Thermal Mass - Energy Savings Potential in Residential Buildings

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ABSTRACT:

In certain climates, massive building envelopes-such as masonry, concrete, earth, and insulating concrete forms (ICFs)-can be utilized as one of the simplest ways of reducing building heating and cooling loads. Very often such savings can be achieved in the design stage of the building and on a relatively low-cost basis. Such reductions in building envelope heat losses combined with optimized material configuration and the proper amount of thermal insulation in the building envelope help to reduce the building cooling and heating energy demands and building related CO_2 emission into the atmosphere. Thermal mass effects occur in buildings containing walls, floors, and ceilings made of logs, heavy masonry, and concrete

This paper presents a comparative study of the energy performance of light-weight and massive wall systems. An overview of historic and current U.S. field experiments is discussed herein and a theoretical energy performance analysis of a series of wall assemblies for residential buildings is also presented. Potential energy savings are calculated for ten U. S. climates. Presented research work demonstrate that in some U. S. locations, heating and cooling energy demands for buildings containing massive walls of relatively high R-values can be lower than those in similar buildings constructed using lightweight wall technologies.

KEY WORDS: DOE-2, whole building energy consumption, heat transfer, thermal resistance, calculation procedure, walls.

INTRODUCTION:

Several massive building envelope technologies (masonry and concrete systems) are gaining acceptance by U. S. builders today. It is believed that building envelopes made of concrete, earth, insulating concrete forms (ICFs), and solid wood (log) may be helpful in lowering building heating and cooling loads. For centuries, the vast majority of European and Mid East residential buildings have been built using massive wall technologies. They have made life without air conditioners relatively comfortable even in countries with hot climates such as Spain, Italy, or Greece.

Numerous historic and current field studies have demonstrated that in some U.S. locations, heating and cooling energy demands in buildings containing massive walls of high R-value could be lower than those in similar buildings constructed using lightweight wall technologies. This better performance results from the thermal mass encapsulated in the building reducing temperature swings and absorbing energy surpluses both from solar gains and from heat produced by internal energy sources such as lighting, computers, and appliances. In addition, massive building envelope components delay and flatten thermal waves caused by exterior temperature swings.

Since all U.S. thermal building standards including ASHRAE 90.1 and 90.2 and the Model Energy Code are linked primarily to the steady-state clear wall R-value, calculating heating and cooling needs of a house built with high-mass walls is not straightforward. The steady-state R-value traditionally used to measure energy performance does not accurately reflect the dynamic thermal behavior of massive building envelope systems. This makes it difficult to convince builders, investors, code officials, etc...about the improved energy performance of massive building envelope systems. Such a situation opens the door for many companies to claim unrealistically high energy performance data for their wall technologies.

The main objective of this work is to provide a comparative study of the energy performance of massive wall technologies. Since the majority of U.S. residential buildings are built using light-weight wood-framed technologies, all energy performance comparisons in this paper are made against light-weight wood-framed buildings. An overview of several historic and current U.S. field experiments are discussed. These experiments were performed in a wide range of U.S. climates utilizing several building sizes and shapes. Theoretical energy performance analysis is presented for a series of four wall assemblies.

The wall material configurations of these assemblies represent most of massive wall systems utilized in U.S. residential buildings. Theoretical and experimental results presented in this paper should enable approximate energy performance evaluations for the most popular massive wall configurations.

SOME RESULTS OF FIELD ENERGY STUDIES PERFORMED ON MASSIVE RESIDENTIAL BUILDINGS

A wide selection of historic and current field experiments are discussed in the following section. Some early experiments were initiated in late 70's as a result of the energy crisis and focused on application of passive solar techniques in residential buildings.

Passive solar designers used glazing and thermal mass to utilize solar energy and stabilize interior air temperature. A Los Alamos National Laboratory team headed by J. D. Balcomb and R. D. McFarland investigated the energy performance of several passive solar wall systems and a various thermal mass storage materials. All systems were tested in field conditions in 2.6x1.9x2.9 m (100x80x120 in.) insulated lightweight containers [J. D. Balcomb et al. - 1978]. The only thermal mass provided was by the tested solar systems. Several materials were tested as a potential energy storage during these experiments. The most common was the application of conventional masonry blocks or solid concrete walls. However, Los Alamos researchers also studied the energy performance of water and phase change materials as energy storage means. The results from these experiments demonstrated that passive solar systems had a great potential in reducing energy consumption in residential buildings. They were published in the Passive Solar Handbook [J. D. Balcomb et al. - 1983] and Passive Solar Construction Handbook [Steven Winters Inc. - 1981] which have been widely used as a reference in the designing of passive solar houses.

Several other experiments focused on more conventional applications. These field studies demonstrated the potential energy demand reductions in buildings containing massive walls, floors, or roofs. It was observed and documented that heating and cooling energies in massive houses can be far lower than those in similar buildings constructed using lightweight wall technologies. This better performance resulted because the thermal mass encapsulated in the walls reduces temperature swings and absorbs energy surpluses both from solar gains and from heat produced by internal energy sources such as lighting, computers, and other appliances.

In June 1982, ORNL hosted the Building Thermal Mass Seminar [Courville, Bales 1982]. This seminar gathered a very interesting collection of results from theoretical and experimental studies on building thermal mass. Experimental work of T. Kusuda, D. Burch, and G.N. Walton from the National Institute of Standards (NIST), A.E. Fiorato from the Construction Technology Lab, and P.H. Shipp from Owens Corning, created a solid foundation for the future studies in this field. During the seminar, several presenters indicated a possibility of potential energy savings in houses using massive building envelope components.

Almost two decades ago, several thermal mass field experiments were carried out for DOE by researches in Gaithersburg, Maryland, Santa Fe New Mexico, and Oak Ridge, Tennessee [Burch 1984a, b, c, Robertson, Christian -1985, Christian 1983, 84, 85]. The primary focus of these projects was to collect reliable performance data for structures that emphasized exterior wall thermal mass effects. Several principal data-collecting efforts are described below.

