Use of Thermal Inertia for Reduction of HVAC Energy Consumption in Cooling Dominated and Mixed Climates

Jan Kośny,* Elizabeth Kossecka,** Ali Fallahi* and David Yarbrough***

*Fraunhofer CSE, Boston, MA, USA

**Polish Academy Sciences, Warsaw, Poland

***R&D Services, Inc., Cookeville, TN, USA

ABSTRACT

This paper discusses potential ways to improve the thermal design of thermal envelopes in residential and commercial buildings to minimize the cooling energy consumption in cooling-dominated and mixed climates. This paper cites a number of field demonstration projects where both conventional thermal mass and Phase Change Materials (PCMs) were successfully used in the whole building scale. Dynamic thermal characteristics of various configurations of thermal insulation, massive structural components, and blends of phase change materials (PCMs) with insulations are analyzed. A series of whole building energy simulations are used in this work to analyze the dynamic response of these thermal systems. Conventional assemblies using concrete-foam sandwiches were utilized as an illustration of massive wall applications. Energy performance of PCM applications was demonstrated with examples of attic-floor applications. The work presented here confirms that interior facing location of the thermally massive building components is most beneficial from the perspective of energy savings.

INTRODUCTION

In buildings, the annual energy demand for space heating and cooling is very often affected by dynamic thermal characteristics of the building fabric. Building thermal stability is understood as the ability to hold the internal temperature within a certain interval under both external and internal dynamic thermal loads. This may happen either with or without some energy supply from an external source. Most often building thermal stability depends on the dynamic thermal responses of the exterior envelope components, internal partitions, ceilings, and floors to external and internal temperature variations.

In a conventional building assembly, dynamic response is determined by the thermal properties of materials, the mass of materials used, and their specific arrangement within the structure~~s~~. From ~~that~~ this perspective, it is very important to optimize the mass and insulation distribution of interior building components. Past performance comparisons of massive building with the same R-value, demonstrated that the superior thermal performance can be realized for specific distributions of thermal mass and insulation – Kośny et al. [1998], Kossecka and Kośny [2002]. In the case of wall assemblies, results of whole building energy simulations lead to the conclusion that the material configuration of the exterior wall can significantly affect the annual thermal performance of the whole building; however, this effect depends on the type of climate. Walls with massive internal layers showed the best thermal performance for different climatic zones having minimum annual heating and cooling energy demand.

Bulk thermal insulation is one of the best-known ways of improving thermal performance of the building envelopes. In traditional simplified understanding, the thermal performance of insulation is directly proportional to the insulation thickness, when isolating the interior of the building from the exterior environment. Thermal efficiency of using thermal insulation in building envelopes was previously analyzed by Wilkes et al. [1991], Parker and Sherwin [1998], Miller and Kośny [2007], and Miller et al. [2007]. However, available results of field testing, energy simulations, and cost analysis demonstrated that conventional thermal insulation, due to relatively high cost and diminishing energy benefits, is not the only system to achieve improved thermal performance – Desjarlais et al. [2001][1], Miller and Kośny [2007], Kośny et al. [2013]. From the whole-system perspective, the impact of thermal insulation thickness on overall building envelope energy efficiency is complex. Thermal analysis becomes more difficult when adding the effects of framing (caused by structural members), local thermal bridging (caused by imperfections in insulation installation), and air leakage. In addition, in heating dominated climates, during the winter time, thermal performance of some fiber insulations can be compromised by internal convection – Wilkes et al. [1991].

The addition of PCM to insulation is a promising thermal performance enhancement method. PCMs are substances with a high heat of phase transition and melt or solidify in a certain temperature range. This high heat outcome gives PCMs the capability of storing and releasing large amounts of energy. In PCMs, energy is absorbed or released when the material changes phase from solid-to-liquid and vice versa. PCMs may reduce the overall heat flows across attic insulation and shift thermal peak-hour loads. In 2002, a research project sponsored by the U.S. Department of Energy was initiated to work on thermal insulations blended with microencapsulated PCMs – see Kośny et al. [2006, 2007]. These PCM–insulation mixtures function as lightweight thermal mass components. PCMs enhanced materials are expected to contribute to reduce energy consumption for space conditioning and reshape peak-hour loads.

New applications of PCMs in the design of building components require careful selection of materials, identification of PCM location, bounding thermal resistances, and specification of the amount of PCM to be used. Concentrated PCM applications (like, for example, gypsum boards or arrays of PCM containers) have been tested as a thermal mass component in Northern American buildings for at least 40 years. Most of the published research data has demonstrated that PCMs can notably enhance energy performance of walls, roofs and attics. Numerous research studies - Salyer and Sircar [1989], Feustel [1995], Kissock et al. [1998], Schossig et al. [2004], Zhang et al. [2005], Shilei et al. [2007], Muruganantham et al. [2010] demonstrated that localized PCMs could generate heating and cooling energy savings of up to 25% in well-insulated residential buildings in the southern United States and worldwide. In addition, in 2012, an ORNL research team performed numerical analysis of the thermal performance of different configurations of layered wall-cavity insulation containing microencapsulated PCM - Childs and Stovall [2012].

EXAMPLES OF EXPERIMENTAL ENERGY STUDIES PERFORMED ON MASSIVE RESIDENTIAL BUILDINGS

In this section, a selection of historic and current field experiments are discussed. 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 2.6 by 1.9 by 2.9 m insulated lightweight containers - Balcomb et al. [1978]. The only thermal mass provided was by the tested building envelope components. Several thermal storage materials such as concrete blocks, solid concrete walls, and water tanks were tested as a part of this research. However, Los Alamos researchers also studied the energy performance of inorganic phase change materials ~~as~~ for energy storage. The results from this research demonstrated that passive solar systems had significant potential for reducing energy consumption in residential buildings. The results were published in the Passive Solar Handbook - Balcomb et al. [1983] and Passive Solar Construction Handbook – Crosbie [1997], which have been widely used as a reference for the design~~ing~~ of passive solar houses.

Other experiments focused on more conventional applications. Field studies demonstrated the potential for 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 light-weight wall components. Improved performance resulted because the thermal mass encapsulated in the walls reduced temperature swings and absorbed energy surpluses from both solar gains and heat produced by internal energy sources such as lighting, computers, and other appliances.

