MEASURING FIELD PERFORMANCE OF AEROGEL INSULATION IN A HOT, DRY CLIMATE

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Keywords: insulation, field testing, thermal performance, Aerogel, radiant barrier

1. ABSTRACT

Aerogel materials offer the potential for high thermal performance in a small material thickness, yet more information is needed to characterize their thermal and energy performance under dynamic field conditions. To evaluate cooling season performance, two types of Aerogel insulation – one with reflective facing surfaces and one with non-reflective facing surfaces – were installed in outdoor test structures and monitored during the summer in the hot, arid climate of Albuquerque, NM. Three identical 8x12 ft (2.4x3.7m) test structures were built with an unconditioned attic space above a single air conditioned zone. The first was a baseline structure with no insulation. The second and third huts had a 1 cm (0.4 inch) thick layer of Aerogel insulation attached to the wall studs and rafters, creating a stud cavity. We measured heat flux and temperature profiles across the walls, ceiling, and roof deck of each hut, along with ambient weather conditions and space conditioning electricity consumption. Each structure was conditioned with an identical portable air conditioning unit to a consistent cooling setpoint temperature. Air leakage was measured in each structure before and after the installation of the Aerogel to assess its impact on infiltration. Results indicate the relative performance and energy benefits associated with each system in terms of thermal resistance, air infiltration, and energy savings.

2. INTRODUCTION

Aerogel materials have great promise for reducing energy consumption in building retrofit applications (Shukla et al. 2014). In this project, we investigated the thermal performance of two kinds of Aerogel insulation blankets, one with a non-reflective facing material and a second with a reflective facing material. We performed a combination of laboratory testing, field testing, and calibrated simulation to compare their performance. This paper will focus on the field testing aspects of this project only. The field testing program was designed to compare the energy performance, temperature distributions within wall and roof assemblies, heat flow through building components, and thermal loads within the conditioned zone using full-scale outdoor test structures.

Field testing is a critical component of the new building material product development cycle. Full-scale outdoor field testing offers many benefits that other kinds of analysis cannot provide. New building enclosure technologies must be evaluated and tested before going to market to ensure functionality, durability, and to help quantify their benefits to potential customers.

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Although laboratory testing of insulation materials is useful for characterizing material or system performance under specific conditions, these tests fail to fully represent the dynamic interactions between building components and the systems in which they are installed. Similarly, while building energy simulation can be useful for designing and predicting energy performance of new products, the validity of simulation models of new materials remains questionable until the models can be validated with data from real buildings. Aside from helping to quantify energy and durability characteristics of new products, field testing also helps identify and address practical issues with installation before products go to market.

From an energy and durability standpoint, it is desirable to measure system-level performance on several dimensions, including: thermal performance (heat gain or loss through components), occupant comfort (temperature and humidity in occupied zones), moisture performance (moisture accumulation and material durability), air tightness (and its impact on energy consumption), and energy performance (HVAC energy reduction, peak load shifting).

In this paper, we present an experimental approach that is useful for making direct comparisons between competing enclosure systems and for characterizing the performance of specific enclosure technologies. We present a flexible, near-calorimetric testing platform that combines the advantages of outdoor field testing with the controllability of a laboratory experiment. Variations of this approach have appeared throughout the literature (e.g., Athienitis et al. 1997, Szymocha 2005, Khudhair and Farid 2007, Shilei et al. 2007, Baker et al. 2008, and Medina et al. 2008).

The platform is comprised of multiple small testing structures or huts. One hut is built to standard construction practices (e.g., typical residential construction) and acts as a control or baseline case. The other hut(s) are constructed identically, with the exception of the novel building materials or components. All huts are conditioned with identical HVAC systems and control strategies, and HVAC energy consumption is metered during the experiment along with detailed temperature and heat flux measurements across the assemblies of each hut. Prior to each experiment, air tightness of each hut is measured. A weather station records outdoor climatic conditions. Resulting data may be used to support the validation of energy models for advanced systems or to rapidly evaluate prototype building systems or components.

