SERI/TP-254-2019
UC Category: 59c
DE83011983

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July 1983

To be presented at the ASES
PASSIVE 83 Conference
Glorieta, New Mexico
7-9 September 1983

Prepared under Task No. 1511.00
WPA No. 005

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $4.50
Printed Copy $7.00

SOLAR AND INTERNAL GAIN ADJUSTMENTS IN CALCULATION OF ENERGY CONSERVATION SAVINGS

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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 lower base temperature are sometimes 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 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.

1. INTRODUCTION

A large number of home energy audits have been completed by utilities across the country; these programs are continuing and expanding to include multifamily and commercial buildings. In these audits, energy savings are typically calculated by simplified procedures, many of which are derived from the Residential Conservation Service (RCS) model audit (1). At SERI, we have worked on verification of portions of the RCS model audit by comparison with hourly simulations. In the course of these verification efforts, we have investigated the use of degree-day correction factors in energy savings calculations and building load calculations. The term "energy savings" refers to a reduction in heating "load," and the important distinction is that "savings" are calculated as a difference. The focus of this paper is on savings calculations; 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. This paper is based on degree-day theory, and simplified methods are said to be "inappropriate" or "in error" relative to the more detailed version of the theory (see discussion of the variable-base degree-day method in Section 3.) We have found problems when the C_d factor from the modified degree-day method for load calculations has been inappropriately used for savings calculations.

2. THE MODIFIED DEGREE-DAY METHOD

In the ASHRAE modified degree-day method (2), annual building heating loads are calculated as:

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

where

Q = annual heating load

UA = overall building heat-loss coefficient

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

C_d = degree-day correction factor.

The C_d factor in Eq. 1 is needed primarily because degree days are used to a 18.3°C (65°F) base temperature (3), 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 (2), the C_d factor was introduced in the modified degree-day method. C_d is a multiplier, generally 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 Eq. 1 will be in error for buildings that do not match the C_d assumptions.

2.1 The C_d Factor in Energy Savings Calculations

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

$$Q_1 = 24(UA_1)(HDD_{65})C_d \qquad [2]$$

and

$$Q_2 = 24(UA_2)(HDD_{65})C_d \,, \qquad [3]$$

where

Q_1 = annual heating load before retrofit

Q_2 = annual heating load after retrofit

UA_1 = building heat-loss coefficient before retrofit

UA_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 Eq. 3 from Eq. 2, and that the result should be

$$\Delta Q = 24(UA_1 - UA_2)(HDD_{65})C_d \,, \qquad [4]$$

where

ΔQ = annual energy savings due to retrofit

UA_1 = component heat-loss coefficient before retrofit

UA_2 = component heat-loss coefficient after retrofit.

Note that only component UA values for the retrofit measure remain, because the other UA values, which are equal before and after retrofit, have been cancelled out.

Even though Eq. 4 appears to be a reasonable extension of Eq. 1 based on the above derivation, a more detailed analysis presented in the following section shows that this is not the case. The approximate nature of the heating loads calculated in Eqs. 2 and 3 will cause large errors when savings are calculated as the difference in Eq. 4. Even if the C_d factor is accepted as a reasonable approximation in Eq. 1, the use of C_d in Eq. 4 is not theoretically correct.

3. 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 (2). Predictions of annual heating loads based on the VBDD method have been shown to compare well with results from hourly simulation programs (4). The VBDD method is applied by first determining the balance-point temperature T_b for a particular building. T_b 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_b can be calculated as:

$$T_b = T_{set} - (I + S)/UA \,, \qquad [5]$$

where

T_b = 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:

$$Q = 24(UA)(HDD_{T_b}) \,, \qquad [6]$$

where

HDD_{T_b} = the heating degree days to base temperature T_b.

The VBDD method does not explicitly account for hour-to-hour or day-to-day variability of solar or internal gains, nor 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 calculation methods. The issue of coincidence is addressed in the concept of sol-air heating degree days recently developed by Erbs et al. (5). The utilizability of solar gains including the effect of thermal mass is addressed in correlation-based techniques such as the solar-load-ratio method (6) and the unutilizability method (7). Energy savings due to a particular conservation measure can be calculated by use of these passive solar methods to calculate heating loads before and after retrofit. In this paper, 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 (8) for Altanta, Denver, and Madison. The data have been fitted by using the following quadratic expression:

$$HDD_{T_b} = A + B(T_b) + C(T_b)^2 \,, \qquad [7]$$

where A, B, and C are location-dependent constants.

