A SIMPLIFIED MICROCOMPUTER METHOD FOR HEATING AND COOLING CALCULATIONS USED IN THE COMPUTERIZED INSTRUMENTED RESIDENTIAL AUDIT (CIRA)

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ABSTRACT - The Computerized, Instrumented Residential Audit (CIRA) was developed to determine economically optimal mixes of energy-saving measures in existing residential buildings. To this purpose, a large number of heating and cooling loads and energy consumptions have to be calculated in a short time. In this paper, we present a simplified method of calculation that satisfies the requirements of speed and memory imposed by the microcomputer on which CIRA runs. The method is based on monthly calculations of degree-days and degree-nights for both heating and cooling seasons. The reference temperatures used in calculating the degree-days and degree-nights are derived from thermostat settings, solar and internal gains, and the thermal performance of the building envelope. Thermostat setbacks are handled by using the concept of effective thermal mass of the house. Performance variations of HVAC equipment with changes of part load and ambient conditions are taken into account using correlation curves based on experimental data. Degree-days and degree-nights for different reference temperatures are evaluated by using a climate-specific simple correlation with monthly average daily and nightly temperatures. Predictions obtained by this method and by DOE 2.1 are compared for several different houses and for four different climates in the United States.

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INTRODUCTION

This paper describes the heating and cooling methods developed for CIRA, the Computerized Instrumented Residential Audit. The algorithms were designed to be as accurate and flexible as possible within the limitations of memory size and speed imposed by the microcomputer. To reduce computing time some of the calculations, such as those for air infiltration, total solar radiation distribution and degree-day coefficients, are done in advance for "standard conditions." The precalculated values are corrected to reflect the building and site characteristics under consideration.

Highlights of the heating and cooling algorithms are:

- the calculation of effective conductances for below-ground walls and floors, in addition to a conventional "UA" approach for all other envelope components;

- the concept of an effective leakage area and a leakage distribution of the house that, together with terrain information, is used to correct air infiltration values pre-calculated for standard condition;

- the use of solar apertures and information on overhangs, to compute monthly average solar gains; solar apertures are calculated on the basis of window, wall and roof types and dimensions;

- the concept of effective outdoor night and day temperatures that are functions of outdoor temperature, solar and other internal gains, sky radiation losses;

- variable-base heating and cooling degree-days calculated from effective monthly temperatures using an empirical correlation formula. The loads calculated using the degree-days are further modified to account for thermostat setbacks, if any, using the concept of effective thermal mass of the house;

- the calculation of output capacities and seasonal efficiencies of heating and cooling equipment, as functions of indoor and outdoor temperature and of part-load.

Previous papers [1,2] described aspects of an earlier version of this program. The method described here is a continuation of that work. Algorithms for treating overhangs, radiation loss to the sky and HVAC equipment efficiencies have been added. Moreover, the concept of dynamic degree-days has been improved to one of variable-base degree-days correlated to outdoor temperature.

What follows is a step by step review of the calculation algorithms used in CIRA. The basic calculation time step is one calendar month. Unless otherwise stated, all variables are monthly averages. Several variables are divided between day and night, defined, respectively, as the periods separated by 8 a.m. and 8 p.m.

HEAT CONDUCTION

A heat conduction coefficient, K, is computed as a sum of the conduction through all individual envelope components, such as walls, windows, doors, etc. For all components except subfloors, the standard assumption of one-dimensional heat flow is made.

$$K = \sum_{\text{all } i} U_i A_i$$

where: K is the overall heat conduction coefficient [W/°C]

U_i is the U-value of the i-th component [W/m^2-°C]

A_i is the area of the i-th component [m^2]

Subfloor Conduction

The assumption of one-dimensional heat flow, almost universal in calculating non-steady heat flow within buildings, is not acceptable for heat flow through the ground (especially for detached domestic buildings) because the edge effects are too important to ignore. To calculate U_{sf}, the effective subfloor U-value, we use separate algorithms for basements, crawlspaces and slab-on-grade floors.

For below-grade walls, the U-value is determined as follows. At a depth h below ground level there are two contributions to the R-value: the R-value, R_w, of the wall itself, and the R-value of the soil along the line of the heat flow. One finds (see for example [3]) that the lines of heat flow can be approximated by circular arcs with center at the point where the ground meets the wall. So the length of the line of heat flow is the length of this circular arc i.e. @p/2 h, and the R-value and U-value at a depth h is given by

$$R(h) = R_w + \frac{\pi h}{2K_g} \qquad U(h) = \left\{ R_w + \frac{\pi h}{2K_g} \right\}^{-1}$$

where: R_w is the R-value of the wall [m^2-°C/W]

K_g is the soil thermal conductivity [W/m-°C]

To get the average U-value for the entire below-grade wall, U_{wb}, the U-value must be integrated over the depth below ground level, h, then divided by the total height, H.

$$U_{wb} = \frac{1}{H} \int_0^H \frac{dh}{R_w + \frac{\pi h}{2K_g}} = \frac{2K_g}{\pi H} \ln \left\{ 1 + \frac{\pi H}{2K_g R_w} \right\}$$

where: H is the total depth below grade [m]

This has been shown to give adequate agreement with the results of detailed three-dimensional, transient computer modeling [4].

Basements and Crawl Spaces

For basements and crawl spaces U_{sf}, the equivalent subfloor U-value, is calculated by combining the U-values of the components:

$$U_{sf} = \left\{ \frac{1}{U_f} + \frac{A_f}{A_{wa}U_{wa} + A_{wb}U_{wb} + A_f U_g} \right\}^{-1}$$

where: U_f A_f are the U-value and area of the floor [$W/^oC-m^2$, m^2]

U_{wa} A_{wa} are the U-value and area of the part of the subfloor wall that is above grade [$W/^oC-m^2$, m^2]

U_{wb} A_{wb} are the U-value and area of the part of the subfloor wall that is below grade [$W/^oC-m^2$, m^2]

U_g is the U-value of the subfloor or ground [$W/^oC-m^2$]

To calculate U_{wb}, equation (3) is used for basements, while for crawl spaces we use U_{wb} = 1.33 W/m^2-^oC (calculated from reference [5] assuming the depth of the foundation below ground to be 0.9m). To calculate U_g for the basement subfloor we use reference [6]:

$$U_g = (2.11 + R_{slab})^{-1}$$

For crawl spaces we use:

$$U_g = (4.23 + R_{slab})^{-1}$$

where: R_{slab} is 0.176 (air film) plus the R-value of the slab or any other insulation on top of the ground.

