Dynamic Thermally Disconnected Building Envelopes—A New Paradigm for Walls and Roofs in Low-Energy Buildings

Jan Kosny, PhD
Member ASHRAE

William Miller, PhD
Member ASHRAE

Abdi Zaltash, PhD
Member ASHRAE

ABSTRACT

This paper describes numerical and experimental analysis of a novel design concept. Traditionally, the thermal design of building envelope assemblies is based on a static energy flow. However, building envelopes are subject to varying environmental conditions. This mismatch between the steady-state principles used in the design of roofs and walls and their dynamic operation results in relatively low thermal efficiency. Design work in support of the development of zero-energy houses showed that conventional insulations may not be the most cost-effective energy solution. Testing conducted on several strategies to thermally disconnect wall and roof components showed 70% to 90% reductions in peak hour loads as compared to conventional building practice.

INTRODUCTION

Current practice bases roof and wall thermal design on steady-state resistance (R-value). However, the day-to-day change in weather causes varying component loads that, through proper design, can be exploited to enhance thermal performance of the envelope. The concept is herein termed a thermal disconnect, which we define as a material or system that can control, or control and redirect, the flow of heat between two working surfaces of a building. As an example, the varying temperature excitations of an exterior wall can be disconnected from its interior surface by simply adding insulation to improve the wall's overall thermal resistance. Some thermal disconnect systems, like phase-change materials or ventilation strategies, can either exhaust or absorb part of the dynamic loads reaching the exterior building surface.

Conventional attic design having soffit and ridge ventilation is another example of a working thermal disconnect. The ventilation air redirects some of the heat emanating from the roof deck away from the insulation on the attic floor. The attic insulation works against an internal attic air temperature instead of the dynamic temperatures observed on the roof surface. In comparison, a cathedral roof directly conducts heat into the conditioned space. In general, benefits of the attic thermal disconnect system can be listed as follows:

- Effectively reduces roof solar loads
- Reduces nocturnal cooling effects
- Provides a conduction break between the attic floor and the roof deck.
- Causes stratification of the attic air and adds thermal resistance to the attic insulation
- Causes a shifting of attic thermal loads.

Conventional practice uses thermal insulations as a thermal disconnect. The typical problems associated with application of conventional insulations are lack of space and thermal bridging in locations where structural members penetrate thermal insulation. That is why several other thermal disconnect systems have been developed. Some of these systems have been successfully used by the US building industry during the last decades. They can be grouped into the following basic areas:

- Exterior radiation barriers: cool roof and cool wall coatings

Jan Kosny *was previously a senior research scientist at the Oak Ridge National Laboratory, Oak Ridge, TN, and is currently at the Fraunhofer Center for Sustainable Energy Systems (CSE), Cambridge, MA.* ***William Miller*** *and* ***Abdi Zaltash*** *are research scientists in the Energy and Transportation Sciences Division, Building Envelopes Group, at the Oak Ridge National Laboratory, Oak Ridge, TN.*

Table 1. Calculated Annual Space Conditioning Cost Energy Savings for Added R-4 Attic Insulation, $

added R-value	Atlanta	Bakersfield	Chicago	Denver	Houston	Knoxville	Miami	Minneapoli	Phoenix	Seattle	Wash. DC
6 to 10	123.46	116.90	173.72	167.60	98.67	132.54	64.86	196.89	107.92	157.11	156.71
10 to 14	52.91	50.10	74.45	71.83	42.29	56.80	27.80	84.38	46.25	67.33	67.16
14 to 18	29.40	27.83	41.36	39.91	23.49	31.56	15.44	46.88	25.70	37.41	37.31
18 to 22	18.71	17.71	26.32	25.39	14.95	20.08	9.83	29.83	16.35	23.80	23.74
22 to 26	12.95	12.26	18.22	17.58	10.35	13.90	6.80	20.65	11.32	16.48	16.44
26 to 30	9.50	8.99	13.36	12.89	7.59	10.20	4.99	15.15	8.30	12.09	12.05
30 to 34	7.26	6.88	10.22	9.86	5.80	7.80	3.82	11.58	6.35	9.24	9.22
34 to 38	5.73	5.43	8.07	7.78	4.58	6.15	3.01	9.14	5.01	7.30	7.28
38 to 42	4.64	4.39	6.53	6.30	3.71	4.98	2.44	7.40	4.06	5.91	5.89
42 to 46	3.83	3.63	5.40	5.21	3.06	4.12	2.01	6.11	3.35	4.88	4.87
46 to 50	3.22	3.05	4.53	4.37	2.57	3.46	1.69	5.14	2.82	4.10	4.09

- Interior infrared radiation barriers: radiant barriers and foil-faced insulations
- Thermal mass: conventional thermal mass, passive solar applications, and phase-change materials (PCMs)
- Air spaces and naturally ventilated cavities
- Active ventilation of attics, above-deck inclined air spaces, and wall cavities.

This paper proposes to replace "statically" designed conventional building shells with novel, fully integrated, dynamically working envelope systems using active rather than static thermal disconnects. The following five major system components were considered during the design process of the dynamic thermally disconnected envelopes:

- Optimized thermal envelope with high R-value and low thermal bridging
- Conventional and PCM (phase-change material) thermal mass
- Infrared reflective (IRR) surfaces and radiant barriers
- Active and passive ventilation schemes, and low-E (cool) exterior surfaces

DIMINISHING ENERGY BENEFITS OF ADDED EXTRA BUILDING ENVELOPE INSULATION

Thermal insulation is one of the best-known ways of improving thermal performance of building envelopes. Traditionally, more insulation is considered good for improving thermal performance. Thermal efficiency of using insulating sheathing was previously analyzed by several authors (Strzepek 1980; Trethowen 1988; Barbour et al. 1994; Kosny and Christian 1995). In addition to improvement of thermal performance, several types of insulations such as sprayed foams can enhance building airtightness.

In a microscale of a wall or roof cross section, thermal performance of insulation is a function of its thickness. However, if framing effects, local thermal bridging (caused by imperfections in insulation installation), and air leakage are added to the picture, the overall thermal analysis becomes more difficult. On the whole-building scale, the impact of thermal insulation thickness on overall building energy efficiency is even more complex.

A series of EnergyPlus whole-building energy simulations were performed in order to analyze the impact of added thermal insulation on overall building energy performance. The building considered for this study was a 16.8 m (55 ft) × 8.4 m (27.5 ft) single-story ranch house with three bedrooms, one living room, and an attic. In this modeling exercise, thermal insulation was added to the exterior walls and attic in R-4 intervals. It is good to realize that adding of extra insulation is associated with adding extra thickness to the wall or roof assembly. An addition of R-4 insulation usually requires about 2.5 cm (1 in.) of extra space. Sometimes this type of thermal improvement is not possible due to space restrictions. The modeling results are presented in Figures 1 and 2 for wall and attic insulations, respectively.

In the next step, attic insulation data were used for payback time approximations. After making an assumption that cost of the attic fiber insulation is approximately $0.04 per R per ft^2 and considering that total area of the analyzed attic is approximately 150 m^2 (1400 ft^2), the cost of the extra R-4 attic insulation for the entire house is about $224. In that light, annual insulation costs will be $45 and $32 for 5-year and 7-year payback times, respectively.

