Numerical and Experimental Analysis of Building Envelopes Containing Blown Fiberglass Insulation Thermally Enhanced with Phase Change Material (PCM)

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ABSTRACT: Different types of Phase Change Materials (PCMs) have been tested as dynamic components in buildings for at least 4 decades. Most of historical studies have found that PCMs enhance building energy performance. The PCMs store energy and alter the temperature gradient through the insulated cavity because they remain at a nearly constant temperature during the melting and solidifying stages. The use of organic PCMs to enhance the performance of thermal insulation in the building envelope was studied at the Oak Ridge National Laboratory during 2000–2009. PCMs reduce heat flow across an insulated region by absorbing and desorbing heat (charging and discharging) in response to ambient temperature cycles. The amount of heat that can be stored in PCMs is directly related to the heat of fusion of the material, which is between 116 J/g to 163 J/g (or 50 to 70 Btu/lb) for the most-popular microencapsulated paraffinic PCMs, or fatty acid materials used in this research. This paper presents experimental and numerical results from the long-term thermal performance study focused on blown fiber glass insulation modified with a novel spray-applied microencapsulated PCM. Experimental results are reported for both laboratory-scale and full-size building elements tested in the field. Test work was followed by detailed whole building Energy Plus simulations in order to generate energy performance data for different US climates.

1 INTRODUCTION

During the late 1980s and early 1990s, Oak Ridge National Laboratory (ORNL) tested several configurations of gypsum boards enhanced with phase-change materials (PCMs) [Tomlinson et al. 1992]. In 1994 blends of lightweight aggregates and salt hydrates were analyzed and tested [Petrie et al. 1997]; and in 2002, an ORNL research team started working on fiber insulations blended with microencapsulated PCMs [Kośny et al. 2006 Kośny et al. 2007a, Kośny et al. 2007b, Kossecka and Kośny 2009]. These PCM–insulation mixtures function as lightweight thermal mass components. It is expected that these types of dynamic insulation systems will contribute to the objective of reducing energy use in buildings and to the development of "zero-net-energy" buildings. This is a consequence of this technology's ability to reduce energy consumption for space conditioning and reshape peak-hour loads. Other anticipated advantages of PCMs include improvements towards occupant comfort, compatibility with traditional wood and steel framing technologies, and potential for application in retrofit projects. ORNL research demonstrated that PCMs can be mixed with fiber insulations, incorporated into structural and sheathing materials, or packaged for localized application. Results from a series of small-scale laboratory measurements and field experiments indicate that a new generation of PCM-enhanced fiber insulations could have excellent potential for successful application in U.S. buildings because of their ability to reduce energy consumption for space conditioning and reduce peak loads [Kośny 2008, Kośny et al. 2009, Kośny et al. 2010]. New PCM applications require a careful selection of materials, identification of PCM locations, bounding of thermal resistances, and specification of the amount of PCM to be used. This paper describes the results from small-scale dynamic testing, laboratory-scale, and full-size field testing of building elements using PCM-enhanced blown fiber glass insulation. Experimental work was followed by detailed whole building EnergyPlus simulations in order to generate energy performance data for different US climates.

2 EXPERIMENTAL ANALYSIS

Since 1998, ORNL has been the world's only laboratory performing dynamic hot-box experiments on a daily bases. In this project, a 2.4x2.4-m. (8x8-ft) wood-framed wall containing blown fiber glass insulation combined with microencapsulated PCM was utilized for dynamic hot-box testing. The test wall was constructed with nominal 14-cm. (2x6) studs installed on 40-cm. (16-inch) spacing. Three wall cavities were insulated with conventional blown fiber glass at a density of about 29-kg/m3 (1.8-lb/ft3). The other three wall cavities were insulated with a multilayered fiber glass-PCM mixture.

2.1 *Encouraging results of dynamic hot-box measurements*

The dynamic hot-box experiment was performed using the same testing procedure as in earlier ORNL tests with use of PCM-impregnated foams and blends of blown cellulose insulation with microencapsulated PCM [Kośny 2008, Kossecka and Kośny 2008]. At the beginning of the measurement, temperatures were stabilized at about 18.3 ºC (65 ºF) on the cold side and 22.2 ºC (72 ºF) on the warm side. Next, the temperature of the warm side was rapidly increased to 43.3 ºC (110 ºF) – on the side of the wall cavity containing PCM. It was observed that PCM content in the wall stabilized thermally the PCM section of the wall. It was associated with significantly lower local temperatures in the wall part containing PCM during the rapid heating process. Thermal lag time for that heating process was between 7 to 8 hours for the PCM part of the wall.

