HVAC Sizing Methodology for Insulated Concrete Homes

U. S. Department of Housing and Urban Development
Office of Policy Development and Research

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Prepared for:
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Office of Policy Development and Research

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INTRODUCTION AND SCOPE OF WORK

The objective of this work was to compile available information regarding energy use in concrete homes, develop additional information as needed, and use this information to develop a methodology to properly size heating, ventilating, and air-conditioning (HVAC) equipment for concrete homes in the US and Canada.

The authors prepared a literature review on thermal performance of insulated concrete walls and on sizing HVAC equipment in residential construction. The literature review, attached as Appendix A, identifies and briefly summarizes published information on (i) thermophysical properties of concrete and concrete walls, (ii) thermal behavior of concrete walls, including work performed to support the development of energy codes, (iii) general information on sizing HVAC equipment independent of construction type, and (iv) sizing HVAC equipment for insulated concrete homes. Appendix B is a summary of thermal mass in concrete and masonry.

The authors developed an Excel-based program intended for use by residential contractors to estimate the required heating and cooling system capacity for single-family concrete homes. The capacity is based on a user-defined thermostat set point, the house dimensions, construction materials, and location (US and Canada). The program uses the DOE2.1E (Winkelmann, 2002) program modules to determine energy loads for equipment sizing. A recent version of Microsoft Excel for Windows (such as Excel 97, 2000, or XP) is required to use the program. The program User’s Manual is included on this CD as a separate document.

Background

Insulated concrete walls are increasingly being utilized as an alternative to wood frame walls in residential construction. Insulated concrete walls include insulating concrete form (ICF) walls, cast-in-place insulated concrete walls, insulated precast concrete walls, autoclaved aerated concrete (AAC) walls, and insulated concrete masonry (CMU) walls. Houses constructed with concrete wall systems are both disaster resistant and energy efficient. Energy efficiency is imparted by the inherent thermal mass, high levels of insulation, and low air infiltration of these walls.

Considerable work has been performed by a variety of researchers to compare the energy performance of concrete homes to that of wood framed alternatives. The consensus is that the inherent energy-saving properties of insulated concrete walls can result in HVAC equipment being downsized by as much as 15 to 40% in concrete homes in comparison to identical wood framed homes.

Unfortunately, widely used HVAC sizing methods such as Manuals J and S (Rutkowski, 2002 and Rutkowski,1995) and the ASHRAE Handbook of Fundamentals (ASHRAE, 2001) are either cumbersome or do not account for the thermal mass, high levels of insulation, and/or low air infiltration of the insulated concrete walls. Even worse, many builders and HVAC contractors size HVAC equipment based on a “rule-of-thumb” developed for wood framed homes that equates equipment size with square footage of living space. The net result is an inefficient HVAC system that is typically oversized. An oversized HVAC system will have a higher initial cost than a correctly sized system, and it will consume more energy than necessary to maintain thermostat set points. Additionally, an oversized system will have a shortened “on” time, which can lead to larger temperature swings and reduced thermal comfort. Air conditioning systems with short “on” times do not remove enough moisture from the indoor environment, which can promote moisture problems and increase the probability of occupant respiratory problems.

The Department of Housing and Urban Development (HUD) has a long history of supporting the development of information and technology related to energy-efficient affordable housing. HUD supports insulated concrete construction because it is energy-efficient and affordable. This project extends HUD’s work through the creation and distribution of guidelines and methodology for properly sizing HVAC equipment in insulated concrete homes.

Thermal Mass and Residential HVAC Equipment Sizing

Properties of the exterior mass walls that affect the energy use of the house include the type and thickness of insulation, thermal mass, and air infiltration. Wood and metal frame walls are considered low-mass walls. Heat loss through a frame wall is dependent on the amount of insulation and air infiltration. More insulation typically means less heat loss and less energy required for heating and cooling. The benefits of using more insulation are well publicized by insulation manufacturers and consumers understand these benefits. However, thermal mass also has a significant effect on the heating and cooling energy. The concept of thermal mass is less publicized and is poorly understood by consumers. Walls with high thermal mass, such as concrete walls, have the ability to store and later release heat. This ability tends to moderate indoor air temperatures, and reduces energy associated with heating and cooling.

Thermal mass is not a new concept; it has been used for centuries to build comfortable living environments. For example, traditional adobe houses in Mexico and the Southwest have thermal mass walls typically constructed of very thick sun-dried clay, sand, and straw bricks. Adobe houses moderate indoor air temperatures by capturing and slowing the transfer of heat. Similarly, concrete and stone houses in the Mediterranean and other parts of the world moderate indoor temperatures.

The effects of thermal mass is illustrated in Figure 1 where the heating and cooling energy to maintain an indoor air temperature of 70°F is shown over a 48-hour period for two houses in Boulder, Colorado: one has frame walls and the other has mass walls. Assuming average U.S. energy costs (from 2000) of \$0.786 per therm for natural gas and \$0.082 per kilowatt-hour for electricity, heating and cooling costs for the two-day period are \$7.54 for the frame wall, and \$5.96 for the mass wall. The frame wall has a U-factor of 0.078 $\text{Btu/hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}$ and a heat capacity (measure of thermal mass) of less than 1 $\text{Btu/ft}^2\cdot{}^\circ\text{F}$, while the mass wall has a U-factor of 0.090 $\text{Btu/hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}$ and a heat capacity of 29 $\text{Btu/ft}^2\cdot{}^\circ\text{F}$. Although the mass wall has less insulation (that is, a higher U-factor), the total heating and cooling energy and costs for the house with the mass walls are significantly less. Thermal mass of the mass wall moderates the indoor temperature, reducing the load on the heating and cooling equipment.

In many locations, less peak energy and therefore smaller equipment sizing is required for heating and cooling a house with mass walls compared to a house with frame walls of similar thermal resistance. As shown in Figure 1, peak heating generally occurs at approximately 5 AM and peak cooling generally occurs in the mid-afternoon. The mass wall required less peak energy for this house, climate, and daily outdoor temperatures. The peak heating generally occurs on a cold, cloudless night in January, and the peak cooling generally occurs on a warm, sunny, humid afternoon in July or August.

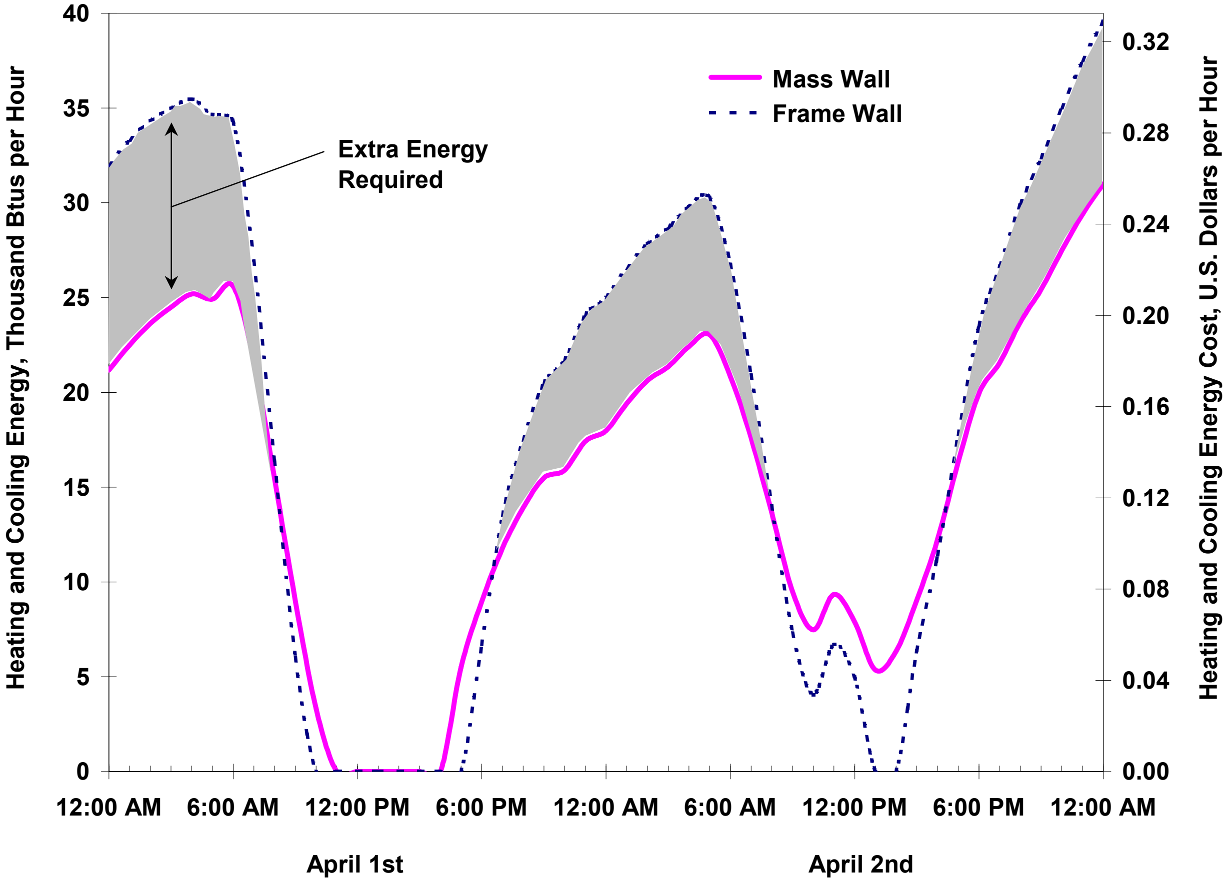

Figure 1: Comparison of Heating and Cooling Energy and Costs for Identical Houses with Mass and Frame Walls in Boulder, Colorado.

METHODOLOGY

The starting point in developing the HVAC sizing methodology was to establish a base-line comparison between the results from two widely-used HVAC sizing methods, Manuals J and S and the ASHRAE Load Calculation Method, with DOE2.1E, the industry-standard energy analysis tool for buildings.

