup and setback, or massive envelopes.

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## ACKNOWLEDGMENTS


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Table 1 Comparison of Energy Consumption Computed by Four Point Vs. Standard Bin Methods (all values in btu/yr-sf)

| System | Component | Four Pt. Method | | | Standard Bin Method | | |
|---|---|---|---|---|---|---|---|
| | | Occ | Unocc | Total | Occ | Unocc | Total |
| Reheat | Cooling | 38040 | - | 38040 | 38055 | - | 38055 |
| | Heating | 115315 | 6864 | 122179 | 116024 | 6028 | 122052 |
| | Fans | 11455 | 5294 | 16749 | 11449 | 7059 | 18508 |
| | Total | 164810 | 12158 | 176968 | 165528 | 13087 | 178615 |
| DDMZ | Cooling | 27223 | - | 27223 | 27022 | - | 27022 |
| | Heating | 56916 | 6810 | 63726 | 56083 | 6001 | 62084 |
| | Fans | 11455 | 5294 | 16749 | 11449 | 7059 | 18508 |
| | Total | 95594 | 12104 | 107698 | 94554 | 13060 | 107614 |
| VAV | Cooling | 19153 | - | 19153 | 17182 | - | 17182 |
| | Heating | 9177 | 12128 | 21305 | 8330 | 12825 | 21155 |
| | Fans | 4327 | - | 4327 | 4205 | - | 4205 |
| | Total | 32657 | 12128 | 44785 | 29717 | 12825 | 42542 |
| TDMZ | Cooling | 21156 | - | 21156 | 20717 | - | 20717 |
| | Heating | 12475 | 6810 | 19285 | 9331 | 6002 | 15333 |
| | Fans | 11455 | 5294 | 16749 | 11449 | 7059 | 18508 |
| | Total | 45086 | 12104 | 57190 | 41497 | 13061 | 54558 |
| DFDD | Cooling | 19347 | - | 19347 | 18048 | - | 18048 |
| | Heating | 11547 | 11366 | 22913 | 7269 | 11984 | 19253 |
| | Fans | 6284 | 545 | 6829 | 5920 | 544 | 6464 |
| | Total | 37178 | 11911 | 49089 | 31237 | 12528 | 43765 |

Table 2 System Comparison Based On Annual Energy Consumption (Btu/SF/YR)

| Basic Systems | Cooling | Heating | Fans | Total |
|---|---|---|---|---|
| 1) Reheat | 38055 | 122052 | 18508 | 178615 |
| 2) DDMZ | 27022 | 62084 | 18508 | 107614 |
| 3) VAV | 17182 | 21155 | 4205 | 42542 |
| 4) TDMZ | 20717 | 15333 | 18508 | 54558 |
| 5) DFDD | 18048 | 19253 | 6464 | 43765 |

| Modified Systems | | | | | % Savings |
|---|---|---|---|---|---|
| 6) TDMZ W/Heat Recovery | 20837 | 8561 | 18508 | 47906 | 12.2 |
| 7) DFDD W/Economizer | 13906 | 18587 | 6464 | 38957 | 11.0 |
| 8) VAV W/Dual Set Point Thermostat | 16180 | 20148 | 3493 | 39821 | 6.4 |
| 9) DDMZ W/Heating De-Energized | 24538 | 43833 | 18508 | 86879 | 19.3 |
| 10) DDMZ W/Economy Cycle | 14004 | 75617 | 18508 | 108129 | -0.48 |
| 11) VAV W/DX Unit | 15860 | 21155 | 4205 | 41220 | 3.11 |