Slab-on-grade

The U-values for slab-on-grade floors are determined using an algorithm developed by Muncey and Spencer [7] and adapted to microcomputer use by Kusuda [8]:

$$R_s = \frac{pF_c}{K_g}\left\{0.1208 + 0.0195\ \ln\left(\frac{K_g}{pC_f}\right) + 0.0011\left[\ln\left(\frac{K_g}{pC_f}\right)\right]^2 + 0.2347\ \frac{t}{p} - 20.336\ \left(\frac{t}{p}\right)^2 - 0.1421\ \frac{t}{p}\ \ln\left(\frac{K_g}{pC_f}\right)\right\}$$

where:
- R_s is the modified soil thermal resistance [m^2-°C/W]
- t is the average wall thickness [m]
- K_g is the soil thermal conductivity [W/m-°C]
- P is the slab perimeter length [m]
- C_f is the slab thermal conductance between the room air and the slab soil interface, i.e. $(R_{slab})^{-1}$, [W/m^2-°C]
- F_c is the non-dimensional shape correction factor:

$$F_c = 0.0904 + 1.1115\ x - 0.2038\ x^2$$

and:

$$x = \frac{\text{floor area}}{(p/4)^2}$$

R_s is combined with the slab thermal conductance to get the overall subfloor U-value for slab-on-grade, U_{sf}:

$$U_{sf} = (R_s + R_{slab})^{-1}$$

Roof/Ceiling Conduction

The U-value of the roof/ceiling when there is a pitched roof and an attic space is given by:

$$U_{rc} = \left\{ \frac{1}{U_c} + \left(U_r \sqrt{1 + (\alpha/100)^2} + \rho c V_r \right)^{-1} \right\}^{-1}$$

where:
- U_{rc} is the U-value of the roof plus ceiling [W/°C-m^2]
- U_c is the U-value of the ceiling [W/°C-m^2]
- U_r is the U-value of the roof [W/°C-m^2]
- c is the volumetric specific heat capacity of the air [Wh/°C-m^2]
- V_r is the roof ventilation rate per unit area [m^3/h-m^2]
- α is the pitch of the roof [%]

For cathedral ceilings this becomes:

$$U_{rc} = \left\{ \frac{1}{U_c} \cdot \frac{1}{\sqrt{1+(\alpha/100)^2}} + \left(U_r \sqrt{1+(\alpha/100)^2} + \rho c V_r \right)^{-1} \right\}^{-1}$$

AIR INFILTRATION

To compute air infiltration we use the model developed by Sherman and Grimsrud [9].
The leakage model used assumes the flow to be dominated by inertial effects (turbulent flow), implying that an area, L, can be defined to characterize the leakage:

$$Q = L\sqrt{\frac{2\Delta P}{\rho}}$$

where: Q is the air flow rate through the house $[m^3/h]$

is the density of air $[kg/m^3]$

P is the average pressure difference across the house envelope [Pa]

The infiltration for each month is calculated as a superposition of flows from stack and wind effects, which are given by:

$$Q_{stack} = L\, f^*_s\, (gH\triangle T \div T)^{1/2}$$

$$Q_{wind} = L\, f^*_w\, v$$

where:

Q_{stack} is the stack induced infiltration $[m^3/h]$

Q_{wind} is the wind induced infiltration $[m^3/h]$

L is the total house leakage area $[m^2]$

g is the acceleration due to gravity

H is the house height [m]

T is the outside temperature $[^oC]$

$\triangle T$ is the inside to outside temperature difference $[^oC]$

v is the windspeed [m/s]

f^*_s is the reduced stack parameter:

$$f^*_s = \frac{1}{3}\left(1 + \frac{R_L}{2}\right)\left\{1 - \frac{X_L^2}{(2-R_L)^2}\right\}^{3/2}$$

f^*_w is the reduced wind parameter:

$$f^*_w = C' \left(1 - R_L\right)^{1/3} \left\{ \frac{\alpha \left[\frac{H}{10}\right]^{\gamma}}{\alpha_w \left[\frac{H_w}{10}\right]^{\gamma_w}} \right\}$$

X_L and R_L are defined as:

$$R_L = (L_C + L_F) \div L \qquad X_L = (L_C - L_F) \div L$$

where:		
	L_C and L_F	are the ceiling and floor leakage areas [m^2]
	α and γ	are terrain parameters for the house
	α_w and γ_w	are terain parameters for the weather measurement site
	C'	is a local shielding parameter
	H_w	is the measurement site height [m]

Since the stack and wind effects interact through pressure, and since the infiltration is a function of the square root of pressure, we assume that the effects add as the square root of the sum of the squares of the individual wind and stack infiltration rates, i.e.:

$$Q = (Q^2_{wind} + Q^2_{stack} + Q^2_{unbalanced})^{1/2}$$

where: $Q_{unbalanced}$ is the flow from unbalanced sources such as ventilator fans

Leakage Area

The model computes air infiltration on the basis of leakage area, leakage distribution, building height, indoor-outdoor temperature difference and wind speed, and terrain and shielding classes. Normally, the leakage area is measured using a blower door, whereby a house is pressurized at several different pressure differences and the low-pressure region of the resulting curve of flow vs. pressure fitted to a turbulent flow equation. The leakage area is defined as:

$$L = Q_4\sqrt{\frac{\rho}{2\Delta P}}$$

where: Q_4 is the air flow extrapolated to a pressure difference of 4 Pa [m^3/h]

In the absence of actual measurements with a blower door, the floor ceiling and total leakage areas are calculated using specific leakage information on all envelope components:

$$L = \sum_{\text{all } i} l_i A_i \qquad L_F = \sum_{\text{all } i_F} l_i A_{iF} \qquad L_C = \sum_{\text{all } i_C} l_{i_C} A_{i_C}$$

where: L L_F L_C are the total, floor and ceiling leakage areas [m^2]

l_i is the specific leakage area of the i-th envelope component [m^2], of area A_i [m^2]

F C indicate that the component is part of the floor or ceiling

Specific leakage area, l_i, is the average amount of leakage associated with the i-th envelope component per unit component area, even though the leakage area will not usually be evenly distributed over the component. Measured (or where necessary estimated) values of specific leakage area are used to estimate the leakage area of components of the same type but different area.

The calculated leakage areas from equation above are used to divide up the total leakage area when component leakage areas are not measured. A correction ratio, r, is first calculated. It is the measured total leakage area divided by the calculated total leakage area, i.e. $r = L^m/L^c$. This factor is used as shown in the table below. L is the total leakage area, L_C is the ceiling leakage area, and L_F is the floor leakage area. Superscript c means calculated; no superscript means actual, i.e. measured.

