EXECUTIVE SUMMARY

Energy Efficient Phase Change Materials (PCM) Insulation

ESTCP Project EW-201149

FEBRUARY 2019

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1.0 INTRODUCTION

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 Act of 2007 (EISA 07). This project demonstrated the application of Phase Change Materials (PCM) based insulation, an emerging technology, to mitigate energy losses via building envelopes.

1.1 BACKGROUND

The PCM enhanced insulation 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. The latent heat is released back into the building when the temperature drops at night. 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.

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2.0 OBJECTIVES

This project sought to explore the impacts of using PCM integrated into standard insulation products on heat transfer through building envelopes. This project incorporated PCM to enhance the effective "R-value" of insulation, thus reducing energy transfer through the ceiling. The goal was to also maintain comfortable temperatures for the building occupants. The building was monitored for approximately two years prior to installing the PCM-enhanced insulation. Phase 1 monitored the building in its baseline condition with standard R-19 fiberglass insulation on the attic floor. Phase 2 monitored the building 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 isolate its impact. Using lessons learned in Phase 2, a change of the PCM was made to an alternative technology, BioPCMats. This change was expected to improve the quality of the demonstration by using materials that have suitable ruggedness and durability and would decrease labor costs and enhance the potential for rapid technology transfer.

In Phase 3 (year 3), the PCM-insulation was installed, and the building was monitored for one additional year. Heat flow was modeled to calculate the reduction in heat transfer and to enable optimal design and engineering of the PCM additive to be used. Success predictions were developed for the PCM-insulation in this application. The PCM 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.

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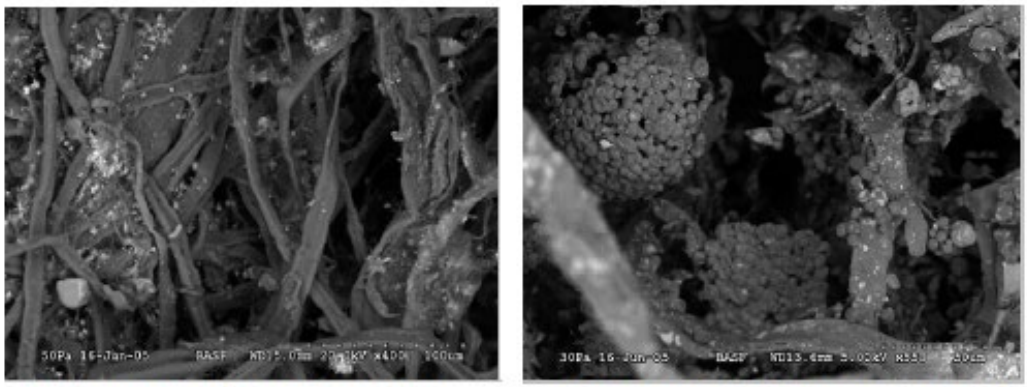
3.0 TECHNOLOGY DESCRIPTION

3.1 TECHNOLOGY OVERVIEW

This technology combines fiberglass or cellulose insulation with a phase change material (microcapsules that contain organic fatty acids and fatty acid esters) to control heat flow and maintain comfortable temperatures (Figure 1). This capability provided by the PCM is known as the "thermal mass effect," i.e., capacity to store energy. For this project, the demonstrated product contains the phase change material enclosed between a polymer layer and a foil layer and can be applied in large sheets (Figure 1a) that lowers labor and installation costs.

This technology is based on combining PCM with cellulose or fiberglass insulation as shown in Figure 1 & 1a. The PCM used 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 "hot" days the PCM changes phase to absorb heat, thus reducing the cooling load. On cold days, the PCM stores energy as "latent heat" and is released back into the building as "sensible heat" when the temperatures drop. The enhanced insulation helps maintain comfortable temperatures by impeding heat flow, effectively enhancing the "R" value of the "standard" fiberglass or cellulose insulation. Analysis at Oak Ridge National Laboratory's (ORNL) indicated R-38 attic insulation enhanced with PCM to be equivalent to greater than an R-50 thickness in conventional insulation.



Cellulose without PCM - visible fire-retardant chemicals.

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

Figure 1. Cellulose Insulation with PCM

Figure 1a. BioPCM Sample

3.2 PCM 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.

3.3 ADVANTANGES AND LIMITATIONS OF THE TECHNOLOGY

3.3.1 Cost Advantages

ORNL research projected this technology could mitigate 30% of the annual heating and cooling energy consumption by retrofitting the Ft. Bragg test building attic. 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 Military Construction Analysis: Energy Conservation Investment Program (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.