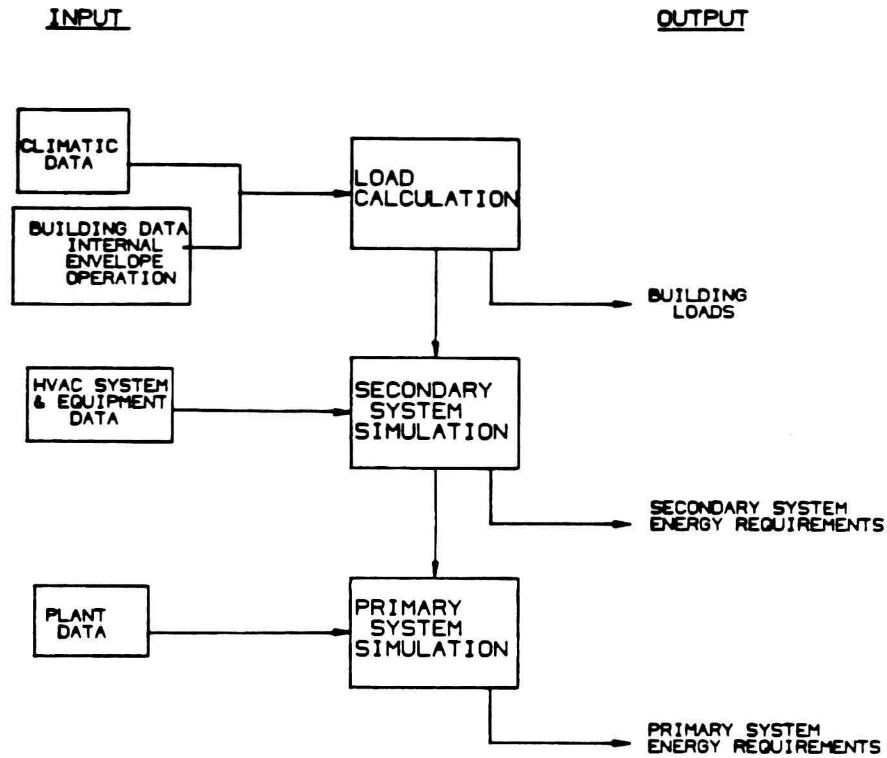



*Figure 1. Simplified schematic of steps involved in estimating building energy use*

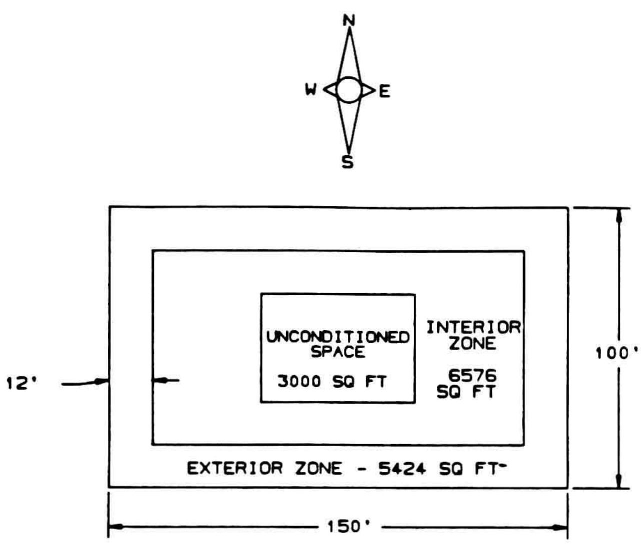
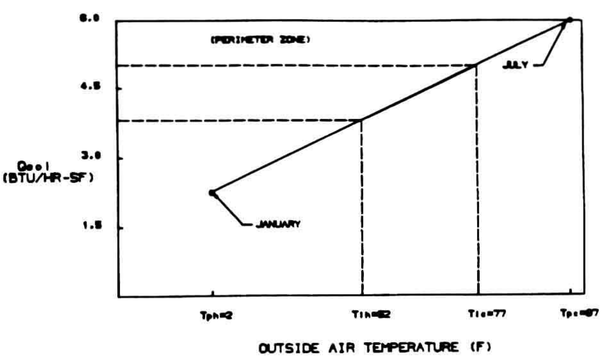
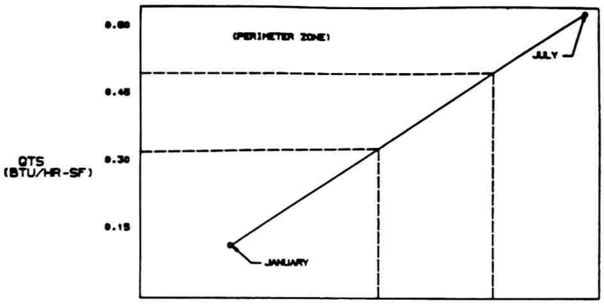