3.1 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:

$$C_v = HDD_{T_b}/HDD_{65} \qquad [8]$$

or

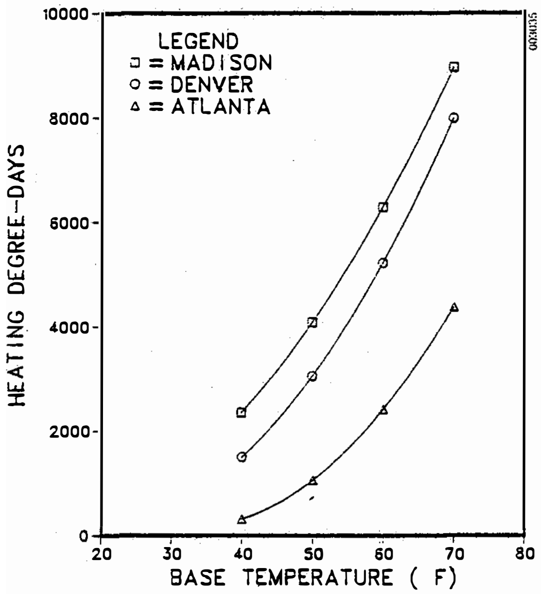

Fig. 1. Heating Degree-Days as a Function of Base Temperature

$$C_v = [A + B(T_b) + C(T_b)^2]/HDD_{65} , \quad [9]$$

where C_v is the heating degree-day correction factor according to the VBDD method.

Thus, annual heating loads can be accurately determined for a building using the following modification of Eq. 1:

$$Q = 24(UA)(HDD_{65})C_v . \quad [10]$$

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

$$Q_1 = 24(UA_1)(HDD_{65})C_{v_1} \quad [11]$$

and

$$Q_2 = 24(UA_2)(HDD_{65})C_{v_2} , \quad [12]$$

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:

$$\Delta Q = 24[(UA_1)C_{v_1} - (UA_2)C_{v_2}]HDD_{65} . \quad [13]$$

Eq. 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.

4. THE C_s FACTOR

Based on Eq. 13, a new factor, C_s, will be derived for use in Eq. 4 in place of C_d.

Inserting C_s for C_d in Eq. 4 gives:

$$\Delta Q = 24(UA_1 - UA_2)(HDD_{65})C_s , \quad [14]$$

and combining Eq. 14 with Eq. 13 gives:

$$C_s = [(UA_1)C_{v_1} - (UA_2)C_{v_2}]/(UA_1 - UA_2) . \quad [15]$$

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. Combining Eqs. 5, 9, and 15 gives:

$$C_s = (HDD_{T_{set}}/HDD_{65}) - C(I + S)^2/(UA_1)(UA_2)(HDD_{65}) . \quad [16]$$

The first term in this equation merely converts from a base temperature of 18.3°C (65°F) 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 + S values become small, the value of C_s approaches $HDD_{T_{set}}/HDD_{65}$.

The differences between C_s and C_v are shown in Fig. 2. According to the VBDD method, heating load is a function of overall building UA, as given in Eq. 6. The result is the solid curve in Fig. 2, assuming internal gains equal to 646 W (2208 Btu/h) and average solar gains equal to 880 W (3000 Btu/h). According to the modified degree-day method, the heating load is directly proportional to overall building UA. For a building-specific C_v factor (Eq. 10), the result is the dashed straight line in Fig. 2, but 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 holds for Eq. 11, and the dotted line in Fig. 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.

5. COMPARISON OF DEGREE-DAY CORRECTION FACTORS

In Figs. 3 through 5, C_d, C_v, and C_s factors are plotted as functions of overall building UA for three locations. The ASHRAE C_d factors have a single value for each location and are, therefore,