Figure 1. Instrumentation of the test wall cavity.

As shown in the Figure 1 test wall cavity was instrumented with temperature sensors installed at 2.5-cm. (1-in.) intervals. The first 2/3 of the wall thickness (counting from the interior surface) was filled with conventional blown fiber glass of the same density as in the other non-PCM section of the wall. The remaining part of the wall cavity was filled with several layers of proprietary PCM blend with adhesive and blown fiber glass. The test wall contained approximately 20 wt. % PCM. It is estimated that about 13.6-kg (30-lb) of PCM-enhanced fiber glass insulation (containing 0.79-kg/m^3 or 0.16-lb/ft^2 of PCM) was used for this dynamic experiment. The PCM melting temperature was about 29 ºC (84 ºF). The PCM sub-cooling effect was about 6 °C (11 °F) wide with freezing temperature close to 23 °C (73 °F). The phase change enthalpy was about 170 J/g (73 BTU/lb).

Test-generated heat flux results are shown in Figure 2 for the wall surfaces of constant temperatures. It took about 8-1/2 hours to fully charge the PCM material within the wall. Heat fluxes on both PCM and non-PCM sides of the wall were measured and compared. For 2-hour and 8-1/2-hour time intervals, heat fluxes were integrated for each surface. Comparisons of measured heat flow rates on the wall surface opposite to the thermal excitation enabled estimation of the potential thermal load reduction generated by the PCM. On average, the PCM part of the wall demonstrated over 27% of the cooling effect (total reduction of the heat flow) during 8-1/2 hours, and over 50% during the first two hours of the rapid heating process.

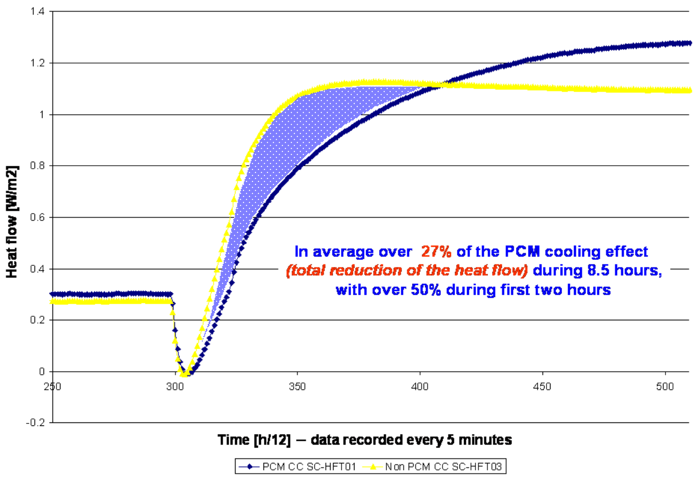


Figure 2. Heat flows measured during dynamic hot-box experiment.

In real field conditions, most thermal excitations generated by the climate generally last less than 5 hours (peak hour time). As a comparison, during similar previously conducted hot-box experiments with dynamic cellulose insulation containing uniformly distributed 25% PCM-cellulose blend [Kośny 2008], it was determined that during the first 5-hours after the thermal ramp, PCM-enhanced cellulose material reduced the total heat flow through the wall by over 40%. In this case it took about 15 hours to fully charge walls PCM. Recorded load reductions for the entire 15 hours were close to 20%.

2.2 *Full scale filed testing of residential attic containing PCM –insulation blend*

During July of 2008, a full-scale experimental attic was constructed and instrumented in order to test in field conditions blown fiber glass insulation combined with microencapsulated PCM. The main goal of this experiment was to investigate at what level and how often PCM was going through the phase change process. As shown on Figure 3 a full-scale residential attic was filled with about 25-cm. (10-in.) of blown fiber glass insulation of approximate density 29-kg/m^3 (1.8-lb/ft^3). Next, on top of this insulation, four 1.3-cm. (1/2-in.) thick layers of PCM-adhesive blend were installed with 1.3-cm. (1/2-in.) thick layers of blown fiber glass installed in-between. The total thickness of added PCM-fiberglass multilayer sandwich was approximately 10-cm. (4-in.).

