EFFECT OF INTERIOR MASS SURFACES ON THE SPACE HEATING AND COOLING LOADS OF A SINGLE-FAMILY RESIDENCE

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ABSTRACT

A Computer Program called TARP is used to analyze the effect of interior mass surfaces (i.e., partition walls and interior furnishings) on the weekly space heating and cooling loads of an insulated and a poorly insulated residence.

In space heating applications, when the outdoor temperature deviated from the balance point, the inclusion of interior mass surfaces in the modeling of the houses increased the interior radiant temperature. This, in turn, increased the overall envelope heat-transfer coefficients of the houses. This effect was found to be more significant in the poorly insulated house compared to the insulated house. When the outdoor temperature was near the balance point, the thermal storage provided by interior surfaces caused the internal heat gains to be more effectively utilized, and weekly space heating loads tended to approach a "high mass limit" that coincided with steady-state theory. Under this condition, additional mass has only a small effect on space heating loads.

In space cooling applications, the inclusion of interior surfaces increased the "effective envelope heat-transfer coefficient" in a linear regime away from the balance point, but produced little change in space cooling loads in a nonlinear regime near the balance point. Thermal insulation in the building envelope was found to have a small effect in reducing annual space cooling loads.

The results of this study indicated that errors can occur when interior mass surfaces are excluded from dynamic computer simulations of residences.

INTRODUCTION

The National Bureau of Standards recently carried out field studies using six one-room test cells in Gaithersburg, MD to investigate the effect of wall mass on space heating and cooling loads. The test cells were extensively instrumented, and their space heating and cooling loads were monitored over a one-year period. The results of these studies were reported separately for space heating loads (Burch, Krintz, and Spain 1984) and space cooling loads (Burch, Davis, and Malcolm 1984). The study pertaining to space heating found that wall mass did not have a measurable effect on space heating loads during the cold part of the winter. However, during mild spring heating days, when the internal heat gains caused the indoor temperature to rise above the thermostat setpoint temperature, a significant thermal mass effect was observed. The heavyweight masonry and log buildings consumed less space heating energy than identical lightweight buildings having equivalent thermal resistance in their building envelopes. Wall mass was found to be more effective when it was placed inside, as opposed to outside, the wall insulation. The study pertaining to space cooling found that wall mass of these test buildings had a significant effect on space cooling loads during the entire summer season of Gaithersburg, MD.

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While the field study results conclusively demonstrated the existence of a thermal mass effect, they were found to have limited applicability to real houses because the test cells were small, the solar gains through windows were small, and the top surfaces of the floors were insulated.

A limited series of tests was conducted with a partition wall installed in two of the test cells. However, both the field measurements and computer predictions indicated that the effect of a partition wall in these test cells was very small. This was because direct solar gain through windows did not enter the test cells during periods when a thermal mass effect would normally be expected. For this reason, these partition wall tests were believed not to be directly applicable to residential buildings.

This study investigates the predicted effect of interior mass features on weekly space heating and cooling loads in an insulated and a poorly insulated single-family residence under more realistic conditions of solar gain through windows.

DESCRIPTION OF COMPUTER PROGRAM

The Thermal Analysis Reseach Program (TARP) is a computer program that predicts either the indoor temperature or space heating/cooling loads of a building under a dynamic set of boundary conditions. TARP uses a detailed heat-balance method to determine heating/cooling requirements from the predicted heat losses and heat gains. The computer algorithms are partly based on subroutines from the Building Loads Analysis and System Thermodynamics (BLAST) Computer Program. In using TARP, a detailed description of the building including the heat-transfer parameters for all materials comprising the building envelope, an operation schedule for the building, and hourly outdoor climatic data are specified as input for the program. Further information on TARP may be found in (Walton 1980).

Space heating and cooling loads predicted by TARP were compared to corresponding measured space heating and cooling loads for the six thermal mass test cells with good agreement in (Burch, Walton, Cavanaugh, and Licitra 1984). In these comparisons, TARP predictions accurately followed the general trends of the measured data. TARP predicted peak space heating and cooling loads within 15% and 18%, respectively. This level of agreement was considered to be reasonable in view of the uncertainty in the heat-transfer properties of the building materials specified as input for the program and the simplifying approximations in the computer algorithms. The level of agreement is comparable and in most cases better than that for other similar computer programs cited in the literature (Arumi-Noe 1984, Burch et al. 1975, Judkoff et al. 1983, and Anderson et al. 1980). A strong case for the validity of the TARP program relative to the thermal mass studies (Burch, Krintz, and Spain 1984 and Burch, Davis, and Malcolm 1984) is that during climatic periods when a thermal mass effect was experimentally observed, the TARP program predicted the correct relative cumulative space conditioning loads. That is, the ranking of the test cells and the relative magnitudes of the predicted thermal mass effects were the same as those for the actual test cells.

DESCRIPTION OF HOUSES USED IN THE ANALYSIS

The geometric design of the two houses used in the computer analysis was fashioned after the Hastings' ranch house (Hastings 1977). The houses were wood-frame ramblers having a floor area of 1180 ft^2 (110 m^2). They had a pitched roof and ventilated attic. The wall construction consisted of 2 x 4 in (50 x 100 mm) framing placed 16 in (0.41 m) on center with wood siding and gypsum board attached to exterior and interior surfaces, respectively. The windows had a surface area of 141 ft^2 (13.1 m^2), or 12% of the floor area. For each orientation, the ratio of window area to gross wall area was constant. The floor consisted of 1 in (2.5 cm) wood covered with carpet placed over a ventilated crawlspace. A floor plan and elevation are given in Figure 1.

Using the above basic geometric design, an insulated house and a poorly insulated house were considered as separate cases. The basic features of these two houses are given in Table 1. Heat-transfer parameters are given in Table 2 for the insulated house and in Table 3 for the poorly insulated house.