Comparative field experiments may be conducted in several ways, and their advantages depend on the specific application, testing goals, and budget as discussed in (Urban et al. 2014) and summarized here. Parallel testing of multiple products, each with its own hut structure as outlined above, has the advantage of ensuring consistent outdoor environmental conditions between tests, however, careful attention is required to ensure huts are constructed identically and that interior temperatures are well-controlled and consistent. Single-hut tests, where multiple specimens are tested in a single large hut, helps maintain consistent indoor and outdoor conditions among tests, but it suffers from the inability to characterize the dynamic energy performance because each product may influence the internal loads differently, in particular because of differences in radiant temperatures, convection rates, and the thermal mass effect. Sequential testing, where a one or more huts are used to test products during different time periods, can reduce instrumentation cost while making direct comparisons more difficult or less accurate due to non-identical weather conditions.

Prior studies have implemented a range of instrumentation and measurement points depending on the goals of the experiment. In this project, we aimed to characterize heat flow and temperature profiles through all major building surfaces to obtain a near-calorimetric of energy performance.

This paper demonstrates an application of a parallel multi-hut testing platform by presenting measurements from a field experiment designed to characterize two kinds of Aerogel blanket insulation materials. Here we focus on description of the platform, construction and experimental technique, and the measurements obtained during testing. Through a six month experiment, we have determined that this platform may be used to effectively test and compare thermal performance of building enclosure insulation systems.

3. EXPERIMENTAL METHOD

3.1 Test Hut Construction

In this experiment, we set out to measure the thermal and energy performance of two kinds of Aerogel insulation blanket systems (one with non-reflective surfaces and one with reflective surfaces) for use in the exterior walls and roof of a wood-framed structure. The insulation systems were identical other than the presence of a reflective surface foil. We also set out to measure the thermal and energy response of a baseline uninsulated structure.[3]

We constructed three identical structures composed of uninsulated 8x12 ft wood framing with 2x4 studs spaced 16" on center. The exterior walls and roof deck were composed of oriented strand board (OSB). A hinged door on the north-facing side of each hut was the only means of access to the interior. The unvented gable roof was comprised of an OSB layer beneath a dark green colored metal roof. The huts were positioned on the test site to minimize solar shading. Each hut contained a single room zone beneath an unconditioned attic space. We installed a portable air conditioning unit (4.1 kW cooling capacity) in each test hut with identical constant-temperature cooling setpoints.

Each hut was conditioned to an identical setpoint temperature, and allowed to run for several months during the summer and fall of 2013 in the desert climate of Albuquerque, NM. We monitored temperature and heat flux through the assemblies, energy consumption of the cooling equipment, and climate conditions. We used the results to analyze energy reduction potential, peak load shifts and reductions, and zone temperature behavior.

The floors were made of tongue-in-groove plywood and rest above 2x4 floor joists with the floor cavities insulated with R-3.3 fiberglass insulation. The floors were insulated with a further R-1.8 foam board above the plywood layer. Initially, the huts were built without a ceiling to permit the installation of insulation on the interior side of the roof deck. In this state, the huts were tested for initial air tightness to ensure similar air leakage rates in the baseline condition.

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[3] Ordinarily, the baseline condition would include some standard insulation materials; however, in this case, the uninsulated case was more representative of the client's particular end-use application.

FIGURE 1: Three identical test huts, pictured from the North-east corner of the lot.

FIGURE 2: From left to right: uninsulated hut interior prior to installation, insulation installed on roof of Hut 2, reflective insulation installed on the walls of Hut 3 with ceiling in place.

The Aerogel insulation was then nailed to the wall and roof deck studs of Huts 2 and 3, while Hut 1 remained uninsulated. Afterwards, ceilings were installed in each hut to separate the interior conditioned zone from the unconditioned attic space. Hut 2 received the insulation packaged in a non-reflective facing surface, while Hut 3 received insulation packaged with a reflective foil surface on both sides of the batts. The purpose of the reflective facing on the Hut 3 insulation was to reduce radiative heat transfer across the stud cavities created by the insulation. After the insulation was installed in Huts 2 and 3, OSB ceilings were installed on all three huts to create a separate, unconditioned attic space.