In June 1982, the Oak Ridge National Laboratory (ORNL) hosted a Building Thermal Mass Seminar – see Courville and 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

[1] http://web.ornl.gov/sci/roofs+walls/PowerPoint/HabitatTVIII.pdf

Standards and Technology (NIST), A.E. Fiorato and M.G. Van Geem 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 – see Kusuda [1977], Zarr [2001], Van Geem et al. [1982], and Shipp [1983]. In addition, almost three 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 - see Burch et al. [1984a, b, c], Robertson and Christian [1985], and Christian [1985]. 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.

Doug Burch built four one-room test huts 6 by 6 m at 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 with the same thermostat settings. 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 as well. The net effect of thermal mass in buildings was believed to cause the average indoor temperature and difference across the building envelope to be maintained at an elevated level. It was observed that, night temperature setback caused the envelope heat-losses rate to be higher in massive buildings. 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~~ to be only 0.3%.

Robertson and Christian investigated eight one-room test buildings 6 by 6 m 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 were 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_{SI}-2.3vs R_{SI}-0.3 to R_{SI}-0.9 for adobe, concrete masonry, and log walls) – Robertson and Christian [1985]. This gives completely different meaning to the 5% energy savings that were reported.

During three years of 1982 -84, Jeff Christian of ORNL monitored an occupied 372 m^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 whole building energy 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 – Christian [1985].

In 1999, a field investigation on thermal mass effect in residential buildings was performed by the NAHB Research Center - see NAHB RC [1999]. NAHB RC evaluated three side-by-side homes 102 m^2 of floor area to compare the energy performance of Insulated Concrete Form (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 experimental evidence of the superior energy performance of buildings constructed using massive wall materials. About 20% lower energy consumption was recorded for the ICF house, when compared to the conventional wood-framed house. In the final report, NHAB researches concluded that this difference was caused by the R_{SI}-1.2 difference in wall R-values (ICF wall R-value was about R_{SI}-3.5, conventional 2 by 4 wood stud wall R-value was about R_{SI}-2.3). However, simulation data developed by ORNL for a similar 121m^2 one story house suggests that for the same climate a difference between R_{SI}-3.5and R_{SI}-2.3 should yield a maximum 8 to 9% difference in annual whole building energy consumption – Kośny et al. [2001]. This suggests that most likely thermal mass related energy savings during the NAHB ICF study were in the neighborhood of 11%.

A field investigation of the thermal mass effect in residential buildings was performed by Petrie and Kośny with support from the Insulated Concrete Forms Association and the local Habitat for Humanity - Petrie et al. [2003]. The goal was to evaluate the relative energy performance of insulated concrete form (ICF) wall systems. A major task of the project was to field monitor the energy efficiency of a typical ICF residential building side-by-side with another house that has traditional 2 by 4 in. wood-framed walls installed on concrete masonry unit foundations (see Figure 1). The interior floor space and floor plans were identical as well the ceilings, attics, and floor construction, heating/cooling system, and ductwork for the single-story, 111 m^2 houses. The field monitoring of the houses began in mid-June of 2000 and continued for one year, during which time the tested houses remained unoccupied with the heating/cooling systems operated on identical schedules. This allowed a strong experimental basis for the differences in energy consumption due to the differing outside wall constructions. Detailed instrumentation and monitoring were very important during this project because, the tested walls were differed in construction, amount of thermal mass and thermal resistance. Blower-door tests showed that the ICF house was about 10% more airtight than the conventional wood-framed house. Air leakage in both houses was less than anticipated based on literature values for conventional construction. The total energy consumption for about a year of monitoring showed that the ICF house used 7.5% less energy than the conventional house for no occupants and identical operation of space conditioning systems in the test houses.

Figure 1. ORNL/Habitat test houses – during construction (left) and fully completed (right) – source: ORNL

EXAMPLES OF SUCCESSFUL FULL-SCALE APPLICATIONS OF PCM IN BUILDING FABRIC COMPONENTS

Ongoing technological improvements suggest that future residential and commercial buildings will soon be routinely constructed to achieve super-low heating and cooling loads. The use of novel building materials containing active thermal components (e.g., PCM, subventing, radiant barriers, and integrated hydronic systems) would be an ultimate step in achieving significant heating and cooling energy savings. The key benefit of PCM-enhanced materials is that they afford structures improved thermal storage capabilities with minimal changes to the existing building design - Sharma [2013]. The main methods for incorporating PCM into building materials include the use of gypsum plaster boards and other structural boards, blending PCM with thermal insulations, and by macro-packaging. The thermal energy storage property of PCM is based on its capability of latent heat storage, given that large amounts of energy can be stored in a small volume. Therefore, the material containing PCM can absorb and release heat more effectively than conventional building materials. However, the selection of the PCM locations, PCM transition temperature range, and the amount of PCM used are essential for effective and durable use of the PCM- enhanced technologies, considering ~~a~~ the relatively long lifespan of building envelopes.

That is why, whole building testing is critical for full performance analysis of many building envelope designs that include PCM. There is a large number of whole building demonstrations in the area of PCM-enhanced building envelopes worldwide. The following section contains a selection of projects from different geographic regions. Most of these projects use either PCM-enhanced wall boards, internal plasters containing PCM, or ceiling panels with PCM.

BASF Three-Liter PCM House – Ludwigshafen, Germany:

Figure 2. The Three-Liter BASF house - Ludwigshafen, Germany – source BASF.

The three-liter house project was launched in 2001 in Ludwigshafen, Germany as a housing unit for BASF employees . It maintains comfortable interior temperatures with only three liters of heating fuel consumption per m^2 per year, utilizing energy efficient construction technologies, highly efficient insulation materials, and a fuel-cell system. The main project focus was whole-building energy retrofit of the building constructed during the 1950s and conversion into a low-energy multifamily house shown in Figure 2. Initially, the main project goal was to lower the annual heating oil consumption to seven liters of heating oil per square meter per year. In practice this energy savings target was exceeded by the application of high R-value exterior opacified foam sheathing, installation of triple-glazed windows, passive solar heating from large newly glazed sunspaces, a controlled ventilation system with 85% thermal recovery, efficient heat and electricity generation by a new miniature power plant in the basement, and PCM-enhanced gypsum boards or internal plasters. Three-year long energy monitoring demonstrated an annual average consumption in the three-liter house of 2.6 liters of heating oil per square meter. The three-liter house has since attracted considerable attention worldwide.