3.4 PERFORMANCE LIMITATIONS

The PCM technology, is significantly more expensive than conventional fiberglass insulation due to the cost of the PCM component. This added first cost may be offset by the reduction in energy bills for heating and cooling due to the efficacy of the enhanced 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 the American Society of Heating Refrigeration and Air Conditioning Engineers Climate Zones 3-5, i.e., about 50% of the US, and will be limited

to use in these areas. PCMs should be used in conjunction with insulation, but not in attics with radiant barriers installed as it decreases the PCM phase change advantages. The new insulation configuration was expected to reduce heat flux through the building attic by 25% over the course of a full year when compared to the current configurations. Addition of PCM was 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.

This would be 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.

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4.0 PERFORMANCE ASSESSMENT

The Engineer Research and Development Center-Construction Engineering Research Laboratory and ORNL measured the energy benefits of the retrofits with cellulose-only insulation and PCM-enhanced insulation by installing a suite of instruments.in the attic. Four instrumentation packages consisting of a heat flux transducer, 5 thermistors, and 2 relative humidity sensors were installed under the roof deck. These packages and additional measurements of 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 were tracked.

Metered energy usage, monthly energy bills, and annual energy bills for the building before installation of the insulation (and PCM-loaded insulation) were compared with the monthly and annual energy bills after installation of cellulose insulation and then the PCM-enhanced cellulose insulation. These were corrected for the occupancy rates, and temperature set-points were taken into consideration. Data collected was used as input to EnergyPlus to help analyze the differences in energy required for heating and cooling 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.

4.1 PCM TESTING

Laboratory testing of PCM-insulation results were compared with the data taken from the measurements in the field. The results of these tests were used to determine the estimated service life, as predicted by the number of cycles for which their performance remains unchanged. The number of cycles was set to simulate at least 40 years.

4.2 THERMOGRAPHY

Sensors and infrared thermography was used to directly measure the reduction in heat loss through the building walls both prior to and after installation of the new PCM-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 2).

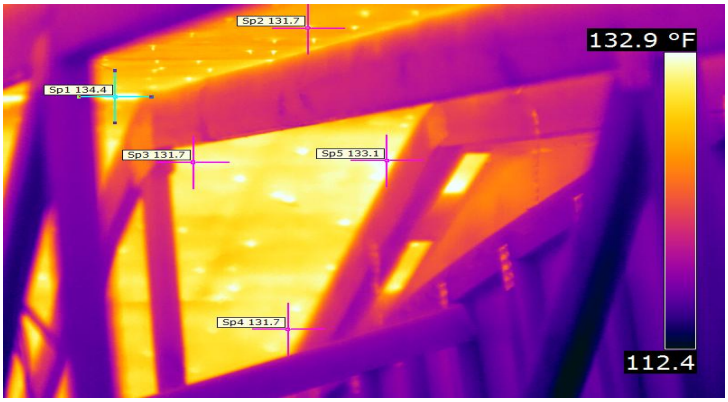

Figure 2. Thermal Image Taken Inside of Attic of Demonstration Building in August 2011 (prior to installation of any insulation)

Note very hot surface temperatures due to heat conduction through the roof, especially at location of roofing nails

4.3 FIELD DEMONSTRATION

The PCM field test was split into three phases (Table 1 below) and performed at Building 3-2232: Directorate of Public Works Classroom at Fort Bragg, North Carolina. 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 1. 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 3. Phase 1 Unisulated Attic

Figure 4. Phase 2 Cellulose Insulation

Figure 5. 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 chart below (Figure 6) 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 delayed the peak temperature slightly.

