

**DIVISION OF THE HUMANITIES AND SOCIAL SCIENCES  
CALIFORNIA INSTITUTE OF TECHNOLOGY**

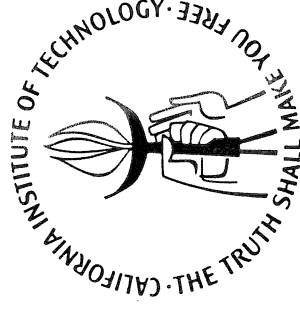
**PASADENA, CALIFORNIA 91125**

A HEATING AND COOLING LOAD MODEL FOR SINGLE-FAMILY  
DETACHED DWELLINGS IN ENERGY SURVEY DATA

Jeffrey A. Dubin  
California Institute of Technology

and

Daniel L. McFadden  
Massachusetts Institute of Technology



**SOCIAL SCIENCE WORKING PAPER 469**

March 1983

TABLE OF CONTENTS

ABSTRACT

The National Interim Energy Consumption Survey (NIECS) and the Pacific Northwest Residential Energy Survey (PNW) are clustered random samples of households interviewed between 1978 and 1980. These surveys report household equipment holdings and energy consumption levels by fuel, as well as selected household and dwelling characteristics. To study the economic determinants of equipment and usage behavior, it is necessary to first describe the economic environment in which behavior is determined. This technical report carries out the construction of heating-ventilating-air conditioning (HVAC) physical characteristics and costs for the alternative systems available to single-family owner-occupied households.

The approach of this report is to construct a very simple thermal model of representative dwellings with characteristics corresponding to those available in typical energy survey data. This model is used to estimate heating and cooling capacity requirements, energy usage, and physical characteristics, for households in the (NIECS) and (PNW) surveys. Cost data from Means (1981) are then used to estimate the capital and operating costs of 19 alternative HVAC configurations for the actual thermal integrity of the building shell and for two alternative thermal standards.

1. INTRODUCTION . . . . . 1

2. THERMAL MODELING PRINCIPLES . . . . . 2

3. BENCHMARK ENERGY CONSUMPTION LEVELS . . . . . 19

4. CHARACTERISTICS OF SINGLE-FAMILY DWELLINGS . . . . . 31

APPENDIX A:

Seasonal Heating and Cooling Efficiencies  
of Air Conditioners and Heat Pumps . . . . . 39

APPENDIX B:

Computer Routines . . . . . 42

TABLES 1 - 21 . . . . . 67

FIGURES 1 - 2 . . . . . 93

FOOTNOTE . . . . . 95

REFERENCES . . . . . 96

A HEATING AND COOLING LOAD MODEL FOR SINGLE-FAMILY  
DETACHED DWELLINGS IN ENERGY SURVEY DATA<sup>1</sup>

Jeffrey A. Dubin  
California Institute of Technology  
and  
Daniel L. McFadden  
Massachusetts Institute of Technology

1. Introduction

The National Interim Energy Consumption Survey (NIECS) and the Pacific Northwest Residential Energy Survey (PNW) are clustered random samples of households interviewed between 1978 and 1980. These survey were designed to report household equipment holdings and energy consumption by fuel, as well as selected household and dwelling characteristics. To study the economic determinants of equipment and usage behavior, it is necessary to first describe the economic environment in which behavior is determined. This technical report carries out the construction of heating-ventilating-air conditioning (HVAC) physical characteristics and costs for alternative systems available to single-family owner-occupied households.

The approach of this report is to construct a very simple thermal model of representative dwellings with characteristics corresponding to those available in typical energy survey data. This model is used to estimate heating and cooling capacity requirements, energy usage, and physical characteristics for households in the (NIECS) and (PNW) surveys. Cost data from Means (1981) are then used to estimate the capital and operating costs of 19 alternative HVAC

configurations for the actual thermal integrity of the building shell and for two alternative thermal standards.

2. Thermal Modeling Principles

Heating and cooling system design capacities of a dwelling are determined by the rates of heat transfer between the interior and exterior under extreme weather conditions. Conduction and infiltration are the dominant modes of transfer in winter; radiation is also important in summer. Heating capacity calculations normally assume steady state thermal conditions, while cooling calculations take account of inertial (flywheel) effects.

The approach to capacity calculation adopted here follows engineering practice, as detailed in ASHRAE (1977, 1978, 1979), Anderson (1973), Khashab (1977), Streeter (1966). Application of these principles to the (NIECS) and (PNW) households requires a number of assumptions and model simplifications due to incomplete data on dwelling characteristics.

A dwelling may be pictured as a box with walls of varying thermal resistances to conduction of heat, as depicted in Figure 1. The net heat loss by conduction from the dwelling in Btuh is the sum of the loss through each area, which equals the area times the temperature differential divided by the resistance (measured in sq. ft. x deg f/Btuh):

$$(1) \text{ Net conduction heat loss} = \frac{A_1 (T_i - T_e)}{R_1} + \frac{A_2 (T_i - T_e)}{R_2} + \frac{A_3 (T_i - T_e)}{R_3} + \frac{A_4 (T_i - T_e)}{R_4}$$



hand, construction standards tend to compensate for differences in resistance which would tend to arise in dwellings which do not fit these assumptions. For example, construction standards for flat roofs generally call for insulation between roofing and sheathing which offsets the loss of resistance provided by an attic. Similarly, masonry walls with lower resistance than frame are normally more heavily insulated, as are slab floors in comparison with construction over an unheated basement. Consequently, we do not expect resistance calculations based on the assumptions above to be systematically biased for alternative types of construction.

[Tables 1, 2, 3, and 4 here]

Table 1 gives the resistance of standard frame exterior wall construction. Table 2 gives the resistance of ceiling and roof for flat and pitched roofs. A later analysis incorporating the effects of solar radiation will combine these resistances into a single effective ceiling-roof resistance. Table 3 gives the resistance of glass, excluding radiation effects. Table 4 gives floor resistance.

#### Winter Heating Load

The combined resistance of ceiling, attic, and roof is calculated as follows: In winter, thermal equilibrium requires

$$(4) \quad 0 = -\frac{A}{R_I} (t_a - t_e) - \frac{A}{R_W} (t_a - t_e) + \frac{A}{R_C} (t_i - t_a),$$

where  $t_a$  is attic temperature,  $A_c$ ,  $A_r$ ,  $A_w$  are ceiling, roof, and attic

wall areas, and  $R_c$ ,  $R_r$ ,  $R_w$  are resistances. Then

$$(5) \quad t_i - t_a = \frac{\frac{A}{R_I} + \frac{A}{R_C} (t_i - t_e)}{\frac{A}{R_C} + \frac{A}{R_I} + \frac{A}{R_W}},$$

so the net ceiling heat flux is

$$(6) \quad \frac{Q}{A_c} = \frac{\frac{A}{R_I} \frac{1}{R_I} + \frac{A}{R_C} \frac{1}{R_C}}{\left(1 + \frac{A}{R_C} \frac{1}{R_I} + \frac{A}{R_C} \frac{1}{R_W}\right)} (t_i - t_e) = \frac{t_i - t_e}{R_{eff}}$$

For a sample of six representative dwellings with pitched roofs, the average value of  $A_r/A_c$  is 1.12 and the average value of  $A_w/A_c$  is 0.08. These are used along with the resistances in Table 2 to calculate the effective winter ceiling resistance for a dwelling with an attic,

$$(7) \quad R_{eff} = \frac{1 + 1.12 \frac{R_c}{R_I} + 0.08 \frac{R_c}{R_W}}{1.12 \frac{1}{R_I} + 0.08 \frac{1}{R_W}} = \frac{3.416 + 1.031 I}{0.9276 + 0.0165 I}.$$

A first order Taylor's expansion of (7) about  $I = 3$  gives the approximation

$$(8) \quad R_{eff} = 3.834 + 0.943 I.$$

For comparison, the resistance of a flat roof and ceiling is approximately

$$(9) \quad R = 4.064 + 0.960 I.$$

Typical values are

| I                | .85  | 3    | 6    | 9     |
|------------------|------|------|------|-------|
| $R_{eff}$        | 4.56 | 6.66 | 9.35 | 11.80 |
| approx $R_{off}$ | 4.63 | 6.66 | 9.50 | 12.32 |
| R                | 4.83 | 6.95 | 9.74 | 12.37 |
| approx R         | 4.88 | 6.95 | 9.83 | 12.71 |

On the basis of this comparison, we chose (8) as an adequate approximation to the resistance of all roofs, pitched or flat.

Infiltration is a function of the integrity of the dwelling shell, and pressure differentials created by wind, stack effects, and temperature differences. A common method of calculating infiltration effects is to determine the number of air changes per hour in the dwelling,  $K$ . Then the heat transfer is

$$(10) \quad \text{Net infiltration heat loss} = 0.018 KV (t_i - t_e),$$

where  $V$  is the volume of the dwelling ( $ft^3$ ),  $0.018$  equals the Btu required to heat one cubic foot of air by one degree  $F$ , and  $t_i - t_e$  is the temperature differential (ASHRAE, 1977. 24.6).

Air changes per hour in most dwellings are in the range

$0.5 \leq K \leq 1.5$  for heating and  $1 \leq K \leq 2$  for cooling. Dwellings with

$K < 0.5$  are "stuffy" and  $K \geq 2$  are "drafty." Experimental measurements by Achenback and Coblenz (1963) give an air change rate

$$(11) \quad K = 0.25 + 0.02165 (\text{wind velocity}) + 0.00833 |t_i - t_e|$$

for an average dwelling. Detailed calculations by Anderson (1973) permit a calculation of the effect of integrity of the shell on this rate. For tight construction, with storm doors and windows, the rate is reduced 14 percent, and for loose construction it is increased 14 percent. Therefore, we multiply the value of  $K$  in (11) by a factor

$$(12) \quad 1.14 - 0.28 (\text{proportion of window area stormed}).$$

An additional factor entering thermal calculations is the heat generated internally by occupants and appliances. ASHRAE (1977, 25.17, 25.41) design standards typically assume each occupant generates 225 Btuh in normal activity, while lighting and appliances generate 1200 Btuh. Anderson reports a higher internal load from lighting and appliances of 3083 Btuh, and an effective load per occupant of 318 Btuh due to the daily pattern of occupancy. For purposes of calculating design capacity, we use the ASHRAE standards.

We follow the usual practice of including internal load in the calculation of air conditioner capacity requirements, but excluding it in heating capacity requirements. The winter heat transfer calculations may now be summarized in Table 5.

[Table 5 here]

#### Summer Cooling Load

The rate of instantaneous heat gain during the summer is classified by the mode in which it enters the residence. Heat gain

occurs in the form of: (1) solar radiation through transparent surfaces; (2) heat conduction through interior partitions, ceilings, and floors; (3) heat conduction through exterior walls and roof; (4) heat generated within the space by occupants and equipment; (5) energy transfer as a result of ventilation and infiltration of outdoor air; and (6) all miscellaneous heat gains.

Precise calculation of the effects of solar radiation on air conditioning requirements requires measurement of the angle of incidence of radiation on each surface of the shell, degree of shading, and reflectance of the surface, over the day. Heat flux into the surface satisfies (ASHRAE, 1977, 25.4).

$$(13) \quad (\text{Btuh per ft}^2) = \alpha I_r + (t_o - t_i)/R - \xi p$$

where

$t_o$  = outdoor air temperature, degrees F

$\alpha$  = absorptance of surface for solar radiation

$I_r$  = solar radiation incident on surface (Btuh/ft<sup>2</sup>)

$R$  = resistance of surface to radiation and convection heat transfer

$\xi$  = emittance of surface

$p$  = correction for difference between sky and black body radiation spectrum

The value of  $I_r$  will be a function of latitude, time of day, and the orientation of the surface. ASHRAE converts this equation to a sol-air temperature equivalent,

$$(14) \quad t_{sa} = t_o + R \cdot (\alpha I_r - \xi p)$$

so that

$$(15) \quad (\text{Btuh per ft}^2) = (t_{sa} - t_i)/R.$$

The temperature  $t_{sa}$  is that outdoor temperature which, in the absence of radiation exchanges, gives the same rate of heat entry into the incident surface as exists under standard conditions. The calculation of heat gain combines transient thermal properties of building materials and sol-air equivalent temperatures by the transfer function method (ASHRAE, 1977, 25.27). However, the rate of instantaneous heat gain will not in general determine instantaneous cooling load. Radiant energy is first absorbed by surfaces which enclose the space. As these surfaces become warmer than the space air, heat is transferred into the room by convection. A transfer function method is used to convert instantaneous heat gain into cooling load.

For hour-by-hour calculation ASHRAE provides values of the thermal transfer coefficients for roofs and walls under a variety of constructions indexed by weight and average conductivity (ASHRAE, 1977, 25.28, Table 26, and 25.29, Table 27). In Table 6 we estimate roof density and weight for the roof materials assumed in Table 2. To approximate the conditions maintained in Table 2, we examine ASHRAE roofs #22 and #25 with weight of 8lbs/cu ft. and conductances 0.109 and 0.170 respectively.

[Table 6 here]

The transfer function method for calculation of instantaneous heat gain through roofs and exterior walls assumes constant indoor temperature and represents outdoor conditions by sol-air equivalent temperatures. Heat gain (at hour h) arising through a roof or wall

is:

$$(16) \quad q(h)/A = B(L)t_{sa}(h) - D(L)q(h)/A - t_i C$$

where

A = indoor surface area of a roof or wall, sq. ft.

q(h) = heat gain, Btuh/sq ft.

h = solar hour

$t_{sa}(h)$  = sol-air temperature at hour h, degrees F

$t_i$  = indoor temperature, degrees F

B(L), D(L) = lag-polynomials of the transfer function

[Table 7 and 8]

Table 7 presents the transfer function polynomials for ASHRAE roofs #22 and #25. Note that (16) implies:

$$(17) \quad (I + D(L))q(h)/A = B(L)t_{sa}(h) - t_i C$$

In the calculation of q(h)/A, initial conditions may be arbitrary provided the polynomial (I + D(L)) is invertible. This condition in turn requires that the characteristic equation

$$F(X) = 1 + d_1 X + d_2 X^2 + d_3 X^3$$

have roots which lie within the unit

circle in the complex plane. It may be verified that the roofs (and walls) considered in our analysis satisfy this property by direct solution of the cubic equation. The driving function  $t_{sa}(h)$  is assumed periodic (with a one day period) so that calculation of q(h)/A simply requires repeating successive 24-hour cycles in (16) to allow the effect of initial conditions to become negligible.

The hourly cycle for  $t_{sa}(h)$  will depend on roof and/or wall orientation and the daily cycle of outdoor temperatures. Outdoor temperature will itself follow a pattern determined by the average temperature and daily range of temperatures. Table 8 presents the percentages of the daily range used in the calculation of the daily temperature cycle.

ASHRAE (1977, 25.2, Table 2) provides sol-air temperatures for roofs and walls on a day with maximum temperature of 95°F and daily range of temperatures equal to 21°F. We assume that the difference between sol-air temperatures and outdoor temperatures remains constant independent of the daily mean and range of temperatures. Table 9 presents the sol-air temperature differences.

[Table 9 here]

To determine cooling load for varied materials and weather conditions we generate hourly heat flux values when average temperature varies between 70° and 110° (in increments of 5°), daily temperature range varies between 10° and 30° (in increments of 10°), and inside temperature varies between 68° and 84° (in increments of



2°). A convergence criteria for the heat flux profile is suggested by equation (17) evaluated at mean values:

$$(18) \quad (I + D(L))(\bar{q}/A) = B(L) \bar{t}_{sa} - t_i \quad C$$

which implies

$$(19) \quad (1 + d_1 + d_2 + d_3)(\bar{q}/A) = (b_0 + b_1 + b_2 + b_3) \bar{t}_{sa} - t_i \quad C$$

where  $\bar{q}$  and  $\bar{t}_{sa}$  are average values of  $q(h)$  and  $t_{sa}(h)$  respectively.

From (19) we see that:

$$(20) \quad \bar{q}/A = \frac{(b_0 + b_1 + b_2 + b_3)}{(d_0 + d_1 + d_2 + d_3)} \bar{t}_{sa} - \frac{C}{(d_0 + d_1 + d_2 + d_3)} t_i$$

It is easy to check that the coefficients used in the transfer

function method satisfy  $C = b_0 + b_1 + b_2 + b_3$  and that conductance  $U$  satisfies:

$$(21) \quad U = (b_0 + b_1 + b_2 + b_3) / (d_0 + d_1 + d_2 + d_3)$$

Thus convergence of the heat flux profile is accomplished when the sample average of a 24 hour predicted heat flux profile is approximately  $U(\bar{t}_{sa} - t_i)$ .

Having determined an estimated hourly heat flux profile we may use the transfer function method to determine hourly cooling load:

$$(22) \quad Q(h)/A = v_0 q(h)/A + v_1 q(h-1)/A - w_1 Q(h-1)/A$$

where

$Q(h)$  = cooling load at hour  $h$  (Btuh) (per sq. ft.)

$v_0, v_1, w_1$  = coefficients of the room transfer function.

The values of  $v_0, v_1$ , and  $w_1$  were determined under the assumptions of (1) low room air circulation; (2) 2" wood floor; and (3) frame exterior wall (ASHRAE, 1977, 25.35 - 25.36, Tables 30 and 31).

Iterating the stationary heat flux profile until convergence provides hourly cooling loads. Daily cooling load attributable to a surface is then approximately the sum over the day of positive cooling loads arising from that surface. This relationship is only approximate since the cooling load transfer function applies to the total of all sources of heat flux rather than the sum of each source cooling load.

To illustrate the calculation we present in Table 10 the daily profile of outdoor and sol-air temperatures as well as instantaneous heat flux and cooling loads for ASHRAE roof #22 on a day with mean 85°, range 21°, and inside temperature 75°.

[Table 10 and 11 here]

To summarize the relationship of cooling load to standard weather inputs we have calculated total and maximal cooling load temperature differences for 2 roofs and 4 walls over the ranges of temperatures specified above. A FORTRAN program which implements the thermal transfer function calculations is reproduced in Appendix B. Each test surface generates 243 observations which are used to estimate summary regression formulae. The regression results presented in Table 11 are used below in the calculation of daily

cooling load and cooling load capacity.

Noting the similarity in the regression results we assume that ASHRAE roof #22 and exterior wall #37 provide adequate approximations for cooling load determination. These relationships must be modified for differences in actual levels of thermal resistance.

Using the ceiling and roof resistances given in Table 2 and the definition of average heat flux, we can calculate an effective cooling resistance for the combined ceiling and roof in the case of a pitched roof. It is necessary to account for the effective resistance contributed by natural ventilation of the attic. Assume the ASHRAE (1977, 22.23, Table 6 and 24.2) design standard of 0.1 cu.ft. per minute per square foot of ceiling area for ventilation, assume the effective cross-section of the roof for solar radiation equals the square feet of ceiling, and neglect the effect of radiation on attic walls. Then thermal equilibrium evaluated at mean values requires:

$$(23) \quad \frac{A_c}{R_I} (\bar{t}_{sa} - t) + \left( \frac{A_I}{R_I} + \frac{A_w}{R_w} \right) (t - t_a) + (0.018)(.1)(60)A_c(t - t_a) = \frac{A_c}{R_c}(t_a - t_i)$$

where  $\bar{t}_{sa}$  is average sol-air temperature,  $t_a$  is attic temperature, and  $t$  is daily mean temperature. Then

$$(24) \quad t_a - t_i = \frac{\frac{A_c}{R_I} (\bar{t}_{sa} - t) + \left( \frac{A_I}{R_I} + \frac{A_w}{R_w} + 0.108A_c \right) (t - t_i)}{\frac{A_c}{R_c} + \frac{A_I}{R_I} + \frac{A_w}{R_w} + 0.108A_c}$$

and net ceiling heat flux is

$$(25) \quad \bar{q}/A_c = \frac{\frac{1}{R_I} (\bar{t}_{sa} - t) + \left( \frac{A_I}{R_I} + \frac{A_w}{R_w} + 0.108 \right) (t - t_i)}{1 + \left( \frac{A_I}{R_c} + \frac{A_w}{R_w} + 0.108 \right) \frac{A_c}{R_c}}$$

The values in Table 2 and the ratios  $A_I/A_c = 1.12$  and  $A_w/A_c = 0.08$  imply

$$(26) \quad \bar{q}/A_c = \frac{0.9310 + 0.0157I}{2.097 + 0.608I} \cdot (0.40485(\bar{t}_{sa} - t) + 0.59163(t - t_i))$$

We may then define

$$(27) \quad \bar{q}/A_c = U_1^{\text{effective}} \cdot (\bar{t}_{sa} - t_i) + U_2^{\text{effective}} \cdot (t - t_i)$$

where

$$(28) \quad U_1^{\text{effective}} = \frac{0.3769 + 0.00636I}{2.097 + 0.608I}$$

$$U_2^{\text{effective}} = \frac{0.17389 + 0.00293I}{2.097 + 0.608I}$$

From (22) and the values of  $v_0$ ,  $v_1$ , and  $v_1$  we note that average cooling load and average heat flux satisfy  $\bar{Q}/A_c = \bar{q}/A_c$ . If effective resistance in the attic is approximately uniform over the day then

$$(29) \quad \frac{\bar{Q}}{A_c} = U_1^{\text{effective}} \cdot \left[ \frac{\text{total cooling load}}{\text{temperature difference}} \right] + U_2^{\text{effective}} \cdot (t - t_i) \cdot 24.$$

For a flat roof we use the resistance values given in Table 2

to obtain:

$$(30) \quad \bar{Q}_{\text{flat}}/A_c = \left( \frac{0.937 + 0.1I}{3.96 + I} \right)$$

\*[total cooling load temperature difference].

[Table 12 here]

Typical values of the ceiling cooling load are given in Table 12 for  $t_i = 75^\circ\text{F}$ . For total cooling load temperature difference we use the regression estimates for roof #22:

$$(31) \quad \begin{aligned} & \text{[total cooling load temperature difference]} \\ & = 22.66 * (t - t_i) - 1.032 * t_r + 355.6 \end{aligned}$$

We assume the pitched roof formula (29) to be consistent with our assumptions in the heating load calculation.

