Final Report

Energy Efficient Phase Change Materials (PCM) Insulation
Project Number: EW-201149

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14. ABSTRACT
This project “Energy Efficient Phase Change Materials (PCM) Insulation” demonstrated the application of phase change materials based insulation, an emerging technology, to mitigate energy losses via building envelopes. The idea of mitigating envelope-related energy losses has been at the forefront of the Department of Energy and the Department of Defense High Priority Performance Goals since the Energy Independence and Security of 2007 (EISA 07).

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ACRONYM LIST

AFB	Air Force Base
AFCESA	Air Force Civil Engineer Support Agency
ASHRAE	American Society of Heating refrigeration and Air Conditioning Engineers
ASTM	American Society for Testing Materials
BLCC	Building Life-Cycle Cost
BOID-DPW	Business Operations and Integration Division- Directorate of Public Works
BTU	British thermal unit
CERL	Construction Engineering Research Laboratory
DoD	Department of Defense
DOE	Department of Energy
ECIP	Energy Conservation Investment Program
EI	Engineering Instructions
EISA	Energy Independence and Security Act
EO	Executive Order
EM	Engineering Manual
ESTCP	Environmental Security Technology Certification Program
ERDC	Engineer Research and Development Center
HVAC	Heating, ventilation, and air conditioning
ITTP	Installation Technology Transfer Program
Kwh	Kilowatt-hour(s)
MILCON	Military Construction
MOU	Memorandum of Understanding
NIBS	National Institute of Building Science
NIST	National Institute of Standards and Technology
ORNL	Oak Ridge National Laboratory
PCM	Phase Change Material
SOW	Scope of Work
TI	Technical Instructions
TM	Technical Manual
UFGS	Unified Facilities Guide Specifications
USAF	United State Air Force

1.0 INTRODUCTION

This project “Energy Efficient Phase Change Materials (PCM) Insulation” demonstrated the application of phase change materials (PCM) based insulation, an emerging technology, to mitigate energy losses viabuilding envelopes. The idea of mitigating envelope-related energy losses has been at the forefront of the Department of Energy (DOE) and the Department of Defense (DoD) High Priority Performance Goals since the Energy Independence and Security of 2007 (EISA 07).

1.1 BACKGROUND

The PCM enhanced insulation originally planned to be demonstrated is made by combining cellulose insulation with hard shell polymer microcapsules (2-20 microns in diameter) that contain organic fatty acids and fatty acid esters as core materials. The core materials change phase from solid to a liquid or semi-liquid to prevent excessive heat flow, and maintain comfortable temperatures; they exhibit a “thermal mass effect,” i.e., capacity to store energy, as latent heat. On very hot days the PCM will prevent the outside heat from entering the building by changing phase to soak up the extra heat, thus reducing the cooling load. On cold days, the PCM helps to conserve heat energy from escaping into the walls, by storing that energy as “latent heat.” The latent heat is released back into the building when the temperature drops at night. This demonstration project attempted to show that significantly less energy is required to maintain comfortable temperatures using the PCM insulation under the roof deck, on gables and on knee walls, compared to (1) cellulose insulation under the roof deck, on gables and on knee walls and (2) the currently used R-19 fiberglass insulation only on the attic floor.

The Department of Defense (DoD) currently uses fiberglass insulation in the attic areas above the ceilings as shown in Figure 1. This type of insulation has been used for many years and provides adequate insulation with “R values per inch” of 3 to 5.

Figure 1. Attic in building showing typical fiberglass insulation.

By performing this demonstration, a reduction in energy use provided by using the PCM insulation will show the benefits in using this new technology. The innovative PCM–insulation technology was expected to enhance energy efficiency in heating and cooling buildings in moderate climates, by reducing excess sensible heat in the summer and reducing heat loss in the winter.

1.2 OBJECTIVE OF THE DEMONSTRATION

This project demonstrated the incorporation of phase change materials (PCM), to enhance the effective "R-value" of insulation, thus reducing energy transfer through the ceiling, while maintaining comfortable temperatures for the building occupants. The building was monitored for approximately two years prior to installing the PCM-enhanced insulation – (Phase 1) was spent monitoring the building in its existing condition baseline with fiberglass insulation on the floor of the attic and the second year (Phase 2) was spent monitoring the building in the new insulation configuration baseline with cellulose insulation installed under the roof deck, on gables and on knee walls. The two sets of baseline data were used to help in determining the effectiveness of the PCM insulation and also isolate the impact of the PCM.

In the third year (Phase 3), the PCM insulation was installed, and the building was monitored for one additional year. Models of heat flow for this building were developed, and calculations of the reduction in heat transfer were intended to enable optimal design and engineering of the PCM additive to be used, as well as predictions of the success of the PCM insulation in this application. This innovative passive technology does not require maintenance once installed.

This demonstration project attempted to show that significantly less energy is required to maintain comfortable temperatures using the PCM insulation under the roof deck, on gables and on knee walls, compared to (1) cellulose insulation under the roof deck, on gables and on knee walls and (2) the currently used fiberglass insulation only on the attic floor.

1.3 REGULATORY DRIVERS

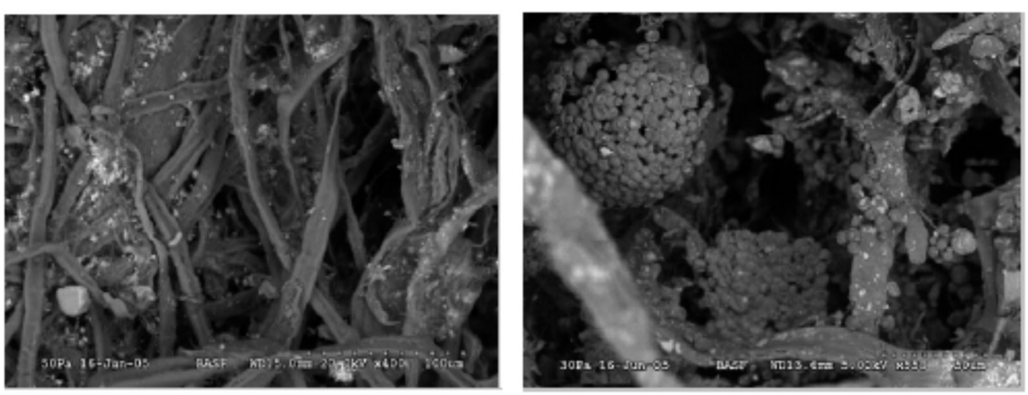
This technology addresses the problem faced by DoD to reduce energy intensity (BTUs per square foot) by 3% per year, or 30% overall, by 2015 from the 2003 baseline, as per the EISA 2007. Under DoD's High Priority Performance Goals, the interim target is an 18% reduction by the end of 2011. Two Executive Orders (E.O.) 13514 (Federal Leadership in Environmental, Energy, and Economic Performance) and 13423 (Strengthening Federal Environment, Energy, and Transportation Management) with goals of fostering markets for sustainable technologies and environmentally preferable materials; design, construct, maintain, and operate high performance sustainable buildings by increasing energy efficiency and reducing energy intensity are also prime drivers for this project. Designing Federal buildings to achieve zero net energy by 2030 is one of the goals of the EO 13423. The Energy Policy Act of 2005 which sets Federal energy management requirement in several areas, including: metering and reporting (by October 1, 2012), and building performance standards will be addressed with this project. By performing this demonstration the team of researchers addresses the reduction in energy needed to reduce the energy intensity (BTUs per square foot) by 3% per year, or 30% overall, by 2015 from the 2003 baseline data, as per the EISA 07.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

Fiberglass or cellulose insulation can be combined with microcapsules that contain organic fatty acids and fatty acid esters, which change phase from solid to liquid or semi liquid to prevent excessive heat flow, and maintain comfortable temperatures. This capability provided by the PCM is known as the "thermal mass effect," i.e., capacity to store energy.

This technology is based on combining PCM with cellulose or fiberglass insulation (Ref. 2, 3), as shown in Figure 2. The PCM is available from Microtek Laboratories, Inc. and is tailored to be integrated into commercially available fiberglass or cellulose insulation. The contents of the small, 2 to 20 micrometer sized microcapsules melt at 78.5 ºF (25.8 ºC), and they are capable of changing phase from solid to liquid and back continuously, thus storing and releasing heat as required. On very hot days the PCM will reduce heat transfer into the building occupant space by changing phase to absorb heat, thus reducing the cooling load. On cold days, the PCM helps to conserve heat energy escaping into the walls, by storing that energy as "latent heat." The latent heat is released back into the building as "sensible heat" when the temperature drops at night. In this way, the insulation can help to maintain comfortable temperatures by providing an additional impediment to heat flow, effectively enhancing the "R" value of the insulation. For example, Oak Ridge National Laboratory's (ORNL) analysis has indicated that conventional attic insulation would have to be greater than R-50 in order to yield the same annual whole house energy consumption compared to a home with R-38 attic insulation with PCM-enhancement (Ref.1).



Cellulose without PCM - visible fire-retardant chemicals.

Cellulose with 30% PCM - visible clusters of PCM pellets.

Figure 2. Cellulose insulation with PCM

For this project, Phase Change Energy Solutions (https://phasechange.com/) was the selected manufacturer of the PCM. The selected contains the phase change material is enclosed between a polymer layer and a foil layer and can be applied in large sheets.

2.1.1 PCM Theory

Phase-change materials are materials that store large amounts of thermal heat as latent heat at its liquid-solid phase-change temperature. This storage of thermal heat also occurs at gas-liquid and gas-solid phase changes, but has drawbacks when compared to liquid-solid phase-change.

An ideal material without phase-change, known as a sensible heat storage material, has a change of temperature that is linearly related to the heat that is absorbed or released. Similarly, a phase-change material follows the same linear relationship above and below its phase-change temperature, but at its phase-change temperature, the temperature remains fairly constant while large amount of heat is either absorbed or dissipated. The heat that is absorbed or released by the phase-change material can be described by the enthalpy function of the material. Enthalpy of a material, h, is dependent upon the integrated function of the specific heat, c_p, which is given by:

$$h(T) = h_{ref} + \int_{T_o}^{T} c_p(T)dT$$

Where, h_{ref} is the reference, or initial, enthalpy. The specific heat function, $c_p(T)$, is integrated from the initial temperature T_o to some variable temperature T.

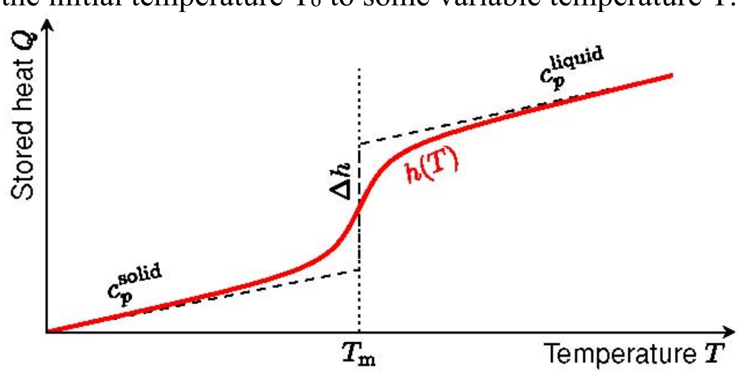


Figure 3. Thermal storage capacity Q(T) of an ideal PCM (dashed) and a real PCM (solid)

Figure 3 details the enthalpy function of a material across a typical phase-change. An ideal phase-change material can be modeled by using the specific heats, c_p, at the liquid and solid states, and a change of enthalpy, Δh, at the T_m, the ideal phase-change temperature. However, real phase-change materials have a broad melting range and the change in enthalpy occurs over a range of temperatures, which is correctly modeled by the enthalpy function h(T).