Burch built four one-room test huts 6x6 m (20x20 ft) at the National Institute of Standards and Technology (NIST) to compare the seasonal energy performance of wood-framed, masonry, and log constructions. Site weather data were collected for periods during winter, spring and summer. The buildings were of identical construction except for the walls and were operated at the same thermostat setting. This study conclusively demonstrated the effect of thermal mass on space heating and cooling loads. Significant energy savings were noted for the house with a higher internal thermal mass.

During the same study, the impact of thermal mass on the night temperature setback savings was investigated. It was believed that night temperature setbacks might cause a significant reduction in the setback energy savings in massive buildings. The following observations were made during this project:

> -When thermostat setpoint temperature was suddenly reduced by a fixed amount, the indoor temperature decreased from higher to lower level. During that period, the heating plant remained off. Thermal mass in buildings increased the time for the indoor temperature to decrease during the setback period.
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> - Similarly, during the morning period when the indoor temperature setpoint was increased, the presence of thermal mass extended the time to reach setpoint. The output capacity

of the heating plant was sufficiently large that the temperature setup was short compared to setback.

The net effect of thermal mass in buildings containing heavyweight components was believed to cause the average indoor temperature and difference across the building envelope to be maintained at a more elevated level. As a result, night temperature setback caused the envelope heat-losses rate to be higher in massive buildings. All of this supported a common belief that night temperature setbacks in massive buildings caused a reduction in the setback energy savings. D. Burch investigated this penalty in setback energy savings and his research confirmed the fact that such a reduction took place. However, the magnitude of this phenomenon was very insignificant. For example, for a typical residence the difference in setback energy savings in the massive house and traditional wood-framed was predicted as only 0.3%.

Robertson and Christian investigated eight one-room test buildings 6x6 m (20x20 ft) that were constructed in the desert near Santa Fe, New Mexico, to determine the influence of thermal mass in exterior walls. The buildings were identical except for the walls (adobe, concrete masonry, wood-framed, and log). Data was collected for two heating seasons from mid-winter to late spring. This study demonstrated that on small windowless massive test huts, energy consumption can be up to 5% lower than in lightweight building. It is important to point out that during this study, the massive walls had about three-to-four times lower R-value than wood-framed walls (wood-framed wall R-value was about R-13 vs R-2 to R-5 for adobe, concrete masonry, and log walls). This gives completely different meaning to the 5% energy savings that were reported.

During three years of 1982 -84, Christian monitored an occupied 372 m^2 (4000 ft^2) dormitory constructed of massive building materials in Oak Ridge, Tennessee. This study demonstrated the potential for energy savings in buildings using massive envelope materials. Whole building energy simulations were performed employing the DOE-2.1B computer model. This computer model was calibrated using experimental data collected and analyzed during the testing period of the dormitory. Later, massive building envelope components in the computer model were replaced by wood-framed components. Predicted energy demands with the wood frame were compared with the energy required with the massive building components. Final comparisons showed a potential 10% savings in cooling energy and a 13% savings in heating energy.

In 1999 a field investigation on thermal mass effect in residential buildings was performed by the NAHB Research Center [NAHB RC-1999]. NAHB RC evaluated three side-by-side homes 102 m^2 (1098 ft^2) of floor area to compare the energy performance of Insulated Concrete Forms (ICF) wall systems versus traditional wood-framed construction. All three homes had identical orientation, window area, roof construction, footprint, duct-work, and air handler systems. This research provided another experimental evidence of the superior energy performance of buildings constructed using massive wall materials. A 20% difference was noticed between the ICF house and the conventional wood-framed house's energy consumption. In the final report, NHAB researches concluded that this 20% difference was caused by the R-7 difference in wall R-values (ICF wall R-value was about R-20, conventional 2x4 wood stud wall R-value was about R-13). However, simulation data developed by ORNL for a similar 121m^2 (1300 ft^2) one story house suggests that for the same climate a difference between R-20 and R-13 should yield a maximum 8 to 9% difference in annual whole building energy consumption. This suggests that most likely thermal mass related energy savings during the NAHB ICF study were in the neighborhood of 11%.

Currently, a field investigation of the effect of thermal mass in residential buildings is being performed by the Oak Ridge National Laboratory's Buildings Technology Center with support from the Insulated Concrete Forms Association and the local Habitat for Humanity. The goal is to evaluate the relative energy performance of insulated concrete form (ICF) wall systems. A major task of the project is to field monitor the energy efficiency of a typical ICF residential building side-by-side with another house that has traditional 2x4 wood-framed walls installed on concrete masonry unit foundations (see Figure 1). The interior floor space and floor plan are identical as are the ceiling and floor construction, heating/cooling system, and ductwork for the single-story, 111m^2 (1200 ft^2) houses.

The field monitoring of the houses began in mid-June 2000 and will continue for a calendar year, during which time the houses will be unoccupied with the heating/cooling systems operated on identical schedules. This will allow a strong experimental basis for the differences in energy consumption due to the differing outside wall constructions.

The purpose of the monitoring for one year is to provide data sufficient to validate annual energy models of the two houses in the Knoxville climate. Developed computer models will be used to investigate benefits of the ICF construction in climates different from the field-test climate of East Tennessee. A detail report from this project will be available at the end of 2001.

Figure 1. ORNL/Habitat test houses.

METHODOLOGY FOR ESTIMATING POTENTIAL ENERGY BENEFITS OF USING THERMAL MASS

General Procedure

Dynamic Whole Building Energy Modeling of Residential Buildings

Evaluation of the dynamic thermal performance of massive wall systems combines experimental and theoretical analysis. For complex three-dimensional building envelope components, it is based on dynamic three-dimensional finite difference simulations, whole building energy computer modeling, dynamic guarded hot box tests, and sometimes, comparative field performance investigations [Kosny et.al. 1998a]. Dynamic hot box tests serve to calibrate detailed computer models. It is important to know, that all these costly and time-consuming steps are not necessary for all wall assemblies. For simple one-dimensional walls, only theoretical analysis can be performed without compromising accuracy.