[Table 12 here]

For design cooling load arising from window gains, sol-air temperature equivalents are given as a function of glazing, orientation, and covering. For windows with draperies, venetian blinds, or half-drawn roller shades, the formula (ASHRAE, 1977, 25.40, Table 36) is

$$(32) \quad [\text{Btuh/per ft}^2] = -a + bt_e$$

where  $b = 0.8$  for single glazed and  $b = 0.6$  for double glazed (stormed) windows,  $t_e = \text{design temperature}$ , and  $a$  has the following values:

| <u>Orientation</u> | <u>Single glazed</u> | <u>Double Glazed</u> | <u>Prop.</u> |
|--------------------|----------------------|----------------------|--------------|
| N                  | 52                   | 39                   | .10          |
| NE and NW          | 33                   | 21                   | .25          |
| E and W            | 16                   | 6                    | .25          |
| SE and SW          | 24                   | 13                   | .25          |
| S                  | 43                   | 30                   | .15          |
| average            | 30                   | 18                   |              |

The average above is calculated by assuming that square footage of window space in a characteristic dwelling is distributed in the proportions given in the last column.

For the purpose of cooling load calculations, we assume that the window gain effect is essentially uniform over the day so that

$$(33) \quad [\text{Btuh/per ft}^2] = -a + bt$$

The summer heat gain calculation is summarized in Tables 13 and 14 for daily cooling load and design capacity. The calculations differ in two ways. Wall gains and ceiling gains use total cooling load temperature difference in the daily cooling load calculation and use maximal cooling load temperature difference in the capacity calculation. The second difference concerns the treatment of mean versus design temperatures in the calculation of window and infiltration gains. Cooling load calculations use daily mean temperature under the assumption that relevant gains are uniform due to the thermal flywheel effect. Capacity calculations use design temperature to determine maximal load.

[Tables 13, 14, 15, and 16 here]

Tables 15 and 16 consider additional allowances for transmission losses in forced hot water and hot air systems.

### 3. BENCHMARK ENERGY CONSUMPTION LEVELS

Implicit in the thermal calculations for heating and cooling system design capacities are energy consumption levels under the benchmark behavioral assumptions used. These consumption levels can be calculated as a function of weather and time to give benchmark HVAC load curves, or can be summed over the season to give annual HVAC consumption. This section provides the formulae for these calculations.

Consider first the treatment of temperatures through time. When seasonal, monthly, or hourly temperatures are available, they can be used directly in the calculations described below. However, it is convenient for seasonal or annual calculations to use several simple approximations to temperature patterns over time. Let  $F(t)$  denote the cumulative distribution function of daily mean temperatures. Then average heating degree days per day over the year, to base temperature  $\tau$ , satisfies

$$(34) \quad HD_{\tau} = \int_{t_0}^{t_1} \max(0, \tau-t)F'(t)dt = \int_{t_0}^{\tau} F(t)dt,$$

where  $t_0$  and  $t_1$  are extreme possible temperatures. Similarly average cooling degree days per day to base temperature  $\tau$  satisfies

$$(35) \quad CD_{\tau} = \int_{t_0}^{t_1} \max(0, t-\tau)F'(t)dt = \int_{\tau}^{t_1} [1-F(t)]dt.$$

Approximate  $F(t)$  by a logistic CDF,

$$(36) \quad F(t) = (1 + e^{-a-bt})^{-1}.$$

Then

$$(37) \quad HD_{\tau} = \frac{1}{b} \ln(1 + e^{a+b\tau})$$

$$(38) \quad CD_{\tau} = \frac{1}{b} \ln(1 + e^{-a-b\tau}).$$

If  $HD_{65}$  and  $CD_{65}$  are given, then the parameters  $a$  and  $b$  can be determined by solving

$$(39) \quad 1 = e^{-b \cdot CD_{65}} + e^{-b \cdot HD_{65}}$$

$$(40) \quad a = b(HD_{65} - CD_{65} - 65)$$

Then  $HD_{\tau}$  and  $CD_{\tau}$  can be calculated for other bases. The value of  $b$  is quickly calculated by iteratively splitting the interval containing the solution, starting from

$$(41) \quad (\ln 2) / \max(HD_{65}, CD_{65}) \leq b \leq (\ln 2) / \min(CD_{65}, HD_{65})$$

Note that  $F(t)$  has mean  $-a/b$ , variance  $\pi^2/3b^2$ , and a 95 percent temperature range  $t_{high} - t_{low} = 2.9444/b$ . For the NIECS data, national average values are  $b = .1218$  and  $a = -6.870$ , implying annual mean temperature 56.4, standard deviation 14.9, and 95 percent temperature range 24.2, or  $32.2 \leq t \leq 80.6$ . These match the actual

distribution of mean daily temperatures for average U.S. locations quite well.

#### Heating Load Calculation

Space heat capacity as a function of ambient temperature and thermostat setting may be interpreted as a measure of average hourly consumption of delivered energy over a day with the specified temperatures. Therefore, benchmark consumption levels can be calculated from the capacity models by replacing design temperatures with the seasonal pattern of daily mean temperatures. Delivered energy per hour on a winter day with mean ambient temperature  $t$  and thermostat setting  $\tau$  is, from Table 6:

$$(42) \quad Q = [A_w U_w + A_c U_c + A_{win} U_{win}] (\tau - t) + A U_f (\tau - t) + \theta V [ .01035 + .00015 (\tau - t) ] (\tau - t) - \text{INTERNAL}$$

The notation is

$A_w, A_c, A_{win}$  wall, ceiling, and window areas

$U_w, U_c, U_{win}, U_f$  conductivities of wall, ceiling, window (average), and floor

$\theta$  window infiltration loss factor

$V$  volume

$t_g$  ground temperature, assumed constant throughout the winter

INTERNAL internal load from occupants and appliances.

In this formula, no attempt is made to correct for the effect of the

non-linearity in infiltration with temperature difference over the daily temperature cycle. For typical daily temperature ranges, this correction is negligible at the level of precision of the overall calculation.

Rewrite (42) in the form

$$(43) \quad Q = w_0 + w_1 (\tau - t) + w_2 (\tau - t)^2$$

with

$$w_0 = A U_c f (\tau - t_g) - \text{INTERNAL}$$

$$w_1 = A U_w + A U_c + A_{win} U_{win} + .01035 \theta V$$

$$w_2 = .00015 \theta V$$

Then the annual average delivered heat (Bth/hr.) is given by

$$(44) \quad Q_{\text{seas}} = \int_{t_0}^{\tau} \max(Q(t), 0) F'(t) dt.$$

If  $w_0 < 0$ , then there is a balance temperature  $t_b < \tau$  above which heat is not required:

$$t_b = \tau + \frac{w_1}{2w_2} [1 - (1 - 4w_2 w_1^{-2} \min(w_0, 0))^{.5}]$$

Then (44) can be rewritten

$$\begin{aligned} Q_{\text{seas}} &= \int_{t_0}^{t_b} (w_0' + w_1' (t_b - t) + w_2' (t_b - t)^2) F'(t) dt \\ &= w_0' F(t_b) + w_1' \int_{t_0}^{t_b} F(t) dt + 2w_2' \int_{t_0}^{t_b} (t_b - t) F(t) dt \end{aligned}$$

where

$$\begin{aligned} w'_0 &= w_0 + w_1(\tau-t_b) + w_2(\tau-t_b)^2 = 0 \\ w'_1 &= w_1 + 2w_2(\tau-t_b) \\ w'_2 &= w_2 \end{aligned}$$

using integration by parts,

$$\int_{t_0}^{t_b} (t_b-t)F'(t)dt = \int_{t_0}^{t_b} F(t)dt$$

$$\int_{t_0}^{t_b} (t_b-t)^2 F'(t)dt = 2 \int_{t_0}^{t_b} (t_b-t)F(t)dt$$

Using the approximation (36) to the seasonal temperature distribution

yields

$$(45) \quad F(\tau) = (1 + e^{-a-b\tau})^{-1}$$

$$(46) \quad \int_{t_0}^{\tau} F(t)dt = \frac{1}{b} \ln(1 + e^{a+bt\tau})$$

$$(47) \quad 2 \int_{t_0}^{\tau} (\tau-t)F(t)dt = \frac{2}{b} \int_{t_0}^{\tau} \ln(1 + e^{a+bt})dt = 2 \gamma(a+b\tau)/b^2$$

where

$$(48) \quad \gamma(\lambda) = \int_{-\infty}^{\lambda} \ln(1 + e^s)ds = \int_0^{\lambda} \ln(1+x) \frac{dx}{x}$$

Note that for  $0 \leq x \leq 1$ ,

$$(49) \quad \ln(1+x) = \sum_{k=1}^{\infty} \frac{(-1)^{k-1}}{k} x^k.$$

Also, with error at most  $10^{-5}$  for  $0 \leq x \leq 1$ ,

$$(50) \quad \frac{\ln(1+x)}{x} = a_1 + a_2x + a_3x^2 + a_4x^3 + a_5x^4$$

with

$$\begin{aligned} a_1 &= .99949556 & a_4 &= -.13606275 \\ a_2 &= .49190896 & a_5 &= .03215845 \\ a_3 &= .28947478 \end{aligned}$$

Then

(51)

$$\begin{aligned} \gamma(0) &= \int_0^1 \ln(1+x) \frac{dx}{x} = \sum_{k=1}^{\infty} \frac{(-1)^{k-1}}{k} \int_0^1 x^{k-1} dx \\ &= \sum_{k=1}^{\infty} (-1)^{k-1} / k^2 = \pi^2/12 \end{aligned}$$

and for  $\lambda < 0$ , with error at most  $10^{-5}$ ,

(52)

$$\begin{aligned} \gamma(\lambda) &= \int_0^1 \ln(1+x) \frac{dx}{x} - \int_{e^{\lambda}}^0 \ln(1+x) \frac{dx}{x} \\ &= \frac{\pi^2}{12} - \sum_{k=1}^5 a_k \int_{e^{\lambda}}^1 x^{k-1} dx \\ &= \frac{\pi^2}{12} + \sum_{k=1}^5 \frac{a_k}{k} (e^{k\lambda} - 1) \end{aligned}$$

For  $\lambda > 0$ , with error at most  $10^{-5}$ ,

(53)

$$\begin{aligned}
 \gamma(\lambda) &= \int_{-\infty}^0 \ln(1 + e^s) ds + \int_0^\lambda \ln(1 + e^s) ds \\
 &= \frac{\pi^2}{12} + \int_0^\lambda s ds + \int_0^\lambda \ln(1 + e^{-s}) ds \\
 &= \frac{\pi^2}{12} + \frac{\lambda^2}{2} + \int_{-\lambda}^1 \frac{1}{e^{-x}} \ln(1 + x) \frac{dx}{x} \\
 &= \frac{\pi^2}{12} + \frac{\lambda^2}{2} + \sum_{k=1}^{\infty} \frac{e^{\lambda k}}{k} (1 - e^{-k\lambda})
 \end{aligned}$$

Defining  $\alpha = \max(\lambda, 0)$ ,  $\beta = e^{-\alpha}$ ,  $\delta = e^\lambda$ , and  $c_k = a_k/k$ , all cases can be combined in the formula

(54)

$$\gamma(\lambda) = \frac{\pi^2}{12} + \frac{\alpha^2}{2} + \sum_{k=1}^{\infty} c_k \beta^k (\delta^{k-1})$$

We summarize the annual average delivered heat per hour as:

$$\begin{aligned}
 Q_{\text{seas}} &= w_0 / (1 + e^{-a-b\tau}) + w_1 / b \ln(1 + e^{a+b\tau}) \\
 &\quad + (2w_2/b^2) \gamma[a+b\tau] \quad \text{for } w_0 \geq 0 \text{ and} \\
 &\quad (w_1'/b) \ln(1 + e^{a+bt_b}) + (2w_2'/b^2) \gamma(a+bt_b) \quad \text{for } w_0 < 0
 \end{aligned}$$

#### Cooling Load Calculation

Delivered energy per hour on a summer day with mean ambient

temperature  $t$  and thermostat setting  $\tau$  is from Table 13:

$$Q = S_0 + S_1'(t - \tau) + S_2'(t - \tau)^2 \quad \text{where}$$

$$S_0 = [(A_w U_w)(362.1 - 0.9638 * t_f)]$$

$$+ A_{c1} U_{c1}^{\text{eff}} (355.6 - 1.032 * t_f) / 24$$

$$+ (A_{ws} + A_{wn} + A_{sdn})(0.8\tau - 30)$$

$$+ A_{sds} (0.6\tau - 18) + \text{INTERNAL}] * 1.25$$

$$S_1 = [(A_w U_w * 22.67 + A_{c1} U_{c1}^{\text{eff}} * 22.66 + A_w U_w^{\text{eff}} * 24) / 24$$

$$+ (A_{ws} + A_{wn} + A_{sdn})(0.8) + A_{sds}(0.6) + 0.00742 * V] * 1.25$$

$$S_2 = (0.00015 * V) * 1.25$$

(Notation is given in Tables 13 and 14.) Then annual average

delivered cooling (Btuh) is given by

$$(55) \quad Q_{\text{seas}}^{\text{AC}} = \int_{\tau}^{t_1} \max(Q(t), 0) F'(t) dt.$$

If  $S_0 < 0$ , then there is a balance temperature  $t_b > \tau$  below which cooling is not required:

$$t_b = \tau - \frac{S_1}{2S_2} [1 - (1 - 4S_2 S_1^{-2} \min(S_0, 0))^{.5}]$$

Then (55) can be rewritten

$$(56) \quad Q_{\text{seas}}^{\text{AC}} = \int_{t_b}^{t_1} [S_0' + S_1'(t - t_b) + S_2'(t - t_b)^2] F'(t) dt$$

$$\text{where } S_0' = S_0 + S_1(t_b - \tau) + S_2(t_b - \tau)^2 = 0$$

$$S_1' = S_1 + 2S_2(t_b - \tau)$$

$$S_2' = S_2$$

Note that we may relate the integral in (56) to the form evaluated in the heating load calculation since:

$$\begin{aligned} & \int_{t_o}^{t_1} [S'_o + S'_1(t - t_b) + S'_2(t - t_b)^2] F'(t) dt \\ &= \int_{t_o}^{t_1} [S'_o - S'_2(t_b - t) + S'_2(t_b - t)^2] F'(t) dt \\ & - \int_{t_o}^{t_b} [S'_o - S'_1(t_b - t) + S'_2(t_b - t)^2] F'(t) dt \\ &= S'_o - S'_1(t_b - \mu) + S'_2[(t_b - \mu)^2 + \text{var}(t)] \\ & - \int_{t_o}^{t_b} [S'_o - S'_1(t_b - t) + S'_2(t_b - t)^2] F'(t) dt \end{aligned}$$

where  $\mu = -a/b$  and  $\text{var}(t) = \pi^2/3b^2$ .

The cases  $S_o < 0$  and  $S_o \geq 0$  imply:

$$S'_o = \begin{cases} 0, & S_o < 0 \\ S_o, & S_o \geq 0 \end{cases}$$

$$S'_1 = \begin{cases} S_1 + 2S_2(t_b - \tau), & S_o < 0 \\ S_1, & S_o \geq 0 \end{cases}$$

$$S'_2 = S_2$$

Duct losses for air conditioning are ignored, so the expression for  $Q_{\text{seas}}^{\text{AC}}$  gives gross air conditioner output. For duct and pipe systems, additional furnace output is required to offset transmission losses.

These losses can be divided into a component due to conduction losses

from the delivery system and a component due to heat gains and losses of the delivery system components under cyclic operation. The first component is to a close approximation proportional to heat delivered, and the coefficient of proportionality can be obtained from the calculation of capacity requirements for non-central and central systems. Thus,

$$(57) \quad Q_D = Q_{\text{seas}} \cdot \text{SHEATD}/\text{SHEATN}$$

$$(58) \quad Q_P = Q_{\text{seas}} \cdot \text{SHEATP}/\text{SHEATN}$$

where SHEATN, SHEATD, SHEATP are capacities of non-central, duct, and pipe systems respectively, and  $Q_D, Q_P$  are seasonal furnace outputs net of cyclic losses.

Seasonal energy conversion efficiencies of heating equipment depend on climate, through cyclic heat loss, and on fuel. Empirical seasonal efficiencies of heating equipment, or coefficients of performance, can be obtained from ASHRAE. Distribution cyclic heat losses are small relative to the furnace losses and will be ignored. The coefficients for gas, oil, electric resistance (baseboard), and heat pump are respectively

$$(59) \quad \text{COP}_G = .46 + .0146 \cdot \text{HD}_{65}$$

$$(60) \quad \text{COP}_O = .404 + .0130 \cdot \text{HD}_{65}$$

$$(61) \quad \text{COP}_E = 1.0$$

$$(62) \quad \text{COP}_{\text{HP}} = 1.94 + \frac{2.85}{\text{HD}_{65}} - .046 \text{HD}_{65} - .081 \text{CD}_{65}$$



The efficiency loss in central electric resistance units is relatively small, and is ignored. The approximation of the heat pump COP is discussed in Appendix A.

The coefficient of performance for an air conditioner is approximately

$$(63) \quad \text{COP}_{AC} = 3.44 + \frac{1.23}{\text{HD}_{65}} + \frac{1.23}{\text{CD}_{65}} - .036 \text{Hd}_{65} - .038 \text{CD}_{65}.$$

This approximation is developed in Appendix A.

The base technological calculations of seasonal energy consumption can now be summarized. Take, for example, a gas-fired forced air system. Energy input in MB over the year is  $8.76 Q_D / \text{COP}_G$ .

Similarly, an electric baseboard system requires an input of  $8.76^* Q_{\text{seas}} / \text{COP}_E$ , while an air conditioner requires  $8.76 Q_{\text{seas}}^{\text{AC}} / \text{COP}_{AC}$ . Multiplied by marginal fuel prices, these figures give the technologically based operating costs of alternative systems.

These calculations are carried out for specified winter and summer thermostat settings. Repeating the calculations for a one degree change in the thermostat setting and taking differences yields an overall calculation of the seasonal price of comfort. In carrying out these "price" calculations, we ignore the very small change in  $w_0$  induced by the thermostat change.

The seasonal calculations just completed can also be applied to time periods within a season, such as billing periods. The temperature distribution  $F(t)$  should then be that applicable for the period in question. The logistic approximation used for the seasonal

temperature distribution requires some modification for use in billing periods.

A more accurate temperature distribution can be obtained using degree-day calculations for alternative bases. Let  $H_v$ ,  $C_v$  denote heating and cooling degree-days (per day) to base  $v$ ; then

$$\begin{aligned} H_v &= \int_{-\infty}^v (v-t)F'(t) = \frac{1}{b} \ln(1+e^{b(v-\mu)}) = v-\mu + \frac{1}{b} \ln(1+e^{-b(v-\mu)}) \\ &= \max(0, v-\mu) + \frac{1}{b} \ln(1+e^{-b|v-\mu|}) \end{aligned}$$

$$\begin{aligned} C_v &= \int_v^{\infty} (t-v)F'(t)dt = \frac{1}{b} \ln(1+e^{-b(v-\mu)}) \\ &= \max(0, \mu-v) + \frac{1}{b} \ln(1+e^{-b|v-\mu|}) \end{aligned}$$

Note that  $C_v - H_v = \int_{-\infty}^{+\infty} (t-v)F'(t)dt = \mu-v$ . For a base  $\tau \geq v$ , one has

$$\begin{aligned} (\tau-v)F(v) &\leq H_{\tau} - H_v = \int_v^{\tau} F(t)dt \leq (\tau-v)F(\tau) \\ (\tau-v)[1-F(\tau)] &\leq C_v - C_{\tau} = \int_v^{\tau} [1-F(t)]dt \leq (\tau-v)[1-F(v)]. \end{aligned}$$

Given  $C_v$ ,  $H_{\tau}$  for  $\tau \geq v$ , consider the function

$$G(b) = (1-e^{-\tau}) \cdot (1-e^{-v})^{-b} \cdot e^{-bC_v} \cdot b(v-\tau+H_{\tau}+C_v) - 1,$$

derived by eliminating  $\mu$  from the equations for  $H_{\tau}$  and  $C_v$ . This function has  $G(0) < 0$  and  $G'(0) > 0$ . If  $G(1) > 1$ , then a unique solution can be obtained by successive interpolation, with the consistent value

$$\mu = v + C_v + \frac{1}{b} \ln(1-e^{-bC_v}).$$

On the other hand, if  $G(1) < 1$ , as will be the case if  $C_v$  or  $H_r$  are sufficiently small, then the temperature distribution has little mass in the range of  $v$  and  $\tau$ , where balance temperatures are attained. Outside this range, marginal heating and cooling requirements are linear in the temperature differential, except for small stack and ground effects in heating which can be neglected. Hence, in this case it is a good approximation to assume that mean temperature for the period under study is concentrated at  $\mu = v + C_v - H_v$ , and set  $Q_{AC} = Q(\mu)$ , with an analogous procedure for heating.

#### 4. CHARACTERISTICS OF SINGLE-FAMILY DWELLINGS

The thermal calculations in the preceding sections require information on wall, window, and ceiling areas, volume, and feet of pipe of ducting for central heating systems. The NIECS/PNW data do not provide this level of detail, but do provide (incomplete) information on square footage, and numbers of rooms, floors, and windows. To fill this gap, we have sampled seven typical dwellings, and from their detailed characteristics obtained relationships between the required variables and those observed in NIECS/PNW. Table 17 lists the measured characteristics. Figures 3-17 give floor plans and elevations of these dwellings.

