A STATISTICALLY BALANCED PARAMETRIC STUDY FOR BUILDING SIMULATION

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ABSTRACT

Based on DOE thermal mass research, consisting of field measurements, consistency checks, main-frame building simulation model validation and data bases, a simplified prediction procedure is developed for estimating the effect of exterior envelope thermal mass on annual energy usage. This procedure is cross-checked using a real building and DOE 2.1B simulations selected by a fractional factorial experimental design for accuracy and comprehensiveness. This procedure estimates the annual delta load between two buildings with identical characteristics except that one has framewalls, the other insulated mass walls. The delta loads are a function of wall R-value and heat capacity. The sensitivity of delta loads to interior mass in the foundation, partition walls, and ceiling are examined as well as the south-facing window area and use of window insulation. The results of this statistically based parametric analysis show that for buildings with substantial interior thermal mass in excess of that found in typical single-family construction, the simplified prediction procedure overestimates the exterior wall mass effect. However, for frame construction with or without slab foundations and with or without extensive south-facing glass, the prediction procedure is valid in the mid-southeastern United States.

INTRODUCTION

Since 1979, the U.S. Department of Energy (DOE) has supported research directed at a systematic study of the effect of thermal mass in building exterior walls on the annual space-conditioning load of a building. The result is a reliable experimental data base consisting of thermal performance measurements on 14 test houses in two locations with various amounts of external wall mass, independent consistency checks on the measurements, validation of a variety of main-frame building simulation models, an extensive simulated data base of full-size single-family residences, and a simplified technique for building designers to predict the effect of exterior thermal mass on annual heating and cooling loads.

This paper summarizes the DOE thermal mass research that resulted in a simplified prediction technique that has been validated using a real building. The Joint Institute Dormitory (JID) building was first described in 1982 at the ASHRAE/DOE conference in Las Vegas (Christian 1982). The JID, located at a national laboratory, was monitored for two years by collecting hourly thermal performance data, sufficient to show major component energy balances on a weekly basis within 5% to 15% (Christian 1983, 1984, 1985).

The validation of the simplified prediction technique consists of calibrating the DOE 2.1B building simulator to the JID building and then modifying the structure in the model to show the sensitivity of the heating and cooling loads to various amounts of exterior wall mass. A statistically based parametric analysis is then performed. The analysis determines the significance of building design variables on the prediction of annual exterior wall

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thermal mass effects. An empirical model is fit to the simulated data base of a conventional 1200 ft^2 (110 m^2) three-bedroom ranch-style house. The building used to validate this tool is a very massive 4000 ft^2 (372 m^2) gross floor area with extensive south-facing glazing. The building is actually used as an office/dormitory facility; however, the internal electric loads and occupancy in 1982 of two to eight people was found to be similar to residential usage.

EXPERIMENTAL TEST DATA

Test Houses

Exterior wall thermal mass effect field work on 20 ft (6 m) by 20 ft (6 m) test houses was carried out by the National Bureau of Standards (NBS) at Gaithersburg, and by a New Mexico energy research and development institute (NMERDI) at Santa Fe, NM. Six one-room test houses were built at NBS to compare seasonal energy performance of wood-frame, masonry, and log construction (Burch 1982, 1984:1, 1984:2, 1984:3, 1984:4). Site weather data were collected for periods in the winter, spring, and summer. The test houses had identical envelope construction except for the walls and were operated at the same thermostat setting. Average hourly heating and cooling energy consumption was recorded, along with temperatures, relative humidities, wall heat flow, and time. Eight one-room test buildings were constructed near Santa Fe by NMERDI to study the influence of thermal mass in exterior walls (Gustinis 1984, Robertson 1984). The 8 NMERDI buildings are identical to each other except for wall construction (adobe, concrete and masonry unit, wood-frame, and log). They were constructed to isolate the effects of the walls. The roof, floor, and stem walls were all well insulated, and the buildings had average infiltration rates of less than 0.4 air change per hour. The buildings were instrumented to record envelope component temperatures and heat fluxes, outside weather conditions, and heating energy use. Data were collected for two heating seasons from midwinter to late spring, without windows and for a second season with windows.

The major results were: In the cold part of the winter, thermal mass did not have a measurable effect. During mild spring heating days with internal heat gain causing indoor temperatures to exceed thermostat setting, a significant thermal mass effect was observed (less heating energy for masonry and log wall houses especially where substantial wall mass was located adjacent to inside surface and insulation was placed to the outside of that mass). During the summer season, wall mass had an important effect in space cooling loads. The maximum annual heating load savings of mass observed at the New Mexico site was around 4%.

Real Building

Continuous detailed hourly thermal performance measurements for a two-year period on an occupied, massive 4000 ft^2 (372 m^2) dormitory in Oak Ridge, TN were analyzed, along with DOE 2.1 modeling of the effect of thermal mass (Christian 1983, 1984, 1985). Once the model was calibrated with the building measured thermal performance data, sensitivity studies were run on the effect of exterior wall thermal mass. The percentage energy savings resulting from the presence of exterior massive walls insulated on the outside, in both the heating and cooling season predicted by the DOE 2.1B model, depends on the amount of mass in other parts of the building. The largest effect of exterior wall thermal mass in a building of this type occurs when the base building roof, foundation, and partition walls are all wood frame construction. For a similar building with R-20 (3.5 h$\cdot$m$^2\cdot$C/W) walls in the Oak Ridge climate, the maximum effect of wall mass, in excess of that found in typical frame construction, is about a 2% savings of the total annual energy usage. The opaque wall surface area in this building accounts for around 8% of the total heating compared to the NMERDI test houses of around 75% and NBS test houses of around 40%.

DATA CONSISTENCY AND MAIN-FRAME MODEL VALIDATION

BLAST, DOE 2.1, DEROB, and TARP can simulate mass effects. Cumulative heating and cooling loads and the characteristic influences of wall thermal mass on hourly behavior can be reproduced by these models (Arumi 1984:1, 1985, 1984:2; McClain 1984; Birdsall 1985; Carroll 1985). If all building variables except mass were held constant, then test houses, modeled with increased wall mass, showed that the thermal performance improved or stayed the same as measured at both sets of test houses. The relative magnitude of the thermal mass energy savings in different seasons was confirmed. The models show no energy savings due to mass when the building inside air temperature does not float above the thermostat set-point as observed by the experiments. A larger mass effect at the Maryland and New Mexico sites is predicted by the models in the spring, fall, and summer than the winter. The models also predict larger mass effects when insulation is placed on the outside of the mass layer than when placed on the inside.

More than 100 comparisons of model predictions with experimental data were made using DEROB, DOE 2.1, and BLAST. The comparison periods varied from one day to two weeks. The cumulative comparison of all test periods, test houses, and models predicted on average 1.5% above the measured data, and 88% of these comparisons fell within ±25% of the measured loads. These statistics suggest the absence of systematic errors in the models used to predict annual loads.