Manual J is a detailed procedure that takes into account construction materials, climate, glass, duct, infiltration, and internal loads. Although Manual J includes factors for calculating loads using many combinations of CMU, brick, ICFs, and 4-in. uninsulated and insulated concrete walls, it does not consider mass effects when calculating heating loads. Manual S (Rutkowski, 1995) is used to determine the size and type of equipment once the heating and cooling loads are determined. However, the heating and cooling loads are based on steady-state winter and summer design temperatures, respectively. Manuals J and S do not consider hourly and daily temperature swings, and therefore do not accurately account for the thermal mass of concrete wall systems.

The ASHRAE method also assumes static conditions. However, DOE2.1E is capable of simulating dynamic, hourly conditions. In the preliminary analysis we considered average and design weather conditions. From these results, we determined that only DOE2.1E was capable of adequately modeling the dynamic nature of mass walls.

Original Approach: Regression

One option for sizing methodology consisted of performing all of the initial modeling at the beginning, summarizing and simplifying the data, and creating a computer program based on the reduced data. This approach would involve performing a series of DOE2.1E modeling runs for a representative set of the ASHRAE 90.1-2001 climate zones so that heating and cooling loads could be determined per unit area of wall for a variety of wall types and orientation, and for a variety of window types, shading, and orientation. This information would then be supplemented with calculations for other building envelope loads, occupant loads, and infiltration loads to size the heating and cooling equipment for the house.

Preliminary modeling indicated that this methodology was sound for the trial location (Chicago, Illinois). The modeling was therefore extended to nine wall types, one standard window type, and 29 climate locations representing the normal range of climatic conditions experienced in the US and Canada. This modeling generated an enormous amount of data, which we began to summarize and analyze. While analyzing the data, we realized that the results could not be summarized effectively into a simple *and* accurate form. Hence, we conceived the present, and more direct, approach.

Present Approach: Modeling

The present approach incorporates the DOE2.1E calculation engine directly into the program. The user-interface is a Microsoft Excel worksheet. The user inputs thermostat set points, house dimensions, construction materials, and location. Excel macros pass the user inputs to the DOE2.1E modules. The modules calculate the heating and cooling loads of the space for each hour of a year and simulate operation and response of the equipment and systems that control temperature and humidity and distribute heating, cooling and ventilation to the building. Excel macros return the results back to the worksheet for interpretation and further analysis.

A special license was purchased to distribute derivative programs that use the DOE2.1E program modules. A copy of the distribution statement is included in Appendix C. The license allows the distribution of DOE2.1E as part of a software package that utilizes it.

The software and user manual were sent to 13 reviewers, and comments were received from all reviewers or their representatives. The majority of their comments have been included. Typical comments related to inputs, layout, structure, and ease of use. Several reviewers compared the results to those of other software, and most compared favorably. In general, comments were positive and encouraging.

Limitations

An Excel-based program was developed for residential contractors to estimate the heating and cooling system capacity for single-family concrete homes. Assumptions were made to simplify the inputs. The intent was to make the program easy to use and, therefore, widely used. This program takes a different approach than other HVAC sizing methodologies, such as Manuals J and S and the ASHRAE Load Calculation Method. These sizing methodologies were developed for low-mass frame walls and utilize the summer and winter design conditions. Design conditions are predicted to be exceeded approximately 1% of the time (88 hours) in a typical 8760-hour year.[*] To account for the thermal mass imparted by concrete walls, this program utilizes hourly weather data for a full typical year. These hourly data are commonly utilized in energy modeling software and are based on typical mean (average) conditions from the past 30 years (TMY2 data). This is more representative of actual conditions in which the HVAC system will be operating. Although insulated concrete walls moderate indoor temperatures, during extended periods of extreme hot or cold temperature conditions that last two or more days, the walls may become “fully loaded” and indoor temperatures may fluctuate outside of the desired temperature ranges. Mass walls store heat that can be released in later portions of the day. “Fully loaded” in this sense means the walls have reached their full potential to store heat.

In general, most occupied houses will not have the same heating and cooling loads as predicted by energy simulation software. This is due to many reasons including, but not limited to the following:

1. Variations in house occupant use, such as number of occupants, appliance use, setting back thermostats, optimal use of windows and doors, and optimal use of window shades.
2. The construction of the as-built house as compared to the construction as modeled.

Software Assumptions

The authors used DOE2.1E software as a basis for the project software. Many assumptions were made to simplify user input. The following is an overview of the major assumptions.

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[*] The actual design conditions typically chosen vary from 0.4% to 2% of the hours in a year.

HVAC system. The HVAC system is a residential-type system with direct expansion air-cooled air conditioning and forced-air heating. The HVAC system is controlled by a typical residential thermostat with 2°F throttling range.

Number of zones. The furnace and air conditioner condition the house as a single zone. Basements surfaces, if present, are considered part of the conditioned space.

Ducts. Ducts for air distribution are located within the conditioned space. Ducts located in unconditioned spaces such as attics and garages contribute to distribution losses that will increase energy use.

Unconditioned spaces. The program does not model heat transfer to unconditioned spaces, such as unconditioned basements and attached garages. However, the user's manual contains some suggestions on how to overcome this limitation. For example, if the basement is not conditioned, the user may choose to model the basement as a slab-on-grade. An unconditioned attached garage tends to lower the peak heating load and increase the peak cooling load. Therefore, to model this situation the user can (i) ignore the exterior walls of the garage and (ii) consider the area of walls between the garage and the house to be completely shaded or on the north-facing wall (or the wall that is closest to north-facing).

Shape of house. Assuming the house is box-shaped greatly simplifies the effort of describing the geometry of the house. This assumption is acceptable if the house is roughly box-shaped. However, even if the house is not box-shaped and as a consequence a significant part of some wall is mostly shaded by another part of the building, the results will tend to be conservative for cooling (that is, cooling capacity may be over-sized) and neutral for heating. The user manual advises to check the validity of this assumption in non-box-shaped houses by running the program as described above and then running the program again after revising the inputs to place a portion of the walls and windows that are significantly shaded on the north wall. The user can then compare the output from these different runs and determined the validity of the results.

Occupancy. Occupant energy consumption for uses other than heating and cooling were assumed to range on a daily basis from 960 to 32,000 Btu/hr. This maximum value is from *ASHRAE 2001 Handbook of Fundamentals* (ASHRAE, 2001) and the daily schedule is from *ASHRAE Standard 90.2* (ASHRAE, 1993). There are a maximum of four occupants in the house (in the evening, at night, and in the morning) and a minimum of one (during the day).

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Rutkowski, Hank, *Manual S Residential Equipment Selections*, Air-Conditioning Contractors of America, Arlington, VA, 1995. www.acca.org

Rutkowski, Hank, *Manual J Residential Load Calculation*, 8th edition, Air Conditioning Contractors of America, Arlington, VA, 2002. www.acca.org

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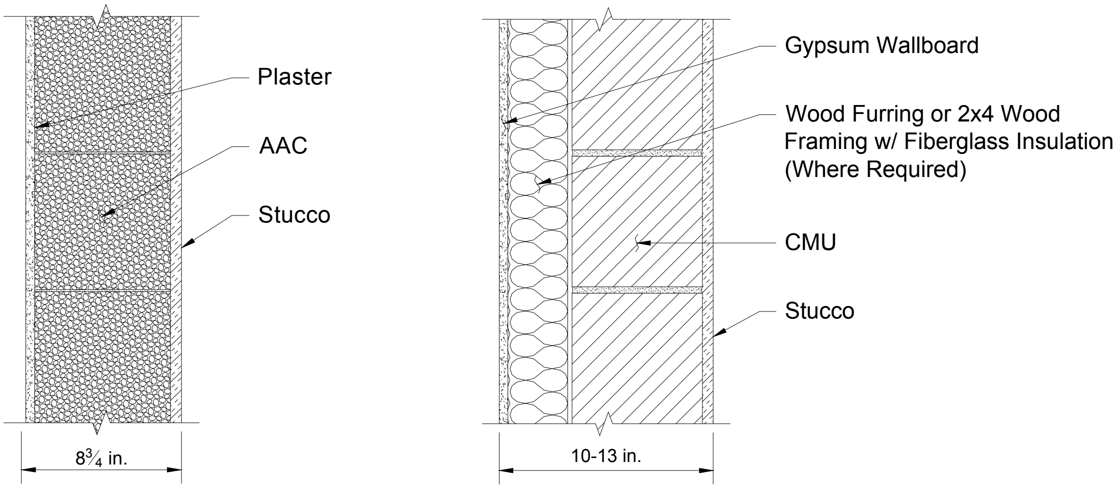
APPENDIX A – LITERATURE REVIEW

This literature review identifies and briefly summarizes published information on (i) thermophysical properties of concrete and concrete walls, (ii) thermal behavior of concrete walls, including work performed to support the development of energy codes, (iii) general information on sizing heating, ventilating, and air-conditioning (HVAC) equipment independent of construction type, and (iv) sizing HVAC equipment for concrete homes. Sources of information include documents available from the Portland Cement Association (PCA) (www.cement.org), Construction Technology Laboratories, Inc. (CTL) (www.CTLgroup.com), and a focused literature review. The literature review yielded many case studies of specific concrete products or buildings that saved energy through the use of thermal mass or passive solar design. These case studies are not included in this report.