A series of regressions on these seven observations provide a link from variables in NIECS to structural characteristics, as follows:

$$(64) \quad \begin{bmatrix} \text{Wall area} \\ \text{incl. windows} \end{bmatrix} \ln = 2.96 + 0.92 \ln [\text{no. floors}] + 0.57 \ln [\text{sq.ft. ceiling}] \\ (0.68) (0.14) \quad \sigma^2 = 19 \quad (0.10) \quad \bar{R}^2 = 0.99$$

(65)

$$\ln [\text{sq. feet ceiling}] = -0.04 + 0.815 \ln [\text{no. floors}] + 1.006 \ln [\text{sq. feet}] \\ (0.45) (0.108) \quad \sigma^2 = 0.007 \quad (0.064) \quad \bar{R}^2 = 0.996$$

(66)

$$\ln [\text{Volume}] = 2.19 + 0.80 \ln [\text{no. floors}] + 0.98 \ln [\text{sq. ft. ceiling}] \\ (0.58) (0.12) \quad \sigma^2 = 0.01 \quad (0.08) \quad \bar{R}^2 = 0.98$$

Average area per picture window = 38.9; average area per other window = 8.7; average area per sliding glass door = 52.5.

(67)

$$\begin{bmatrix} \text{Average roof ft}^2 \text{ per} \\ \text{ceiling ft}^2 \end{bmatrix} = 1.12 \quad \sigma^2 = 0.15$$

(68)

$$\begin{bmatrix} \text{Average attic wall ft}^2 \\ \text{per ceiling ft}^2 \end{bmatrix} = 0.08 \quad \sigma^2 = 0.07$$

The next group of results relate heating system characteristics to measured quantities.

(69)

$$\text{No. registers} = 2.55 + 1.07 [\text{rooms}] + 0.003 [\text{sq. ft.}] \\ (3.20) (0.72) \quad (0.001) \quad \sigma^2 = 4.52 \quad \bar{R}^2 = 0.97$$

(70)

$$\text{Feet of duct} = 3.89 (\text{no. registers}) + 0.067 (\text{sq. ft.}) \\ (2.08) \quad (0.018) \quad \sigma^2 = 427 \quad \bar{R}^2 = 0.99$$

(71)

$$\begin{aligned} \ell_n \text{ [Feet of hot water pipe]} &= -1.95 + 1.03 \ell_n \text{ [sq. ft.]} \\ &\quad (0.71) \quad (0.10) \\ \sigma^2 &= 0.02 \quad \bar{R}^2 = 0.99 \end{aligned}$$

(72)

$$\begin{aligned} \text{[no. radiators]} &= 1.04 \text{ [no. rooms]} + 0.0014 \text{ [sq. ft.]} \\ &\quad (0.34) \quad (0.0013) \\ \sigma^2 &= 364 \quad \bar{R}^2 = 0.96 \end{aligned}$$

We use these equations to estimate structural characteristics of the NIECS/PNW dwellings, expect that for hot water systems we assume baseboard radiators rather than conventional radiators, and use the ASHRAE design standard that one linear foot of baseboard radiator is required per 645 Btuh designed capacity of the heating system.

The proportion of window area to total wall area in the typical houses ranges from 0.04 to 0.27. We shall assume that for the NIECS/PNW houses this proportion is bounded between 0.03 and 0.7, and use these bounds if the regression predicts a more extreme value.

The NIECS/PNW data reports square footage of the dwelling as estimated by the respondent. However, there is evidence in the NIECS data that these responses are subject to error. Therefore, we regress reported square footage on several variables which we believe to be measured more accurately, and use the predicted values from this equation in our analysis. The method was to remove the accurately measured square footage of the largest room from the reported total square feet, predict the square footage of the remainder of the dwelling, and then add back in the largest room square footage. The

estimated equation is given in Table 18. Some average characteristics of the NIECS/PNW dwellings are given in Table 19.

[Table 17, 18, and 19 here]

Typical house 7 is taken from ASHRAE (1977, 24.7-24.9), which calculates its heating system capacity to be 114 MBH for a Syracuse, N.Y. location with a design temperature of -10 degrees F when there is no wall or attic insulation. The thermal program developed here, using the same inputs as are provided for the NIECS/PNW households, and the design temperature for this location, yields a capacity of 131 MBH. The thermal program yields a central AC capacity of 65 MBH for this house under the Syracuse summer design temperature of 90 with a daily range of 20. The corresponding ASHRAE calculation using actual characteristics of the shell gives an AC capacity of 44 MBH.

The usage calculations in Section 3 applied to the NIECS/PNW households imply the coefficients of performance and usages in Table 20. Note that these are averages over all dwellings of the performance of the specified equipment if it were installed in every dwelling, not the performance of equipment actually installed.

To test the sensitivity of the thermal model, we have calculated capacity and usage under two alternative levels of building thermal characteristics. The first alternative is an uninsulated dwelling without storm windows or double glazing. The second alternative is the ASHRAE 90-75 voluntary thermal standard for new construction. Under this standard, all windows are storm or double

glazed, walls and ceiling are insulated, heating and cooling system capacities are reduced, and tight construction is used to reduce infiltration. The ASHRAE standards vary by region, as follows:

|  | Region 1<br>Northeast | Region 2<br>Northcentral | Region 3<br>South | Region 4<br>West |
|--|-----------------------|--------------------------|-------------------|------------------|
| R-value ceiling insulation                     | 17.14                 | 17.14                    | 19.5              | 19.5             |
| R-value wall insulation                        | 15.44                 | 15.44                    | 9.45              | 9.45             |
| Reduction in heating design temp. differential | 12                    | 14                       | 12                | 14               |
| Reduction in cooling design temp. differential | 7                     | 6                        | 6                 | 5                |

[Table 20 and 21 here]

Table 21 summarizes the differences in capacities and energy consumption under these alternatives, for dwellings built since 1970. Note first that observed thermal performance achieves a substantial fraction of that achievable under the ASHRAE 90-75 standards; for example, for electric resistance heat, 81 percent of the energy conservation achievable by the ASHRAE standard compared to the uninsulated case is in fact achieved. However, substantial conservation is still attainable from the ASHRAE standard: for electric resistance heating, electricity consumption could have been reduced 19 percent relative to actual construction, with comparable reductions for other heating systems. The following calculation gives

the sample average capital costs of the thermal improvements and heating system for the observed construction since 1970 and for the ASHRAE standards, in 1981 prices:

|                                      | Observed<br>Dwellings | ASHRAE<br>Standard |
|--------------------------------------|-----------------------|--------------------|
| (1) Insulation cost                  | \$ 1,105.00           | \$1,276.00         |
| (2) Storm/Double glazing cost        | 315.00                | 457.00             |
| (3) Electric resistance capital cost | 897.00                | 709.00             |
| (4) (1) + (2) + (3)                  | \$ 2,317.00           | \$2,442.00         |
| (5) Gas forced air capital cost      | 1,036.00              | 1,019.00           |
| (6) Total (1) + (2) + (5)            | \$ 2,456.00           | \$2,752.00         |
| (7) Heat pump capital cost           | 4,308.00              | 2,801.00           |
| (8) Total (1) + (2) + (7)            | \$ 5,728.00           | \$4,534.00         |

These costs are taken from an equipment and construction costing program which is described in Cowing-Dubin-McFadden (1981). Note first that for heat pumps, the savings in equipment cost from reduced design capacity requirements and down-sizing more than offset the added cost of meeting the ASHRAE standards, even before the reduction in life cycle costs from reduced operating cost is taken into account. On the other hand, for gas forced air systems, there is an average increment in capital cost of \$296.00 required to meet the ASHRAE standards and reduce energy consumption by 32,100,000 Btu/year. At an average gas price of \$3.54 per 10<sup>6</sup> Btu, the operating cost savings is approximately \$114/year. Ignoring the effects of finite dwelling and equipment life, the real rate of return to adoption of the ASHRAE standards is 39 percent. Since this rate exceeds the real interest

rate to most non-credit-constrained consumers, it appears that improvement of thermal performance to the ASHARE standard should in fact benefit most consumers and be adopted voluntarily if they are fully appraised of the life cycle costs. This conclusion is subject to a caveat that a comparison is being made between actual and standards thermal levels for gas forced air heat, irrespective of the type of heat actually chosen. In fact, actual insulation levels are higher for electrically heated homes than for other fuels, as should be expected when thermal performance is adjusted in the direction of minimizing life cycle cost. This will tend to lead the preceding calculation to overstate the benefit attainable from imposing standards on electrically heated homes, and understate the benefit for other fuels. A more careful behavioral analysis of joint choice of heating fuel and thermal shell performance will be reported separately.

We conclude this report with a few comments on the uses and limitations of the thermal and costing models we have developed. First, it was not our objective to construct a detailed thermal model suitable for engineering new dwellings or carrying out energy audits for existing structures, and it would be a mistake to try to use the model for these purposes. The data requirements for such modeling are greater by an order of magnitude than the structural information in the NIECS or PNW data set. Second, it was our objective to utilize the data available from NIECS/PNW to approximate thermal requirements across a statistical sample in a way which explained most of the technologically determined scale of capacity and usage. The outputs

of the thermal model can then be used as inputs to an analysis of choice behavior, with econometric models explaining behavioral deviations from the engineering base.

The thermal and costing models we have developed appear to give a much more satisfactory basis for pricing out alternative HVAC systems than one could achieve using simple formulae for cost per square foot or cost per square foot-degree day. Further, the implied energy consumption under alternative weather conditions should be adequate for indexing the expected operating costs of alternative systems.

We see several advantages to combining the simple engineering thermal model we have developed and a behavioral analysis of consumer response. We can avoid the problems of a pure econometric approach which "burns degrees of freedom" to explain usage variations which are technically determined. We also avoid a pure engineering model which fails to account for economic behavioral response. In addition, the use of the thermal model as an input to the behavioral analysis allows one to calculate readily the technical and behavioral response of households to energy policies. This permits logically consistent and complete method for translating policy which effects voluntary or mandatory building standards into technical consequences in terms of capital cost and energy requirements, modified by consumer's behavioral responses to these consequences.

APPENDIX A: Seasonal Heating and Cooling Efficiencies of Air Conditioners and Heat Pumps

The coefficient of performance of air conditioners and heat pumps in the cooling mode from ASHRAE graphs, is approximately

$$(A.1) \quad \text{COP} = 1 / (.235 + .0051 (t - \tau)).$$

where  $t$  is daily mean ambient temperatures and  $\tau$  is thermostat setting. As a basis for a seasonal efficiency calculation, consider a typical residence in which the average cooling load over a day in the cooling season (defined by  $t > \tau = 75$ ) is  $17900 + 791 (t - 75)$  Btuh.

The energy output per hour for cooling, averaged over the year, is

$$(A.2) \quad Q_{\text{out}} = \int_{75}^t \text{up} [17900 + 791 (t - 75)] F'(t) dt,$$

where  $F(t)$  is the distribution of daily mean temperatures.

The corresponding energy input is

$$(A.3) \quad Q_{\text{in}} = \int_{75}^t \text{up} [17900 + 791 (t - 75)] \frac{F'(t)}{\text{COP}} dt \\ = \int_{75}^t \text{up} [17900 + 791 (t - 75)] \cdot [.235 + .0051 (t - 75)] F'(t) dt$$

Using the approximation to the annual distribution of mean temperatures given by (36), we compute these expressions at a representative location in each of the seven AIA weather zones in the U.S., and compute the seasonal efficiency  $Q_{\text{out}}/Q_{\text{in}}$ . These values are then fitted empirically as a function of daily average heating and

cooling degree days. The empirical function is accurate to within one percent.

In the heating mode, the COP of heat pumps is approximately constant, with value 3.25, over the range where the unit is operational. However, below an ambient mean temperature of 40 degrees, build-up of frost on the outdoor coil prevents operation, and backup heating is required. The usual system has electric resistance heating for extreme weather. We analyze this system. This method could be applied with obvious modifications to oil or gas backup units.

The energy output per hour for heating, averaged over the year, is

$$(A.4) \quad Q_{\text{out}} = \int_{t_{\text{low}}}^{\tau} [800(\tau - t) - 1600] F'(t) dt,$$

where  $\tau$  is the thermostat setting and  $800(\tau - t) - 1600$  is the average heating load in Btuh over a day in the heating season (defined by  $t < \tau$ ). If the input for days with  $t < 40$  is provided by resistance heating, then

$$(A.5) \quad Q_{\text{in}} = \int_{t_{\text{low}}}^{\tau} [800(\tau - t) - 1600] F'(t) dt + \frac{1}{3.25} \int_{40}^{\tau} [800(\tau - t) - 1600] F'(t) dt \\ = \frac{1}{3.25} \{ 2.25 \int_{t_{\text{low}}}^{40} [800(\tau - t) - 1600] F'(t) dt + \int_{40}^{\tau} [800(\tau - t) - 1600] F'(t) dt \}$$

we compute  $Q_{\text{out}}/Q_{\text{in}}$  at representative locations in the seven AIA weather zones, using the approximation (36) to the temperature

distribution. The resulting efficiencies are then approximated empirically as functions of heating and cooling degrees per day. The reported efficiencies are for a thermostat setting of 65 degrees. The empirical formula is accurate to within 4 percent.

#### APPENDIX B: Computer Routines

This appendix lists the computer routines used to process NIECS/PNW data, provide the structural characteristics of dwellings in the sample, compute equipment capacities and energy usage, and cost out alternative HVAC systems. These programs are written in QUAIL, a statistical language for econometric analysis of discrete data. Experienced programmers should have no difficulty rewriting these programs in SAS, TSP, SPSS or FORTRAN if QUAIL is not available at their installation. The computations carried out by the programs are summarized as follows:

1. Fortran program to determine daily cooling load and maximum cooling load using transfer function method.
2. Pacific Northwest Data: Thermal programs HVAC11, HVAC125, HVAC13.
3. NIECS Data: Thermal Programs HVAC11, HVAC12, HVAC125, HVAC13.

HVAC11—Recodes selected NIECS/PNW variables, fills in missing data on inches of attic insulation and square footage from regression on complete observations (NIECS only), estimates window, wall, and ceiling areas and volume from regressions on typical houses, and estimates lengths of pipe for hot water systems, duct for forced air systems, and vent chimney.

HVAC12—Sets up alternative thermal standards calculations. (NIECS only).

HVAC125—Approximates the annual temperature distribution using degree-day data, by an iterative method.

HVAC13—Contains the thermal model used to calculate equipment capacity and energy usage. Overall resistances of thermal shell components are calculated. Then coefficients of the quadratic formulae for heat gain and loss under design conditions are

calculated. These coefficients and climatological data are used to calculate design capacities, coefficients of performance of alternative systems, and energy consumption. Repeating the calculation for alternative thermostat settings permits calculation of the energy cost of comfort.

[Computer Routines here]

```

C      DIMENSION TSA(24),HQ(24),CL(24),DR(24),T(24),TSAD(24)
C
C      ATTRIBUTES OF TRANSFER FUNCTION FOR COOLING LOAD
V0= 0.703
V1= -0.583
W1= -0.88
C
C      READ IN VALUES FOR PERCENTAGE OF THE DAILY RANGE
DO 4 I=1,24
  READ(9,100) DR(I)
  FORMAT(F15.8)
C
C      READ IN TEMPERATURE DIFFERENCES (SOL-AIR - OUTSIDE):
DO 5 I=1,24
  READ(9,100) TSAD(I)
C
C      READ IN ASHRAE MATERIAL PROPERTIES
READ(8,100) B0
READ(8,100) B1
READ(8,100) B2
READ(8,100) B3
READ(8,100) D0
READ(8,100) D1
READ(8,100) D2
READ(8,100) D3
READ(8,100) C
READ(8,100) U
READ(8,100) XINSUL
C
C      SET COUNTER TO ZERO
JJ=0
C
C      TMEAN=85.0
C      TRANGE=21.0
C      TRC=75.0
C      ADVANCE COUNTER
JJ=JJ+1
C
C      CREATE DAILY TEMPERATURE PROFILE USING MEAN AND RANGE
C      TO THE DAILY TEMPERATURE PROFILE
DO 11 I=1,24
  T(I)=TMEAN + (0.5-(DR(I)/100.0))*TRANGE
  TSA(I)=TSAD(I)+T(I)
CONTINUE
C
C      SET INITIAL CONDITIONS
HQ(24)=0.0
HQ(23)=0.0
HQ(22)=0.0
C
C      SET UP 24 HOUR CLOCK WITH HOUR ZERO SET TO 24; REPEAT
DO 10 I=1,96
  II=MOD(I-0+24,24)
  III=MOD(I-1+24,24)
  II2=MOD(I-2+24,24)
  II3=MOD(I-3+24,24)
  IF (I+EQ.0) II0=24

```



```

10      IF (I11.EQ.5) I11=24
C       IF (I12.EQ.0) I12=24
C       IF (I13.EQ.0) I13=24
C       HQ(I10)=R0*ISA(I10) + B1*ISA(I11) + B2*ISA(I12) + B3*ISA(I13)
C       - D1*HQ(I11) - D2*HQ(I12) - D3*HQ(I13) -C*TRC
C       CONTINUE
C
C     CHECK FOR CONVERGENCE OF HEAT FLUX PROFILE BY COMPARING
C     ACTUAL AVERAGE HEAT FLUX WITH THE AVERAGE OF HOURLY
C     PREDICTED HEAT FLUX
C     AVGTSA=0.0
C     AVGHQ=0.0
C     DO 1 I=1,24
C       AVGTSA=ISA(I) + AVGTSA
C       AVGHQ =HQ(I) + AVGHQ
C     AVGTSA=UX*(AVGTSA/24.0)-TRC)
C     AVGHQ=AVGHQ/24.0
C
C     CALCULATE COOLING LOAD USING TRANSFER FUNCTION METHOD
C     CL(24)=0.0
C     DO 20 I=1,96
C       I1=MOD(I-1+24,24)
C       I2=MOD(I-1+24,24)
C       IF (I1.EQ.0) I1=24
C       IF (I2.EQ.0) I2=24
C     CL(I0)=V0*HQ(I1)+V1*HQ(I2)+V1*HQ(I1)-W1*CL(I1)
C
C     DO 30 I=1,24
C     CL(I)=CL(I)/U
C
C     NOW COMPUTE TOTAL COOL LOAD TEMP DIFF FOR THE DAY
C     COOL=0.0
C     DO 2000 I=1,24
C     COOL=COOL + MAX(CL(I),0.0)
C     CONTINUE
C     AT=0.0
C     ATSD=0.0
C     ATSA=0.0
C     ACL=0.0
C     AHQ=0.0
C     DO 1000 I=1,24
C     WRITE(10,2010) I,T(I),TSAD(I),TSA(I),CL(I),Hq(I)
C     AT=AT+T(I)/24.0
C     ATSD=ATSD+TSAD(I)/24.0
C     ATSA=ATSA+TSA(I)/24.0
C     ACL=ACL+CL(I)/24.0
C     AHQ=AHQ+HQ(I)/24.0
C     CONTINUE
C     FORMAT(I5,5(F15.2))
C     WRITE(10,2010)
C     WRITE(10,2010) JJ,AT,ATSD,ATSA,ACL,AHQ
C     WRITE(10,2010)
C     WRITE(10,2010) JJ,AVGTSA,AVGHQ,COOL
C     END
1000
2010

```

```

0.0012
0.0180
0.0150
0.0011
1.0000
-0.8098
0.1357
-0.0007
0.0353
0.109
2.0000
0.0043
0.0385
0.0202
0.0007
1.0000
-0.7314
0.1061
-0.0003
0.0637
0.170
1.0000
0.00509
0.02664
0.00836
0.00010
1.00000
-0.59602
0.08757
-0.0002
0.06001
0.081
3.00000
0.00984
0.03810
0.00869
0.00003
1.00000
-0.57344
0.08074
0.00000
0.05666
0.112
2.00000
0.02069
0.06369
0.01131
0.00001
1.00000
-0.53187
0.06834
0.00000
0.09570
0.178
1.00000
0.07874
0.18185
0.02157
0.00001
1.00000
-0.37759
0.02246
0.00000
0.28217
0.438
0.00000

```

ATTRIBUTES OF ASHRAE ROOF #22

ATTRIBUTES OF ASHRAE ROOF #25

ATTRIBUTES OF ASHRAE WALL #36

ATTRIBUTES OF ASHRAE WALL #37

ATTRIBUTES OF ASHRAE WALL #38

ATTRIBUTES OF ASHRAE WALL #39

```

B0
B1
B2
B3
D0
D1
D2
D3
C
U
INSULATION

```

```

/*HVAC11*/
/*SETS UP EXTRACT OF SINGLE FAMILY OWNER OCCUPIED, DETACHED DWELLINGS*/
/*RECORDS SELECTED VARIABLES, CALCULATES FITTED VALUES*/
/*MODIFIED BY JEFFREY DUBIN JANUARY,1983; VACS VERSION*/
STORE CORE(100000) ECS(6000000)$
PROGRAM NA(HVAC11) TA(BONN,NEW) LB(MASTER)$
LIST CORE(OFF) TIME(OFF) TTY$
SMPL INCL(4030)$
/*CHANGES ADDED ON FEBRUARY 1,1983 */
B=(SEQNUM.EQ.280)$
SUNDES=88 B0(B) RPS WINTDES=26 B0(B) RPS RANGE=21 B0(B) RPS
B=(SEQNUM.EQ.728)$
SUNDES=94 B0(B) RPS WINTDES=21 B0(B) RPS RANGE=21 B0(B) RPS
B=(SEQNUM.EQ.1265) .OR. (SEQNUM.EQ.1268)$
SUNDES=91 B0(B) RPS WINTDES=13 B0(B) RPS RANGE=28 B0(B) RPS
B=(SEQNUM.EQ.2113)$
SUNDES=96 B0(B) RPS WINTDES= 6 B0(B) RPS RANGE=32 B0(B) RPS
B=(SEQNUM.EQ.2678)$
SUNDES=79 B0(B) RPS WINTDES=28 B0(B) RPS RANGE=19 B0(B) RPS
B=(SEQNUM.EQ.2871)$
SUNDES=93 B0(B) RPS WINTDES= 4 B0(B) RPS RANGE=31 B0(B) RPS
B=(SEQNUM.GE.1298).AND.(SEQNUM.LE.1309)$
SUNDES=87 B0(B) RPS
/*END OF LATEST CHANGES*/
B=(SEQNUM.EQ.148).OR.(SEQNUM.EQ.489)$
WINTDES=26 B0(B) RPS
RANGE=21 B0(B) RPS
B=(SEQNUM.GE.682).AND.(SEQNUM.LE.745)).OR.
((SEQNUM.GE.891).AND.(SEQNUM.LE.1257)).OR.
((SEQNUM.GE.1280).AND.(SEQNUM.LE.1309))$
MEANSINST=102 B0(B) RPS
B=(SEQNUM.GE.746).AND.(SEQNUM.LE.822)).OR.
((SEQNUM.GE.2006).AND.(SEQNUM.LE.2559))$
MEANSMAT=103 B0(B) RPS
B=(SEQNUM.GE.453).AND.(SEQNUM.LE.890)).OR.
((SEQNUM.GE.3222).AND.(SEQNUM.LE.3753))$
MEANSMAT=100 B0(B) RPS
B=(SEQNUM.GE.1258).AND.(SEQNUM.LE.1279)$
MEANSMAT=101 B0(B) RPS
MEANSINST=111 B0(B) RPS
B=(SEQNUM.GE.1310).AND.(SEQNUM.LE.1969)).OR.
((SEQNUM.GE.2151).AND.(SEQNUM.LE.2261))$
MEANSMAT=101 B0(B) RPS
MEANSINST=114 B0(B) RPS
B=(SEQNUM.EQ.1591).OR.(SEQNUM.EQ.1728)$
WINTDES=28 B0(B) RPS
SUNDES=79 B0(B) RPS
RANGE=19 B0(B) RPS
B=(SEQNUM.GE.1970).AND.(SEQNUM.LE.2150)).OR.
((SEQNUM.GE.2606).AND.(SEQNUM.LE.2672)).OR.
((SEQNUM.GE.2718).AND.(SEQNUM.LE.2738)).OR.
((SEQNUM.GE.3164).AND.(SEQNUM.LE.3193)).OR.
((SEQNUM.GE.3754).AND.(SEQNUM.LE.3866))$
MEANSMAT=103 B0(B) RPS
MEANSINST=105 B0(B) RPS
B=(SEQNUM.GE.2262).AND.(SEQNUM.LE.2505)).OR.
((SEQNUM.GE.2560).AND.(SEQNUM.LE.2605)).OR.
((SEQNUM.GE.2673).AND.(SEQNUM.LE.2717)).OR.