Table 1 Floor and Ceiling Leakage areas

Areas measured:	None	Total only	Total+floor	Total+ceiling	All
Total leakage	L^c	L	L	L	L
Ceiling leakage	L_C^c	rL_C^c	rL_C^c	L_C	L_C
Floor leakage	L_F^c	rL_F^c	L_F	rL_F^c	L_F

Specific Air Infiltration for Reference Conditions

Temperature and average wind speed will vary for each month of CIRA's monthly calculations, while the reduced stack and wind parameters won't. Stack and wind effects are precalculated for a reference house in reference surroundings and are corrected to reflect actual circumstances and actual temperature difference. The reference house is a single-story dwelling (height=2.5m) with average leakage distribution (i.e., ceiling and floor leakage areas together are equal to the wall leakage area). The reference surroundings are terrain class III (rural areas with low buildings and trees) and shielding class III (some obstructions within two house heights). The total air infiltration is then given by

$$Q = L\ (\ \{C_s q_s\}^2 + \{C_w q_w\}^2 + \{q_{unbalanced}\}^2\ )^{1/2}$$

where: q_s q_w are the monthly specific stack and wind induced infiltrations [$m^3/h\text{-}cm^2$]

C_s C_w are factors to correct for the non-standard house in non-standard surroundings.

The correction factors are:

$$C_s = 1.60\left(1 + \frac{R_L}{2}\right)\left\{1 - \left(\frac{X_L}{2-R_L}\right)^2\right\}^{3/2}\sqrt{\frac{H}{10}}$$

$$C_w = 8.15\ C' \left(1 - R_L\right)^{1/3} \alpha \left[\frac{H}{10}\right]^{\gamma}$$

where the symbols are as defined above.

The monthly specific infiltrations q_s and q_w [m^3/h-cm^2] for this reference house have been calculated for a number of cities using weather tapes. Table 2 shows the values for Minneapolis and Los Angeles.

Table 2: Monthly specific infiltration [m^3/h-cm^2]

Minneapolis	Stack	Wind	Los Angeles	Stack	Wind
January	.26	.21	January	.12	.17
February	.24	.23	February	.10	.18
March	.21	.22	March	.12	.22
April	.15	.30	April	.10	.21
May	.10	.26	May	.08	.18
June	.05	.23	June	.06	.18
July	.05	.21	July	.04	.18
August	.04	.21	August	.03	.17
September	.09	.22	September	.05	.16
October	.14	.24	October	.07	.15
November	.20	.26	November	.10	.16
December	.23	.22	December	.11	.14

RADIATIVE HEAT EXCHANGES

Solar gains

The solar gains, S, for 5 orientations (including horizontal) are computed as a product of a solar aperture, a solar exposure modifier and the solar flux for that orientation. The total solar gain for the house is computed for each month as the sum of the above five solar gains.

$$S = \sum_{v=1}^{5} \sigma_v \psi_v \theta_v I_v + \frac{1}{2} \rho_g I_5$$

where: v is a subscript denoting nominal orientation

σ_v is the solar aperture for the v-th orientation [m^2]

ψ_v is the solar exposure modifier for the v-th orientation

θ_v is the overhang modifier for the v-th orientation

I_v is the daily average solar flux on a flat surface with orientation v [W/m^2]

I_5 is the daily average solar flux on a horizontal surface [W/m^2]

ρ_g is the ground reflectivity [fraction]

The solar apertures are calculated for walls, windows and roofs:

σ = SGF A (windows) $\qquad \sigma = \alpha_w \frac{UA}{h_o}$ (walls and roofs)

where: SGF is the solar gain factor for a window [m^2]

A is the area of the window, wall or roof [m^2]

α_w is the short wave absorptivity of the wall or roof surface

U is the U-value of the wall or of the roof/ceiling combination [W/m^2-^{o}C]

h_o is the outside film coefficient [W/m^2-^{o}C]

The solar gain factor, SGF, is defined as the ratio of transmitted solar heat gain to incident solar flux. It is similar to the concept of a shading coefficient, except that while SGF is 0.87 for a single pane window, the shading coefficient is defined to be 1.0 for the same case.

The overhang modifier, θ_v, describes the effects of overhangs, such as awnings and roof overhangs. A value of one indicates no obstruction; a value of 0.5 indicates that half as much solar flux reaches the house surface as in a totally unobstructed situation. We use the correlations developed by Balcomb et al. [10] in which the modifier is given as a function of the difference between latitude and monthly values of sun declination, with coefficients depending on the values of the separation and the overhang ratios. The interested reader should refer to [10], where full details may be found.

$$\text{Overhang modifier} = B_0 - B_1.X + B_2.X^2 - B_3.X^3 + B_4.X^4 - B_5.X^5 + B_6.X^6$$

where: X = (Latitude - Declination)/100

The solar exposure modifier, ψ_v, (which describes obstruction by landscape features) is, whenever possible, measured using a solar site meter. (Otherwise it must be eyeballed.) Typically, such a device projects the view from the house in a particular direction on a flat surface that also carries the drawing of the apparent solar path for different months of the year. The proportion of the solar path not covered by the projected landscape features is the solar exposure modifier.

Day-night distribution of solar gains

So far we have only examined daily average solar gains. Most of these gains will be felt during daytime, some of them at night. If the indoor temperature is kept constant day and night, the partition between nighttime and daytime solar gains is not overly important, except for the swing months. If, however, the thermostat is set back at night (8pm to 8am), the partition becomes very important, especially for the spring and fall months. We model this partition by use of a solar storage factor, β, the fraction of the solar gain received over 24 hours released during the night period. How this factor is used will be shown in the section on internal gains. Numerical values for the solar storage factor, dependent mostly on the house's thermal storage, are derived from correlations of computer runs using the BLAST program [11]. The correlations are based on the work of J.Y. Garnier, and are summarized below.