MODELING THE HOUSES

The houses were simulated as three zones including a living space, an attic, and a crawl-space. Space conditioning was provided in the living space. Partition walls and interior furnishings were included as separate surfaces within the living space. The air temperature within each zone was treated as being uniform at each time step of the analysis. The radiant interchange among the surfaces within each zone was computed by the mean-radiant-temperature network method (Carroll 1980). This method is equivalent to putting all surfaces on a hypothetical sphere permitting each surface to have some view of every other surface. Compared with other contemporary computer programs, TARP is one of the few programs that handles the radiation exchange among interior surfaces and envelope surfaces. The heat-transfer coefficents at vertical interior surfaces, at horizontal interior surfaces with heat flow down, and at horizontal interior surfaces with heat flow up were taken as the constant values given in (ASHRAE, 1985).

The partition walls consisted of 2 x 4 in (50 x 100 mm) framing with 1/2 in (13 mm) gypsum board attached at opposite sides. The surface area of the partition walls was identical to the actual partition wall surface area of the Hastings' ranch house. Interior furnishings were modeled as a 2-in-thick (5 cm) slab of wood. The total weight of the interior furnishings was 7,000 lb (3,200 kg), and its specific heat was taken to be 0.29 Btu/lb•F (1,200 J/kg•K).

For the computer simulations, the thermostat was set at 68 F (20°C) for space heating and 76 F (24°C) for space cooling. Within the 8 F (4°C) range between the setpoints, space conditioning was not provided, and the test house was not ventilated. A constant internal load of 0.75 W/ft^2 of floor (8.1 W/m^2) was used to simulate heat release associated with occupancy.[1] The rate of air infiltration was taken to be constant at one volume change per hour.

RESULTS

Using climatic data from WYEC[2] computer tapes, annual space heating and cooling loads were predicted for the following cities: Madison, WI; Lake Charles, LA; Washington, DC; Los Angeles, CA; and Charleston, SC. These cities were selected to represent the climates of the northern U.S., gulf coast, mid-atlantic, southern region of the west coast, and southeastern region of the United States, respectively.

Space Heating Load Correlations

Weekly average[3] space heating loads for the insulated house without interior surfaces (i.e., an empty building shell) located in Washington, DC are plotted as a function of average outdoor temperature in Figure 2A. Weekly averages were found to reduce scatter in the data due to variations in solar radiation and thermal mass effects. Note that when the outdoor temperature is below a break point of 47 F (8.3°C) and deviates from the balance point, the weekly heating loads follow a linear relationship. This break point was determined from a visual inspection of the plotted results. Here the term "balance point" denotes the outdoor temperature at which the heating load decreases to zero. When the average outdoor temperature is above this break point and near the balance point, the heating load departs from and lies above the linear relationship. In this nonlinear regime, the internal heat gains (i.e., solar and occupancy gains) cause the indoor temperature to rise above the thermostat setpoint temperature. As a result, the house is unable to utilize all of its internal heat gains, and its interior rejects thermal energy to the outdoor environment.

Interior surfaces (i.e., partition walls and furniture) were incorporated into the model of the building in two stages. First, surfaces without thermal storage capacity were

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1 A special computer simulation with a diurnal occupancy profile having the same average value predicted very similar weekly space heating and cooling loads.

2 Weather Year for Energy Calculations (Crow 1981).

3 It should be pointed out that the weekly averages are actually running averages over a 168-hour period (i.e., weekly averages with progressively shifted starting points).

added. Second, surfaces with thermal storage capacity were added.

The space heating load correlation for the case of interior surfaces without thermal storage is given in Figure 2B. The inclusion of interior surfaces without thermal storage increased the overall envelope heat-transfer coefficient by 3.0%. The overall envelope heat-transfer coefficient corresponds to the slope of the line. The inclusion of interior surfaces in the computer model for the house causes an interior envelope surface to view a higher radiant temperature (see Figure 3A), thereby increasing the rate of heat transfer at the surface.

The heating load correlation for the case of interior surfaces with thermal storage is given in Figure 2C. The addition of thermal storage to the interior surfaces produced a further increase of 1.9% in the overall envelope heat-transfer coefficient. This effect was believed to be due to the storage of solar energy in the interior surfaces, resulting in a further increase in the indoor radiant temperature. The thermal storage also caused the weekly heating loads near the balance point more closely to follow the linear relationship. The thermal storage considerably reduced overheating of the indoors during warm day periods. This increased the utilization of internal heat gains near the balance point. Under such a condition, the addition of more mass (i.e., wall mass) has been shown to have a small effect on annual space heating loads (Burch, Walton, Cavanaugh, and Licitra 1984).

Another interesting result is that the overall effect of including interior surfaces with thermal storage produced only a 0.5% increase in the annual heating load of the insulated residence located in Washington, DC. The overall effect is small because the individual effects on the overall envelope heat-transfer coefficient and the utilization of internal heat gains tend to offset each other. The impact of climate is considered later.

A similar set of results for the poorly insulated house is given in Figure 4. Here it is seen that the inclusion of interior surfaces increased the overall envelope heat-transfer coefficient by 12.6% compared to 4.9% for the insulated house. In the poorly insulated house, the inclusion of interior surfaces produced a larger change in the indoor radiant temperature (see Figure 3). Moreover, since the building envelope of the poorly insulated house contains smaller thermal resistance, changes in the interior radiant temperature produce a larger effect on the overall envelope heat-transfer coefficient.

In Figure 4, it is seen that the inclusion of interior surfaces in the modeling of the poorly insulated house did not have much effect on heating loads near the balance point.

Note that in Washington, DC the inclusion of interior surfaces with thermal storage produced a net increase in the annual space heating load of 0.5% in the insulated house and a net increase of 8.6% in the poorly insulated house. In the insulated house, the effect on the overall envelope heat-transfer coefficient and the effect on utilization of internal heat gains tend to offset each other. On the other hand, in the poorly insulated house, the effect on the overall envelope heat-transfer coefficient is the more dominant mechanism, resulting in a larger increase in the annual space heating load.