A1. CONCRETE WALLS

References to detailed information on all aspects of concrete homes can be found on one of the Portland Cement Associations' websites (www.concretehomes.com/publications/). Information for homebuilders on concrete construction is covered in *Residential Concrete* (National Association of Home Builders, 1998). *The Portland Cement Association's Guide To Concrete Homebuilding Systems* (VanderWerf and Munsell, 1995) contains a thorough description of the various concrete systems. This fully illustrated book describes these modern systems and gives advice to the homebuilder on choosing and using them. Based on comprehensive research involving hundreds of builders, architects, tradespeople, real estate agents and buyers, this book provides data to aid in design and decision-making. The book covers the entire range of concrete systems—from concrete masonry and poured-in-place, to shotcrete and precast, plus the latest information on insulating concrete forms (ICFs). The book describes each system's design, discusses how it has worked in the field, and explains where to get additional technical information. A detailed source of technical information on ICFs can be found in *Insulating Concrete Forms Construction Manual* (VanderWerf and Munsell, 1996) and *Insulating Concrete Forms for Residential Design and Construction* (Vanderwerf et al, 1997). More information on ICFs is available from the Insulating Concrete Form Association at www.forms.org.

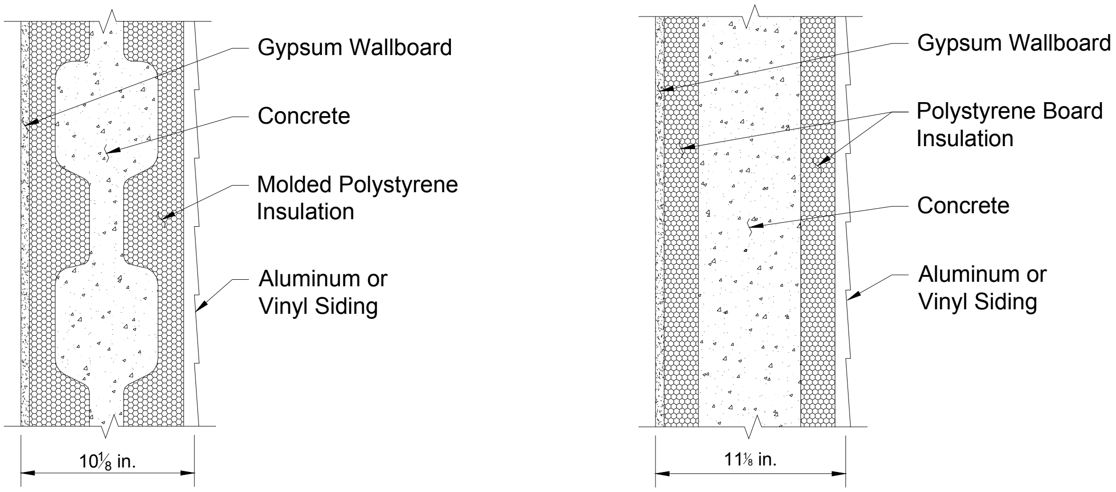
Conventional concrete and concrete masonry unit (CMU) walls can be insulated on the inside, on the outside, or have insulation between two layers of concrete (sandwich panel walls). ICFs have a layer of rigid foam insulation on the outside, a layer of concrete in the middle, and a second layer of foam on the inside. Autoclaved aerated concrete (AAC) has an air void matrix rather than sand and gravel commonly used in conventional concrete. The density of AAC is in the range of 30 to 50 pounds per cubic foot compared to conventional concrete with a density of approximately 140 pounds per cubic foot. Figures A1 through A4 provide cross-sections of eight types of insulated concrete walls (Gajda, 2001).



AAC

CMU

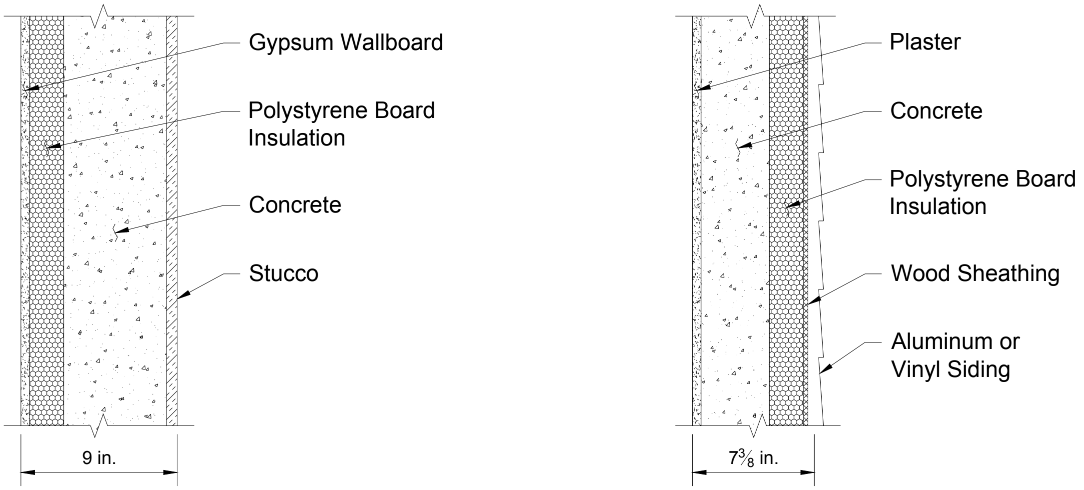
Figure A1: Typical AAC and CMU Wall Sections



Waffle Grid ICF

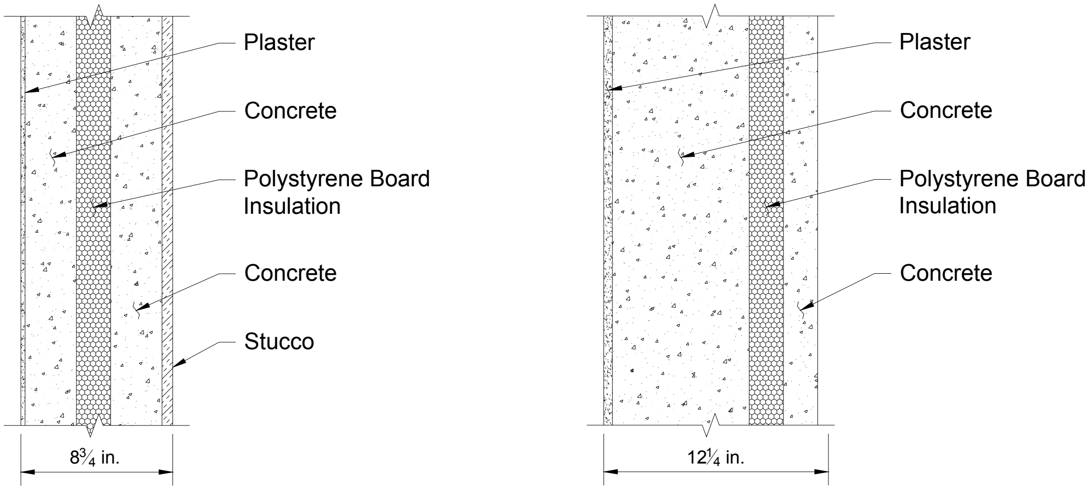
Flat Panel ICF

Figure A2: Typical ICF Wall Sections



Interior Insulation **Exterior Insulation**

Figure A3: Typical Cast in Place Wall Sections



Engineered Sandwich Panel **Typical Sandwich Panel**

Figure A4: Typical Sandwich Panel Wall Sections

A2. THERMOPHYSICAL PROPERTIES OF CONCRETE WALLS

The first step in developing a methodology to size HVAC equipment in a concrete home is to understand the unique thermal behavior of concrete walls. The thermal behavior of concrete walls depends on the thermophysical properties of the components of the walls. Thermophysical properties include thermal conductivity, density, and heat capacity. The term “thermal mass” is commonly used to mean the ability of a material to store significant amounts of thermal energy and delay heat transfer through a building component (ASHRAE, 1999). Concrete, masonry, adobe, and logs have much more thermal mass than other building materials so they modulate temperature swings within a building. Thermal mass is also effective in commercial buildings because it moderates internal loads generated by occupants, lighting, and equipment. Thermal resistance (R-values) and thermal transmittance (U-factors) do not take into account the effects of thermal mass, and by themselves, are inadequate in describing the heat transfer properties of construction assemblies with significant amounts of thermal mass (VanGeem, 1987). Appendix A provides more information on thermal mass.

An extensive compilation of thermophysical properties of masonry and its constituents is presented in *Assessment of the Thermal and Physical Properties of Masonry Block Products* (Valore et al., 1988). The data were collected from about 50 references dating from 1935 to 1985. The tables in the report list the thermophysical properties of cement paste; various sands, aggregates, and clays; perlite; vermiculite; concrete; and masonry units. A summary of properties, the effect of moisture, and how they are measured is also available (VanGeem and Fiorato, 1983). The American Concrete Institute (ACI) Committee 122 on Energy Conservation has published a guide on thermal properties of concrete and masonry systems (ACI, 2002). The guide includes chapters on thermal conductivity, R-values, thermal mass, passive solar, and condensation. An up-to-date source of thermophysical data on masonry, concrete, and concrete constituents can be found in Chapter 25 of the *2001 ASHRAE Handbook of Fundamentals* (ASHRAE, 2001).

A3. THERMAL BEHAVIOR OF CONCRETE WALLS

The impetus for research on the thermal behavior of concrete walls came with the awareness of energy conservation due to the energy crisis in the early 1970’s. The U.S. Department of Energy (DOE) supported research on energy conservation, insulation, behavior of mass walls, and passive solar design.

Passive solar design refers to the use of the sun's energy to heat a building when needed. The building itself, or some integral element of it, takes advantage of thermophysical properties of materials and exposure to the sun. Concrete is an ideal material to use because of if its high heat capacity and density and its relatively low conductivity. These three properties together account for thermal mass—the key property affecting the thermal behavior of concrete walls.