The energy data for various houses in various climates from the BLAST program is used to perform the following calculation. The exact energy consumption per hour as predicted by BLAST is compared to the energy gained/lost through steady state infiltration and conduction alone. In the absence of thermostat setbacks and any other internal gains, the difference is ascribed to solar storage.

$$\Delta i = E_i \left(UA + \rho c Q\right) \left(T_i^{in} - T_i^{out}\right)$$

where: Δi is the energy absorbed/released by solar storage [Wh]

E_i is the "exact" energy consumption of the house [Wh]

$K \; \rho c Q$ are the conduction and infiltration losses [Wh]

$T^{in} \; T^{out}$ are the inside and outside temperatures [°C]

i runs from 1 to 24 and indicates hourly quantities

The solar storage factor is defined as the "extra" energy released during the night period:

$$\beta = \frac{\sum_{8pm}^{8am} \Delta i}{\sum_{all\ i} \Delta i}$$

β varies with the climate, in particular with outside temperature. An empirical correlation between β and outside temperature was developed for use in the program.

$$\beta = \beta_m \left(1.64 - \frac{T_m}{38.7}\right)^{\frac{0.44}{\beta_m}} \qquad \text{for } T_m < 21$$

$$\beta = \beta_m \left(0.56 + \frac{T_m}{38.7}\right)^{\frac{0.44}{\beta_m}} \qquad \text{for } T \geq 21$$

where:

$$T_m = T + \left\{\frac{S + F - \Delta R}{K + \rho c Q}\right\}$$

β_m is a first approximation to the solar storage factor based on house mass: light, β_m = .22, medium, β_m = .28, heavy, β_m = .34

T is the daytime average outdoor temperature [°C]

S is the daily solar gain [W]

F is the daily "free heat" [W]

ΔR is the daytime sky radiation loss [W]

K is the building conduction constant [W/°C]

$\rho c Q$ is the building conduction infiltration heatloss constant [W/°C]

Sky Radiation Losses

The heat losses to the sky are calculated using the concept of an equivalent sky temperature, T_{sky}, related to the sky emissivity and the outdoor temperature through the equation:

$$T_{sky} = \varepsilon_{sky}^{1/4} \, T_o$$

where: T_o is the outside air temperature [K]

ε_{sky} is the clear sky emisssivity

The clear sky emissivity is estimated from the dew point, T_{dp}, [°C] using the equations [12]:

$$\varepsilon_{sky} = 0.727 + 0.0060 \, T_{dp} \qquad \text{Daytime}$$

$$\varepsilon_{sky} = 0.741 + 0.0062 \, T_{dp} \qquad \text{Nighttime}$$

The dew point is estimated from the monthly average dry bulb and wet bulb temperatures and from the site altitude. Standard ASHRAE psychrometric routines are used [13]. Excluding solar terms that are lumped into the concept of solar aperture, we can write an energy balance for the roof:

$$q_r = h_c (T_r - T_o) + \sigma (\varepsilon_r T_r^4 - \varepsilon_{sky} T_{sky}^4)$$

where: q_r is the total heat flow from the roof [W/m²]

h_c is the convective film coefficient [W/m²-°C]

ε_r is the roof emissivity

σ is the Stephan-Boltzmann constant [5.67 10^{-8} W/m²d-K⁴]

T_o is the absolute outside aitr temperature [K]

T_{sky} is the apparent sky temperature [K]

Using the approximation for T_o^3:

$$4 \, T_o^3 \approx \left\{ T_r^2 + \left(\frac{\varepsilon_{sky}}{\varepsilon_r}\right)^{1/2} T_o^2 \right\} \left\{ T_r + \left(\frac{\varepsilon_{sky}}{\varepsilon_r}\right)^{1/4} T_o \right\}$$

then the heat flow from the roof is:

$$q_r \approx h_c (T_r - T_o) + 4\sigma\,\varepsilon_r\,T_o^3 \left\{ T_r - \left(\frac{\varepsilon_{sky}}{\varepsilon_r}\right)^{1/4} T_o \right\}$$

Using the expression for T_{sky}, this can be rewritten:

$$q_r = h_o (T_r - T_o) + 4\sigma\,\varepsilon_r\,T_o^4 (1 - \varepsilon_{sky}^{1/4})$$

where h_o is the familiar radiative-convective film coefficient [W/m^2-°C].

$$h_o = h_c + 4\sigma\,\varepsilon_r\,T_r^3$$

The heat flow into the roof is given by:

$$q_r = U^* (T_i - T_r)$$

where: U^* is the U-value from inside the roof to the roof outer surface, i.e. without the film coefficient [W/m^2-°C]

$$U = \frac{U^* h_o}{U^* + h_o}$$

T_i is the inside temperature [°C]

Equating the expression for heat flow into the roof and that for heat flow out of the roof:

$$T_r = \frac{U\,T_i}{h_o} + \frac{U\,T_o}{U^*} - \frac{4\sigma\,\varepsilon_r\,T_o^4}{U^* + h_o} \left\{ 1 - \left(\frac{\varepsilon_{sky}}{\varepsilon_r}\right)^{1/4} \right\}$$

Solving for q_r:

$$q_r A = U A (T_i - T_o) + \frac{U A\, 4\sigma\,\varepsilon_r\,T_o^4}{h_o} \left\{ 1 - \left(\frac{\varepsilon_{sky}}{\varepsilon_r}\right)^{1/4} \right\}$$

The first term is already included in our overall conduction coefficient, K [W/°C]. The second term is a radiative loss term, which we treat as a negative internal gain.

The foregoing analysis is for horizontal surfaces; it can be shown that the radiative loss per unit surface for a vertical wall is approximately one-third that for a horizontal surface because of the smaller aspect ratio. Then the total radiation loss to the sky, ΔR [W], can be expressed as:

$$\Delta R = 4\sigma\,T_o^4 \left\{ 1 - \left(\frac{\varepsilon_{sky}}{\varepsilon_r}\right)^{1/4} \right\} \left\{ \sum_{roof} U_r\,A_r\,\varepsilon_r + \frac{1}{3} \sum_{walls} U_w\,A_w\,\varepsilon_w \right\}$$

where: $_r$ $_w$ are the long wave emissivities of the roof and walls

A_r A_w are the areas of the roof and walls [m^2]

U_r U_w are the U-values of the roof and walls [W/m^2-°C]

As shown in the next section, we include the radiative term by lumping it with the internal and solar gains. The conductive term we include with the overall conduction coefficient, K.