A data base was developed that extrapolates the test building data to real building types and other climates (Carroll 1985:2). Prior to data base development, the BLAST model was calibrated by showing a comparison between predictions and measured data from six of the experimental test houses in two climates (Carroll 1985:1). For each test house, comparisons were made for three ten-day simulation time periods representing different seasonal conditions. Hourly comparisons were made for ten selected parameters, including heating or cooling loads, air temperature, wall inside surface temperature, and heat flux for each of the time periods. The results showed that the predictions are generally within the range of the measurement uncertainties. The BLAST simulations, on average, predicted the loads for the ten-day periods within 7% of the measured loads for both the NBS and NMERDI test buildings. The BLAST simulations were able to predict the average inside air temperatures and inside wall surface temperatures within ±1°F (0.6°C). On average, BLAST predicted the net heat flow through the exterior walls to within ±4%.

Most importantly, the model was able to predict when inside air temperature actually floats above or below the building thermostat setpoints. It is this event that leads to thermal mass effects.

SIMULATION DATA BASE DEVELOPMENT AND ANALYSIS

The test facilities' field data are used as the basis for extrapolating the mass effect to other climates and real building designs. The calibrated BLAST model was used to produce an extensive set of parametric variations of wall thermal mass configurations for a typical residence and the effect of thermal mass on the annual heating and sensible cooling loads for six cities (Minneapolis, Denver, Washington, Atlanta, Phoenix, Miami) (Carroll 1985). A 1200 ft^2 (110 m^2) three-bedroom residence was selected for the "typical" house design and modified to reflect average current practice thermal integrity [R-19 (3.3 h•m^2•C/W) ceiling, R-10 (1.76 h•m^2•C/W) floor, glass area 15% of floor area, and one air change per hour]. For each of the six cities, there were five generic wall configurations: the thermally massive single-layer homogeneous wall (73 simulations) and the four two-layer (insulation and mass) configurations where the thermally massive layer was combined with R-5 (0.9 h•m^2•C/W) or R-20 (3.5 h•m^2•C/W) insulating layers on either the inside or outside, respectively (60 simulations for each). Parametric variations of the walls were formed by variations over the following ranges:

Insulation layer - Thermal resistance: 0, 5, 20 h•ft^2•F/Btu (0, 0.9, 3.5 h•m^2•C/W)

Thermal mass layer - Thermal conductivity: 0.0 - 1.0 Btu/h•ft•F (0.0 - 1.73 W/h•m•C)

Density: 0 - 150 lb/ft^3 (0 - 2403 kg/m^3)

Specific heat: .3 Btu/lb•F (1256 J/kg•k)

Thickness: 0 - 1.5 ft (0 - .46 m)

A total of 313 simulations were performed for each climate. Each simulation yielded annual heating and cooling sensible loads.

BLAST was also used to assess the effect of mass on heating and sensible cooling loads with respect to thermostat setting, use of nighttime ventilation, infiltration, solar gain, and foundation mass. The building operating and construction variable sensitivities were as follows:

Parameter	Base Case	Sensitivity
Dead band	70–78 F (21–25.5 C)	72–76 F (22.2–24.4)
Winter night setback	to 60 F from 11 p.m.–7 a.m.	No setback
Summer natural ventilation	5 ach when $T_{inside} > T_{outside}$	Fixed - 1 ach
Infiltration	1.0 ach	.5 ach
Solar	.5 solar absorptance of window system	0 solar absorptance, No shades
Foundation mass	zero	Equivalent to 4 inch (0.1 m) concrete slab

Figure 1 shows that the foundation mass appears to be the only change that significantly affects the ability of external wall thermal mass to reduce loads. Each bar represents the seasonal cooling savings calculated when typical lightweight exterior frame walls (R-12) are replaced by typical heavyweight exterior walls (R-12), brick and block construction. Figure 1 shows the estimated difference in cooling load between lightweight and massive buildings (ΔL) with the same R-value for one location, Phoenix, labeled as the base. The other bars show that ΔL remains nearly constant despite changes in a number of building parameters. However, ΔL decreases by 26% if a slab foundation is used instead of a massless foundation. The mass effect for all climates is about 25% less (2.0 compared with 2.7 MBtu/year)(790 kWh/year) in the cooling season and 75% less (0.5 compared with 1.8 MBtu/year) (527 kwh/year) in the heating season in the case of slab foundations compared to massless foundations.

The DOE 2.1 program was used to check the loads predicted using BLAST since the DOE slide rule data base used DOE 2.1 (Birdsall 1985). First a comparison of DOE 2.1 results was made with test house measurements at both sites. The conclusion was that DOE 2.1 agrees within a reasonable tolerance (+20%) to data from the test cells. The results of the data base using the same 1200 ft^2 modified rancher used in BLAST produces results indicating that the DOE 2.1 computer program and the BLAST program agree.

A SIMPLIFIED EXTERIOR WALL THERMAL MASS PERFORMANCE PREDICTION TOOL

Present national building standards dealing with the thermal design of residential building envelopes, such as ASHRAE 90-80 (ASHRAE 1980), place heavy emphasis on the thermal resistance of building insulation without regard for the effects of building thermal mass. For cooling heat-gain calculations, a design equivalent temperature difference is specified with reference to the thermal time constant of the envelope. Prescriptive heating criteria, however, are based strictly upon a U_0 factor, which is an envelope heat transfer coefficient that includes the thermal resistance of walls, windows, doors, and skylights, but not the thermal effect of mass. This U_0 concept is valid only when the steady-state heat transport is the major factor for the building heating energy requirement.

Several methods have been developed to estimate these effects more generally and thus cause their inclusion into insulation standards (e.g., M-factor) (Cantani 1978). While these methods do suggest that there will be conditions under which mass effects will be quite significant, none have been experimentally validated. Thus, there is a strong need for a simplified prediction procedure that correctly predicts the effects of various combinations of envelope mass and insulation for all regions of the nation and is based on a reliable experimental data base.

It is important, not only to develop a simplified mass effect predictor on a reliable model, but also the inputs to the model must be representative of real buildings. The dominant thermal mass effect in a whole building is actually the cumulative storage and release of excess heat inside the insulating envelope from the exterior walls, internal furnishings, floor, partition walls, and all other massive materials in contact with the conditioned space. The annual energy savings will be large (typically >10%) if mass is added to a "zero mass" exterior wall. If you already have a very massive building (i.e., concrete block partition walls, slab floor with no carpeting, exposed concrete ceiling), the annual energy change due to the added mass of a concrete block exterior wall from that of a frame wall is very small (<1%).

Regression Analysis to Extend Data Base

To enable a builder to use the results of this research, a simplified method is presented to determine the potential annual energy savings of exterior wall mass in excess of that found in typical wood-frame construction used in single-family buildings. Equation 1 can be used to estimate the exterior wall mass energy savings per square foot of floor area for buildings with exterior wall mass in excess of typical frame-wall construction. Delta load is defined as follows:

delta load = load (frame wall) - load (mass wall)

where

load = building annual heating or cooling load (MBtu/year).

The R-value of the frame wall equals the R-value of the mass wall.