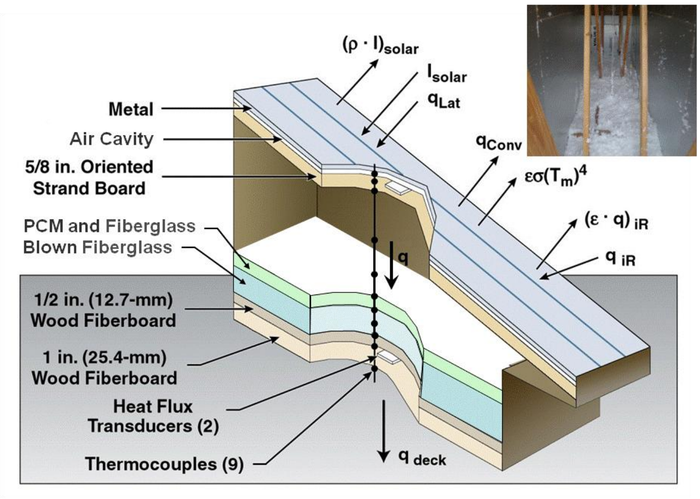


Figure 3. Instrumentation of the test attic containing PCM-enhanced fiber glass insulation.

In this field experiment a relatively advanced attic containing an over-the-deck ventilated cavity and metal cool roof (SR28 E81) was used. Monitored test data included the temperatures of the roof deck on both sides of the 1.6-cm. (5/8-in.) Oriented Strand Board (OSB) and the heat flux transmitted through the roof deck. As shown on Figure 3, the test roof deck had a routed slot with a heat flux transducer (HFT) inserted to measure the heat flow crossing the deck. Each HFT was placed in a guard made of the same OSB material used in construction and was calibrated using a FOX 670 heat flow meter to correct for shunting effects (i.e., distortion due to three-dimensional heat flow) [Miller et al. 2007, ASTM 2006]. It was a 10-cm. (4-in.) ventilated air space between the roof deck and the roof metal cover. Reflective insulation was installed on the top of the roof deck. The attic cavities also had an instrumented area in the floor (i.e., ceiling) for measuring the heat flows into the conditioned space. The attic floor under the blown fiber glass insulation consists of a metal deck, a 2.5-cm. (1-in.) thick piece of wood fiberboard lying on the metal deck with a 1.2-cm. (½-in) thick piece of wood fiberboard placed on top (Figure 3). The HFT for measuring ceiling heat flow was embedded between the two pieces of wood fiberboard.

Detailed temperature profiles across the roof, attic space, and within the attic insulation were collected for two summer seasons of 2008 and 2009. In order to estimate optimum attic air temperatures (necessary for full melting and later full freezing of PCM), a detailed temperature analysis was performed using recorded data. Characteristic temperature points of melting PCM are as noticeable as shown in Figure 4 for August 17th 2009.

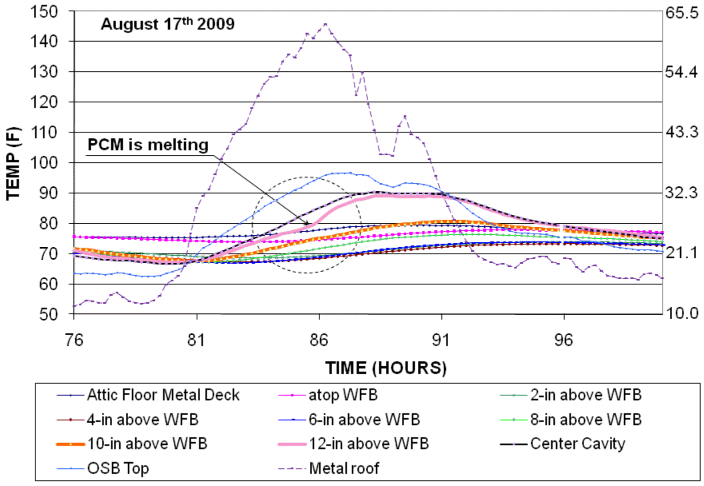


Figure 4. Temperature profiles measured in test attic during sunny day in August 2009.

