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VARIABLE-BASE DEGREE-DAY CORRECTION FACTORS FOR ENERGY SAVINGS CALCULATIONS

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ABSTRACT

Heating degree-days are often used as a climatic measure in building energy calculations. To account for the effects of solar and internal gains, degree-days at a base temperature, lower than the heating set point temperatures are used, or the number of degree days is adjusted downward by a degree-day correction factor. In this paper, we present a theoretical derivation, which demonstrates that ASHRAE C_d factors are not the appropriate correction factors for the calculation of energy savings from envelope conservation measures. The results of this derivation can be used to develop new correction factors appropriate for savings calculations.

INTRODUCTION

A large number of home energy audits have been completed by utilities across the country. Many audit procedures are derived from the Residential Conservation Service (RCS) Model Audit (DOE 1980) which includes use of ASHRAE C_d degree-day correction factors in predicting savings due to energy conservation retrofits. The authors have worked on verifying portions of the RCS model audit by comparing it with hourly simulations. In the course of these verification efforts, we have investigated the use of degree-day correction factors in the calculation of energy savings and building heating loads. In this paper, the term "energy savings" refers to the difference between heating loads before and after application of an energy conservation measure. An important distinction is that "savings" are calculated as a difference, while "loads" are calculated as an absolute amount. Some aspects of load calculations are discussed to demonstrate and support our conclusions regarding savings calculations, but many related issues regarding load calculations are beyond the scope of this paper and are mentioned only briefly.

Three types of degree-day correction factors are discussed: C_d and C_v factors for heating load calculations and C_s factors for savings calculations. The C_d factor is used in the ASHRAE modified degree-day method. The C_v factor, as defined in this paper, is based on the variable-base degree-day method. The C_s factor is derived from variable-base degree-day theory.

The results of this study are not presented as values recommended for use in practice. They are intended to illustrate typical and theoretical values of C_d, C_v, and C_s, including magnitudes, differences, and variations. The specific results given here depend on (1) assumed values of utilizable solar and internal gains, (2) degree-days based on TMY weather data for three locations, and (3) assumed building characteristics. Thus, values used with specific buildings and climates should be independently developed.

CALCULATION OF HEATING LOADS

Degree-day-based methods have long provided simple techniques for the calculation of building heating loads. The two approaches in common use include the modified degree-day method and the variable-base degree-day method. These will be discussed in the following sections.

The Modified Degree-Day Method

The following expression for annual heating load can be derived from the ASHRAE (1981) modified degree-day method:

$$Q = 24(UA_b)(HDD_{65})C_d \qquad [1]$$

where

Q = annual heating load

UA_b = overall building heat-loss coefficient, including infiltration and losses to ground

HDD_{65} = annual heating degree days to base temperature 65 F (18.3°C)

C_d = degree-day correction factor.

The C_d factor in Equation 1 is needed primarily because degree days are used to a 65 F (18.3°C) base temperature (Reeves 1981), a value based on work done in the 1930s when the degree-day method was originally developed. For modern residential buildings, lower base temperatures should be used because of better insulation, higher internal gains, and lower thermostat settings. Because degree-day data were not available for lower base temperatures until recently (ASHRAE 1981), the C_d factor was introduced in the modified degree-day method. C_d is a multiplier, less than 1.0, which modifies HDD_{65} to a smaller number of degree days, thereby approximating the effect of a lower base temperature. Appropriate base temperatures are a function of building characteristics and use. The ASHRAE C_d factors, however, are given only as a function of climate. Therefore, the C_d factors include assumptions of average building characteristics and use, and Equation 1 will be in error for buildings that do not match the C_d assumptions. Factors that affect the value of C_d are described in Reeves (1981).

The Variable-Base Degree-Day Method

The variable-base degree-day (VBDD) method involves determining the appropriate number of degree-days for a specific building in a given climate (ASHRAE 1981). Predictions of annual heating loads based on the VBDD method compare well with results from hourly simulation programs (Kusuda et al. 1981). The VBDD method is applied by first determining the balance-point temperature, T_{bal}, for a particular building. T_{bal} is defined as the outdoor temperature above which heating is not required on the average, because heat losses are balanced by internal and solar gains. T_{bal} can be calculated as:

$$T_{bal} = T_{set} - (I + S)/UA_b \qquad [2]$$

where

T_{bal} = balance-point temperature

T_{set} = thermostat set point temperature

I = average hourly utilizable internal gains

S = average hourly utilizable solar gains.