The exclusion of interior mass surfaces from computer predictions causes the benefits of envelope modifications for saving energy to be underestimated. This may be seen by considering the annual heating loads given in figures 2 and 4. Here it is seen that the evelope modifications resulted in a predicted savings of 3.01×10^7 Btu (3.18×10^{10} J) without interior surfaces and 3.49×10^7 Btu (3.68×10^{10} J) with interior surfaces, or a 14% difference.

An interesting adjunct to these results is that, when interior surfaces were included in the modeling of the house, most of the heating loads were well correlated by a linear relationship. Moreover, this linear relationship coincided closely with steady-state theory as shown in the next section.

Comparisons to Steady-State Theory

The space heating loads (Q_h) of a house with interior surfaces may be predicted using the relation:

$$Q_h = K \cdot (T_b - T_o) \qquad (1)$$

Here T_o is the average outdoor temperature, and T_b is the balance-point temperature. The overall envelope heat-transfer coefficient (K) is given by:

$$K = \sum_{i=1}^{N} U_i \cdot A_i + \rho \cdot V \cdot I \cdot C_p \qquad (2)$$

where $U_i \cdot A_i$ = thermal transmittance and surface area product for the i-th building component;
ρ = density of air;
V = volume of house;
I = rate of infiltration;
C_p = specific heat of air; and
N = total number of heat-transfer surfaces.

The balance-point temperature (T_b) is given by:

$$T_b = T_i - \frac{Q_i + Q_s - Q_e}{K} \qquad (3)$$

Here T_i is the indoor temperature, Q_i and Q_s are the internal heat gains for occupany and solar, and Q_e is the earth heat loss that was treated as constant over the entire year.

Neglecting data near the balance point, the slope and T_b values derived from the heating load correlation were determined by regression analysis. The earth loss was determined to be 176 Btu/h (51.6 W) for the insulated house and 383 Btu/h (112 W) for the poorly insulated house. The solar gains (Q_s) for both houses were computed by the relation:

$$Q_s = \tau \cdot SC \sum_{i=1}^{4} A_i \cdot H_i \qquad (4)$$

where A_i = surface area for windows for i-th orientation;
H_i = average incident solar radiation for i-th orientation;
τ = solar transmittance for DSA glass; and
SC = mean shading coefficient for window glazing.

The values for H_i were obtained from TARP. The mean shading coefficient was taken to be 0.81 for double-pane glazing and 0.92 for single-pane glazing. The solar transmittance for double-strength sheet (DSA) glass was taken to be 0.86. These values were evaluated at a 40° incident angle to represent mean daily performance.

The above steady-state model was used to predict the linear portion of the heating load correlations for both houses with interior surfaces. The overall envelope heat-transfer coefficients and balance-point temperatures independently derived from the heating-load correlations and the steady-state theory are compared in Table 4.

Since the overall envelope heat-transfer coefficients and balance-point temperatures derived independently from the heating load correlation and steady-state theory are in close agreement, it follows that the linear portion of the heating load correlations for both houses with interior surfaces is equivalent to steady-state theory.

Space Cooling Load Correlations

Space cooling load correlations for the insulated house located in Washington, DC are given in Figure 5A for the case without interior surfaces, in Figure 5B for the case of interior surfaces without thermal storage, and in Figure 5C for the case of interior surfaces with thermal storage. The inclusion of interior surfaces produced a net increase in the effective overall envelope heat-transfer coefficient of 3.8% compared to 4.9% for the space heating load correlations. Here the term "effective overall envelope heat-transfer coefficient" denotes the rate of change of space cooling loads with outdoor temperature (i.e., the slope of a space cooling load correlation). Comparing Figures 5C and 5A, it is seen that the inclusion of interior surfaces only slightly affected space cooling loads near the balance point. An explanation is given below.

In the previous section dealing with space heating loads, the departure of weekly space heating loads from a linear relationship near the balance point was caused by the inability of the house to utilize all of its internal heat gains during warm day periods. In the case of the space cooling load correlations, the departure of weekly space cooling loads from a linear relationship near the balance point is believed to be due to the inability of the house to fully utilize all of the night cooling potential. For cooling days near the balance point, the outdoor temperature decreases well below the indoor setpoint temperature, and the house is naturally cooled at night by the outdoor environment. This causes the indoor temperature to decrease below the indoor setpoint temperature. The inclusion of interior surfaces produces only a small change in this temperature decline, thereby producing little effect on the space cooling loads.

From Figure 5C, it would appear that the linear portion of cooling load correlation departs from steady-state theory. That is, the slope of the correlation is 10.9% larger than the overall envelope heat-transfer coefficient given in Table 4. This peculiar behavior for the space cooling load correlation is not well understood, but it may be related to a variation in the utilization of the solar energy absorbed by the opaque surfaces of the building envelope with outdoor temperature.

A similar set of cooling load correlations for Washington, DC is given for the poorly insulated house in Figure 6. Here the inclusion of interior surfaces with thermal storage produced a net increase in the slope of the cooling load correlation of 12.7%, compared to 12.6% for the space heating load correlation.

A comparison of Figures 5C and 6C indicates that for the mild summer climate of Washington, DC the inclusion of insulation in the house had a small effect on the annual space cooling loads. It is seen that the annual cooling load for the poorly insulated house is only 5.2% above that for the insulated house. The effect is small because the insulation not only reduces the effective overall envelope heat-transfer coefficient but also decreased the balance-point temperature. A lower balance point caused more climatic periods to require space conditioning. These two effects tend to offset one another.

Impact of Climate

The effect of including interior surfaces in the computer model on annual space conditioning loads of the insulated house are summarized in Table 5 for the five climatic regions. The values represent the difference in space conditioning loads between the insulated house without interior surfaces and the identical house with interior surfaces.