The following empirical nonlinear model predicts the difference in load between a wood-frame wall and a massive wall with the same total wall U-value:

$$\Delta L = (B_1 + B_2\sigma + B_3 Ut + B_4\sigma Ut)\ \frac{W_A{}^2}{V_A} \tag{1}$$

where

B_i = regression coefficients - one set for each - climate i = 0,1,2,3,4

σ = exp (B_0 x HC)

HC = wall heat capacity (Btu/ft^2•F)

Ut = total wall U-value (Btu/h•ft^2•F)

W_A = opaque exterior wall area of interest (ft^2)

V_A = building volume (ft^3)

This equation is of a form similar to that used to develop the DOE Slide Rule to account for exterior wall mass (Lawrence Berkeley Laboratory 1985). The delta load here, however, is scaled to the building of interest by the relative wall areas and the wall surface to building volume ratio. In general, the magnitude of the delta load predictions are consistent with the Slide Rule results; however, a different data base and a different technique are used to derive the coefficients. The coefficients shown in Table 1 are based on the BLAST simulated data base (Carroll 1985:2). Starting with the 313 BLAST-generated annual heating and cooling load simulations in each of the six climates, a data base of delta loads was derived of a 1200 ft^2 prototypical building with various amounts of mass and insulation. The delta loads consist of the differences between heating and cooling loads of low mass building simulation cases and a second set of high mass simulations with the same R-value. The low mass cases had an average HC of 0.23 Btu/ft^2•F (1.3 W/m^2•C). Wall heat capacity is defined as:

$$\text{Heat Capacity} = \text{Wall Mass} \cdot \text{Specific Heat}$$

where

Wall Mass = weight of wall per ft^2 of wall area (lb/ft^2)

Specific Heat = specific heat of wall mass ($Btu/lb \cdot F$)

The BLAST data base had a set of low-mass runs with a complete set of identical R-values as the set of high mass runs. The load data from matching sets of low and high mass walled buildings is needed to derive Δ load values used in the regression analysis.

To account for the fact that the low mass wall building simulations are lighter than typical frame construction (20% frame), an adjustment was made to the regression coefficients so that the delta load was zero for wall heat capacities of 1.6 $Btu/ft^2 \cdot F$ (9.0 $W/m^2 \cdot C$) of wall area. The effective mass in an insulated frame wall is estimated to be 1.6 $Btu/ft^2 \cdot F$ (9.0 $W/m^2 \cdot C$).

A second alteration was made to the coefficients to account for the mass of the foundation. By assuming a zero mass foundation in the data base, the interior mass of the building is even lighter than a house with wood floors. The base case house used to produce the load data assumed an insulated massless foundation. As previously stated, the sensitivity study of the data reveals that by adding foundation mass equivalent to a 4-inch-thick concrete slab, the delta loads were reduced by about 75% in the heating season and 25% in the cooling. The use of these foundation mass correction factors presents more realistic estimates of mass effects, particularly in the southern half of the U.S. where mass has the most influence and slab foundations are most common. In single family houses with unconditioned basements or crawl space foundations, the mass effects predicted by this model are conservatively low. Coefficients for Equation 1 derived from a nonlinear regression analysis, employing least squares fit, are given in Table 1 for six climates and three wall configurations, for both heating and cooling seasons. The three configurations are insulation located on the outside of a mass layer, insulation on the inside of a mass layer, and a mixed case representative of log construction.

To estimate the delta load for a specific building in climates similar to the six shown in Table 2:

1. Select the set of coefficients for one climate, wall type (insulation location: inside, outside, mixed), and the season (heating or cooling),

2. Select the total wall U-value desired,

3. Select the wall heat capacity of interest.

Results for Atlanta Region

Figures 2 and 3 show the heating and cooling delta loads calculated by the prediction tool for a 1200 ft^2 (110 m^2) prototypical single-family dwelling with R-20 (3.5 $h \cdot m^2 \cdot C/W$) walls and varying heat capacities. The three curves represent one wall type with insulation location positioned on the outside of the mass, inside the mass layer, and a mixed case representing log construction. The figures clearly show that the largest savings occur with outside insulation in the cooling season. To illustrate the near maximum mass effect for typical residential designs in the mid-southeastern United States, a building with concrete block walls insulated on the outside is used. An 8-inch (0.2 m) concrete block wall has a heat capacity of around 10 $Btu/ft^2 \cdot F$ (57 $W/m^2 \cdot C$). Figure 2 indicates that the delta load for the outside insulated case in the heating season is 0.3 MBtu/yr (88 kWh/year). This is in a building that uses a base heating load of 18 MBtu/yr (5276 kWh/year). Figure 3 indicates that the delta load for the outside case in the cooling season is 0.8 MBtu/year (234 kWh/year and a base sensible cooling load of 21 MBtu/year (6155 kWh/year). The dynamic effect of the outside insulated 8-inch (0.2 m) concrete block wall with a total wall R-value of 20 (3.5 $h \cdot m^2 \cdot C/W$) is 1.7% less heating load than a R-20 (3.5 $h \cdot m^2 \cdot C/W$) frame-wall house and 3.8% less cooling load.

The delta loads for this case can be converted to a delta R, which is the reduction in R-value of the massive wall to produce the same annual energy consumption as the R-20 (3.5 h•m^2•C/W) frame-walled building. The DOE affordable housing building data base (Lawrence Berkeley Laboratory 1985) was used, starting with the annual loads of a 1200 ft^2 (110 m^2) single-family dwelling with R-20 (3.5 h•m^2•C/W) frame walls. A sensitivity study was performed on the R-value to determine the R-value that produced the total difference in annual energy loads as the sum of delta heating and cooling loads shown in Figures 2 and 3. Removing R-5 (0.9 h•m^2•C/W) was found to increase the loads such that if the HVAC system conversion efficiency was nearly the same for both the heating and cooling season, the energy consumption of an R-20 frame-wall building would be the same as for an R-15 (2.6 h•m^2•C/W) massive-wall building with the insulation on the outside. The delta R-value is arrived at by actually using some of the cooling season savings and applying it to the heating to attain the same annual energy usage. This results in the massive building using more energy in the heating season than the R-20 (3.5 h•m^2•C/W) frame and less in the cooling season. Larger delta R-values could be attained in passive solar homes and in more conventional single-family buildings with crawl spaces and unconditioned basements. However, it is necessary to insulate on the outside of the mass layer to expect delta R-values larger than 5 h•ft^2•F/Btu (0.9 h•m^2•C/W) in an Atlanta-type climate.

Figures 2 and 3 show that the same 8-inch (0.2 m) concrete block insulated on the inside has a delta load of 0.1 MBtu/year (29 kWh/year) in the heating season and 0.25 MBtu/year (73 kWh/year) in the cooling season. The inside insulated block saves 0.5% in the heating season and 1.2% in the cooling season. The delta loads for the inside case can be converted to a delta R. For instance, by using the affordable housing data base (Lawrence Berkeley Laboratory 1985) starting with the annual loads of a 1200 ft^2 (110 m^2) single-family dwelling with R-20 (3.5 h•m^2•C/W) frame walls, a sensitivity study was performed on the R-value to determine the R-value which produced the same total difference in annual energy loads as the sum of delta loads described above. A change of R-1 (.56 h•m^2•C/W) was found to increase the loads such that if the HVAC system conversion efficiency were nearly the same for both the heating and cooling season, the energy consumption of an R-20 (3.5 h•m^2•C/W) frame-walled building would be the same as a R-19 (3.3 h•m^2•C/W) massive-walled building with the insulation on the inside.