A3.1 Influence of Energy Codes

Jeff Christian of Oak Ridge National Laboratory (ORNL) (Christian, 1991) recounts the history of DOE-sponsored research on thermal mass and illustrates how it lead to the inclusion of thermal mass credits in two concurrent energy codes: the *Model Energy Code* (CABO, 1995) [now the *International Energy Conservation Code* (*IECC*)] and *ASHRAE Standard 90.2, Energy Efficient Design of New Low-Rise Residential Buildings* (ASHRAE, 1993):

> *From the beginning of 1979, there was considerable private industry debate over the magnitude of the effect of envelope mass on annual heating and cooling loads of buildings. The result was an experimental database consisting of thermal performance measurements on 14 test houses in two locations with various amounts of external wall mass; detailed measurements on a massive 4,000-ft*^{2} *office/dormitory; independent consistency checks on the measurements; validation of a variety of building simulation models; several extended simulated databases of full-size, single-family residences; and several simplified techniques for predicting the effect of exterior thermal mass on annual heating and cooling loads. The simplified technique used to develop the Thermal Mass Credit Tables in the then proposed Model Energy Code was the simplified technique that is most consistent with the DOE-2.1C simulated database used to develop the envelope component recommendations in ASHRAE Standard 90.2.*
>
> *BLAST, DOE-2.1, and DEROB can simulate mass effect tendencies. More than 100 comparisons of model predictions with measured experimental data were made. The periods of comparison varied from one day to two weeks. The cumulative comparison of all test periods, test houses, and models predicted 1.5% above the measured loads, and 8896 of these comparisons fell within ±25% of the measured loads.*
>
> *Results of DOE thermal mass research showed that if all building parameters remain constant, exterior wall mass improves or maintains the annual thermal performance of buildings. Thermal mass in the exterior walls does not save energy if the building load is continuously a gain or a loss for all hours of the day. An insulated mass wall is most effective with the insulation outside the mass.*

In 1992, the U.S. Congress passed the U.S. Energy Conservation and Production Act. This legislation mandated each state certify that it has a commercial building energy code that meets or exceeds the *ASHRAE Standard 90.1*. This, in effect, made the requirements in *ASHRAE 90.1* the minimum energy requirements for the US for the buildings it covers: all buildings except low-rise residential. In this sense low-rise residential is three stories or less above grade. *ASHRAE 90.1* specifies requirements for energy use and conservation, and includes criteria for lighting, HVAC systems, and heat loss through walls. The current benchmark for the federal mandate is *ASHRAE Standard 90.1-1999*. The legislation also *recommended* that each state have a residential energy code that meets or exceeds the requirements of the *Model Energy Code* (*MEC*), now the IECC. Much of the work done on thermal mass and the behavior of concrete walls has been done to support the requirements for mass walls in these energy codes.

The status of residential energy codes by states is available from the Building Codes Assistance Project (BCAP) (www.bcap-energy.org/backissues.html) and is presented in Table A1. Some states, such as Florida and California, have independently developed and adopted their own energy codes. Some states and jurisdictions do not yet have residential energy codes despite the federal requirement.

Prescriptive requirements in early energy codes penalized concrete and masonry by specifying minimum R-values regardless of the type of wall system. Recent energy codes like *ASHRAE 90.1*, however, account for thermal mass of concrete and masonry (Gajda and VanGeem, 1995). The codes also recognize that thermal mass behavior depends on climate, wall heat capacity, and insulation position.

Table A1: Residential Energy Code Adoption, Autumn 2002

MEC Version or Equivalent State Code	States Adopted or Adopting
2000 IECC, IRC or equivalent state code adopted or under review or in rulemaking for statewide adoption/equivalence	19 States (NM, CA, OR, WA, ID, ND, FL, KY, MD, NC, SC, NH, NY, PA, TX, UT, GA, WI, RI)
1998 IECC	1 State (OK)
95 MEC, Mandatory statewide adoption/equivalence	8 States and DC (CT, MA, MN, NJ, OH, VA, VT, HI)
95 MEC, Partial adoption/equivalence	1 States (LA[2])
93 MEC, Mandatory statewide adoption/equivalence	3 States (DE, KS, MT,)
92 MEC, Mandatory statewide adoption/equivalence	4 States (AR, IA, IN, TN)
No statewide residential code or residential code is not EPAct compliant	14 States (AZ[1, 3], AK[1], AL[3], CO[3], IL[3], ME, MI, MO[1], MS[3], NE[1], NV, SD, WV[3], WY[3])

1. State code is required for state-owned and -funded buildings only.
2. LA has adopted 95 MEC for multi-family residential only.
3. Code implementation depends upon the voluntary adoption of the code by local jurisdictions.

(Source: http://www.bcap-energy.org/backissues.html Sept./Oct. 2002)

A3.2 Laboratory Research

Concrete walls have a relatively low R-value yet can perform as well as frame walls with higher R-values in many climates. The process for getting this concept adopted by codes was to perform laboratory studies and then use applicable computer models to show these mass effects. These computer models were then used to generate criteria for acceptance by codes.

Results of laboratory tests of building envelope components under steady-state and dynamic temperature conditions have been used to develop methods to accurately predict heat losses and gains through the building envelope. PCA, DOE, and others sponsored tests (VanGeem, 1984; VanGeem 1985; VanGeem, 1986) to measure the thermal characteristics of 21 wall assemblies. Walls included different types of concrete, masonry and wood-frame walls and two standard calibration assemblies, and were tested using a calibrated hot box in general accordance with ASTM C976, “Standard Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box.” The measured steady-state values were used to calculate average heat transmission coefficients. These heat transmission coefficients from testing are compared with the heat transfer coefficients calculated from material properties of the individual components making up the assembly. The transient and diurnal dynamic tests provide data on thermal performance under controlled conditions that simulate actual temperature changes in building envelopes. Measured heat flow through the walls is compared to heat flow predicted by steady-state analysis. The difference between measured and predicted heat flow is shown to be due in general to thermal storage capacity (thermal mass) of the wall assembly.

Oak Ridge National Laboratory (ORNL) (Kosny et al., 1998), under the sponsorship of DOE, measured the dynamic thermal performance of an 8 ft by 8 ft insulated concrete form (ICF) system using a calibrated hot box. Test results were compared to calculations using the finite difference computer code HEATING 7.2. The test method and computer modeling results were in good agreement. This ICF wall had a clear wall R-value of 12 $hr \cdot ft^2 \cdot {}^oF/Btu$. Computer and test results were used to define a thermally equivalent wall with a simple multilayer structure with the same thermal performance as the ICF wall with the complex three-dimensional heat flow structure. This thermally equivalent wall and lightweight wood frame walls with R-values from 2.3 to 29.0 $hr \cdot ft^2 \cdot {}^oF/Btu$ were modeled as part of single-family houses for six representative U.S. climates. The heating and cooling loads from the analyses were used to estimate the R-value of a wood frame wall that would have the same thermal load as the ICF wall. This was then said to be the "effective R-value" of the ICF wall. These "effective R-values" for the ICF wall ranged from 16 to 23 depending on the climate. These values are not the true R-values of the ICF wall, since a true R-value is a physical property determined from steady-state tests. This paper also analyzed the effect of a 20% reduction in uncontrolled air infiltration of an ICF house compared to a wood frame house. This reduction was based on blower door tests of seven ICF houses. These results indicated wood frame walls would require R-values in the range of 26 to 44 to perform as well as the R-12 ICF wall.

A3.3 Analytical Studies

The PCA sponsored an analytical program (Wilcox, 1987; Wilcox and VanGeem 1997; Wilcox and VanGeem, 1998) to determine whether or not thermal mass tables in the *MEC* fairly represent the performance of ICF walls and, if not, to propose an alternative approach. ICF walls have a high insulation R-value and significant thermal mass. In the *MEC*, the wood frame wall requirements are in the form of an overall U-factor and are a function of heating degree-days and whether the building is single-family or multifamily. The *MEC* includes three mass wall insulation requirement tables for exterior, interior, and integral insulation, which depend on heating degree-days. The intent of the *MEC* mass wall tables is to produce a total annual heating and cooling load for a mass wall in a home equal to the lightweight wall. For this study, Wilcox performed computer simulations using DOE2 and BLAST to determine the relative performance of ICF and wood frame walls in a prototypical house in a range of climates. The BLAST results fall between the *MEC* integral and interior insulation position table values. The DOE2 results are consistent with the *MEC* interior insulation table. The authors recommend that the interior insulation position be used for showing compliance of ICF walls with the *MEC*.

The PCA sponsored another analytical program (Gajda, 2001) to model a typical 2,450 square-foot single-family house for energy consumption in twenty-five cities, representing the twenty-five *ASHRAE 90.1-1999* zones across the US and Canada. In each location, the house was modeled using DOE2.1E software with eleven different exterior wall systems: conventional wood frame walls, steel frame walls, autoclaved aerated concrete walls, concrete masonry unit walls, insulating concrete form (ICF) walls, and insulated concrete hybrid walls with exterior insulation, interior insulation, or internal insulation. Walls were designed with typical materials to meet or exceed the minimum energy code requirements of the *2000 IECC* for U.S. locations and the *1997 Model National Energy Code of Canada for Houses* for Canadian locations. Annual energy use of the otherwise identical homes was calculated on an hourly basis using DOE2.1E to determine the effects of exterior wall R-value and thermal mass. Analyses showed that energy for heating and cooling accounted for 20 to 70% of the total annual energy cost, depending on location. Other occupant energy uses such as appliances and hot water accounted for the remainder, with a higher percentage of occupant energy use in milder climates. Due to the thermal mass, houses with concrete walls had lower heating and cooling costs than houses with frame walls, except for locations where the concrete walls were extremely under-insulated. Building orientation and uncontrolled air infiltration were also shown to have a significant effect on house energy use.

Government reports published in the 1980s (Flanders, 1980; Childs et al, 1983) explained the theory behind thermal mass. The thermal time constant is a good indicator of a wall’s thermal mass. The time constant is related to the material’s thermal diffusivity and thickness. Thermal diffusivity is a function of density, specific heat, and thermal conductivity. CTL has also prepared proprietary reports on wall systems using simplified methods that are now outdated (VanGeem, 1996, Greenblock; VanGeem, 1996, ICFA).