3.2 Instrumentation and Testing

3.2.1 Weather Station

We measured the ambient climatic conditions throughout the experiment at one-minute intervals, including solar radiation, outdoor air temperature and relative humidity, and wind speed and direction. Since this work was completed at our outdoor research facility in Albuquerque, NM, we employed a permanent high-grade weather station that is concurrently used for ongoing photovoltaic research.

3.2.2 Temperature

We measured temperature across all key wall assembly components and the interior zone temperatures of all huts at 20 second intervals. By measuring temperature across lightweight construction materials of known properties, it becomes possible to estimate the heat flux through those materials. This provides a backup method for calculating heat flux through surfaces where sensors fail or where cost prohibits their use. Temperature measurements were obtained using NIST-calibrated type-T thermocouples with specified accuracy of ±0.5°C or 0.4%. To improve temperature measurement accuracy we apply cold-junction compensation using an insulated junction box in each test hut. Accurate temperature measurement practices are critical when attempting to derive heat flux from temperature differentials.

3.2.3 Heat Flux

We installed heat flux transducers on all six walls of the conditioned zone, and on one roof deck surface of each hut. This allowed us to construct a virtual energy balance on the huts by estimating the heat flow through each component surface. We calibrated heat flux transducers according to ASTM C1130-07 (2012), and determined calibration coefficients for the specific materials of the assembly. We apply thermally conductive paste to ensure a good thermal contact between the sensor and the building material. When installing sensors on a reflective surface, we covered the sensors with matching reflective tape to ensure the sensors have the same radiative properties as the building material surface.

FIGURE 3: Installing temperature and heat flux sensors. Left to right: temperature sensor on exterior wall, heat flux sensor on interior side of OSB and thermocouple array through assembly, and installing heat flux sensor on reflective insulation with reflective tape.

3.2.4 Electricity Consumption

We monitored the circuit-level electricity consumption of each hut each minute to approximate the cooling energy required by each hut. In this experiment, the instrumentation power was very low (<5W), and there were no additional internal building loads.

3.2.5 Air Tightness

Test hut structures are often too small and too air tight to accurately measure the air tightness using standard, full-sized blower door equipment. Instead, we used a duct-blaster unit with a blower-door frame that was capable of measuring air flow in the appropriate pressure range. In this experiment, there were no windows in any of the test huts. We found that the air tightness was similar among all huts, both before (2.98 to 3.36 ACH50) and after (2.59 to 3.26 ACH50) the Aerogel blankets were installed. Adding the Aerogel blankets had a minor positive impact on the air tightness of the structures. These tightness levels are within the typical ranges for U.S. residential construction (3-10 ACH50).

4. RESULTS AND DISCUSSION

4.1 Weather

Weather during the experiment was typical of the Albuquerque, NM summertime desert climate. Daytime temperatures were high, approaching 35°C (95°F) with nighttime lows falling to 15°C (59°F). These substantial temperature swings affect the dynamic response of the test huts. Rainfall took place occasionally during the final week of the summer period, as indicated by lower temperature and higher relative humidity.