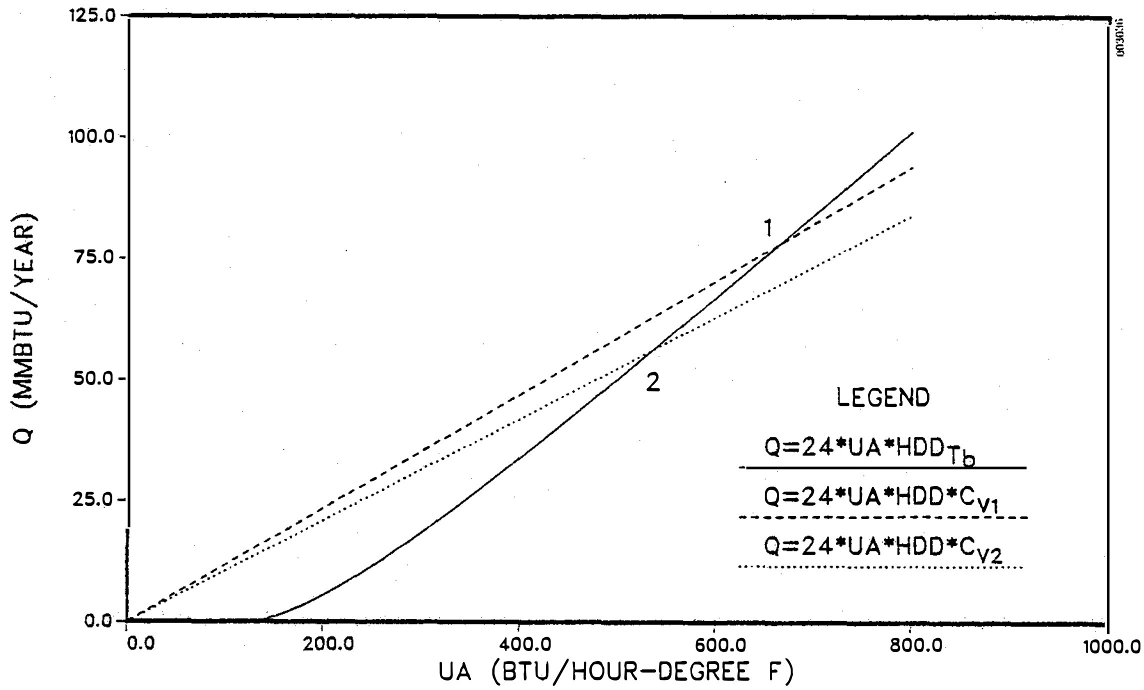

Fig. 2. Annual Heating Load as a Function of Building UA

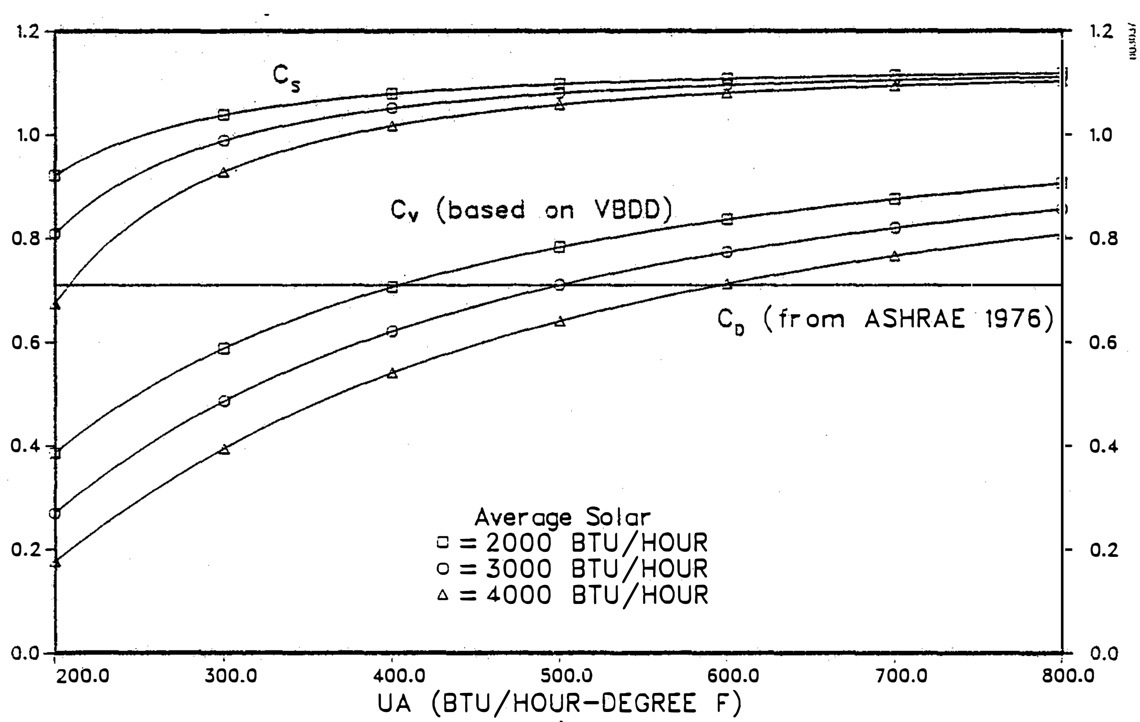

Fig. 3. Degree-Day Correction Factors (Denver, CO): C_d and C_v for Calculating Loads and C_s for Calculating Savings