SUMMARY RESULTS FOR ALL REGIONS

Table 3 lists the percent of energy savings for an 8-inch (0.2 m) block wall insulated on the outside and insulated on the inside for all six climates studied. The percentage energy savings are between zero and 7%. A set of delta R-values are also listed in Table 3. These values represent the decrease of exterior wall insulation from the massive wall system to obtain a design that has equivalent performance to a frame building. The delta loads are calculated using the affordable housing data base for R-20 (3.5 h•m^2•C/W) walls (Lawrence Berkeley Laboratory 1985). For smaller R walls, the resulting delta R-values are always less. The delta R-values are between zero and 5 (1 h•m^2•C/W). The highest delta R of 5 is for exterior insulation in Atlanta.

VALIDATION BASED ON REAL BUILDING THERMAL PERFORMANCE MEASUREMENTS

An underlying theme throughout the thermal mass research program has been to provide reliable, credible information — multiple test sites, consistency checks, validation, multiple models have been part of the program. The path leading to the simplified prediction is directly traceable to measured data. Yet to check this design tool, for consistency and sensitivity to other factors not in the model, an analysis is made based on field data from a full-size building.

BUILDING DESCRIPTION

The building contains 3700 ft^2 (345 m^2) of net heated floor space used for offices, dormitory rooms, lounge, and dining area. The north wall and part of the east wall and all of the roof are insulated concrete with extruded polystyrene, and covered with earth, and planted with grass and small shrubs. Parts of the south, west, and east walls are block construction, externally insulated with 3 in (0.075 m) of expanded polystyrene with a stucco-type coating.

The south-facing glass area amounts to 17% of the net floor area. The building envelope construction is primarily poured concrete and masonry. The heat pump circulating fan operates continuously. Supply air ducts are located within the wall footings to enhance the coupling between the building air and thermal mass in the envelope. Most of the exhaust air is vented through two exhaust fan ports in the roof, one in the restrooms and a second in the kitchen. Repetitive air exchange measurements using tracer-gas techniques indicate that the air change rate varies from 0.4 air change per hour with no exhaust fan operation to 0.7 air change per hour with one fan. The exhaust fan operation was checked every minute, and the total operating time recorded hourly.

The three entrances to this building are through vestibules. Results from the tracer gas air change rate tests show no significant differences in air change rate as a function of door openings. The vestibule doors are closed at all times, so the variable traffic rate into and out of the building does not alter the fact that air exchange in the building is predominantly a function of ventilating fan operation.

Space heating and cooling in this building is provided by a heat pump with a manufacturer's nominally rated 12.3-kW (3.5-ton at 95 F) heat pump and enthalpy-controlled economizer. The economizer control is set to bring in ambient cooling only when the outside air enthalpy is below the inside air enthalpy. Because the building circulating fan runs continuously, during those times when the outside air enthalpy is less than the inside air enthalpy, the economizer cycle essentially increases the air change rate to about 4 per hour.

The single thermostat located in the north zone of the building was manually set to maximize thermal comfort by using a thermal comfort meter and recording the predicted mean vote (PMV) in various positions within the building. The PMV scale is an index that predicts the mean value of the subjective ratings of a large group of people on a seven-point thermal sensation scale ranging from -3 (cold) to +3 (hot) (Fanger 1973). The thermostat was set to keep the entire building within a PMV range of 0 to +0.5 during the cooling season and -1.0 to +0.5 during the heating season. The north zones, surrounded on three sides with earth contact, were typically more stable and had a smaller PMV diurnal cycle amplitude. The south-facing windows dominated the envelope heat flows both in the heating and cooling seasons.

FIELD MEASUREMENTS COMPARED WITH 2.1B MODEL PREDICTION TOOL

The Joint Institute Dormitory was modeled using the DOE 2.1B building simulation code. A six-zone model of the dormitory was developed, along with the following measured values used as inputs: average internal electric loads, actual 1982 weather data coinciding with the period of thermal performance measurements, actual thermostat settings, average observed occupancy schedule, infiltration and ventilation rates, as-built construction geometries, and component thermal physical property data leading to reproducible measured heat flow data on the roof, floor, exterior walls, and interior partitions, window shade factors, cfm delivered to each zone, continuous operating circulating fan performance, and cooling plant performance. The BDL file describing this actual building is over 900 lines of input coding.

This version of the DOE 2.1B code did not have the capacity to account for multiple-dimension heat flows or for the actual thickness of the soil on the roof and in the berm on the north and east walls. The model was calibrated to the building as close as possible despite these deficiencies. To account for the solar shading of the grass, the full roof and bermed walls were shaded with a hypothetical shade screen with zero transmittance; however, the effect of evapotranspiration was not modeled. This seemed to produce larger errors in the summer cooling season than in the winter. The model was able to come within 5% of the measured annual heating energy and 30% of the measured annual cooling energy. Closer examination of hourly data revealed that the model was overpredicting the heat gain of the roof and bermed walls; once this error was accounted for, the cooling energy prediction was much closer to measured values. Comparing hourly measured heat flows into the building from the berm and roof during several typical summer days in late July indicated that the model was overpredicting the heat flow in the roof by an average of 381 Wh (1300 Btu/h) and in the bermed walls by 352 Wh (1200 Btu/h). Figure 4 shows the measured vs. predicted heating energy usage for February 1982 and cooling energy usage corrected for the measured effect of soil for August 1982. The heating energy prediction is 3.3% higher than measured, and the cooling energy consumption is 14% higher.

Because the DOE 2.1 model did not simulate the thermal performance of the soil accurately in the roof or the berm, and earth-sheltered construction is not typical, the soil was removed from the model before conducting the analysis of the exterior wall mass effect.

PARAMETRIC ANALYSIS OF THERMAL MASS EFFECT PREDICTIONS

It has been shown that regression Equation 1 can be used to estimate the annual heating and cooling load reductions. To determine the sensitivity of Δ load predictions to a variety of other variables, a statistically based parametric analysis of thermal mass effect predictions has been run. The variables of particular interest that were thought to be the most sensitive factors affecting the Δ load prediction are foundation mass, interior partition wall mass, ceiling mass, shutters, and the area of south-facing windows. The ability of exterior wall mass to alter heating and cooling loads depends not only on climate and wall type but also on solar gain and interior mass. This parametric analysis was run to check Equation 1 and to determine the relative importance of solar gain and interior mass on the delta load predictions from Equation 1. Since the delta load is generated as the difference between the output calculated with high mass to the output calculated at low mass, the mass is implicit in the data but not used explicitly in the model. It is a known factor of importance.

The method for exploring the sensitivity of Equation 1 is by first setting up an experimental design. The type of design employed is called a factorial analysis design, which entails setting each factor (input variable) at a high and low level, then selecting combinations of highs and lows in such a manner as to be able to isolate the main effects and interactions using the fewest number of runs (Walpole 1978).

A complete factorial design consists of all combinations of high and low levels from each factor. For example, if the design has six variables each at two levels, that amounts to 2^6 or 64 runs.

The effects estimated in a full 2^6 factorial analysis are: 1 average, 6 main effects, 15 two-factor effects, 20 three-factor interactions, 15 four-factor interactions, 6 five-factor interactions, and 1 six-factor interaction. The high order interaction effects are generally of least interest and are akin to higher order terms in numerical approximation, which tend to become negligible. A fractional factorial analysis reduces the number of runs by using a fraction of the full design. This method estimates only low order effects and assumes the higher order interactions are negligible.

