Title

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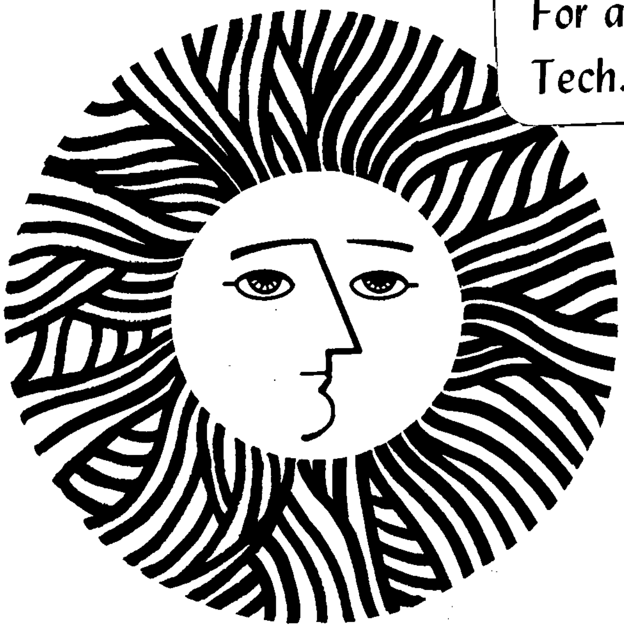

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A Simplified Method for Calculating Heating and Cooling Energy in Residential Buildings

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ABSTRACT

We have recently developed a microcomputer-based program, "Computerized, Instrumented, Residential Audit" (CIRA), for determining economically optimal mixes of energy-saving measures in existing residential buildings. This program requires extensive calculation of heating and cooling energy consumptions. In this paper, we present a simplified method of calculation that satisfies the requirements of speed and memory imposed by the type of 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 base temperatures used in calculating the degree-days and degree-nights are derived from thermostat settings, solar and internal gains, sky radiation losses and the thermal characteristics 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 -nights for different base temperatures are evaluated by using a climate-specific empirical correlation with monthly average daily and nightly temperatures. Predictions obtained by this method and by DOE-2.1 are compared for the so-called Hastings ranch house for seven different climates in the United States. Heating and cooling energy consumptions predicted by CIRA lie generally within ±10% of DOE-2.1 predictions.

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INTRODUCTION

An energy audit procedure, CIRA, for determining the economically optimal retrofit package for a given residential building has been developed. CIRA is a microcomputer-based, interactive, site- and house-specific package addressing conservation and solar measures. Energy savings for all retrofit packages considered during the audit are estimated with a new heating and cooling model. In addition to the usual criteria of accuracy and flexibility, this model also has to take into account the limitations of memory and speed imposed by the microcomputer, and, in addition, must be able to perform, in short order, many yearly energy estimations needed for economic optimization. This paper describes the heating and cooling model developed for this audit.

To speed up the calculations some of the calculations, such as air infiltration, total solar radiation distribution and degree-day coefficients, are done in advance for "standard conditions." In an actual application, the precalculated values are corrected to reflect the building and site characteristics under consideration.

Highlights of the heating and cooling algorithms are:

- variable-base degree-days calculated from monthly temperatures using an empirical correlation formula;

- the concept of an effective outdoor night and day temperature that is a function of outdoor temperature, solar and other internal gains, sky radiation losses, thermostat setbacks and house thermal time constant;

- the calculation of effective conductances for below-ground walls and floors;

- the concept of an effective leakage area and a leakage distribution of the house that, together with terrain information, is used to correct the pre-calculated air infiltration values 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 calculation of output capacities and seasonal efficiencies of heating and cooling equipment, as functions of indoor and outdoor temperature and of part-load.

In a previous paper[1], we described some aspects of a similar calculation procedure. 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.

We now review, step by step, the calculation algorithms used in CIRA. The basic calculation time step is one calendar month. Thus, unless otherwise stated, all variables are monthly averages; in addition, several variables are divided between day and night, defined, respectively, as the periods separated by 8 a.m. and 8 p.m.