One of the major difficulties in conducting experimental analysis on phase-change materials is the presence of a temperature gradient in the material. In an ideal experiment, the temperature is assumed to be constant throughout the material, but in reality, the temperature is not constant due to heat transfer limitations, causing a temperature gradient to form in the sample. This problem causes the measured temperature at the surface to be higher than the average temperature of the sample during heating and lower than average temperature of the sample during cooling. When conducting both heating and cooling tests, the real temperature effects on the thermal properties of the sample can be assumed to be between values obtained during heating and cooling tests. Figure 4 illustrates the temperature gradient problem that is present inside phase-change materials.

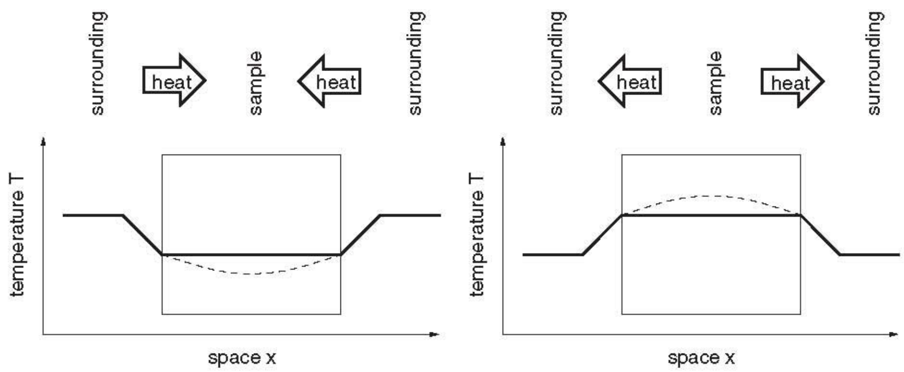


Figure 4. Sketch of the temperature gradient inside the sample during heating (left) and cooling (right).

Since production of insulation already includes the addition of dry chemicals, the addition of a dry PCM component does not require significant changes in the manufacturing or packaging processes. The apparent thermal conductivity of the new material was tested in a heat-flow meter apparatus operated in accordance with ASTM C 518. Dynamic tests in a hot-box facility were also performed. The tests demonstrated that the addition of 30% (all percentages reported by weight) of PCM to the cellulose fibers did not negatively impact the R-value of the insulation. Smoldering Combustion Tests (ASTM C-739) showed that the cellulose-PCM blend did not compromise the fire resistance of the material (Ref. 2, 3).

Dynamic heat-flow apparatus tests were performed on two-inch thick specimens of cellulose insulation and cellulose-PCM blend containing 30% PCM. Heat flow analysis confirmed a thermal mass effect in the PCM-enhanced material. Dynamic hot-box tests with a 40 ºF (22 ºC) thermal ramp, performed on a wood-framed wall insulated with cellulose insulation containing 22% PCM, demonstrated about 40% reduction of the surface heat flow. A field experiment at ORNL showed that peak-hour heat flux was reduced by at least 30% compared with the conventional wall without PCM [with exterior surface temperatures on the Oak Ridge walls cycling between 120°F (49°C) during the days and 55°F (12.7°C) during most nights], as shown in Figure 5.

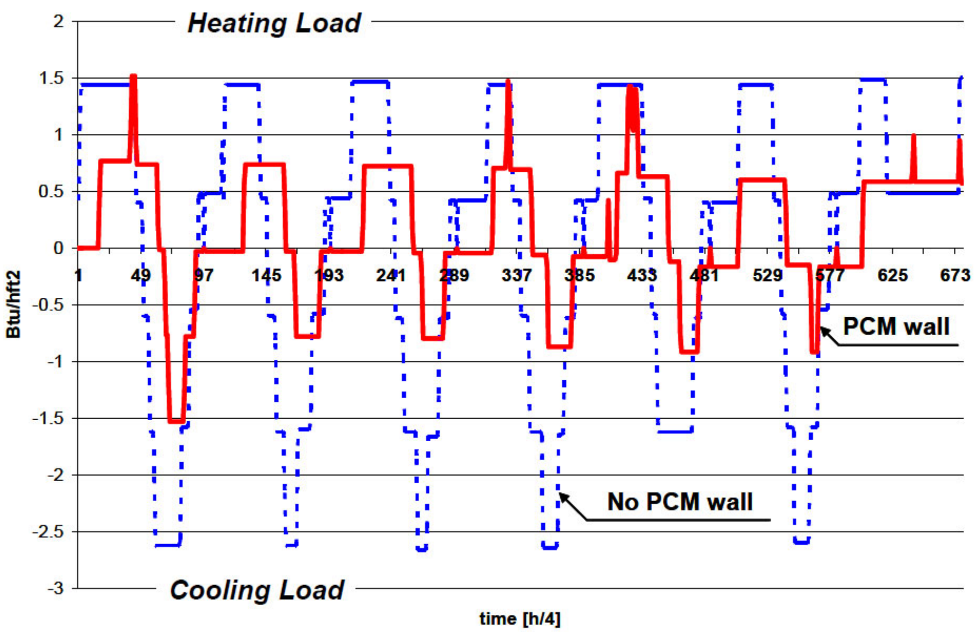


Figure 5. Comparison of surface heat fluxes in cellulose-insulated walls with and without PCM insulation. Note that both heating and cooling loads were reduced by using the PCM insulation.

Chronological summary: During 2005, the first specimens of the cellulose/PCM material were produced at a commercial pilot plant facility operated by Advanced Fiber Technology. The technology was lab-tested and field test at ORNL. A series of flammability tests were performed to ensure that this new material will not cause fire problems (Ref. 4). The technology is now ready for demonstration in an operational environment.

Future potential for DoD: PCM-enhanced insulations have a high potential for successful adoption in U.S. buildings because of their ability to reduce energy consumption for space conditioning and reduce peak loads. Other anticipated advantages of PCMs are improvement of occupant comfort, compatibility with traditional wood and steel framing technologies, and potential for application in retrofit projects.

Anecdotal Observations: This is a passive form of technology; therefore, will require no maintenance. Using the proposed blown-in process techniques allows the applicator to modify the amount of PCM per unit area so that the optimum quantity can be applied, and quickly and easily blend it with the required amount of cellulose which is them blown into the attic space. The total required "space" needed for insulation is reduced by approximately 50%, making more attic space available.

2.1.2 Application

Typical application of PCM insulation in an attic under the roof deck is expected to ensure that the attic functions as a "conditioned space." This thermal environment is generally easier to maintain and more conducive to the efficiency of the HVAC system since the ducts will be operating in more moderate temperatures. Figure 6 shows the unconditioned attic space, with HVAC ducts, at the Ft. Bragg test building. The application of the PCM-enhanced cellulose insulation is shown in Figure 7.

Figure 6. View from attic of Demonstration Bldg. at Ft. Bragg. Left: Cellulose insulation is to be blown in to adhere to the roof deck. Right: HVAC ducts run through the attic.

Figure 7. Typical application of blown-in cellulose insulation

2.2. TECHNOLOGY DEVELOPMENT

Based on results from an Engineer Research and Development Center (ERDC) Direct Funded 6.2 Program (FY11-14) titled "Modeling and Mitigation of Energy Losses in Building Envelopes," and lessons learned during Phase 2 of the subject ESTCP project, it was recommended that the Phase Change Material (PCM) utilized in Phase 3 of the project be changed from micro-encapsulated PCM to an alternative technology, BioPCMats. It was expected that this change will improve the quality of this demonstration by utilizing materials that have been demonstrated in the laboratory to have suitable ruggedness and durability. Further, this alternative resulted in decreased labor associated with retrofit costs and enhance the potential for rapid technology transfer.

The ERDC Direct Program investigated stability of microencapsulated PCM and BioPC Mats over long term (20 year) simulated aging cycles. Stability of the barrier material, latent heat, and PCM chemical composition were monitored at multiple times during the simulated aging cycle. Within six years of simulated aging, it was observed that the barrier material of microencapsulated PCM exhibited nearly complete degradation, latent heat was reduced from 180 to 130 J/g, and the chemical composition of the PCM (as indicated by thermogravimetric analysis) was altered. Over 20 years of simulated aging, the BioPCMat barrier material remained intact, latent heat was reduced from 130 to 115 J/g, and no discernible chemical degradation was observed.

The DoD annual estimated energy intensity for heating and cooling, is estimated to be $1.6B, out of which roofing contribution is 30% or $480M. The use of BioPCMat was expected to reduce this energy use by 30% or $144M/year. Over the 40 year lifetime of all DoD buildings, the life cycle savings is projected to be $5.8B. By implementing the technology at just 20% of all DoD installations, the cost savings projected to be $1.2B over the installation buildings' lifetimes, compared to the currently used insulation technologies. The annual savings is expected to be $30M.

2.3 ADVANTANGES AND LIMITATIONS OF THE TECHNOLOGY

Cost Advantages:
Based on research conducted by ORNL using this technology, it is projected that the 30% of the annual heating and cooling energy consumption could be mitigated by retrofit of the attic with the PCM insulation. Since electricity cost 8 cents per Kwh, the annual energy savings for heating and cooling the building would be $384. Using the National Institute of Standards and Technology (NIST) Building Life-Cycle Cost (BLCC) Program for MILCON Analysis: ECIP Project, the simple payback is 2.27 years, and the 10-year savings-to-investment ratio is 3.37, while the 20-year savings-to-investment ratio is 6.26

Conventional cellulose attic insulation would have to be greater than R-50 at a cost of $16,200 in order to yield the same annual whole building energy consumption compared to a home with R-38 attic insulation with PCM-enhancement, at a cost of $12,720.

Social Acceptance: The PCM insulation will be installed above the ceiling and will not be seen by anyone other than the contractor installing the insulation. This is a passive technology where the building occupants will not see the PCM insulation. No maintenance is required once the PCM insulation is installed.

Performance Limitations:

The PCM technology, is considerably more expensive than conventional fiberglass insulation due to the cost of the PCM component. This added first cost may be offset within by the reduction in energy bills for heating and cooling due to the efficacy of the insulation.

In order to be cost effective, PCM should only be used in climates and constructions where ambient temperatures allow it to undergo frequent phase transitions. For example, PCM-insulation will be most effective for climates in ASHRAE Climate Zones 3-5, i.e., about 50% of the US, and will be limited to use in these areas (See Figure 8). These are relatively moderate climate zones, where at certain times during the year (especially spring and autumn) there are days with day-time temperatures above 75ºF and night-time temperatures below 65ºF. In such situations, the PCM insulation will store heat during the day and release it at night. In summer, at temperatures greater than 80ºF the PCM will melt and reduce the sensible heat in the attic. PCM will not be effective in the winter months, as it will not change phase. It is thus not effective in colder climates (e.g, Zones 6-8). If used in hot climates (e.g., Zones 1 and 2), it will remain in a melted state most of the time, and rarely solidify.   PCMs should be used in conjunction with insulation, but not in attics with radiant barriers installed.