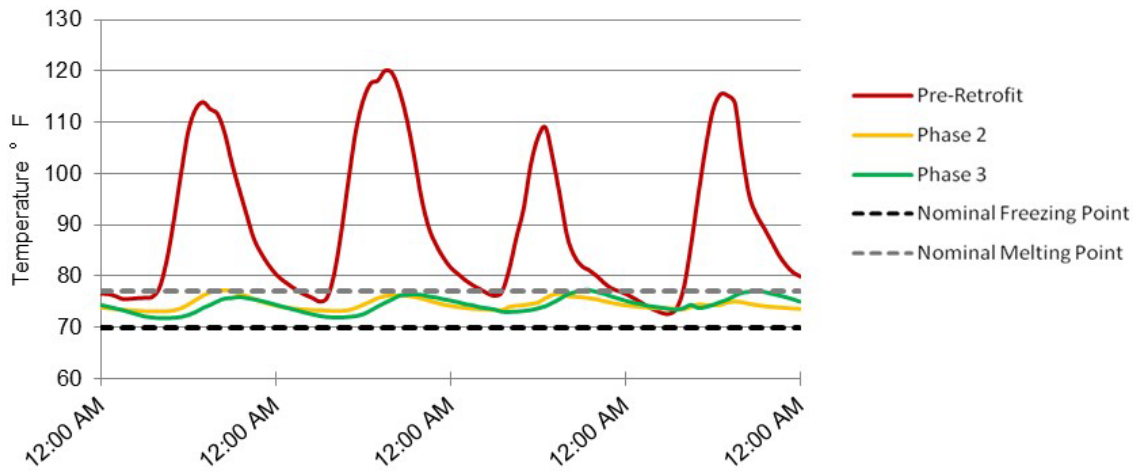

Figure 6. Representative Average Temperature Flux (North Deck)

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 2.

Table 2. 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 occupancy 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.

In addition, the average temperature for each phase also showed variation. At the yearly phase level, we could not conclusively determine the 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 occupancy 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 7-9.