*Figure 2. Floor plan of sample building*



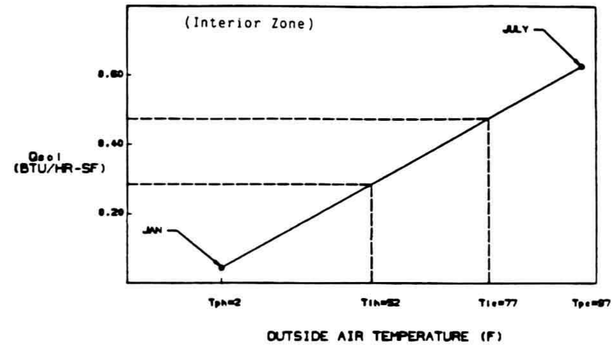

| TEMP | Qsol |
|---|---|
| 97 | 5.969 |
| 77 | 5.188 |
| 52 | 4.211 |
| 2 | 2.258 |

*Figure 3. Graphical interpolation of solar heat gain through glass*




| TEMP | QTS |
|---|---|
| 97 | .635 |
| 77 | .526 |
| 52 | .390 |
| 2 | .118 |

*Figure 4. Graphical interpolation of solar contribution to transmission through opaque surfaces*




| TEMP | Qsol |
|---|---|
| 97 | .622 |
| 77 | .503 |
| 52 | .355 |
| 2 | .0584 |

*Figure 5. Graphical interpolation of solar contribution to transmission through opaque surfaces*