Masonry or concrete walls having a mass greater than or equal to 146 kg/m^2 (30 lb/ft^2) and solid wood walls having a mass greater than or equal to 98 kg/m^2 (20 lb/ft^2) are defined by the Model Energy Code [MEC-1995, Christian 1991] as massive walls. They have heat capacities equal to or exceeding 266 J/m^{2}K (6 Btu/ft^2 ^{0}F). The same classification is used in this work.

Since 95 percent of U.S. residential buildings is constructed using light-weight building envelope technologies, energy performance of wood-framed walls is utilized as a base for performance comparisons in this work. A wide range of traditional wood-framed wall assemblies is considered, R-values from 0.4 to 6.9 Km^2/ W (2.3 to 39.0 hft^2 F/Btu). Energy performance data, generated by whole building energy simulations for residential buildings containing wood-framed walls, is compared against similar data generated for four basic types of massive walls. Each wall type consists of the same materials, concrete and insulating foam. Within the same type of walls, all sequences of materials are the same, however, individual material thicknesses change to match necessary R-values. Massive wall R-values range in this work from R - 0.88 m^{2}K/W (5.0 hft^{2}F/Btu) to R - 3.03 m^{2}K/W

(17.2 hft^2F/Btu). Four basic material configurations are considered for massive walls:

- Exterior thermal insulation, interior mass **(Intmass)**
- Exterior mass, interior thermal insulation **(Extmass)**
- Exterior mass, core thermal insulation, interior mass, and **(CIC)**
- Exterior thermal insulation, core mass, interior thermal insulation **(ICI).**

The four types of massive walls above approximate most of the currently used multilayer massive wall configurations. For example, the first two wall configurations may represent any masonry block wall insulated with rigid foam sheathing. The last wall configuration may represent Insulated Concrete Forms (ICF) walls. Therefore, results presented in this work can be used for approximate energy calculations of most massive wall systems.

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This procedure is similar to that used to create the thermal mass benefits tables in the Model Energy Code [MEC-1995]. The thermal mass benefit is a function of the climate. The R-value Equivalent for Massive Systems is obtained by comparing the energy performance of the massive wall with the light-weight wood-frame walls [Kosny et.al.1998, Kosny et. al. 1998a] and should be understood only as the R-value needed by a house with wood-framed walls to match the annual energy required by identical house containing massive walls.

The DOE-2.1E computer code is utilized to simulate single-family residences in representative U.S. climates. Heating and cooling energies calculated for residences with massive walls are compared to the heating and cooling energies for identical buildings simulated with lightweight wood-frame exterior walls. To find a relation between wall R-value and heating and cooling energies, a lightweight ranch-type building is simulated. Twelve different wood-frame walls with R-values from 0.4 to 6.9 Km^2 / W (2.3 to 39.0 hft^2F/Btu) are considered. This simulation is performed on ten U.S. climates using TMY2 weather files for a total of 120 simulations. The energy output data generated by these whole building simulations is used to estimate the R-value equivalents that would be needed in conventional wood-frame construction to produce the same energy demand as for the house with massive walls in each of the ten climates. The resulting values account for not only the steady state R-value but also the inherent thermal mass benefit.

To enable simple comparisons of dynamic energy performances of wall systems, ORNL’s BTC introduced in 1995 the Dynamic Benefit for Massive Systems model (DBMS) [Kosny at al 1998]. DBMS is a dimensionless multiplier of steady-state R-value. The product of DBMS and steady-state R-value is called “ Dynamic R-value Equivalent for Massive Systems.” It should be used only as an answer to the question: *“What wall R-value should a house with wood frame walls have to obtain the same space heating and cooling energy consumption as a similar house containing massive walls?”*

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Comparative analysis of the space heating and cooling energies from two identical residences, one with massive walls and the other containing lightweight wood-frame exterior walls, was introduced in the Model Energy Code for development of thermal requirements for massive wall and was adopted by the authors. The DOE-2.1E computer code was utilized to simulate three single-family residences in ten representative U.S. climates. Two single-story ranch style houses of approximately 74 m2 (800 ft2) and 143 m2 (1540 ft2) floor area, were accompanied by a two story 279 m2 (3000 ft2) house. Over ten thousand whole building energy simulations were performed during this study. The heating and cooling energies generated from these building simulations served to estimate the R-value equivalents for massive walls. A list of cities and basic climate data are presented in Table 1.

Table 1. Ten U.S. climates used for DOE 2.1E computer modeling

Cities:	HDD 18.3 C(65 deg F)	CDD 23.3 C(74 deg F)
Atlanta	1705 (3070)	9335 (16803)
Bakersfield	1182 (2127)	16641 (29954)
Boulder	3037 (5466)	4269 (7684)
Chicago	3588 (6459)	3670 (6606)
Fort Worth	1344 (2420)	20163 (36294)
Miami	110 (198)	21889 (39401)
Minneapolis	4450 (8010)	3781 (6806)
Phoenix	802 (1444)	30224 (54404)
Seattle	2602 (4684)	498 (897)
Sterling (Washington D.C.)	2781 (5005)	4286 (7715)

The Sherman-Grimsrud Infiltration Method, which is an option in the DOE 2.1E whole-building simulation model [Sherman et al 1980], is used in all whole building simulations. An average total leakage area of 0.0005 expressed as a fraction of the floor area is assumed. This is the considered average for a single-zone wood-framed residential structure. This number cannot be converted directly to average air changes per hour because it is used in an equation driven by hourly wind speed and temperature difference between the inside and ambient which varies for the six climates analyzed for this study. However, for the ten climates this represents an air change per hour range which will not fall below an annual average of 0.35 ACH.

The total space heating and cooling energies for twelve lightweight wood-frame walls were calculated using DOE-2.1E simulations. The total space heating and cooling energies divided by floor area are presented on Figure 2. Regression analysis was performed to analyze the relation between the steady-state clear wall R-values of wood-stud walls and the total building annual energies for ten U.S. climates.