A3.4 Field Studies

Statistical comparisons sponsored by PCA (VanderWerf, 1997) indicate that constructing the exterior walls of a house with insulating concrete forms (ICFs) instead of conventional wood frame will reduce the amount of energy consumed for space heating by approximately 44%, and for space cooling (where applicable) by approximately 32%. Values are averages for houses constructed across the US and Canada. All ICF homes were constructed with a wall system made of pure foam (no foam-cement composites). The statistics derive from analysis of 58 homes: 29 ICF and 29 wood frame. The investigators solicited participation so each ICF house would be compared with one frame house that was (1) nearby, (2) of similar square footage, and (3) of new construction (less than 6 years old). They then adjusted the energy consumption of each house to control for differences in size, design, foundation, number of occupants, thermostat settings, and HVAC equipment. The corresponding estimated dollar savings for ICF homes averaged approximately $221 per year for heating energy and (where applicable) $89 for cooling energy. Energy savings on a percentage basis were independent of climate. *Absolute* savings will be higher in extreme climates, where total bills are higher. Responses to open-ended questions revealed differences in reasons for why owners had positive feelings about their homes.

Four demonstration projects were coordinated by the NAHB Research Center (NAHB, 1997) with sponsorship provided by the U.S. Department of Housing and Urban Development (HUD) and PCA to evaluate the use of ICF in residential construction. The demonstration homes are located in Virginia Beach, Virginia; Austin, Texas; Sioux City, Iowa; and Chestertown, Maryland. Construction details of the homes were documented and also photographed. After construction, thermographic imaging and air infiltration tests were performed. Homeowners were interviewed concerning their impressions of the design, construction, thermal comfort, sound comfort, and overall satisfaction with their homes. Homeowners were generally pleased with their homes and cited reduced transmission of "street noise" and being part of new technology. Builders, and general contractors where appropriate, were also interviewed and they provided information on the construction process and construction costs, including concrete mixing, placement, use of forms, and code requirements. Costs of constructing homes with ICFs were compared to typical framing by project location. Builders did not have difficulty in selling these homes, and plan to continue using this construction. Thermographic imaging showed ICF walls have fewer cold spots than frame construction. However, testing also showed that construction details at window and door openings, penetrations, and foundations had a significant impact on energy use. Blower door tests on the demonstration homes indicate winter infiltration rates ranged from 0.15 to 0.55 air changes per hour.

The NAHB Research Center (NAHB, 1999) conducted a study to compare cost, energy performance, and thermal comfort of ICF walls to conventional wood-frame exterior walls. Three identical homes except for the wall construction were built adjacent to each other in Chestertown, Maryland. Walls consisted of an ICF plank system, an ICF block system, and conventional 2 by 4 lumber construction. Energy monitoring was installed in the three homes, which were unoccupied. Annual energy used on an hourly basis was modeled using BLAST in conjunction with site weather data to compare predicted and actual energy use of the homes. The measured and calculated energy performance were similar, and the ICF homes were approximately 20% more energy efficient than the wood-frame house. This was expected due to the higher R-value of the ICF walls. The continuous insulation at the slab also contributed to energy savings of the ICF homes. The effects of ground coupling were not significant. Results from air leakage tests were similar for the three homes. One ICF home and the wood frame home were also monitored to provided data for thermal comfort analysis in accordance with *ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Comfort*. The ICF home showed significantly better performance in comfort measures than wood frame homes.

The ORNL Buildings Technology Center (Desjarlais et al, 2002) compared the energy performance of houses with ICF and typical wood frame construction. The project included field monitoring of two identical 1094-ft^2 houses except for the walls; one has ICF walls and the other has wood frame walls with a concrete masonry unit foundation. The sponsors teamed with the Loudon County Habitat for Humanity, Inc. to construct the two adjacent single-story houses in Knoxville, TN. The whole-wall R-values of the ICF and R-11 wood frame walls were 15.0 and 10.6 hr·ft^2·F/ Btu, respectively. The houses were monitored for energy use for one calendar year, during which they were unoccupied and operated on identical heating and cooling schedules. The ICF house used 7% less energy than the wood frame house. Measured results were compared to

DOE2 energy analyses and found to be in good agreement. Using DOE2 to extrapolate results to other climates, total annual energy savings for the ICF house was predicted to be 1.5 to 11%. These results include all house and occupant energy uses. Predicted energy savings for heating in Atlanta, Phoenix, and Minneapolis is 26, 61, and 15%, respectively, for the ICF house. For cooling, the predicted energy savings are 7, 6, and 11% in the same cities for the ICF house. During the peak heating season, the ICF house exhibited lower overall and lower peak energy use on a daily basis. During 15 weeks between the heating and cooling seasons, no heating or cooling or ventilation was used and air temperatures within the house were allowed to float. The ICF house exhibited a much narrower band of temperature swings with a minimum temperature of 57ºF, compared to a minimum of 50ºF in the frame house despite freezing temperatures outside. Since the fluctuations in temperatures are lower in the ICF house, fewer decisions need to be made about when to use natural ventilation or when to turn on the HVAC equipment. Infrared images during the winter indicated an exterior wall corner of the ICF house was significantly warmer than the same corner in a wood frame house: 65ºF versus 57ºF[†]. Blower door tests at the end of winter indicated 10% less uncontrolled infiltration through the exterior of the ICF house. This was attributed to the foundation wall-to-external wall joint in the frame-wall house. Also, infiltration in the both houses was greatest in the winter due to shrinkage of the wood trusses.

Additional results of analytical, laboratory, and field studies are reported in the *Building Thermal Mass Seminar* (Courville and Bales, 1983).

A3.5 Design Guides

The PCA sponsored a project to develop two manuals of guidelines for using ICFs with energy codes; one for complying with the MEC (VanGeem, 1998, *MEC*) and one for complying with *ASHRAE 90.2-1993, Energy-Efficient Design of New Low-Rise Residential Buildings* (VanGeem, 1998, *90.2*). The *MEC* and *ASHRAE 90.2* pertain to all one and two family residences regardless of height and multi-family residences with three or fewer stories above grade. Generally, this includes condominiums, rooming houses, rectories, monasteries, convents, boarding houses, and sorority congregate residences with complete facilities including kitchens. The *MEC* and *ASHRAE 90.2* set requirements for maximum energy loss through walls, roofs, and floors. They also set requirements for heating and air-conditioning equipment, domestic hot-water heaters, and over-all energy-efficiency. The manuals guide ICF users through the provisions of the *1995 MEC* and *ASHRAE 90.2* as they relate to ICF walls. The manuals describe thermal properties of ICF walls needed to show compliance and three methods of complying with the codes. Detailed step-by-step procedures and examples are provided. The documents also include background information on types of ICF walls, how to calculate R-values, and thermal mass. A general user's manual published by ASHRAE for use with *ASHRAE 90.2-1993* is also available (ASHRAE, 1996).

[†] Note from CTL: this may result in more comfortable living conditions and less potential for condensation and moisture problems in ICF houses.

The National Codes and Standards Council of the Concrete and Masonry Industry published a guide for using concrete and masonry and complying with *ASHRAE 90.1* (Eley Associates, 1994). *ASHRAE 90.1* specifies requirements for energy use and conservation within commercial buildings, and includes criteria for lighting, HVAC systems, and heat loss through the walls, roofs, and floors. It includes all buildings except low-rise residential. The manual guides users of concrete and masonry through the provisions of *ASHRAE 90.1-1989*. The manual also describes the basics of heat flow, thermal mass, and daylighting. A general user's manual published by ASHRAE for use with *ASHRAE 90.1-2001* is also available (ASHRAE, 2002).

A guide covering the topics of heat transfer, air leakage, rain penetration, thermal mass, insulation, fenestration, energy savings, and cost-benefits analysis was published by the Masonry Council of Canada. (Masonry Council of Canada, 1982).

Mr. J. Douglas Balcomb has been the premier author of guidelines and procedures for passive solar design. He is now associated with the U.S. National Renewable Energy Laboratory (NREL) and a search of their website (www.NREL.gov) yields 44 publications by him on passive solar design, solar energy, and energy analysis. The design manual *Passive Solar Heating Analysis* (Balcomb et al, 1984) provides guidelines for passive solar design and analysis methods to calculate energy use of passive solar buildings. The book is primarily for residential and small commercial buildings and provides detailed guidance for specific design strategies. The thermal mass of concrete and masonry play a major part in passive solar design strategies by storing solar energy that can be used to heat spaces. In a supplement (Balcomb and Wray, 1987), the authors provide additional methods for calculating the energy required to maintain comfort in the heating season and estimate energy savings of passive solar design. Methods are based on the "solar load ratio" concept (SLR). The "diurnal heat capacity" (DHC), the capacity of an element to store and return heat on a daily basis, is provided for concrete and masonry materials. The supplement also develops an analytical expression for the total "effective heat capacity" (EHC) of buildings. EHC is similar to DHC except it also includes heat that can be stored for periods longer than one day. Both DHC and EHC are measures of thermal mass.

A4. GENERAL INFORMATION ON HVAC SIZING

The goal of proper HVAC sizing is to provide occupant comfort in the form of heating, cooling, "fresh air", humidification, or dehumidification. Humidification is most often used in the winter heating season in northern climates while dehumidification is most important in the cooling season in the eastern half of the United States[‡].

Most residential HVAC equipment installations are not designed but are selected based on square-foot rule-of-thumb tables. These tables generally do not take into account the type of wall and roof construction or its thermal performance. Most are based on typical steady-state R-values of wood frame construction and do not take into account thermal mass.

[‡] The eastern portion of the US is divided from the western portion, for moisture purposes, by a north-south line through the center of the state of Texas.