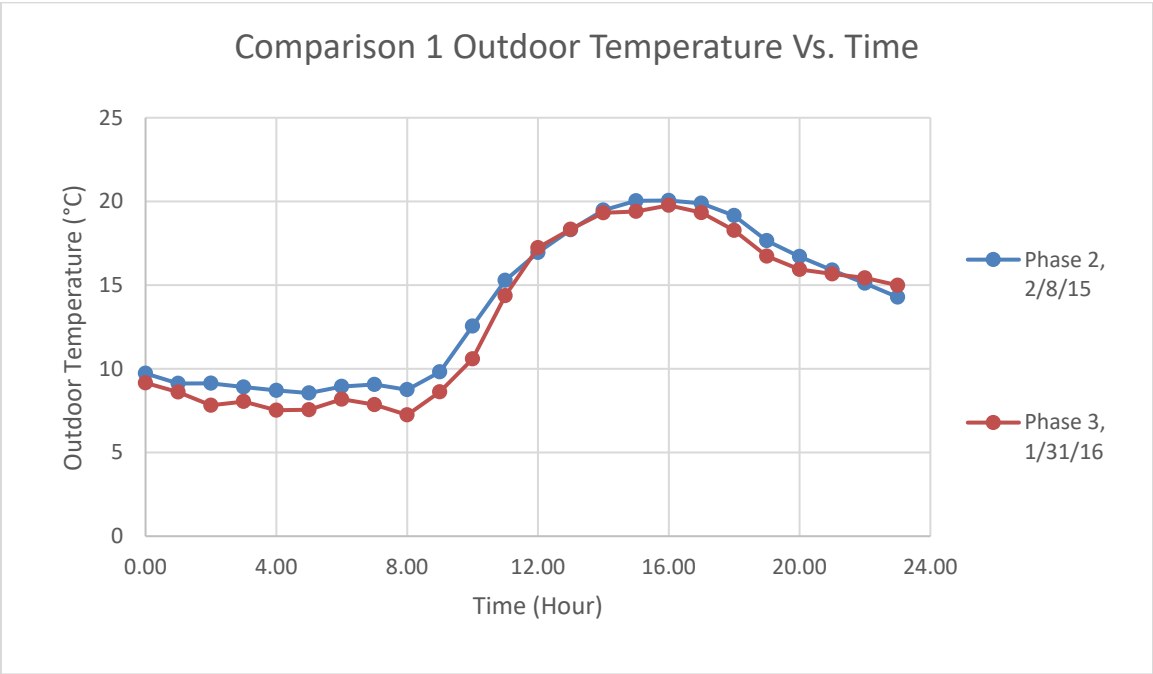

Figure 7. Weekend Day Comparison 1

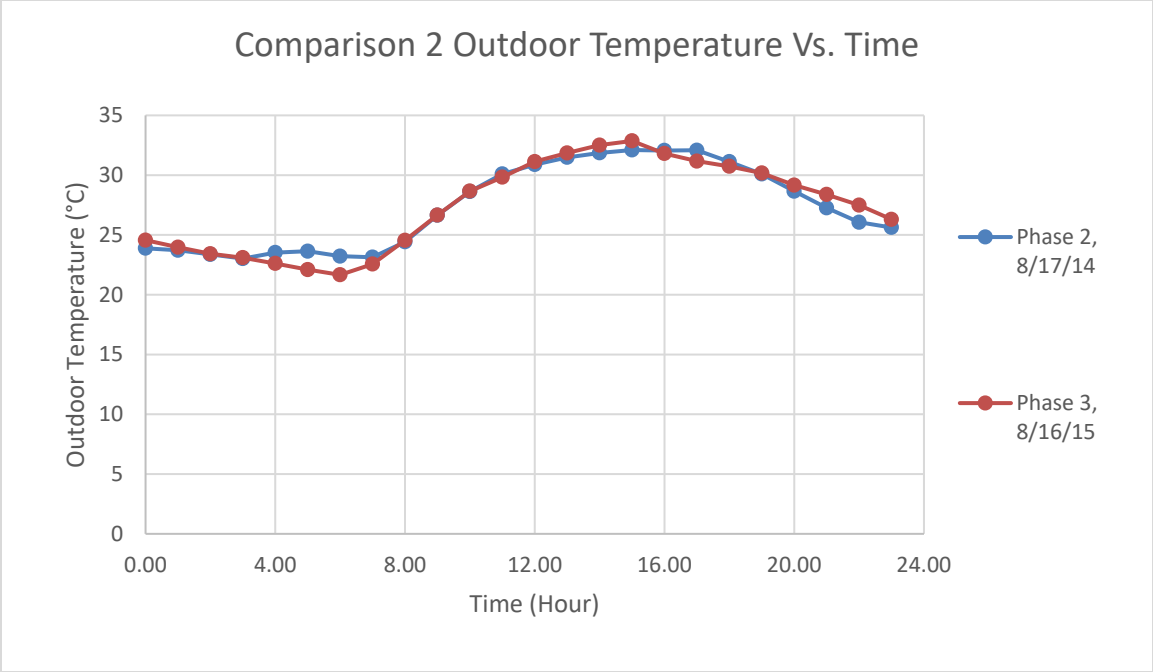

Figure 8. Weekend Day Comparison 2

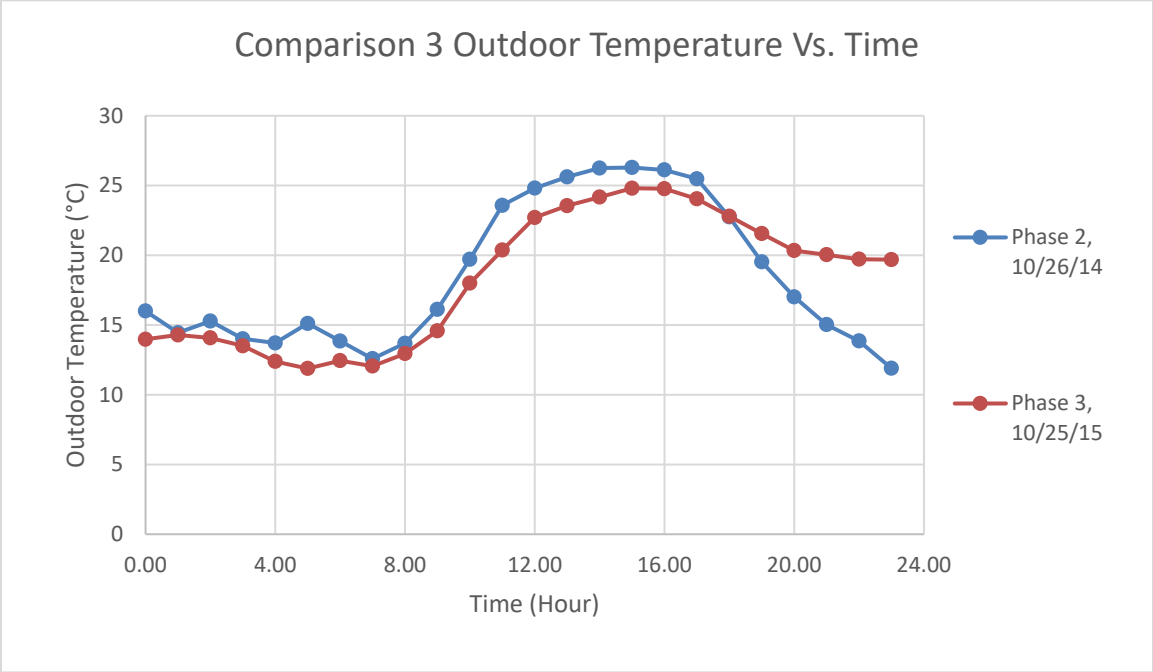

Figure 9. Weekend Day Comparison 3

Quantitatively, their respective weather and energy data is shown below in Table 3.

Table 3. 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 4.

Table 4. 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.

5.0 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 BLCC for this 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.

Since 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.

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6.0 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 since 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 led to the removal of the PCM layer at the completion of the demonstration.