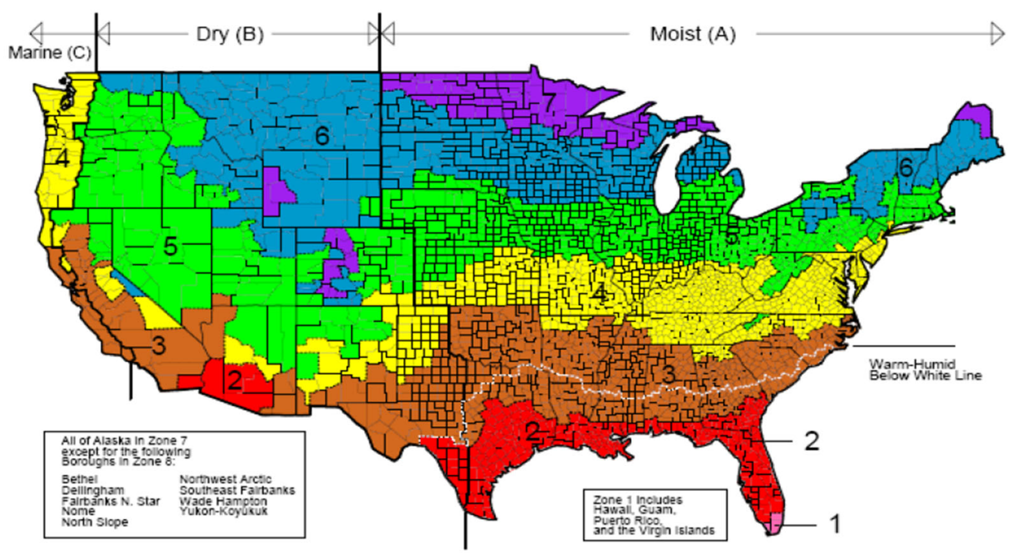


Figure 8. ASHRAE climate zones

3.0 PERFORMANCE OBJECTIVES

The new insulation configuration is expected to reduce heat flux through the building attic by 25% over the course of a full year when compared to the current configuration. Addition of PCM is expected to further reduce heat flux by 5%. Significant efficiency improvements are anticipated by incorporating the HVAC system ducting into the thermal envelope of the building, thereby reducing heating and cooling losses in ducts.

The innovative PCM–insulation technology is expected to enhance energy efficiency in heating and cooling buildings in moderate climates, by reducing excess sensible heat in the summer and reducing heat loss in the winter, in support of EO 13423. A key benefit of the PCM technology is the ability to shift peak load demand in buildings. This allows for cost savings by shifting energy usage outside of the peak demand window. Use of the new insulation configuration with PCM can help to mitigate peaks in demand, thereby reducing the total required electric supply capacity. This is particularly advantageous when coupled with renewable energy technologies, as it can reduce costs associated with storage of energy. The PCM insulation technology can easily be installed as a retrofit or used in new construction in typical barracks, training facilities, healthcare clinics, and command, control and administration buildings.

3.1 "TABLE 1" SUMMARY OF PERFORMANCE OBJECTIVES

The data to analyze the performance objectives will be tracked for (1) the existing condition baseline, (2) the new insulation configuration baseline and (3) the new insulation configuration using PCM. Success criteria in Table 1 compare the new insulation configuration without PCM and the new insulation configuration with PCM to the existing R-19 fiberglass batt insulation. Cost calculations compare the cost of installing 3,500 sq. ft. of fiberglass batt insulation on the attic ceiling to the cost of the new insulation configuration without PCM and with PCM.

Table 1. Summary of Performance Objectives

Performance Objective	Metric	Data Requirements	New Insulation Configuration (no PCM)	New Insulation Configuration (with PCM)
Heat Lost or Gained by Attic	Year-Averaged Heat Flux	Watt/m^2	25% Reduction	30% Reduction
Annual Attic Heating Load	Reduction in Attic/Roof Generated Heating Load	Electricity (kBtu)	50%	50%

Performance Objective	Metric	Data Requirements	New Insulation Configuration (no PCM)	New Insulation Configuration (with PCM)
Annual Attic Cooling Load	Reduction in Attic/Roof Generated Cooling Load	Electricity (kWBtu)	20%	25%
Load Reduction	Peak Demand Shift	hours	0 hr	> 1 hr
Load Reduction	Peak Demand Reduction in Roof Heat Flux (during cooling)	Watt/m^2	25%	35%
Foot Print	Increase in area needed for operation	m^2	= 0 m^2	= 0 m^2
System Economics	Years to Payback, Simple Payback Period (SPP), Savings to Investment Ratio (SIR)	$ costs	Payback= 9 years SPP=4.6 SIR=2.55	Payback= 22 years SPP = 12.3 SIR=1.1
Availability	Time ready to operate: Insulation system	Days/year	365 days/year	>300 days/year
Reliability	Time system performs as expected: Insulation system	Years	40 years	40 years
Stability of Design	Number of post-design changes: Insulation system*	Number of adjustments	= 0*	= 0*
Usability	Number of hours for training/maintenance: Insulation system	hours/year	= 0 hours/year	= 0 hours/year
Safety	Number of accidents/injuries	Number of events	0	0
Security	Vulnerability to theft/damage/destruction		No significant change from present	No significant change from present
Scalability	Number of Installations across DoD that could benefit	# of DoD installations in Climate zone 3-5	95	95
Attic Temperature Range Reduction	Load reduction for building's HVAC system	Temperature reduction in attic space	>20F spring and summer reduction during daytime >10F spring increase at night	>20F spring and summer reduction during daytime >10F spring increase at night

Performance Objective	Metric	Data Requirements	New Insulation Configuration (no PCM)	New Insulation Configuration (with PCM)
Behavior Change			No Change	No Change
Anecdotal Observations*	perspectives from building operators, Directorate of Public Works, and maintenance personnel	Survey data	30% increase in satisfaction	30% increase in satisfaction

NOTES:

1) "Heat Lost of Gained by Attic," "Annual Attic Heating Load," and "Annual Atic Cooling Load" values are based on simulations using *Attic Sim* modeling package.
2) For "System Economics" - a discount rate of 3% is used and material lifetime of 40 years is assumed. SPP is calculated as (total investment/first-year savings). SIR is calculated as (total discounted operation savings/total investment). Calculations assume that heating and cooling losses in HVAC ducting will be reduce by 50% of the current value by enclosing the HVAC ducts in the thermal envelope. This is estimated as 10% of the total HVAC system load. Payback calculations assume that PCM cost will be reduced by 66% due to economy of scale.
3) "System Integration" brings subsystems together and ensures they behave in a satisfactory manner.
4) Stability of design – Lessons learned may be used to adjust insulation/PCM design after the demonstration, when transferring technology to other installations.
5) User Satisfaction – survey and/or interview results describing the user's attitude and/or opinion toward the added value of the technology.

*For "System Economics" - Refer to the NIST Building Life Cycle Cost program, available on the DOE website:
http://www1.eere.energy.gov/femp/information/download_blcc.html#blcc

4.0 FACILITY/SITE DESCRIPTION

The insulation will be installed in the attic of Ft. Bragg, NC Directorate of Public Works Classroom Building (Building 3-2232), shown in Figure 9, to insulate the inner roof deck. This 3,500 square foot building currently has R-19 fiberglass insulation above the ceiling on the attic floor which will be removed prior to installing the new insulation configuration. Visual inspection of the facility indicated that significant disruption to the insulation on the attic floor has occurred since it was installed, with many batts being compressed, rolled back, or removed entirely. Due to the location of the fiberglass batt insulation, it is often necessary to disturb or entirely remove insulation to service the HVAC system and electrical fixtures. This test building is located in ASHRAE Zone 3.

Figure 9. Ft. Bragg Building 3-2232 where the Energy Efficient Phase Change Materials (PCM) Insulation was demonstrated

4.1 FACILITY/SITE SELECTION CRITERIA

The facility site selection is based on the proximity to the Department of Public Works office (DPW), the availability of the building for easily installing instrumentation without interruption to normal use, the typical R-19 fiberglass insulation in the ceiling, and the size of the building.

In addition, the Ft. Bragg DPW Office has demonstrated cooperation of several demonstration projects related to emerging technologies that reduce corrosion in recent years.

4.2 FACILITY/SITE LOCATION AND OPERATIONS

The building selected for this demonstration is in Ft. Bragg, NC known as Directorate of Public Works Classroom Building (Building 3-2232). The building is located near the DPW headquarters so it can be easily accessed if any problems with monitoring should arise. This 3,500 square foot building is used for training purposes; therefore availability for installing, monitoring and retrofitting with the new PCM insulation will be completed when there is no classroom instruction and thus no interruption to normal building use. As this building is a training facility, it is vacant at night, and normally occupied only Monday-Friday about 80% of the year.

4.3 FACILITY/SITE CONDITIONS

Ft. Bragg is located adjacent to Fayetteville, NC. Because Ft. Bragg, NC is located in the Northern most part of Zone 3, it is considered a "swing" climate with relatively mild winters (average temperature of 40ºF), but hot summers (average temperature= 85ºF), with Spring and Autumn days when days are warm (70ºF) and nights are cool (55ºF). This site provides the ideal opportunity to measure the ability of the PCM-enhanced cellulose insulation to reduce the heat flux through the attic, especially during the hot summers. During the more temperate days in autumn and spring, the PCM is expected to be most effective, since it will store excess heat during the hotter hours, and release some of that heat during the cooler nights in order to maintain comfort levels. It is expected that this site will provide about 120 days per year where these conditions are present.

4.4 SITE-RELATED PERMITS AND REGULATIONS

No site related permit or regulations will be required. DPW's permission and authorization will be obtained before any work is done. A contractor certified in the application of phase change material and blown-in cellulose insulation will be contracted.

5.0 TEST DESIGN

The application replaced the existing R-19 fiberglass batt insulation currently on the floor of the attic with the cellulose-PCM blend on the underside of the roof sheathing, and at the gables and knee walls. The PCM cellulose was expected to have advantages over the existing R-19 fiberglass insulation, due to thermal mass effect. We estimated that the peak demand reduction in roof heat flux will be improved 35% from the existing condition baseline and 13% from the new insulation configuration baseline when using PCM. .

ERDC-CERL and ORNL measured the energy benefits separately of (Phase 1) placing blown-in cellulose insulation without PCM under the roof deck and on gables and knee-walls to create a conditioned space in the attic and (Phase 2) the benefits of adding PCM to the cellulose insulation. In each case, the cellulose insulation will be 10 inches thick, equivalent to R-38.