The most common design approaches for sizing HVAC systems in houses are the *ASHRAE Handbook of Fundamentals* (*HOF*) method in Chapter 28, "Residential Cooling and Heating Load Calculations" (ASHRAE, 2001) and the *Manual J* method (Rutkowski, 2002). The *HOF* Chapter 28 method for cooling loads accounts for "light, medium and heavy-weight walls and doors" for multifamily but not for single-family detached residences. The text states this difference is due to the "averaging technique required" to develop the factors. The heating load calculation is based on steady-state R-values. Heating and cooling loads are based on winter and summer design temperatures, respectively for indoor and outdoor air. *Manual J* is a detailed procedure that takes into account construction materials, climate, and glass, duct, infiltration, and internal loads. The manual includes factors for calculating loads using many combinations of CMU and brick, ICFs, and 4-in. uninsulated and insulated concrete walls. The procedure does not include mass effects when sizing heating equipment. Companion software for *Manual J* is available from the Air Conditioning Contractors of America (www.acca.org). Manual S (Rutkowski, 1995) is used to determine the size and type of equipment once the heating and cooling loads are determined. Heating and cooling loads are based on winter and summer design temperatures, respectively, for indoor and outdoor air.

The *ASHRAE HOF* Chapter 29, "Nonresidential Cooling and Heating Load Calculation Procedures," includes the "radiant time series" (RTS) method for accounting for wall thermal mass in cooling load calculations (p. 29.26). The heating load calculations do not include the "thermal storage effect of the building structure or content."

The November 2002 draft of the California Energy Commission *2005 Residential Alternate Calculation Methods (ACM) Manual*, Appendix RM, (Eley, 2002) requires the use of the *ASHRAE HOF* Chapter 28.

Oversized cooling equipment is not energy efficient and because of the shorter cycling time, has the potential to be ineffective in removing the moisture (latent load) in buildings. This can lead to moisture problems in residences. For this reason, the California draft manual (Eley, 2002) includes maximum allowable cooling capacities. The use of winter and summer setback temperatures at night effect the equipment size, especially for homes with thermal mass.

Industry practice is to not consider mass effects when sizing heating equipment. Heating system loads are generally calculated assuming indoor and outdoor temperatures are constant at their design values. Solar gains and internal gains are not considered because the peak load time is at night or early morning when it is dark and before people and appliances have offsetting effects. There are no thermal mass effects under these design conditions. For sizing purposes, heating system loads are often increased by a factor to account for morning warm-up periods. The short term energy required to return from a night time setback is greater when there is more thermal mass.

A5. HVAC SIZING IN CONCRETE HOMES

A5.1 Laboratory Research

A concrete and masonry building was constructed and monitored for energy performance in a large environmental chamber at the National Bureau of Standards, now the National Institute of Standards and Technology (NIST) (Peavy et al, 1973). Results showed that steady-state methods of predicting heating and cooling loads could result in oversizing heating equipment for this type of building by 30% or more for the temperature cycles tested. The two diurnal cycles tested had temperatures ranging from approximately 40 to 100ºF and 10 to 70ºF, respectively.

A5.2 Analytical Studies

The PCA sponsored an analytical program to determine cooling load factors for houses with ICF walls (Wilcox, 1998). Manual J, 7th edition (Rutkowski, 1986), Figure 7-4 provides Equivalent Temperature Differences (ETD) for calculating the cooling load impact of exterior walls. The cooling load per square foot of wall is the wall U-factor times the ETD. The ETDs are tabulated for climates based on design temperatures and daily temperature ranges. Since the Manual J table provides ETDs for only two types of exterior walls, "frame and veneer-on-frame" and "Masonry walls, 8-in CMU or brick," Wilcox calculated ETDs for ICF walls. For the R-16.7 ICF and R-13 wood-frame wall houses he considered, cooling system sizes for ICF house were 75 to 95% of the size required for the frame house for the range of U.S. climates covered by Manual J. Although Wilcox found ICF walls have lower peak heating loads than wood-frame walls with the same U-factor, he does not recommend reducing heating system sizes for mass effects due to the industry practice previously discussed.

Further work was sponsored by PCA to calculate heat transfer multipliers (HTMs) for ICF walls (Wilcox and VanGeem, 1997; Wilcox and VanGeem, 1998). *Manual J* uses HTMs to calculate heating and cooling loads. The HTM for a wall is the amount of heat that flows through one square foot of wall at a given temperature difference. For climates with medium and high daily temperature ranges as defined by Manual J, HTMs (cooling) for ICF walls are significantly less than those in *Manual J, 7th edition*, for masonry walls. *Manual J, 8th edition*, has incorporated HTMs for many more wall systems than were in the 7th edition. However, the values for ICF walls for medium and high daily ranges in the 8th edition are the same as those for low daily ranges, and therefore not as favorable as in this study. Wilcox and VanGeem also present HTMs (heating) for ICF walls.

A5.3 Field Studies

Six test buildings were constructed at NBS (now NIST) in Gaithersburg, MD, and extensively monitored to measure heating and cooling loads (Burch, 1983). The one-room buildings had the same floor plan and orientation, and were identical except for the wall construction. The six walls were: insulated wood frame, uninsulated wood frame, CMU, CMU and brick insulated on the inside, CMU and brick with insulation in the cavity, and, log. Wall mass did not reduce heating loads in the winter heating season. Wall mass significantly reduced cooling loads in the summer cooling season. Load reductions due to wall mass were also observed in the intermediate season. The mass effects were greatest when the insulation was placed on the outside of the wall.

The ORNL Knoxville project with ICF and frame homes, previously discussed (Desjarlais et al., 2002), showed heating and cooling sizes were oversized for both wall types. Heating system sizes could be 5 to 100% smaller and cooling system sizes could be 3 to 55% smaller when DOE2 analyses were performed for the homes for a full range of U.S. climates. The ICF house required smaller system sizes than the frame house. The report also states, “A procedure for sizing that is less painstaking than trying smaller and smaller equipment sizes in DOE2 is needed to take advantage of this feature in ICF construction.”

A5.4 Design Guides

The PCA sponsored a project to develop a manual of guidelines for sizing cooling and heating equipment for ICFs in residential buildings (VanGeem et al, 1998). This publication guides ICF users through *Manual J, 7th edition*. The PCA publication provides HTMs for heating and cooling for ICF walls so Manual J procedures can be used for these systems. For climates with medium and high daily temperature ranges as defined by Manual J, HTMs (cooling) for ICF walls are significantly less than those currently in Manual J for masonry walls. However, the design cooling load is dominated by the heat gain through windows rather than walls. Simplified worksheets are provided with step-by-step examples of *Manual J* cooling load calculations for homes with ICF walls. The PCA publication also provides more general guidelines or rules-of-thumb in response to current practice. Many air-conditioning systems in residences are sized using rules-of-thumb based on square feet of floor area. These methods are crude because they neglect building geometry and orientation; the insulating capabilities of the walls, windows, and roofs in the building envelope; and numerous other building features. Nevertheless, cooling factors for use with such rules-of-thumb are also provided in this publication. Recommended reductions in cooling loads for homes with ICF walls compared to frame walls range from 1 to 23% depending on the climate. Typical HTM values for ICF walls for designing heating equipment are also provided. Manual J and standard industry practice make no allowance for mass effects when sizing heating systems.

A6. SUMMARY

This literature review is Task 1 of a project to develop an HVAC Sizing Methodology Manual for insulated concrete homes. This literature review identifies and briefly summarizes published information on (i) thermophysical properties of concrete and concrete walls, (ii) thermal behavior of concrete walls, including work performed to support the development of energy codes, (iii) general information on sizing of heating, ventilating, and air-conditioning (HVAC) equipment independent of construction type, and (iv) sizing HVAC equipment for concrete homes. The literature review supports these conclusions:

1.) Thermal mass in concrete and masonry buildings saves energy in many climates. Thermal mass shifts peak loads to a later time and reduces peak energy. Laboratory, analytical, and field studies support the theory.

2.) The effect of thermal mass in a concrete element is time dependent and it is related to the specific heat, density, and thermal conductivity of the materials in the element. Thermal diffusivity is a function of specific heat, density, and thermal conductivity.

3.) Thermal resistance (R-values) and thermal transmittance (U-factors) do not take into account the effects of thermal mass, and by themselves, are inadequate in describing the heat transfer properties of construction assemblies with significant amounts of thermal mass.

4.) Commonly used energy codes recognize the benefits of thermal mass and provide separate criteria for mass and frame walls.

5.) Most residential HVAC equipment installations are not designed but are selected based on square-foot rule-of-thumb tables that do not take into account thermal mass of concrete and masonry systems. These methods will result in oversized equipment in many cases.

6.) The most common design approaches for sizing HVAC systems in houses are the *ASHRAE Handbook of Fundamentals* (*HOF*) method in Chapter 28, "Residential Cooling and Heating Load Calculations" and the ACCA *Manual J* method for cooling. Both methods are time-consuming.

7.) The *ASHRAE HOF* method does *not* take into account thermal mass for single-family homes.

8.) The *Manual J* method takes into account thermal mass for cooling but benefits may not be fully realized. The *Manual J* method does *not* take into account thermal mass for heating.

9.) Laboratory, analytical, and field studies support reducing cooling equipment sizes due to thermal mass. Results are mixed for whether heating equipment sizes should be reduced due to thermal mass.

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APPENDIX B – THERMAL MASS IN CONCRETE AND MASONRY*

Thermal mass is a property that enables building materials to absorb, store, and later release significant amounts of heat. Buildings constructed of concrete and masonry have a unique energy-saving advantage because of their inherent thermal mass. These materials absorb energy slowly and hold it for much longer periods of time than do less massive materials. This delays and reduces heat transfer through a thermal mass building component, leading to three important results. First, there are fewer spikes in the heating and cooling requirements, since mass slows the response time and moderates indoor temperature fluctuations. Second, a massive building uses less energy than a similar low mass building due to the reduced heat transfer through the massive elements. Third, thermal mass can shift energy demand to off-peak time periods when utility rates are lower.

The impact of thermal mass on building envelope performance varies with several interrelated factors. The most important of these are the climate at the building site, the building design and occupancy, and the position of the wall insulation relative to the mass.