HEAT CONDUCTION AND CONVECTION

Conduction

A heat conduction coefficient is computed as a sum of the conduction through all individual envelope components, such as walls, windows, doors, etc.

$$K = \sum_{i=0}^{i_{tot}} U_i A_i \qquad (1)$$

where: U_i is the U-value of the i-th component [$W/^{o}C/m^2$];
A_i is the Area of the i-th component [m^2].

the U-values for below-grade walls and floors are determined using an algorithm developed by Muncey and Spencer[2] and adapted to microcomputer use by Kusuda[3].

Air Infiltration

To compute air infiltration we use the model developed by Sherman and Grimsrud[4]. This 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 fitting parameter is the leakage area, or

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

where: Q_4 is the air flow measured at a pressure difference of 4 Pa;
ρ is the density of air [kg/m^3];
ΔP is the pressure difference (4 Pa).

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

$$L = \sum_{i=0}^{i_{tot}} l_i A_i \qquad L_F = \sum_{i_F=0}^{i_{tot}} l_{i_F} A_{i_F} \qquad L_C = \sum_{i_C=0}^{i_{tot}} l_{i_C} A_{i_C} \tag{3}$$

where: L, L_F, L_C are the total, floor and ceiling leakage areas, respectively;
l_i is the specific leakage area of the i-th envelope component;
i_F, i_C denote envelope components in the floor and ceiling, respectively.

When part or all of the leakage areas are measured, the calculated leakage areas above are scaled accordingly.

The infiltration for each month is calculated as a superposition of stack and wind effects. Stack and wind effects precalculated for a reference house in reference surroundings are corrected to reflect actual circumstances and actual temperature difference:

$$Q = L \sqrt{(c_s q_s)^2 + (c_w q_w)^2} \tag{4}$$

where: q_s, q_w are the monthly specific infiltrations due to stack and wind, respectively [$m^3/hr/cm^2$];
c_s, c_w are factors to correct for the non-standard house in non-standard surroundings.

The correction factors, c_s, c_w, have been described elsewhere[1].

RADIATIVE HEAT EXCHANGES

Solar gains

The solar gains 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.

$$S = \sum_{v=1}^{5} \sigma_v \psi_v \left(I_v + \frac{\rho_g}{2} I_5 \right) \qquad (5)$$

where: v is a subscript denoting nominal orientation (1=N, 2=E, 3=S, 4=W, 5=Horiz.);
- 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;
- I_v is the daily average solar flux on a vertical surface with orientation v [W/m^2].
- ρ_g is the ground reflectivity.

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

$$\sigma = SGF\ A \quad \text{(windows)} \qquad \sigma = \alpha_W \frac{U}{h_o} A \quad \text{(walls, roofs)} \qquad (6)$$

where: SGF is the solar gain factor of the window [m^2];
- A is the area of the window, wall or roof;
- 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 [$W/^oC/m^2$];
- h_o is the outside film coefficient [$W/^oC/m^2$].

The solar gain factor 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 the latter is defined as unity for a single pane window. For a wall or a roof/ceiling section, we compute the solar aperture as:

The solar exposure modifier, ψ_v, is a combination of the effect of trees and other landscape features and 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. For overhangs, we use the correlations developed by Balcomb[5]. The obstruction by landscape features is, whenever possible, measured using a solar site meter. 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 covered by the projected landscape features is a direct measure of 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. If, however, the thermostat is set back at night, the partition becomes very important, especially during the spring and fall months. We simulate this partition by the concept of a solar storage factor, β. See the equation below for the internal gains for an exact definition. Numerical values for the solar storage factor, dependent mostly on the house's thermal storage, are derived from correlation of computer runs using the BLAST program[6].