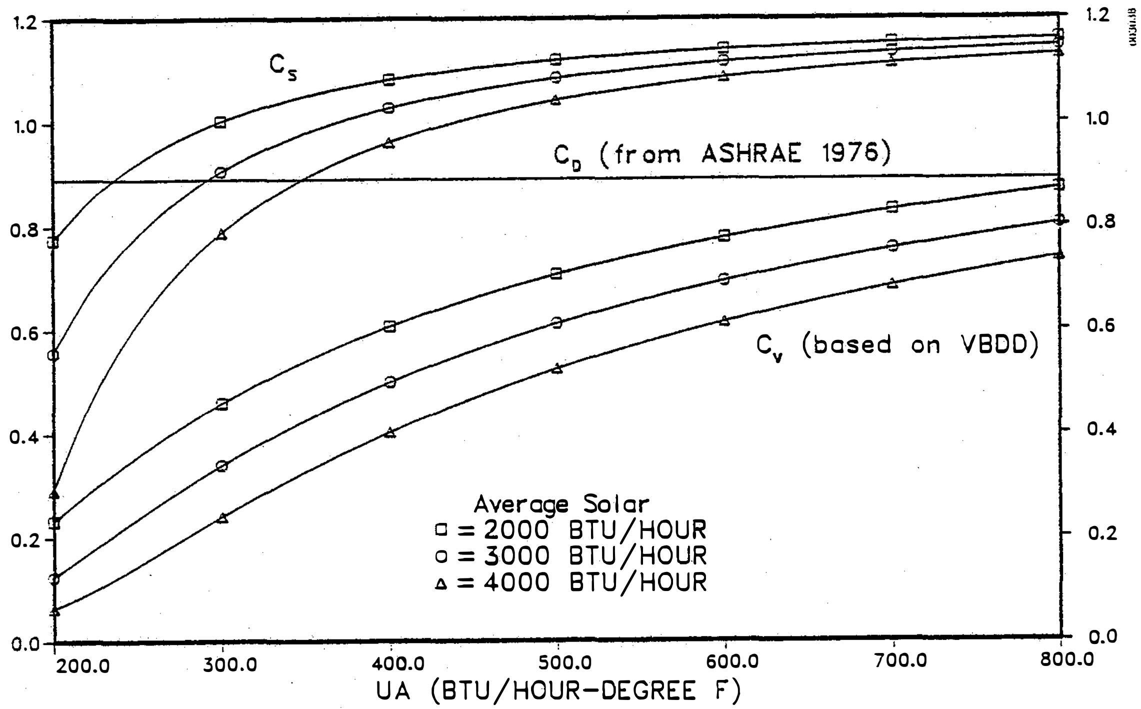

Fig. 4. Degree-Day Correction Factors (Atlanta, GA): C_d and C_v for Calculating Loads and C_s for Calculating Savings