Heating loads are assumed to be proportional to degree days to a base temperature equal to the balance-point temperature. Then according to the VBDD method, building heating loads are calculated as:

$$Q = 24(UA_b)(HDD_{T_{bal}}) \qquad [3]$$

where

$HDD_{T_{bal}}$ = heating degree days with base temperature equal to T_{bal}.

The VBDD method does not explicitly account for hour-to-hour or day-to-day variability of solar or internal gains, nor does it account for the degree of coincidence of gains with hourly heating loads. Consequently, there is some uncertainty as to the proper determination of average utilizable solar and internal gains. The effect of solar gains is accounted for more explicitly in various passive solar calculative methods. The issue of coincidence is addressed in the concept of sol-air heating degree-days recently developed by Erbs et al. (1983). The utilizability of solar gains, including the effect of thermal mass, is addressed in correlation-based techniques such as the solar-load-ratio method (Balcomb et al. 1981) and the unutilizability method (Monsen et al. 1981). Energy savings due to a particular conservation measure can be calculated in a two-step process by using these passive solar methods to calculate heating loads before and after a retrofit is applied to a building. In this paper, however, we discuss degree-day correction factors to be used in a simple, one-step approach and the applicability of this method to certain types of buildings.

Figure 1 shows heating degree-days plotted as a function of balance-point temperature, based on TMY and ersatz TMY data (Hall et al. 1978) for Atlanta, Denver, and Madison. The data have been fitted by using the following quadratic expression:

$$HDD_{T_{bal}} = A + B(T_{bal}) + C(T_{bal})^2 , \qquad [4]$$

where A, B, and C are location-dependent constants. The quadratic form of Equation 7 was used because it fit the heating degree-day data extremely well for the three cities and the base temperature range of interest.

In our original study, TMY data was used because it facilitated heating load comparisons with simulations based on TMY weather tapes. The A, B, and C coefficients can also be developed from long-term weather data or from analytical relationships for degree-days as given by Thom (1954) and Erbs et al, (1981).

C_v Factors from the VBDD Method. To demonstrate the effects of degree-day correction factors on the calculation of loads and savings, we define C_v factors to be building-specific C_d factors calculated according to the VBDD method. The new correction factor can be defined as:

$$C_v = HDD_{T_{bal}}/HDD_{65} \qquad [5]$$

or

$$C_v = [A + B(T_{bal}) + C(T_{bal})^2]/HDD_{65} , \qquad [6]$$

where C_v is a heating degree-day correction factor based on the VBDD method. Thus, annual heating loads can be accurately determined for a building using the following modification of Equation 1:

$$Q = 24(UA_b)(HDD_{65})C_v . \qquad [7]$$

CALCULATION OF HEATING SAVINGS

The modified and variable-base degree-day methods both have been used to calculate heating energy savings. The following sections will describe how these methods are applied to savings calculations, and the potential problems of using the modified degree-day method with C_d factors. C_s, a new correction factor based on the variable-base degree-day method, is developed.

The Modified Degree-Day Method

According to Equation 1, the heating loads before and after the application of a conservation measure can be calculated using the following two equations:

$$Q_1 = 24(UA_{b_1})(HDD_{65})C_d \qquad [8]$$

and

$$Q_2 = 24(UA_{b_2})(HDD_{65})C_d \qquad [9]$$

where

Q_1 = annual heating load before retrofit

Q_2 = annual heating load after retrofit

UA_{b_1} = building heat-loss coefficient before retrofit

UA_{b_2} = building heat-loss coefficient after retrofit.

The energy savings from a particular conservation measure are equal to the difference between heating loads before and after retrofit. It seems logical that the difference, $Q_1 - Q_2$, can be calculated by subtracting Equation 9 from Equation 8, and that the result should be

$$\Delta Q = 24(UA_{b_1} - UA_{b_2})(HDD_{65})C_d \quad [10]$$

where

ΔQ = annual energy savings due to retrofit

Equation 10 appears to be a reasonable extension of Equation 1, and has been used in the calculation of energy savings in buildings (DOE 1980). However, a more detailed analysis presented in the following section shows that this is not the case. The approximate nature of the C_d correction factors in Equations 8 and 9 will cause large errors when savings are calculated as the difference in Equation 10. Even if the C_d factor is accepted as a reasonable approximation in Equation 1, the use of C_d in Equation 10 is not theoretically correct.