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:

$$T_{sky} = \epsilon_{sky}^{\frac{1}{4}} T_o \tag{7}$$

The clear sky emissivity is estimated from the dew point, T_{dp}, using the equations[7]:

$$\epsilon_{sky} = 0.741 + 0.0062\, T_{dp} \qquad \text{(night)} \tag{8.1}$$

$$\epsilon_{sky} = 0.727 + 0.0060\, T_{dp} \qquad \text{(day)} \tag{8.2}$$

It can be shown that the sky losses can be approximated by a steady negative internal gain, ΔR[8]:

$$\Delta R = 4\sigma T_o^4 \left(1 - \epsilon_{sky}^{\frac{1}{4}}\right) \left(\sum_{roof} A_{roof}\, \epsilon_{roof} + \sum_{walls} A_{walls} \frac{\epsilon_{wall}}{3} \right) \tag{9}$$

where: ϵ_{roof}, ϵ_{walls} are the long-wave emissivities of the roof and the walls, respectively.

As shown in the next section, we include the radiative term by lumping it with the internal and the solar gains.

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," $F^{d,n}$, minus the radiation loss to the sky, $\Delta R^{d,n}$. 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. Thus the definition of effective outdoor temperature:

$$T_f^d = T_o^{\ d} + \frac{2\ (1-\beta)\ S + F^d - \Delta R^d}{K + \rho c Q} \quad \text{(Day effective temperature)} \qquad (10.1)$$

$$T_f^n = T_o^{\ n} + \frac{2\ \beta\ S + F^n - \Delta R^n}{K + \rho c Q} \quad \text{(Night effective temperature)} \qquad (10.2)$$

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 consumtptions. 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 stored in the house structure released and absorbed during such indoor temperature changes.

Let us define several indoor temperatures, as indicated in Fig. 1:

$T_s^{d,n}$ is the thermostat setting for day or night;

$T_b^{d,n}$ is the room temperature at the beginning of a day or night period;

$T_e^{d,n}$ is the room temperature at the end of a day or night period;

$T_a^{d,n}$ is the average outdoor temperature throughout the day or night period;

$T_\infty^{d,n}$ is the indoor temperature that would be reached after infinite time.