Next, based on energy consumption data presented in Figure 2, potential energy cost savings were computed for different levels of added R-4 insulation. The following approximate energy costs were considered: electricity cost of $0.10 per kWh and gas cost of $1.00 per therm. Energy cost savings for different levels of attic insulation are presented in Table 1 for 11 US locations for attic insulation installed in the roughly 150 m^2 (1400 ft^2) attic area of the single-story house. It was found that, for almost all climates considered in this study, 7 years of payback time (with $32 annual payback cost) can be only expected for added insulation level between R-10 and R-18. This is well below the widely used attic insulation level of R-38 in new US houses, where annual payback cost of extra R-4 insulation is about 5 times higher. This fact leads to the conclusion that, for higher levels of thermal insulation, added R-value has a diminishing return on investment.

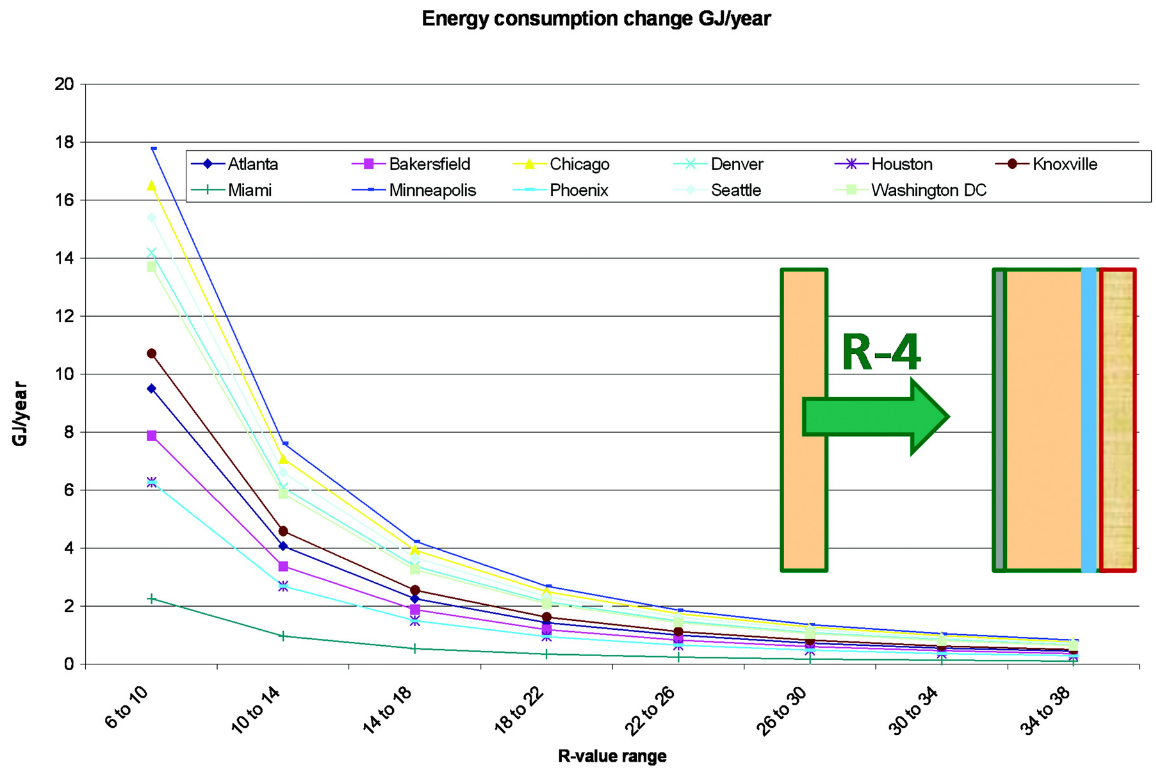

Figure 1 *Diminishing whole-house HVAC energy savings due to addition of R-4 wall insulation.*

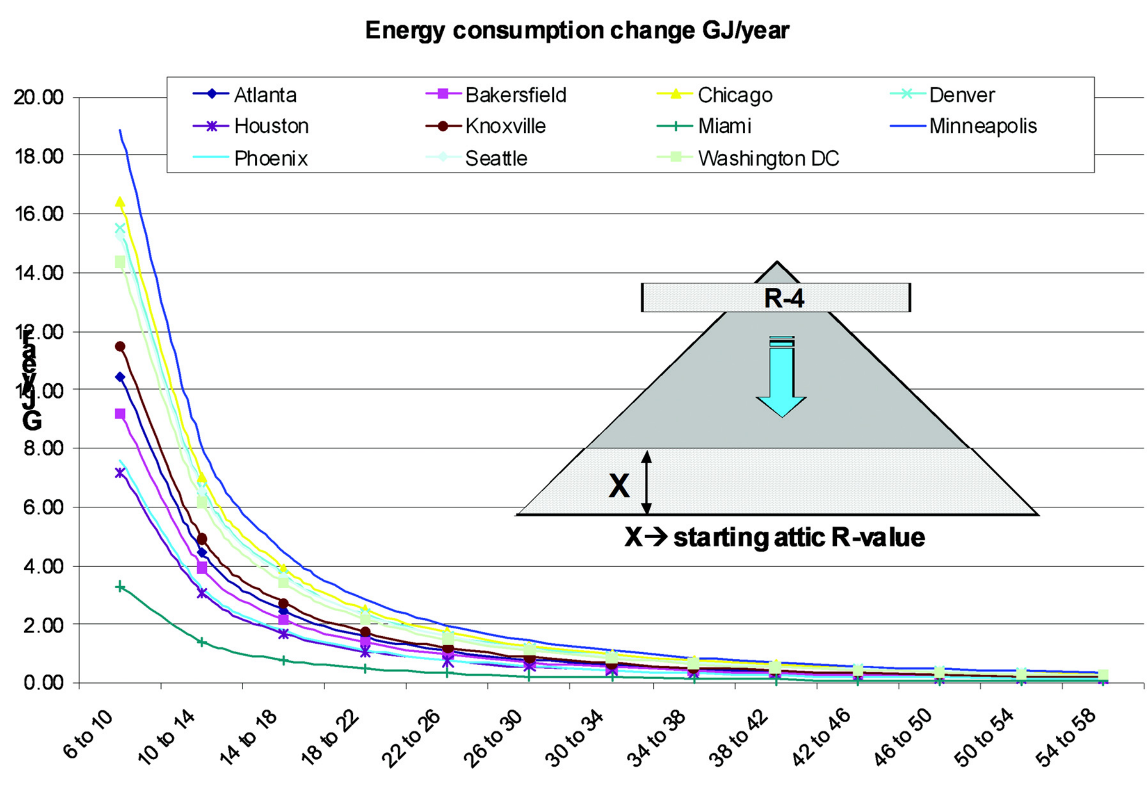

Figure 2 *Diminishing whole-house HVAC energy savings due to addition of R-4 attic insulation.*

Similar calculations can be also undertaken for wall insulations. However, wall insulation data are more complex since, in most cases, additional wall insulation is usually added in form of the plastic foam sheathing. This material is significantly more expensive than the fiber insulations, making wall R-value additions even less cost attractive.