The Variable-Base Degree-Day Method

The energy savings from a conservation measure can be calculated by taking the difference between the calculated loads before and after the retrofit:

$$Q_1 = 24(UA_{b_1})(HDD_{65})C_{v_1} \quad [11]$$

and

$$Q_2 = 24(UA_{b_2})(HDD_{65})C_{v_2} \quad [12]$$

where

C_{v_1} = VBDD heating degree-day correction factor before retrofit

C_{v_2} = VBDD heating degree-day correction factor after retrofit.

Therefore, the annual energy savings from the conservation measure are:

$$\Delta Q = 24[(UA_{b_1})C_{v_1} - (UA_{b_2})C_{v_2}]HDD_{65} \quad [13]$$

Equation 13 allows the calculation of energy savings according to VBDD theory. However, this equation can be developed further into a simpler method that loses little in accuracy.

The C_s Factor. Based on Equation 13, a new factor, C_s, will be derived to replace C_d in Equation 10. Inserting C_s for C_d in Equation 10 gives:

$$\Delta Q = 24(UA_{b_1} - UA_{b_2})(HDD_{65})C_s \quad [14]$$

and combining Equation 14 with Equation 13 gives:

$$C_s = [(UA_{b_1})C_{v_1} - (UA_{b_2})C_{v_2}]/(UA_{b_1} - UA_{b_2}) \quad [15]$$

This equation, which results from VBDD theory, shows that C_s is not equal to any single value of C_v, nor is it an average of C_v values before and after a retrofit measure. Observing that:

$$HDD_{T_{set}} = A + B\,(T_{set}) + C\,(T_{set})^2 \quad [16]$$

and combining Equations 2, 6, and 15 gives:

$$C_s = (HDD_{T_{set}}/HDD_{65}) - C(I + S)^2/[(UA_{b_1})(UA_{b_2})(HDD_{65})] \quad [17]$$

The first term in this equation merely converts from a base temperature of 65 F (18.3°C) to the heating set-point temperature. The second term is a second-order adjustment, which is the result of the nonlinearity of heating degree days as a function of base temperature. It should be noted that as the UA values become large, or the I plus S values become small, the value of C_s approaches $HDD_{T_{set}}/HDD_{65}$.

For a particular component retrofit:

$$UA_{b_1} - UA_{b_2} = UA_{c_1} - UA_{c_2} \qquad [18]$$

where

UA_{c_1} = component heat-loss coefficient before retrofit
UA_{c_2} = component heat-loss coefficient after retrofit.

Then Equation 14 can be stated as:

$$Q = 24\ (UA_{c_1} - UA_{c_2})\ (HDD_{65})C_s\ . \qquad [19]$$

An advantage of this approach is that only the difference in the UA value resulting from the retrofit need be known. The overall before and after building UA values do not enter into the savings calculation.

DISCUSSION

The reason for the differences between C_s and C_v are shown in Figure 2. According to the VBDD method, heating load is a function of overall building UA, as given in Equation 6. The result is the solid curve shown in Figure 2, assuming internal gains equal to 2208 Btu/h (646 W) and average solar gains equal to 3000 Btu/h (880 W). According to the modified degree-day method, the heating load is directly proportional to overall building UA. For a building-specific C_v factor (Equation 11), the result is the dashed straight line shown in Figure 2. However, for this case, the heating load is correct only at the point where the straight line intersects the curve, i.e. when $UA = UA_1$. A similar condition is true for Equation 12, and the dotted line shown in Figure 2 is the result. The energy savings for a change from UA_1 to UA_2 are given by the vertical distance between point 1 and point 2. This vertical distance can be determined by multiplying ($UA_1 - UA_2$) by the slope of a line connecting the two points. The C_s factor is defined so that $24(HDD_{65})C_s$ equals the slope of a line between the two points. For the modified degree-day method, the slope of the line will not match the slope of the VBDD curve, even if the intersection is approximately correct, i.e., C_d is not the correct factor for calculating energy savings, even if the value of C_d is approximately correct for calculating heating loads.