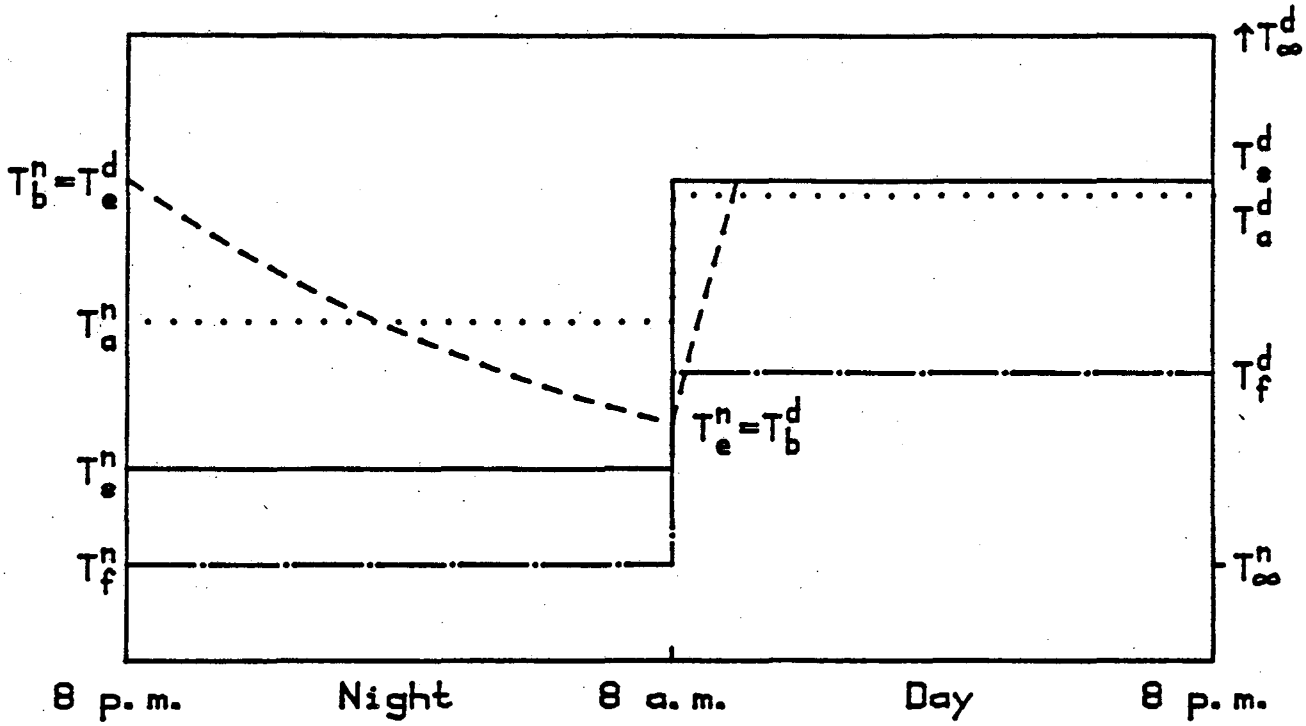

Fig. 1: Schematic Night Thermostat Setback, Heating

We start with the time period (night or day) when the thermostat setting is being "relaxed", in other words, when the indoor temperature is free floating. Then, the temperature T_∞^{float} is:

$$T_\infty^{float} = T_f^{float} \tag{11.1}$$

The following time period, when the equipment re-heats (or re-cools) the indoors, the temperature T_∞^{rechg} is:

$$T_\infty^{rechg} = T_f^{rechg} + IND_{h,c} \frac{C_{h,c}^{rechg}}{K + \rho c Q} \tag{11.2}$$

where: $IND_{h,c}$ is a seasonal index (=1 for heating, =-1 for cooling).

The float period is normally at night, although the opposite may occur when the thermostat setting is relaxed during the day.

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 of the preceding period. 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"

$$T_e^{d,n} = T_s^{d,n} \tag{12.1}$$

$$T_a^{d,n} = T_s^{d,n} + (T_b^{d,n} - T_s^{d,n}) \frac{\tau}{12} \left(1 - \frac{\ln(1+X)}{X}\right) \tag{12.2}$$

where

$$X = \frac{T_b^{d,n} - T_s^{d,n}}{T_s^{d,n} - T_\infty^{d,n}} \quad \text{and} \quad \tau = \frac{M}{K + \rho c Q_y} \tag{12.3}$$

where: τ is the principal time constant of the house [hr];
M is the equivalent thermal capacityl of the house [Wh/°C];
Q_y is the yearly average air infiltration [m^3/hr].

Case b) — "All-float"

$$T_e^{d,n} = T_b^{d,n} - (T_b^{d,n} - T_\infty^{d,n}) \left[1 - e^{\frac{-12}{\tau}}\right] \tag{13.1}$$

$$T_a^{d,n} = T_\infty^{d,n} + (T_b^{d,n} - T_e^{d,n}) \frac{\tau}{12} \tag{13.2}$$

Case c) — "No float"

$$T_e^{d,n} = T_s^{rechg} \tag{14.1}$$

$$T_a^{d,n} = T_s^{rechg} \tag{14.2}$$

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. To this purpose, we use an empirical, three-coefficient correlation formula that relates the monthly degree-days to the monthly average temperature. The equation is:

$$DD^{d,n}_{h,c} = \frac{1}{2}\left[[DT]_+ + \mu^{d,n}_{h,c}\,[\lambda^{d,n}_{h,c} - |DT|]_+^{\nu^{d,n}_{h,c}}\right] \qquad (15.1)$$

where

$$DT = IND_{h,c}\,(T^{d,n}_a - T^{d,n}_f) \qquad (15.2)$$

where: $IND_{h,c}$ is the seasonal index denoting heating (+1) or cooling (-1).