DYNAMIC THERMAL PERFORMANCE OF SIMPLE MULTILAYER WALL ASSEMBLIES

The whole building energy calculation program DOE-2 E was utilized to simulate residential buildings containing simple multilayer wall assemblies. Simple walls without thermal bridges can be accurately represented by one-dimensional models like DOE-2 [Kossecka & Kosny - 1998, Kosny et.al.- 2000, ASHRAE - 2001]. Four sets of massive walls representing different sequences of concrete and foam layers were simulated. Each set consisted of four walls of the same material sequence. These four wall sets (sixteen walls total) represented the majority of existing massive wall material configurations used in construction today. For all wall configurations analyzed in this section, the same material properties were used and are presented in Table 2.

The above walls had different thicknesses of concrete and insulation layers. For each analyzed material configuration, four different sets of thicknesses were considered are were organized according to their R-value;

- R - 3.03 m^2K/W (17.2 hft^2F/Btu), in total: 10.6 cm (4-in) of foam, 15.2-cm. (6-in) of concrete.

- R - 2.29 m^2K/W (13.0 hft^2F/Btu), in total: 7.6 cm (3-in) of foam, 10.2-cm. (4-in) of concrete.

- R - 1.58 m^2K/W (9.0 hft^2F/Btu), in total: 5.2 cm (2-in) of foam, 10.2-cm. (4-in) of concrete.

- R - 0.88 m^2K/W (5.0 hft^2F/Btu), in total: 2.5 cm (1-in) of foam, 10.2-cm. (4-in) of concrete.

Table 2. Thermal properties of material for multilayer walls.

Material	**Thermal conductivity W/mK (Btu-in./hft^{2}F)**	**Density kg/m^3 (lb/ft^3)**	**Specific heat kJ/kgK (Btu/lbF)**
Concrete	1.44 (10.0)	2240 (140)	0.84 (0.20)
Insulating Foam	0.036 (0.25)	25.6 (1.6)	1.21 (0.29)
Gypsum Board	0.16 (1.11)	800 (50)	1.09 (0.26)
Stucco	0.72 (5.00)	1856 (116)	0.84 (0.20)

Due to the limited size of this paper, only some examples of the results are presented below. Detailed results for all considered houses are scheduled to be available at the end of 2001under the following Internet address: http://www.ornl.gov/roofs+walls/.

Figure 3 depicts an example of the relationships between wall steady-state R-value and Dynamic R-value Equivalents for the Washington D.C. climate. A one-story ranch house of 143 m^2 (1540-ft^2) [Hasting 1977, Huang 1987] is chosen to illustrate the dynamic energy performance of a one-story residential building. Similar relations were observed for all considered climatic conditions and for all sizes and types of buildings. This data shows that the most effective wall assemblies were walls with thermal mass (concrete) being in good contact with the interior of the building (Intmass and CIC). Walls where the insulation material is concentrated on the interior side (Extmass) were the worst performing wall assemblies. Wall configurations with the concrete wall core and insulation placed on both sides of the wall (ICI) performed slightly better than Extmass configurations. However, their performance was significantly worse than CIC and Intmass configurations. The ICI configuration can be used for approximate analysis of the very popular Insulated Concrete Forms (ICFs) constructions, since ICF walls consist of the internal concrete core placed between shells made of insulating foam.

Figure 3. Dynamic R-value equivalents for Washington D.C. for 1540-ft^2. one-story ranch house

The relationship between DBMS and wall R-value is not linear. For CIC and Extmass configurations DBMS is relatively close to 1.0. Figure 4 depicts DBMS values for a 143 m^2 (1540-ft^2) one-story residential building in the Washington D.C. climate. As in Figure 3, CIC and Intmass walls outperformed other wall systems. Walls where the insulation material is concentrated on the interior side of the wall have the smallest DBMS values. DBMS values for walls with the concrete core and insulation placed on both sides fell between these configurations. It was observed for all simulated cases that the DBMS was at its maximum for wall R-values between 2.3-3.0 m^2K/W [13 - 17 hft^2F/Btu].

Figure 4. DBMS values for Washington D.C. for 143 m^2 (1540-ft^2.) one-story ranch house.

Figure 5 shows the relationship between wall material configurations and DBMS for ten climates. A one-story ranch house and two R- 3 m^2K/W (17 hft^2F/Btu) walls were considered. One wall had a concrete core with insulation placed on both sides and the second wall was built with concrete on the interior side and insulation on the exterior. The first wall exemplifies popular ICF systems used in the U.S. and Canada. The second wall could represent a concrete block wall insulated with external rigid foam sheathing. Figure 5 clearly demonstrates significant differences in energy performance between the two wall systems. The wall with external foam insulation (Intmass on Figure 5) was much more effective than the ICF wall. The most favorable climates for both wall systems were in Phoenix and Miami and the worst locations were Minneapolis and Chicago. However, even for the worst locations, the DBMS values were close to 1.5. The range of DBMS values for walls with exterior foam insulation (DBMS - from 1.4 to 2.8) is much wider than a very flat chart of DBMS values for the ICF wall system (oscillating around 1.5). This is caused by different distributions of mass and thermal insulation in these walls, generating significant differences in DBMS values for the same climate.

Figure 5. DBMS values for two massive wall systems in ten U.S. climates for 143 m^2 (1540-ft^2) one-story ranch house.