The values may be understood by considering the distribution of average outdoor temperatures for the various climates. For instance, consider the space heating loads for the insulated house located in Madison, WI. Most of the heating days occur away from the balance point. In this situation, the effect of including interior mass surfaces on the overall envelope heat-transfer coefficient is aproximately of equal magnitude to the effect on the utilization of internal heat gains, and the two effects tend to offset each other. On the other hand, in a mild heating climate (such as the Gulf Coast, southeastern, or southern West Coast regions), most of the heating days are distributed near the balance point, where the increase in solar utilization is dominant. The net effect on the insulated house is a large percentage reduction in the prediction of the annual space heating load.

With regard to space cooling loads for the insulated house in hot climates, where the house operates predominantly away from the balance point, the effect on the effective overall envelope heat-transfer coefficient is the dominant mechanism, resulting in a net increase in prediction of the annual space cooling load. On the other hand, in mild climates, where the house operates predominantly near the balance point, space heating and cooling loads occur at different times of the day. In this situation, interior surfaces provide reductions in the prediction of both annual space heating and space cooling loads.

A similar set of results for the poorly insulated house is given in Table 6. Here the same considerations apply, except that interior surfaces produce a considerably larger increase in the overall envelope heat-transfer coefficient. This effect tends to dominate space conditioning loads, causing positive differences except in Los Angeles, CA where the house operated predominantly near the balance point.

These results indicate that the inclusion of interior surfaces in dynamic computer models has an important effect on the space conditioning loads of houses. The inclusion of interior surfaces produced differences ranging from 0.3% to 12%, except for the insulated house located in Los Angeles where it operated at the balance point.

Caviats and Cautions

The predicted effect of interior mass surfaces depends upon the way in which these surfaces are modeled in a computer program. It is the belief of the authors that the mean-radiant-temperature network method more closely approximates the thermal performance of the multi-room situation than other contemporary approximate models for interior mass surfaces. A strong need exists to investigate the relative accuracies of these different models.

SUMMARY AND CONCLUSIONS

In space heating applications, the inclusion of interior surfaces (i.e., partition walls and interior furnishings) in the TARP Computer Program affected space conditioning loads in two ways: they increased the overall envelope heat-transfer coefficient in a linear regime away from the balance point and increased the utilization of internal heat gains in a non-linear regime near the balance point. The effect on the overall envelope heat-transfer coefficient was observed to be considerably larger in the poorly insulated house. The effect on the overall envelope heat-transfer coefficient increased the annual heating load, while the effect on the utilization of internal heat gains decreased the annual heating load. The inclusion of interior surfaces in the modeling of the houses was observed to cause predicted space heating loads to approach steady-state theory.

In space cooling applications, the inclusion of interior surfaces increased the effective overall envelope heat-transfer coefficient in a linear regime away from the balance point, but produced little change in space cooling loads in a nonlinear regime near the balance point. Thermal insulation in the building envelope was found to have a small effect in reducing annual space cooling loads. This was because the insulation produced a decrease in the balance-point temperature that tended to offset the increase in the effective overall envelope heat-transfer coefficient.

In computer predictions of annual space condition loads of the houses, including interior mass surfaces in the TARP Computer Program produced differences ranging from 0.3% to 12%, except for the insulated house located in Los Angeles where it operated at the balance point. The exclusion of interior mass surfaces from computer predictions causes the benefit of energy conserving modifications in houses to be underestimated.

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TABLE 1

Features of the Houses

Component	Insulated House	Poorly Insulated House
Glazing	Double Pane	Single Pane
Walls	R-11 Insulation	None
Ceiling	R-19 Insulation	R-11 Insulation
Floor	R-11 Insulation	None

TABLE 2

Heat-transfer Coefficients for the Insulated House

Component	Surface Area (A) ft^2	(m^2)	Thermal Transmittance (U) Btu/h•ft^2•F	(W/m^2•K)	U•A Product Btu/h•F	(W/K)
Glazing	141.	(13.1)	0.485	(2.75)	68.4	(36.0)
Walls	959.	(89.1)	0.083	(0.471)	79.6	(42.0)
Floor/Crawl space[1]					44.4	(23.4)
Ceiling/Attic					61.1	(32.2)
Door	20.1	(1.87)	0.285	(1.62)	5.7	(3.03)
Infiltration[2]					167.3	(88.2)
Overall Envelope Heat-Transfer Coefficient					426.5	(224.7)

[1] Calculated from 3-node model that included an air node, a bottom surface node, and top surface node. The bottom and top surfaces exchanged heat by radiation.

[2] Calculated from relation: $H_I = \rho \cdot V \cdot I \cdot C_p$, where ρ = density of air, V = volume, I = rate of infiltration, and C_p = specific heat of air.

TABLE 3

Heat-Transfer Coefficients for the Poorly Insulated House

Component	Surface Area (A) ft^2	(m^2)	Thermal Transmittance (U) Btu/h•ft^2•F	(W/m^2•K)	U•A Product Btu/h•F	(W/K)
Glazing	141.	(13.1)	0.961	(5.46)	135.5	(71.5)
Walls	959.	(89.1)	0.280	(1.59)	268.5	(141.0)
Floor/Crawl space[1]					96.6	(50.9)
Ceiling/Attic					76.4	(40.3)
Door	20.1	(1.87)	0.285	(1.62)	5.7	(3.01)
Infiltration[2]					167.3	(88.2)
Overall Envelope Heat-Transfer Coefficient					750.0	(395.)

[1] Calculated from 3-node model that included an air node, a bottom surface node, and top surface node. The bottom and top surfaces exchanged heat by radiation.

[2] Calculated from relation: $H_I = \rho \cdot V \cdot I \cdot C_p$, where ρ = density of air, V = volume, I = rate of infiltration, and C_p = specific heat of air.