The team measured differences in temperatures and heat fluxes using a suite of instruments, flush with the roof deck (underneath the insulation, when installed) and suspended above the insulation. The energy use of the building was measured for each of the three phases. Periodic infrared inspections were conducted to determine if there is any degradation in performance of the PCM. Inspections will checked for any separation of PCM from insulation and settling of the insulation.

The impact of installing both insulation variations wasquantified by the reduction in unwanted heat entering the attic on hot days and heat escaping through the attic on cold days. Heat flux transducers installed in the attic underneath the roof deck provided this measurement. Also, the reduction in electric energy necessary to operate the building's heat pump was compared before and after installation of the PCM-insulation.

5.1 CONCEPTUAL TEST DESIGN

There was four instrumentation packages installed under the roof deck, two on each side of the pitched roof. Each package will consist of a heat flux transducer, five thermistors, and two relative humidity sensors, and will be installed under the roof deck. In each set, thermistors and RH sensors were installed across the thickness of the roof deck and insulation (once installed), starting from the underneath the shingles to the surface facing the attic. Also in each package a heat flux transducer will measure the heat flux through the deck and through the insulation when it is installed.

Differences in heat flux and temperatures helped quantify the efficacy of the insulation. The energy usage in the building was documented from metered data available from the Ft. Bragg DPW Office.

5.2 BASELINE CHARACTERIZATION

Thermistors were placed to measure parameters including: outdoor temp, roof outdoor surface temp, roof under-deck temp, attic space temp, and indoor temp. The building was monitored in the current configuration, with R-19 fiberglass batt insulation on the floor of the attic. This constitutes the existing condition baseline. After the first year the fiberglass insulation on the attic floor was removed, and replaced by cellulose insulation, with and without PCM, as described below.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The design of the PCM-enhanced insulation was not necessary since this product is in the market. Phase Change Energy Solutions (https://phasechange.com/) was the selected manufacturer of the PCM. The selected product had the following characteristics.

Table 2. PCM Characteristics

Property	Value
Specific heat	2.1 kJ/kg-K
Latent heat	200 J/g
Thermal conductivity	0.2 W/m/K

Figure 10: BioPCM sample

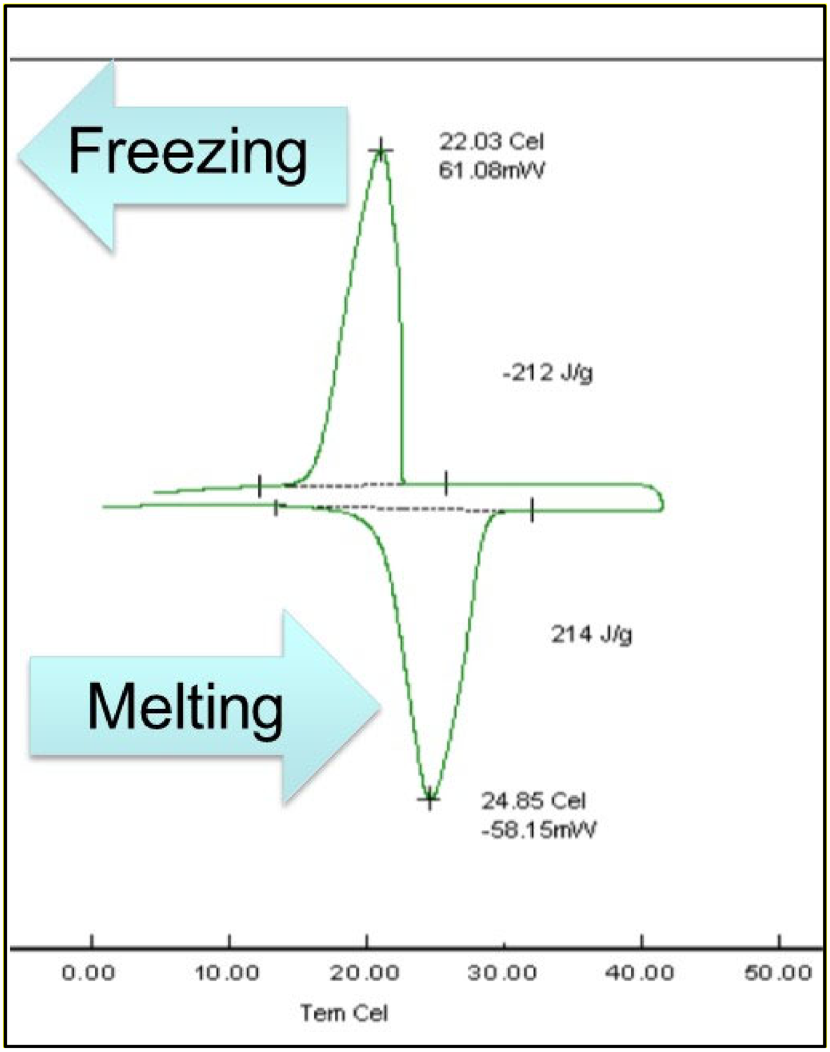


Figure 11. PCM melting and freezing characteristics

Table 3. PCM melting and freezing characteristics

	Freezing Temperature	Melting Temperature
Start	23.1ºC (73.6ºF)	20.6ºC (69.1ºF)
Nominal	22.0ºC (71.6ºF)	24.8ºC (76.6ºF)
End	17.2ºC (63.0ºF)	28.2ºC (82.8ºF)

5.4 OPERATIONAL TESTING

A team of researchers from DOE's Oak Ridge National Laboratory (ORNL) and U. S. Army ERDC installed various sensors for monitoring the temperatures, heat flux and weather data at test site, i.e., Bldg 3-2232 (Training Classroom Bldg. Ft. Bragg). A weather station was mounted on the East end of the building's roof, approx. 2 feet above the roof surface. The weather station consists of two devices mounted along a horizontal mast: (1) WST-520 Vaisala instrument suite, and (2) Huskeflux NR01 solar radiation instrument (consisting of a flux pyrgeometer for LW far infrared solar flux, and a pyranometer for measuring short wave solar radiation).

In addition, 2 Licor pyranometers were mounted along roof gable at the East end to measure the solar radiation impinging on the sloped roof. The Vaisala instrument suite consists of a wind velocity indicator, a precipitation gauge, barometric pressure indicator, and temperature and relative humidity indicator. The weather station will be electrically grounded to protect against lightning strikes.

Inside of the building on the classroom side, heat flux transducers (by Engineering Concepts) were installed in four locations in the attic just underneath the roof deck, two on the North side and two on the South side. In addition, two heat flux transducers were installed in the attic against the walls, where they intersect with the roof, one of the North side and the other on the South side. These transducers are 1.5 inch square and mounted to OSB, which in turn mounted directly against the roof deck or wall surfaces. All of those six heat flux transducers were mounted on the interior side of the roof deck or the interior wall above the classroom portion of the building. Two more heat flux transducers were attached to the ceiling (attic floor), one each in the eastern and western halves of the attic. Four instrumentation packages consisting of 1 heat flux transducer (HFT), 5 thermistors, and 3 RH sensors were installed on the roof of the building. Data was sampled every 15 seconds and averaged of 60 seconds.

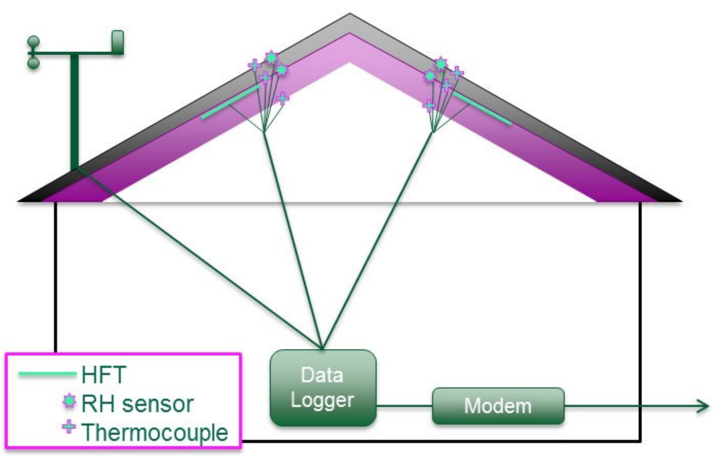


Figure 12. Instrumentation of building 3-2232

5.5 DATA SAMPLING PROTOCOL

Heat flux, temperature, and weather data before and after installation of the PCM-enhanced insulation were sampled 15 seconds, and averaged over 60 seconds during the demonstration period in order to provide the necessary measurements to measure the impact of the demonstrated technology. Data analysis was determined by stochastic analysis of energy used, along with weather data, which will be analyzed in "EnergyPlus" to determine changes in energy usage due to differences in insulation installed.

The following data was collected as per Tables 4-8: (a) 35 temperature readings, (b) 22 relative humidity readings, (c) 8 heat flux readings, (d) 10 solar variables sensors, and (e) 9 weather variable sensors.

Table 4. Temperature Sensors and their Locations at Ft. Bragg ESTCP Demonstration Site

Running Count	Sensor Type	Sensor Name	Location/ Panel	Physical Location	Notes
1	Temperature	T_Shingle_RF_SE	Roof SE	Roof surface (under shingle)	RF=roof
2	Temperature	T_Deck_RF_SE	Roof SE	Roof deck surface inside attic	WL=wall
3	Temperature	T_InsulMid_RF_SE	Roof SE	Middle of insulation (attic)	RM=room
4	Temperature	T_InsulSurf_RF_SE	Roof SE	Insulation surface (attic)	N=north
5	Temperature	T_Attic_RF_SE	Roof SE	Attic air	S=south
6	Temperature	T_Shingle_RF_SW	Roof SW	Roof surface (under shingle)	W-west
7	Temperature	T_Deck_RF_SW	Roof SW	Roof deck surface inside attic	E=east
8	Temperature	T_InsulMid_RF_SW	Roof SW	Middle of insulation (attic)	
9	Temperature	T_InsulSurf_RF_SW	Roof SW	Insulation surface (attic)	
10	Temperature	T_Attic_RF_SW	Roof SW	Attic air	
11	Temperature	T_Shingle_RF_NE	Roof NE	Roof surface (under shingle)	
12	Temperature	T_Deck_RF_NE	Roof NE	Roof deck surface inside attic	
13	Temperature	T_InsulMid_RF_NE	Roof NE	Middle of insulation (attic)	
14	Temperature	T_InsulSurf_RF_NE	Roof NE	Insulation surface (attic)	
15	Temperature	T_Attic_RF_NE	Roof NE	Attic air	
16	Temperature	T_Shingle_RF_NW	Roof NW	Roof surface (under shingle)	
17	Temperature	T_Deck_RF_NW	Roof NW	Roof deck surface inside attic	
18	Temperature	T_InsulMid_RF_NW	Roof NW	Middle of insulation (attic)	
19	Temperature	T_InsulSurf_RF_NW	Roof NW	Insulation surface (attic)	
20	Temperature	T_Attic_RF_NW	Roof NW	Attic air	
21	Temperature	T_Stucco_WL_S	Wall S	Between gypsum & stucco (attic wall)	
22	Temperature	T_Gyp_WL_S	Wall S	Gypsum surface (attic wall)	
23	Temperature	T_InsulMid_WL_S	Wall S	Middle of insulation (attic wall)	
24	Temperature	T_InsulSurf_WL_S	Wall S	Insulation surface (attic wall)	
25	Temperature	T_Attic_WL_S	Wall S	Air at attic wall	
26	Temperature	T_Stucco_WL_N	Wall N	Between gypsum & stucco (attic wall)	
27	Temperature	T_Gyp_WL_N	Wall N	Gypsum surface in attic (wall)	
28	Temperature	T_InsulMid_WL_N	Wall N	Middle of insulation (attic wall)	
29	Temperature	T_InsulSurf_WL_N	Wall N	Insulation surface (attic wall)	
30	Temperature	T_Attic_WL_N	Wall N	Air at attic wall	
31	Temperature	T_Air_RM_E	Room E	Classroom wall	
32	Temperature	T_Air_RM_W	Room W	Classroom wall	
33	Temperature	T_T_Spare_1	-	spare	-
34	Temperature	T_T_Spare_2	-	spare	-
35	Temperature	T_T_Spare_3	-	spare	-