BASF House - Nottingham, England:

The BASF House, located on the university campus in Nottingham, England was built in 2008 with a UK's first-time home buyer's budget in mind. The BASF House is intended to demonstrate performance of new building materials and systems in full-scale field conditions and to showcase modern innovations and system integration. Life-time cost and energy use analyses were performed in order to select building materials and to balance the first cost of the building with the requirement to make the house affordable to a first-time buyer. The use of alternative construction methods allowed reduction of cost, construction time, and eliminated a need for expensive skilled labor. The house was designed using PassivHaus Standard[2] to have near-zero carbon emissions, relying heavily on features such as passive solar energy design, a ground-air heat exchanger and a rainwater collection tank. The BASF house is part of the University of Nottingham's "Creative Energy Homes Project." It is a unique showcase of innovative state-of-the-art energy efficient home of the future made with today's materials.

The BASF House is a 82 m^2 single-family home which can be extended to a row of terraces on demand. It has been inhabited by University of Nottingham's students and faculty since 2008. A low carbon emissions target was set for the house. The house complies with the PassivHaus Standard requirement of energy consumption of 15 kWh/m^2. Actual measured energy consumption is 12.5 kWh/m^2/year, including hot water. The BASF House can be called a 1.5 liter house - an average annual consumption of 1.5 liter of heating oil equivalent per square meter per year.

A combination of insulation materials and products has been used on this project to demonstrate their potential for an application in affordable low-energy buildings. In order to minimize energy losses and infiltration through an opaque building envelope, structural insulated panels (SIPs) with closed-cell polyurethane foam core and insulated concrete forms (ICFs) were selected for the first floor and ground floor exterior walls, respectively. Similarly SIPs were used for

[2] http://www.passivhaus.org.uk/standard.jsp?id=122

construction of the roof. Thermal insulation on the ground floor was provided for by the use of ICFs made of opacified expanded polystyrene foam produced by BASF. ICF blocks are filled with a light-weight concrete mixture, which generates tiny air-cells during the first hours of concrete setting, resulting in improved concrete thermal resistance. All of this helped to achieve an overall RSI-value of about 6.7 m^2·K/W for the walls and roof. In addition, the roof was covered with metal panels containing a reflective coating to reduce solar-generated cooling loads during the summer time.

The BASF House can naturally maintain a comfortable temperature range for indoor space by combining solar gains, natural ventilation and thermal mass provided by PCM- enhanced gypsum boards. PCM-wall boards are produced with use of microencapsulated PCM manufactured by BASF. Melting temperature is 23 °C and phase change enthalpy of 110 kJ/kg. As shown in Figure 3, there is a south-oriented, fully-glazed, adjustable two-layer sunspace. The sun warms the air in the sunspace and acts as the primary heating source for the house. Windows between the solar area and the main part of the house can then be opened to enable the warm air to flow around the rest of the house. An affordable ground- air heat and cooling exchange system and a biomass boiler are used to provide an effective, affordable heat and cooling for the house.

Figure 3. The BASF House, located on the University of Nottingham campus, England – source BASF.

Kingspan Lighthouse - Watford, Hertfordshire, UK:

The Kingspan Lighthouse was built in 2007, at Building Research Establishment Ltd. (BRE) Innovation Park in Watford, Hertfordshire, UK. BRE's Innovation Park is an urban field test facility with selection of experimental buildings shown in Figure 4. It is ~~a~~ home to some of the UK's most sustainable buildings, landscape designs and hundreds of innovative building materials and technologies. Designed by Sheppard Robson, the Kingspan Lighthouse is a 100 m^2 single family home built by Kingspan Off-Site and Arup. It is the first home to meet Level-6 guidelines of the UK Code for Sustainable Homes (net zero carbon emission home).

As such, the Kingspan Lighthouse serves as a demonstration and prototype house for the standard which will become mandatory for all UK residential buildings in 2016. High-performance building materials were used for construction of the Lighthouse with low U-values for all building shell components - 0.07 W/m^2·K (R_{SI} – 14.3 m^2·K/W) for the windows, 0.11 W/m^2·K for the opaque envelopes, with air-tightness of 1.0 m^3/h·m^2 at 50 Pa. The walls and roof are made of two layers of structural insulated panels. The windows are wood-frame gas-filled with triple glazing. The home was built using recycled and reclaimed materials when possible. In addition, the ratio of glazing to the wall area in the Lighthouse is 18% as opposed to 25-30% which is common in UK houses.

The Lighthouse utilizes a variety of low and high-technologies coupled with a strong integrated design approach. In order to increase the thermal inertia of house and to achieve a low-energy and zero carbon emission status, PCM-enhanced wall boards using microencapsulated PCM manufactured by BASF, have been included in suspended ceilings and south facing walls. Melting temperature of microencapsulated PCM used in the Lighthouse was 23 °C and phase transition enthalpy - 110 kJ/kg. PCM-enhanced ceiling and southern wall surfaces help absorb daytime heat and then give it up to cooler night-time purge ventilation.

Figure 4. The Kingspan Lighthouse - Building Research Establishment Ltd. (BRE) Innovation Park in Watford, Hertfordshire, UK. - source Kingspan.

Crossway Eco-House - Staplehurst in Kent, UK

Located near Staplehurst in Kent, England, the Crossway Eco-House was the first in the UK to use PVThermal systems and has officially been named as Kent’s first Zero-Carbon house. Since 2008, it is a family home of its visionary architect, Richard Hawkes. One of several innovative energy-saving features in the project was the installation of shape stabilized PCM boards manufactured by DuPont. For over two years, about 127 m^2 of PCM boards with melting point 21.7 °C have been tested in the Crossway House. The monitoring analysis performed by Cambridge University, UK shows that an application of PCM boards helped in reduction of summer peak temperatures by on average 4 °C .
This building is probably the world's largest vaulted wood-brick arch incorporating 26,000 handmade red-brick tiles, fabricated from local clay within four miles of the site. It spans 20 m and is 9 m high. The Arch's thermal mass provides thermal inertia during summer months and the clay's hygroscopic properties help maintain a healthy internal environment. As shown in Figure 5, the 12 mm thick tiles are bonded together with a mortar without formwork.