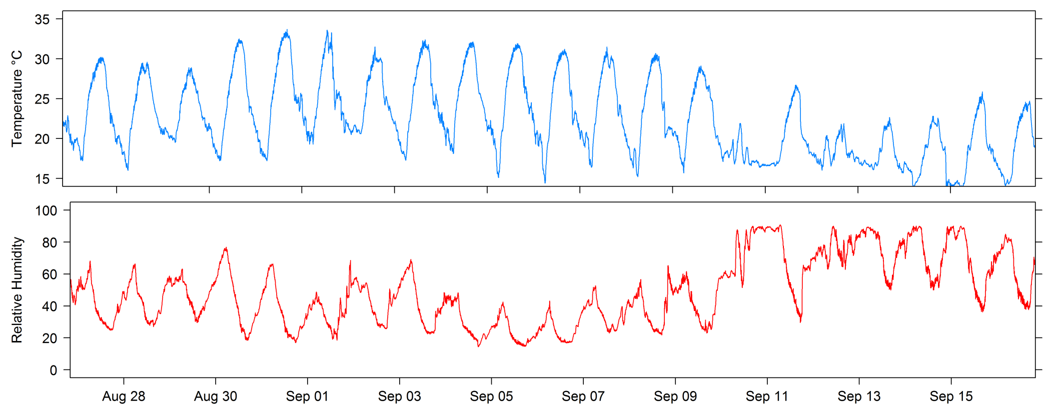

FIGURE 4: Outdoor environmental conditions during the experiment period.

4.2 Temperature Measurements

The zone temperature of each hut was controlled by the air conditioning unit. Each hut was controlled using identical constant setpoint temperature settings, with the intent of maintaining a consistent indoor boundary condition. Both Aerogel huts were able to maintain consistent indoor air temperatures throughout the experiment, as indicated by Figure 5. The air conditioner in the baseline uninsulated hut was unable to maintain its setpoint temperature during the daytime during the first two weeks of testing, even with the air conditioner running constantly at full capacity, as the cooling loads were simply too high for the equipment. As a result, the subsequent comparisons of energy consumption and heat loss represent a minimum expected savings relative to the uninsulated condition. Notably, the daily peak unconditioned attic zone temperatures were significantly cooler for both Aerogel huts compared with the uninsulated hut.

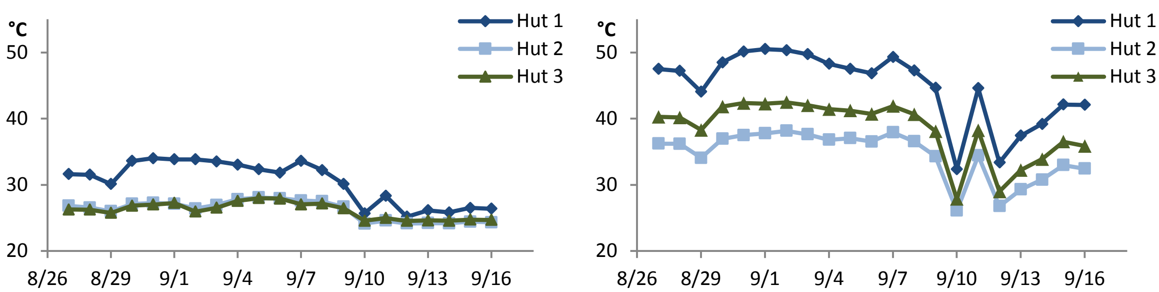

FIGURE 5: Daily peak air temperatures: LEFT=conditioned zone; RIGHT=unconditioned attic.

We measured temperature profiles across all wall assemblies. South wall and roof deck profiles are shown for a sample day for all the three test huts in Figure 6. Notably, the temperature drop across the Aerogel material was significant, indicating good insulation performance. During mid-day, the temperature difference between the interior side of the OSB and the Aerogel was greater in Hut 3 than in Hut 2, which suggests that the reflective insulation has a measurable effect on thermal performance.