A one-quarter fraction of the 2^6 factorial design using only 16 runs is employed. This method estimates the effects of (1) south-facing windows, (2) interior partition wall mass, (3) foundation, (4) ceiling mass, (5) wall R-value, (6) insulated window shutters and interactions 1-2, 1-3, 1-4, 1-6, 2-3, 2-4, 3-4, 1-2-4, 1-3-4.

The analysis of the fractional factorial design can be done using regression analysis. Letting dummy variables x_1, x_2, x_3, x_4, x_5, and x_6 represent each of the six factors listed above (south-facing windows, interior partition wall mass, foundation, ceiling mass, wall R-value, and insulated window shutters, respectively), the value of any x_i is 1 when the factor it represents is at its high value and -1 when it is at its low level. If the effect of the factor is linear over the range investigated, then intermediate values between -1 and 1 are acceptable in the regression equation. In general, going outside the range is considered unwise in that the behavior in the extremes may be very nonlinear.

Using the dummy variables above, we can express the delta load as a function of them and their interactions. The model is:

$$\Delta L = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_1 x_2 + \beta_8 x_1 x_3 + \beta_9 x_1 x_4 + \beta_{10} x_1 x_6 + \beta_{11} x_2 x_3 + \beta_{12} x_2 x_4 + \beta_{13} x_3 x_4 + \beta_{14} x_1 x_2 x_4 + \beta_{15} x_1 x_3 x_4 \qquad (2)$$

where β_0 = intercept (expected value of ΔL when all the inputs are set at zero) and β_1 thru β_{15} are the estimated effects of each of the factors and their associated interactions.

Since each dummy variable takes on the value plus or minus one, the estimates are all comparable. The relative influence of a factor, x_i, is directly related to the absolute value of its coefficient, β_i. This allows a ranking of the factors with respect to their influence on the delta load.

Two sets of 15 β_i regression coefficients are produced: one for predicting the delta cooling load and a second for the delta heating load. Tables 4 and 5 show the list of 15 factors in the model in the order of significance along with the parameter label and estimated effect. The ΔL values are based on DOE 2.1 runs of the dormitory using the actual building minus the earth on the roof and north earth berm. The delta load values are produced by 16 running combinations of the following variables: one for a R-20 frame-walled building and a second for a R-20 (3.5 $h \cdot m^2 \cdot C/W$) block wall with exterior insulation. The variables at their high and low level are shown in Table 6.

Figure 5 shows a graph of the delta loads for a variety of parametric variations of the JID-DOE 2.1B model. The "P" represents the simplified prediction procedure Equation 1 using the case which best describe the actual building. The other points are the cases discussed below.

The results from Equation 2 using the closest building to the prototype used to develop Equation 1 are shown in Table 7 labeled #1-Base Case. The delta heating load is 0.84 MBtu/year, (246 kWh/year) delta cooling load is 0.45 MBtu/year (132 kWh/year) and the total delta load is 1.3 MBtu/year (381 kWh/year). This corresponds to 2.2% of the total heating [20 MBtu/year (5860 kWh/year)] and sensible cooling [37.8 MBtu/year (11078 kWh/year)] load in this building. The delta-R is 4 (0.7 $h \cdot m^2 \cdot C/W$). This compares to the simplified prediction procedure estimate Equation 1 which gives a delta heating load of 0.37 MBtu/year (108 kWh/year), delta cooling load of 0.99 MBtu/year (290 kWh/year), and a total delta load of 1.36 MBtu/year (398 kWh/year). The simplified prediction procedure based on a more typical residential building predicted a lower heating load effect and a higher cooling load effect, although the total load is about the same. Case 2 shows that with a very typical building with a crawl space foundation, the delta R is slightly higher at 5.5 (1 $h \cdot m^2 \cdot C/W$).

Six other variations of the JID type building are run through Equation 2 to produce delta load values. Case 3 labeled JID is a very massive building; the foundation, partition walls and ceiling all are made of concrete (similar to the actual JID). The total delta load is 0.73 MBtu/year (214 kWh/year). Although this is about half of what the simplified prediction procedure Equation 1 predicts, the resulting delta R is 2.5 (.44 $h \cdot m^2 \cdot C/W$) compared with the base case of 4. The difference of R-1.5 (.26 $h \cdot m^2 \cdot C/W$) is less than 1/2 inch (0.0013 m) of most foam board insulation.

Case 4 shows the delta loads with a very massive building (i.e., concrete foundation, partition walls and ceiling) and without nighttime window insulation. The total ΔL is only .37 MBtu/year (108 kWh/year) representing an R-1. Single-family residential buildings are mostly built with frame construction. Therefore, the fact that the effect of exterior wall mass in an already very massive building deviates considerably from the simplified prediction procedure defined by Equation 1 does not represent a serious shortcoming, although in multiple-family buildings this conclusion does suggest that the degree of interior mass should be accounted for, especially in any simplified model of exterior envelope mass effect.

The largest effect observed is case 5 when a massive wall is added to a frame building with a crawl space. The total delta load is 2.21 MBtu/year (648 kWh/year), representing a delta R of 6.5 (1.14 $h \cdot m^2 \cdot C/W$). Again, the difference of R-2.5 (0.44 $h \cdot m^2 \cdot C/W$) from the base case is only about 1/2 inch (0.0013 m) of foam board insulation. Case 6 shows that if nighttime window insulation is not used, the ΔL is 1.85 MBtu/year (542 kWh/year), leading to a delta R of 5.5 (1.0 $h \cdot m^2 \cdot C/W$). Cases 5 and 6 are similar to a passive solar building, which should have some additional interior mass anyway to avoid overheating. This would pull the estimate of the exterior wall mass effect more in line with the simplified model.

In general, the simplified prediction procedure, Equation 1, seems to hold up quite well despite the fact that the empirical model is not sensitive to the amount of south-facing window area and range of interior thermal mass that can exist in residential buildings. When the delta load differences are put in terms of delta R, the differences for the most part appear to be insignificant.