Figure 5. Construction details of the Crossway House - Staplehurst in Kent, UK

The Crossway House hosts an experimental 580 liter PCM heat-storage unit linked to the UK's first PV-Thermal system. Heat storage helps buffer the solar-generated thermal energy during ~~periods of~~ cloudy days. Crossway’s annual PV electricity generation is about 5,500 kWh. At the same time 1,800 kWh of solar thermal energy is produced each year by the integrated solar-thermal part of the system. The PV-Thermal panels are supported by an 11 kW wood-pellet boiler. Four years of monitoring by the University of Cambridge have shown Crossway's Primary Energy consumption to be 54.59 kWh/m^2 per year with annual heating load of 14.82 kWh/m^2.

Academic Office Building, Charles Sturt University – Victoria, New South Wales, Australia

Charles Sturt University's (CSU) located in Victoria is a developing, dynamic model of how communities can address environmental concerns and sustainable living in inland Australia. The $4.2 mln. Academic Office Building at CSU Thurgoona Campus is the first building which was constructed in 2008 as a part of the Albury-Wodonga Campus relocation program.

It was designed by Wayne McPhee Architects and constructed by Zauner Constructions. Architects and CSU worked with BASF to develop a new approach for achieving super low energy office buildings, with the use of microencapsulated PCM in floors and through an application of the PCM-enhanced gypsum boards. PCM ceiling boards with melting point of 23^{o}C have been used on the first and second floor ceilings. The PCM microcapsules have been embedded in the concrete floor throughout the building. Both PCM applications effectively doubled the buildings thermal storage capacity. Operating temperatures inside the building are between 21 – 23^{o}C in winter and 23 – 26^{o}C in summer. It is good to mention that the use of microencapsulated PCM in the concrete floor in 2008 was one of the first world's applications of that type! This building had also a first in Australia as an office building application of PCM in ceilings.

Both of the above PCM applications were integrated with the radiant space conditioning system. Hydronic tubing that has been imbedded into the concrete slabs ~~is~~ freezes PCM during summer nights using off-peak power for release during the warm days. During the warm days the PCM's role is to stabilize the interior space temperature. PCM-enhanced concrete floors and ceilings act as oversized radiators to cool or heat the internal occupied office spaces. During a summer's day, as the ambient air temperature increases, the temperature of the building components remains relatively constant at 23^{o}C due to PCM's heat-storage capacity. No refrigerative cooling is used. An integrated evaporative cooling system chills the water for the hydronic system; working mostly during the night to maximize the efficiency of the system.

This 880 m^2 building was constructed using light-weight steel framing technology. That is why the low-mass building structure, thermal mass of massive concrete slabs and precast walls were integrated together with the PCM's heat storage capacity into a well-insulated building fabric, minimizing fluctuations of temperature and humidity – see Figure 6. The building design team paid a lot of attention to reduction of energy losses through the building envelope. As a result the roof RSI was 5.6 m²·K/W and wall RSI was 3.6 m²·K/W. Natural ventilation was achieved through the use of windows to control heat and air flow. Window sizes and position have been optimized by daylighting, thermal performance and the creation of a natural, healthy and yet productive office environment.

Figure 6. Academic Office Building at CSU Thurgoona Campus, Victoria, New South Wales, Australia – Source - Charles Sturt University.

A network of temperature sensors has been installed in the strategic positions in order to monitor actual building performance and long-term behavior of the various materials and systems throughout the structure. In 2009, the Academic Office Building at the Charles Sturt University's (CSU) Thurgoona site has been awarded six green stars and ‘world leader’ status for its environmentally sustainable features by the Green Building Council Australia (GBCA). According to GBCA, the principles used in buildings at Thurgoona demonstrate a unique environmentally sensitive process that spans from site planning to selection of non-conventional materials and applications. One of the innovative aspects of the building that received special attention from GBCA was reduction of carbon dioxide production and energy consumption by about 65 %, compared to similar conventional office buildings in Australia. The University’s commitment to the environment can be seen in a wide range of design features on the campus including existing buildings made from rammed earth and recycled building materials, rehabilitated creeks and wetlands, dry-composting toilets, ‘grey-water’ recycling wetlands, wind mills and solar collectors.

SARL Busipolis Company Building - Metz, France

Since construction in 2010, the SARL Busipolis company building, in Metz, France has received several awards for its excellent energy performance. This 1950 m^2 office building has a total annual energy consumption of 38 kwh/m^2 . One of the awards was from the PREBAT competition for the Lorraine region and the other from the “Lorraine Qualité Environnementale”. This contemporary-architecture building (shown in Figure 7) with steel-and-glass structure incorporates more that 500 m^2 of shape-stabilized PCM boards with melting point 21.7 °C . In light-weight structures like this, if PCM is not used, internal temperature fluctuations are much higher than in massive buildings and typically they have to be taken care of by increased use of space-conditioning systems, which usually results in high energy consumption and high operational costs and CO_2 emissions. The PCM used in the Busipolis company building was ~~been~~ installed behind the gypsum wallboards and within the suspended ceilings in order to provide the required thermal inertia and increase the comfort in the building. The product is manufactured by DuPont and has a latent heat storage capacity of 515 kJ/m^2, for phase change temperature range between 18°C and 24°C. A special ventilation system is used to help with discharging the PCM panels.

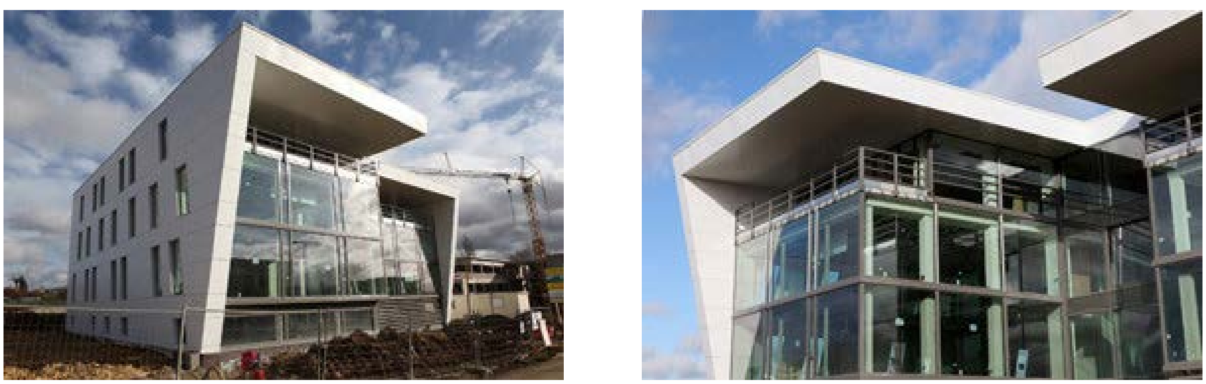

Figure 7. SARL Busipolis company building constructed in 2010, in Metz, France

Oak Ridge PCM House – Oak Ridge, TN, USA:

Several high-performance building envelopes have been studied and monitored in actual homes as part of a collaborative research project sponsored by the U.S. Department of Energy and the Tennessee Valley Authority. This project is a partnership between Oak Ridge National Laboratory and building materials and construction companies to demonstrate and develop new energy efficient technologies for U.S. homes. Four homes were constructed in 2009/10 using four different envelope systems - Miller et al. [2010]. One of the test houses was designed to demonstrate thermal performance of high R-value walls and attics containing PCM-enhanced thermal insulation. The PCM house is two-story with total floor area of 253 m^2 - Figure 8. The building is equipped with over 250 sensors and an on-site weather station. Air tightness of the building was 3.5 air changes per hour at 50 Pa. Windows in the PCM house are argon gas-filled triple pane vinyl units that have a U-value of 1.25 W/m·K and a solar heat gain coefficient of 0.17. The inside surfaces of exterior and middle panes are low emittance.

The house has a conventionally framed attic with dynamic PV-powered ventilation and PCM-enhanced insulation installed on the attic floor and attic gable walls. The attic floor is insulated with a 10.2 cm thick layer of PCM-enhanced cellulose insulation on top of 25.4 cm of regular cellulose insulation. Approximately 9 cm of PCM-enhanced cellulose insulation was installed on the attic gable walls and all internal partitions. An infrared reflective painted metal shake was used as the roofing material with solar reflectance and thermal emittance of 0.34 and 0.85, respectively. A tapered EPS insulation was inserted under the metal shakes to reduce roof-generated peak-hour thermal loads. Reflective OSB boards were used on the roof deck with the low-e aluminum foil surface ~~is~~ facing the attic space. Solar powered gable ventilators are installed on the attic gables to reduce attic-generated cooling loads.

(a) Framing work (b) PCM house during construction (c) Completed PCM house

Figure 8. PCM test house – PCM-enhanced double wall system and attic designed by Jan Kośny for the Oak Ridge field experiment (Miller et al. 2010).

Figures 8a. and 8b. show the PCM test house during construction, while Figure 8c depicts the completed PCM house. It has double walls filled with PCM-enhanced cellulose insulation. The wall studs are made of laminated 2x4 strand lumber spaced 0.60 m o.c. The studs from one layer of framing are offset by 0.30 m from the other wall's studs. The interior framing is supported on top of the bottom plate that is fastened through floor sheathing and floor truss, while the exterior framing is supported on the sill plate and is fastened to the floor truss. A wide top plate was used to tie the two walls together for lateral strength. It was anticipated that this double wall would function as a composite system. The interior frame acts as the structural wall component responsible for transmitting gravity and lateral force to the foundation. However, since the two double top plates are mechanically connected and wall sheathing is provided in the exterior wall, a portion of lateral load is carried by the exterior walls as well. In double walls thermal bridging at the corners is minimized by applying a double-stud corner design. To allow an application of two different types of blown cellulose insulation, a fiber fabric can be stapled between the two sets of 2x4 studs. The wall interior cavity ~~is~~ was insulated with dense-packed cellulose with 20 wt% micro-encapsulated bio-based PCM was added to the blown cellulose fibers in the exterior framed cavity – Miller et al. [2010]. Since 2002, the ORNL and Fraunhofer CSE research teams have analyzed several configurations of building envelope board products and insulations blended with micro-encapsulated PCMs - Kośny et al. [2006, 2007, 2012, Fallahi et al. [2012], Childs & Stovall [2012], and Shukla et al. [2012].

TrekHaus – Portland, OR, USA:

Low-energy duplexes designed using PassivHaus principles are hardly unique. TrekHaus is a small building successfully completed in 2012 by a design-and-build team headed by architect Robert Hawthorne, of PDX Living, LLC, and builder Bart Bergquist of Willamette Valley Remodeling in Portland, Oregon, USA. The two adjacent homes in this project divide the space under the roof. The unit floor plans are mirror images, each with about 155 m^2. of conditioned space, which includes three bedrooms and two baths, plus a 13 m^2 semi-conditioned workshop **–** as shown in Figure 9.
High-performance building envelope components are used throughout the TrekHaus to reduce winter heat losses and summer cooling loads. Thermal resistance ~~is~~ was RSI-6.7 for the floor slab insulation, RSI-8.6 for the exterior walls, and R_{SI}-14.6 for the roof. Airtightness came in at 0.34 air changes per hour at 50 Pascals pressure difference. Triple-glazed Thermotech fiberglass-framed windows ~~are~~ were used throughout. Mechanical systems in the TrekHaus units include a heat-pump water heater, a minisplit heat-pump for space conditioning, and a heat-recovery ventilation system. The TrekHaus ~~is~~ was expected to operate at net zero energy with three people in each unit. The building ~~is~~ was designed with

two independent 4.14 kW roof-mounted photovoltaic systems, which were monitored to document performance. Another energy savings component of the building is BioPCM - a soy-based phase-change material. This PCM product is manufactured by Phase Change Energy Solutions located in Asheboro, North Carolina, USA. Arrays of BioPCM pouches packed in plastic foil were installed behind the drywall of one unit's interior walls and second-floor ceiling. Construction costs, excluding the land and PV system but including everything else, came to $1,500 per m^2. In order to monitor its energy performance the TrekHaus building is equipped with a system of sensors and data acquisition~~s~~ systems installed by the Green Building Research Laboratory, of Portland State University. The overall energy performance of the building, the performance of the building envelope and the building's mechanical systems will be monitored during coming years. In addition the effects of occupant behavior on the building's performance will be documented and analyzed.

Figure 9. Construction details of the TrekHaus duplex building constructed in 2012 in Portland Oregon, USA – source: PDX Living, LLC.

CONFIGURATION OF THERMAL MASS AND INSULATION ARE IMPORTANT FOR ENERGY SAVINGS

In massive buildings, the configuration of wall insulation and thermal mass plays an important role in whole building energy performance. Work performed by the authors demonstrated that selection of building envelope materials may considerably affect whole building energy performance – Kośny et al. [2001]. In that light, the most important decisions affecting building energy performance have to be made during the designing stage. Due to different arrangements of thermally massive and insulating layers, building envelope assemblies may demonstrate a wide range of dynamic thermal properties.