```

```

((SEQNUM.GE.2739).AND.(SEQNUM.LE.2748))$
MEANSMAT=101 B0(B) RPS
B=(SEQNUM.GE.2749).AND.(SEQNUM.LE.3163)).OR.
((SEQNUM.GE.3896).AND.(SEQNUM.LE.4030))$
MEANSINST=96 B0(B) RPS
B=(SEQNUM.EQ.3562)$
WINTDES=7 B0(B) RPS
SUNDES=89 B0(B) RPS
RANGE=36 B0(B) RPS
RECODE VI(WINTDES) VO(M99T) CI(999) CO(MD)$
RECODE VI(SUMDES) VO(SDDB) CI(0,999) CO(MD,MD)$
RECODE VI(RANGE) VO(SODR) CI(99) CO(MD)$
RECODE VI(NSHUR) VO(BATHS) CI(8,9) CO(MD,MD)$
RECODE VI(ARCEL) CI(0,9999) CO(MD,MD)$
RECODE VI(SPACE) CI(99998,99999) CO(MD,MD)$
RECODE VI(YRBLT) VO(YEARBT) CI(1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 98 99)
CO(0 5 15 25 35 45 55 62 67 72 75 76 77 78 79 MD MD)$
RECODE VI(INCOME) VO(INCOME) CI( 1 2 3 4 5 6 7 8 9 10 11 12 13 14 97 98 99)
CO( 1 5 4 6 5 9 11 13 5 17 5 22 5 27 5 32 5 37 5 42 5 47 5 60 MD MD MD)$
RECODE VI(EXTINSI) VO(HINMALL) CI(1 2 3 4 5 9) CO(.656 .656 1 1 .656)$
RECODE VI(NUMFURS) VO(RHSLDREM) CI(98,99) CO(MD,MD)$
RECODE VI(NDRSU) VO(NDDOORS) CI(8,9) CO(MD,MD)$
RECODE VI(NUMFLRS) CI(98,99) CO(MD,MD)$
FLOORS=((NUMFLRS.EQ.3) .OR. (NUMFLRS.EQ.1)))*1*(NUMFLRS.EQ.4)*1.5
+(NUMFLRS.EQ.5) .OR. (NUMFLRS.EQ.2))*2+
(NUMFLRS.EQ.6)*2.5*(NUMFLRS.GE.7))*3$
RECODE VI(NUMITS) VO(NROOMS) CI(98,99) CO(MD,MD)$
LROOMS=LOG(NROOMS)$
COVA VA(OHNR) PR(NO MEA)$ COVA VA(DWELL) PR(NO MEA)$
COVA VA(TYPAC) PR(NO MEA)$
BOOLL=(OHNR.EQ.1).AND.(DWELL.EQ.2)).AND.
(TYPAC.NE.1).AND.(TYPAC.NE.9) MD(0)$
CO=1.$
BREG1=STATE.EQ.1 MD(0.)$
BREG2=STATE.EQ.2 MD(0.)$
BREG3=STATE.EQ.3 MD(0.)$
BREG4=STATE.EQ.4 MD(0.)$
/* */
/*PROCEDURES USED TO FILL IN MISSING OBSERVATIONS AND CHECK RESULTS*/
/* */
DEFINE STAT(AA,CC)$
AA1=AA MD(-100000)$
REDUCE VI(AA1) VO(MAX) OP(MAX)$
AA1=AA MD(100000)$
REDUCE VI(AA1) VO(MIN) OP(MIN)$
COVA VA(AA) PR(NO MEA,STD) BO(CC)$
SMPL IN(1,1)$
PRINT VA(MIN MAX)$
SMPL IN(1,4030)$
ENDDF$
STAT(BOOLL,CO)
BOOLLIT=BOOLL*(YEARBT-GE.62)$
STAT(BOOLLIT,CO)
RECODE VI(MEANSMAT,MEANSINST) CI(0) CO(MD)$
STAT(MEANSMAT,CO)
STAT(MEANSINST,CO)
MINDEX=MEANSMAT/100$
INDEX=MEANSINST/100$
COVA VA(W99T) PR(NO MEA)$ COVA VA(SDDR) PR(NO MEA)$
COVA VA(SDDB) PR(NO MEA)$ COVA VA(RHSLDREM) PR(NO MEA)$

```

COVA VAC(MINDEX) PR(NOB MEA)\$ COVA VA(IINDEX) PR(NOB MEA)\$  
 BOOLL=BOOLL\*(1-0\*W9ST)\*(1-0\*SDDR)\*(1-0\*SDD8)\*(1-0\*NHSLDMEM)  
 \*(1-0\*MINDEX)\*(1-0\*IINDEX)  
 STAT(BOOLL,CO)  
 /\* \*/

DEFINE FIT(Y,Z,NM,BB,BBB,MM)\$  
 OLSQ DV(CY) RV(ZZ) GF(BETA) B0(BB)\$  
 SMPL INCL(NN)\$  
 MATRIX VA(BETA) DI(NN,1)\$  
 SMPL INCL(9030)\$  
 MPROD VL(CZZ) VR(BETA) VO(WM)\$  
 BB=1-0.\*MM MD(0.)\$  
 WM=WM MD(0.)\$  
 ENDDF\$  
 RECODE VI(LOCUM) CI(9) CO(MD)\$  
 CLIM2=CLIMATE.EQ.2\$  
 CLIM3=CLIMATE.EQ.3\$  
 CLIM4=CLIMATE.EQ.4\$  
 RECODE VI(HDDAV) VO(HDD4170) CI(9999) CO(MD)\$  
 RECODE VI(CDDAV) VO(CDD4170) CI(999) CO(MD)\$  
 STAT(HDDAV,CO)  
 STAT(CDD4170,CO)  
 STAT(CDD4170,CO)  
 RECODE VI(LWINDS,MMINDS,NLWIND,NMMIND,NSWIND) CI(98,99) CO(MD,MD)\$  
 SMSA=(LOCUM.EQ.1)\$  
 /\* \*/

DEFINE LIST\$  
 BATHS FLOORS YEARBT NDOORS LROOMS BREG2 BREG3 BREG4  
 HDD4170 CDD4170 SMSA  
 CLIM2 CLIM3 CLIM4 LWINDS MMINDS SWINDS  
 ENDDF\$  
 /\* \*/  
 /\* \*/  
 /\* \*/

/\*CALCULATE ESTIMATED INCHES OF ATTIC INSULATION IF NOT REPORTED\*/  
 RECODE VI(PERINSUL) CI(8,9) CO(MD,MD)\$  
 RECODE VI(FOANCEIL,LOOSCEIL) CI(98,99) CO(MD,MD)\$  
 BATTICEIL=BATTICEIL\*(BATTICEIL.LT.35.)+(-99.0)\*(BATTICEIL.GE.35)\$  
 RECODE VI(BATTICEIL) CI(-99.) CO(MD)\$  
 NINATINS=BATTICEIL+FOANCEIL+LOOSCEIL\$  
 B10=(PERINSUL.NE.8).AND.(PERINSUL.NE.9) MD(0)\$  
 B12=NINATINS.LT.90. MD(0.)\$  
 BATTIC=BOOLL\*B10\*B12\$  
 FIT(NINATINS,'LISTI HINWALL CO',19,BATTIC,BOOLL,INSATI)  
 BOOLL=BOOLL\*B0OLL\$  
 /\*NEED TO SET THE MD'S IN NINATINS TO ZERO BEFORE MIXING\*/  
 NINATINS=NINATINS MD(0.)\$  
 INSATI=B10\*B12\*NINATINS+(1-B10\*B12)\*INSATI B0(BOOLL)\$  
 INSATI=MAX(0.,INSATI) B0(BOOLL)\$  
 INSATI=MIN(1.,INSATI) LA('INCHES ATTIC INSULATION') B0(BOOLL)\$  
 /\* \*/

STAT(BOOLL,CO)  
 STAT(INSATI,CO)  
 STAT(CDWELL,CO)  
 STAT(WHFUEL,CO)  
 STAT(SPACE,CO)  
 STAT(SPACE,BOOLL)  
 STAT(BREG1,BOOLL)  
 STAT(BREG2,BOOLL)

STAT(BREG3,BOOLL)  
 STAT(BREG4,BOOLL)  
 STAT(BATTIC,BOOLL)  
 STAT(INSATI,BOOLL)  
 STAT(NINATINS,BOOLL)  
 STAT(LOOSCEIL,BOOLL)  
 STAT(BATTICEIL,BOOLL)  
 STAT(FOANCEIL,BOOLL)  
 COVA VAC(INSATI, NINATINS) PR(ALL) B0(BATTIC)\$  
 /\* \*/

SFE=SPACES  
 BOOLL=BOOLL\*(1-0\*SPACE) MD(0)\$  
 /\* \*/  
 /\* \* ESTIMATE SQUARE FEET OF WINDOWS BY TYPE\*/  
 SFLWINDS=45\*LWINDS\$  
 SFMWINDS=25\*MMWINDS\$  
 SFSWINDS=8\*SWINDS\$  
 SFLSTRM=05\*NLMINDS\$  
 SFSSTRM=25\*NMWINDS\$  
 SFSSTRM=8\*NSWINDS\$  
 SFMI=SFLWINDS+SFMWINDS+SFSWINDS\$  
 STAT(SFMI,CO)  
 SFMI=SFM MD(0)\$  
 WINDS=LWINDS+SWINDS+MMWINDS\$  
 STAT(WINDS,CO)  
 SFLSTRM=SFLWINDS-SFLSTRM MD(0)\$  
 SFSTRM=SFLSTRM+SFMSTRM+SFSSTRM MD(0)\$  
 SFNSTRM=SFMI-SFSTRM MD(0)\$  
 SFNSTRM=MAX(0,SFNSTRM) MD(0)\$  
 SFLNSTRM=MAX(0,SFLNSTRM) MD(0)\$  
 /\* \*/

/\*CEILING AND WALL SQUARE FEET FROM REGRESSIONS ON TYPICAL HOUSES\*/  
 SFCEIL=.96\*(FLOORS\*\*-.815)\*(SFE\*\*1.006) LA('SF CEILING')\$  
 SFWALL=.19\*1\*(FLOORS\*\*1.92)\*(SFE\*\*1.57)\$  
 SFCEIL=MAX(100.,SFCEIL)\$  
 SFCEIL=MIN(1000.,SFCEIL)\$  
 SFWALL=MAX(320.,SFWALL)\$  
 SFWALL=MIN(9000.,SFWALL)\$  
 BETA=SFMI/SFWALL MD(.2)\$  
 B=MIN(.7,BETA)\$  
 B=MAX(.03,B)\$  
 SFMI=B\*SFWALL\$  
 SFWALL=(1-B)\*SFWALL LA('SF WALL EXCLUDING WINDOWS')\$  
 B=BETA/B\$  
 B=MAX(B,1.)\$  
 SFLSTRM=SFLSTRM/B MD(0.)\$  
 SFNSTRM=SFLNSTRM/B MD(0.)\$  
 SFSTRM=SFSTRM/B MD(0)\$  
 SFNSTRM=SFNSTRM/B MD(0.)\$  
 /\* \*/

/\*CUBIC FEET\*/  
 VOL=8.94\*(FLOORS\*\*8)\*(SFCEIL\*\*98) LA('VOLUME IN CUBIC FEET')\$  
 VOL=MAX(800.,VOL)\$  
 VOL=MIN(90000.,VOL)\$  
 /\* \*/  
 /\* \* PIPE, DUCT, AND CHIMNEY\*/  
 /\* \*/  
 REG=2.55+1.07\*HROOMS+.003\*SFE LA('NUMBER REGISTERS')\$  
 DUCT=3.89\*REG+.067\*SFE LA('LF DUCT')\$  
 PIPE=0.142\*SFE\*\*1.03 LA('LF PIPE')\$

```

CHIMLF=16+.5*FLOORS LA('LF VENT CHIMNEY')$
/* *
/*INSULATION R-VALUES*/
RINSCCELL=3.*INSATIS
RINSCCELL=MAX(.85,RINSCCELL) LA('CEILING INSULATION R-VALUE')$
RINSMALL=(1.+0.001*HDD4170)*RINSMALL$
RINSMALL=MAX(.95,RINSMALL) LA('WALL INSULATION R-VALUE')$
STAT(SFCELL,BO0LL)
STAT(SFWALL,BO0LL)
STAT(SFMI,BO0LL)
STAT(SFSTRM,BO0LL)
STAT(SFNSTRM,BO0LL)
STAT(SFLSTRM,BO0LL)
STAT(SFLNSTRM,BO0LL)
STAT(RINSCCELL,BO0LL)
STAT(RCEIL,BO0LL)
STAT(RINSMALL,BO0LL)
STAT(RWINDS,BO0LL)
STAT(PIPE,BO0LL)
STAT(DUCT,BO0LL)
STAT(CHIMLF,BO0LL)
STAT(REG,BO0LL)
STAT(VOL,BO0LL)
STAT(FLOORS,BO0LL)
STAT(BATHS,BO0LL)
STAT(NROOMS,BO0LL)
COVA VA(SFCELL,SFWALL,RINSCCELL,PR(ALL))$
COVA VA(RCELL,RINSCCELL) PR(ALL)$
STORE VA(BO0LL)$
SODR=SODB LA('SUMMER DESIGN TEMPERATURE')$
W99T=W99T LA('WINTER DESIGN TEMPERATURE')$
SODR=SODR LA('SUMMER OUTDOOR DAILY TEMP RANGE')$
MINDEX=MINDEX LA('MEANS MATERIAL INDEX/100')$
INDEX=INDEX LA('MEANS INSULATION INDEX/100')$
HDD4170=HDD4170 LA('HEAT DEGREE DAYS 30 YEAR AVER')$
CDD4170=CDD4170 LA('COOL DEGREE DAYS 30 YEAR AVER')$
NROOMS=NROOMS LA('NUMBER OF ROOMS IN LIVING SPACE')$
NHSLDME=NHSLDME LA('TOTAL NUMBER OF RESIDENTS')$
NDOORS=NDOORS LA('NUMBER OF DOORS TO UNHEATED AREA')$
HINWALL=HINWALL LA('AMI OF EXT WALL INSUL')$
COMPRESS V(LSDDB,W99T,SODR,MINDEX,INDEX,HDD4170,CDD4170,NROOMS,
NHSLDME,NDOORS,HINWALL) BO(BO0LL)$
STORE VA(SODB,W99T,SODR,MINDEX,INDEX,HDD4170,CDD4170,NROOMS,
NHSLDME,NDOORS,HINWALL)$
EC500N=EC500N LA('RATES FOR 500 KWH FROM TEB')$
EC1000N=EC1000N LA('RATES FOR 1000 KWH FROM TEB')$
EC500=EC500 LA('COST OF 500 KWH YEAR DWELLING BUILT')$
EC1000=EC1000 LA('COST OF 1000 KWH YEAR DWELLING BUILT')$
TOTGAS=TOTGAS LA('TOTAL THERMS CONSUMED FOR YEAR')$
TOTTELEC=TOTTELEC LA('TOTAL KWH CONSUMED FOR YEAR')$
AGEHEAD=AGEHEAD LA('AGE OF HEAD OF HOUSEHOLD IN YEARS')$
EDUC=EDUC LA('LEVEL OF EDUC-HEAD OF HOUSEHOLD')$
MPELEC=MPELEC LA('UNIT COST OF ELECTRICITY')$
SEX=SEX LA('SEX OF RESPONDENT')$
OCCUP=OCCUP LA('TIME PERIOD HOUSEHOLD IS OCCUPIED')$
WHFUEL=WHFUEL LA('TYPE OF FUEL USED FOR HEATING WATER')$
WHFURN=WHFURN LA('WAT HEAT WITH FURN OR ETACH')$
AGEWH=AGEWH LA('AGE OF WTAER HEATER IN YEARS')$
HWPPIP=HWPPIPINS LA('HOT WATER PIPES ARE INSULATED')$
FUELTYP=FUELTYP LA('TYPE OF FUEL MAIN HEAT SYSTEM')$
RESIDY=RESIDY LA('BEGINNING YEAR OF PRESENT RESIDENCE')$
COMPRESS V(INCG64,NG69,NG74,NG75,NG76,NG77,NG78,NG79,NGC0,FN1,FN2,
EC500N,EC1000N,EC500,EC1000,TOTGAS,TOTELEC,AGEHEAD,EDUC,
MPELEC,SEX,OCCUP,WHFUEL,WHFURN,AGEWH,HWPPIPINS,FUELTYP,HEATMN,RESIDY)
BO(BO0LL)$
STORE VA(NG64,NG69,NG74,NG75,NG76,NG77,NG78,NG79,NGC0,FN1,FN2,
EC500N,EC1000N,EC500,EC1000,TOTGAS,TOTELEC,AGEHEAD,EDUC,
MPELEC,SEX,OCCUP,WHFUEL,WHFURN,AGEWH,HWPPIPINS,FUELTYP,HEATMN,RESIDY)$
YEARBT=YEARBT LA('YEAR DWELLING BUILT')$
INCOME=INCOME LA('COMBINED 1978 INCOME')$
FLOORS=FLOORS LA('TOTAL NUMBER OF FLOORS')$
BATHS=BATHS LA('NUMBER OF SHOWER FAC IN HOME')$
BREG1=BREG1 LA('STATE 1')$
BREG2=BREG2 LA('STATE 2')$
BREG3=BREG3 LA('STATE 3')$
BREG4=BREG4 LA('STATE 4')$
SMSA=SMSA LA('TYPE OF HOME LOCATION')$
INSATI=INSATI LA('INCHES ATTIC INSULATION')$
SFMI=SFMI LA('NUMBER OF SQUARE FEET OF ALL WINDOWS')$
SFSTRM=SFSTRM LA('SQUARE FEET OF STORMED WINDOWS')$
SFNSTRM=SFNSTRM LA('SQUARE FEET OF NON-STORMED WINDOWS')$
SFLNSTRM=SFLNSTRM LA('SQUARE FEET OF LARGE STORM WINDOWS, DOORS')$
SCELL=SCELL LA('SQUARE FEET CEILING')$
SFWALL=SFWALL LA('SQUARE FEET WALLS')$
VOL=VOL LA('VOLUME IN CUBIC FEET')$
RINSMALL=RINSMALL LA('WALL INSULATION R-VALUE')$
PIPE=PIPE LA('LINEAL FEET PIPE')$
DUCT=DUCT LA('LINEAL FEET DUCT')$
REG=REG LA('NUMBER OF REGISTERS')$
CHIMLF=CHIMLF LA('LINEAL FEET OF VENT CHIMNEY')$
DEFINE LIST3$
INCOME FLOORS BATHS BREG1 BREG2 BREG3 BREG4 SMSA
SFE INSATI SFMI SFSTRM SFNSTRM SFLNSTRM
SCELL SFWALL VOL RINSCCELL RINSMALL PIPE DUCT REG
ELECDSHM CHIMLF RCELL YEARBT SEQNUM
ENDDFES
COMPRESS V(LIST3) BO(BO0LL)$
STORE VA(LIST3)$
END PR(DIRECT)$