INTERNAL GAINS AND EFFECTIVE OUTSIDE TEMPERATURE

Internal gains are computed on a month-by-month basis, separately for night and day, as the sum of solar gains, S, and other gains from appliances and people, referred to as "free heat," F^d by day and F^n by night, minus the radiation loss to the sky, $\triangle R^d$ by day and $\triangle R^n$ by night. The ratio of internal gains and the overall building loss coefficient (encompassing both conduction and infiltration) has dimension of a temperature: it describes the outdoor temperature increase equivalent to the internal gains. This suggests the definition of effective outdoor temperature:

$$T_{eff}^{day} = T_o^d + 2 \left\{ \frac{(1-\beta)S + F^d - \Delta R^d}{K + \rho c Q} \right\}$$

where:

T_{eff}	is the effective daytime outdoor temperature [°C]
$T_o^{\ d}$	is the actual daytime outdoor temperature [°C]
	is the solar storage factor, as defined above
S	is the average daily solar gain [W]
F^d	is the average daily free heat [W]
ΔR^d	is the average daily sky radiation loss [W]
K	is the building conduction heatloss constant [W/°C]
$\rho c Q$	is the building infiltration heatloss constant [W/°C]

and similarly for the nighttime effective temperature:

$$T_{eff}^{night} = T_o^n + 2 \left\{ \frac{\beta S + F^n - \Delta R^n}{K + \rho c Q} \right\}$$

The effective outdoor temperature is that outdoor dry-bulb temperature that would produce the same heat transfer through the envelope by conduction and convection only, under steady-state conditions, as the superposition of conductive, convective and radiative heat transfer (short and long-wave) and internal "free heat" actually occuring.

THERMOSTAT SETBACKS

If there were no changes in indoor temperature between night and day, one could now proceed and calculate monthly loads, part-load efficiencies and energy consumptions. In the case of a change in indoor temperature between night and day, however, one must calculate average daytime and nighttime indoor temperatures and the quantities of heat released and absorbed by the house during such indoor temperature changes.

We define several temperatures [°C] as indicated in Fig. 1:

T_s is the thermostat setting for the day.

T_b is the room temperature at the beginning of the day.

T_e is the room temperature at the end of the day.

T_a is the average indoor temperature throughout the day.

T_{inf} is the indoor temperature that would be reached after infinite time.

T_{eff} is the effective outdoor temperature throughout the day.

An identical series of temperatures is defined for the nighttime.

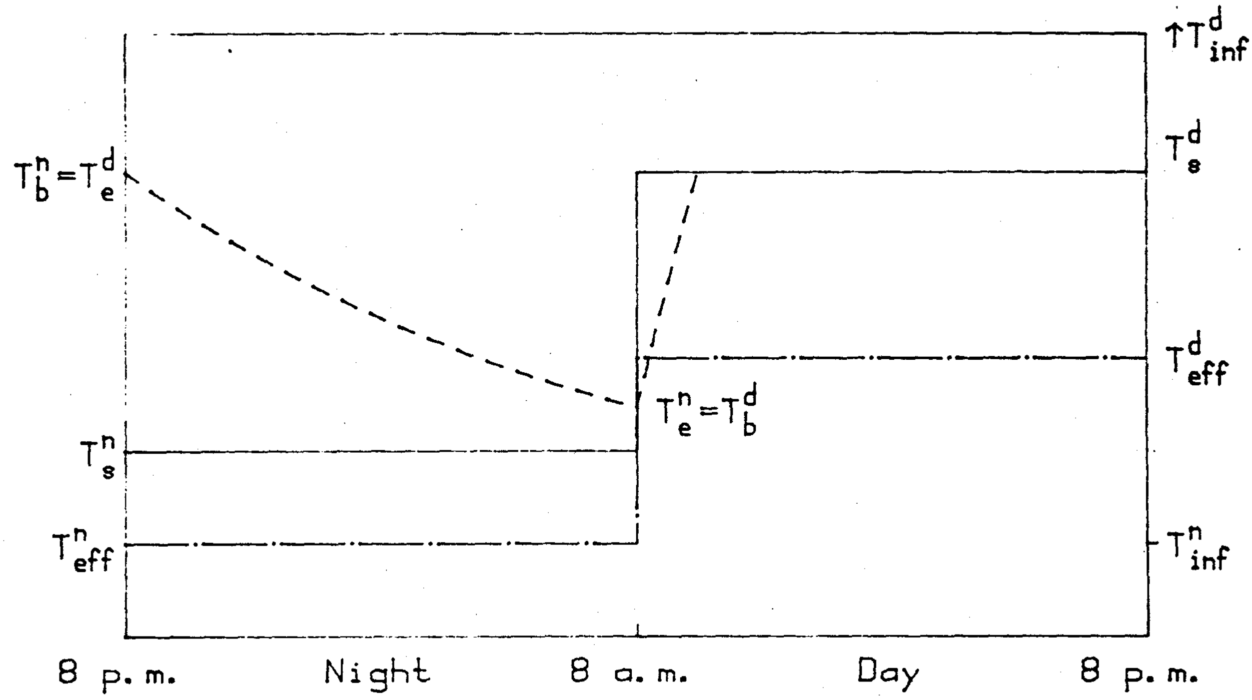

Fig. 1 Schematic Night Thermostat Setback, Heating

For simplicity in the following example we treat only the heating case where the daytime thermostat setting is higher than the nighttime setting. The program permits the three other combinations of heating and cooling, daytime and nighttime settings.

We start at 8pm when the thermostat setting is lowered and the house temperature begins to float downwards towards the outside effective temperature, T_{eff}, which is also the infinite temperature, T_{inf}:

$$T_{inf} = T_{eff}$$

The temperature during the float period is given by:

$$T(t) = T_{inf} + (T_b - T_{inf})e^{-t/\tau}$$

where: t is the time since 8pm [h]

τ is the principal time constant of the house [h]

$= M \div (K + \rho cQ)$

M is the equivalent thermal capacity of the house [Wh/^{o}C]

K is the building conduction heatloss constant [W/^{o}C]

ρcQ is the building infiltration heatloss constant [W/^{o}C]

Q is the seasonal average infiltration rate [m^3/h]

The equivalent thermal capacity, M, is estimated for three types of houses, "Light", "Medium", and "Heavy". At 8am when the equipment re-heats the house, the indoor temperature rises up towards the daytime T_{inf}, defined as:

$$T_{inf} = T_{eff} + \{ IH \div (K + \rho cQ) \}$$

where: I is a seasonal index, 1 for heating, -1 for cooling
H is the heating system capacity, as defined below

There are three cases to consider depending on the comparative magnitudes of the effective outdoor temperature:

a) The outdoor effective temperature is so low compared to the new thermostat setting, that, after some free floating, the indoor temperature reaches the new thermostat setting and heating resumes;

b) The outdoor effective temperature is comparable to the new thermostat setting and the indoor temperature floats throughout the entire period.

c) The outdoor effective temperature is higher than the thermostat setting. In this case we assume that the thermostat setback has no effect and the indoor temperature stays constant.