Table 5. Relative Humidity Sensors and their Locations at Ft. Bragg ESTCP Demonstration Site

Running Count	Sensor Type	Sensor Name	Location/ Panel	Physical Location	Notes
1	RH	RH_Deck_R_SE	Roof SE	Roof deck surface inside attic	RF=roof
2	RH	RH_InsulMid_RF_SE	Roof SE	Middle of insulation (attic)	WL=wall
3	RH	RH_Attic_RF_SE	Roof SE	Attic air	RM=room
4	RH	RH_Deck_RF_SW	Roof SW	Roof deck surface inside attic	N=north
5	RH	RH_InsulMid_RF_SW	Roof SW	Middle of insulation (attic)	S=south
6	RH	RH_Attic_RF_SW	Roof SW	Attic air	W-west
7	RH	RH_Deck_RF_NE	Roof NE	Roof deck surface inside attic	E=east
8	RH	RH_InsulMid_RF_NE	Roof NE	Middle of insulation (attic)	
9	RH	RH_Attic_RF_NE	Roof NE	Attic air	
10	RH	RH_Deck_RF_NW	Roof NW	Roof deck surface inside attic	
11	RH	RH_InsulMid_RF_NW	Roof NW	Middle of insulation (attic)	
12	RH	RH_Attic_RF_NW	Roof NW	Attic air	
13	RH	RH_Gyp_WL_S	Wall S	Gypsum surface in attic (wall)	
14	RH	RH_InsulMid_WL_S	Wall S	Middle of insulation (attic wall)	
15	RH	RH_Attic_WL_S	Wall S	Air at attic wall	
16	RH	RH_Gyp_WL_N	Wall N	Gypsum surface in attic (wall)	
17	RH	RH_InsulMid_WL_N	Wall N	Middle of insulation (attic wall)	
18	RH	RH_Attic_WL_N	Wall N	Air at attic wall	
19	RH	RH_Air_RM_E	Room E	Classroom wall	
20	RH	RH_Air_RM_W	Room W	Classroom wall	
21	RH	RH_Spare_1	-	Spare	
22	RH	RH_Spare_2	-	Spare	

Table 6. Heat Flux Sensors and their Locations at Ft. Bragg ESTCP Demonstration Site

Running Count	Sensor Type	Sensor Name	Location/ Panel	Physical Location	Notes
1	Heat flux	HF_Deck_RF_SE	Roof SE	Roof deck surface inside attic	RF=roof
2	Heat flux	HF_Deck_RF_SW	Roof SW	Roof deck surface inside attic	WL=wall
3	Heat flux	HF_Deck_RF_NE	Roof NE	Roof deck surface inside attic	RM=room
4	Heat flux	HF_Deck_RF_NW	Roof NW	Roof deck surface inside attic	N=north
5	Heat flux	HF_Gyp_WL_S	Wall S	Attic wall surface inside attic	S=south
6	Heat flux	HF_Gyp_WL_N	Wall N	Attic wall surface inside attic	W-west
7	Heat flux	HF_Ceil_W_g	Ceiling	Ceiling_West	E=east
8	Heat flux	HF_Ceil_E_b	Ceiling	Ceiling_East	

Table 7. Solar Variable Sensors and their Locations at Ft. Bragg ESTCP Demonstration Site

Running Count	Sensor Type	Sensor Name	Location/ Panel	Physical Location	Notes
1	Pyranometer	Solar_RF_South	South Roof	Roof surface, South roof slope	RF=roof
2	Pyranometer	Solar_RF_North	North Roof	Roof surface, Nouth roof slope	WL=wall
3	Pyranometer	Solar_Total_Up	Roof	~4ft above roof surface east end	RM=room
4	Pyranometer	Solar_Total_Dn	Roof	~4ft above roof surface east end	N=north
5	Pyrgeometer	Solar_IR_Up	Roof	~4ft above roof surface east end	S=south
6	Pyrgeometer	Solar_IR_Dn	Roof	~4ft above roof surface east end	W-west
7	Pyranometer	SR01Up	Roof	NE Roof	E=east
8	Pyranometer	SR01Dn	Roof	NE Roof	
9	Pyrgeometer	IR01Up	Roof	NE Roof	
10	Pyrgeometer	IR01Dn	Roof	NE Roof	

Table 8. Weather Variable Sensors and their Locations at Ft. Bragg ESTCP Demonstration Site

Running Count	Sensor Type	Sensor Name	Location/ Panel	Physical Location	Notes
1	Temp	NR01TC	Roof	NE Roof	RF=roof
2	Wind	Wind_Dir	Roof	NE Roof	WL=wall
3	Wind	Wind_Speed	Roof	NE Roof	RM=room
4	Temp	T_Outdoor	Roof	NE Roof	N=north
5	RH	RH_Outdoor	Roof	NE Roof	S=south
6	Pressure	BarP	Roof	NE Roof	W-west
7	Rain	Rain_Total	Roof	NE Roof	E=east
8	Rain	Rain_Hits	Roof	NE Roof	
9	Temp	PTemp	Roof	CR1000 wiring panel	

6.0 PERFORMANCE ASSESSMENT

ERDC-CERL and ORNL measured the energy benefits of the retrofits with cellulose-only insulation and PCM-enhanced insulation by installing a suite of instruments, which will measure temperatures and heat fluxes at various locations in the attic. There will be 4 instrumentation packages installed under the roof deck, 2 on each side of the pitched roof. The packages consisted of a heat flux transducer, 5 thermistors, and 2 relative humidity sensors, and will be installed under the roof deck. Thermistors will also be placed to measure several other parameters including: outdoor temp, roof outdoor surface temp, roof under-deck temp, attic space temp (which will be semi-conditioned after install of PCM-insulation), and indoor temp.

Also, metered energy usage, monthly energy bills and annual energy bills for the building before installation of the insulation (and PCM-loaded insulation) will be compared with the monthly and annual energy bills after installation of cellulose insulation and after the installation of the PCM-enhanced cellulose insulation. In each case, the occupancy rates of the buildings and temperature set-points, will be taken into consideration. Data collected, including heat flux, temperature data, and weather data was used as inputs to EnergyPlus to help analyze in detail the differences in energy required for heating and cooling the building due to cellulose insulation and PCM-cellulose insulation on the roof deck compared to the existing condition baseline case with insulation at the attic floor and no insulation on the roof deck.

PCM Testing

Samples of PCM-insulation were tested in laboratory measurements using a Laser Comp 801 and differential scanning calorimetry (DSC), as shown in Figure 13, and the results will be compared with the data taken from the measurements in the field.

The results of these tests of the candidate PCM-insulation materials were used to determine their relative abilities and the estimated service life, as predicted by the number of cycles for which their performance remains unchanged. The number of cycles will be set to simulate at least 40 years.

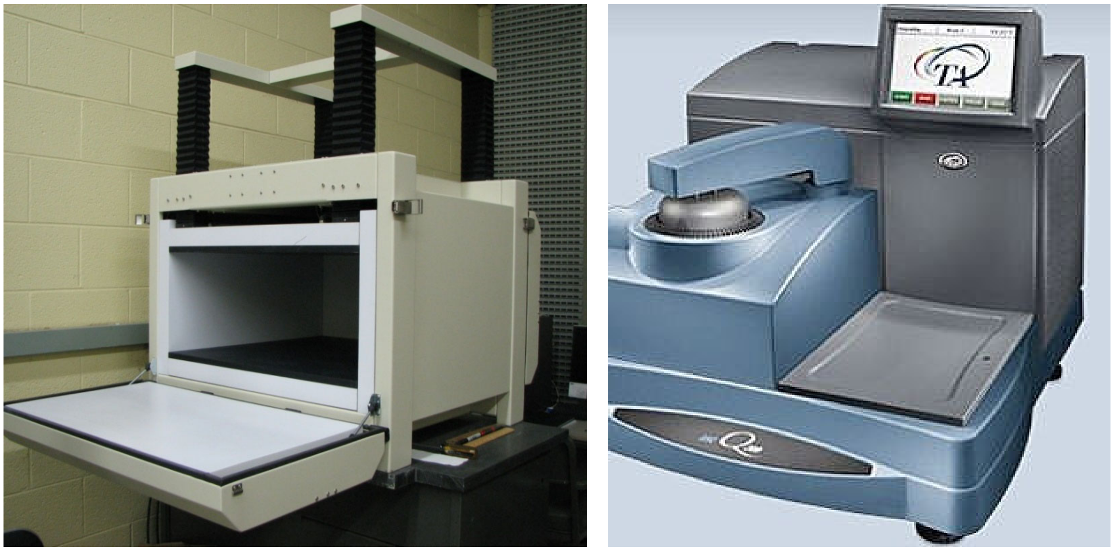


Figure 13. Laser Comp 801 thermal conductivity instrument and Differential scanning calorimeter (DSC) for phase change materials (PCM)

Differences in heat flux and temperatures were used to determine the efficacy of and advantages of the insulation. These measurements were taken in accordance with ASTM Standard C518, Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.

In the experimental analysis of phase-change materials, there are several different methods that are used to calculate the enthalpy and specific heat functions of a material while overcoming the problem of a temperature gradient being present. For microscopic, homogenous samples of phase-change materials, there are three different methods to measure the thermal properties: dynamic, step, and T-history method. Both the dynamic and step methods can be implemented by a differential scanning calorimeter (DSC). The T-history method typically uses a custom made apparatus not available for this research, and will not be further discussed. The dynamic and step methods can also be to experimentally measure insulations that incorporate phase-change materials. While conducting a test on a DSC with either the dynamic or step methods, the DSC outputs voltage signal that is proportional to the thermal response of the sample.