In Figures 3 to 5, C_d, C_v, and C_s factors are plotted as functions of overall building UA for three locations. The C_d factors have a single value for each location and are, therefore, shown as horizontal lines. The building and climate-specific C_v factors (from VBDD) were calculated according to Equation 6. The values for C_s were calculated according to Equation 17 assuming that T_{set} is equal to 68 F (18.3 °C). Higher thermostat settings will result in higher C_s values, e.g., for T_{set} = 72 F (22.2°C), the C_s value will increase by approximately .18, .23, and .16 in Madison, Denver, and Atlanta, respectively. The C_s values assume a 20% difference between UA_1 and UA_2 and are plotted as a function of the average of UA_1 and UA_2. The sensitivity to this assumption increases for small C_s values. If $C_s = 0.8$ for a 20% change in the overall building UA, then errors of less than 6% will result if changes in building UA are between 0% and 50%. Both C_v and C_s are plotted for three levels of average utilizable solar gains and a constant value for internal gains of 2208 Btu/h (646 W).

Comparison of the C_d factors with the C_v factors for the three locations presented in Figures 3 to 5 shows that if the building UA is large, the standard ASHRAE C_d factor will underpredict heating loads compared to the VBDD method. Conversely, if the UA is small, then use of the standard C_d factor will overpredict heating loads compared to the VBDD method. For each location, there is only a single UA value for which the C_d factor is equal to the VBDD C_v factor for a given level of solar gain. Assuming average solar gains of 3000 Btu/h (880 W) for Denver and 2000 Btu/h (590 W) for Madison and Atlanta, then the C_d factor is equal to the C_v factor when the UA is approximately 300, 400, and 500 Btu/h F (158, 211, and 264 W/°C) for Madison, Denver, and Atlanta, respectively. That is, the C_d factors correspond to building UA values that are relatively low, average, and high in Madison, Denver, and Atlanta, respectively. This conclusion is based on a preliminary analysis with approximations for solar gains and assumptions for internal gains. The trend, however, is as expected and is consistent with development of the modified degree-day method.

Comparison of the C_s factors with the C_d factors for the three locations presented in Figures 3 through 5 shows that the use of C_d factors will underpredict energy savings in most cases. For buildings with overall UA values above a certain threshold, and with internal and solar gains within the range represented on the figures, the values for C_s do not differ by more than 10% from the asymptotes. The threshold UA values are approximately 300, 400, and 500 Btu/h F (158, 211, and 264 W/^{o}C) for Madison, Denver, and Atlanta, respectively. For such buildings, appropriate values of C_s are are slightly less than the asymptotic values and can be presented as shown in Figure 6. This approach will be valid for most existing single-family detached residences, particularly those that have large UA values and are most in need of energy saving retrofits, and will allow the calculation of energy savings in a simple manner. As shown in Figure 6, asymptotic C_s factors will predict increased energy savings compared to savings calculated with C_d by approximately 64%, 79%, and 49% in Madison, Denver, and Atlanta, respectively. For the locations studied, a single value of C_s equal to 1.09 will differ from any of the three location-dependent asymptotic C_s factors by less than 3%. It appears likely that assuming C_s equal to 1.09 will also be a reasonable approximation to asymptotic C_s values for other locations.

For other buildings that are highly insulated or have exceptionally high levels of internal or solar gains, C_s factors (and C_d factors) could be developed as functions of location, overall UA, solar gains, and internal gains, and presented in graphical form.

CONCLUSIONS

The ASHRAE C_d degree-day correction factors were developed for load calculations. However, the modified degree-day method with C_d factors has, in practice, been used to calculate energy savings in buildings. The use of C_d factors in savings calculations is not consistent with degree-day theory.

New heating degree-day correction factors specifically for savings calculations, C_s factors, can be developed based on the results presented in this paper. C_s factors, based on the variable-base degree-day method, avoid the inaccuracies that result from the use of the C_d for the calculation of energy savings. C_s factors can be used in place of C_d factors to extend the modified degree-day method for the calculation of energy savings.

For many existing single-family-detached residences, it appears that the use of a single value of C_s of 1.09 is justified, and will result in an increase in predicted energy savings of approximately 50% to 80%.