All three cases can be described by algebraic inequalities. The equations governing thermostat setbacks are:

Case a) — "Partial float"

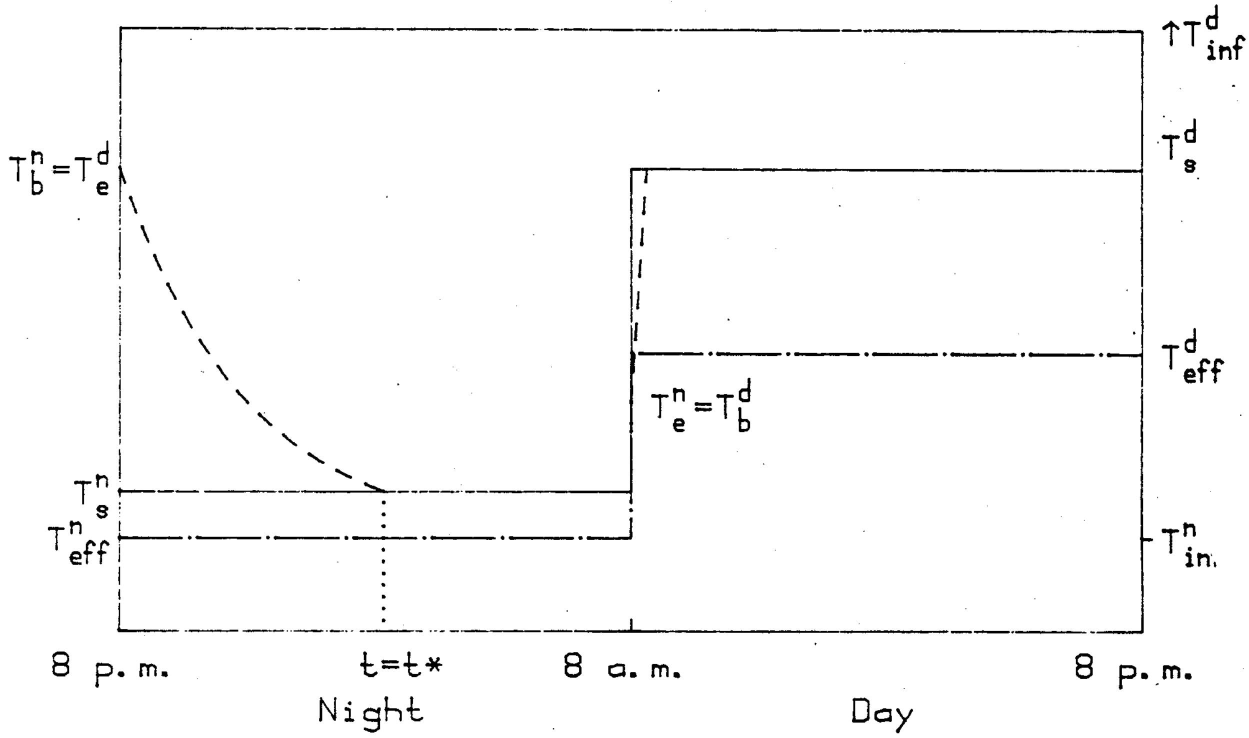

Fig. 2 Schematic Night Thermostat Setback, Heating

We have:

$$T_e = T_s$$

The time t^* at which heating resumes, is the time at which the indoor temperature equals the setpoint temperature, i.e.:

$$T_s - T_{inf} = \left(T_b - T_{inf}\right) e^{-t^*/\tau} \quad ; \quad t^* = \tau \ln (1 + x)$$

Thus partial float occurs if the time at which heating resumes is less than 12 hours. The average temperature, T_a, is given by:

$$T_a = T_s + \left(T_b - T_s\right) \frac{\tau}{12} \left\{1 - \frac{\ln(1 + x)}{x}\right\}$$

$$x = \frac{T_b - T_s}{T_s - T_{inf}}$$

Case b) — "All-float"

The temperature floats exponentially for the entire 12 hour period, as illustrated in Figure 1.

$$T_e = T_b - (T_b - T_{inf})\ (1 - e^{-12/\tau})$$

$$T_a = T_{inf} + (T_b - T_e)\ (\div 12)$$

The condition for "all-float" is that the final nighttime temperature, T_e, is greater than the nighttime thermostat setpoint, T_s.

Case c) — "No float"

There are no temperature changes in this condition.

$$T_e = T_b = T_s = T_a$$

VARIABLE-BASE DEGREE-DAYS

After the indoor average night and day temperatures have been established for each month, the monthly heating or cooling degree-days are determined. We use an empirical, three-coefficient correlation formula that relates the monthly degree-days to the monthly average temperature. We chose to develop our own correlation rather than use an existing one, e.g. [14], because of our need to differentiate between night and day.

$$DD = \frac{1}{2} \left\{ [\Delta T]_+ + \mu[\lambda - |\Delta T|]_+^{\nu} \right\}$$

$$\Delta T = I \left(T_a - T_{eff} \right)$$

where: DD are the degree-days per day [°C]

I is a seasonal index, 1 for heating, -1 for cooling

μ ν are dimensionless empirical degree-day coefficients (two for each combination of heating/cooling & day/night)

λ is an empirical degree-day temperature (one for each combination of heating/cooling & day/night

$[X]_+$ is equal to X when X is greater than zero, otherwise it is zero

T_a is the average indoor temperature [°C]

T_{eff} is the effective outdoor temperature [°C]

Table 3: Empirical Degree-day Coefficients for Two Sample Cities

City		μ^d	μ^n	ν^d	ν^n	λ^d	λ^n
Minneapolis	heat	$3.305\ 10^{-2}$	$1.147\ 10^{-4}$	1.780	3.135	8.9	16.7
	cool	$4.710\ 10^{-4}$	$7.427\ 10^{-2}$	2.808	1.608	14.8	5.7
Los Angeles	heat	$1.823\ 10^{-4}$	$1.085\ 10^{-3}$	2.549	3.157	13.9	5.6
	cool	$2.683\ 10^{-12}$	$1.600\ 10^{-14}$	8.702	9.939	12.2	13.9

If there were no thermostat setback, the heating or cooling load L^* [Wh/day] would be:

$$L^* = 24\ (K + UA_s + \rho cQ)\ DD$$

where: UA_s is the UA value of all passive solar components [W/°C]

K is the building conduction heatloss coefficient [W/°C]

ρcQ is the building infiltration heatloss coefficient [W/°C]

Where there is a heating season thermostat setback, the maximum amount of heat H_{max} [Wh/day or Wh/night] released or absorbed during a change in thermostat setting is:

$$Hmax = M \left| T_s^d - T_s^n \right|$$

where: M is the thermal mass of the house

T_s^d is the daytime thermostat setting [°C]

T_s^n is the nighttime thermostat setting [°C]

The actual amount of stored heat, [Wh/day or night] released or absorbed is the lesser of H_{max} and L* (evaluated for the period during which the temperature floats):

$$H^* = \text{minimum}\ [L^*_{float}\ ;\ H_{max}\ ]$$

Thus, the actual heating load is calculated as:

$$L_{float} = I(L^* - H^*)$$

$$L_{recharge} = I(L^* + H^*)$$

Cooling loads are calculated similarly. However, note that cooling loads are negative numbers.