POTENTIAL ENERGY SAVINGS IN HOUSES WITH MASSIVE WALL SYSTEMS

In certain climates, buildings containing massive building envelopes- such as concrete, earth, insulating concrete forms (ICFs), and solid wood (log) - can be more energy efficient than similar conventional wood-framed houses. This was well known by Native American Tribes who commonly used adobe structures in the past. Also, European residential buildings have been built for centuries using massive wall technologies. Several research studies performed in the last decade or so have compared energy performance of buildings containing massive walls with similar buildings constructed using lightweight wall technologies [Burch 1984a, b, c, Robertson, Christian -1985, Christian 1983, 84, 85]. These experiments required construction of identical houses having the same floor plane, shape, orientation, HVAC equipment, etc... One of the most difficult conditions for such comparisons was the requirement of identical R-values for all building envelope components in all compared buildings. Many experimental studies did not fulfill this requirement making necessary the deployment of whole building energy simulation models. Investigation of differences in energy consumption between massive and lightweight buildings can help in the analysis for potential benefits of using massive building envelope components. Two examples of energy consumption comparisons are presented below for Minneapolis, Minnesota (heating climate) and Bakersfield, California (cooling climate).

Figure 6. A portion of the whole building energy which can be saved in Minneapolis, Minnesota by replacement of conventional wood framed walls by massive wall technologies.

Annual whole building energy savings, attainable when lightweight walls are replaced by massive walls of the same R-value, were calculated for a 143 m^2 (1540-ft^2) one-story ranch house located in Minneapolis, Minnesota. These energy savings were defined as a difference between energies required to heat and cool the house containing massive walls v.s. the same house constructed with wood frame technology. Energy savings for this house were estimated between 3 and 7 MBtu/year for R-1.8 to 4.4 m^2K/W (10 to 25 hft^2F/Btu) walls. This is approximately 1900-4400 Btu/year per ft^2 of floor area of the residential building.

Figure 6 depicts the percentage annual energy savings for a massive house located in Minneapolis (heating climate). Data presented in Figure 6 shows that it is possible for buildings with high R-value walls to save up to 8% of annual energy consumption when traditional wood stud walls are replaced by massive wall systems. It is interesting to note that low R-value massive walls may actually increase energy consumption in this location.

Figure 7 shows similar energy savings comparisons as shown in Figure 6 but for buildings located in Bakersfield, California (cooling climate). Data presented in Figure 7 demonstrates that during the design process, an architect may save 5 to 18% of future whole building energy use simply by replacing traditional light-weight walls with massive systems.

Figure 7. A portion of the whole building energy which can be saved in Bakersfield, California by replacement of conventional wood framed walls by massive wall technologies.

Insulated Concrete Forms (ICFs) have been gaining acceptance by U. S. builders during the last decade. These massive building envelope technologies are using foam forms which are filled with concrete at the building site. Since most of these systems have a similar configuration of materials, foam/concrete/foam, it was possible to develop a single chart which shows approximate energy savings available when conventional wood framed walls are replaced by ICF walls in residential buildings. Figure 8 depicts the potential energy savings available in ten U. S. locations for ICF wall systems. This figure represents combined data from all three simulated houses. It shows the average whole building energy savings potential in houses with 74 - 279 m^2 (800-3000 ft^2) of floor area. For individual building size and shape, this data may vary within "2%. Assuming that average ICF wall R-value is between R- 2.6 and 3.5 m^2K/W (15 and 20 hft^2F/Btu), average potential whole building energy savings (ICF house v.s. conventional wood-framed house) for all U.S. locations are between 6 and 8%.

Figure 8. Potential energy savings available in ten U. S. locations for ICF wall systems.

CONCLUSIONS

Experimental and theoretical analysis of the energy performance of light-weight and massive wall systems was presented in this paper. Dynamic thermal performance of sixteen wall assemblies was investigated for residential buildings and the potential energy savings were presented for ten U.S. climates. It was found that some massive building envelope technologies can help in the reduction of building annual energies.

Several comparative field experiments have demonstrated that in many U. S. locations, heating and cooling energy demands in buildings containing massive walls of relatively high R-values can be lower than those in similar buildings constructed using equivalent R-value with lightweight wall technologies.

The thermal mass benefit is a function of wall material configuration, climate, building size, configuration, and orientation. From ten analyzed U.S. locations, the most beneficial for application of thermal mass are Phoenix, AZ and Bakersfield, CA.

Comparative analysis of sixteen different material configurations showed that the most effective wall assembly was the wall with thermal mass (concrete) applied in good contact with the interior of the building. Walls where the insulation material was concentrated on the interior side, performed much worse. Wall configurations with the concrete wall core and insulation placed on both sides of the wall performed slightly better, however, their performance was significantly worse than walls containing foam core and concrete shells on both sides.

Potential whole building energy savings, available when lightweight walls are replaced by massive walls of the same R-value, were calculated for 143 m^2 (1540-ft^2) one-story ranch houses located in Minneapolis, Minnesota and Bakersfield, California. For high R-value walls, up to 8% of the whole building energy could be saved in Minneapolis and 18% - in Bakersfield when wood-framed walls were replaced by massive wall systems. Thermal mass layers must be in good contact with the interior of the building in these walls.

Whole building possible energy savings in houses built with ICF walls were estimated as well. Three houses with 74 - 279 m^2 (800-3000 ft^2) of floor area were simulated for this purpose. It was found that for ten U.S. locations, ICF walls of R- 2.6 and 3.5 m^2K/W (15 and 20 hft^2F/Btu), the average potential whole building energy savings (ICF house vs conventional wood-framed house) can be between 6 and 8%.

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Figure 1. ORNL/Habitat test houses.