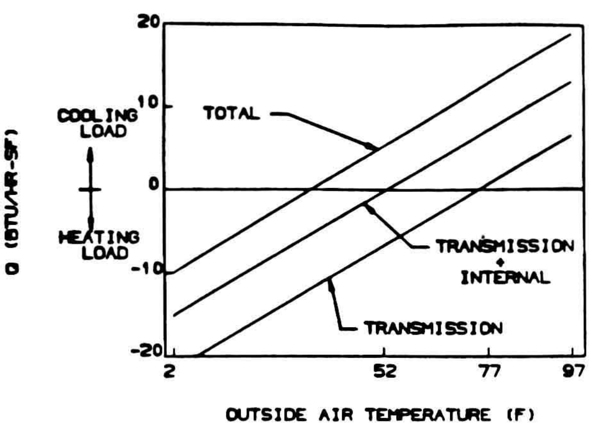



*Figure 6. Load profiles for perimeter zone occupied period (Ti = 75 F)*

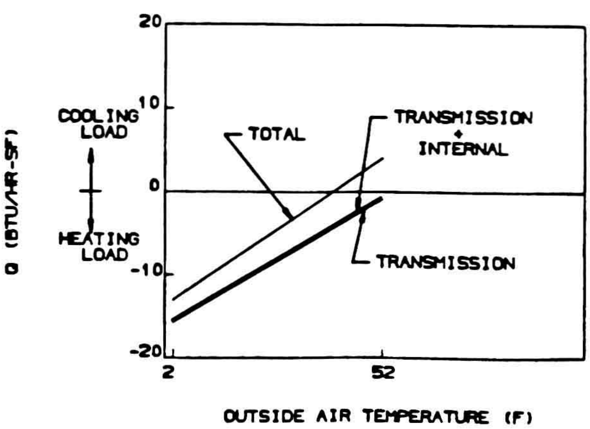



*Figure 7. Load profiles for perimeter zone unoccupied period (Ti = 55 F)*

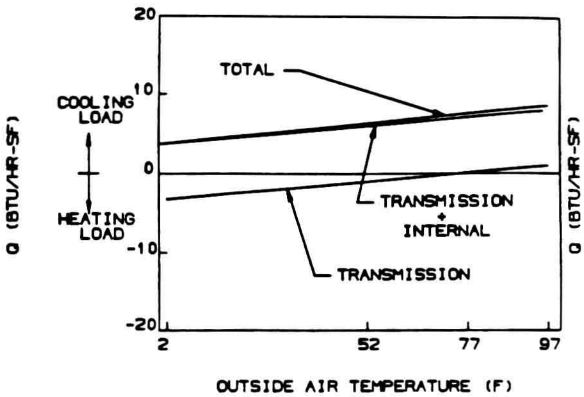



*Figure 8. Load profiles for interior zone occupied period (Ti = 75 F)*

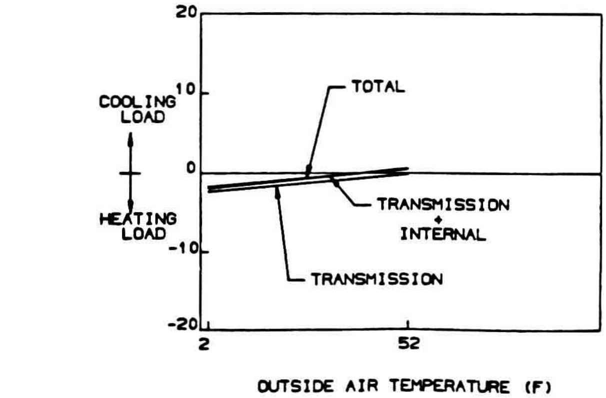



*Figure 9. Load profiles for interior zone unoccupied period (Ti = 55 F)*

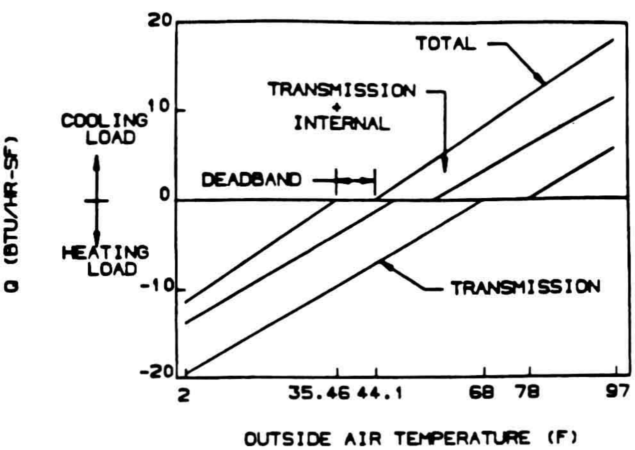



*Figure 10. Load profiles for perimeter zone with dual setpoint thermostat control (68 F heating, 78 F cooling)*

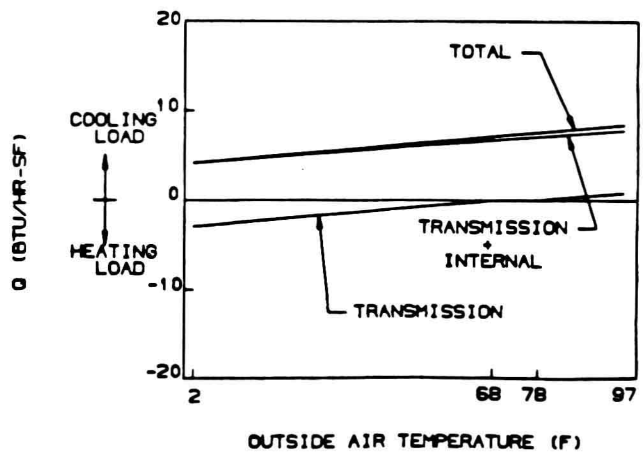



*Figure 11. Load profiles for interior zone with dual setpoint thermostat (68 F heating, 78 F cooling)*