```

```

/*HVAC13*/
/*CALCULATES HEATING AND COOLING EQUIP CAPAC AND DESIGN EXPECTED USE*/
/*PROGRAM MODIFIED FOR BONNEVILLE DATA SET*/
STORAGE CORE(100000) ECS(2500000)$
LIST CORE(OFF) TIME(OFF)$
PROGRAM NA(CHVAC125) TAC(BONN)$
SMPL IN(1,1773)$
RECODE VI(HDD4170,CDD4170) VO(HDD,CDD) CI(0.0) CO(MD)$
DEFINE BADJ$
BPAR=(BTOP+BBOT)/2$
DELTA=1-EXP(-BPAR*CDD/365)-EXP(-BPAR*HDD/365)$
BTOP=(BTOP*(DELTA.LT.0))+BPAR*(DELTA.GE.0)$
BBOT=(BBOT*(DELTA.GT.0))+BPAR*(DELTA.LE.0)$
ENDDF$
BTOP=(LOG(2))*365/MIN(CDD,HDD)$
BBOT=(LOG(2))*365/MAX(HDD,CDD)$
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
DELTA=(BTOP-BBOT)/2$
APAR=BPAR*(CDD-CDD)/365.-65.)$
TMEAN=-1.0*APAR/BPAR$
B=1.-0.*TMEAN MD(0.)$
TMEAN=TMEAN MD(0.)$
TMEAN=TMEAN*B+(65.0 - HDD4170/365 + CDD4170/365)*(1-B)$
LAM=APAR+BPAR*70.$
B1=(LAM.LT.0.)$
B2=(LAM.GE.0).AND.(LAM.LT.1)$
B3=(LAM.GE.1).AND.(LAM.LT.2)$
B4=(LAM.GE.2).AND.(LAM.LT.3)$
B5=(LAM.GT.3).AND.(LAM.LT.10)$
B6=(LAM.GT.10).AND.(LAM.LT.25)$
B7=(LAM.GT.25)$
COVA VA(B1 B2 B3 B4 B5 B6 B7) PR(NO, MEA, STD)$
COVA VA(APAR BPAR LAM DELTA) PR(MEA, STD)$
COVA VA(TMEAN) PR(NO, MEA, STD)$
STORE VA(APAR BPAR TMEAN)$
END$

/*HVAC13*/
/*CALCULATES HEATING AND COOLING EQUIP CAPAC AND DESIGN EXPECTED USE*/
/*PROGRAM MODIFIED FOR BONNEVILLE DATA SET*/
STORAGE CORE(100000) ECS(3500000)$
LIST TIME(OFF) CORE(OFF) ITY$
PROGRAM NA(CHVAC13) TAC(BORN)$
SMPL IN(1,1773)$
DEFINE STAT(AA,CC)$
AA=AA MD(-100000)$
REDUCE VI(AA) VO(MAX) BO(CCC)$
AA=AA MD(100000)$
REDUCE VI(AA) VO(MIN) OP(MIN) BO(CCC)$
COVA VA(AA) PR(NO, MEA, STD) BO(CCC)$
SMPL IN(1,1)$
PRINT V(MIN MAX)$
SMPL IN(1,1773)$
ENDDF$
RECODE VI(HDD4170,CDD4170) CI(0.) CO(MD)$
TIGHT=1$
CO=1$
SDTEMPD=SDDB-75$
MDTEMPD=75-M99T$
COVA VA(TIGHT, SDTEMPD, MDTEMPD) PR(NO, MEA, STD)$
/* */
/*RESISTANCES*/
RESMALL=(2.85*RINSMALL)/(0.9394+0.0138*RINSMALL)$
RESCEILM=3.834+.943*RINSCEIL$
UEFF1=(0.3769+0.00636*RINSCEIL)/(2.097+0.608*RINSCEIL)$
UEFF2=(0.17389+0.00293*RINSCEIL)/(2.097+0.608*RINSCEIL)$
STAT(RESMALL,CO)
STAT(RESCEILM,CO)
STAT(UEFF1,CO)
STAT(UEFF2,CO)
ZGLASS=(SFLSTRM/1.32)+(SFLNSTRM/.88)$
ZGLASRM=(SFLSTRM-SFLSTRM)/2.78*(SFLNSTRM-SFLNSTRM)/.98$
STAT(ZGLASS,CO)
STAT(ZGLASRM,CO)
INFIL1=TIGHT*(1.14-.28*(SFLSTRM)/SFLM1)$
INFIL2=.00833*INFIL1$
INFIL=.575*INFIL1$
INTERNAL=1200+225*NHSLDMEM LA('SENSIBLE HEAT GAIN')$
/* */
/*HEAT LOSS AND GAIN COEFFICIENTS*/
H0=SECEIL*(3.88 - 0.0299*W99T)$
W1=(SFWALL/RESMALL)+(SFCEIL/RESCEILM)+ZGLASRM
+ZGLASS+.018*VOL*INFIL1$
W2=.018*VOL*INFIL2$
STAT(H0,CO)
STAT(W1,CO)
STAT(W2,CO)
S0=(SFWALL/RESMALL)*(26.27+0.3196*SODR) + SFCEIL*UEFF1*(25.35+
0.2820*SODR) + INTERNAL + 30*(SFWI-SFESTRM) + 27*SFLSTRM)*1.25$
S1=(1.0050*(SFWALL/RESMALL) + SFCEIL*UEFF1*0.9958 + SFCEIL*UEFF2 +
0.8*(SFWI-SFLSTRM) + 0.6*SFLSTRM + 0.007423*VOL)*1.25$
S2=0.00015*VOL*1.25$
STAT(S0,CO)
STAT(S1,CO)
STAT(S2,CO)
/* */
/*DESIGN CAPACITIES*/

```

```

SHEATH=(W0+WDTEMPD*(W1+HDDTEMPD*(W2)))/1000$
SHEATP=SHEATH+.01128*PIPE$
SHEATD=CHEATH+.0249*DUCT$
RADHLF=CHEATH/.645$
RADELFF=SHEATH/.6394$
ACHEAT=(C0+SDETEMPD*(S1+SDETEMPD*(S2)))/1000$
/* */
/*SEASONAL HEATING EFFICIENCIES*/
COPG=.46+.0146*HDD4170/365$
COP0=.404+.013*HDD4170/365$
COPHP=1.94+1040.25/HDD4170+350.4/CDD4170-.000126*HDD4170
COPAC=3.44+271.56/HDD4170+448.95/CDD4170-.0000936*HDD4170
/* */
/* TEMPERATURE PROFILES TO CREATE APAR AND BPAR ARE CONSTRUCTED IN
/* */
/* SEASONAL DESIGN USE
/* */
DEFINE GAMMA(RRR,GGG)$
TEMP1=MAX(C0,RRR)$
TEMP2=EXP(-TEMP1)$
GGG=TEMP2*(0.0643169*(EXP(5.*RRR)-1.))+GGG$
GGG=TEMP2*(0.03401569*(EXP(4.*RRR)-1.))+GGG$
GGG=TEMP2*(0.0649159*(EXP(3.*RRR)-1.))+GGG$
GGG=TEMP2*(0.24595468*(EXP(2.*RRR)-1.))+GGG$
GGG=TEMP2*(0.99949556*(EXP(RRR)-1.))+GGG$
GGG=(TEMP1*TEMP1/2.)*.82246703+GGG$
ENDDF$
/* */
DEFINE HEAT(RR1,C0,C1,C2,HHH)$
HHH=C0/(1+EXP(-RR1))$
HHH=HHH+G1*(LOG(1+EXP(RRR)))/BPAR$
JAMMA(RRR1,GG)
HHH=HHH+2.*C2*GG/(BPAR*BPAR)$
ENDDF$
/* */
/*CALCULATE HEATING UEC. FIRST A BALANCE INSIDE-OUTSIDE TEMPERATURE
/* */
/*DIFFERENTIAL LAM IS CALCULATED. THIS QUANTITY IS INDEPENDENT OF
/* */
/*THE THERMOSTAT SETTING THEN W1 AND W0 COEFFICIENTS ARE REDEFINED
/* */
/*SO HEAT GIVES THE AVERAGE OF Q OVER THE TEMPERATURE DISTRIBUTION
/* */
/*UP TO THE BALANCE TEMPERATURE. NOTE THAT THE ENERGY COST OF A ONE
/* */
/*DEGREE THERMOSTAT INCREASE IS SIMPLE TO COMPUTE BECAUSE BALANCE
/* */
/*TEMPERATURE RISES ONE DEGREE, BALANCE DIFFERENTIAL IS UNCHANGED.
/* */
/* */
/* HEATING UEC CALCULATION */
/* LAM= CBALANCE TEMP - INSIDE TEMP. ) */
W0=W0-INTERNAL$
LAM=W1*(1-(1-4*W2*(MIN(W0,0)))/(W1*2))**0.5)/(2*W2)$
W0A=(W0.LT.0.0)*0.0+(W0.GE.0.0)*W0$
W1A=W1+W2*2*(-1.0*LAM)$
W2A=W2$
STAT(W0,C0) STAT(W0A,C0) STAT(W1A,C0) STAT(W2A,C0) STAT(LAM,C0)
LAM=APAR+BPAR*(70*LAM)$
HEAT(LAM,W0A,W1A,W2A,SHEUCE)
LAM=LAM+BPAR$
/* */
/* EVALUATE HEATING USAGE AT MEAN TEMP. WHEN CDD4170 = 0.0
ASHUE =W0A + W1A*(70.-TMEAN) + W2A*(70.-TMEAN)*(70.-TMEAN)$
ADSHUE=W0A + W1A*(71.-TMEAN) + W2A*(71.-TMEAN)*(71.-TMEAN)$
/* */
STAT(CASHUE,C0) STAT(ADSHUE,C0)
BDSHUE=1-.0.*SHEUCE MD(C0)$
RDSHUE=1-.0.*DSHUECE MD(C0)$
RECODE VI(SHEUCE,DSHUECE) CI(MD) CO(C0.)$
SHEUCE=BDSHUE*SHEUCE+(1-BDSHUE)*ASHUE$
DSHUECE=BDSHUE*DSHUECE+(1-BDSHUE)*ADSHUE$
/* */
/* */
SHEUCE=SHEUCE*8.76$ DSHUECE=DSHUECE*8.76$
DSHUECE=DSHUECE-SHEUCE$
SHEUCE=SHEUCE/COPG$
DSHUECE=DSHUECE/COPG$
SHEUCO=SHEUCE/COP0$
DSHUECO=DSHUECE/COP0$
SHEUECHP=SHEUCE/COPHP$
DSHUECHP=DSHUECE/COPHP$
SHEUCE=SHEUCE$
DSHUECE=DSHUECE$
SHUCO=SHEUCO$
DSHUECO=DSHUECO$
SHUDE=SHEUCE*SHEATD/SHEATH$
DSHUECO=SHUCO*SHEATD/SHEATH$
SHUDE=SHEUCE*SHEATP/SHEATH$
DSHUECO=SHUCO*SHEATP/SHEATH$
SHUP=SHEUCE*SHEATP/SHEATH$
DSHUECO=SHUCO*SHEATP/SHEATH$
SHUP=SHEUCECHP*SHEATD/SHEATH$
DSHUECO=SHUCO*SHEATD/SHEATH$
/* AIR COOLING USAGE */
S0=(45FWALL/RESWALL)*(362.1-0.9638*SODR)/24 + SFCEIL*UEFFI*(355.6-
1.032*SODR)/24 + INTERNAL + 30*(SFWI-SFLSTRM) + 27*5F5FLSTRM)*1.25$
S1=(22.67*(SFWALL/RESWALL)/24 + SFCEIL*UEFFI*22.66/24 + SFCEIL*UEFFI2 +
0.8*(SFWI-SFLSTRM)+0.6*SFLSTRM*0.007423*VOL)*1.25$
S2=0.00015*VOL*1.25$
STAT(S0,C0) STAT(S1,C0) STAT(S2,C0)
/* COOLING UEC CALCULATION */
/* LAM=(INSIDE TEMP. - BALANCE TEMP. ) */
LAM=51*(1-(1-4*S2*(MIN(S0,0)))/(S1*2))**0.5)/(2*S2)$
S0A=(S0.LT.0.0)*0.0+(S0.GE.0.0)*S0$
S1A=(S1.LT.0.0)*0.0+(S1.GE.0.0)*S1$
S2A=S2$
STAT(S0A,C0) STAT(S1A,C0) STAT(S2A,C0) STAT(LAM,C0)
LAM=APAR+BPAR*(75-LAM)$
HEAT(LAM,S0A,S1A,S2A,ACUEC)
ACUEC=S0A*S1A*(75-(1-1.*APAR/BPAR))*S2A*(75-(1-1.*APAR/BPAR))*2.)
+S2A*(3.289868)/(BPAR*BPAR) - ACUEC$
LAM=LAM-BPAR$
HEAT(LAM,S0A,S1A,S2A,DACUEC)
DACUEC=S0A*S1A*(74-(1-1.*APAR/BPAR))+S2A*(74-(1-1.*APAR/BPAR))*2.)
+S2A*(3.289868)/(BPAR*BPAR) -DACUEC$
ACUEC=ACUEC*8.76/COPAC$ DACUEC=DACUEC*8.76/COPAC$
DACUEC=DACUEC-ACUEC$
/* NEED TO CHANGE ACUEC TO ZERO WHEN CDD4170 = 0.0 */
RECODE VI(ACUEC,DACUEC) CI(MD) CO(C0.)$
COVA VA(ACUEC,DACUEC) PR(NOB MEA STD)$
COVA VA(SHEUCE,SHUCO) SHUDE SHUDDO SHUPE SHUFG SHUPO
SHUHP) PR(NOB MEA STD)$
COVA VA(W0 W1 W2 S0 S1 S2 SHEATH SHEATP SHEATD RADELFF RADHLF
COPAC COPG COP0 COPHP SHEUCE DSHUECE DSHUECHP PR(NOB MEA STD)$
SHEUCE DSHUECE SHUCO DSHUECO DSHUECHP DSHUECHP)
BD1=(YEARBT.GE.70)$
COVA VA(W0 W1 W2 S0 S1 S2 SHEATH SHEATP SHEATD RADELFF RADHLF
COPAC COPG COP0 COPHP SHEUCE DSHUECE DSHUECHP DSHUECHP)

```

```

SHUECG DSHUECG SHUECO DSHUECO SHUECHP DSHUECHP) PR(NOB MEA STD) BO(BBI)$
STORE VAC40 MI W2 S0 S1 S2 SHEATN SHEATP SHEATD RADELF RADHLF
COPAC COP6 COP0 COPHP SHUECE DSHUECE ACHEAT ACUEC DACUEC
SHUECG DSHUECG SHUECO DSHUECO SHUECHP DSHUECHP)$
STORE VACSHUCE SHUCG SHUCO SHUDE SHUDG SHUDO SHUPE SHUPG SHUPO SHURP)$
END$

```

```

/*HVACILX/
/*SETS UP EXTRACT OF SINGLE FAMILY OWNER OCCUPIED DETACHED DWELLINGS*/
/*REGDES SELECTED VARIABLES, CALCULATES FITTED VALUES*/
/*MODIFIED BY JEFFREY DUBIN JANUARY,1983; VACS VERSION*/
STORE CORE(10000) ECS(600000)$
PROGRAM NACHVAC11) TA(NIECSX3,NEW) LB(NIECSX2)$
LIST CORE(DEF) TIME(OFF)$
SMPL IN(1,3842)$
RECODE VI(NCOMBATH NHAFBATH) CI(6 7 8 9) CO(0 0 0 0)$
RECODE VI(NSQFEET) CI(9995,9996,9999) CO(MD,MD,MD)$
RECODE VI(NSQFTLGR) CI(99995,999996,999999) CO(MD,MD,MD)$
RECODE VI(KYHOUSBT) VO(YEARBT) CI (1 2 3 4 5 6 7 8 9 10 11 96 99)
CO (30 45 55 62 67 72 75 76 77 78 79 MD MD)$
RECODE VI(KINCOME) VO(INCOME) CI(1 2 3 4 5 6 7 8 9 10 11 12 13 14 96 97 99)
CO(2 4 6.5 9 11 13.5 17.5 22.5 27.5 32.5 37.5 42.5 47.5 55 MD MD MD)$
RECODE VI(HINWALL) CI(6,9) CO(.656 .656)$
RECODE VI(KOMNVALU) VO(OMHVALU) CI(1 2 3 4 5 6 7 8 9 10 11 99)
CO(5 15 25 35 50 70 90 125 175 225 275 MD)$
SMSA=KSMSA5Z.EQ.1$
RECODE VI(NHSLDMEM NDOORS) CI(99) CO(MD)$
FLOORS=(KNUMFLRS.EQ.1)*2.5+(KNUMFLRS.EQ.2)*1.5+(KNUMFLRS.EQ.3)*2+
(KNUMFLRS.EQ.4)*2.5+(KNUMFLRS.EQ.5)*3 $
BATHS=NCOMBATH+(NHAFBATH*.5)$
DLS=KLRGRMSP.EQ.2$
DFEET=NSQFEET-NSQFTLGR$
ROOMS1 = NROOMS-1$
LROOMS=LOG(NROOMS)$
BOOLL=(CERTCODE.NE.3).AND.(KTYPLVQT.EQ.2.).AND.(KOMNRENT.EQ.1) MD(0)$
BOOL=BOOLL.AND.(DFEET.GT.0.).AND.(ROOMS1.GT.0.) MD(0.)$
CO=1.0$
DFEET = DFEET/ROOMS1 BO(BOOL)$
LDFEET = LOG(DFEET) BO(BOOL)$
BREG1=KREGION.EQ.1 MD(0.)$
BREG2=KREGION.EQ.2 MD(0.)$
BREG3=KREGION.EQ.3 MD(0.)$
BREG4=KREGION.EQ.4 MD(0.)$
B5=BOOL.AND.BREG1$
B6=BOOL.AND.BREG2$
B7=BOOL.AND.BREG3$
B8=BOOL.AND.BREG4$
/* */
/*PROCEDURES USED TO FILL IN MISSING OBSERVATIONS AND CHECK RESULTS*/
/* */
DEFINE STAT(AA,CC)$
AA1-AA MD(-100000)$
REDUCE VI(AA1) VO(MAX) OP(MAX)$
AA1=AA MD(100000)$
REDUCE VI(AA1) VO(MIN) OP(MIN)$
COVA VAC(AA) PR(NOB MEA STD) BO(CC)$
SMPL IN(1,1)$
PRINT VA(MIN MAX)$
SMPL IN(1,3842)$
ENDD$
DEFINE FI(Y,Y,ZZ,NN,BB,BB,MM)$
OLSQ DV(Y) RV(ZZ) CF(BETA) BO(BB)$
SMPL IN(1,NN)$
MATRIX VA(BETA) DI(NN,1)$
SMPL IN(1,3842)$
MPROD VL(ZZ) VR(BETA) VO(LM)$
BBB=1.-0.*MM MP(0.)$

```

```

NHWINP=NHWINPIC-NSWINPIC$
NHWIN=NHINSQDR-NSWINSQD$
SFWISR=8.7*NSMINR*38.9*NSHINPIC LA('SF STORM WINDOW')$
SFWINR=8.7*NSMINR*38.9*NSHINPIC LA('SF NON STORM WINDOW')$
SFWISR+SFWINR LA('SF WINDOW')$
SFWISR+SFWINR LA('SF STORM SLIDING GLASS DOOR')$
SFWINS=52.5*NSWINSQD LA('SF NO STORM SLIDING GLASS DOOR')$
SFWIS+SFWISS+SFWINS LA('SF SLIDING GLASS DOOR')$
SFWIS+SFWIR+SFWIS LA('SF GLASS')$
/* */
/*CEILING AND WALL SQUARE FEET FROM REGRESSIONS ON TYPICAL HOUSES*/
SFCFEL=96*(FLOORS**-.815)*(SFE**1.006) LA('SF CEILING')$
SFWALL=19.1*(FLOORS** .92)*(SFE** .57)$
SFCFEL*MAX(100.,SFCFEL)$
SFCFEL=MIN(10000.,SFCFEL)$
SFWALL=MAX(320.,SFWALL)$
SFWALL=MIN(4000.,SFWALL)$
BETA=MIN(.7,BETA)$
B=MAX(.03,B)$
SFWI=B*SFWALL$
SFWALL=(1.-B)*SFWALL LA('SF WALL EXCLUDING WINDOWS')$
B=BETA/B$
B=MAX(B,1.)$
SFWISR=SFWISR/B MD(0.)$
SFWINR=SFWINR/B MD(0.)$
SFWIR=SFWIR/B MD(0.)$
SFWIS=SFWIS/B MD(0.)$
SFWISS=SFWISS/B MD(0.)$
SFWINS=SFWINS/B MD(0.)$
/* */
/*CUBIC FEET*/
VOL=8.96*(FLOORS** .8)*(SFCFEL** .98) LA('VOLUME IN CUBIC FEET')$
VOL=MAX(800.,VOL)$
VOL=MIN(90000.,VOL)$
/* */
/*PIPE, DUCT, AND CHIMNEY*/
/* */
REG=2.55+1.07*NR00MS+.003*SFE LA('NUMBER REGISTERS')$
DUCT=3.89*REG+.067*SFE LA('LF DUCT')$
PIPE=0.142*SFE**1.05 LA('LF PIPE')$
CHIMLF=16+8.5*FLOORS LA('LF VENT CHIMNEY')$
/* */
/*INSULATION R-VALUES*/
RINSCFEL=3*XINSATI$
RINSCFEL=MAX(.85,RINSCFEL) LA('CEILING INSULATION R-VALUE')$
RINSWALL=(1.+0.01*HDD4170)*HINWALL$
RINSWALL=MAX(.94,RINSWALL) LA('WALL INSULATION R-VALUE')$
STAT(SFCFEL,BOOLL) STAT(SFWALL,BOOLL) STAT(SFWI,BOOLL)
STAT(RINSCFEL,BOOLL) STAT(RINSWALL,BOOLL)
COVA VA(SFCFEL,SFWALL,RINSCFEL,RINSWALL,SFWI) (R(ALL))$
/* */
COMPRESS VICAEMPE78 M99T
AHTPUMP ANEMFURN ANEMHTR AVEPYB AVEP78 AVGPYB AVGP78
AVOPYB AVOP78 CDD4170 CDD78 CERTCODE HAUTOMSH HCERTAC HDD4170 HDD7879
HELCLSDY HELDISHM HELRANGE HINATTIC HINMALL HSPFDFKZ HWRNGMSH IINDEX
KFLCNAC KFLMHEAT KFLSHEAT KIHIEATEQ KHELOVEN
KREDEFEL KREDEF2 KREFRFL1 KREFRFL2 KRMCLOSE KSMASZ
KURRURL KWEATHRZ KWHEATEL KYHOUSBT MINDEX NDOORS NHSLDMEM
HTRIACUNT HTRPMHCC NRCOMS NSDOORS