The dynamic method is the most widely used testing method that uses a constant heating or cooling ramp with a constant rate. Typical heating and cooling rates for measurements range from 2 K/min to 10 K/min. As the heating and cooling rate increases, the enthalpy determination becomes more accurate, but the uncertainty of the temperature increases greatly. The increase uncertainty of the temperature is caused by the internal temperature gradient of the sample increasing in magnitude. The dynamic method uses three different measurements with the crucible empty, filled with a standard material, and filled with a sample material, all using the same constant heat or cooling rate to find the specific heat function. The specific heat function of the sample material is given by:

$$c_{p,sample}(T) = c_{p,standard}(T) \cdot \left[\frac{U_{sample} - U_{empty}}{U_{standard} - U_{empty}}\right](T) \cdot \frac{m_{sample}}{m_{standard}}$$

where, m is the mass of the sample and standard material, and U is the voltage signals of the empty, standard, and sample runs. This method relies on the known thermal properties of a standard material. The enthalpy function can be determined by integrating the specific heat function over a given temperature range. Shown below in Figure 14 is a typical temperature profile and heat flow signal. The peaks in the heat flow signal indicates a change of the heat flux into the sample and bounds the region that phase-changing is occurring in the sample.

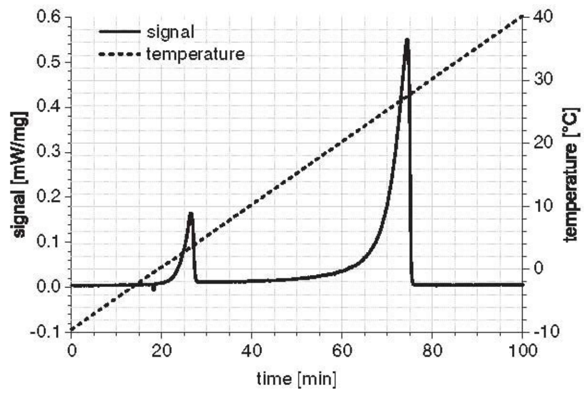


Figure 14. Typical heat flow and temperature profile for a dynamic test

The step method is another commonly used measurement method for phase-change materials. Unlike the dynamic method, the heat or cooling rate is not constant and continuous, but instead increases or decreases in increments. During each temperature increment, the temperature is kept constant and the sample is allowed to reach thermal equilibrium. The step method produces a temperature profile that has small steps, and a signal that has a sequence of varying peaks. The size of the temperature step needs to be long enough for the sample to reach thermal equilibrium, which is when the signal goes back to the baseline. The temperature resolution of the obtained data is equal to the step size. The resolution of the temperature can be increased by reducing the step size, but as the step size becomes very small, the signal will vanish and the precision in the measurement disappears. The enthalpy function is determined by integrating all of signal peaks. Shown below in Figure 15 is a typical temperature profile and heat flow signal.

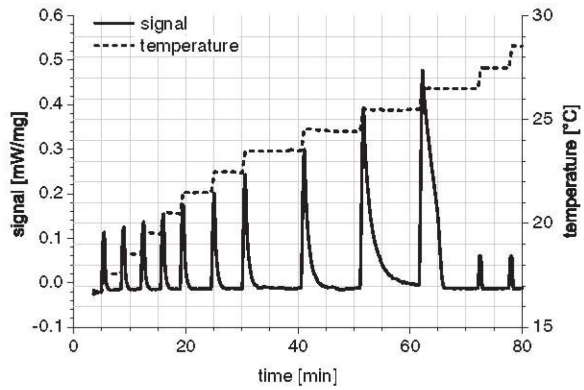


Figure 15. Typical heat flow and temperature profile for step test

PCM Test Methods

The testing of phase-change materials was accomplished by two different approaches. The first approach will try to determine the thermal properties of the phase-change material that is imbedded in traditional insulation. The second approach will look at the thermal properties of the phase-change materials in a pure state. Both approaches will use the same two testing methods, but with different measuring equipment to obtain experimental results. The phase-change material embedded in traditional insulation will be tested by the Laser 800 Heat Flux Analyzer in conjunction with special dynamic testing software. The phase-change material that is in a pure state will use a differential scanning calorimeter (DSC).

The phase-change materials/insulations will be analyzed by using a dynamic and a step mode. The dynamic mode uses a ramp function to raise or lower the temperature at a constant rate from the upper to lower bound temperatures. The step mode raises or lowers the temperature at increments while waiting for the sample to reach thermal equilibrium at each increment. Both processes have distinct advantages and disadvantages. The dynamic mode is simple and provides continuous data on the thermal properties. Since the dynamic mode heats or cools the sample at a constant rate, the sample is never in thermal equilibrium, producing a temperature gradient to form inside the sample. This results in deviations in data between the different heating rates and samples sizes. The step mode provides high resolution data that is equal to the temperature step size. The advantage that the step mode has over the dynamic mode is that the uncertainty in the temperature is precisely known, as it is restricted to the step size. Temperature resolution and accuracy of the data improves as the step size decreases. As the step size decreases in size, the observable change in data vanishes and the precision in the measurement is lost.

The testing of the pure phase-change material will be conducted by a DSC. A total of three samples of each material will be tested in the DSC by using both the step and dynamic modes. The sample sizes will be 10 mg, but to ensure that the influence of the sample size is negligible, additional tests will be carried out at 5 mg and 15 mg.

Thermography

Once the PCM insulation was installed, sensors and infrared thermography was used to directly measure the reduction in heat loss through the building walls prior to and after installation of the new insulation material being demonstrated. Thermographic images provide a visual indication and temperature map of area underneath the roof deck. A thermograph of the attic roof deck taken with a FLIR P660.IR camera in August 2011 shows very high surface temperatures, up to 132ºF (Figure 16).

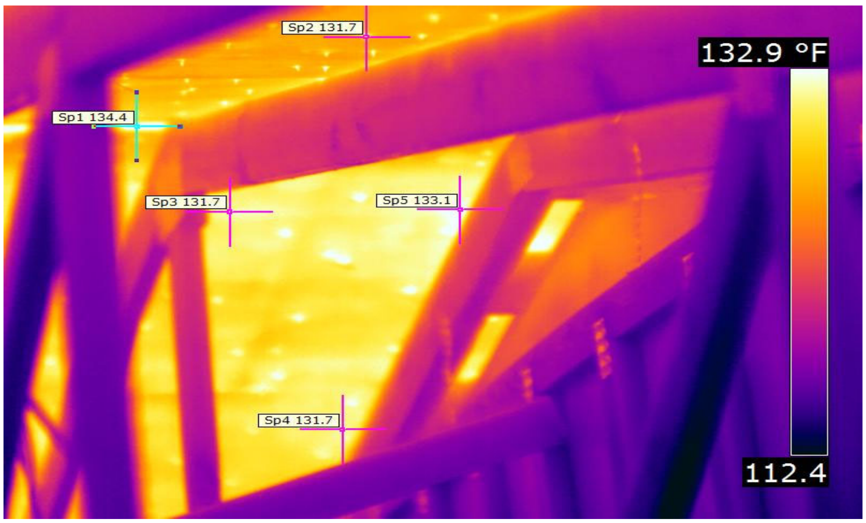


Figure 16. Thermal image taken inside of attic of demonstration building in August 2011 (prior to installation of any insulation. Note very hot surface temperatures due to heat conduction through the roof, especially at location of roofing nails

Field Demonstration

The PCM field test was split into three phases and performed at Building 3-2232: DPW Classroom at Fort Bragg, North Carolina. Shown below in Table 9, the first phase measured normal energy usage as a control. Phase 2 recorded energy data with the attic sealed and the addition of 9 inches of cellulose insulation (approximately 5.5” of R16.5 batt cellulose insulation and about 3.5” of R12.5 densely-packed, blown-in cellulose) against the gables and underside of the attic roof decking. Phase 3 recorded energy data with a PCM layer attached to the underside of the cellulose layers in the attic.

Table 9. Phase Definitions

Phase	Dates	Status
1	July 2013- June 2014	Uninsulated Attic
2	July 2014- June 2015	Cellulose Insulation
3	July 2015-June 2016	Cellulose + PCM

Figure 17. Phase 1 unisulated attic

Figure 18. Phase 2 cellulose insulation

Figure 19. Cellulose + PCM

Data was collected from ORNL and the US Army Meter Data Management System (MDMS). Attic temperature was monitored across the three phases. The below chart shows a snapshot of attic temperature across the three phases using days with similar outside temperature. The installation of cellulose had a significant impact on reducing the peak attic temperatures and the temperature fluctuations. The addition of the PCM had little impact on further reducing the maximum temperatures compared to the cellulose-only case, but it did delay the peak temperature slightly.

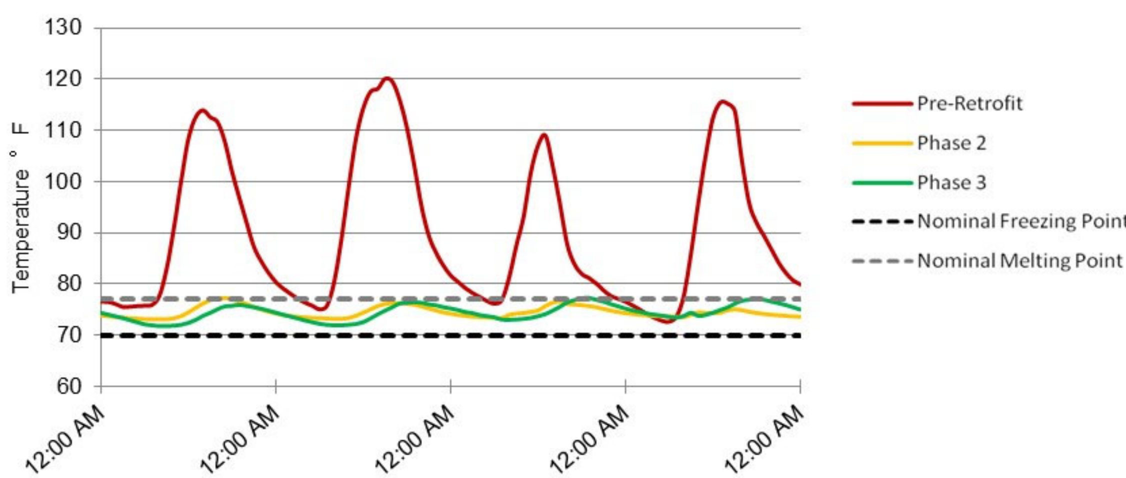


Figure 20 Average Heat Flux (North Deck) (W/m^2)

Attic heat flux was also measured, again significant reduction in heat flux was gained by the addition of the cellulose insulation. A slight additional reduction in peak heat fluxes occurred with the addition of the PCM, and again the peak was delayed slightly.