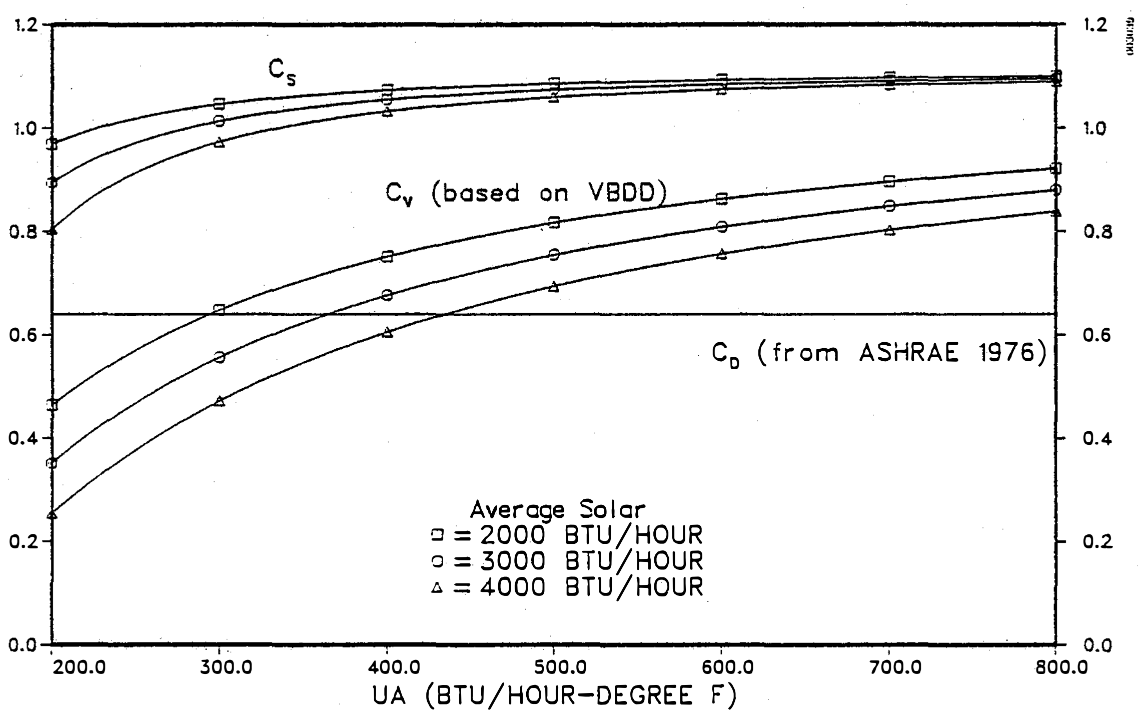

Fig. 5. Degree-Day Correction Factors (Madison, WI): C_d and C_v for Calculating Loads and C_s for Calculating Savings

shown as horizontal lines. The building- and climate-specific C_v factors (from VBDD) were calculated according to Eq. 9. The values for C_s were calculated according to Eq. 16. 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. It can be shown that reasonable deviations from these assumptions will result in only slightly different values for C_s. Both C_v and C_s are plotted for three levels of average utilizable solar gains and a constant value for internal gains of 646 W (2208 Btu/h).

Comparison of the C_d factors with the C_v factors for the three locations presented in Figs. 3 through 5 shows that if the building UA is large, then use of the standard ASHRAE C_d factor will underpredict heating loads compared to the VBDD method (except in Atlanta). Conversely, if the UA is small, then use of the standard ASHRAE 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 ASHRAE C_d factor is equal to the VBDD C_v factor for a given level of solar gain. Assuming average solar gain of 880 W (3000 Btu/h) for Denver and 590 W (2000 Btu/h) for Madison and Atlanta, then the C_d factor is equal to the C_v factor when the UA is approximately 49, 65, and 81 W/°C (300, 500, and 800 Btu/h °F) for Madison, Denver, and Atlanta, respectively. That is, the C_d factors correspond to building insulation levels that are relatively good, average, and poor 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 Figs. 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 vary by more than 10%, and C_d factors will underpredict energy savings by approximately 42%, 37%, and 23% in Madison, Denver, and Atlanta, respectively. The threshold UA values are approximately 49, 65, and 81 W/°C (300, 400, and 500 Btu/h °F) for Madison, Denver, and Atlanta, respectively. For such buildings, constant C_s factors can be presented in tabular form similar to the ASHRAE C_d factors and used directly in the modified degree-day method. This approach will be valid for most existing single-family detached residences. 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.

6. CONCLUSIONS

The ASHRAE C_d degree-day correction factors were developed for load calculations. The use of these C_d factors in savings calculations is theoretically incorrect and produces results that underpredict energy savings by 23%-42% for typical, existing single-family detached residences in a range of climates.

New heating degree-day correction factors specifically for savings calculations, C_s factors, can be developed based on the results presented in this paper. These factors, based on the variable-base degree-day method, avoid the theoretical problems of the C_d factors and can be derived in a form that is directly usable in the ASHRAE modified degree-day method.

7. ACKNOWLEDGEMENTS

The authors thank Kris Subbarao and Jay Burch for insightful discussion on this work. This work was supported by the U.S. Department of Energy, Building Energy Research and Development Division.

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