Results of energy simulations and limited cost analysis presented above for attic insulation demonstrated that, due to relatively high cost, thermal insulations cannot be considered as the only thermal disconnect system. Other less conventional alternative methods should be investigated to develop a mix of thermal disconnect systems that are cost effective and capable of reducing building thermal loads.

EXAMPLES OF THERMAL DISCONNECT SYSTEMS IN RESIDENTIAL ROOFS AND ATTICS

During 2006–2009, the Oak Ridge National Laboratory (ORNL) Buildings Technology Research and Integration Center (BTRIC) team evaluated several configurations of roofs and attics, including novel thermal disconnect designs and thermal storage. Three generations of metal roofs containing dynamic attics were used to demonstrate the significance of thermal disconnect such as air gaps, reflective insulation, and PCM thermal storage (Figure 3). This research found energy savings benefits from air movement that develops in the space between the metal roof covering and deck over which it is installed. Providing an air space above the sheathing of a roof deck offers thermal benefits for metal roofs that yield energy savings in the summer and winter, while also helping to remove unwanted moisture. The natural ventilation above the sheathing improves the durability of the underlying structure of the roof. Metal roofs are sometimes offset mounted from the roof deck using a double-batten (counter-batten) construction.

The novel ORNL design, with an application of the perforated metal spacers, provides a single air space or two air spaces between the exterior face of the roof deck sheathing and the underside of the roof cover so that a clear, albeit complex, a single air pathway (or two pathways separated by a layer of PCM) exist beneath the roof cover. Solar irradiance absorbed at the roof's surface is conducted through the metal roof and it is absorbed by the PCM heat sink. As shown in Figure 3, PCM material can be packed into the reflective aluminum foil, additionally acting as a reflective insulation and improving thermal performance of the over-the-deck air cavity. Three different types of inorganic and organic PCMs have been tested in this project. The ventilation scheme helps remove unwanted heat, but it also removes unwanted moisture from the roof deck, thereby improving the roof's thermal performance as well as its durability. The thermally induced airflow occurring in this air space is termed above-sheathing ventilation. During three years of full-scale field testing, all three configurations of the dynamic thermally disconnected attics performed superior to traditional attic configurations. In these designs, thermal disconnect was provided by low-E (cool coatings), reflective insulations, air cavities, forced (PV-powered) or natural air cavity ventilation, and PCM thermal storage.

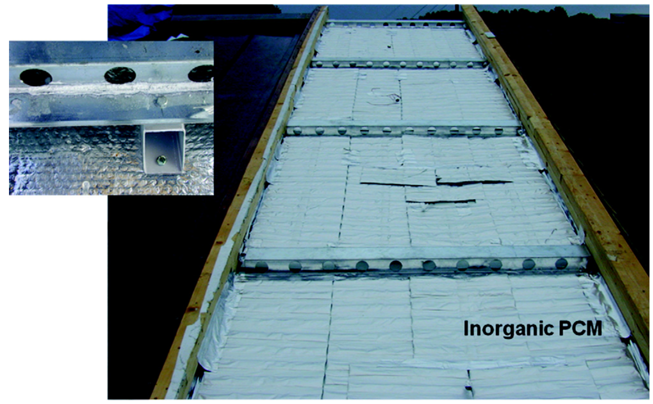

Figure 3 *Dynamic attic using air gaps, reflective insulation, and inorganic PCM thermal storage.*

Field data showed significant reduction in the heat flow through the roof deck in attic systems with thermal disconnect compared to conventional asphalt-shingle roof. In addition to the attic systems containing PCM thermal storage, separate tests were performed on the attic using only over-the-deck ventilation air cavity with no PCM. Figure 4 shows heat flow reduction of approximately 70% for a metal roof with cool-roof surface and subventing and approximately 90% heat flow reduction for a metal roof with dynamic PCM-enhanced thermal disconnect. It can be observed that dynamic PCM roof did not show night overcooling effects, a characteristic of conventional shingle roofs and cool roofs. In some northern US areas, overnight cooling effect may generate a notable increase in heating energy consumption, reducing potential energy benefits of cool roof technologies. An additional positive effect of application of the PCM heat sink is shifting of the peak hour cooling loads. Figure 4 shows this peak heat flow shift to be approximately 2 to 3 hours compared to the roof with no PCM (no-thermal-mass roof).

THERMAL DISCONNECT SYSTEM IN WALL APPLICATION

Thermal disconnect designs can be used in walls, as well. During the past decades, exterior sheathing insulations have been successfully applied to improve thermal performance of residential and commercial walls. In most cases, continuous plastic foam sheathing was installed on the exterior wall surfaces. Recently, the ORNL team field tested different wall cladding systems in the South Carolina climate (Karagiozis and Edgar 2008), including exterior insulation finish systems (EIFS) with exterior plastic foam sheathing. It was found that the drained EIFS demonstrated potential for significant energy savings compared to other types of wall cladding (e.g., 2.6

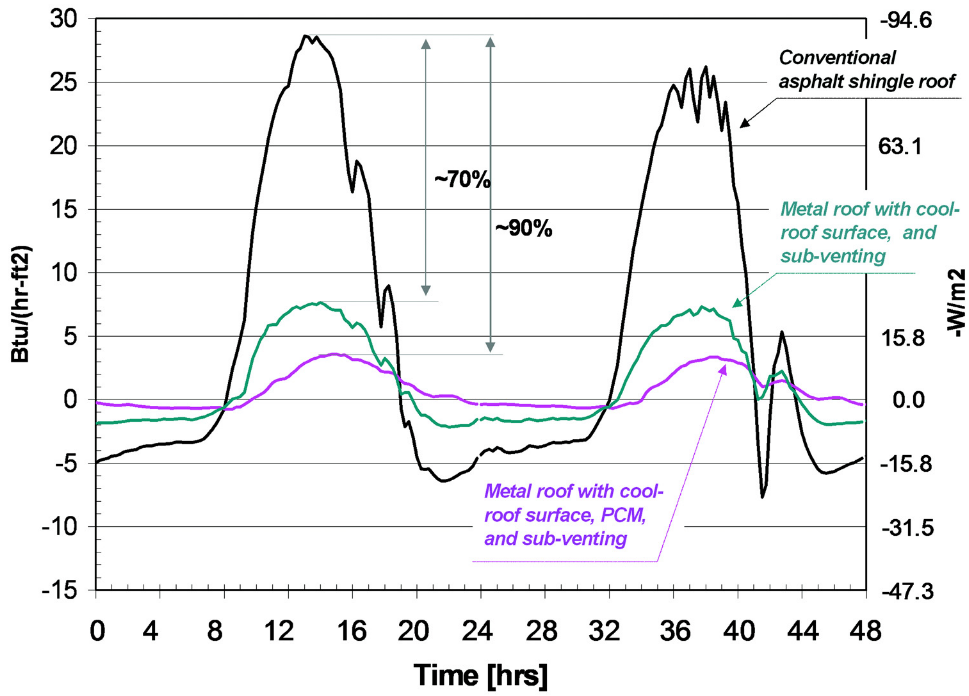

Figure 4 *Comparison of cooling loads of conventional asphalt-shingle roof and two metal roofs with thermal disconnect components.*

times reduction of the cooling loads compared to brick cladding).