Thermal mass is more effective in reducing cooling loads than heating loads. In some climates, thermal mass buildings have better thermal performance than low mass buildings, regardless of the level of insulation in the low mass building. Mass has the greatest benefit in climates with large daily temperature fluctuations above and below the balance point of the building. For these conditions, the mass can be cooled by natural ventilation during the night, and then be allowed to "float" during the warmer day. When outdoor temperatures are at their peak, the inside of the building remains cool, because the heat has not yet penetrated the mass. Although few climates are this ideal, thermal mass in building envelopes will still improve the performance in most climates. Often, the benefits are greater during spring and fall, when conditions most closely approximate the "ideal" climate described above. In heating-dominated climates, thermal mass can be used to effectively collect and store solar gains or to store heat provided by the mechanical system to allow it to operate at off-peak hours.

Building design and occupancy significantly impact the effectiveness of thermal mass. In low-rise residential buildings, for example, heating and cooling loads are primarily determined by the thermal performance of the building envelope. In commercial buildings, loads are influenced more by internal heat gains from occupants, lights, and equipment. Because exposed thermal mass can absorb intermittent internal heat gains, thermal mass is generally more effective in commercial buildings than in low-rise residential. However, thermal mass is effective in may climates in both building types.

To best moderate indoor temperatures, the thermal mass should be exposed to the interior conditioned air and insulated from outdoor temperature variations. Thermal resistance (R-values) and thermal transmittance (U-factors) do not take into account the effects of thermal mass, and by themselves, are inadequate in describing the heat transfer properties of construction

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∗ Adapted from Eley Associates, *Thermal Mass Handbook, Concrete and Masonry Design Provisions Using ASHRAE/IES 90.1-1989*, Portland Cement Association, 1994.

assemblies with significant amounts of thermal mass. Only computer programs such as DOE2 that take into account hourly heat transfer on an annual basis are adequate in determining energy loss in buildings with mass walls and roofs. The heat flow through the wall is dependent on the materials' unit weight (density), thermal conductivity, and specific heat.

B1. Temperature, Damping and Thermal Lag

In addition to holding up the roof and keeping out the rain, walls act as thermal dividers between conditioned interior space and the outdoor environment. Their thermal function is complex, because heat is absorbed from solar radiation and hot air, radiated to cold skies and transferred to cool air, conducted to the interior, stored within the walls, and absorbed from and released to the interior.

The directions and magnitudes of these heat flows are constantly changing in the environment, and the amount of heat stored and released within the mass wall changes accordingly.

Temperature damping is a characteristic of mass construction that describes the way exterior temperatures and heat flows affect the interior of a building. For example, in the summertime, the temperature on the outside surface of a wall fluctuates widely, from a high temperature during the sunny midday to a low temperature in the middle of the night. This can be thought of as a temperature "wave." The inside surface of the wall, however, will experience a much smaller temperature fluctuation or wave. The wall "damps," or reduces, the amplitude of the temperature wave. The narrower temperature fluctuation on the interior means that the cooling loads are lower, and the inside of the building is more comfortable. The damping depends on both the insulation and the heat capacity of the construction. For two walls with the same insulation, the more massive wall will display greater temperature damping characteristics, as shown in Figure B1.

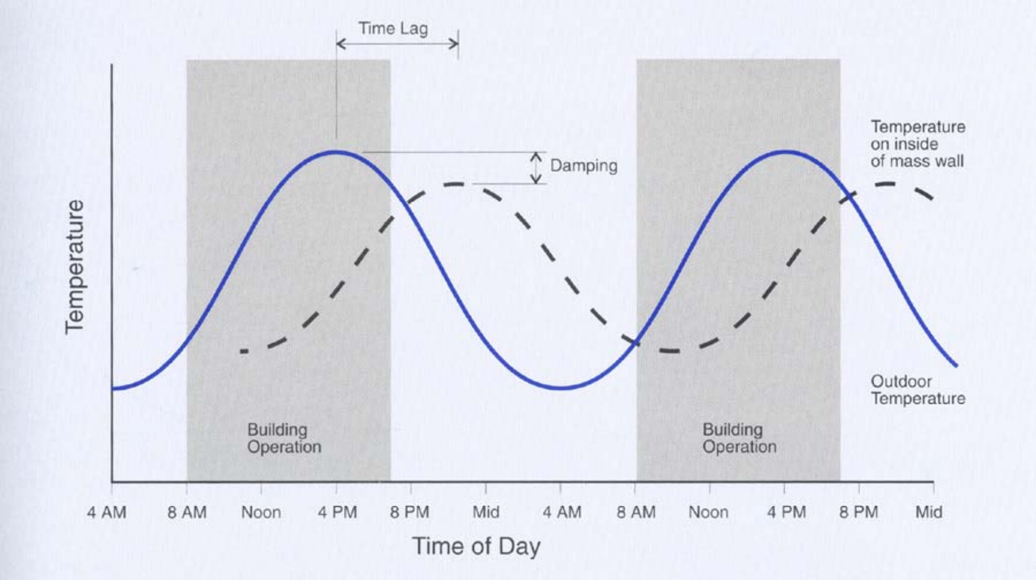


Figure B1: Time Lag and Temperature Damping

Another result of thermal mass is that the time of peak temperatures and heat gains on the interior is delayed, compared to the peak times on the exterior. This phenomenon is called *thermal lag.* With concrete and masonry walls, the time of highest interior temperature will be three to eight or more hours later than the time of highest exterior temperatures. As a result, peak cooling loads are delayed to cooler times of the day when the air conditioning equipment operates more efficiently, or when the building is unoccupied and not air conditioned at all. The thermal lag in wood and metal frame walls is generally less than two hours.

B2. Temperature Gradients

The benefits of thermal mass may be illustrated by considering transient or changing heat flow conditions. When the temperature on one side of a wall in steady-state equilibrium is changed to another constant value, steady-state heat flow is not achieved immediately. Heat flow from the time the temperature is changed until steady-state conditions are reached is referred to as transient heat flow. The difference between steady-state and transient heat flow may be illustrated by considering idealized temperature profiles across a homogeneous wall section.

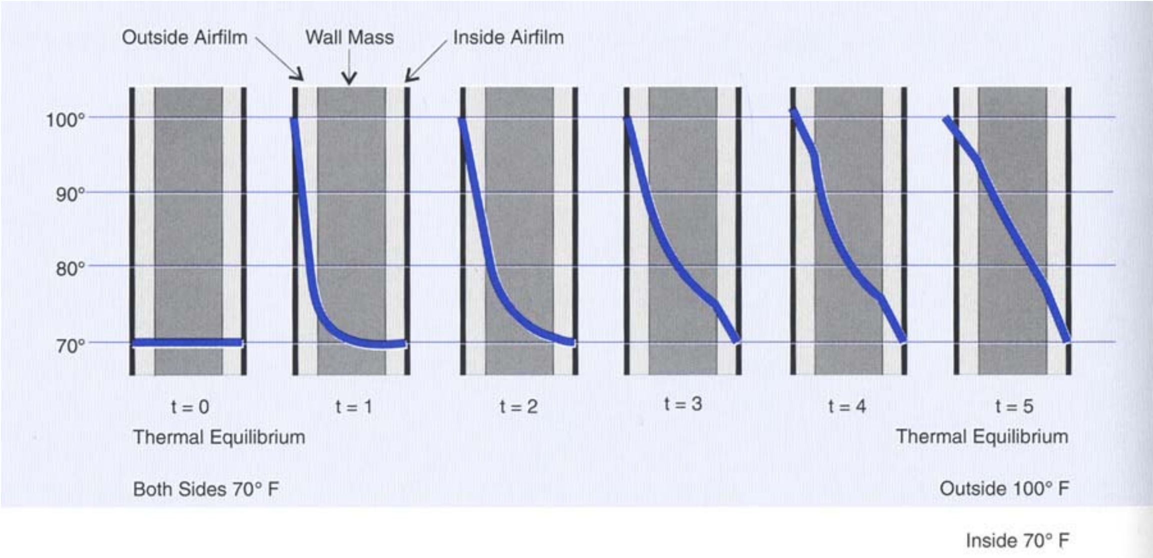


Figure B2: Temperature Gradients for Transient Heat Flow through a Homogeneous Wall

Figure B2 shows the temperature profile (or gradient) through a mass wall at six time intervals. The air films (surface conductances) are shown with exaggerated thickness for each time interval. At t = 0, the outdoor surface of the wall and the outdoor surface temperatures are both 70°F and the homogeneous wall is in a steady-state condition. The temperature gradient is zero, and there is no heat flow through the wall. At t = 1, the outdoor temperature is increased to 100°F, which causes the outdoor surface temperature to increase. Heat enters the wall from the outdoors, but only that part of the wall close to the outdoor surface responds to the temperature change. No heat leaves or passes through the wall on the indoor side, because the temperature gradient at the indoor surface is still zero. The accumulated heat is being stored by the wall. At t = 2, t = 3, t=4 and t = 5, more time elapses. At t = 1 and t = 2, heat enters the wall but does not pass through to the indoor surface. At t = 3 and t = 4, some heat is released to the indoor side of the wall. However, the heat entering the space is less than the amount entering the wall from the outdoors. For t = 1 through t = 4, heat is continually being stored by the wall. Heat flow predicted by steady-state R-value or U-factor calculations will overestimate heat gains during periods illustrated by t = 1 through t = 4. Steady-state conditions are finally reached at t = 5. The temperature gradient is linear, and the amount of heat entering the wall is equal to the amount leaving. Mass walls are seldom in steady-state conditions due to the changes in outdoor temperatures during the day.