Recorded summer temperature profiles were analyzed from the perspective of optimum conditions for PCM to undergo through full phase changes. For each month a number for days when PCM went through a complete phase change process was calculated (Figure 5). In order to make PCM fully melt, attic air temperature should be - during the peak of the day - higher than32^{o}C (90^{o}F). During the night attic air temperature should be below 20^{o}C (68^{o}F).It was found that during the two tested seasons, the second week of May was a beginning week for PCM to have at least two full phase changes a week. This process ended during the first week of October. In May and September calculated number of active days for PCM was close to 50% of total number of days. During June and August during over 75% of days phase change processes took place. In July, due to increased night temperature, a number of days when PCM was fully active went down to below 50%. In order to improve PCMs effectiveness during July, it is possible to use PCM of higher melting point. However in that case, a number of active days can be reduced for May and September.

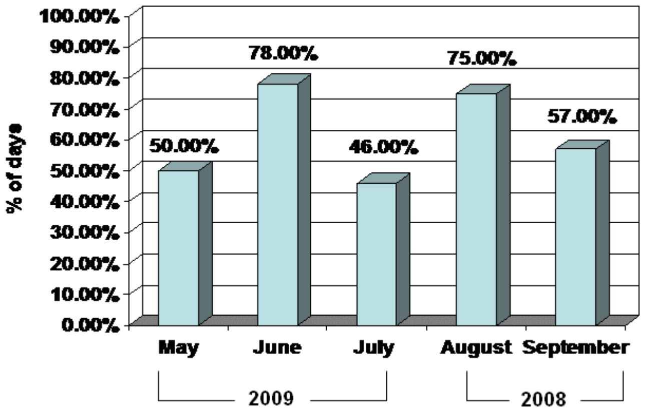


Figure 5. Recorded percents of summer days with fully active PCM.

3 WHOLE BUILDING SIMULATIONS OF PCM-ENHANCED FIBER GLASS APPLICATIONS

Whole house energy modeling was performed in order to evaluate potential benefits of using PCM-enhanced fiber glass insulation for residential attic applications. At the beginning, a series of EnergyPlus whole building energy simulations was performed using climatic data of Atlanta and Chicago to analyze the impact of added attic thermal insulation on building energy performance. The building considered for this study was a 16.8 m (55 ft) x 8.4 m (27.5 ft) single story ranch house with three bedrooms, one living room, and an attic – see Figure 6.

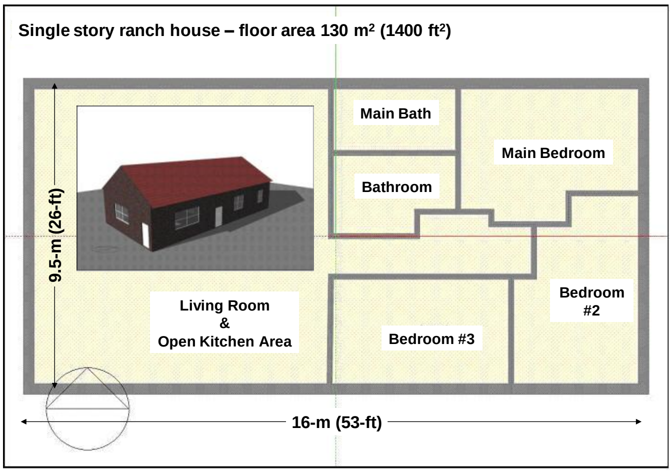


Figure 6. Floor plan of the one-story ranch house used in whole house energy simulations.

The considered task was based on the replacement of existing attic insulation with R_{SI}-6.7 (R-38) blown fiber glass combined with PCM. Three following entry levels of existing attic insulation were considered: R_{SI}-2.1 (R-12), R_{SI}-3.3 (R-19), R_{SI}-5.3 (R-30). It is necessary to mention that a case of the conventional R_{SI}-2.1 (R-12) attic represents approximate effective thermal performance of a most common old residential attic utilizing 14-cm. (5.5-in) fiber glass batts installed with air voids. In addition (in sake of comparisons) two most popular attic levels of insulation R_{SI}-6.7 (R-38), R_{SI}-8.8 (R-50) were simulated as well.