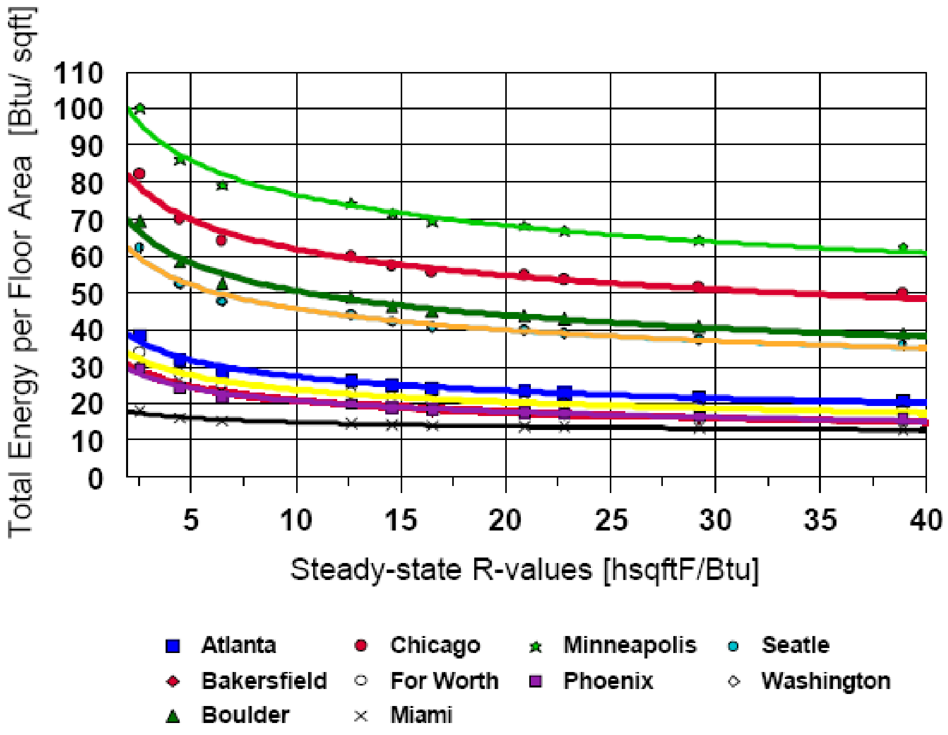

Fig.2. Total energy consumption in residential buildings per floor area for ten U.S. climates..

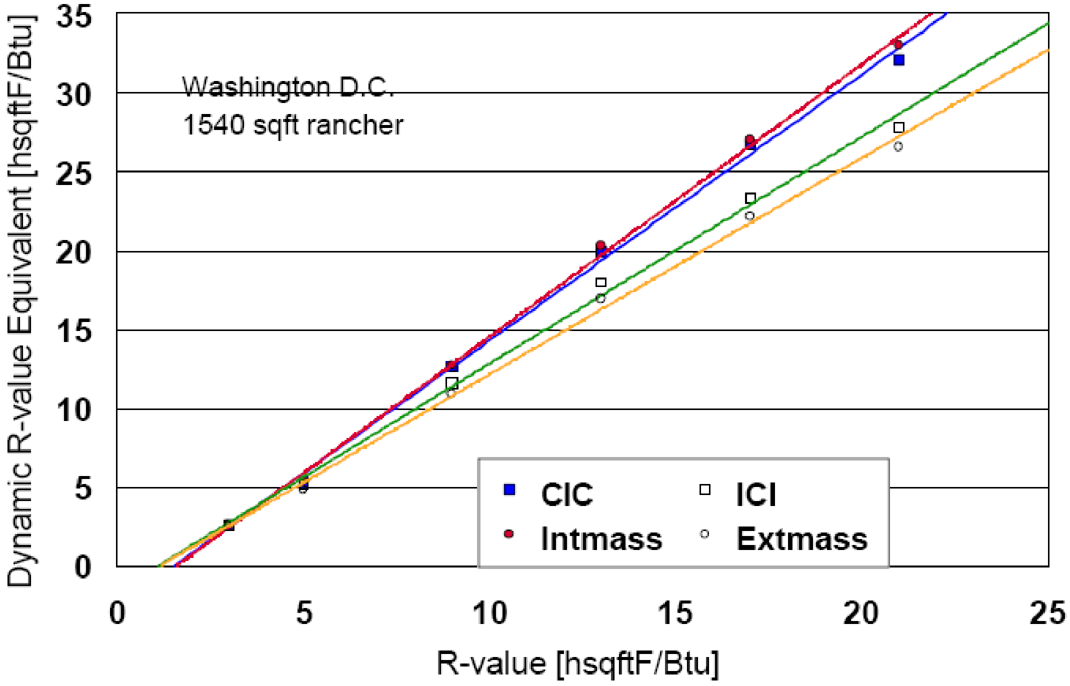

Fig.3. Dynamic R-value Equivaents for Washingtonn D.C. for 1540 ft2 one-story rancher.