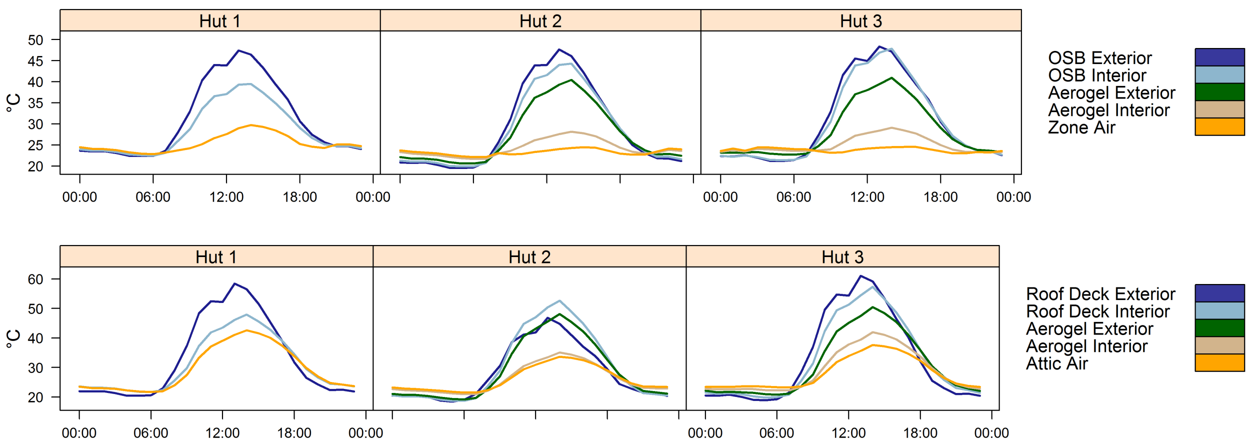

FIGURE 6: Temperature profile across south wall (top) and roof assembly (bottom) for sample day.

4.3 Heat Flux Measurements

We measured the heat flux through the center of one stud cavity on each wall, floor, ceiling and roof, for all three huts. The heat flux data allowed us to perform a simple energy balance on the conditioned zone of each test hut. By multiplying the each heat flux by the surface area of its corresponding surface (e.g., roof, floor, ceiling, wall), we obtain the instantaneous heat load from that component. Summing together these loads provides an indication of the envelope-driven cooling load for each test structure. The calculated positive heat loads are shown in Table 1 and Figure 7. Loads were consistently lower throughout the experimental period for both Aerogel insulation materials, and Hut 3 with its reflective surface had slightly lower loads than Hut 2 with non-reflective surfaces.

TABLE 1: Summary of daily heat load to conditioned zone by hut over 19 days.

	Positive Daily Heat Load (W)			**Max Daily Heat Load (W)**			**AC Daily Avg. Power Draw (W)**		
	Mean	**SD**	**% Diff**	**Mean**	**SD**	**% Diff**	**Mean**	**SD**	**% Diff**
Hut 1: Baseline, no insulation	488	221	-	1,798	172	-	547	127	-
Hut 2: Aerogel, nonreflective	132	79	-73%	689	103	-62%	158	79	-71%
Hut 3: Aerogel, reflective	101	70	-79%	534	100	-70%	122	41	-78%

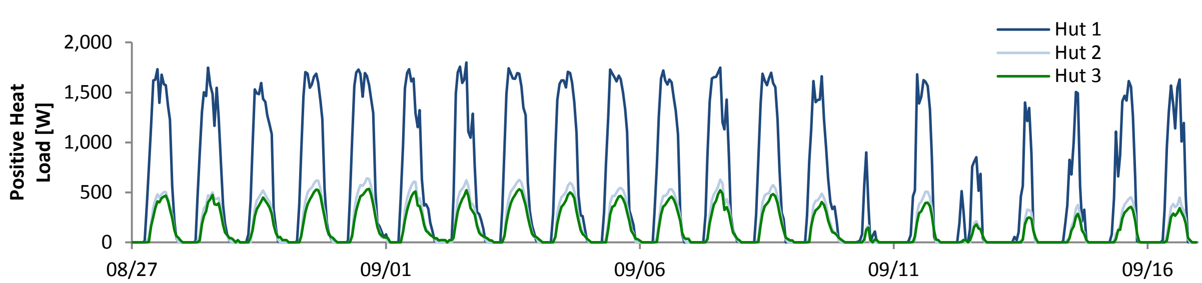

FIGURE 7: Calculated positive heat load to zone for three huts.