```

```

WM=WM MD(0.)$
ENDEF$
/* */
DEFINE LIST1='BATHS FLOORS INCOME YEARBT DLS NDOORS'$
DEFINE LIST3='BREG1 BREG2 BREG3 BREG4'$
DEFINE LIST2='NINATINS LROOMS HDD4170 CDD4170 OWNVALU SMSA KURBRURL'$
DEFINE FFIT(BBBB,CCCC)$
FFIT(UDFEET,LIST1 LIST2 CO,14,BBBB,B10,L1)
LI=MAX(LI,4)$
LI=MIN(LI,7.5)$
LI=EXP(LI)$
SFE=SFE+ROOMSI*LI BO(CCCC) RP$
ENDDEF$
/* */
/* */
/*CALCULATE ESTIMATED INCHES OF ATTIC INSULATION IF NOT REPORTED*/
B10=HINATTIC.EQ.1 MD(0.)$
B11=HINATTIC.GT.1 MD(0.)$
B12=NINATINS.LT.90 MD(0.)$
BATTIC=BOOLL*B10*B12$
FFIT(NINATINS,LIST1 LIST2 LIST3 HINWALL',18,BATTIC,BOOLL,INSATI)
B9=BOOLL*(1.-B11)$
OUT2=NINATINS*B12$
FFIT(OUT2,LIST1 LIST2 LIST3 HINWALL',18,B9,BOOLL,INSAT4)
BOOLL=BOOLL*BOOLL$
INSATI=B10*B12*NINATINS+B10*(1-B12)*INSATI+B11*INSAT4 BO(CBOOLL)$
INSATI=MAX(0.,INSATI)$
INSATI=MIN(.7,INSATI) LA('INCHES ATTIC INSULATION')$
STAT(BOOLL,CO),STAT(BOOL,CO) STAT(BREG1,BOOLL) STAT(BREG2,BOOLL)
STAT(BREG3,BOOLL) STAT(BREG4,BOOLL) STAT(BATTIC,BOOLL)
STAT(CBOOLL,CO) STAT(INSATI,BOOLL) STAT(NINATINS,BOOLL)
COVA VAC(INSATI,NINATINS) PR(ALL) BO(BATTIC)$
/* */
/*CALCULATE AND ESTIMATE CHARACTERISTICS OF BUILDING SHELL*/
/*CALCULATE ESTIMATED SQUARE FEET OF HOUSE*/
/* */
B9=BOOLL*(1.-0.*NSQFTLGR) MD(0.)$
LSFLR=LOG(NSQFTLGR) BO(CB9) MD(0.)$
FFIT(LSFLR,LIST1 LIST2 LIST3',17,B9,B11,OUT1)
OUT1=MIN(OUT1,7.5)$
SFE=B9*NSQFTLGR MD(0.)$
SFE=SFE+(1-B9)*B11*EXP(OUT1) BO(CBOOLL)$
FFIT(B9,BREG1)
FFIT(B6,BREG2)
FFIT(B7,BREG3)
FFIT(B8,BREG4)
C12=0.*NSQFEET MD(1.)$
BETA=NSQFEET MD(0.)$
BETA=B12*SFE+(1-B12)*BETA$
SFE=(BETA*SFE)/2.$
SFE=SFE BO(CBOOLL) LA('ESTIMATED SQUARE FEET')$
STAT(SFE,BOOLL) STAT(NSQFEET,B9)
COVA VA(SFE NSQFEET B9) PR(ALL)$
/* */
/*ESTIMATE SQUARE FEET OF WINDOWS BY TYPE*/
NSTRWINS=NSTRWINS*(NINWINDOUS.GT.0)$
NSWINPIC=NSWINPIC*(NWINPIC.GT.0)$
NSWINSQD=NSWINSQD*(NSWINSQD.GT.0)$
NSWINR=NSTRWINS-NSWINPIC-NSWINSQD$
NSMINR=NSWINDOUS-NSWINPIC-KNINSQDR-NSMINRS

```



```

/*HVAC12*/
/*STACKS OBSERVED CASE, UNINSULATED CASE, AND ASHRAE 90-75 CASE DATA*/
STORE CORE(15000) ECS(400000)$
LIST CCR(OFF) TIME(OFF) TTY$
PROGRAM NACHVAC12) TA(PIECX3A,NEW) LB(PIECX3)$
LIST COFEK(OFF) TIME(OFF)$
SNPL IN(1,6054)$
DEFINE LIST2$
CDD4170 HDD4170 NNSLDMEM SDDR M99T SFMISR SFMHR SFMWR SFMWS SFMINS SFMIS
SFMI SFCEIL SFMALL VOL RINSCEIL RINSWALL PIPE DUCT YEARBT
ENDDF$
/* */
DEFINE LIST3$
SDDB BREG1 BREG2 BREG3 BREG4
ENDDF$
/* */
BBASE=IDORS.LE.2018$
BLOW=(IDORS.GI.2018).AND.(IDORS.LE.4036)$
BHIGH=(IDORS.GI.4036)$
DEFINE TGG='BO(BLOW) RP$'$
DEFINE TFF='BO(BHIGH) RP$'$
EXPAND VI(LIST2 LIST3) TFF
RINSCEIL=.85 TGG
RINSWALL=.95 TGG
SFMISR=0 TGG
SFMIHR=0 TGG
SFMIWS=0 TGG
SFMIWINS=0 TGG
SFMIWINS=0 TGG
SFMINS=SFMIS TGG
SDTEMPD=SDDB-75 LAC'SUMMER DESIGN TEMPERATURE DIFFERENTIAL'$
WDTEMPD=75-M99T LAC'WINTER DESIGN TEMPERATURE DIFFERENTIAL'$
SDTEMPD=SDTEMPD-(BREG1*7+BREG2*6+BREG3*6+BREG4*5) TFF
WDTEMPD=WDTEMPD-(BREG1*12+BREG2*14 +BREG3*12+BREG4*14) TFF
TIGHT=.93 TFF
SFMISR=SFMIHR TFF
SFMISR=0 TFF
SFMINS=SFMIS TFF
SFMINS=0 TFF
RINSWALL=(BREG1+BREG2)*15.44+(BREG3+BREG4)*9.45 TFF
RINSCEIL=(BREG1+BREG2)*17.14+(BREG3+BREG4)*19.5 TFF
STORE VA(LIST2 BBASE BLOW BHIGH SDTEMPD WDTEMPD TIGHT)$
END$

```

```

OSMPE78 SDDB SMP78 SODR WMAET WMPE78 MP678 NSLOCDOE) BO(BOOLL)$
/* */
STORE VA(AEMPE78 M99T
AHTPUMP ANENFURN ANEKHTR AVEPYB AVEP78 AVGPYB AVGP78
AVOPYB AVOP78 CDD4170 CDD78 CERTCODE HAUTOMSH HCENTAC HDD4170 HDD7879
HELCLSDY HELDISHW HELRANGE HINATTC HINWALL HSPFDRZ HWRNGMSH IINDEX
KFLCNAC KFLMHEAT KFLSHEAT KMHEATELQ KNELOVEN
KREFDEF1 KREFDEF2 KREFRFL1 KREFRFL2 KRMCLOSE KMSASZ
KURBRURL KWEATHRZ KUHEATFL KYHUSBT MINDEX NDOORS NNSLDMEM
NRMACUNT NROOMAC NROOMS NSDOORS
OSMPE78 SDDB SMP78 SODR WMAET WMPE78 MP678 NSLOCDOE)$
/* */
COMPRESS VI(YEARBT CHIMLF
INCOME FLOORS BATHS BREG1 BREG2 BREG3 BREG4 OMNVALU SMSA
SFE INSATI BOOLL SFMISR SFMIHR SFMWR SFMWS SFMINS SFMIS SFMI
SFCEIL SFMALL VOL RINSCEIL RINSWALL PIPE DUCT REG) BO(BOOLL)$
/* */
STORE VA(YEARBT CHIMLF
INCOME FLOORS BATHS BREG1 BREG2 BREG3 BREG4 OMNVALU SMSA
SFE INSATI BOOLL SFMISR SFMIHR SFMWR SFMWS SFMINS SFMIS SFMI
SFCEIL SFMALL VOL RINSCEIL RINSWALL PIPE DUCT REG)$
/* */
STORE VA(BOOLL)$
SMPL IN(1 2018)$
B1=HINATTC.EQ.1$
B2=HINWALL.EQ.1$
COVA VA(FLOORS NROOMS BATHS B1 B2 HDD4170 CDD4170) PR(NOB MEA STD)$
END PR(DIRECT)$

```

```

STORAGE CORE(100000) ECS(4000000)$
LIST CORE(OFF) TIME(OFF)$
PROGRAM NA(HVAC125) TA(NIECSX3A) $
/*MODIFIED BY JEFFREY DUBIN FEBRUARY, 1983 */
SPL INCL(,6054)$
RECODE VI(HDD4170,CDD4170) V0(HDD,CDD) CI(0.0) CO(MD)$
DEFINE BADJ$
BPAR=(BTOP+BBOT)/2$
DELTA=1-EXP(-BPAR*CDD/365)-EXP(-BPAR*HDD/365)$
BTOP=(BTOP*(DELTA,LT.0))+CBPAR*(DELTA,GE.0)$
BBOT=(BBOT*(DELTA,GT.0))+CBPAR*(DELTA,LE.0)$
ENDDF$
BTOP=(LOG(2))*365/MIN(CDD,HDD)$
BBOT=(LOG(2))*365/MAX(HDD,CDD)$
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
BADJ
DELTA=(BTOP-BBOT)/2$
APAR=BPARG*(HDD-CDD)/365.-65.$
TMEAN=-1.0*APAR/BPAR$
B=1.-0.*TMEAN MD(0.)$
TMEAN=TMEAN MD(0.)$
LAMB=APAR/BPAR*70.$
B1=(LAM,GT.0)$
B2=(LAM,GE.0).AND.(LAM,LT.1)$
B3=(LAM,GE.1).AND.(LAM,LT.2)$
B4=(LAM,GE.2).AND.(LAM,LT.3)$
B5=(LAM,GT.3).AND.(LAM,LT.10)$
B6=(LAM,GT.10).AND.(LAM,LT.25)$
B7=(LAM,GT.25)$
COVA VA(B1 B2 B3 B4 B5 B6 B7) PR(NOB,MEA,STD)$
COVA VA(CAPAR BPAR LAM DELTA) PR(MEA, STD)$
COVA VAC(TMEAN) PR(NOB MEA STD)$
STORE VAC(APAR BPAR TMEAN)$
END$

/*HVAC13*/
/*CALCULATES HEATING AND COOLING EQUIP CAPAC AND DESIGN EXPECTED USE*/
/*MODIFIED BY JEFFREY DUBIN FEBRUARY, 1983 */
LIST CORE(OFF) TIME(OFF) TIYS
STORAGE CORE(100000) ECS(6500000)$
PROGRAM NA(HVAC13) TA(NIECSX3A)$
DEFINE STAT(CA,CC)$
AA1=AA MD(100000)$
REDUCE VI(AA1) V0(MAX) OP(MAX) BO(CCC)$
AA1=AA MD(100000)$
REDUCE VI(AA1) V0(MIN) OP(MIN) BO(CCC)$
COVA VA(CA) PR(NOB MEA STD) BO(CCC)$
SPL INCL(,1)$
PRINT VA(MIN MAX)$
SPL INCL(,6054)$
ENDDF$
RECODE VI(HDD4170,CDD4170) CI(0.) CO(MD)$
/* */
/*RESISTANCES*/
RESMALL=(2.85+RINSMALL)/(,9394+.0138*RINSMALL)$
RESCEILW=3.834+.943*RINSCCELL$
UEFF1=(0.3769+.00636*RINSCCELL)/(2.097+.0.608*RINSCCELL)$
UEFF2=(0.17389+.00293*RINSCCELL)/(2.097+.0.608*RINSCCELL)$
ZGLASRM=(SFWISR/2.78)+(SFWINR/.98)$
ZGLASS=((SFWISS/1.32)+(SFWINS/.88))$
STAT(RESMALL, BBASE) STAT(RESCEILW, BBASE) STAT(UEFF1, BBASE)
STAT(UEFF2, BBASE) STAT(ZGLASS, BBASE) STAT(ZGLASRM, BBASE)
INFILL1=TIGHT*(.14-.28*(SFWISR+SFWISS)/SFWI)$
INFILL2=.00833*INFILL1$
INFILL1=.575*INFILL1$
INTERNAL=1200+225*NHSLDMEM LA('SENSIBLE HEAT GAIN')$
/* */
/*HEAT LOSS AND GAIN COEFFICIENTS*/
W0=SFCEIL*(3.88-0.0299*W9T)$
W1=(SFMALL/RESMALL)*(SFCEIL/RESCEILW)+ZGLASRM
+ZGLASS*.018*VOL*INFILL1$
W2=.018*VOL*INFILL2$
S0=((SFMALL/RESMALL)*(26.27+.3196*SODR) + SFCEIL*UEFF1*(25.35+
0.2820*SODR) + INTERNAL + 30*(SFWISR+SFWINS) + 27*SFWISS)*KI.25$
S1=(1.0050*(SFMALL/RESMALL) + SFCEIL*UEFF1)*KI.25$
S2=0.00015*VOL*1.25$
STAT(W0, BBASE) STAT(W1, BBASE) STAT(W2, BBASE) STAT(S0, BBASE)
STAT(S1, BBASE) STAT(S2, BBASE)
/* */
/*DESIGN CAPACITIES*/
SHEATN=(W0+WDTEMPD*(W1+WDTEMPD*W2))/1000$
SHEATP=SHEATN+.01128*PIPE$
SHEATD=SHEATN+.0249*DUCT$
RADELH=SHEATN/.6394$
ACHEAT=(S0+SDTEMPD*(S1+SDTEMPD*S2))/1000$
/* */
/*SEASONAL HEATING EFFICIENCIES*/
COP0=.46+.0146*HDD4170/365$
COPD=.404+.013*HDD4170/365$
COPHP=1.94+1040.25/HDD4170+350.4/CDD4170-.000126*HDD4170
-.006222*CDD4170$
COPAC=3.44+270.56/HDD4170+448.95/CDD4170-.0000986*HDD4170

```

```

- .001041*XCDD4170$
/* TEMPERATURE PROFILES TO CREATE APAR AND BPAR ARE CONSTRUCTED IN
/* HVAC125
/* SEASONAL DESIGN USE
/*
DEFINE GAMMA(CRR,GGG)$
TEMP1=MAX(CO,RRR)$
TEMP2=EXP(-TEMP1)$
GGG=TEMP2*(.00643169*(EXP(5.*RRR))-1.)+$
GGG=TEMP2*(-.03401569*(EXP(4.*RRR))-1.)+$GGG$
GGG=TEMP2*(.09649159*(EXP(3.*RRR))-1.)+$GGG$
GGG=TEMP2*(.24595448*(EXP(2.*RRR))-1.)+$GGG$
GGG=TEMP2*(.99949556*(EXP(RRR))-1.)+$GGG$
GGG=(TEMP1*TEMP1/2.)+.82246703+$GGG$
ENDDEF$
/* */
DEFINE HEAT(RRR1,C0,C1,C2,HHH)$
HHH=C0/(1.+EXP(-RRR1))$
HHH=HHH+C1*(LOG(1+EXP(RRR1)))/BPAR$
GAMMA(CRR1,GG)
HHH=HHH+.2.*C2*GG/(BPAR*BPAR)$
ENDDEF$
/* */
/*CALCULATE HEATING UEC. FIRST A BALANCE INSIDE-OUTSIDE TEMPERATURE
/*DIFFERENTIAL LAM IS CALCULATED. THIS QUANTITY IS INDEPENDENT OF
/*THE THERMOSTAT SETTING. THEN W1 AND W0 COEFFICIENTS ARE REDEFINED
/*SD HEAT GIVES THE AVERAGE OF Q OVER THE TEMPERATURE DISTRIBUTION
/*UP TO THE BALANCE TEMPERATURE. NOTE THAT THE ENERGY COST OF A ONE
/*DEGREE THERMOSTAT INCREASE IS SIMPLE TO COMPUTE BECAUSE BALANCE
/*TEMPERATURE RISES ONE DEGREE, BALANCE DIFFERENTIAL IS UNCHANGED.
/* */
/* HEATING UEC CALCULATION */
/* LAM= (BALANCE TEMP - INSIDE TEMP.) */
W0=W0-INTERNAL$
LAM=W1*(1-(1-0*W2*(MIN(W0,0)))/(W1**2))**0.5)/(2*W2)$
W0A=(W0-LT.0.0)*0.0+(W0.GE.0.0)*W0$
W1A=W1+W2*2*(1-0*LAM)$
W2A=W2$
STAT(W0,BBASE) STAT(W0A,BBASE) STAT(W1A,BBASE) STAT(W2A,BBASE)
STAT(LAM,BBASE)
LAM=APAR*BPAR*(70*LAM)$
HEAT(LAM,W0A,W1A,W2A,SHUECE)
LAM=LAM+BPAR$
HEAT(LAM,W0A,W1A,W2A,DSHUECE)
/*
/* EVALUATE HEATING USAGE AT MEAN TEMP. WHEN CDD4170 = 0.0
ASHUE=MAX((W0+W1*(70.-TMEAN))+W2*(70.-TMEAN)),0.0)$
ADSHUE=MAX((W0+W1*(71.-TMEAN))+W2*(71.-TMEAN)),0.0)$
STAT(ASHUE,BBASE) STAT(ADSHUE,BBASE)
BSHUE=1.-0.*SHUECE MD(0)$
BSHUE=1.-0.*DSHUECE MD(0)$
RECODE VI(SHUECE DSHUECE) CI(MD) CO(0.)$
SHUECE= BSHUE*SHUECE + (1-BSHUE)*ASHUES
DSHUECE= BDSHUE*DSHUECE + (1-BDSHUE)*ADSHUES
/*
SHUECE=SHUECE*8.76$ DSHUECE=DSHUECE*8.76$
DSHUECE=DSHUECE-SHUECES
SHUECE=SHUECE/COP$
SHUECO=SHUECE/COP$
SHUECHP=SHUECE/COPH$
END$

```

```

DSHUECG=DSHUECE/COP$
DSHUECO=DSHUECE/COP$
DSHUECHP=DSHUECE/COP$
/* */
/* ATR COOLING USAGE */
S0=((SFMALL/RESMALL)*(362.1-0.9638*SODR)/24 + SFCEIL*UEFF1*(355.6-
1.032*SODR)/24 + INTERNAL + 30*(SFMR+SEMIN) + 27*SFMISS)*1.25$
S1=(22.67*(SFMALL/RESMALL)/24 + SFCEIL*UEFF1*22.66/24 + SFCEIL*UEFF2 +
0.8*(SFMR+SEMIN)+0.6*SFMISS+0.007423*VOL)*1.25$
S2=0.00015*VOL*1.25$
/* COOLING UEC CALCULATION */
/* LAM=(INSIDE TEMP. - BALANCE TEMP.) */
LAM=S1*(1-(1-0*S2*(MIN(S0,0)))/(S1**2))**0.5)/(2*S2)$
S0A=(S0-LT.0.0)*0.0+(S0.GE.0.0)*S0$
S1A=(1-0.0)*S1 + 2*S2*(1-0*LAM)$
S2A=S2$
STAT(S0,BBASE) STAT(S1,BBASE) STAT(S2,BBASE) STAT(S0A,BBASE)
STAT(S1A,BBASE) STAT(S2A,BBASE) STAT(LAM,BBASE)
LAM=APAR*BPAR*(75-LAM)$
HEAT(LAM,S0A,S1A,S2A,ACUEC)
ACUEC=50A*S1A*(75-(1.*APAR/BPAR))+52A*(75-(1.*APAR/BPAR))**2.)
+52A*(3.289868)/(BPAR*BPAR) - ACUEC$
LAM=LAM-BPAR$
HEAT(LAM,S0A,S1A,S2A,DACUEC)
DACUEC=50A*S1A*(74-(1.*APAR/BPAR))+52A*((74-(1.*APAR/BPAR))**2.)
+52A*(3.289868)/(BPAR*BPAR) -DACUEC$
ACUEC=ACUEC*8.76/COPAC$ DACUEC=DACUEC*8.76/COPAC$
DACUEC=DACUEC-ACUEC$
/* NEED TO CHANGE ACUEC TO ZERO WHEN CDD4170 = 0.0 */
RECODE VI(ACUEC,DACUEC) CI(MD) CO(0.)$
STAT(ACUEC,BBASE) STAT(DACUEC,BBASE)
/* */
COVA VA(W0 W1 W2 S0 S1 S2 SHEATH SHEATP SHEATD RADELF RADHLF ACHEAT
COPG COPO COPHP COPAC SHUECE DSHUECE ACUEC DACUEC
PRINOB MEA STD) B0(BBASE)$
COVA VA(W0 W1 W2 S0 S1 S2 SHEATH SHEATP SHEATD RADELF RADHLF ACHEAT
COPG COPO COPHP COPAC SHUECE DSHUECE ACUEC DACUEC
SHUECG DSHUECG SHUECO DSHUECO SHUECHP DSHUECHP)
PRINOB MEA STD) B0(BLOW)$
COVA VA(W0 W1 W2 S0 S1 S2 SHEATH SHEATP SHEATD RADELF RADHLF ACHEAT
COPG COPO COPHP COPAC SHUECE DSHUECE ACUEC DACUEC
SHUECG DSHUECG SHUECO DSHUECO SHUECHP DSHUECHP)
PRINOB MEA STD) B0(BHIGH)$
B1=BRASE*(YEARBT.GE.70)$
B2=BLWX*(YEARBT.GE.70)$
B3=BHLGX*(YEARBT.GE.70)$
COVA VA(W0 W1 W2 S0 S1 S2 SHEATH SHEATP SHEATD RADELF RADHLF ACHEAT
COPG COPO COPHP COPAC SHUECE DSHUECE ACUEC DACUEC
SHUECG DSHUECG SHUECO DSHUECO SHUECHP DSHUECHP)
BO(CB1) PRINOB,MEA,STD)$
COVA VA(W0 W1 W2 S0 S1 S2 SHEATH SHEATP SHEATD RADELF RADHLF ACHEAT
COPG COPO COPHP COPAC SHUECE DSHUECE ACUEC DACUEC
SHUECG DSHUECG SHUECO DSHUECO SHUECHP DSHUECHP)
BO(CB2) PRINOB,MEA,STD)$
COVA VA(W0 W1 W2 S0 S1 S2 SHEATH SHEATP SHEATD RADELF RADHLF ACHEAT
COPG COPO COPHP COPAC SHUECE DSHUECE ACUEC DACUEC
SHUECG DSHUECG SHUECO DSHUECO SHUECHP DSHUECHP)
BO(CB3) PRINOB,MEA,STD)$
STORE VA(W0 W1 W2 S0 S1 S2 SHEATH SHEATP SHEATD RADELF RADHLF ACHEAT
COPG COPO COPHP COPAC SHUECE DSHUECE ACUEC DACUEC
SHUECG DSHUECG SHUECO DSHUECO SHUECHP DSHUECHP)$
END$

```

TABLE 1  
Exterior Wall Resistance

| Material  | R  |
|---|--|
| Outside surface (15 mph windspeed) <sup>1</sup>                       | 0.17   |
| Wood siding   | 0.87   |
| Building paper  | 0.06   |
| Sheathing (0.5" plywood)  | 0.62   |
| Air Space (Framing) <sup>2</sup>                                      | 0.94 (4.38)  |
| Gypsum wallboard  | 0.45   |
| Inside surface  | 0.68   |
| Resistance of portion of wall with framing (10% for 16" o.c. framing) | 7.23   |
| Resistance of portion of wall without framing or insulation           | 3.79   |
| Resistance of portion of wall with insulation (R-value = 1)           | 2.85 + I   |
| Average resistance of wall without insulation <sup>3</sup>            | 3.98   |
| Average resistance of wall with insulation (R-value = 1) <sup>3</sup> | $\left( \frac{2.85 + I}{0.9394 + 0.0138I} \right)$ |

<sup>1</sup>Surface resistance decreases with wind speed. The ASHRAE design standard is 15 mph winter windspeed and 7.5 mph summer windspeed, the latter giving a surface resistance of 0.25.