$\lambda^{d,n}_{h,c}$, $\mu^{d,n}_{h,c}$, $\nu^{d,n}_{h,c}$ are the empirical degree-day coefficients (three for each combination of heating, cooling, day and night);

$[X]_+$ is equal to X when X>0, zero otherwise.

The dimensions of the degree-days are ^oC-day/day, or simply ^oC. Equations 15 are used to evaluate degree-days for each month, by substituting the proper value of the monthly average temperatures in DT. Without taking into account the heat released to or absorbed from the structure during a change in thermostat setting, the steady-state heating or cooling loads (in Wh/day) would be:

$$LDN^{d,n}_{h,c} = 24\,(K + \rho cQ)\,DD^{d,n}_{h,c} \qquad (16)$$

The actual heating or cooling loads, $LD^{d,n}_{h,c}$, are calculated as:

$$LD^{float}_{h,c} = LDN^{float}_{h,c} - MIN[M\,|T^d_{s_{h,c}} - T^d_{s_{h,c}}|\,,\,LDN^{float}_{h,c}] \qquad (17.1)$$

$$LD^{rechg}_{h,c} = LDN^{rechg}_{h,c} + MIN[M\,|T^d_{s_{h,c}} - T^d_{s_{h,c}}|\,,\,LDN^{rechg}_{h,c}] \qquad (17.2)$$

where: M is the equivalent thermal mass of the house, [Wh/^oC].

Thus, in the floating period, the actual heating or cooling load is the steady-state load minus the heat stored in the structure or the steady-state load, whichever is less (plus that quantity during the recharging period).

HVAC-SYSTEMS

Heating and Cooling Capacities

Heating and Cooling Capacities are the maximum heating and cooling powers available to add or extract heat to or from the house, $C_h^{d,n}$ and $C_c^{d,n}$, respectively. Obviously, they are functions of steady-state efficiency, distribution losses and thermodynamic characteristics of the heating or cooling equipment8.

Heating and Cooling efficiency

Heating and cooling efficiencies, $\eta_h^{d,n}$ and $\eta_c^{d,n}$, 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 consumed by the HVAC system to heat delivered to or removed from indoors. The part load ratio is important to determine the part load efficiency of the heating or cooling equipment. In our algorithm it is defined simply as:

$$x_{h,c}^{d,n} = LD_{h,c}^{d,n} \, / \, C_{h,c}^{d,n} \qquad (18)$$

ENERGY CONSUMPTION

Finally, we are ready to compute the monthly energy consumption for day and night, heating and cooling (in Wh/mo):

$$E_{h,c}^{d,n} = N \, LD_{h,c}^{d,n} \, / \, \eta_{h,c}^{d,n} \qquad (19)$$

where: N is the number of days for the month.

DISCUSSION

This methodology has been applied to the Hastings Ranch house[9] 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 Figs. 2-5 with monthly heating and cooling loads predicted by CIRA plotted on the ordinate, those predicted by DOE-2.1 plotted on the abscissa. Figs. 2-3 are for a constant indoor temperature, Figs. 4-5 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 a doubling of the calculation time, presently at 5 seconds for a yearly calculation.

Based on the data in the top figures, the difference between CIRA and DOE-2.1 predictions is 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.

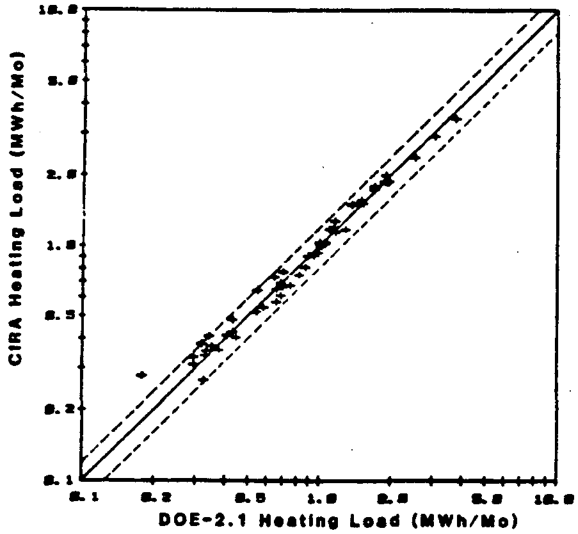

Fig. 2: Comparison CIRA / DOE-2.1 Heating Loads, Hastings Ranch House, 7 Cities.