TABLE 4

Comparison of TARP Predictions to Steady-State Theory

House	Heating Load Correlation[1]				Steady-State Theory			
	K		T_b		K		T_b	
	Btu/h•F	W/K	F	K	Btu/h•F	W/K	F	K
Insulated	423.	223.	58.1	14.5	427.	225.	57.3	14.1
Poorly Insulated	766.	404.	62.5	16.9	750.	396.	61.9	16.6

[1] predicted by TARP

TABLE 5

The Effect of Including Interior Mass Surfaces in Computer Model for the Insulated House

Climatic Region	City	Difference in Annual Space Conditioning Loads			
		Heating		Cooling	
		kWh	%	kWh	%
Northern	Madison, WI	+46.9	+0.3	-99.6	-3.1
Mid Atlantic	Washington, DC	+38.1	+0.5	+234.	+4.0
Gulf Coast	Lake Charles, LA	-276.	-12.5	+357.	+3.6
Southeastern	Charleston, SC	-372.	-11.1	+173.	+2.1
Southern West Coast	Los Angeles, CA	-597.	-47.8	-431.	-10.2

TABLE 6

The Effect of Including Interior Mass Surfaces in Computer Model for Poorly Insulated House

Climatic Region	City	Difference in Annual Space Conditioning Loads			
		Heating		Cooling	
		kWh	%	kWh	%
Northern	Madison, WI	2,549.	8.4	109.	4.3
Mid Atlantic	Washington, DC	1,439.	8.6	656.	11.4
Gulf Coast	Lake Charles, LA	202.	3.8	1,242.	11.7
Southeastern	Charleston, SC	314.	4.1	891	11.1
Southern West Coast	Los Angeles, CA	-366.	-8.5	-147.	-5.5