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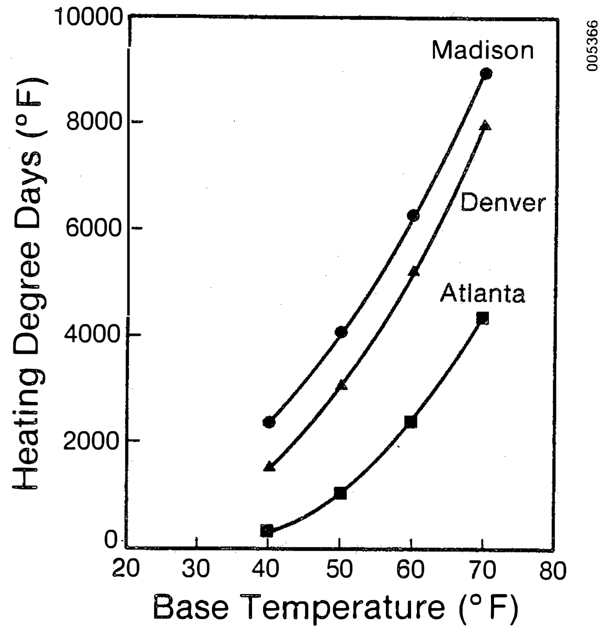

Fig. 1. Heating Degree-Days as a Function of Base Temperature.

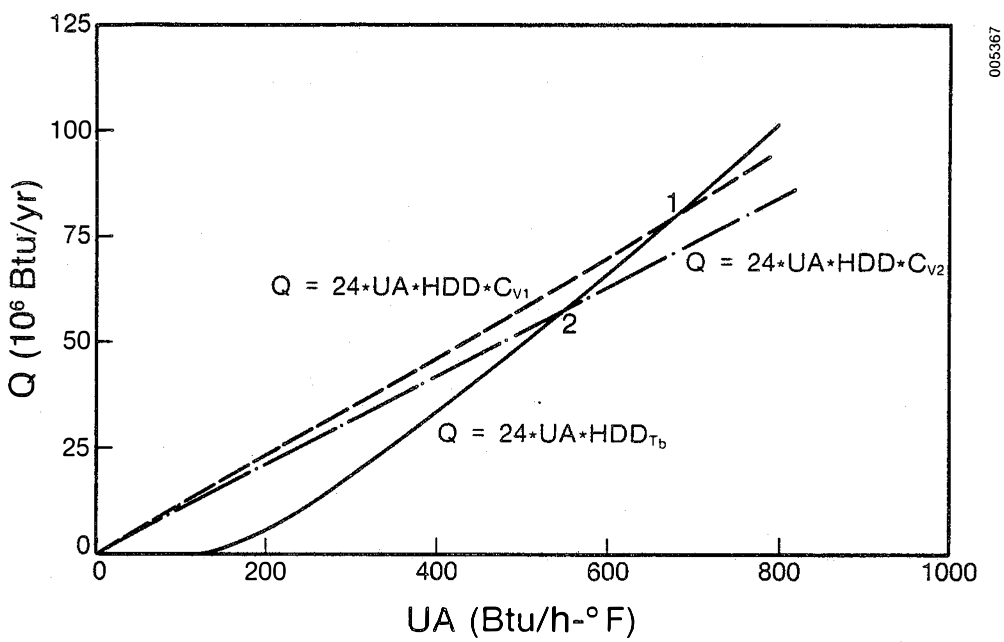

Fig. 2. Denver, Colorado: Annual Heating Load Calculated from Variable-Base Degree-Days (solid curve) and Degree-Day Correction Factors Based on UA_1 (dashed line) and UA_2 (broken line).