<sup>2</sup>Standard 2" x 4" framing is assumed, giving an air space of 3.75". Without insulation the R-value of the air space is 0.94. At typical insulation R-value of 3.0/inch, the R-value of light insulation (1.5") is 4.5, and of heavy insulation (3.5") is 10.5. The R-value of the wood framing members is 1.17 per inch.

<sup>3</sup>The average resistance of the wall satisfies

$$R_{\text{average}}^{-1} = R_{\text{framing}}^{-1} \left( \frac{\text{proportion}}{\text{framing}} \right) + R_{\text{other}}^{-1} \left( \frac{\text{proportion}}{\text{other}} \right)$$

Source: ASHRAE (1977), 22.13-22.22, particularly Tables 4A, C, I, K.

TABLE 2  
Ceiling and Roof Resistance

|   | Heating<br>R                                   | Cooling<br>R                                   |
|---|--|--|
| <u>Flat Roof and Ceiling</u>  |  |  |
| Outside surface (15 mph winter, 7.5 mph summer)                       |  |  |
| Roofing   | 0.17   | 0.25   |
| Roof insulation   | 0.33   | 0.33   |
| Plywood deck  | 1.39   | 1.39   |
| Air space <sup>1</sup> (framing)                                      | 0.78   | 0.78   |
| Gypsum wallboard  | 0.85 (6.73)                                    | 1.23 (6.73)                                    |
| Inside surface  | 0.45   | 0.45   |
|   | 0.61   | 0.76   |
| Resistance without insulation<br>in air space <sup>2</sup>            | 4.85   | 5.47   |
| Resistance with insulation<br>(R-value = I) in air space <sup>3</sup> | $\left( \frac{3.73 + I}{0.936 + .01I} \right)$ | $\left( \frac{3.96 + I}{0.937 + 0.1I} \right)$ |
| <u>Pitched Roof and Ceiling</u>                                       |  |  |
| Roof  |  |  |
| Outside surface (15 mph winter, 7.5 mph summer)                       |  |  |
| Roofing   | 0.17   | 0.25   |
| Building paper  | 0.44   | 0.44   |
| Plywood deck (5/8")   | 0.06   | 0.06   |
| Inside roof surface   | 0.78   | 0.78   |
| Framing <sup>1</sup>  | 0.62   | 0.76   |
|   | 5.84   | 5.84   |
| Roof resistance <sup>2</sup>  | 2.24   | 2.47   |
| <u>Attic Wall</u>   |  |  |
| Outside surface   |  |  |
| Wood siding   | 0.17   | 0.25   |
| Building paper  | 0.87   | 0.87   |
| Sheathing   | 0.06   | 0.06   |
| Inside wall surface   | 0.62   | 0.62   |
| Framing <sup>4</sup>  | 0.68   | 0.68   |
|   | 4.38   | 4.38   |
| Wall resistance <sup>2</sup>  | 2.57   | 2.65   |

(continued)

TABLE 2 (continued)

| Ceiling                           | Heating<br>R                                       | Cooling<br>R                                       |
|-----------------------------------|--|--|
| Upper surface                     | 0.61   | 0.76   |
| Insulation (framing) <sup>4</sup> | I (4.38)   | I (4.38)   |
| Gypsum board                      | 0.45   | 0.45   |
| Inside surface                    | 0.61   | 0.76   |
| Ceiling resistance <sup>2</sup>   | $\left( \frac{1.67 + I}{0.9276 + 0.0165I} \right)$ | $\left( \frac{1.97 + I}{0.9310 + 0.0157I} \right)$ |

<sup>1</sup>Framing is assumed to be 2" x 6", 16" o.d., giving 10% of total area.

<sup>2</sup>The formula is

$$R_{\text{average}}^{-1} = 0.1 R_{\text{framing}}^{-1} + 0.9 R_{\text{other}}^{-1}$$

The contribution of open framing to resistance is negligible.

<sup>3</sup>Insulation fills the air space.

<sup>4</sup>Framing is assumed to be 2" x 4", 16" o.d., giving 10% of total area.

Source: ASHRAE (1977), 22.13-22.22.

**TABLE 3**  
**Resistance of Windows**

| <u>Material</u>                       | <u>Heating<br/>R</u> | <u>Cooling<br/>R</u> |
|---------------------------------------|----------------------|----------------------|
| Single glazed (no storm) <sup>1</sup> | .98                  | 1.05                 |
| Double glazed (storm) <sup>1</sup>    | 2.78                 | —                    |
| Sliding Glass door, single glazed     | .88                  | .94                  |
| doubled glazed                        | 1.32                 | 1.43                 |

---

<sup>1</sup>Assume wood sash, 80% glass

Source: ASHRAE (1977), 22.24.

TABLE 4

Resistance of Floor

| <u>Material</u>               | <u>Heating<br/>R</u> | <u>Cooling<br/>R</u> |
|-------------------------------|----------------------|----------------------|
| Top surface                   | .61                  | .76                  |
| Tile                          | .05                  | .05                  |
| Felt pad                      | .06                  | .06                  |
| Plywood                       | .78                  | .78                  |
| Subfloor                      | .94                  | .94                  |
| Insulation (R-7)              | 7.00                 | 7.00                 |
| Bottom surface                | .61                  | .76                  |
| Total resistance <sup>1</sup> | 10.05                | 10.35                |

<sup>1</sup>The resistance of a slab floor is similar after adjustment for additional insulation. Winter ground temperatures below the frost level are approximately

$$t_g = 36 + 0.3 t_e$$

where  $t_e$  is design temperature. Basement wall losses due to the temperature gradient above the frost line are neglected. Slab edge losses with insulation are assumed comparable to unheated basement losses. Net heat transfer through the floor in summer is neglected.

Source: ASHRAE (1977, 22.20, Table 4C, and 24.4).



**TABLE 5**  
Summary of Winter Heating Capacity Calculation

Design Bruh is the sum of the following components.

1. Wall losses:
 
$$\left[ \begin{array}{l} \text{Exterior wall} \\ \text{area surrounding} \\ \text{heated space,} \\ \text{excluding windows} \end{array} \right] \cdot \left[ \frac{0.9394 + 0.0138 I_v}{2.85 + I_v} \right] \cdot [75 - t_e]$$
2. Ceiling losses:
 
$$\left[ \begin{array}{l} \text{Ceiling} \\ \text{area} \end{array} \right] \cdot [3.834 + 0.943 I_c]^{-1} \cdot [75 - t_e]$$
3. Floor losses:
 
$$\left[ \begin{array}{l} \text{Ceiling} \\ \text{area} \end{array} \right] \cdot (75 - (36 + 0.3 t_e))/10.05$$
4. Window losses:
 
$$\left[ \frac{A_{ws}}{2.78} + \frac{A_{wm}}{0.98} + \frac{A_{eds}}{1.32} + \frac{A_{edn}}{0.88} \right] \cdot (75 - t_e)$$
5. Infiltration losses:
 
$$\left[ \begin{array}{l} 1.14 - \\ \frac{0.28 (A_{ws} + A_{eds})}{(A_{ws} + A_{wm} + A_{eds} + A_{edn})} \end{array} \right] \cdot (0.25 + 0.02165(15) + 0.00833(75 - t_e)) \cdot (0.018) \cdot V \cdot (75 - t_e)$$

Table 5 (continued)

Notation:

|           |   |
|-----------|---|
| $I_w$     | R-value of wall insulation<br>(minimum of 0.94 for air gap if no insulation). |
| $I_c$     | R-value of ceiling insulation   |
| $t_i=75$  | interior design temperature (°F)  |
| $t_e$     | exterior winter design temperature (°F)                                       |
| $A_{ws}$  | area of stormed windows (ft <sup>2</sup> )                                    |
| $A_{wn}$  | area of non-stormed windows (ft <sup>2</sup> )                                |
| $A_{sds}$ | area of stormed sliding glass doors (ft <sup>2</sup> )                        |
| $A_{sdn}$ | area of non-stormed sliding glass doors (ft <sup>2</sup> )                    |
| $V$       | volume of conditioned space (ft <sup>3</sup> )                                |

TABLE 6  
Roof Densities and Weights

| <u>Flat Ceiling and Roof</u> | <u>Thickness</u> | <u>Density (lbs/ft<sup>3</sup>)</u> |
|------------------------------|------------------|-------------------------------------|
| Roofing                      | .375"            | 70                                  |
| Roof Insulation              | --               | --                                  |
| Plywood Deck                 | .625"            | 34                                  |
| Airspace (framing)           | 5.75"            | Ø (32)                              |
| Wallboard                    | .5"              | 50                                  |

Density of section with wood-framing:  
 $(.375 \cdot 70 + .625 \cdot 34 + 5.75 \cdot 32 + .5 \cdot 50) / 7.25 = 35.37$

Density of section without framing:  
 $(.375 \cdot 70 + .625 \cdot 34 + .5 \cdot 50) / 7.25 = 10$

Average density: (assume framing is 10% of material)  
 $(.10 \cdot 35.379 + .90 \cdot 10) = 12.54 \text{ lbs/cu.ft.}$

Weight:

Consider a 1 sq. ft. section of ceiling. Thickness is (7.25/12) ft.  
 which implies a volume of 0.60417 cu. ft. Average weight is 7.8 lbs/sq. ft.

Density and weight for a pitched roof are:  
 9.06 lbs/cu. ft. and 5.47 lbs/sq. ft. respectively.

TABLE 7

Transfer Function Polynomials for

ASHRAE Roofs #22 and #25

$$B(L) = b_0 + b_1L + b_2L^2 + b_3L^3$$

$$D(L) = d_0 + d_1L + d_2L^2 + d_3L^3$$

Roof #22:

|   | n=0    | n=1     | n=2    | n=3     | U     | C      |
|---|--------|---------|--------|---------|-------|--------|
| b | 0.0012 | 0.0180  | 0.0150 | 0.0011  |       |        |
| d | 0.0000 | -0.8098 | 0.1357 | -0.0007 | 0.109 | 0.0353 |

Roof #25:

|   | n=0    | n=1     | n=2    | n=3     | U     | C      |
|---|--------|---------|--------|---------|-------|--------|
| b | 0.0043 | 0.0385  | 0.0202 | 0.0007  |       |        |
| d | 0.0000 | -0.7314 | 0.1061 | -0.0003 | 0.170 | 0.0637 |

U - conductance  
 C - indoor temperature coefficient  
 L - lag operator

Source: (ASHRAE, 1977, 25.4, Table 3)

Application: temperature at hour h = (maximum temperature) -  
 (percentage)(temperature range) = (daily average  
 temperature) + (0.5-percentage)(temperature range)

TABLE 8

Percentage of the Daily Range

| Time, hr. | %   | Time, hr. | %  |
|-----------|-----|-----------|----|
| 1         | 87  | 13        | 11 |
| 2         | 92  | 14        | 3  |
| 3         | 96  | 15        | 0  |
| 4         | 99  | 16        | 3  |
| 5         | 100 | 17        | 10 |
| 6         | 98  | 18        | 21 |
| 7         | 93  | 19        | 34 |
| 8         | 84  | 20        | 47 |
| 9         | 71  | 21        | 58 |
| 10        | 56  | 22        | 68 |
| 11        | 39  | 23        | 76 |
| 12        | 23  | 24        | 82 |

TABLE 9

Sol-Air Temperature Differences

| <u>Time, Temp. Difference</u> | <u>Time, Temp. Difference</u> |
|-------------------------------|-------------------------------|
| 1 0.0                         | 13 25.4                       |
| 2 0.0                         | 14 28.3                       |
| 3 0.0                         | 15 30.4                       |
| 4 0.0                         | 16 29.2                       |
| 5 0.0                         | 17 26.4                       |
| 6 17.6                        | 18 17.6                       |
| 7 26.4                        | 19 0.0                        |
| 8 29.2                        | 20 0.0                        |
| 9 30.4                        | 21 0.0                        |
| 10 28.3                       | 22 0.0                        |
| 11 25.4                       | 23 0.0                        |
| 12 23.4                       | 24 0.0                        |

Source: (ASHRAE, 25.5, Table 2)

Assume dark colored surfaces averaged over orientations in the proportions: N - 10%, S - 15%, NE, E, SE, SW, W, NW - 12.5%

TABLE 10

## Output from Thermal Transfer Function

Calculation for a Typical Day<sup>1</sup>

| Hour          | Outside Temp. | Sol-Air Temp. Difference (Sol-Air - outside) | Sol-Air Temp. | Cooling Load Temp. Diff. <sup>2</sup> | Heat Flux |
|---------------|---------------|--|---------------|---------------------------------------|-----------|
| 1             | 77.23         | 0.00   | 77.23         | 13.88                                 | 0.91      |
| 2             | 76.18         | 0.00   | 76.18         | 11.65                                 | 0.67      |
| 3             | 75.34         | 0.00   | 75.34         | 9.76                                  | 0.48      |
| 4             | 74.71         | 0.00   | 74.71         | 8.11                                  | 0.32      |
| 5             | 74.50         | 0.00   | 74.50         | 6.69                                  | 0.20      |
| 6             | 74.92         | 17.60  | 92.52         | 5.63                                  | 0.12      |
| 7             | 75.97         | 26.40  | 102.37        | 6.97                                  | 0.41      |
| 8             | 77.86         | 29.20  | 107.06        | 11.09                                 | 1.11      |
| 9             | 80.59         | 30.40  | 110.99        | 16.03                                 | 1.89      |
| 10            | 83.74         | 28.30  | 112.04        | 20.66                                 | 2.59      |
| 11            | 87.31         | 25.40  | 112.71        | 24.50                                 | 3.13      |
| 12            | 99.67         | 23.40  | 114.07        | 27.43                                 | 3.50      |
| 13            | 93.19         | 25.40  | 118.59        | 29.76                                 | 3.78      |
| 14            | 94.87         | 28.30  | 123.17        | 32.14                                 | 4.05      |
| 15            | 95.50         | 30.40  | 125.90        | 34.97                                 | 4.40      |
| 16            | 94.87         | 29.20  | 124.07        | 37.94                                 | 4.76      |
| 17            | 93.40         | 26.40  | 119.80        | 40.27                                 | 5.01      |
| 18            | 91.09         | 17.60  | 108.69        | 41.23                                 | 5.06      |
| 19            | 88.36         | 0.00   | 88.36         | 39.98                                 | 4.77      |
| 20            | 85.63         | 0.00   | 85.63         | 35.39                                 | 3.98      |
| 21            | 83.32         | 0.00   | 83.32         | 29.32                                 | 3.02      |
| 22            | 81.22         | 0.00   | 81.22         | 24.09                                 | 2.24      |
| 23            | 79.54         | 0.00   | 79.54         | 19.93                                 | 1.66      |
| 24            | 78.28         | 0.00   | 78.28         | 16.60                                 | 1.23      |
| Daily Average | 83.68         | 14.08  | 97.76         | 22.67                                 | 2.47      |

1) Mean temperature 85° F, temperature range 21° F, inside temperature 75° F, ASHRAE Roof #22 with U = 0.109.

2) Total cooling load temperature difference = 544. BTU/sq. ft.

TABLE 11, cont.

## Summary of Regression Results

| Structure  | (Mean-Inside) Temperature | Temperature Range | Constant |
|--|---------------------------|-------------------|----------|
| Dependent variable is Total Cooling Load Temperature Difference <sup>A</sup>   |                           |                   |          |
| 1  | 22.66                     | -1.032            | 355.6    |
| 2  | 22.71                     | -1.012            | 358.4    |
| 3  | 22.67                     | -0.9638           | 362.1    |
| 4  | 22.49                     | -0.9535           | 359.5    |
| 5  | 22.58                     | -0.9526           | 361.5    |
| 6  | 22.48                     | -0.9357           | 360.9    |
| Dependent variable is Maximum Cooling Load Temperature Difference <sup>B</sup> |                           |                   |          |
| 1  | 0.9958                    | 0.2820            | 25.35    |
| 2  | 1.0010                    | 0.2988            | 25.55    |
| 3  | 1.0050                    | 0.3196            | 26.27    |
| 4  | 0.9972                    | 0.3206            | 26.12    |
| 5  | 1.0020                    | 0.3256            | 26.30    |
| 6  | 0.9990                    | 0.3300            | 26.29    |

## Structure

1. Roof #22, 1" wood, 2" insulation U = 0.109
2. Roof #25, 1" wood, 1" insulation U = 0.170
3. Exterior frame wall #36, 3" insulation U = 0.081
4. Exterior frame wall #37, 2" insulation U = 0.112
5. Exterior frame wall #38, 1" insulation U = 0.178
6. Exterior frame wall #39, no insulation U = 0.438

## Notes

- (A) Daily cooling load temperature difference  
=  $\alpha_{temp}\Delta$  (mean - inside temperature) +  $\alpha_{range}$  (range) +  $\alpha$
- (B) Maximum cooling load temperature difference  
=  $\alpha_{temp}\Delta$  (mean - inside temperature) +  $\alpha_{range}$  (range) +  $\alpha$

All coefficients are significant;  $R^2$ 's range from 0.9944 to 1.0000.

Number of observations = 243

TABLE 12

## Summer Cooling Load

| Daily Mean | Daily Range | R-Value of Attic Insulation | Pitched <sup>1</sup> Roof Q/A <sub>c</sub> | Flat Roof <sup>2</sup> Q/A <sub>c</sub> |
|------------|-------------|-----------------------------|--|---|
| 79.00      | 12.00       | 0.00                        | 85.94                                      | 102.66                                  |
| 75.00      | 20.00       | 0.00                        | 60.20                                      | 79.26                                   |
| 84.00      | 12.00       | 0.00                        | 116.25                                     | 129.47                                  |
| 80.00      | 20.00       | 0.00                        | 90.52                                      | 106.07                                  |
| 89.00      | 12.00       | 0.00                        | 146.57                                     | 156.27                                  |
| 85.00      | 20.00       | 0.00                        | 120.83                                     | 132.87                                  |
| 80.00      | 30.00       | 0.00                        | 88.66                                      | 103.62                                  |
| 94.00      | 12.00       | 0.00                        | 176.88                                     | 183.08                                  |
| 90.00      | 20.00       | 0.00                        | 151.15                                     | 159.68                                  |
| 85.00      | 30.00       | 0.00                        | 118.98                                     | 130.43                                  |
| 79.00      | 12.00       | 10.00                       | 25.76                                      | 60.20                                   |
| 75.00      | 20.00       | 10.00                       | 18.04                                      | 46.48                                   |
| 94.00      | 12.00       | 10.00                       | 53.01                                      | 107.36                                  |
| 90.00      | 20.00       | 10.00                       | 45.30                                      | 93.64                                   |
| 85.00      | 30.00       | 10.00                       | 35.66                                      | 76.49                                   |
| 79.00      | 12.00       | 20.00                       | 16.91                                      | 53.18                                   |
| 75.00      | 20.00       | 20.00                       | 11.84                                      | 41.06                                   |
| 94.00      | 12.00       | 20.00                       | 34.79                                      | 94.85                                   |
| 90.00      | 20.00       | 20.00                       | 29.73                                      | 82.72                                   |
| 85.00      | 30.00       | 20.00                       | 23.40                                      | 67.57                                   |

1. Q/A<sub>c</sub> is total cooling for 24 hr. period in BTU's.

2. Q/A<sub>c</sub> is total cooling for 24 hr. period in BTU's.

3. Internal temperature 75°F.



TABLE 13

Summary of Summer Cooling Calculation - Daily Load

BTU's per day is the sum of the following components:

1. Wall gains:

$$\left[ \begin{array}{l} \text{Exterior wall} \\ \text{area surrounding} \\ \text{conditioned space,} \\ \text{excluding windows.} \end{array} \right] \cdot \left( \frac{0.9394 + 0.138I_w}{2.85 + I_w} \right) \cdot (22.67 * (t - t_i)) - 0.9638 * t_r + 362.1$$

2. Ceiling gains (assume pitched roof):

$$\left[ \begin{array}{l} \text{Ceiling} \\ \text{Area} \end{array} \right] \cdot \left\{ \frac{0.3769 + 0.00636 \cdot I_c}{2.097 + 0.608 \cdot I_c} \cdot (22.66 * (t - t_i)) - 1.032 * t_r + 355.6 \right\} + \left( \frac{0.17389 + 0.00293 \cdot I_c}{2.097 + 0.608 \cdot I_c} \right) (t - t_i) \cdot 24$$

TABLE 13, cont.