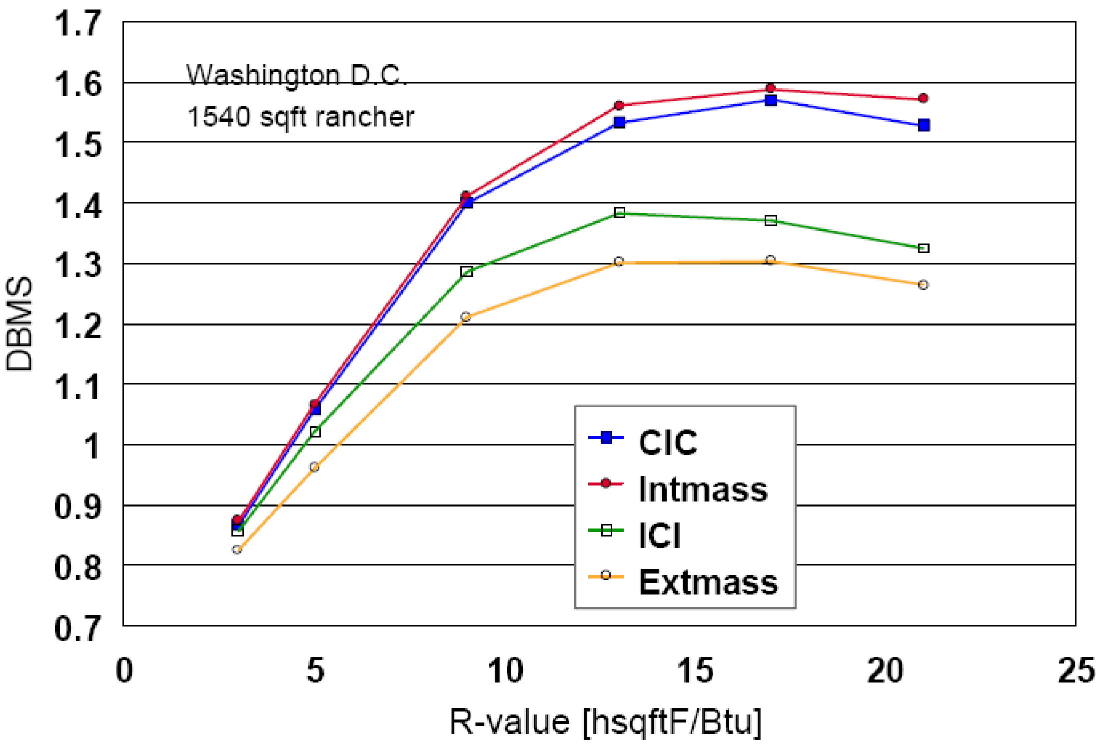

Fig.4. DBMS values for Washington D.C. for 1540 ft$_2$ one-story rancher.

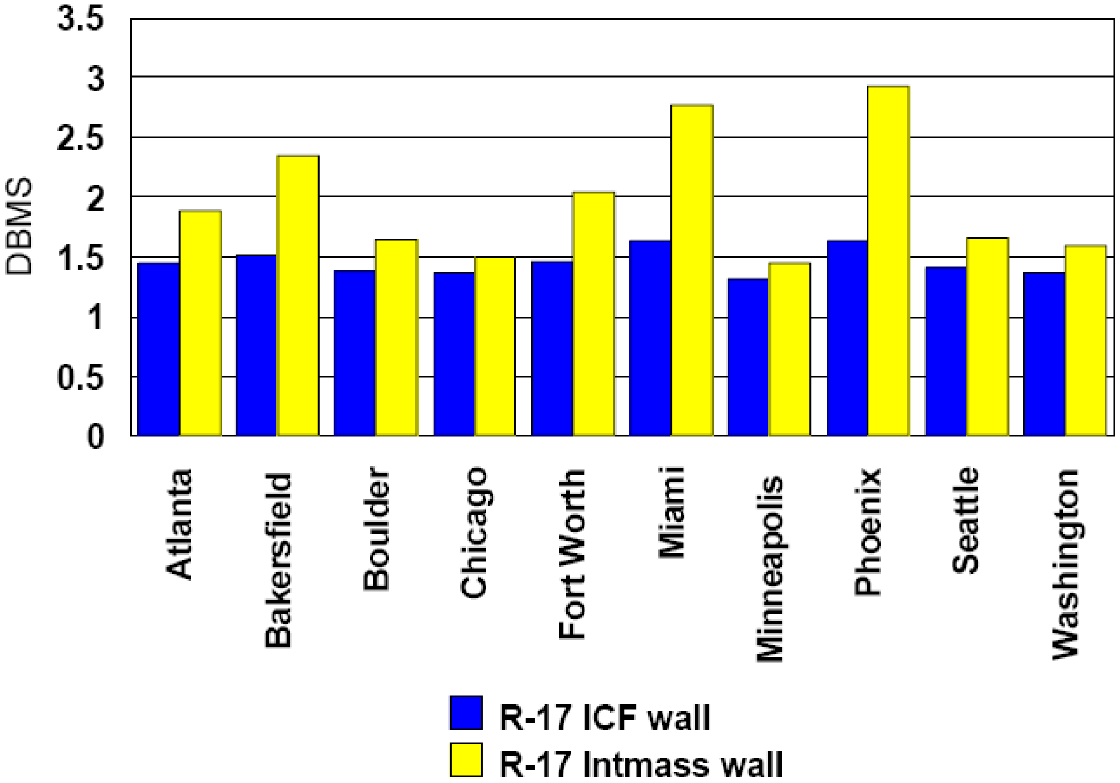

Fig.5. DBMS values for two massive wall systems for ten U.S. climates and 1540 ft_2 one-story rancher.

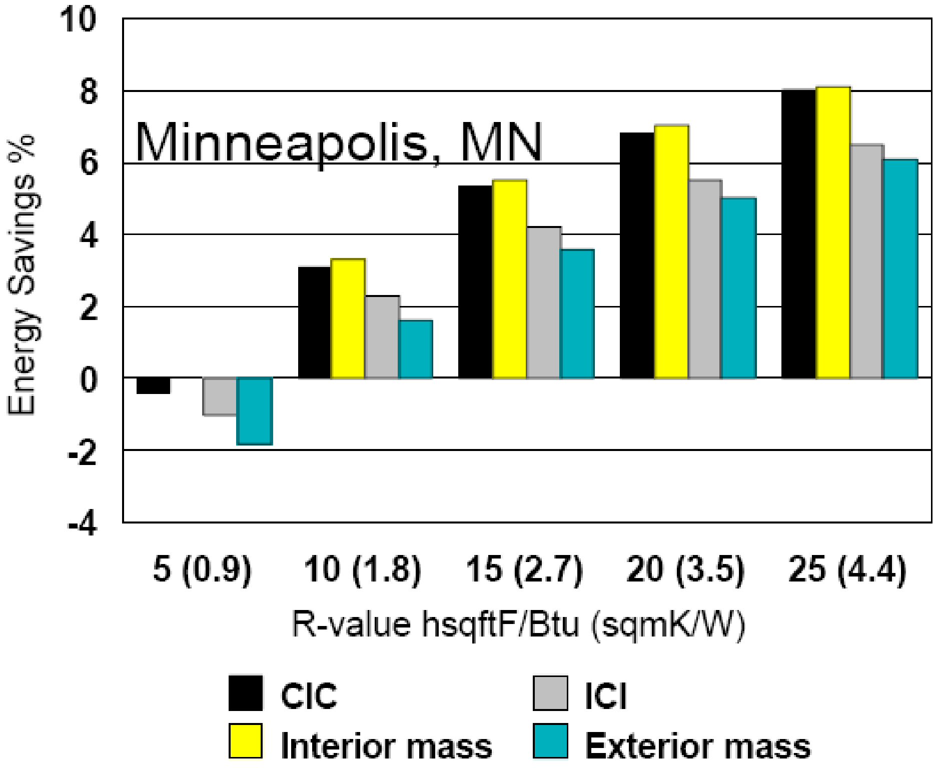

Fig.6. A portion of the whole building energy which can be saved in Minneapolis by the replacement of conventional wood frame walls by massive walls.