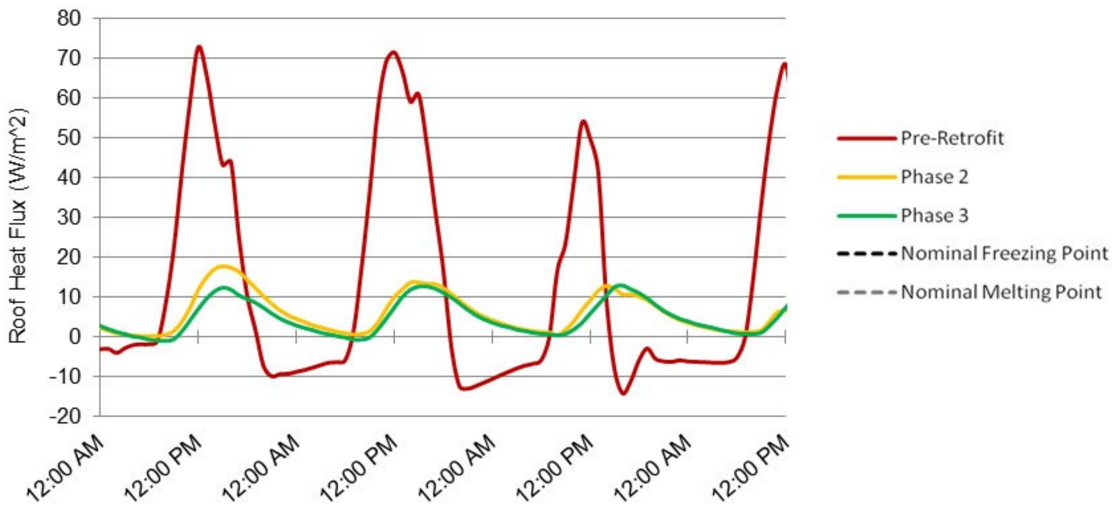


Figure 21 Average Heat Flux (North Deck) (W/m^2)

Investigation of the energy conservation of the PCM field test was performed in a top down method, starting with yearly phase data and moving down to monthly, weekly, daily, hourly, and 15 minute data.

From overall phase data, the PCM retrofit Phase 3 had the highest energy consumption as seen below in Table 10

Table 10. Building Energy Consumption by Phase

	Phase 1	**Phase 2**	**Phase 3**
Energy Consumption (kWh)	63,763.8	54,603.69	67,166.2
Percent Savings from Phase 1 (%)	NA	14.37	-5.34
Average Outdoor Temperature (°F)	61.29	60.91	63.06

Outdoor Temperature Variance	327.59	324.19	257.14
Heating Degree Days	3110	3036	2260
Cooling Degree Days	2014	2050	2123

. While building occupation and usage data was not available, weather data from each phase was compared via Kruskal-Wallis statistical analysis. The years' worth of hourly weather data for each phase could not be compared equally because it was statistically dissimilar. This temperature variation can also be seen intuitively from the temperature histogram below in Figure 22.

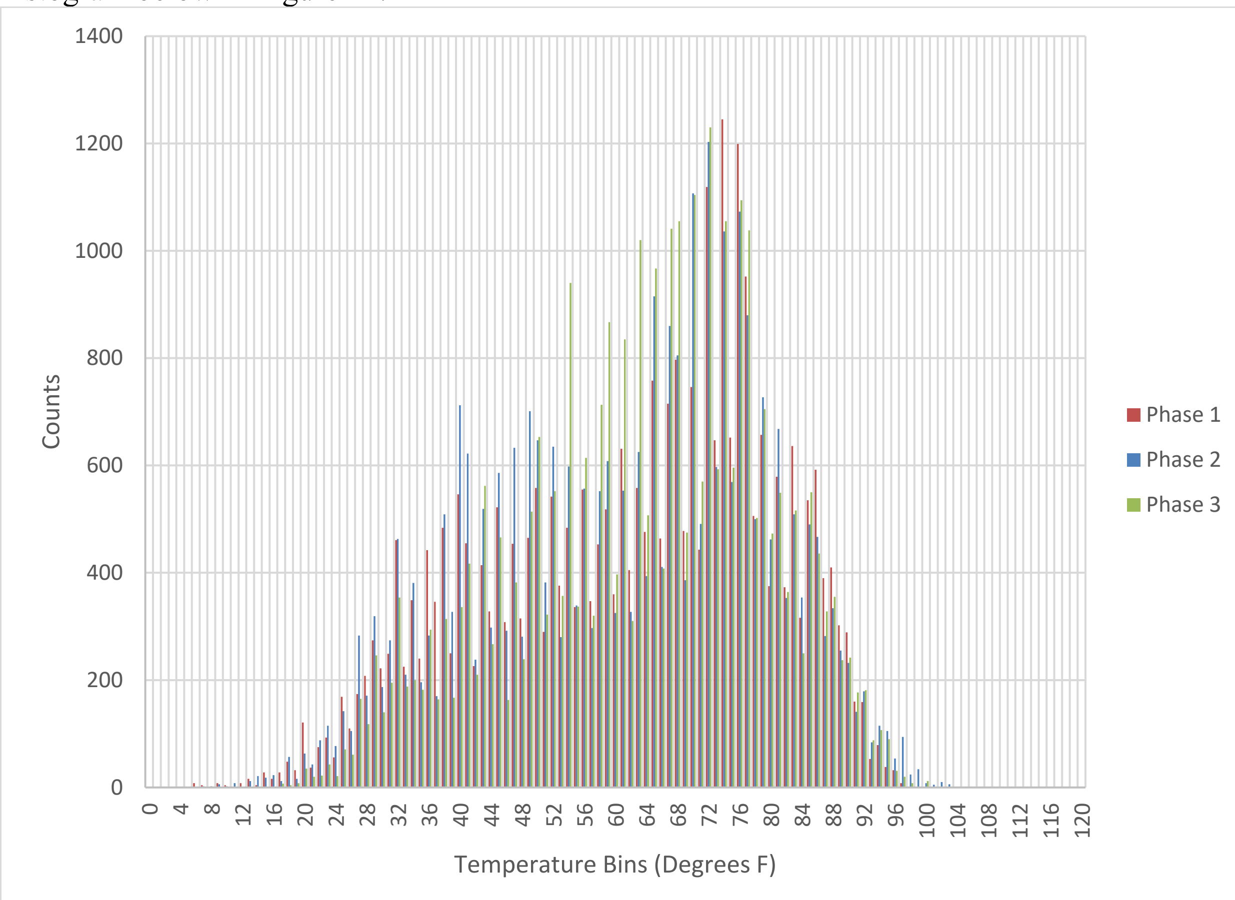


Figure 22. Histogram of Yearly Temperature Data

In addition, the average temperature for each phase also shows variation, as can be seen in Table 10. At the yearly phase level, we could not conclusively determine weather effects on overall phase energy consumption. As a result, to properly compare PCM performance, temperature must be controlled by using a smaller timescale.

Select months provided statistically similar weather data under the Kruskal-Wallis statistical test, and January was identified as a candidate. Heating and cooling degree days were calculated and compared from the Pope Air Force Base weather station (KPOB), while using 65°F as the base temperature. The month of January in Phase 2 with just cellulose was compared to January of Phase 3 with cellulose and PCM. January

Phase 2 had 745.5 heating degree days and 2.9 cooling degree days, and January Phase 3 had a comparable 768.8 heating degree days and 0.3 cooling degree days. Nonetheless, the power consumption during Phase 2 was 4,388.22 kWh compared to Phase 3 consumption of 5,288.8 kWh. While there was a 3.1% increase in heating degree days, there was a 20.5% increase in energy usage when PCM was present. A smaller timescale was subsequently investigated.

While occupation data was not available, any building traffic or usage variation was attempted to be controlled by comparing weekend days, which were assumed unoccupied. Sample weekend days were taken from summer, fall, and winter and compared between phases 2 and 3. These days were verified by the Kruskal-Wallis statistical analysis before assessment. These paired comparisons are graphically shown below in Figures 23-25.