When it comes to the non-foam thermal disconnect configurations, double facades and passive solar walls are the best-known applications. Known and used for decades, the vented trombe wall is one of the best-performing passive solar applications, using glazing, a natural ventilated air cavity, and thermal mass as a thermal disconnect system. In National Renewable Energy Laboratory (NREL) research, trombe walls have been integrated into the envelope of the Visitor Center at Zion National Park and a site entrance building (SEB) at NREL's Wind site (Torcellini and Pless 2004). The trombe wall provides passive solar heating without introducing light and glare into the commercial spaces. It was found that these trombe walls provided significant heating to the buildings. In the visitor center, 20% of the annual heating was supplied by the trombe wall, and the SEB's afternoon and evening heating loads are typically met by the trombe wall.

Following available energy consumption data from the experimental passive solar buildings, ORNL wall designs used several previously developed passive heat storage applications, replacing conventional thermal mass with PCM. ORNL tested several configurations of cavity walls insulated with PCM-enhanced insulations. Full-scale field tests were performed in Charleston, SC, and in Oak Ridge, TN (Kosny 2008). These tests demonstrated potential for up to 30% peak load reductions. In addition, walls with PCM-enhanced insulation provided notable peak load shifting. During 2009–2010, a first test house containing PCM-enhanced cellulose insulation in walls and attic was constructed in Oak Ridge, TN, and is now undergoing full-scale energy performance testing.

In 2008–2009, ORNL research team experimentally evaluated several configurations of thermal disconnect components installed on concrete masonry unit (CMU) walls in a form of a dynamic wall thermal retrofit system. Numerous thermal subsystems (e.g., air gaps, ventilated cavities, reflective insulations, PCM thermal storage) were evaluated as additions to conventional CMU walls, as shown in Figure 5. These extra layers of materials served as a novel dynamic thermal insulation system enhancing thermal performance of a conventional CMU wall.

As shown in Figure 5, the 2.4 m by 2.4 m (8 ft by 8 ft) test wall area was divided into two separate sections representing conventional and dynamic thermal retrofit strategies for CMU walls. Both of these walls had approximately the same R-value, with one of the wall having conventional foam insulation and the other containing air gaps, reflective insulation, and PCM thermal storage. As presented in Figure 5, a multilayer PCM heat sink was fabricated of PCM-enhanced polyurethane foams, PCM-impregnated fabrics, and highly reflective aluminum foil. PCM loading was about 0.39 kg/m^2 (0.08 lb/ft^2) of the surface area. Two types of PCMs were used, with melting temperatures of approximately 78°F and 90°F (26°C and 32°C). The total storage capacity of the PCM was about 54 kJ/m^2 (4.8 Btu per ft^2) of wall area.

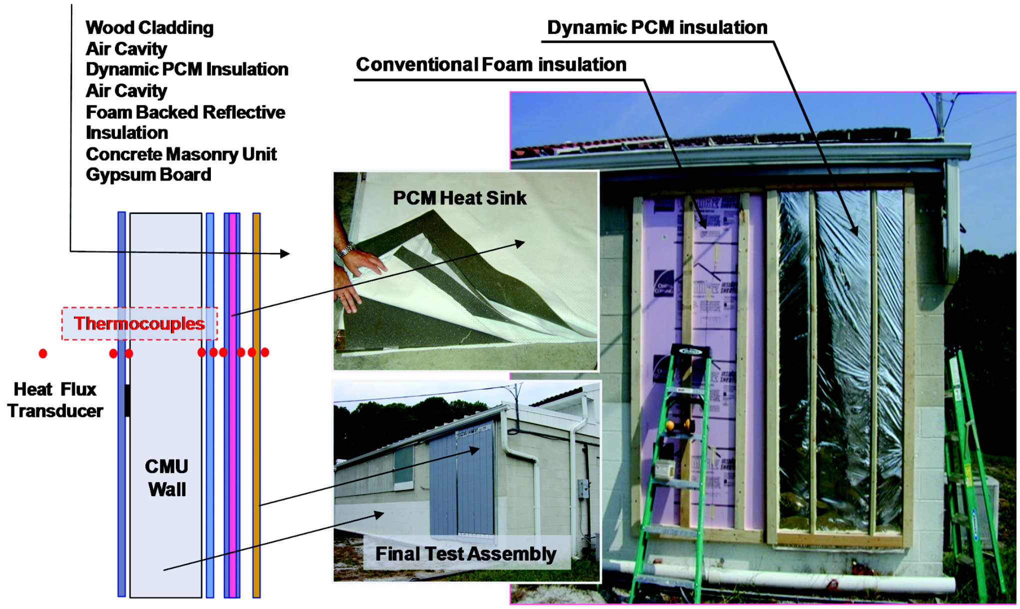

Figure 5 *Test assemblies of two walls with conventional foam insulation and with thermal disconnect (air gaps, reflective insulation, and PCM thermal storage).*

During the summer seasons 2007–2008, experimental PCM-enhanced wall performed very well reducing average peak-hour heat flows by about 60% compared to the conventional wall. During summer 2008, the average cooling loads in PCM wall were reduced by about 35%. Thanks to application of the dynamic thermal disconnect system peak-hour load was shifted by approximately 6 to 8 hours. It was also observed that, in the middle of a sunny day, thanks to PCM-enhanced dynamic insulation exterior surface temperature of the concrete blocks (behind dynamic insulation) was almost the same as on the interior wall surface. At the same time, similar temperature of the wall containing conventional foam sheathing insulation was about 3°C to 5°C (6°F to 10°F) higher (Figure 6).

The heat flow reductions in walls with dynamic thermal disconnect system were very dramatic compared to the heat flows in the traditionally insulated section of the wall using plastic foam sheathing. The results are leading ORNL researchers toward development and validation of a new generation of energy-efficient thermal insulation technologies for wall systems that support zero-energy building initiatives spearheaded by the DOE Building Technologies Program.

COMBINED APPROACH OF USING FIELD TEST DATA WITH TRANSIENT COMPUTER SIMULATIONS

During the last decade, the ORNL BTC team evaluated several configurations of walls, roofs, and attics using thermal disconnect designs. Since many material configurations of experimental envelope systems were dictated by commercial availability of specific products, very often nominal R-values of these technologies were notably different. That is why it was not always easy to directly compare their recorded performance data. In order to enable apple-to-apple comparisons of the same R-value technologies, a combined experimental-analytical methodology was applied, using collected experimental data with support from transient thermal simulations.