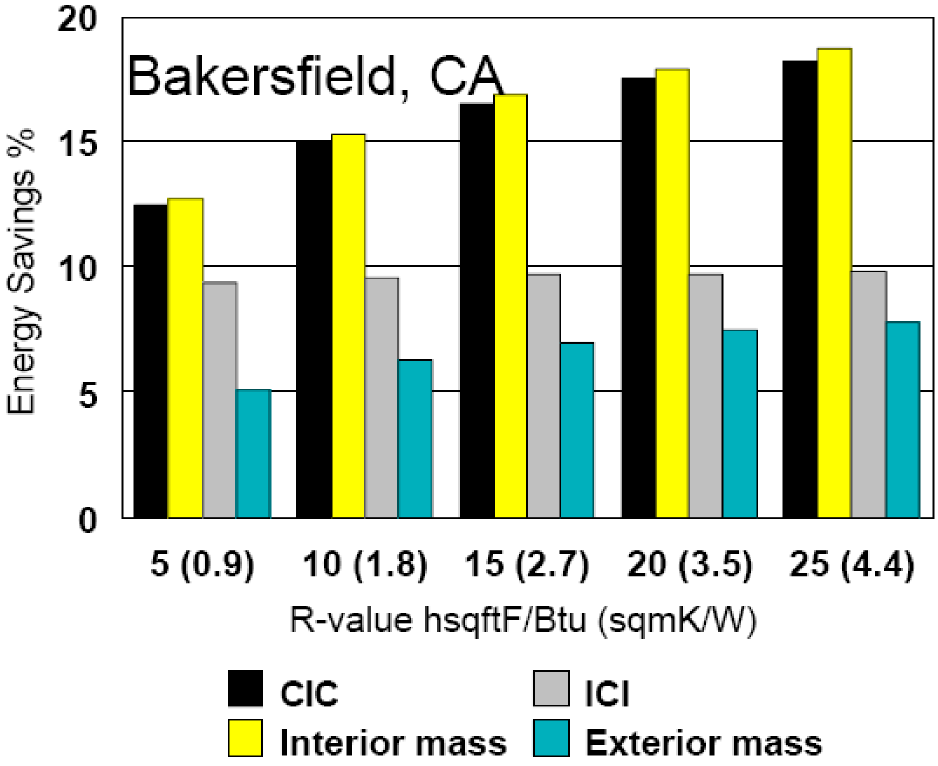

Fig.7. A portion of the whole building energy which can be saved in Bakersfield by the replacement of conventional wood frame walls by massive walls.

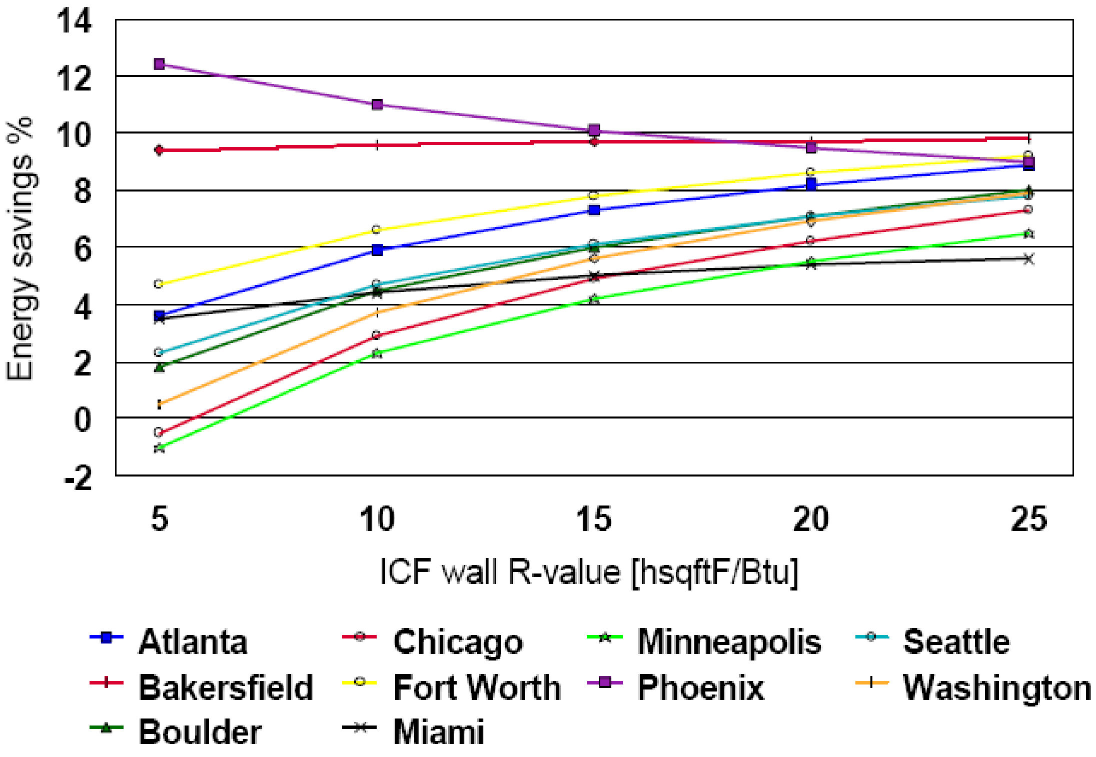

Fig.8. A potential whole building energy which can be saved in ten U.S. locations by the replacement of conventional wood frame walls by ICF walls.