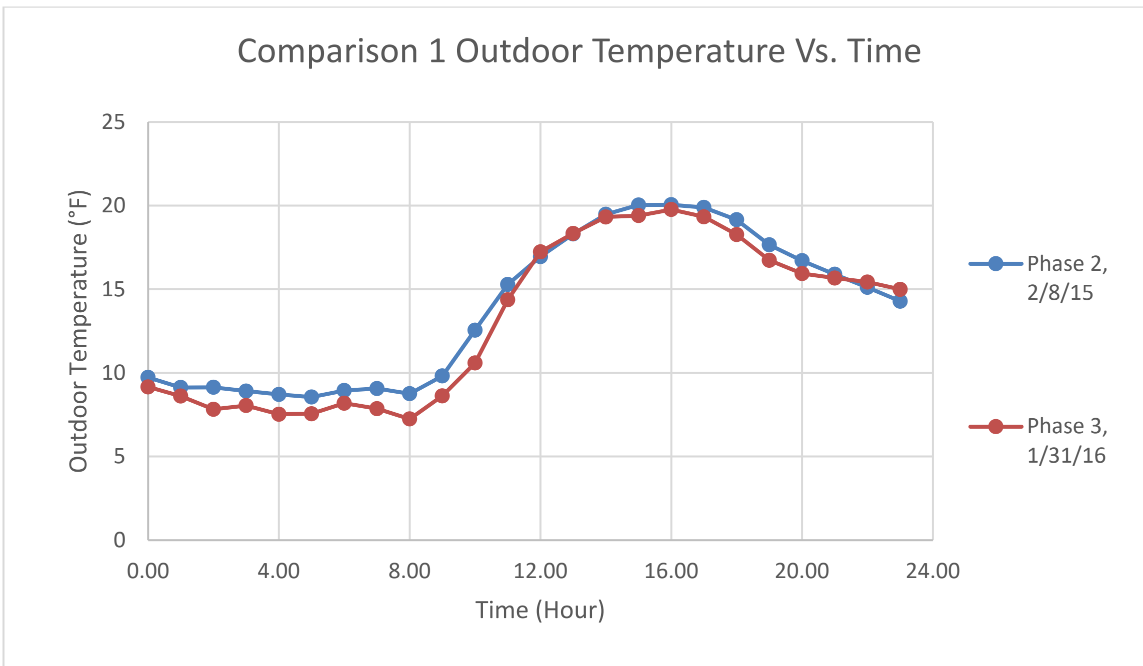


Figure 23. Weekend Day Comparison 1

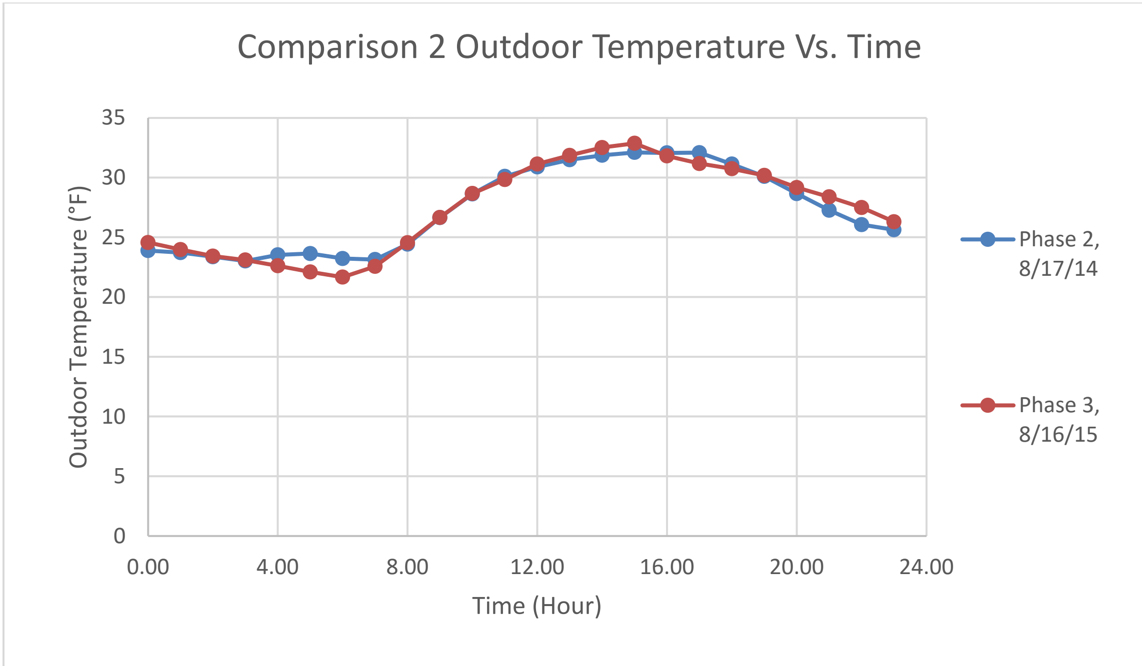


Figure 24. Weekend Day Comparison

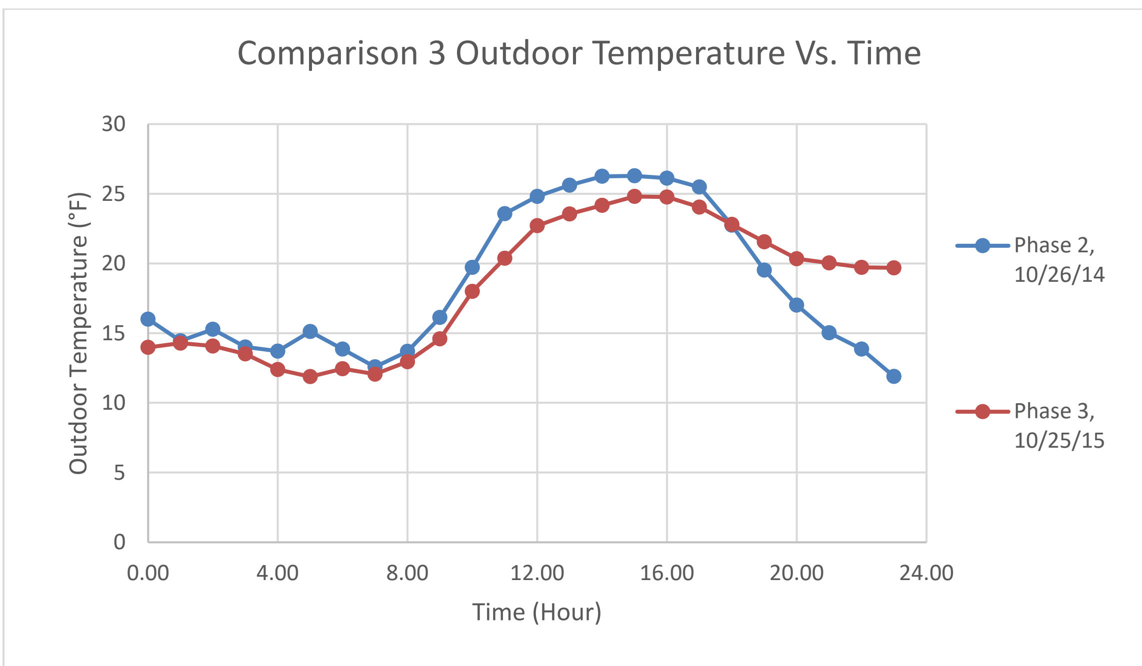


Figure 25 Weekend Day Comparison 3

Quantitatively, their respective weather and energy data is shown below in Table 11.

Table 11. Weekend Day Temperature and Energy Comparison

	Phase	Date	HDD	CDD	Energy (kWh)

Comparison 1	2	2/8/2015	9	0.7	114.6
	3	1/31/2016	13.1	0.3	116.5
Comparison 2	2	8/17/2014	0	16.5	201.39
	3	8/16/2015	0	16.5	208.79
Comparison 3	2	10/26/14	6.9	4.4	109.11
	3	10/25/15	5.2	3.3	141.91

In Comparison 1, the data is taken from the winter season, and while their graphs have similar shapes, the degree days is slightly higher for Phase 3, as well as the energy consumption. In Comparison 2, the data is taken in the summer season, and while both days have identical heating and cooling degree days, the energy consumption in Phase 3 is higher. In Comparison 3, data is taken from the autumn season, and despite lower heating and cooling degree days, Phase 3 has significantly higher energy consumption. In each case, while considering the temperature data, the Phase 3 PCM energy usage was roughly the same if not significantly higher than Phase 2.

Finally, the effect on regulation of attic temperature was investigated for each phase. The difference between the attic temperature for each timestamp as compared to the mean in each phase was calculated. The resulting variance can be seen below in Table 12.

Table 12. Phase Temperature Variance Comparison

Phase	Attic Temperature Variance (°F^2)
1	233.1057
2	80.73046
3	146.5931

As can be seen, Phase 2 provides statistically lower temperature variance compared to Phase 3. This suggests the PCM does not provide any further temperature regulation in the attic space, despite no discernable energy savings.

Energy consumption was tested at yearly phase level between phases 2 and 3 and no energy savings were seen. Energy consumption was tested at the month level between phases 2 and 3 while controlling for outdoor temperature and no energy savings were seen. Energy consumption was tested at the daily level between phases 2 and 3 while attempting to control for outdoor temperature, occupancy, and usage, and no energy savings were seen. Overall, no energy savings could be seen when using the PCM compared to just cellulose.

7.0 COST ASSESSMENT

The National Institute of Standards and Technology (NIST) Building Life-Cycle Cost (BLCC) Program for MILCON Analysis (ECIP Project) was used to determine the LCC for this particular demonstration. Existing annual consumption of energy for the HVAC system on typical building such as Building 3-2232 (DPW Classroom) is 16,000 kWh. The cost of this new technology is $3,480 more than the alternative of using conventional insulation.

Due to the fact that energy consumption increased between phases two and three of the project, no cost savings were achieved by the installation of the PCM. The cost savings would have been achieved through the reduction in electrical energy to operate a heat pump that maintains comfort level within the demonstration building.

8.0 Implementation Issues

Energy consumption of the building increased during phase 3 of the demonstration, PCM with cellulose phase, when compared to the cellulose only phase.

The benefits of the PCM were not achieved each night due to the fact that for significant periods of time the attic temperature did not cross the freeze thaw boundaries. In the summer months the attic temperature stayed above the melting point keeping the PCM liquid for months at a time. Conversely, in the winter the attic temp was below the freezing point, keeping the PCM solid. There were very few days in which the PCM completely changed phases to provide benefit to the building.

Elevated humidity levels were also observed between the roof deck and the PCM layer following the phase 3 retrofit. During a portion of the year the average humidity remained above 80% for greater than 30 days. This duration could potentially cause problems with the roof deck structure. This moisture concern along with lack of any measurable energy benefits lead to the removal of the PCM layer at the completion of the demonstration.

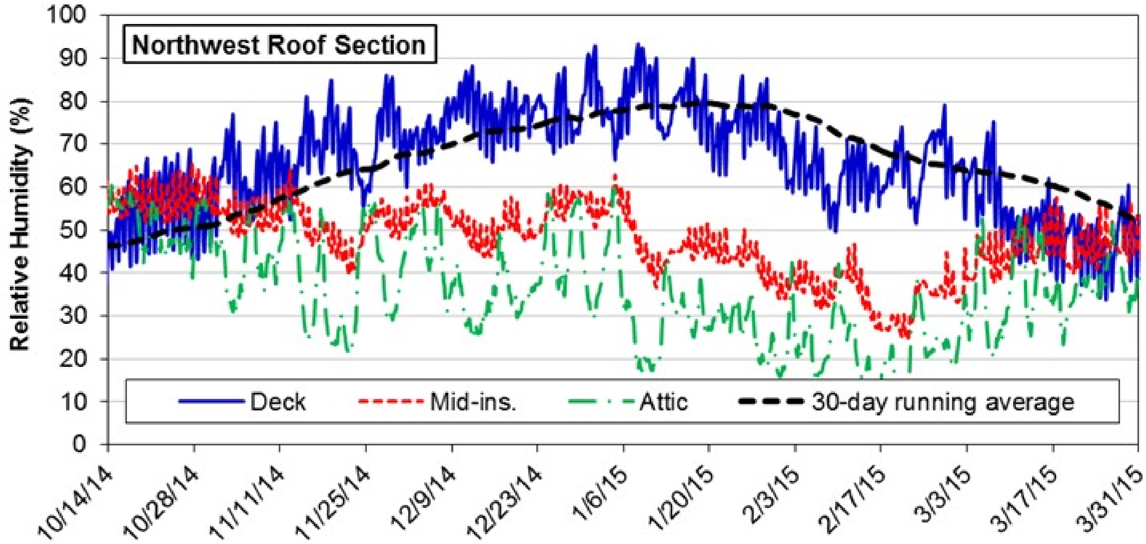


Figure 26. Measured RH at the worst-case roof location following phase 2 (cellulose) retrofit

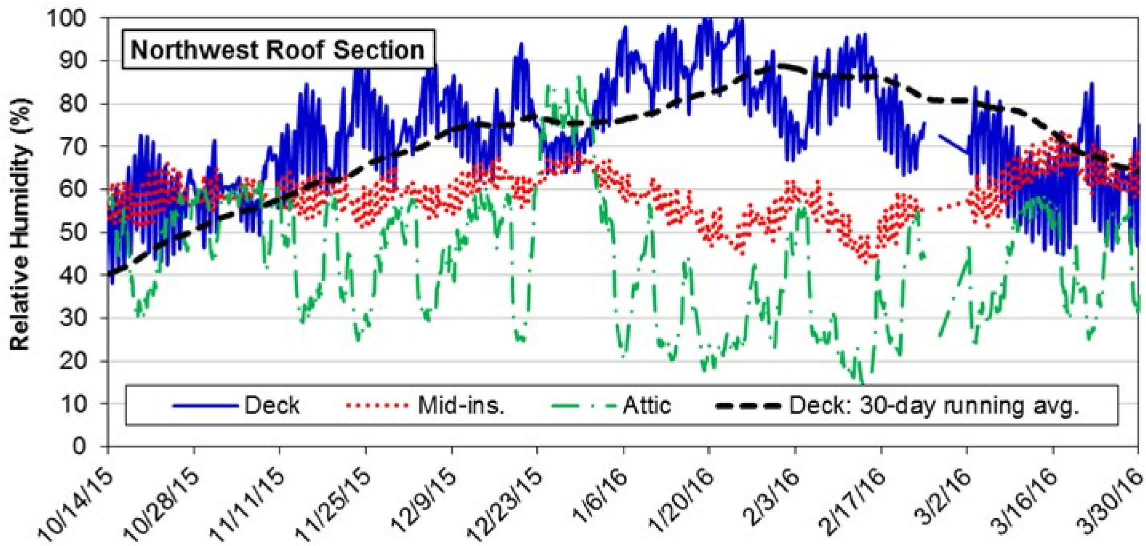


Figure 27. Measured RH at the worst-case roof location following phase 3 (cellulose+PCM) retrofit.