Attic assemblies tested by ORNL during the last two decades had numerous types of roof covers, with and without cool colors, and with and without venting cavities (Miller et al. 2007, 2008). Very often, roofing material studies were combined with evaluation of attic reflective insulations and radiant barriers (Desjarlais and Yarbrough 1991; Yarbrough 1991, 2005). It was found that roof venting resulted in reduction of the heating penalty associated with cool roofs (Salonvaara et al. 2007; Miller et al. 2008). Accelerated testing by ASTM protocols showed that new cool pigmented roof products maintained their solar reflectance and fade resistance. In addition, laboratory tests were completed with phase-change materials (PCMs) placed in numerous locations of walls, attics, and roofs. In these tests, both dispersed and concentrated PCM applications were used (Kosny 2008; Kosny et al. 2009). PCM-enhanced attic insulations stored energy during the day and released this energy during the night to alleviate utility peak demands. The attic and roof research work complemented similar efforts performed on dynamic advanced walls.

Combined analytical-experimental analysis presented in this paper used field test results generated during the ORNL envelope system research apparatus (ESRA) experiments. The ESRA field data included temperatures of the roof deck on both sides of the 5/8 in. oriented strand board (OSB) and the heat flux transmitted through the roof deck. As shown in

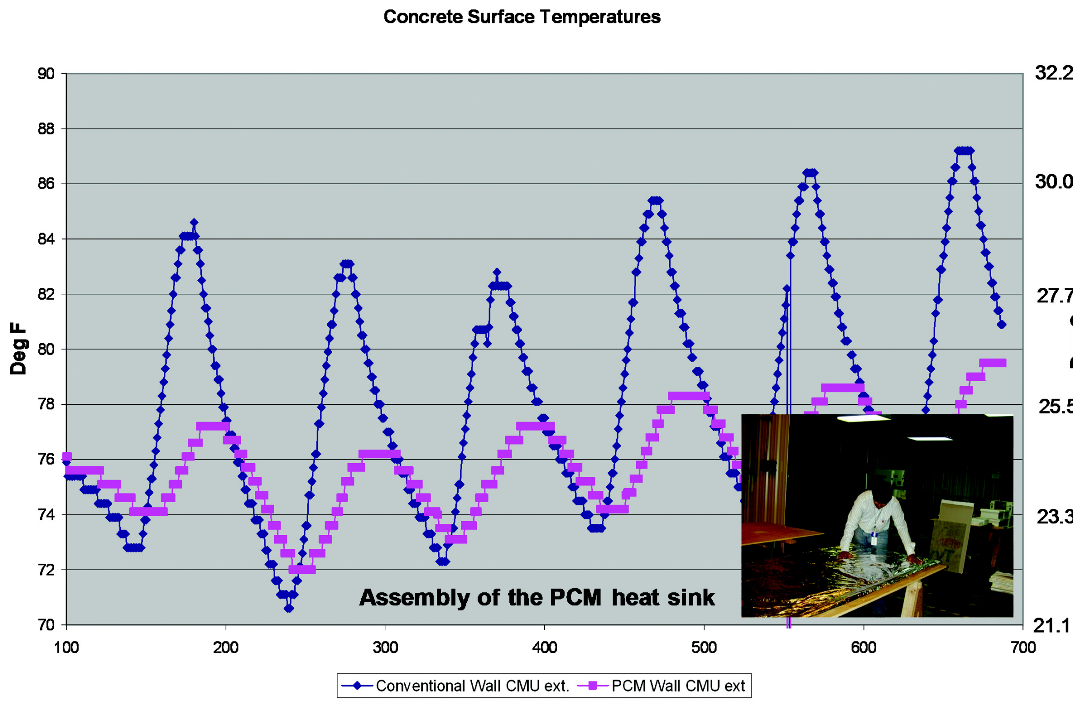

Figure 6 *Comparison of temperature profiles (exterior surface of CMU wall) on the wall with conventional foam insulation and wall with thermal disconnect (air gaps, reflective insulation, and PCM thermal storage).*

Figure 3, all test roof decks had a 2 in.^{2} by 0.18 in. deep 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). 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 consists of a metal deck, a 1 in. thick piece of wood fiberboard lying on the metal deck, and a 1/2 in. thick piece of wood fiberboard placed atop the 1 in. thick piece (Figure 7). The HFT for measuring ceiling heat flow was embedded between the two pieces of wood fiberboard. Field data recorded during the attic experiments were then used as boundary conditions for dynamic finite-difference modeling using AtticSim (Wilkes 1991) and HEATING 7.2 (Childs 1993) computer codes.

Wilkes (1991) formulated and validated AtticSim (an attic simulation tool), which was later published as *ASTM Standard C1340-2004, Standard Practice for Estimation of Heat Gain or Loss Through Ceilings Under Attics Containing Radiant Barriers by Use of a Computer Program*, for estimating the heat transfer through ceilings under attics containing radiant barriers. The AtticSim conduction transfer function model can account for different insulation R-values and/or radiant barriers attached to the various attic surfaces. It also has an algorithm for predicting the effect of air-conditioning ducts placed in the attic as reported by Petrie et al. (2004) and described in *ASTM Standard C1340*. The AtticSim code uses heat balances to mathematically describe conduction at the interior (facing the attic) and the exterior of the two gables, the two eaves, the two roof decks, and the ceiling; convection at the exterior and interior surfaces; radiant heat exchange between surfaces within the attic enclosure; heat transfer to the ventilation air stream; and latent heat effects due to sorption and desorption of moisture at the wood surfaces. The tool was validated by Wilkes (*ASTM Standard C1340*) against summer field experiments and is capable of predicting the ceiling heat flows integrated over time to within 5% to 10% of the field measurement for attics without radiant barriers. In addition Petrie et al. (2004) and Miller et al. (2004) provided validation of the code's ability to predict attic ventilation for soffit and ridge venting.

HEATING 7.2 is a multidimensional general-purpose heat conduction computer code developed by ORNL to analyze building envelopes. HEATING can solve steady-state and/or transient heat conduction problems in one-, two-, or three-dimensional Cartesian, cylindrical, or spherical coordinates (Childs 1993). Multiple materials and time- and temperature-dependent thermal conductivity, density, and specific heat can be specified. The boundary conditions, which may be surface-to-environment or surface-to-surface, may be specified temperatures or any combination of prescribed heat flux, forced convection, natural convection, and radiation. The boundary condition parameters can be time and/or temperature dependent. The mesh spacing may be vari-