B3. Mass Insulation Position

Energy codes (ASHRAE Standard 90.1; IECC) often specify insulation requirements for mass walls based on whether the insulation is interior, integral, and exterior, as shown in Figure B3. Interior insulation isolates the mass from the interior, reducing the ability of the thermal mass to moderate the indoor temperature. Integral insulation refers to thermal mass on both sides of the insulation, as with an insulated masonry cavity wall or insulated concrete panel, or to insulation and mass materials well mixed, as in a log wall. Exterior insulation refers to mass exposed to the interior, isolated from the exterior conditions by insulation. This last is the most thermally effective way to insulate the envelope of a thermal mass building. ICF walls perform somewhere between integral and interior mass walls, and the interior position should be used for meeting code requirements (Wilcox, 1997). It should be noted insulated mass walls combine the benefits of insulation and mass and are often quite energy efficient.

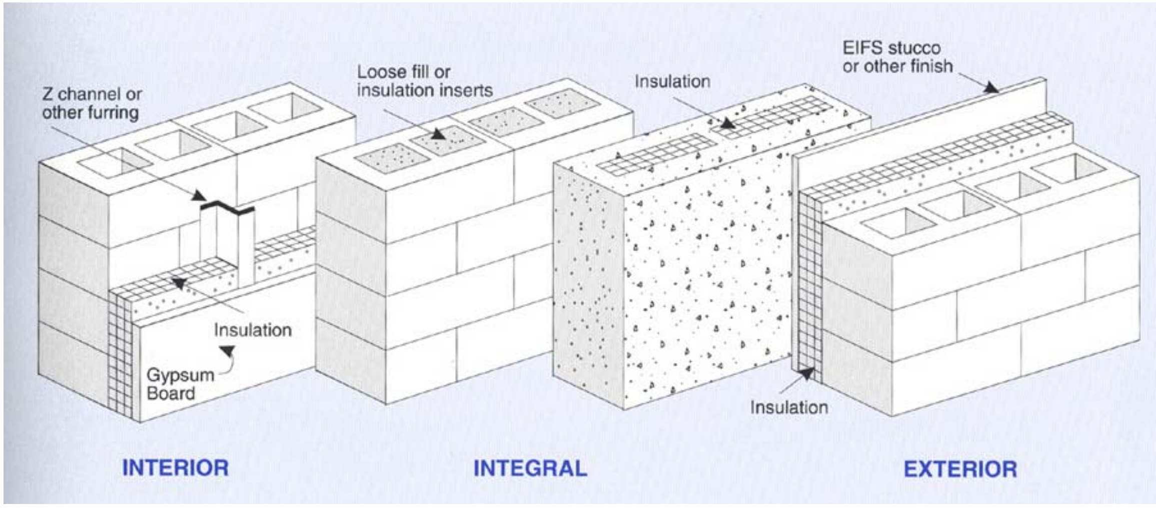


Figure B3: Mass Wall Insulation Methods

B4. Measurable Properties of Thermal Mass

The thermal mass of a wall, roof, or floor is directly related to its thickness, density, thermal conductivity, and specific heat. Thermal mass performance in energy codes is often characterized by heat capacity (HC). For a single layer wall HC is calculated by multiplying the density of the material times its thickness times the specific heat of the material. It is generally assumed that the higher the heat capacity the greater the thermal mass benefits. Heat capacity is an adequate performance measure for comparing materials with similar thermal conductivities. This includes most concrete and masonry constructed with ordinary sand and gravel. However, lightweight materials such as concrete made with low density aggregates have better thermal mass effects although their heat capacity may be lower due to their combination of thermal conductivity and unit weight (VanGeem, 1986).

B5. Weight and Density

Density is a property of raw materials measured in pounds per cubic foot (lb/ft^3). The weight of a wall, roof, or floor is equal to its volume times its density. Ordinary sand and gravel concrete has a density of approximately 140 lb/ft^3, but when steel reinforcing is added the density increases to 145 to 150 lb/ft^3. The clay material used to make typical bricks has a density of about 120 lb/ft^3. The density of concrete used to make concrete masonry units varies from 85 to 135 lb/ft^3. As the material is fabricated into masonry units or bricks, the density of the basic material is unchanged, but the unit weight of the finished product can be lower because of cores in the final product. A cubic foot of a CMU wall includes the hollow cores as well as the solid material, and so its unit weight is lower than that of a cubic foot of solid concrete.

B6. Specific Heat

Specific heat is defined as the quantity of heat energy (in Btu) required to raise the temperature of one pound of a material by one degree Fahrenheit. Because specific heat defines the relationship between heat energy and temperature for a given weight of material, it can also be used to determine the change in temperature for a material as it absorbs or releases energy. Specific heat describes a material's ability to store heat energy. As a material absorbs energy, its temperature rises. A material with a high specific heat, such as water, can absorb a great deal of heat energy per pound of material, with little rise in temperature. The same weight of a material with low specific heat, such as copper, rises to higher temperatures with only a small quantity of heat absorbed. The specific heat of concrete and masonry can generally be assumed to be 0.2 Btu/lb·ºF. (*ASHRAE Handbook of Fundamentals*, 2001)

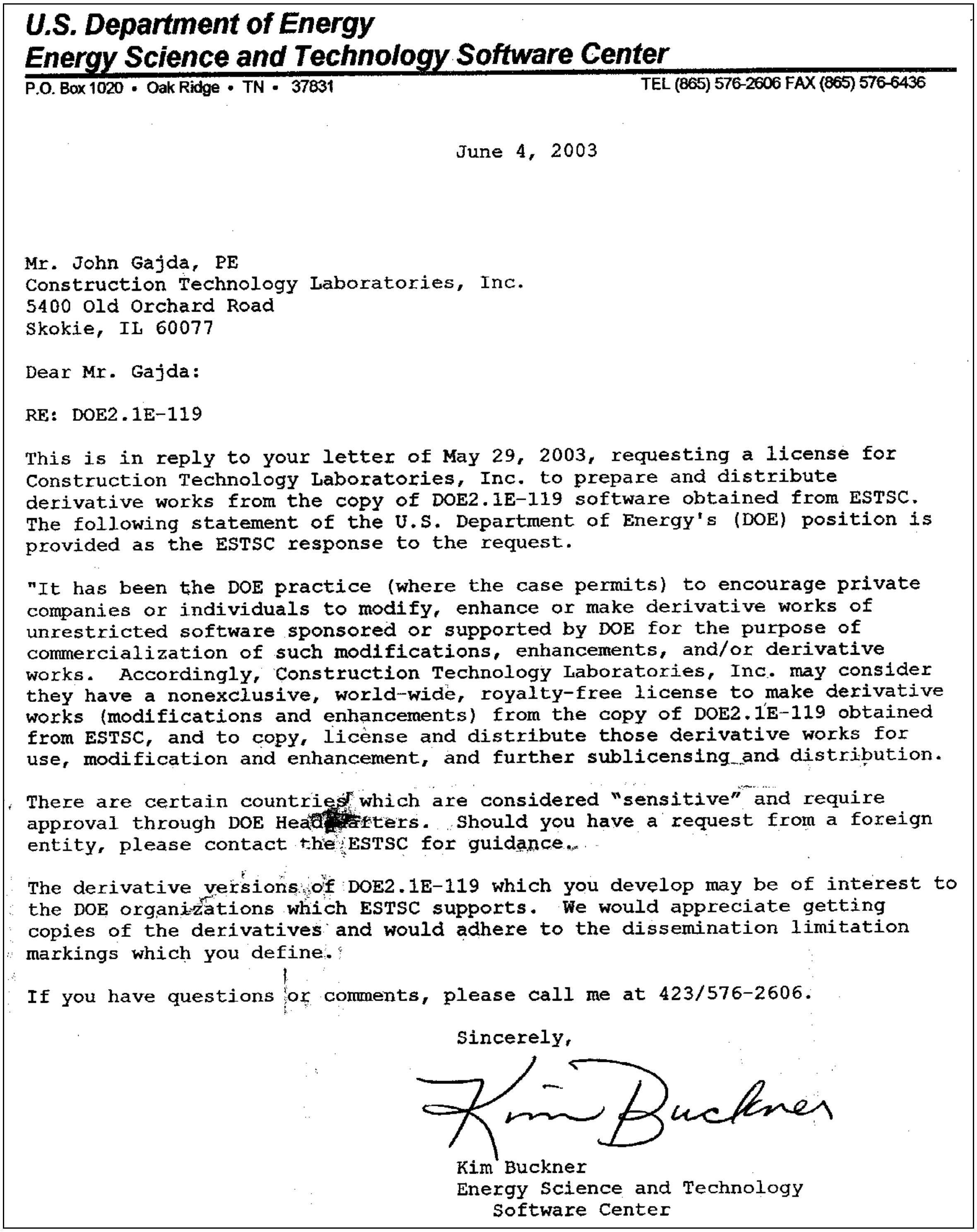
B7. Heat Capacity (HC)

Heat Capacity (HC) is the heat capacity per square foot of wall area (Btu/ft^2·°F) and includes all layers in a wall. For a single layer wall HC is calculated by multiplying the density of the material times its thickness (in ft) times the specific heat of the material. HC for a multilayered wall is the sum of the heat capacities for each layer.

B8. Published Thermal Properties

Values of heat capacity, thermal resistance, and thermal transmittance for concrete and masonry are presented in *ASHRAE Standard 90.1-2001*. Thermal conductivities are presented in the *ASHRAE Handbook of Fundamentals.*

APPENDIX C – LICENSING AGREEMENT



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June 4, 2003

Mr. John Gajda, PE
Construction Technology Laboratories, Inc.
5400 Old Orchard Road
Skokie, IL 60077

Dear Mr. Gajda:

RE: DOE2.1E-119

This is in reply to your letter of May 29, 2003, requesting a license for Construction Technology Laboratories, Inc. to prepare and distribute derivative works from the copy of DOE2.1E-119 software obtained from ESTSC. The following statement of the U.S. Department of Energy's (DOE) position is provided as the ESTSC response to the request.

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Sincerely,

Kim Buckner

Kim Buckner
Energy Science and Technology
Software Center