Analytical solution for the response of a simple building exposed to periodic temperature conditions indicates that the most effective wall assemblies are walls where thermal mass is in good contact with the interior of the building. These walls have high values of the internal surface structure factor φ_{ii} (see Appendix A), and the internal admittance heat flux response amplitude. The thermal structure of a wall is understood as a distribution of thermal resistance and overall heat capacity. Formal relationships, which describe in a quantitative way the effect of structure on dynamic thermal behavior of walls, follow from the integral formulae for the heat flow across the surfaces of a wall in a finite time interval – Kossecka and Kośny [1998, 2002]. A high value of the internal admittance response amplitude definitely improves the thermal stability of a building, expressed as the amplitude of internal temperature periodic oscillations, in response to the exterior temperature oscillations.

Whole building energy modeling with use of EnergyPLus, ESP-r and DOE-2 was performed to predict annual heating and cooling energy demands for different types of residential and commercial buildings – Petrie et al. [2003], Kośny et al. [2001], [2013], Kossecka and Kośny et al. [2003]. Results of the computer simulation lead to the conclusion that walls with massive internal layers, with high values of the structure factor, show the best thermal performance for all U.S. climatic zones with low annual heating and cooling energy demand. Figure 10 depicts a summary of energy modeling results performed for a small single story rancher (similar to the houses shown in Figure 1) for two examples of significantly different cooling and heating dominated climates. Whole building energy performances of four different massive wall configurations of the same R-value were compared in this modeling exercise against the performance of the conventional wood framed with 2x4 stud wall. It can be observed that in the case of massive walls, material configuration can significantly affect annual thermal performance of the whole building. Performance comparisons made with the lightweight wood-framed wall as a baseline, showed on average, that there is a potential to save about 11% of heating and cooling energy in U.S. residential buildings just by application of massive walls. In addition, higher comparative savings were observed for cooling dominated climate of Bakersfield, CA and for high R-value assemblies. A proper optimization of the mass and insulation distribution in these walls may additionally enhance these potential savings – see Kossecka and Kośny [2002].

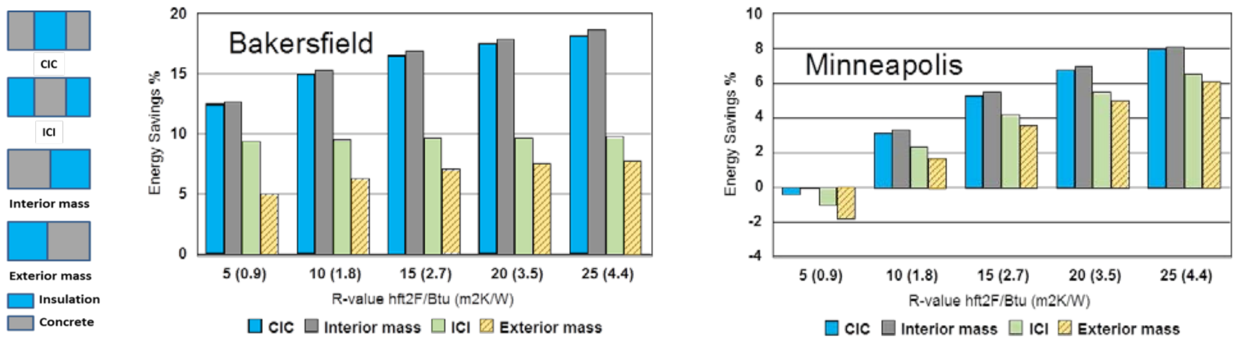

Figure 10. Potential whole building energy savings computed for four different massive wall configurations. Energy savings were computed using as a baseline the energy consumption of an identical house with typical 2x4 wood-framed walls of the same R-value.

In light-weight buildings, latent heat storage can be used as a supplement to thermally massive components such as stone, brick or concrete. In order to demonstrate an energy impact of material configuration in PCM-enhanced building components, a series of whole-building energy simulations were performed. This analysis was focused on energy savings potential ~~in~~ for the case of PCM-enhanced attic assemblies. Energy consumption rates with the application of conventional attic insulation were compared against different configurations of PCM-insulation blends and concentrated PCM applications. For this task ESP-r, a whole building energy simulation software, was used. First, the program was validated against the field test data – Fallahi et al. [2012]. An important factor to predict the behavior of PCM in numerical models is the calculation of corresponding thermal properties at each time step (Cp –specific heat and H – phase change enthalpy). The specific heat of PCMs is a strongly non-linear function with respect to temperature during a phase change process. Because of the highly temperature dependent specific heat of PCMs, it becomes critical to input accurate temperature-dependent values in the numerical simulations. In addition to temperature dependency, specific heat curves may be dependent on the direction of the of phase change process – Mehling and Cabeza [2008], IEA Annex 23 [2011]. In other words, it is possible that measured specific heat as function of temperature may have a different profile for melting and freezing (crystallization) processes. The difference in the peaks of specific heat curves for melting and freezing cycles is defined as the sub-cooling effect. A PCM exhibiting sub-cooling effects will have crystallization temperature below the normal melting temperature.

In most paraffinic PCMs commonly used today, the sub-cooling temperature range is small and negligible. But in case of a large number of bio-based and inorganic PCMs, ignoring the sub-cooling effect leads to major errors in predicting PCM thermal behavior. In such scenarios, it is important to include two separate heat capacity curves representing melting and freezing. ESP-r was chosen in this work because it is one of very few building energy modeling programs that has built-in capability to model the PCM sub-cooling effect.

Effective heat capacity, c_{eff}, for a material which is a blend of insulation or composite with PCM may be expressed as

$$c_{eff} = (1-\alpha)c_{ins} + \alpha c_{effPCM} \ , \qquad (1)$$

where, α denotes the percentage of PCM, c_{ins} the specific heat of insulation or composite without PCM and c_{effPCM} is the effective heat capacity of PCM.