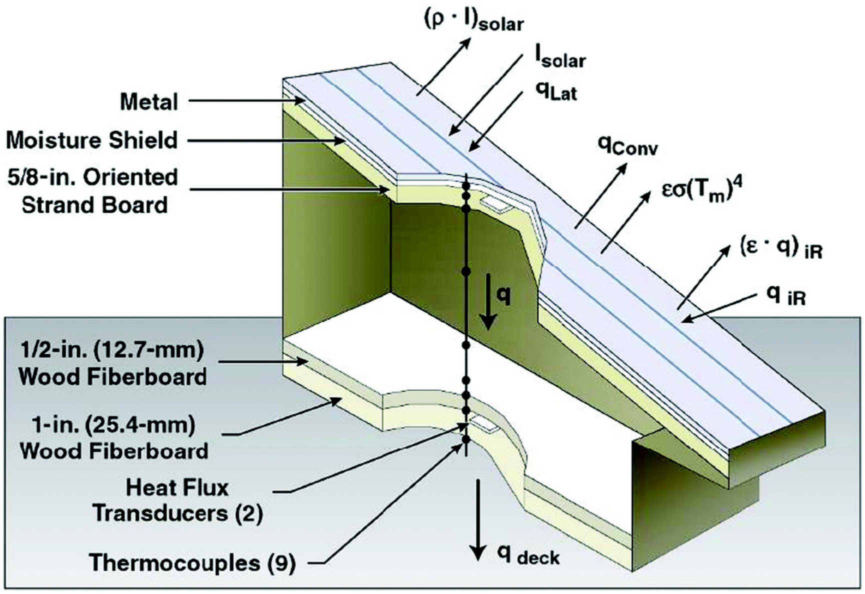

Figure 7 *Set-up of attic assembly showing construction materials, instrumentation, and insulation used to isolate the attic from adjacent attics.*

able along each axis. HEATING solves transient problems by using any one of several finite-difference schemes: Crank-Nicolson implicit procedure, classical implicit procedure, classical explicit procedure, or Levy explicit method. The accuracy of HEATING 7.2's ability to predict wall system R-values was verified by comparing simulation results with published test results for 28 masonry, wood frame, and metal stud walls. Ten empty two-core 12 in. (30 cm) units reported by VanGeem (1986), Valore (1988), and James (1990) were modeled with accuracy better than ±4% (Kosny and Desjarlais 1994). Similarly, eight filled two-core 30 cm (12 in.) units reported by Valore, VanGeem, and James were modeled with accuracy better than ±6%. Traditional 2 × 4 wood stud walls reported by James were also modeled with accuracy better than ±2%. For three metal stud walls tested at ORNL, the average accuracy of computer modeling was within 2.3% (Kosny and Christian 1995).

Initially, AtticSim was used to analyze the impact of changes in the attic floor insulation on the internal attic air temperature. A series of simulations of residential attics having attic floor insulation of different R-values were performed for four US climatic zones. The attic floor was assumed sealed from the conditioned space. It was found that temperature of the attic air is relatively insensitive to the attic floor insulation R-values. At the same time, attic air temperature was strongly dependent on configuration of materials between roof deck and the roof cover (due to limited space in this paper, this part of analysis will be presented as a separate research publication). Since in ORNL tests roofs and attics had different thermal characteristics (different nominal R-values), the combined experimental-numerical procedure was found to be very useful in comparing configurations with the same R-value. Based on the above findings, attic air temperature recorded during the field tests was used as a boundary condition for transient simulations using the finite-difference HEATING 7.2 model. Application of HEATING enabled analysis of PCM-enhanced configurations. This approach also helped with theoretical modifications of attic insulation in order to keep the same nominal R-value in all numerical comparisons. Similarly, in simulations of cathedralized roofs, roof surface temperature data recorded for the test assembly containing over-the-deck foam insulation was used as a boundary condition.

RESULTS OF COMBINED NUMERICAL-EXPERIMENTAL ANALYSIS AND DISCUSSIONS

Numerical Analysis—Residential Attic and Roof Applications

In this paper, a series of finite-difference modeling using AtticSim and HEATING 7.2 was performed to demonstrate energy performance differences between conventional thermal insulation methods and alternative thermally disconnected systems. Experimental data collected during several seasons of testing of different wall, attic, and roof configurations served in validation of computer models.

Traditionally, additional layers of foam or fiber insulation are installed in order to improve thermal performance of building envelope components. Exterior foam sheathing is widely considered as one of the simplest ways to improve the thermal performance of building envelope systems. Thermal efficiency of using insulating sheathing was previously analyzed

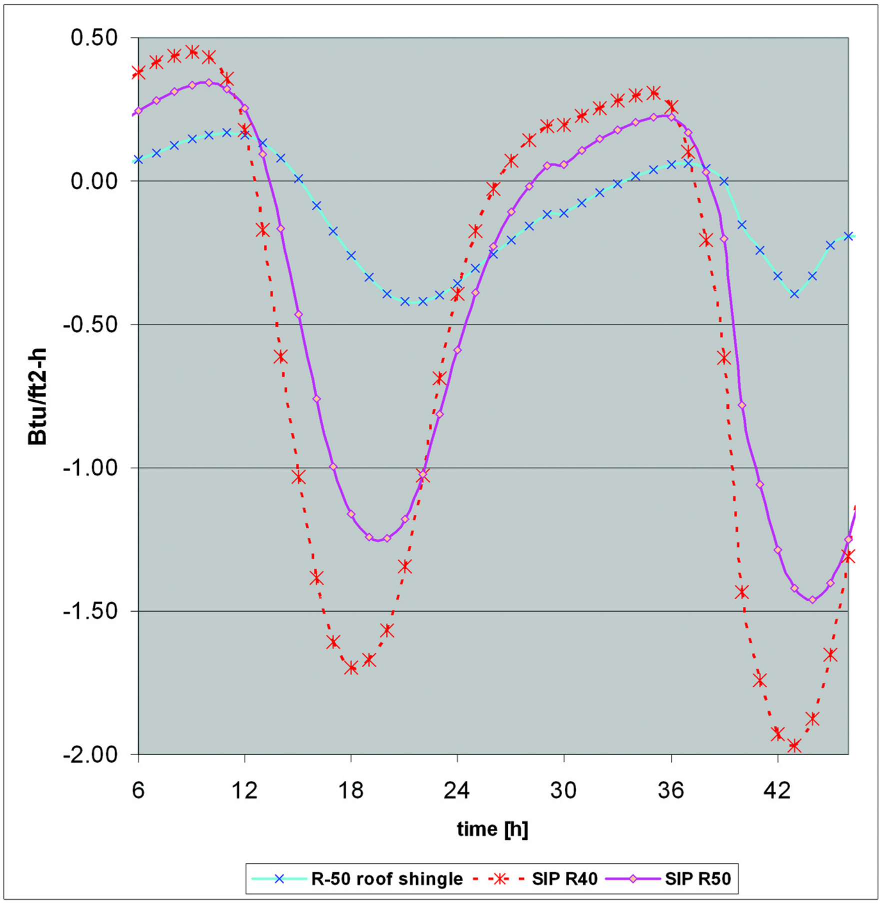

Figure 8 *Comparison of HEAING 7.2-generated cooling loads for sandwiched SIP roofs having two different levels of thermal insulations with loads generated by traditional R-50 attic with shingle roof.*

by several authors (Strzepek 1980; Trethowen 1988; Barbour et al. 1994; Kosny and Christian 1995). Sheathing thermal insulation can also improve building airtightness.

An example of the cathedralized SIP (structural insulated panel) roof is used in this paper to demonstrate the effectiveness of additional foam insulation in improving the thermal performance of building envelopes. Figure 8 shows the change in the roof heat flow as a result of an added R-10 foam insulation to the existing R-40 sandwich roof structure. Using experimental data recorded during two summer days, heat flows in the original R-40 roof and improved R-50 roof have been simulated and compared. It can be seen that, for the considered two sunny days, addition of R-10 to the R-40 roof yielded cooling loads reduction of approximately 15%.