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TABLE 1

Least Squares Fit Coefficients for Delta Load Equation 1

City	Type	Season	Delta Load Regression Coefficients B0	B1	B2	B3	B4
ATLANTA	OUTSIDE	COOLING	-0.11875	0.008546	-0.01006	0.069655	-0.08280
ATLANTA	OUTSIDE	HEATING	-0.13470	0.002381	-0.00301	0.034729	-0.03915
ATLANTA	INSIDE	COOLING	-0.12196	-0.00094	0.002356	0.098488	-0.14156
ATLANTA	INSIDE	HEATING	-0.10678	0.000120	0.000131	0.028455	-0.03657
ATLANTA	MIXED	COOLING	-0.03255	0.014468	-0.01480	0.053215	-0.06235
ATLANTA	MIXED	HEATING	-0.04536	0.006009	-0.00631	0.007228	-0.00923
DENVER	OUTSIDE	COOLING	-0.14676	0.008929	-0.01147	0.103682	-0.11685
DENVER	OUTSIDE	HEATING	-0.17432	0.004675	-0.00587	0.066939	-0.08490
DENVER	INSIDE	COOLING	-0.16003	-0.00195	0.004026	0.123945	-0.18545
DENVER	INSIDE	HEATING	-0.13747	-0.00028	0.000888	0.058238	-0.08112
DENVER	MIXED	COOLING	-0.03559	0.012599	-0.01277	0.068792	-0.08169
DENVER	MIXED	HEATING	-0.04769	0.011335	-0.01190	0.015118	-0.01995
MIAMI	OUTSIDE	COOLING	-0.06100	0.008764	-0.00974	0.040678	-0.04029
MIAMI	OUTSIDE	HEATING	-0.10100	0.001027	-0.00120	0.016953	-0.02014
MIAMI	INSIDE	COOLING	-0.12259	-0.00112	0.002485	0.091854	-0.13193
MIAMI	INSIDE	HEATING	-0.06453	0.000060	0.000004	0.016021	-0.01928
MIAMI	MIXED	COOLING	-0.04516	0.012262	-0.01263	0.059358	-0.06618
MIAMI	MIXED	HEATING	-0.02295	0.003485	-0.00351	0.008696	-0.00985
MINNE	OUTSIDE	COOLING	-0.10003	0.007661	-0.00891	0.062834	-0.06924
MINNE	OUTSIDE	HEATING	-0.18147	0.003741	-0.00511	0.024128	-0.02585
MINNE	INSIDE	COOLING	-0.11468	-0.00029	0.001175	0.072047	-0.10132
MINNE	INSIDE	HEATING	-0.07828	0.000580	-0.00066	0.022874	-0.02513
MINNE	MIXED	COOLING	-0.03207	0.013999	-0.01447	0.039645	-0.04469
MINNE	MIXED	HEATING	-0.04823	0.006744	-0.00714	0.004609	-0.00564
PHOENIX	OUTSIDE	COOLING	-0.13066	0.004038	-0.00607	0.054404	-0.03977
PHOENIX	OUTSIDE	HEATING	-0.21056	0.001664	-0.00208	0.047604	-0.06679
PHOENIX	INSIDE	COOLING	-0.17857	-0.00250	0.005107	0.112124	-0.18087
PHOENIX	INSIDE	HEATING	-0.16002	-0.00048	0.001053	0.041049	-0.05989
PHOENIX	MIXED	COOLING	-0.03609	0.002331	-0.00212	0.075077	-0.08499
PHOENIX	MIXED	HEATING	-0.03805	0.003662	-0.00361	0.020918	-0.02532
WASH DC	OUTSIDE	COOLING	-0.13099	0.008719	-0.01011	0.081578	-0.10602
WASH DC	OUTSIDE	HEATING	-0.12007	0.003275	-0.00403	0.037936	-0.04139
WASH DC	INSIDE	COOLING	-0.12760	-0.00122	0.002837	0.100057	-0.14803
WASH DC	INSIDE	HEATING	-0.09441	0.000384	-0.00035	0.031071	-0.03779
WASH DC	MIXED	COOLING	-0.03207	0.015562	-0.01597	0.054468	-0.06386
WASH DC	MIXED	HEATING	-0.03860	0.008055	-0.00843	0.008857	-0.01097

TABLE 2

Climatic Characteristics of Simulation Locations

Climate City	Climate Parameter[a]			
	HDD	CDD	LEH	$\overline{K}_{\tau}$
Minneapolis	8158	585	1770	0.490
Denver	6016	625	5	0.620
Washington	5008	940	3734	0.470
Atlanta	3094	1588	4931	0.500
Phoenix	1552	3506	968	0.690
Miami	205	4037	27753	0.500

[a] HDD, CDD: annual heating and cooling degree-days, base 65 F; LEH: annual latent enthalpy hours, a measure of the moisture removal or addition needed to maintain comfort; K_{τ}: annual average fraction of horizontal solar insolation transmitted through the atmosphere.

TABLE 3

Sample Exterior Wall Mass Effect
1200 ft^2 Prototype, R-20 Walls, 15% Glass

Climate	Season	Base Load MBtu/yr	Insulation Location Outside Mass			Insulation Location Inside Mass		
			ΔLoad MBtu/yr	% Savings	ΔR	ΔLoad MBtu/yr	% Savings	ΔR
Atlanta	Heat	18	.3	1.7	5	.1	.5	1
	Cool	21	.8	3.8		.25	1.2	
Denver	Heat	36	.65	1.8	2	.2	.5	0
Miami	Cool	40	.53	1.3	3	.22	.5	2
Minnesota	Heat	72	.4	.5	1	.1	.1	0
Phoenix	Cool	43	.5	1.2	3	.25	.6	1
Washington,	Heat	33	.4	1.2	4	.1	.3	1
D.C.	Cool	13	.9	6.9		.25	1.9	

TABLE 4

Listing of Effects for Heating

Factor	Parameter	Estimate	Rank
Intercept	β_0	.38	
Ceiling mass	β_4	-.27	1
Foundation	β_3	-.20	2
Windows * shutters	β_{10}	.16	3
Interior mass * foundation	β_{11}	.11	4
Foundation mass * ceiling mass	β_{13}	.10	5
Interior mass	β_2	-.09	6
Wall R-value	β_5	-.07	7
Interior mass * ceiling mass	β_{12}	.06	8
Windows * interior mass * ceiling mass	β_{15}	.03	9
Shutters	β_6	-.03	10
Windows * ceiling mass	β_9	-.02	11
Windows * ceiling mass * foundation	β_{14}	-.02	12
Windows * interior mass	β_7	-.02	13
Windows	β_1	-.01	14
Windows * foundation	β_8	-.01	15

TABLE 5

Listing of Effects for Cooling

Factor	Parameter	Estimate	Rank
Intercept	β_0	.93	
Wall R-value	β_5	-.36	1
Window	β_1	.34	2
Ceiling mass	β_4	-.10	3
Internal mass	β_2	-.08	4
Internal mass * foundation	β_{11}	-.08	5
Window * interior mass	β_7	.07	6
Foundation	β_3	-.05	7
Window * foundation	β_8	.05	8
Windows * internal mass * ceiling mass	β_{15}	-.05	9
Foundation * ceiling mass	β_{13}	-.04	10
Windows * shutters	β_{10}	.03	11
Shutters	β_6	.02	12
Windows * ceiling mass	β_9	-.02	13
Internal mass * ceiling mass	β_{12}	-.02	14
Windows * foundation * ceiling mass	β_{14}	-.01	15

TABLE 6

List of Six Major Factors used in Fractional Factorial Parametric Analysis

Factors	Dummy Variables	(-1)	(1)
South-facing window area	x_1	137 ft^2 (13 m^2)	422 ft^2 (39 m^2)
Interior mass	x_2	2 in x 4 in frame walls	6 in block
Foundation	x_3	Crawl space	4 in slab
Ceiling mass	x_4	Frame	Precast concrete
Wall R-value	x_5	R-5 (0.9 $h \cdot m^2 \cdot C/W$)	R-20 (3.5 $h \cdot m^2 \cdot C/W$)
Insulated window shutters	x_6	No	Yes