As in earlier described simulations performed on walls, a residential rancher house with PCM-enhanced cellulose ceiling was modeled and the energy savings were compared with a case using loose-fill cellulose insulation. A single-family ranch-style house was simulated for the Phoenix, Arizona climatic conditions, using the ESP-r computer program. ESP-r ~~is~~

has a built-in capability to model two different specific heat profiles (melting and solidification). The dimensions of the modeled house are 16.8 m by 8.4 m by 2.4 m for the conditioned space. The attic height at the ridge is 1.6 m. The house was modeled as two zones representing the conditioned space and the attic space as shown in Figure 11. Outside boundary conditions were specified by ASHRAE IWEC weather files, while the interior conditioned space followed an HVAC set-point temperatures. Simulation details, including material properties, infiltration rate through the walls and the ventilation rate between the attic and the outside are listed in Fallahi et al. [2012].

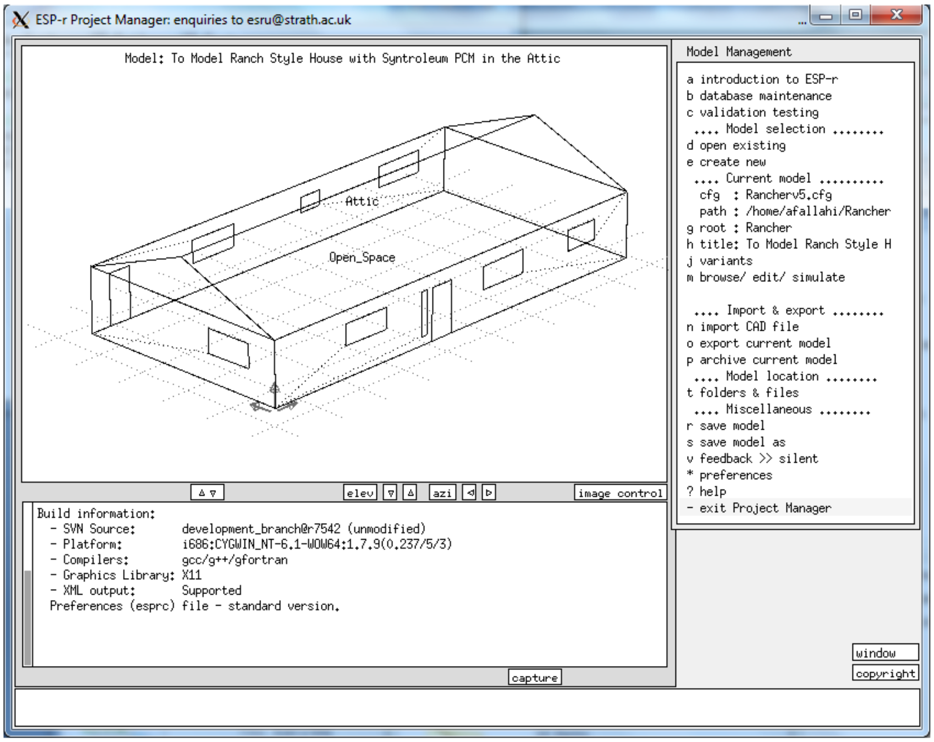

Figure 11: Geometry of the single story rancher used in attic performance analysis.

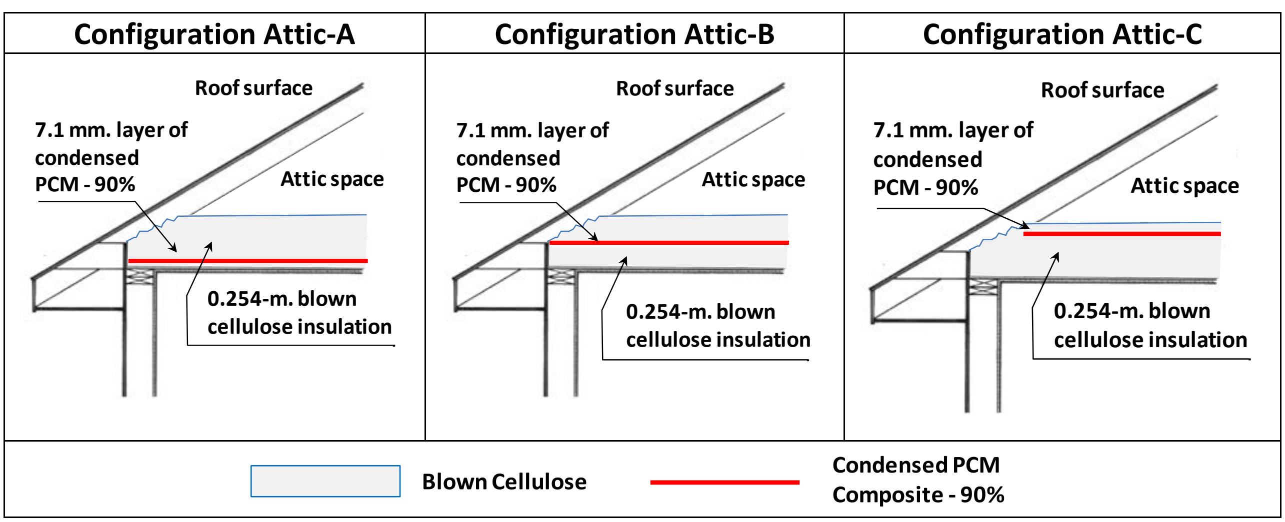

Figure 12: Schematics of three configurations of the condensed PCM application in the attic used in numerical analysis.

As depicted in Figure 12, three different configurations of PCM and thermal insulation were numerically analyzed in order to better understand the impact of the location of concentrated PCM on space conditioning load reductions. Computer generated results were compared against the case of conventional non-PCM insulation. In these comparisons, a 90% concentrated PCM application was considered (90% by weight mix of PCM with the composite carrier). A layer of concentrated PCM was combined with cellulose insulation that had a density of 40 kg/m^3, a conductivity of 0.042 W/m·K and a specific heat of 1380 J/kg·K. Each of material configurations from Figure 12 were simulated for climatic conditions of Phoenix, AZ. The results generated for three cases of concentrated PCM were compared with the base case of non-PCM insulation, and the energy savings are shown in Table 1.

The whole building energy modeling results show that the condensed PCM located on the bottom of the attic cellulose insulation (configuration Attic-A) has the highest potential for thermal load saving of the ~~all~~ three configurations. In this case, the total annual attic-generated loads are reduced by 7.3% compared to the base case house with no PCM in the attic. Configuration Attic-B, where PCM is located in the middle of the attic cellulose insulation, has slightly lower total annual savings of 6.8%. Configuration Attic-C, where condensed PCM is on top of the attic cellulose insulation, shows the lowest total annual savings of only 0.71%.