It was assumed in computer modelling that full-scale residential attic was filled with about 18-cm. (7-in.) of blown fiber glass insulation of approximate density 29-kg/m^3 (1.8-lb/ft^3). Next, on top of this insulation, four 1.3-cm. (1/2-in.) thick layers of PCM-adhesive blend were installed with 1.3-cm. (1/2-in.) thick layers of blown fiber glass installed in-between. The total thickness of the added PCM-fiberglass multilayer sandwich was approximately 10-cm. (4-in.). EnergyPlus simulations were performed for both conventional insulation cases and for dynamic insulation containing PCM. Figures 7 and 8 depict total values of ceiling heat flow simulated for two days of July 2008. Five cases of conventional attic insulation were compared against R_{SI}-6.7 (R-38) PCM-enhanced fiber glass – marked green on Figures 7 and 8.

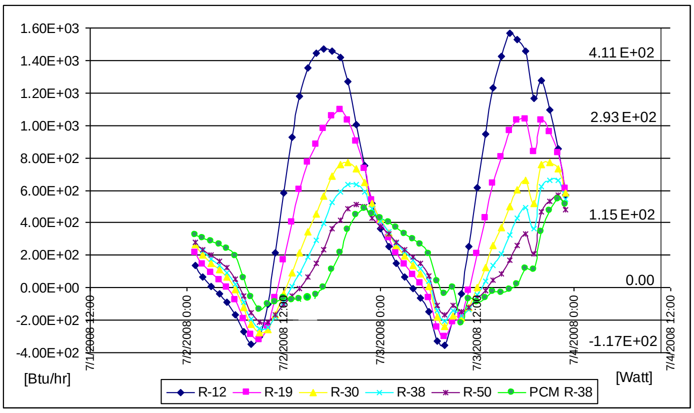


Figure 7. Comparisons of simulated ceiling heat conduction profiles for Atlanta climatic conditions.

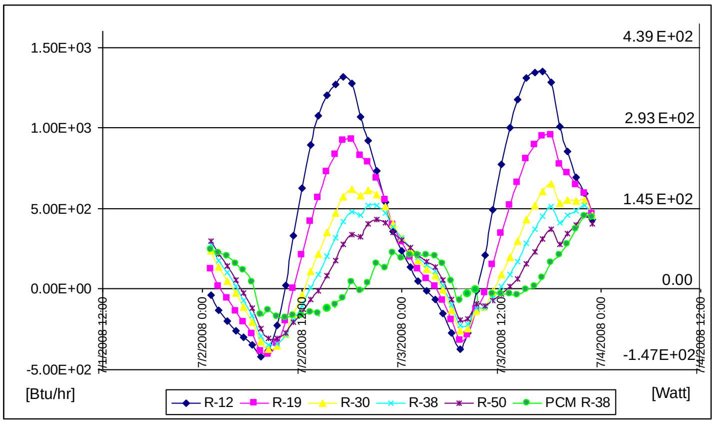
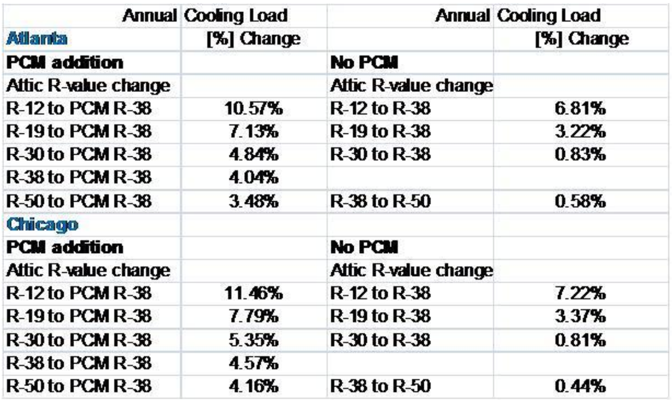


Figure 8. Comparisons of simulated ceiling heat conduction profiles for Chicago climatic conditions.

Simulation results for both climates demonstrated a potential for reduction of about 70% to 80% of roof-generated peak hour loads in the case when conventional R_{SI}-2.1 (R-12) attic insulation is replaced by the R_{SI}-6.7 (R-38) PCM-enhanced fiber glass.