PASSIVE AND ACTIVE SOLAR SYSTEMS

Solar energy systems are incorporated into the calculation by evaluating how much energy they supply to the house, so that the net load supplied by the auxiliary heating equipment can be determined.

Passive solar systems

The passive solar systems addressed, (restricted here to Trombe walls, water walls, and greenhouses) are treated using the correlation method developed by Balcomb et al.[10] to which the interested reader should refer. Simple direct gain systems are treated as windows, as described above in the "Radiative Heat Exchanges" section. A quantity called the solar savings fraction SSF, which is the fraction of the load that is supplied by the solar system, is calculated as a function of the solar load ratio and the load collector ratio. The daytime heating load, L_d, that had been calculated for the building is then reduced:

$$L^d \text{ becomes } L^d (1 - SSF)$$

The nighttime heating load is similarly reduced:

$$L^n \text{ becomes } L^n (1 - SSF)$$

Active Solar Systems

Active solar systems for space and water heating are are treated using the f-chart method from reference [15], to which the interested reader should refer. f is the fraction of monthly space and water heating loads supplied by solar energy. The space and water heating loads are reduced by a factor (1-f).

ENERGY CONSUMPTION

Heating and Cooling Capacities

These heating and cooling capacities are functions of steady-state efficiency, distribution losses and thermodynamic characteristics of the heating or cooling equipment. The daytime heating capacity is calculated from:

$$H = R_H \eta_s (1 - d_H) \phi_{1H}$$

where: H is the daytime heating capacity [W]

R_H is the heating equipment rated input capacity [W]

η_s is the steady-state equipment efficiency [fraction]

d_H is the overall heat distribution loss from ducts [fraction]

ϕ_{1H} is an empirical function correlating equipment caapacity with indoor-outdoor temperature difference

The same equation is used to calculate nighttime heating capacity. The function ϕ_{1H} can be determined from empirical data or from detailed system simulation. For gas and oil burning equipment we use $\phi_{1H} = 1.0$. For heat pumps, we currently use a correlation developed by James Mass at LBL based on data from the National Bureau of Standards [16]. This source is also used for ϕ_{1C}; ϕ_{2H}; ϕ_{2C}; ϕ_{3H}; and ϕ_{3C} below. The data in [16] are in ^oF, which is why these units are used for ΔT.

$$\phi_{1H}(\Delta T) = \Delta T\{(1.4654\ 10^{-7}\ \Delta T + 3.5489\ 10^{-5})\ \Delta T + 1.10553\ 10^{-2}\}\Delta T + 0.3867975$$

where: T_s is the thermostat setting [^oC]

T_o is the outdoor temperature [^oC]

ΔT is $1.8\ (T_o + 21.1 - T_s)$ [°F]

The cooling capacity is calculated from:

$$C = -R_C (1 - d_C) \phi_{1C}$$

where: C is the daytime cooling capacity [W]
R_C is the cooling equipment rated output capacity [W]
d_C is the overall cooling equipment distribution loss [fraction]
ϕ_{1C} is a function describing the dependence of the equipment capacity on outdoor wet-bulb and dry-bulb temperatures

Note that the cooling capacity is a negative number.

Part load ratio

The part load ratio is important to determine the part load efficiency of the heating or cooling equipment. In our algorithm the part load ratio is defined simply as:

$$\chi = \frac{L}{C}$$

where: χ is the part-load ratio
L is the heating or cooling load [W]
C is the heating or cooling capacity [W]

Heating and Cooling efficiency

Heating and cooling efficiencies are evaluated on the basis of rated, or steady-state efficiencies, operating conditions (temperatures and part loads) and distribution losses. Thus, our definition of efficiency is for the whole system, from fuel to heat delivered to or removed from indoors. For heating systems, the daytime efficiency is described by:

$$\eta_H = \eta_s \left(1-d_H\right) \frac{\chi}{\phi_{2H}\ \phi_{3H}}$$

where: ϕ_{2H} is an equipment-specific function describing the efficiency dependence on indoor-outdoor temperature difference
ϕ_{3H} is a similar function describing the dependence on part-load ratio
χ is the part-load ratio

For all heating equipment except heat pumps we use $\phi_{2H} = 1$. For heat pumps we use a correlation derived from data in [16]. For all heating equipment except heat pumps we use ϕ_{3H} equal to the part load ratio, χ. For heat pumps we use a correlation derived from data in [16].

For cooling systems the efficiency is given by:

$$\eta_C = \mathrm{COP}\ (1 - d) \frac{\chi}{\phi_{2C}\ \phi_{3C}}$$

Heating and Cooling Energy Consumption

We are now ready to compute the monthly energy consumption for day and night, heating and cooling [Wh/month]. The four equations are:

$$E_h^d = N\ L_h^d/\eta_h^d \qquad E_c^d = N\ L_c^d/\eta_c^d$$

$$E_h^n = N\ L_h^n/\eta_h^n \qquad E_c^n = N\ L_c^n/\eta_c^n$$

where: E is the monthly heating and cooling energy use [Wh]
N is the number of days in the month
L is the daytime or nighttime load [Wh]
is the efficiency

Other Energy Consumption

i) The energy used for water heating is calculated as:

$$E = S + \{0.04844 \times U \times (T - 12.8) \times 1/n\}$$

where: S is the standby losses [W]
U is the daily hot water use [liters]
T is the water thermostat setting [^{o}C]
is the water heater efficiency [fraction]

The free heat contributed by the water heater is the energy use times a location effect, L, where L is 1.0 for the living space, 0.6 for the basement, 0.3 for the crawl space and 0.5 for the garage.

ii) The energy used by the range and clothes dryer [W] and their free heat contribution [W] are given in the table below:

	Free Heat [W]	Energy Use [W]
Electric range	70	86
Gas Range	123	171
Electric dryer	35	117
Gas dryer	32	161

iii) The electricity used by the refrigerator [kWh/month] is an input. 90% of the energy is assumed to remain in the house as free heat.

iv) Each daytime occupant is assumed to contribute 117 W to the free heat; each nighttime occupant adds 88 W .