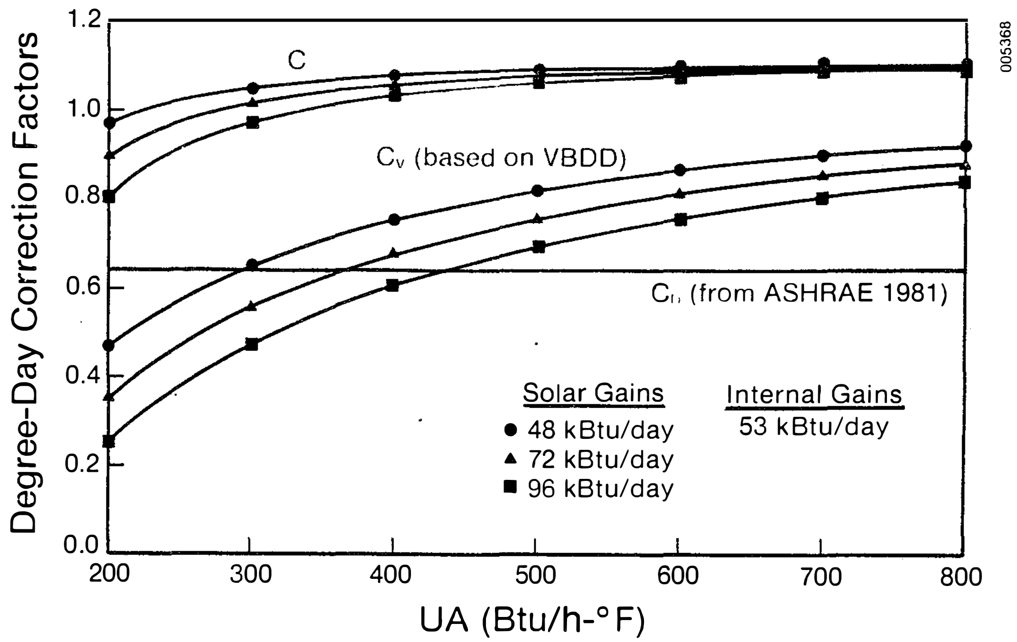

Fig. 3. Madison, Wisconsin: Degree-Day Correction Factors for Calculating Loads (C_d and C_v) and Savings (C_s).

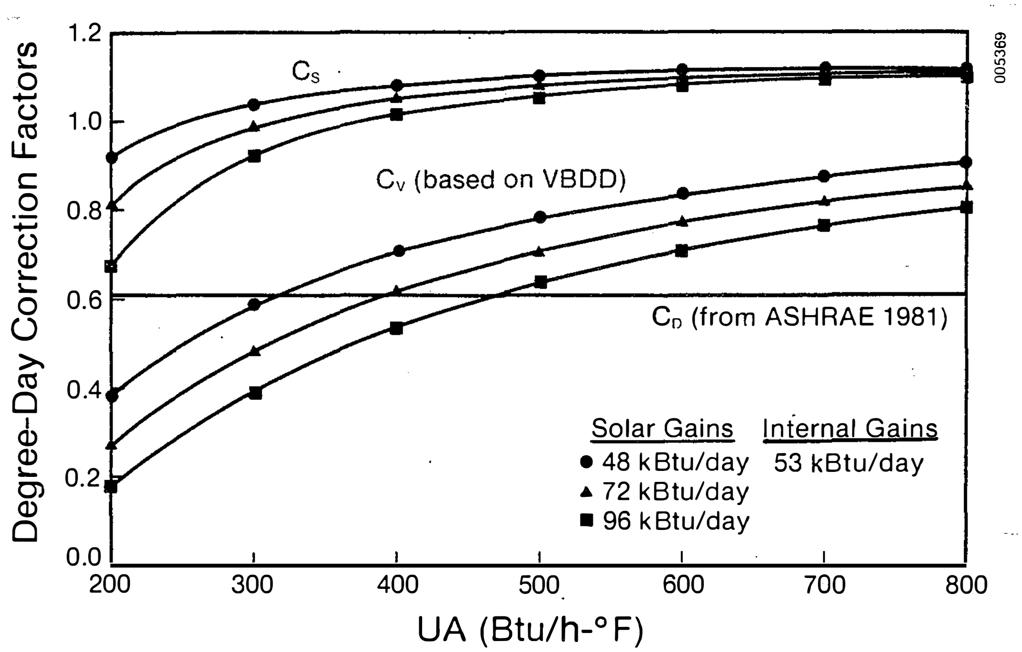

Fig. 4. Denver, Colorado: Degree-Day Correction Factors for Calculating Loads (C_d and C_v) and Savings (C_s).