Table 1. Simulated Annual Energy Load Savings of Condensed PCM Applications for Climate of Phoenix, AZ.

	Configuration Attic-A		***Configuration Attic-B***		***Configuration Attic-C***	
	Heating	***Cooling***	***Heating***	***Cooling***	***Heating***	***Cooling***
Annual Load (kW.hr)	242	15103	277	15137	301	16126
Base Case Annual Load (kW.hr)	328	16217	328	16217	328	16217
Saving	26.2%	6.8%	15.5%	6.6%	8.2%	0.56%
Total Annual Savings	**7.3%**		**6.8%**		**0.71%**	
Time Step	1min		1min		1min	

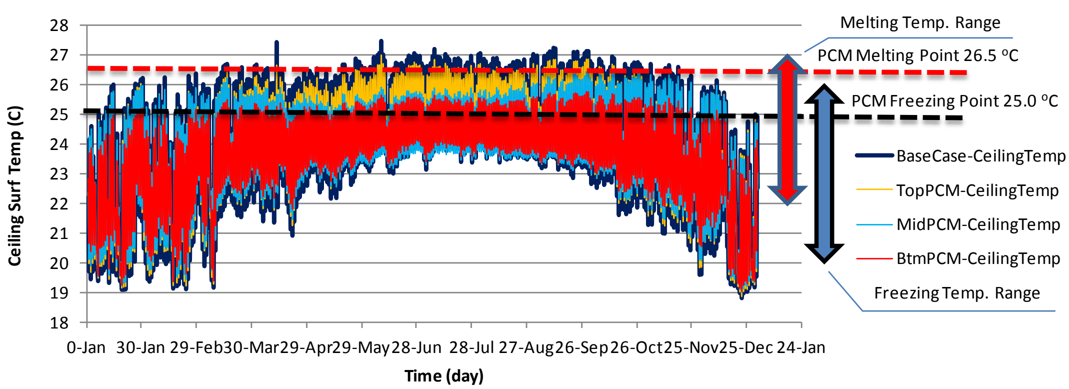

Figure 13. Annual ceiling temperature profiles for three modeled configurations of PCM and a baseline non-PCM attic insulation

A detailed temperature analysis was performed for all three PCM configurations, in order to find the explanation of why the PCM layer located on the top of the attic floor insulation had lowest energy performance, compared to the center and bottom locations. It was found that during almost the entire year in climate of Phoenix, AZ, temperatures on the bottom of the attic floor insulation are within the PCM phase transition range. As shown in Figure 13 for considered type of PCM and for Phoenix, AZ climate, PCM located on the bottom of the attic insulation could daily melt and solidify with exclusion of first six and two last two weeks of the year. Temperatures on the top surface of the attic floor insulation are significantly higher reaching 75.0^{o}C in midsummer. For the climate of Phoenix, AZ, a layer of PCM located on the top surface of the attic insulation could daily melt almost during the entire year. However, this PCM cannot fully solidify between June 01st and September 20th. This is the major reason for lower energy performance of this PCM configuration.

SUMMARY

Thermally massive building envelope and building fabric components can be effectively used to improve the thermal design of thermal envelopes in residential homes and commercial buildings. A number of successful whole building demonstration projects have been discussed, where both conventional thermal mass components as well as PCMs were utilized.

A series of whole building energy simulations with use of EnergyPlus, ESP-r, and DOE-2 was used in this work to analyze the dynamic response of these thermal systems.

Conventional thermal mass was analyzed for wall assemblies using concrete-foam sandwiches. Energy performance of PCM applications was illustrated with examples of attic-floor applications.

Performance comparisons made between light-weight wood-framed walls as a baseline and massive assemblies made of concrete and foam, showed on average, that there is a potential to save about 11% of heating and cooling energy in the U.S. residential buildings just for an application of massive walls. Higher comparative savings reaching 17% were observed for cooling dominated climate and for higher R-value assemblies.

The whole building energy modeling results show that a layer of condensed PCM located on the bottom of the attic cellulose insulation (configuration Attic-A) has the highest potential for thermal load saving of the all three configurations. In this case, the total annual attic-generated loads are reduced by 7.3% compared to the base case house with no PCM in the attic.

The work that has been done demonstrates that interior facing location <not clear wording> of the thermally massive building components is most beneficial from the perspective of energy savings.

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APPENDIX A

Dimensionless quantities φ_{ii}, φ_{ie}, and φ_{ee} are called the thermal structure factors. For plane walls, they are determined directly by the thermal capacity and resistance distribution along thickness. In transitions between two different states of steady-heat flow, they represent fractions of the total variation of heat stored in the wall volume that are transferred across each of its surfaces as a result of ambient temperature variations. Together with the total thermal resistance R_T and total heat capacity C, they constitute basic thermal characteristics of walls; this is also true in the case of three-dimensional heat transfer – see Kossecka [1992], Kossecka and Kośny [2002].

The following identity can be derived for structure factors:

$$\varphi_{ii} + 2\varphi_{ie} + \varphi_{ee} = 1 \ . \tag{A1}$$

Structure factors for a wall composed of n plane homogeneous layers, numbered from 1 to n with layer 1 at the interior surface, are given as follows:

$$\varphi_{ii} = \frac{1}{R_T^2 C} \sum_{m=1}^{n} C_m \left[\frac{R_m^2}{3} + R_m R_{m-e} + R_{m-e}^2 \right] \ , \tag{A2}$$

$$\varphi_{ie} = \frac{1}{R_T^2 C} \sum_{m=1}^{n} C_m \left[-\frac{R_m^2}{3} + \frac{R_m R_T}{2} + R_{i-m} R_{m-e} \right] \ , \tag{A3}$$

$$\varphi_{ee} = \frac{1}{R_T^2 C} \sum_{m=1}^{n} C_m \left[\frac{R_m^2}{3} + R_m R_{i-m} + R_{i-m}^2 \right] \ , \tag{A4}$$

where R_m and C_m denote the thermal resistance and capacity, respectively, of the m-th layer; whereas $R_{i\text{-}m}$ and $R_{m\text{-}e}$ denote the resistance to heat transfer from surfaces of the m-th layer to inner and outer surroundings, respectively.

Structure factor φ_{ii} is comparatively large when most of the total thermal capacity is located near the interior surface $x = 0$ and most of the resistance is located in the outer part of a wall, near the surface $x = L$. The opposite holds for φ_{ee}.