TABLE 7

Parametric Analysis Sample Results

Case	Description	Delta Heat MBtu/yr	Delta Cool MBtu/yr	Delta Total MBtu/yr	% of Total	Delta R
1	Base case, as close as possible to ranch used in Equation 1.	0.84	0.45	1.29	2.2%	4
2	Same as 1, no slab.	1.28	0.49	1.77	3.1%	5.5
3	JID, like real building, massive with window insulation.	0.1	0.63	0.73	1.3%	2.5
4	Same as 3, no window insulation.	-0.16	0.53	0.37	0.6%	1
5	Direct solar gain, all frame with window insulation.	1.32	0.89	2.21	3.8%	6.5
6	Same as 5, no window insulation.	1.06	0.79	1.85	3.2%	5.5
7	Direct solar gain with slab with window insulation.	0.42	1.23	1.65	2.9%	5
8	Same as 6, no window insulation.	0.16	1.13	1.29	2.2%	4

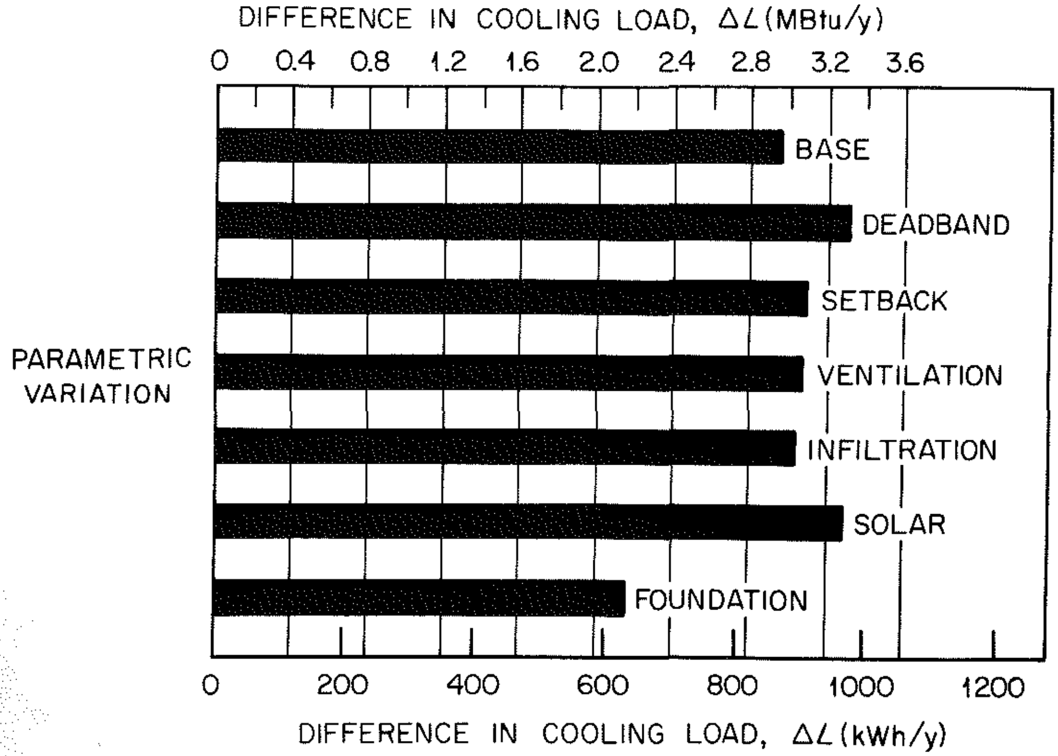

Figure 1. Extrapolation of results to real buildings. The thermal mass effect is dependent on the type of foundation in the building but is not as significantly dependent on other parameters. (R-12 walls insulated on outside; Phoenix)

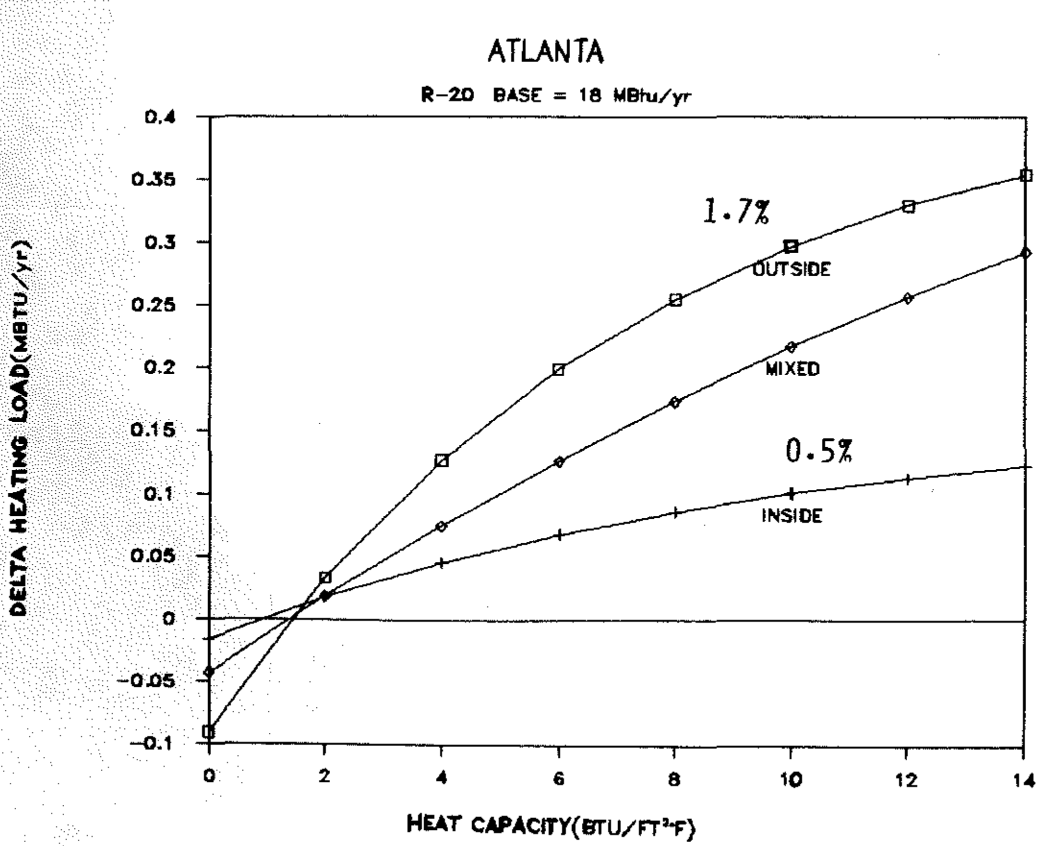

Figure 2. Atlanta, 1200 ft^2 rancher, R-20 wall, delta heating as a function of heat capacity for inside, mixed, and outside cases