In addition percentage changes of annual cooling loads were computed for considered levels of attic insulation. Data presented in Table 1 shows that thermal retrofitting of the residential attic with a use of the PCM-enhance insulation is significantly more effective from using only conventional insulation. For example, an upgrade from the conventional R_{SI}-2.1 (R-12) insulation to PCM-enhanced R_{SI}-6.7 (R-38) is 1/3 more energy effective than just using conventional insulation of the same R-value. Similarly, an upgrade from the conventional R_{SI}-3.3 (R-19) insulation to PCM-enhanced R_{SI}-6.7 (R-38) is more than 50% effective. Most interesting, the R_{SI}-6.7 (R-38) insulation containing PCM is more efficient from conventional R_{SI}-8.8 (R-50). It is necessary to realize, that since in the considered building, roof thermal loads represent approximately 15% of the total building loads, about a 10% change in annual cooling loads represents approximately 65% improvement in scale of the entire roof heat transfer.

Table 1. Computed annual cooling load changes for Atlanta and Chicago climatic conditions.



Annual	Cooling Load	Annual	Cooling Load
Atlanta	[%] Change		[%] Change
PCM addition		**No PCM**	
Attic R-value change		Attic R-value change	
R-12 to PCM R-38	10.57%	R-12 to R-38	6.81%
R-19 to PCM R-38	7.13%	R-19 to R-38	3.22%
R-30 to PCM R-38	4.84%	R-30 to R-38	0.83%
R-38 to PCM R-38	4.04%		
R-50 to PCM R-38	3.48%	R-38 to R-50	0.58%
Chicago			
PCM addition		**No PCM**	
Attic R-value change		Attic R-value change	
R-12 to PCM R-38	11.46%	R-12 to R-38	7.22%
R-19 to PCM R-38	7.79%	R-19 to R-38	3.37%
R-30 to PCM R-38	5.35%	R-30 to R-38	0.81%
R-38 to PCM R-38	4.57%		
R-50 to PCM R-38	4.16%	R-38 to R-50	0.44%

A design of the attic described in this part of the paper was optimized for cooling-dominated and mixed climates. In the Northern U.S., areas, a shingle roof surface, combined with different location of PCM heat sink can be utilized as a passive solar absorber - reducing heating loads during the late fall and early spring months.

4 CONCLUSSIONS

The paper presented experimental and numerical results from thermal performance studies of wall and attic applications of the blown fiber glass insulation modified with a novel spray-applied microencapsulated PCM. Experimental results were reported for both laboratory-scale and full-size building elements tested in the field.

For wall applications, PCM-enhanced fiber glass insulation was evaluated during the dynamic guarded hot box test. The test wall contained approximately 20 wt. % PCM. It was estimated that about 13.6-kg (30-lb) of PCM-enhanced fiber glass insulation (containing 0.79-kg/m^3 or 0.16-lb/ft^3 of PCM) was used. The PCM melting temperature was about 29^{o}C (84^{o}F). The phase change enthalpy was about 170 J/g (73 BTU/lb). Comparisons of measured heat flow rates on the wall surface opposite to the thermal excitation enabled estimation of the potential thermal load reduction generated by the PCM. On average, the PCM part of the wall demonstrated over 27% of the cooling effect (total reduction of the heat flow) during 8-1/2 hours, and over 50% during the first two hours of the rapid heating process.

Whole house energy modeling and full scale field testing was performed in order to evaluate potential benefits of using PCM-enhanced fiber glass insulation in residential attics. Full scale field testing of residential attics using blown fiber glass and PCM was completed in Oak Ridge, Tennessee. Experimental work was followed by detailed whole building EnergyPlus simulations in order to generate energy performance data for different US climates. A series of numerical simulations and field experiments demonstrated a potential for application of a novel PCM-fiber glass insulation as enabling technology to be utilized during the attic thermal renovations. Five cases of conventional attic insulation were compared against R_{SI}-6.7 (R-38) PCM-enhanced fiber glass. Simulation results for both climates demonstrated a potential for reduction of about 70% to 80% of roof-generated peak hour loads in the case when conventional R_{SI}-2.1 (R-12) attic insulation is replaced by the RSI-6.7 (R-38) PCM-enhanced fiber glass. Simulation results showed that an upgrade from the conventional R_{SI}-2.1 (R-12) insulation to PCM-enhanced R_{SI}-6.7 (R-38) is 1/3 more energy effective than just using conventional insulation of the same R-value. Similarly, an upgrade from the conventional R_{SI}-3.3 (R-19) insulation to PCM-enhanced R_{SI}-6.7 (R-38) is more than 50% effective. A design of the attic described in this paper was optimized for cooling-dominated and mixed U.S. climates.

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