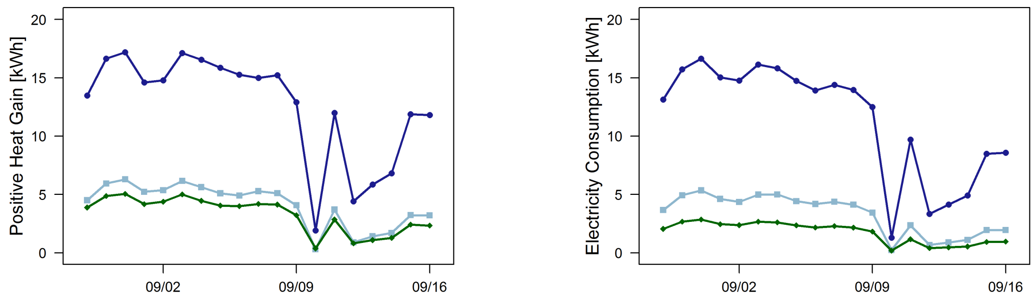

FIGURE 8: Daily positive heat gain to conditioned zone and daily electricity consumption.

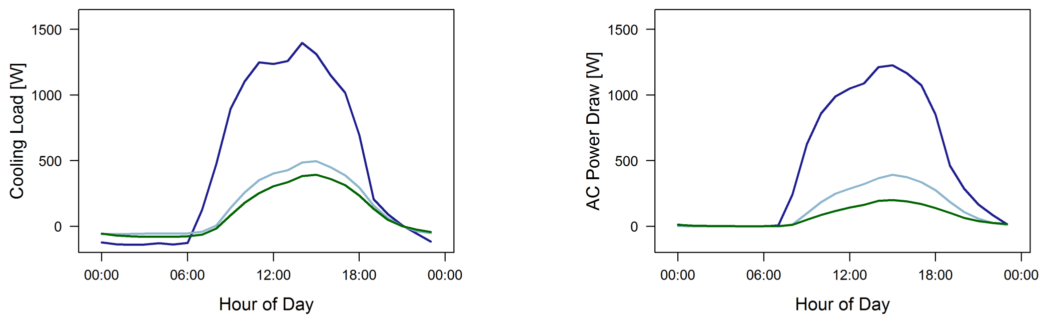

FIGURE 9: Average cooling load and cooling energy consumption profile for 3 huts over 19 days.

Integrating these loads over time yields the positive daily heat gained by the space from the building envelope components. Daily summaries of positive heat gain are shown in Figure 8, alongside the measured air conditioning energy consumption. We then aggregated the time-dependent heat loads to determine the average daily cooling load profile for the conditioned zone, shown in Figure 9, alongside the AC power draw profile. The peak value of the cross-correlation and associated lag of calculated heat load was 0.91, and +44 min for Hut 1 and Hut 2, and 0.91 and +53 min for Hut 1 and Hut 3. This lag can be explained by the added thermal mass and insulating properties of the insulation materials, which slow down the rate of heat transfer.

Strikingly, the shapes of the average profiles are quite similar (though not identical), indicating that the measured AC energy consumption values are closely correlated with the measured heat gains through each building component. The peak value of the cross-correlation function and the associated lag between AC power draw and calculated heat load was 0.89 and -34 min for Hut 1, 0.78 and +1 min for Hut 2, and 0.76 and +1 min for Hut 3. The near-zero lag for Huts 2 and 3 may be due to frequent HVAC cycling, whereas the AC unit ran almost continuously in Hut 1.

Do not mistake this good agreement as a reason to dismiss the need for detailed study of temperature and heat flux. Please note that except for carefully-constructed calorimetric experiments, it is rarely sufficient to use measured air conditioner electricity consumption to make direct energy performance comparisons of different building material test systems, even when systems are tested simultaneously and when identical AC units are used (as in this experiment). The reason is that AC units of the same kind may have different energy efficiency (COP) or operating characteristics due to manufacturing defects, differences, or tolerances. For instance, the amount of standby/fan power that each AC unit drew when it was not running ranged from 23 W to 72 W. We addressed these differences by subtracting away the baseline power draw in our calculations. Slight differences in refrigerant charge among units, for example, could further confound energy comparisons. For these reasons it is critical to measure thermal and energy performance directly using a combination of temperature and heat flux sensors.