The authors of this paper believe that many alternative configurations that are based on conventional attic design with natural thermal breaks between different layers of building shell can often provide better thermal performance than sandwiched structures. That is why, in addition to the two sandwiched roof configurations shown in Figure 8, a traditional attic containing R-50 insulation (for the sake of comparisons) was simulated. Figure 9 depicts thermal performance differences between sandwiched cathedralized roofs and traditional attics. Results of finite difference simulations performed for the same two summer days showed that average cooling loads simulated for the R-50 attic are about 60% lower compared to the sandwiched assembly of the same R-value (R-50). These results still have to be confirmed in full-scale experimental conditions. However, an explanation for that level of thermal performance difference is relatively simple: attic thermal design works against internal attic air temperature, while sandwiched assembly has to work against the roof surface temperature. As shown in Figure 10, an average attic air temperature is higher and its temperature fluctuations are significantly lower than average roof surface temperature and roof surface temperature fluctuations. This figure shows experimental roof surface temperature and attic air temperature recorded during the third week of July 2008.

However, traditional design of the attic can be improved, as well. In this case, thermal disconnect can be effectively provided in two different locations. Traditionally, the attic floor is insulated using either batt or blown fiber insulation. In

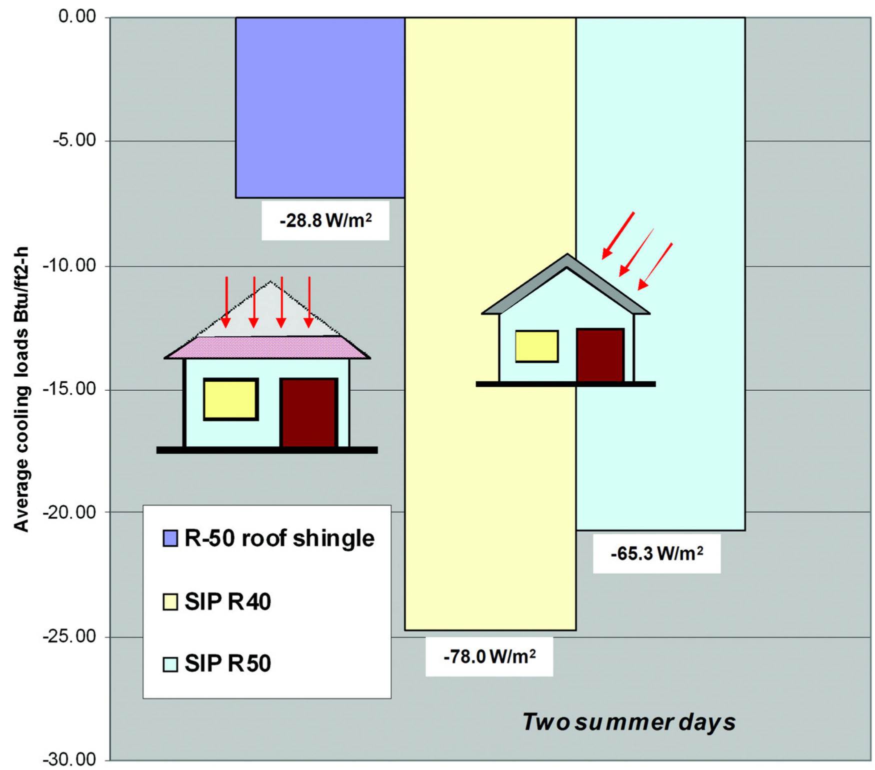

Figure 9 *Comparison of cooling loads of sandwiched SIP roofs and R-50 attic system for two summer days.*

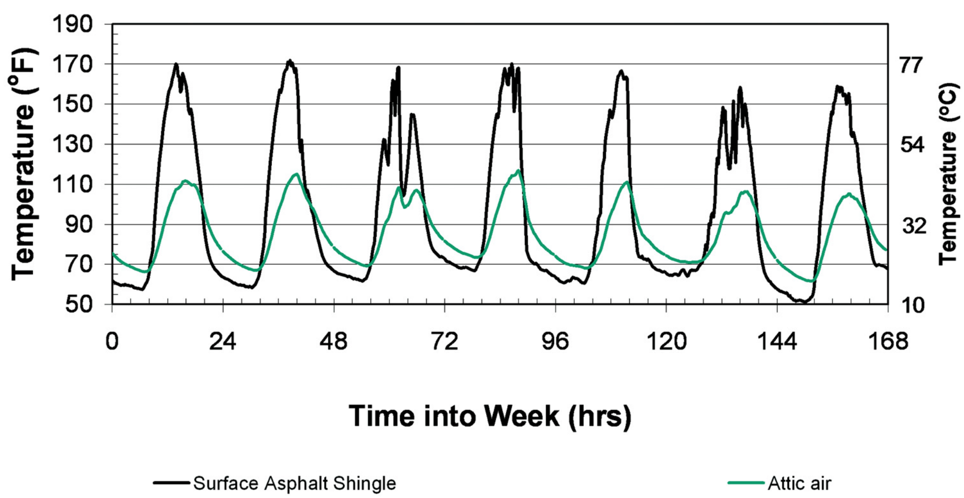

Figure 10 *Average attic air and roof surface temperatures measured during the third week of July 2008.*

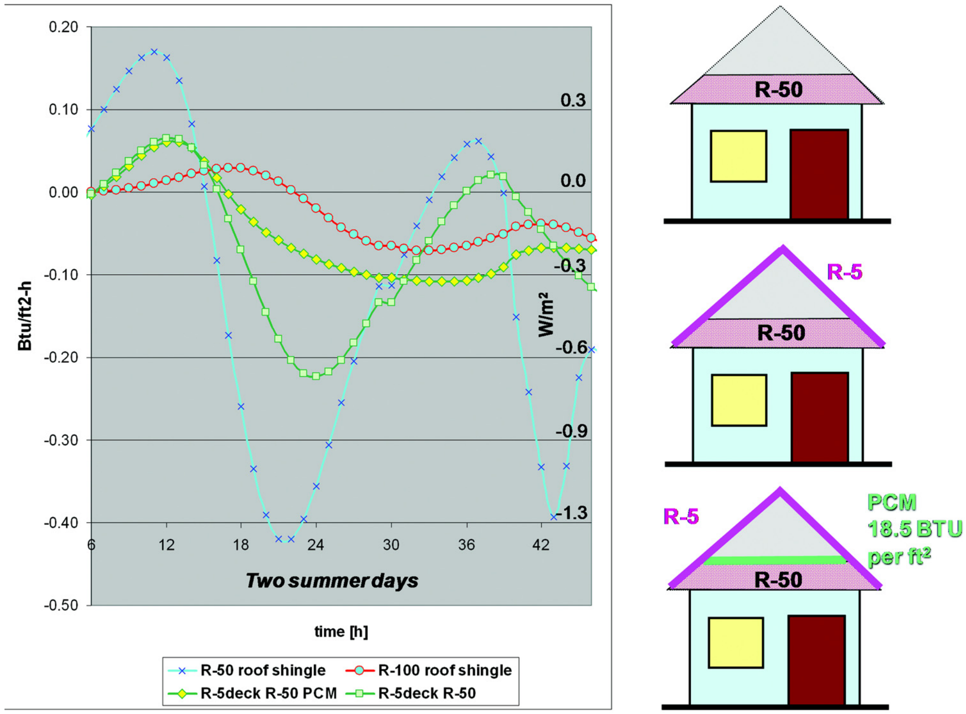

Figure 11 *Comparison of cooling loads of R-50 attic, R-100 attic, R-50 attic + R-5 over the deck, and R-50 attic + R-5 over the deck + PCM systems simulated for two summer days.*