3. Window gains (assuming storms removed on windows):

$$(A_{ws} + A_{wn} + A_{sdn}) \cdot (0.8t - 30) \cdot 24 + A_{sds} \cdot (0.6t - 18) \cdot 24$$

4. Internal load (sensible):

$$(1200 + 225 (\text{number of occupants})) \cdot 24$$

5. Infiltration gains:

$$24 \cdot 0.018 \cdot V \cdot (t - t_i) \cdot [0.25 + 0.02165(7.5) + 0.00833(t - t_i)]$$

The sum of 1-5 is increased by 25% to account for latent heat load (dehumidification) (ASHRAE, 1977, 25.41).

Notation:

- t mean temperature (°F).
- t<sub>r</sub> temperature range (°F).
- I<sub>w</sub> R-value of wall insulation
- I<sub>c</sub> R-value of ceiling insulation.
- V Volume of conditioned space.
- A<sub>ws</sub> + A<sub>wn</sub> + A<sub>sds</sub> + A<sub>sdn</sub> : total area of windows and sliding glass doors.

TABLE 14  
Summary of Summer Cooling Calculation - Design Capacity

BTU's per hour at design conditions is the sum of the following components:

1. Wall gains:

$$\left[ \begin{array}{l} \text{Exterior wall} \\ \text{area surrounding} \\ \text{conditioned space,} \\ \text{excluding windows.} \end{array} \right] \cdot \left( \frac{0.9394 + 0.138 I_w}{2.85 + I_w} \right) \cdot \left( 0.319 t_r + 1.0050 \Delta t_e + 26.27 \right)$$

2. Ceiling gains (assumed pitched roof):

$$\left[ \begin{array}{l} \text{Ceiling} \\ \text{Area} \end{array} \right] \cdot \left\{ \frac{0.3769 + 0.00636 \cdot I_c}{2.097 + 0.608 \cdot I_c} \cdot (0.2820 t_r + 0.9958 \Delta t_e + 25.35) + \left( \frac{0.17389 + 0.00293 \cdot I_c}{2.097 + 0.608 \cdot I_c} \right) \cdot \Delta t_e \right\}$$

3. Window gains (assuming storms removed on windows):

$$(A_{ws} + A_{wn} + A_{sdn}) \cdot (0.8t_e - 30) + A_{sds} \cdot (0.6t_e - 18)$$

4. Internal load (sensible):

$$(1200 + 225 (\text{number of occupants}))$$

TABLE 14, cont.

5. Infiltration gains:

$$0.018 \cdot V \cdot \Delta t_e \cdot [0.25 + 0.02165(7.5) + 0.00833 (\Delta t_e)]$$

The sum of 1-5 is increased by 25% to account for latent heat load (dehumidification) (ASHRAE, 1977, 25.41).

Notation:

$\Delta t_e = t_e - t_i$  where

$t_e$  = summer design maximum temperature (°F).

TABLE 15

Hot Water System Pipe Transmission Losses

Assume 2 1/2" black iron pipe with outside diameter of 2.88", 2" insulation with an R-value of 6, delivery temperature 120°, return temperature 80°, basement temperature 40°.

The formula for loss is

$$B_{tuh} = \frac{(t_w - t_b) (2\pi r_s L)}{r_s \left( \ln \frac{r_s}{r_o} \right) I + R_s}$$

with  $t_w$  = water temperature

$t_b$  = basement temperature

$r_o$  = outside radius of pipe (ft) = 1.44/12

$r_s$  = outside radius of pipe + insulation (ft) = 3.44/12

$I$  = R-value of insulation (per ft.) = 36

$R_s$  = surface resistance = 0.6

$L$  = length of pipe

Delivery loss:

$$B_{tuh} = \frac{80 (2\pi \cdot 0.287 \cdot L/2)}{0.287 \cdot \ln \left( \frac{3.44}{1.44} \right) \cdot 36 + 0.6} = 7.52L$$

Return loss:

$$B_{tuh} = \frac{40 (2\pi \cdot 0.287 \cdot L/2)}{0.287 \cdot \ln \left( \frac{3.44}{1.44} \right) \cdot 36 + 0.6} = 3.76L$$

Total loss:  $B_{tuh} = 11.28L$

Source: ASHRAE (1977) 22.7-22.9, 22.26 (Table 11), 22.27 (Table 15).

TABLE 16  
Heating Duct Transmission Losses

Assume 600 fpm velocity, 4" x 10" ducts, 2" insulation with R-value of 6, average air temperature in delivery duct 120°, basement temperature 40°.

The formula for loss is

$$B_{tuh} = PL (t_d - t_b) / I$$

where P = perimeter (ft)

L = length (ft)

t<sub>d</sub> = average duct temperature (°F)

t<sub>b</sub> = basement temperature (°F)

I = R-value of insulation

Assuming 80% of ducting is for delivery and neglecting return heat loss, the total loss is

$$B_{tuh} = (2.33)(.8) L (80) / 6 = 24.9L$$

Source: ASHRAE (1977), Chap. 30.

TABLE 17  
Characteristics of Typical Dwellings

| Variable                                  | Dwelling |       |      |      |       |       |       |
|---|----------|-------|------|------|-------|-------|-------|
|   | 1        | 2     | 3    | 4    | 5     | 6     | 7     |
| Floors                                    | 1        | 2     | 1    | 1    | 2     | 1     | 2     |
| Rooms                                     | 5        | 9     | 4    | 5    | 9     | 9     | 8     |
| Baths                                     | 1        | 2     | 1    | 1    | 3     | 3     | 2.5   |
| Bedrooms                                  | 3        | 7     | 2    | 3    | 4     | 4     | 4     |
| Sq. ft.                                   | 768      | 1404  | 576  | 1024 | 3128  | 2552  | 1848  |
| Sq. ft.<br>largest room                   | 315      | 275   | 153  | 227  | 271   | 433   | 293   |
| Ceiling area                              | 768      | 864   | 576  | 1024 | 1888  | 2552  | 924   |
| Roof area                                 | 810      | 1222  | 607  | 1109 | 1990  | 2552  | 974   |
| Attic wall area                           | 96       | 81    | 96   | 0    | 171   | 0     | 0     |
| Wall area<br>excl. window                 | 851      | 1396  | 736  | 931  | 2472  | 1532  | 1552  |
| Number picture<br>window                  | 0        | 0     | 0    | 0    | 6     | 0     | 1     |
| S.F. picture<br>window                    | 0        | 0     | 0    | 0    | 248   | 0     | 24    |
| Number sliding<br>glass doors             | 0        | 0     | 0    | 0    | 6     | 2     | 2     |
| S.F. sliding<br>glass doors               | 0        | 0     | 0    | 0    | 308   | 140   | 77    |
| Number other<br>window                    | 10       | 16    | 8    | 11   | 7     | 13    | 20    |
| S.F. other<br>windows                     | 45       | 60    | 32   | 94   | 66    | 128   | 314   |
| Volume                                    | 6144     | 10656 | 4608 | 8192 | 27232 | 22491 | 15246 |
| Hot air system:<br>registers<br>ft. duct  | 11       | 15    | 9    | 9    | 21    | 20    | 20    |
| Hot water system:<br>radiator<br>ft. pipe | 92       | 114   | 81   | 104  | 292   | 251   | 226   |
|   | 6        | 10    | 5    | 5    | 12    | 14    | 14    |
|   | 160      | 230   | 128  | 144  | 564   | 530   | 344   |

TABLE 18

Regression of Log Square Feet per Room  
(for rooms other than the largest) for NIECS households

| Independent Variable               | Region 1         | Region 2         | Region 3         | Region 4         |
|------------------------------------|------------------|------------------|------------------|------------------|
| Baths                              | .149<br>(.071)   | .118<br>(.045)   | .184<br>(.043)   | .124<br>(.053)   |
| Floors                             | .011<br>(.062)   | .055<br>(.037)   | .067<br>(.048)   | .131<br>(.052)   |
| Income (000)                       | .0039<br>(.0033) | .0039<br>(.0019) | .0036<br>(.0020) | .0032<br>(.0021) |
| Year built<br>(30 to 78)           | .0020<br>(.0024) | .0026<br>(.0014) | .0002<br>(.0015) | .0037<br>(.0018) |
| Dummy for L-shaped<br>largest room | -.081<br>(.143)  | -.002<br>(.085)  | -.15<br>(.07)    | -.07<br>(.07)    |
| No. doors                          | -.007<br>(.036)  | .032<br>(.027)   | .029<br>(.022)   | .019<br>(.025)   |
| No. windows                        | .0043<br>(.0057) | .0058<br>(.0033) | .0025<br>(.0041) | .0060<br>(.0036) |
| Log No. Rooms                      | -.377<br>(.171)  | -.317<br>(.103)  | -.592<br>(.101)  | -.577<br>(.112)  |
| Heating Degree Days<br>(000)       | .078<br>(.082)   | -.011<br>(.038)  | -.059<br>(.060)  | .010<br>(.018)   |
| Cooling Degree Days<br>(000)       | -.134<br>(.291)  | .247<br>(.109)   | -.035<br>(.098)  | -.056<br>(.069)  |
| Value of house<br>(000)            | .0015<br>(.0012) | .0020<br>(.0005) | .0016<br>(.0009) | .0018<br>(.0008) |
| SMSA dummy                         | .034<br>(.074)   | -.46<br>(.49)    | -.16<br>(.05)    | -.04<br>(.08)    |
| Urban area dummy                   | -.091<br>(.068)  | .19<br>(.49)     | .078<br>(.042)   | -.027<br>(.080)  |
| Constant                           | 5.30<br>(.70)    | 4.88<br>(.35)    | 6.06<br>(.44)    | 5.68<br>(.25)    |
| R <sup>2</sup>                     | .16              | .17              | .17              | .22              |
| No. observations                   | 230              | 494              | 432              | 253              |

TABLE 19  
Selected Characteristics of NIECS/PNW Households

| <u>Variable</u>                                       | <u>NIECS mean<br/>(estimated)</u> | <u>Typical House<br/>mean</u> | <u>PNW mean<br/>(estimated)</u> |
|---|-----------------------------------|-------------------------------|---------------------------------|
| Floors  | 1.42                              | 1.43                          | 1.29                            |
| Rooms   | 6.06                              | 7.00                          | 5.97                            |
| Baths   | 1.49                              | 1.93                          | 1.17                            |
| Square feet   | 1572 (1533) <sup>1</sup>          | 1614                          | 1513                            |
| Volume  | 11400                             | 13510                         | 11930                           |
| No. windows   | 13.0                              | 14.6                          | 10.43                           |
| Window area   | (179.4)                           | 219.4                         | (246.9)                         |
| Wall area exc. windows                                | (1506)                            | 1353                          | (1341)                          |
| Ceiling area  | (1175)                            | 1228                          | (1292)                          |
| Feet duct   | (151.0)                           | 166                           | (156.1)                         |
| Feet pipe   | (265.6)                           | 300                           | (273.9)                         |
| Space heat cap. net of<br>distribution losses, MBH    | (45.5)                            | --                            | (46.7)                          |
| Central AC capacity, MBH                              | (34.71)                           | --                            | (28.6)                          |
| Proportion with attic insul.<br>Average R-value attic | 81.9%<br>(17.41)                  | --                            | 81.0%<br>(20.28)                |
| Average R-value wall                                  | (7.03)                            | --                            | (8.93)                          |

<sup>1</sup>Correlation .94 between observed and estimated.



TABLE 20  
Energy Usage Characteristics of NIECS/PNW Dwellings

|  | NIECS  |       | PNW    |       |
|--|--------|-------|--------|-------|
|  | Mean   | SD    | Mean   | SD    |
| <b>Coefficients of Performance</b>         |        |       |        |       |
| Gas  | .64    | .08   | .70    | .05   |
| Oil  | .57    | .07   | .62    | .05   |
| Heat Pump                                  | 2.3    | 2.4   | 3.2    | 2.7   |
| Air Conditioner                            | 4.0    | 3.1   |        |       |
| <b>Energy Consumption<sup>1</sup></b>      |        |       |        |       |
| Electric resistance                        | 99420  | 51800 | 130800 | 60610 |
| Gas  | 151300 | 71310 | 186700 | 87070 |
| Oil  | 171600 | 80800 | 211600 | 98700 |
| Heat Pump                                  | 54660  | 32800 | 47960  | 27390 |
| Air Conditioner                            | 6976   | 5780  | 1200   | 1234  |
| <b>Energy Price of Comfort<sup>2</sup></b> |        |       |        |       |
| Electric resistance                        | 4726   | 2120  | 5351   | 2614  |
| Gas  | 7446   | 3455  | 7723   | 3978  |
| Oil  | 8447   | 3922  | 8753   | 4511  |
| Heat Pump                                  | 2523   | 1249  | 1918   | 1046  |
| Air Conditioner                            | 684    | 540   | 155    | 130   |

<sup>1</sup>In 10<sup>3</sup>Btu, net of distribution losses.

<sup>2</sup>In 10<sup>3</sup>Btu per degree thermostat setting, net of distribution losses.

TABLE 21  
Sensitivity of HVAC System to Thermal Characteristics (NIECS) <sup>4</sup>

|   | <u>Observed<br/>Dwelling</u> | <u>Uninsulated<br/>Dwelling</u> | <u>ASHRAE<br/>90-75<br/>Standards</u> |
|---|------------------------------|---------------------------------|---------------------------------------|
| Air Conditioning<br>capacity <sup>1</sup>         | 34.08                        | 57.56                           | 23.53                                 |
| energy consumption (000 Btu)                      | 6883.                        | 10060                           | 5590.                                 |
| Electric Resistance Heat<br>capacity <sup>2</sup> | 47.60                        | 85.02                           | 29.63                                 |
| energy consumption <sup>3</sup>                   | 107500                       | 195200                          | 86920                                 |
| Gas Forced Air<br>capacity <sup>1</sup>           | 51.86                        | 89.28                           | 33.89                                 |
| energy consumption <sup>3</sup>                   | 160400                       | 287000                          | 128300                                |
| Oil Forced Air<br>capacity <sup>1</sup>           | 51.86                        | 89.28                           | 33.89                                 |
| energy consumption <sup>3</sup>                   | 181190                       | 325400                          | 145500                                |
| Heat Pump<br>capacity <sup>1</sup>                | 51.86                        | 89.28                           | 33.89                                 |
| energy consumption <sup>3</sup>                   | 57710                        | 104600                          | 46560                                 |

<sup>1</sup>Capacity for forced air central system in MBH.

<sup>2</sup>Capacity of non-central baseboard system in MBH.

<sup>3</sup>Annual energy consumption in 10<sup>3</sup> Btu, including distribution losses.

<sup>4</sup>Houses built post 1970.

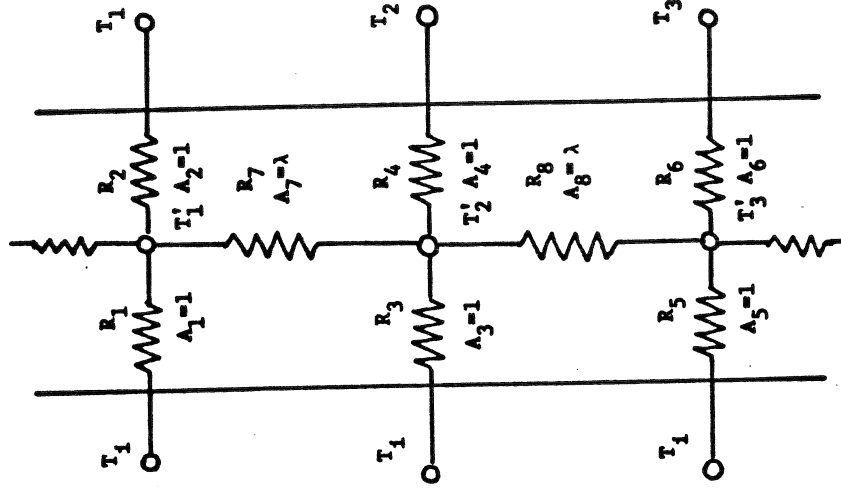


FIGURE 2: Circuit Equivalent of Thermal Equilibrium

$T_1, T_1', T_2, T_2', T_3, T_3'$  temperature.  
 $R_1, R_2, \dots, R_8$  resistances.  
 $A_1, A_2, \dots, A_8$  areas.

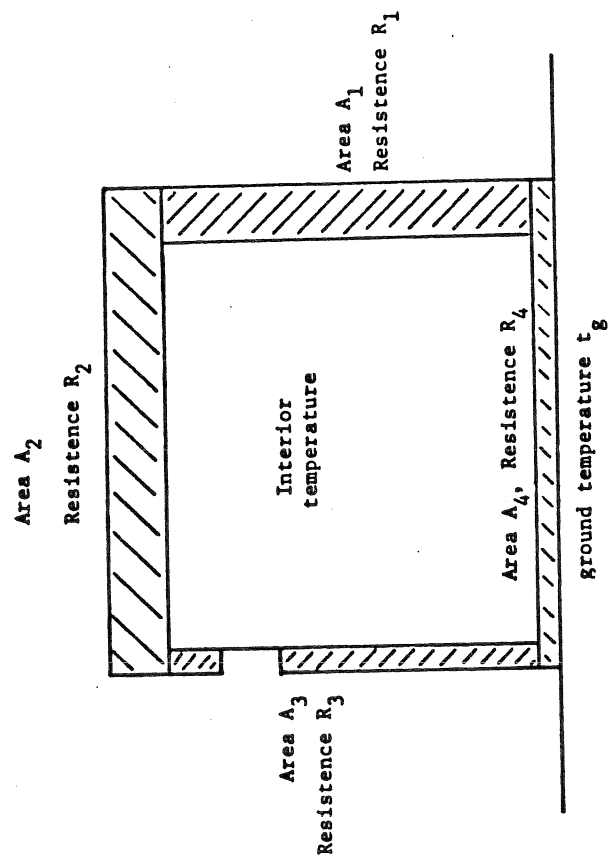


Figure 1: Schematic of Thermal Properties of Building Shell

## FOOTNOTE

1. This paper revises and extends an earlier draft entitled, "A Thermal Model for Single-Family Owner-Occupied Detached Dwellings," in the National Interim Energy Consumption Survey," M.I.T. Energy Laboratory Discussion paper No. 25, MIT-EL 82-040WP. Research was supported in part by NSF Grant No. 80-16043-DAR, Department of Energy under Contract No. EX-76-A-01-2295, Task Order 67, and the Environmental Quality Laboratory of the California Institute of Technology. We wish to acknowledge a substantial contribution to this research by Tom Cowing, who provided weather and location data for NIECS households and to Jean Rimpo who provided assistance with the Pacific Northwest Data.

## REFERENCES

- Achenbach, P. and Coblenz, C. "Field Measurements of Air Infiltration in Ten Electrically-Heated Houses." ASHRAE Annual Meeting, 1963, paper 1845.
- Anderson, K. Residential Energy Consumption: Single Family Housing. U.S. Department of Commerce, Publ. No. HUD-PDR-29.2.
- ASHRAE. Handbook and Product Directory, Fundamentals. New York: ASHRAE, 1977.
- ASHRAE. Handbook and Product Directory, Applications. New York: ASHRAE, 1978.
- ASHRAE. Handbook and Product Directory, Equipment. New York: ASHRAE, 1979.
- Berger, . Building Design and Cost File. Vol. I (General Construction Trades), Vol. II (Mechanical and Electrical Trades). New York: van Nostrand, 1981.
- Cowing, T.; Dubin, J.; and McFadden, D. "The NIECS Data Base and Its Use in Residential Energy Demand Modeling." Discussion Paper No. 24, MIT-EL 82-041WP, June 1982.
- Engelsman, C. Residential Cost Manual. New York: van Nostrand, 1981.

- Hym, D. Preliminary Cost Guide. Pasadena: Architectural Data Corporation, 1974.
- Khashab, A. HVAC Estimating Manual. New York: McGraw-Hill, 1977.
- Means, R. Building Construction Cost Data. Kingston, Massachusetts: Means, 1981.
- Means, R. Mechanical and Electrical Cost Data. Kingston, Massachusetts: Means, 1981.
- Moselle, G. Building Cost Manual. Solana Beach: Craftsman, 1981.
- NAHB. Thermal Performance Guidelines. Washington: National Association of Home Builders, 1978.
- Pereira, P., editor. Dodge Building Cost Calculator and Valuation Guide. New York: McGraw-Hill, 1981.
- Pulver, H. Construction Estimates and Costs. New York: McGraw-Hill, 1969.
- Sarviel, E., editor. National Construction Estimator. Solana Beach: Craftsman, 1981.
- Shoemaker, M. Building Estimator's Reference Book. Chicago: Walker, 1980.
- Streeter, R. "Guide for Estimating Ultimate Cost of Heating Systems." Institute for Building Research, Pennsylvania State University, 1966.