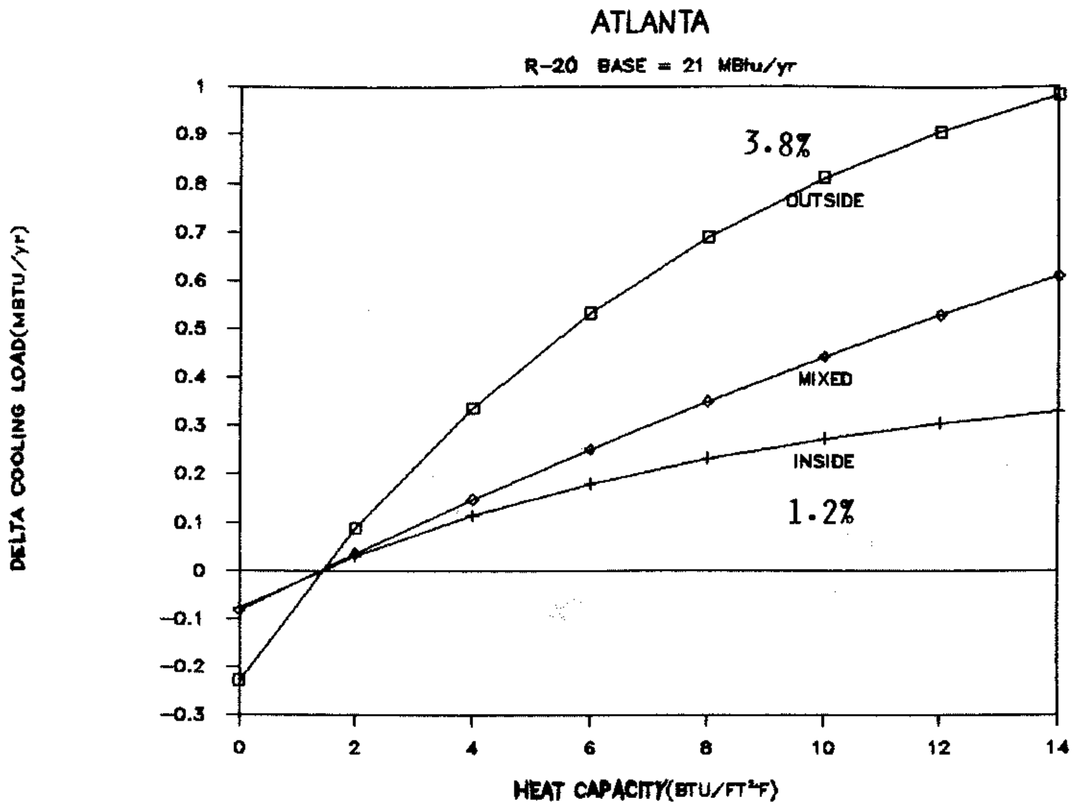

Figure 3. Atlanta, 1200 ft^2 rancher, R-20 wall, delta cooling as a function of heat capacity for inside, mixed, and outside cases

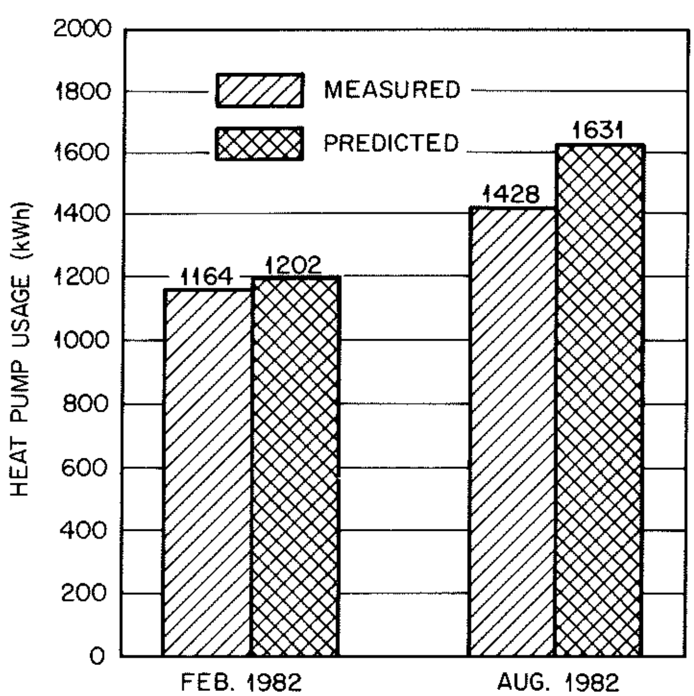

Figure 4. DOE-2.1 calibration with real building

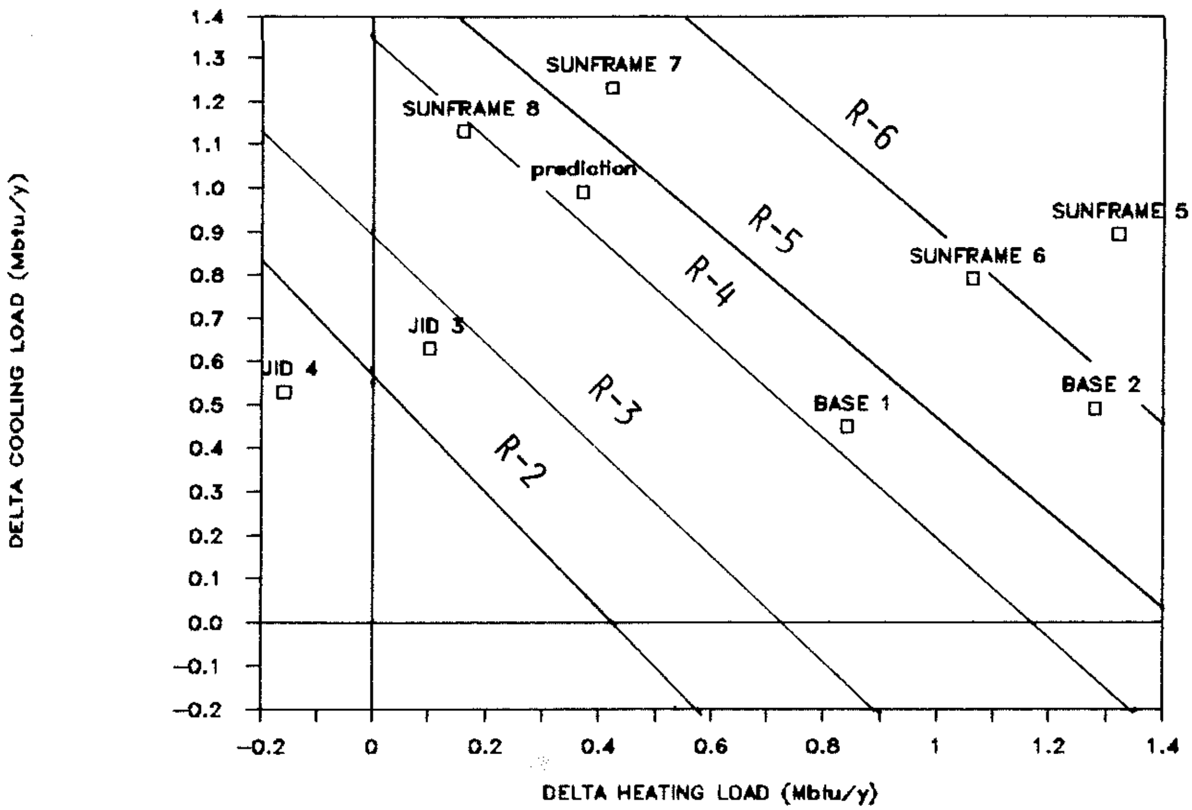

Figure 5. Delta loads and delta R-values from parametric analysis