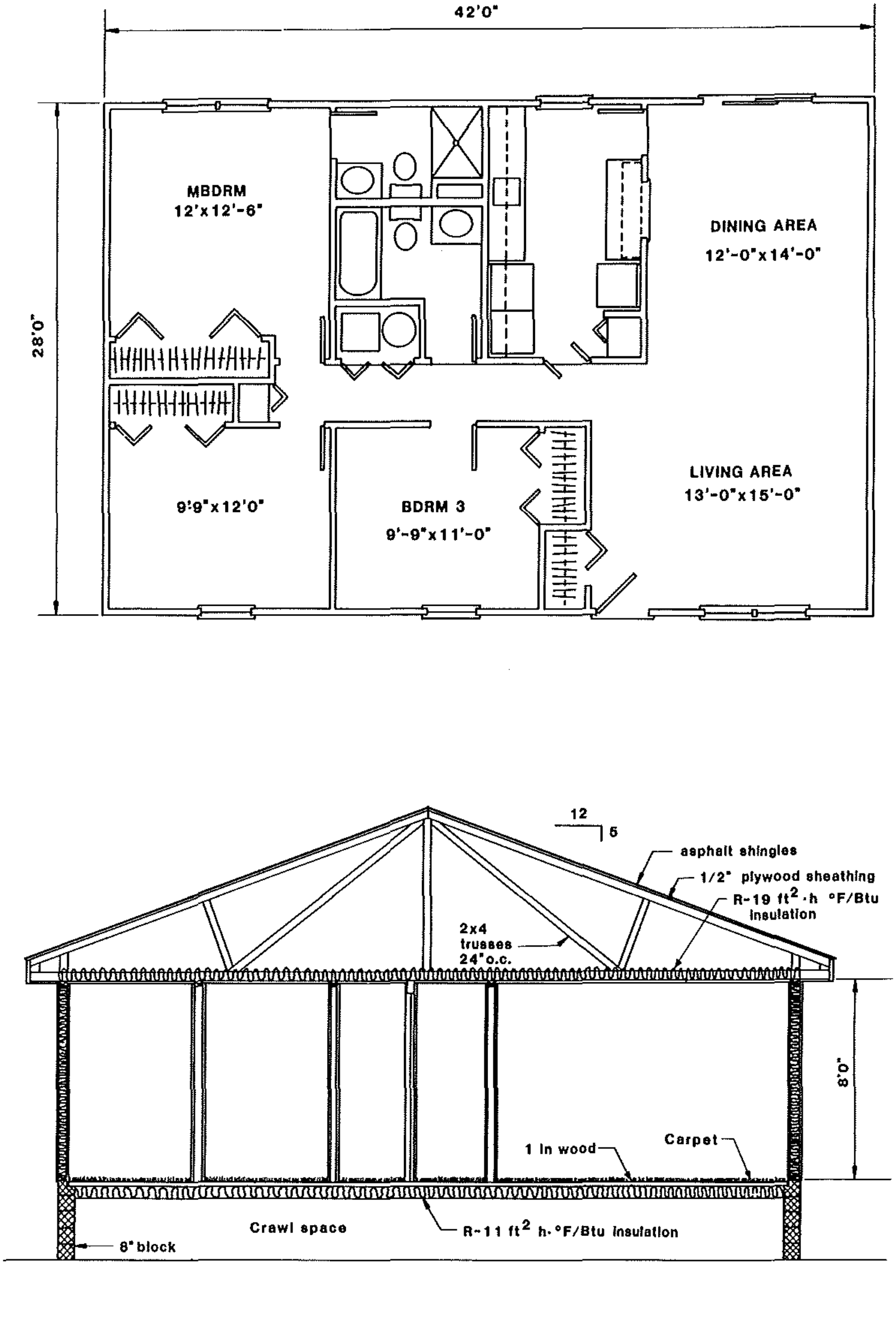


Figure 1. Floor plan (top) and elevation (bottom) for houses used in analysis

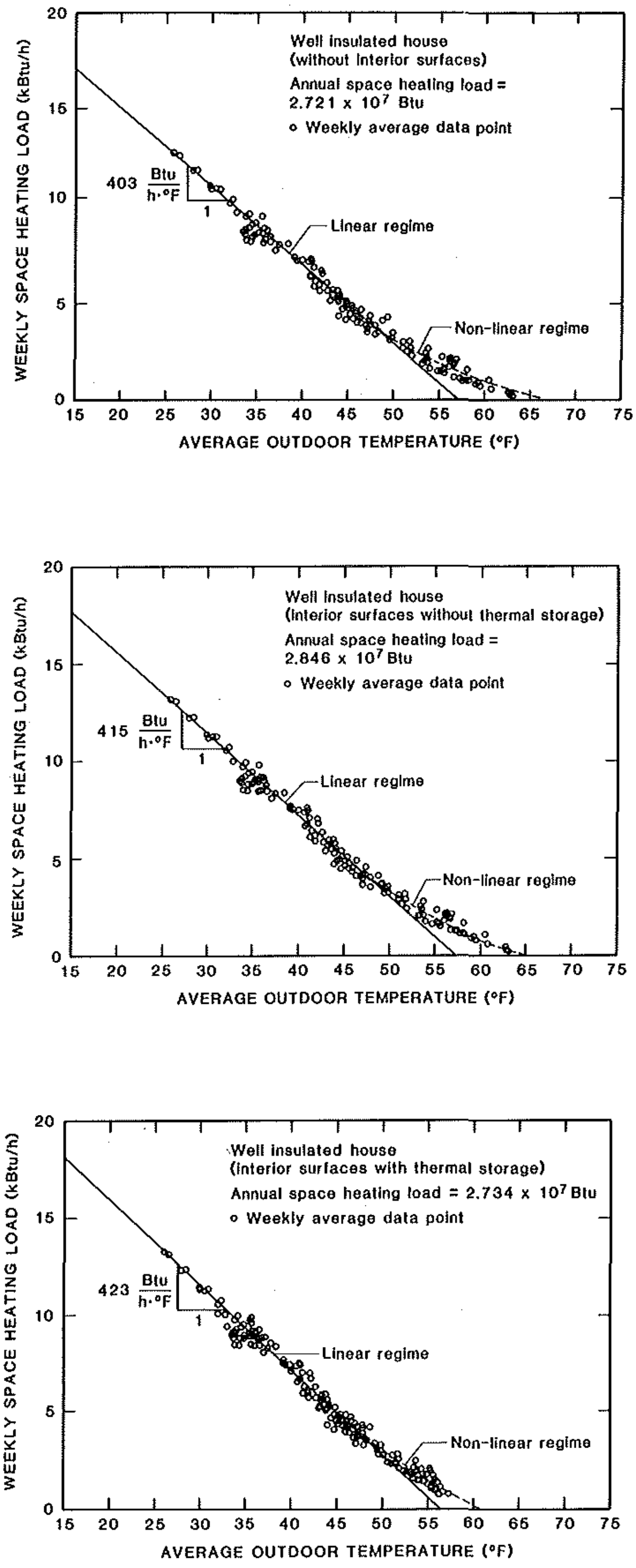


Figure 2. Heating load correlations for insulated house, Washington, D.C.: without interior surfaces (top), interior surfaces without thermal storage (middle), and interior surfaces with thermal storage (bottom)

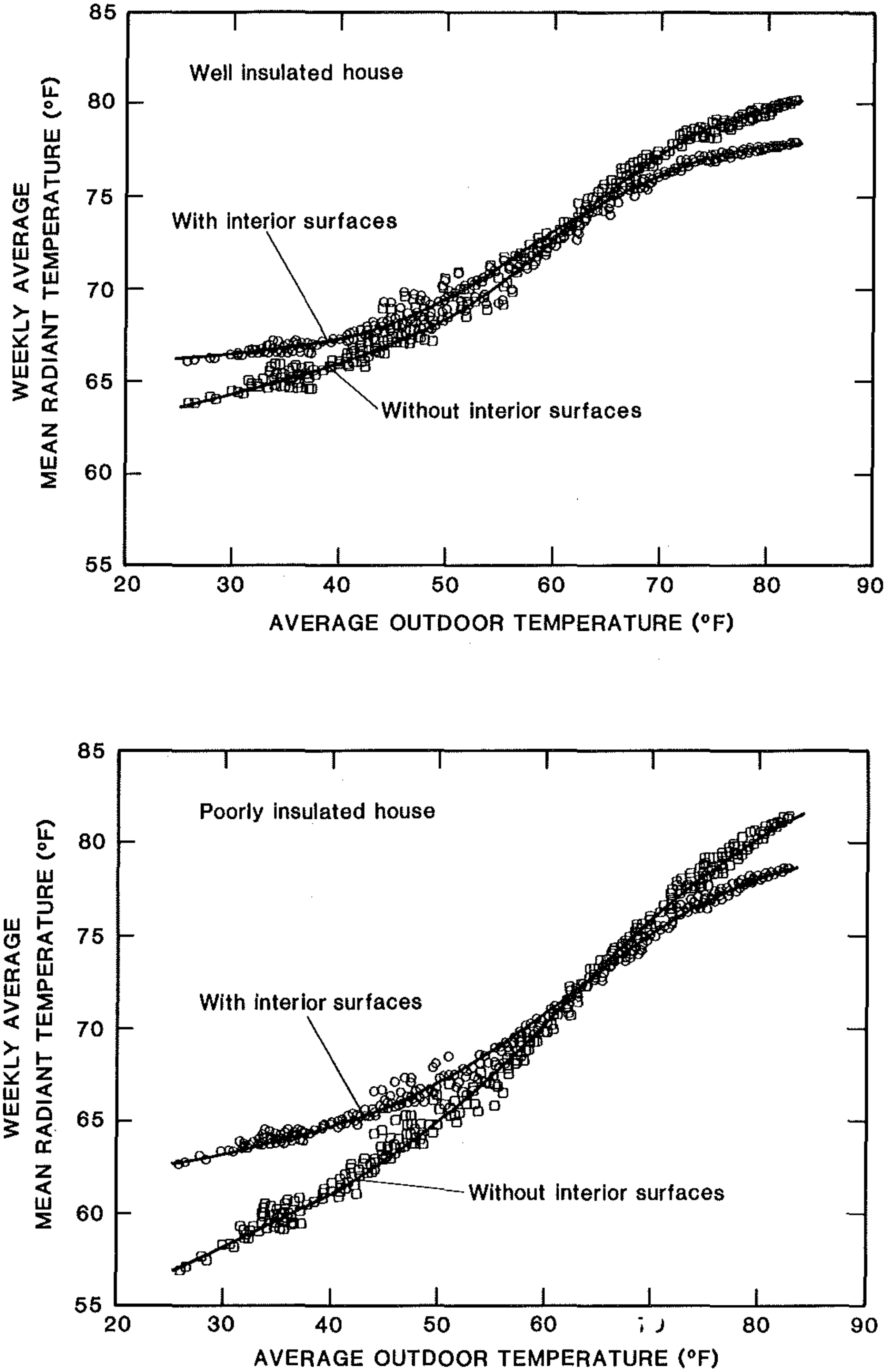
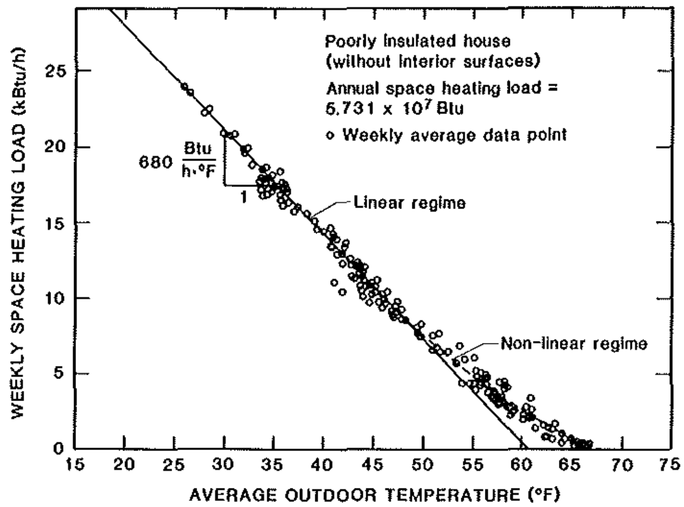
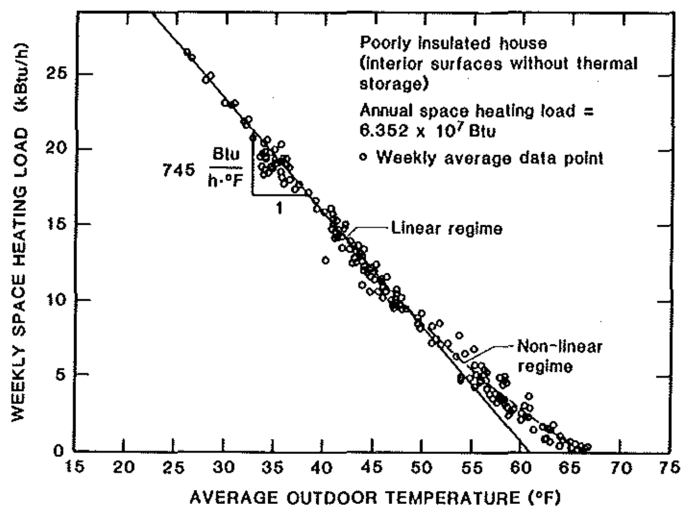