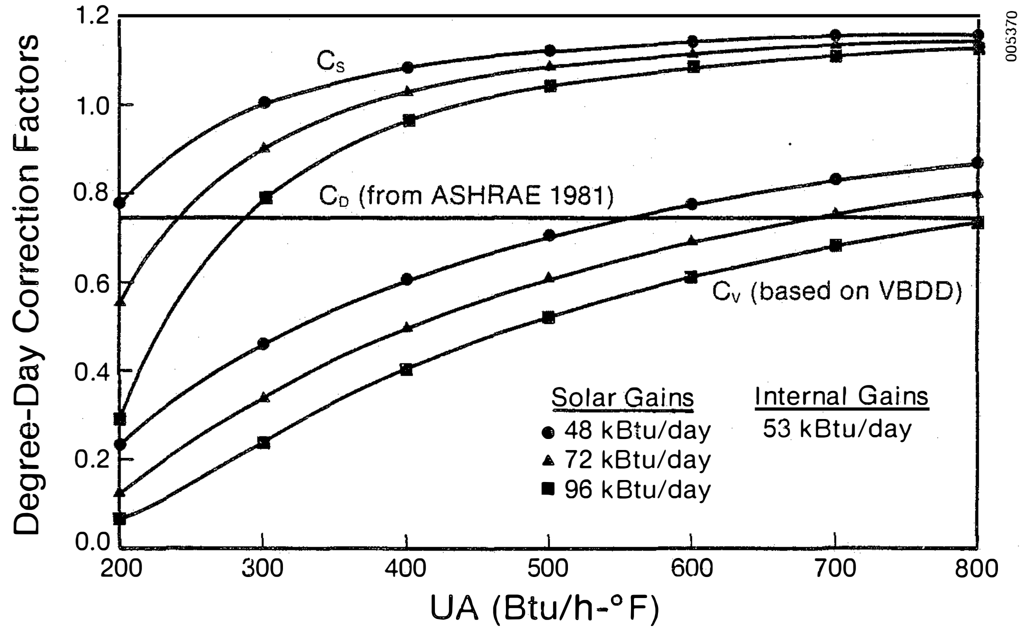

Fig. 5. Atlanta, Georgia: Degree-Day Correction Factors for Calculating Loads (C_d and C_v) and Savings (C_s).

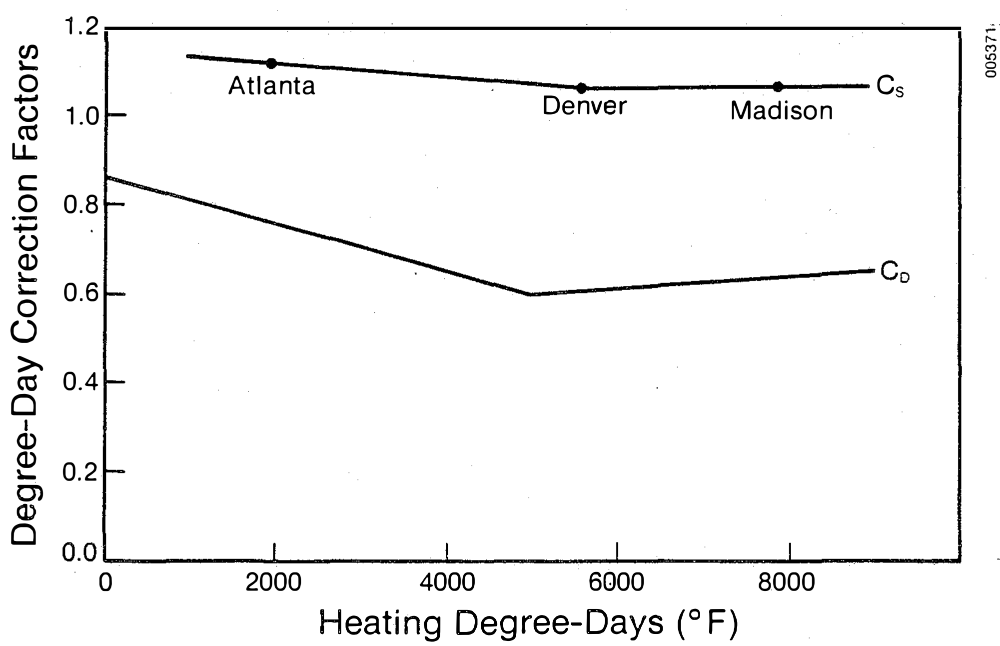

Fig. 6. C_d Factors as a Function of Heating Degree-Days (Ref.2) and C_s Factors for Three Locations (from Figs. 3-5 for Large UA-Values).