DISCUSSION

This methodology has been applied to the Hastings Ranch house [17] and compared to the predictions obtained with DOE-2.1 for seven U.S. cities representing a wide variety of climatic conditions: Washington (D.C.), Albuquerque (N.M.), Minneapolis, San Francisco, Boise (Idaho), Seattle, and Portland (Oregon). The results of the comparison are shown in Figures 3 through 6 with monthly heating and cooling loads predicted by CIRA plotted on the ordinate, those predicted by DOE-2.1 plotted on the abscissa. Figs. 3&4 are for a constant indoor temperature, Figs. 5&6 for a 2.8 ^{o}C (5 ^{o}F) thermostat setback. The scales for both y- and x-axes are logarithmic, due to the large range of loads computed for the different cities, over ten-to-one for cooling, and 20-to-one for heating. The solid line indicates the locus of perfect correspondence, the dashed lines indicate $\pm$ 20% discrepancy.

The outliers at the low end of the scale are caused by a particularity of CIRA: while DOE-2.1 calculates both heating and cooling loads for every month, CIRA calculates only that load that it estimates is likely to be higher. In a few cases this criterion of advance choice fails. Of course, CIRA could calculate both heating and cooling loads for each month and then, having compared the two, use the one that is higher; however, this would entail an additional approximately six seconds calculation time.

Based on the data in the top figures, the difference between CIRA and DOE-2.1 predictions is 0.9% $\pm$ 7.3% for heating and 3.5% $\pm$ 10.5% for cooling. For the data in the bottom figures, the differences are 6.5% $\pm$ 8.5% and 13.7% $\pm$ 10.5%, for heating and cooling, respectively. All percentages are based on the average DOE2.1 predictions. The systematic discrepancies that seem to correlate with the cooling season and thermostat setbacks could be traced to a variety of causes, such as the treatment of thermal mass or solar gains, to name a few. However, rather than refining the model much further using DOE-2.1 as a reference, future research will concentrate on the comparison of CIRA with actual data.

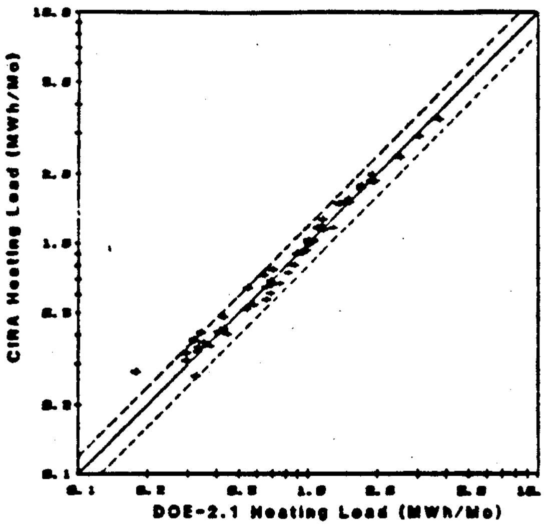

Fig. 3: Comparison CIRA / DOE-2.1 Heating Loads, Hastings Ranch House, 7 Cities.

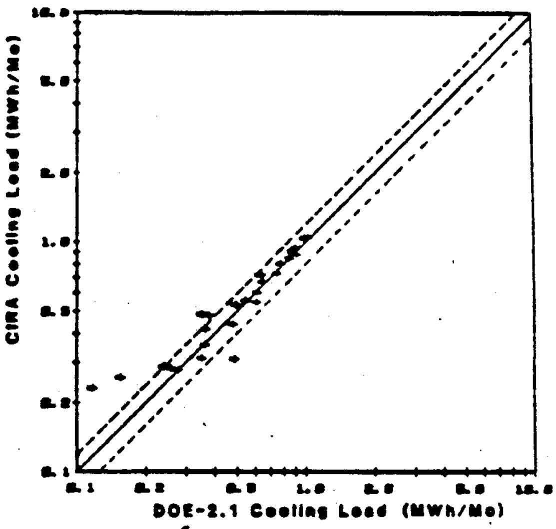

Fig. 4: Comparison CIRA / DOE-2.1 Cooling Loads, Hastings Ranch House, 7 Cities.

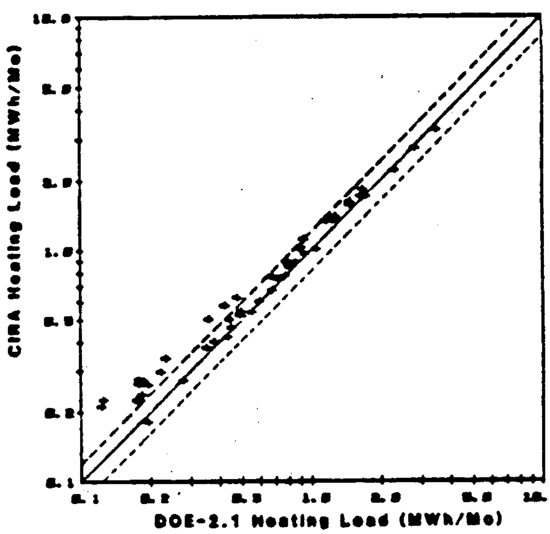

Fig. 5: Comparison CIRA / DOE-2.1 Heating Loads, Hastings Ranch House, 7 Cities, 2.8 °C Night Thermostat Setback.

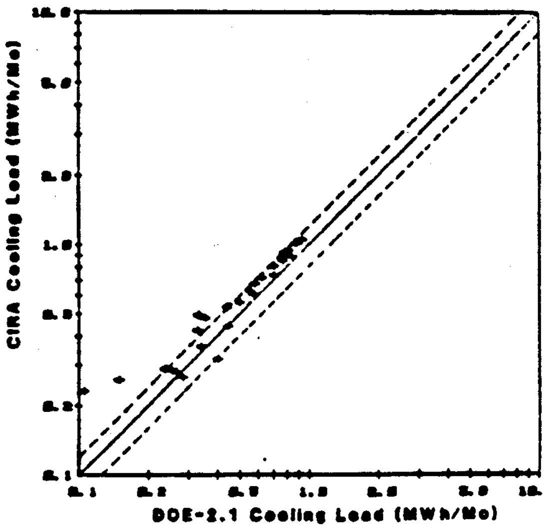

Fig. 6: Comparison CIRA / DOE-2.1 Cooling Loads, Hastings Ranch House, 7 Cities, 2.8 °C Night Thermostat Setback.

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