Figure 3. Plot of indoor mean-radiant temperature as a function of average outdoor temperature for an insulated house (top) and poorly insulated house (bottom)





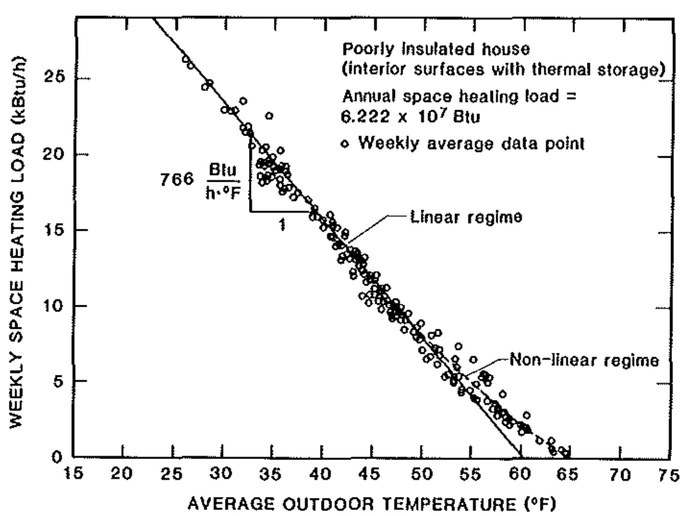
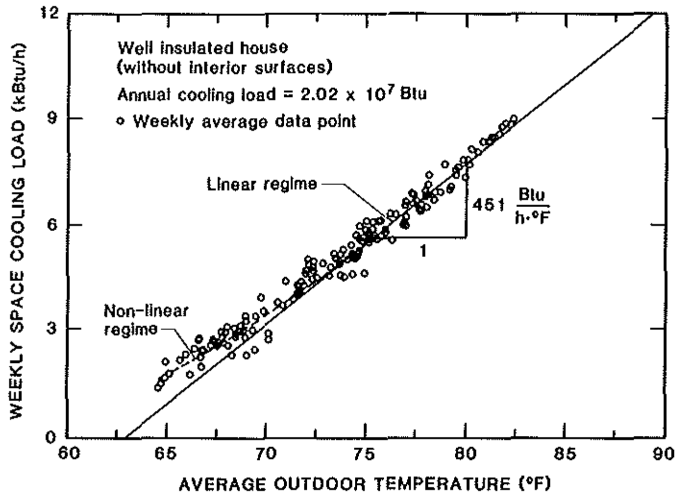
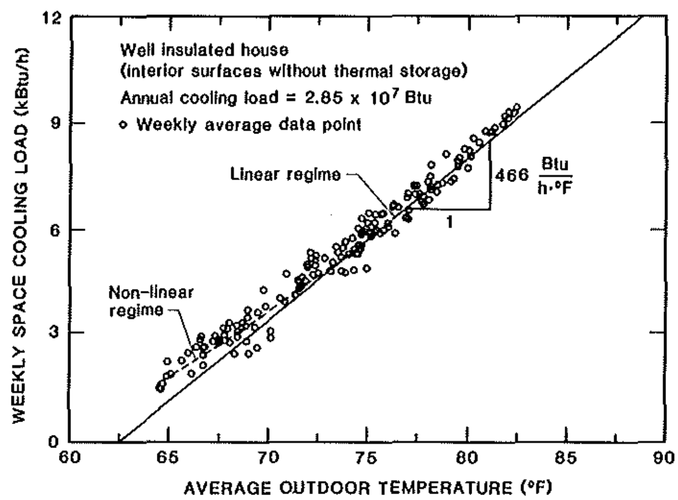