5. CONCLUSIONS

The aim of this project was to evaluate the energy performance of two novel Aerogel insulation systems during the cooling season of the desert climate of Albuquerque, NM. Both novel systems consisted of a 3/8" thick Aerogel layer but differed in the facing materials – one used non-reflective foil and other used reflective foil. To estimate and compare energy savings with each insulation systems, three near-identical test structures were constructed as follows:

- Hut 1: uninsulated walls and uninsulated roof and attic space (baseline).
- Hut 2: walls and roof deck insulated with non-reflective Aerogel insulation.
- Hut 3: walls and roof deck insulated with reflective Aerogel insulation.

During a hot summer period of 21 days, we observed that both insulated huts had far reduced thermal gains compared to the baseline uninsulated Hut 1. Daily cumulative positive heat gains were between 67% and 85% lower than the baseline hut (mean=74%, SD=5%), depending on the day. The reflective insulation product tested in Hut 3 reduced heat gains by an additional 19% compared to Hut 2, primarily through reductions in heat flow through the ceiling.

Peak daily heat gains were reduced substantially compared to the baseline uninsulated structure, by between 56% and 77% (mean=66%, SD=6%). The reflective insulated hut had an average daily peak heat gain that was about 17% less than Hut 2 (SD=4%). Average daily cooling energy consumption was reduced by 71% in Hut 2 and 78% in Hut 3, while daily peak heat gain was reduced by 62% in Hut 2 and 70% in Hut 3.

6. ACKNOWLEDGEMENTS

This material is based upon work supported by The Small Business Innovative Research (SBIR) program and the Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) under Contract No. W9132T-12-C-0012. We would like to thank Bob Andrews and Alliston Watts for their many important contributions to this project.

7. REFERENCES

ASTM. 2007. C1046-95(2007). "Standard Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components." American Society for Testing and Materials.

ASTM. 2012. C1130-07(2012). "Standard Practice for Calibrating Thin Heat Flux Transducers." American Society for Testing and Materials.

Athienitis, A.K., C. Liu, D. Hawes, D. Banu and D. Feldman. 1997. “Investigation of the Thermal Performance of a Passive Solar Test-room with Wall Latent Heat Storage.” Building and Environment, Vol. 32, No.5, pp. 405-410.

Baker, P.H. and H.A.L. van Dijk. 2008. “PASLINK and dynamic outdoor testing of building components.” Building and Environment. 43(2008)143-51.

Khudhair, A.M. and M.M. Farid. 2007. “Use of Phase Change Materials for Thermal Comfort and Electrical Energy Peak Load Shifting: Experimental Investigations. In: GOSWAMI, D. Y. & ZHAO, Y., eds. Solar World Congress 2007, September 18-21. Beijing, China. Solar Energy and Human Settlement.

Medina, M.A., J.B. King, and M. Zhang. 2008. “On the Heat Transfer Rate Reduction of Structural Insulated Panels Outfitted with Phase-change Materials” Energy. Vol. 33, Issue 4:667-678.

Shilei Lv., F. Guohui, Z. Neng, and D. Li. 2007. “Experimental Study and Evaluation of Latent Heat Storage in Phase Change Materials Wallboards.” Energy and Buildings. Vol. 39 (2007), pp 1088-91.

Shukla, N., A. Fallahi, and J. Kosny. 2014. Aerogel Thermal Insulation − Technology Review and Cost Study for Building Enclosure Applications. *American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Transactions.*120 (1) (2014).

Szymocha, K. 2005. “Advanced Thermal Solar System with Heat Storage for Residential House Space Heating.” Proceedings of SESCI 2005 Conference British Columbia Institute of Technology, Burnaby, British Columbia, Canada, August 20-24.

Urban, B., N. Shukla, A. Fontanini, J. Kosny. 2014. An Outdoor Hut Testing Platform for Evaluating Advanced Building Enclosures. *Proc. 10th Nordic Symposium on Building Physics*. Lund, Sweden. June.