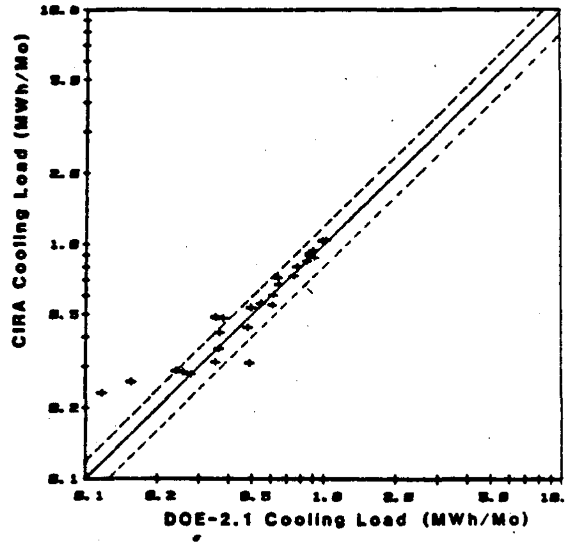

Fig. 3: Comparison CIRA / DOE-2.1 Cooling Loads, Hastings Ranch House, 7 Cities.

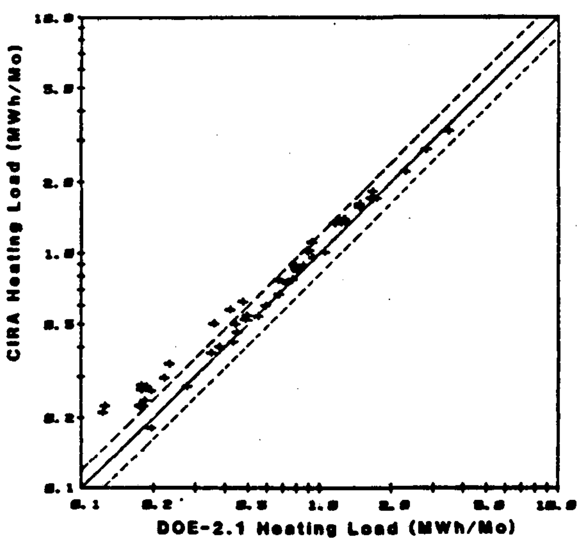

Fig. 4: Comparison CIRA / DOE-2.1 Heating Loads, Hastings Ranch House, 7 Cities, 2.8 °C Night Thermostat Setback.

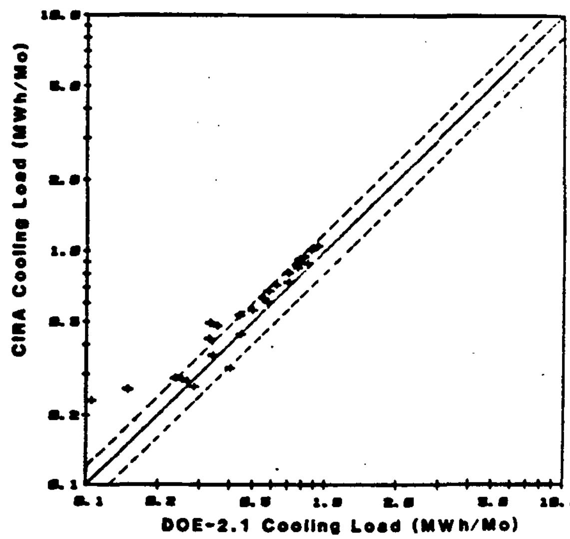

Fig. 5: Comparison CIRA / DOE-2.1 Cooling Loads, Hastings Ranch House, 7 Cities, 2.8 °C Night Thermostat Setback.

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