Figure 4. Heating load correlations for poorly insulated house, Washington, D.C.: without interior surfaces (top), interior surfaces without thermal storage (middle), and interior surfaces with thermal storage (bottom)





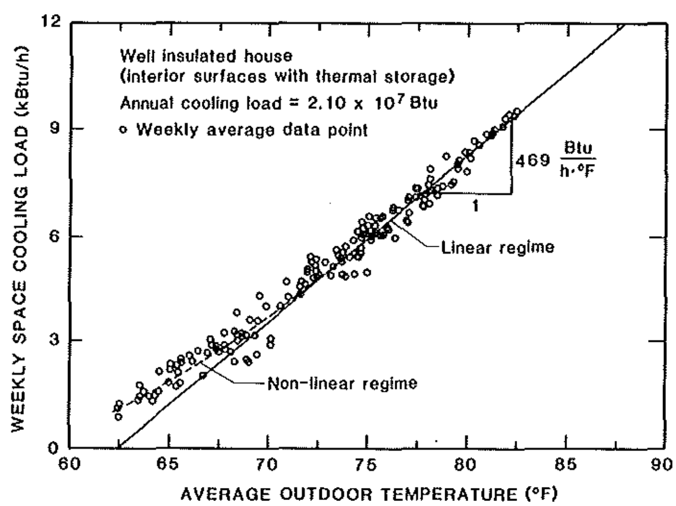
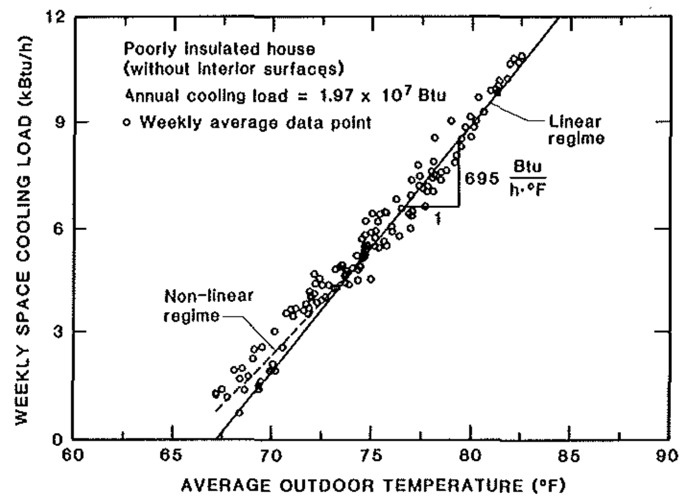
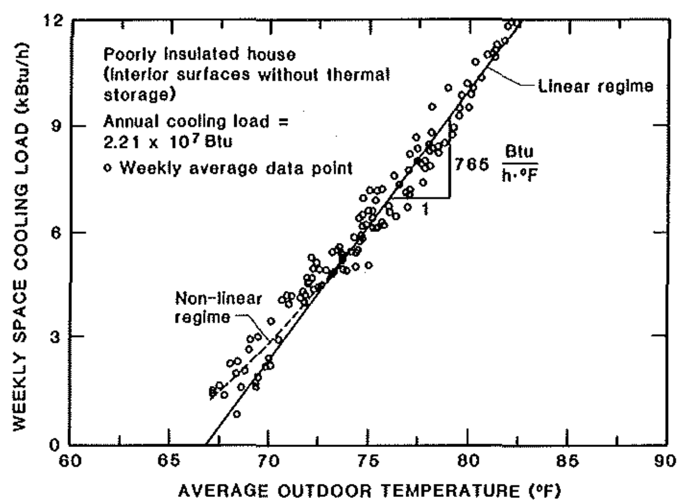


Figure 5. Cooling load correlations for insulated house, Washington, D.C.: without interior surfaces (top), interior surfaces without thermal storage (middle), and interior surfaces with thermal storage (bottom)





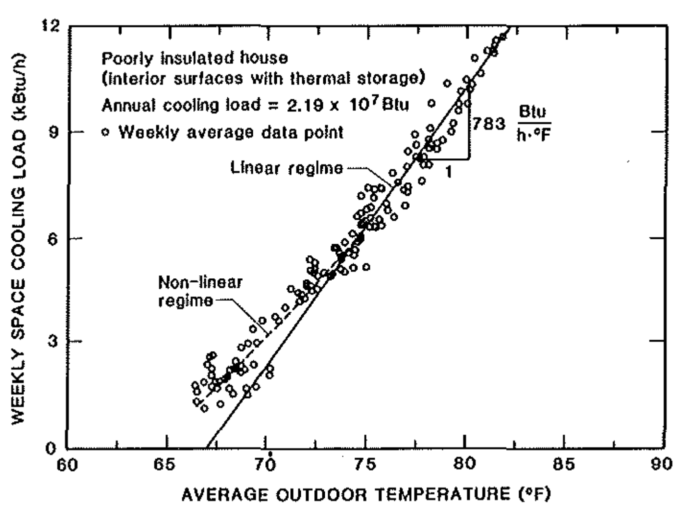


Figure 6. Cooling load correlations for poorly insulated house, Washington, D.C.: without interior surfaces (top), interior surfaces without thermal storage (middle), and interior surfaces with thermal storage (bottom)