several modern applications, additional thermal insulations are installed over or just under the roof deck. Simulation results presented in Figure 11 demonstrate that additional thermal performance improvements can be expected for the traditional attics using thermal insulation in the roof deck area. A design with extra thermal disconnect using R-5 insulation over the deck demonstrates significant improvements in the average cooling loads when compared to the more traditional R-50 attic configuration having only attic floor insulation. These theoretical predictions have been confirmed by the full-scale field experiments (Miller et al. 2007).

As presented in Figure 11, further improvement in the thermal performance could be achieved by the installation of PCM on the top of the attic insulation. Thermal storage density of this heat sink was approximately 24.9 kJ/(kg·m^2) (18.5 Btu/lb·ft^2). This PCM with melting point of 30°C (87°F) provides additional thermal mass effect and energy savings equivalent to extra insulation. ORNL full-scale laboratory and field testing of PCM-enhanced insulations has already demonstrated great potential for energy savings (Kosny 2008). PCMs used in attics can significantly reduce cooling loads and shift peak-hour loads to later evening or night hours. Figure 11 shows the expected improvement with the PCM addition. PCM gives an equivalent thermal effect of extra R-17, which would require approximately 5 in. of blown fiber insulation. It is also notably shifting peak-hour cooling loads (about 14 hours) into the late night time. This feature is very attractive for energy utility companies. In addition, Figures 11 and 12 compare average loads simulated for the above-mentioned systems with hypothetical R-100 insulation (if there were enough space available to install R-100 insulation). The above-mentioned examples show significant energy savings potential with various modifications of the same attic system, but the proper decision about selection of one of these systems should be based on cost and energy effectiveness analysis. In this modeling exercise, thermal loads generated by the conventional R-50 attic were reduced by about 50% by simple addition of R-5 insulation over or just under the roof deck area. Installation of PCM on top of the attic insulation can generate an additional 13% savings over the improved R-50 attic with extra R-5 insulation. The last configuration with PCM yields energy savings which are only 28% worse than the savings generated in a case of the hypothetical R-100 attic floor insulation.

Results of combined numerical-experimental analysis were generated with the assumption of a perfect attic air seal against the conditioned space below. In case of significant air leakage through the attic floor, real-life results can be significantly different. The ORNL research team is currently validating results presented above using experimental data from four low-energy experimental houses constructed in Oak Ridge, TN.

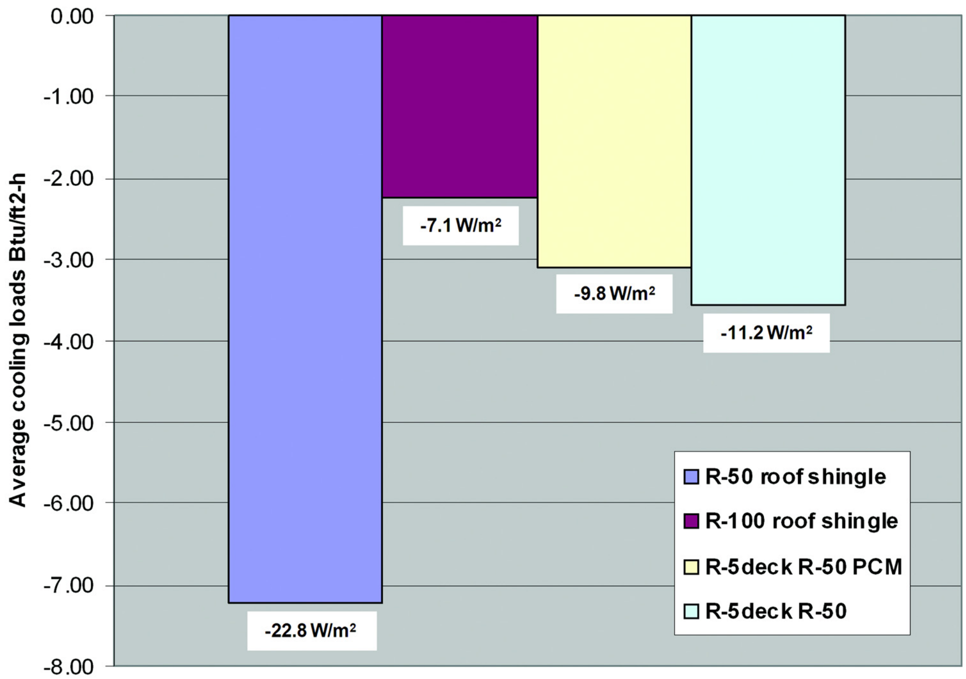

Figure 12 *Comparison of average cooling loads of R-50 attic, R-100 attic, R-50 attic + R-5 over the deck, and R-50 attic + R-5 over the deck + PCM systems simulated for two summer days.*

SUMMARY

This paper describes numerical and experimental analysis of a new type of building envelope technologies, using the energy fluctuations in the surrounding environment to improve overall energy performance. In this paper, thermal disconnect system was defined as a material or system that can control, or control and redirect, the flow of heat between two working surfaces of a building. A well-designed thermal disconnect system not only improves overall thermal resistance but also minimizes transmission of dynamic thermal excitations (by shaving and shifting dynamic loads).

Whole-building energy simulations were used to analyze effectiveness of added conventional thermal insulation in differently insulated building envelopes. Results of energy simulations and limited cost analysis demonstrated that conventional thermal insulation, due to its relatively high cost and diminishing energy benefits, cannot be considered as the only system to achieve improved thermal performance in well- and highly insulated assemblies. Other alternative methods of reducing building thermal loads should be considered, as well.

Results of combined numerical and experimental analysis of several thermal disconnect designs in roofs, attics, and walls were discussed. Thermal performance of conventional attics was compared to the performance of cathedralized roofs. It was found that traditional design of the attic is significantly more efficient. In addition to installation changes within the conventional attic, the following subsystems were considered; optimized insulations, PCM thermal mass, reflective insulations, air gaps, and naturally ventilated cavities. Results of finite-difference modeling demonstrated that an application of thermally disconnected components may bring significant energy savings compared to conventional insulating technologies (very often up to 70% to 90% reductions of peak-hour loads combined with load shifting). Presented experimental results for dynamic attics and walls confirmed numerical predictions.

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