Project Final Report for DOE/EERE

FOA Name and Number:	DE-FOA-0002090, BENEFIT 2019
Award Number:	DE-EE0009156
Award Type:	Cooperative Agreement
Project Title:	**DEVELOPMENT OF LOW-COST, HIGH-PERFORMANCE, EASY-TO-APPLY, NON-FLAMMABLE, INORGANIC PHASE CHANGE MATERIAL (PCM) TECHNOLOGY**
Approved Project Period:	April 1st, 2020, through March 31st, 2023, extended till Dec. 30th, 2023,
Report Submission Date:	April 30th, 2024
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Certification of Compliance: By signing this report, I certify to the best of my knowledge and belief that the report is true, complete, and accurate.

Jan Kosny, Principal Investigator

Acknowledgment: "This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Buildings Technology Office (BTO), Award Number DE-EE0009156."

1. Project Background

The project effort was a 45-months long development program focused on the development of novel, easy-to-apply, non-flammable, and high-performance inorganic phase change materials (PCMs) for building and industrial applications. The University of Massachusetts Lowell (UML) formed a world-class team consisting of researchers form InsolCorp (only N. American manufacturer of inorganic PCM systems for building applications), and a group of industrial advisors, to develop a universal/multipurpose, simple-to-manufacture and cost-effective PCM technology. We expect that the results of this work will spur in the future the adoption of thermal storage materials – a key building energy saving technology as identified by DOE BTO – for a variety of building envelope applications.

In this project, the research and development effort followed the following three objectives:

Objective 1: To demonstrate a suite of low-cost, multipurpose, and durable inorganic PCM formulations with phase transition temperatures encompassing typical building applications (between +5°C and +55°C).

The first objective is to design, fabricate, and experimentally validate a performance of inexpensive, durable, highly efficient, non-flammable, and easy to manufacture PCMs. To allow a variety of building applications, we focus now on formulations that exhibit repeatable phase transitions between +5°C and +55°C. To follow the DOE BTO cost efficiency target without compromising thermal performance, we base our work on inorganic compounds (mostly salt hydrates) and their blends, which represent a fraction of the cost of most of organic PCMs with about twice as high density as well as significantly higher thermal conductivity and phase change enthalpy.

Objective 2: To develop easy-to-manufacture and -install packaging/encapsulation designs that are 1) a superior barrier to current state-of-the-art macro-packaging, which significantly reduces the risk of loss of hydration water and PCM leak, and 2) optimal in enhancing the heat exchange rates with the surroundings and within the PCM core to ensure complete charging/discharging of the entire PCM within the product.

Objective 3: To scale-up the fabrication process to demonstrate installation on system-scale applications, and to validate the performance under field conditions.

The original plan was that, at the end of the project, a group of latent heat PCM formulations will be developed based on salt hydrates, and heat storage technologies will be developed for building applications. This specifically included:

1. At minimum, 6-8 highly-conducting salt hydrate formulations that undergo congruent phase transition and are durable in typical building operation temperature range (5°C–45°C), and
2. Three advanced forms of PCM packaging.

In practice, after the completion of this project, 12 high-performance salt hydrate PCM formulations were developed and validated during the long-term durability testing.

1.1. Project Goal

The project aimed at developing low-cost, high-energy storage, and reliable latent heat storage technology for building applications. This development was realized by formulating and integrating the following two technology components: 1) inorganic salt hydrate based PCMs that have high latent enthalpies and are low-cost and durable, and 2) PCM encapsulation (packaging) technology that maximizes PCM concentration and enhances heat transport characteristics in the product and with the external environment/materials.

High thermal storage capacity, low cost and fire resistance are key to the building market entry for the PCM technology; therefore, our focus is on salt-hydrate-based formulations which satisfy all these criteria. Packaging or encapsulation of PCM is a key processing step. Recent advances in packaging methods involve micro- and nano- encapsulation and deposition techniques (i.e. growth of crystalline PCMs, by molecular beam epitaxy, sputtering, pulsed laser deposition, cold sintering, etc.), and 3D printing. However, these advanced methods are still at the proof-of-concept stage, and they add significantly to the product cost, making technology scalability questionable. Our team recognizes that a low-cost and simple-to-manufacture salt hydrate-based PCM technology holds the best chance to be successful in the building construction market, a market which is traditionally extremely sensitive to cost and where commodity thermal insulations are the benchmark for envelope-related energy saving measures.

In this project our intention was to minimize the production cost and maximize the product energy storage density without sacrificing the PCM performance. That is why our main focus was on:

1. Minimizing the non-PCM components (plastics, additives, packaging/encapsulation materials, etc.) because they are significantly more expensive than salt hydrates,
2. Using highly thermally conductive and lightweight PCM carrier (packaging material) to facilitate more complete phase cycling, and
3. Optimizing the thickness and minimizing air spaces in product design (such as in pouched PCM).

For this purpose, our approach was to enable an easy system design, including selection of the PCM operating temperatures, optimizing the necessary heat storage capacity (by stacking together several layers of PCM products), and if needed, a synchronized usage of PCM products of different temperatures. A specially designed, robust, highly thermally conducting and highly impermeable packaging (to retain salt hydrate water during phase transition cycles) will increase the overall system thermal performance and durability. In addition, it will enable an easy installation within the building envelope, interior building space, or as a part of the interior structural fabric. Furthermore, after further developments and commercialization, the developed PCM technologies may be also applied in space conditioning, energy storage technologies, and heat transfer applications.

Summarizing, as specified in Table 1, the PCM technologies developed during the project were expected to meet the following minimum performance targets:

Table 1. Performance Requirements for PCM Technologies Developed During the Project.

Metric Description	Minimum Targets
Phase Change Temperature	5ºC to 55ºC
Cost	<$15/kWh
Energy Density	>100 kWh/m3
Thermal Conductivity	>1 W/m·K
Thermal Reliability	>90% after >5000 cycles
Safety	Non-toxic, non-flammable, non-explosive, and non-reactive
Corrosion	eliminated or minimized

1.2. Project Timeline

This almost four-year-long research and development project was focused on the development of a novel group of high-performance inorganic PCM formulation and innovative PCM packaging technologies, which are expected to allow a wide range of building applications in North America. PCM technologies developed/considered during the project are based on high-performance, cost-competitive, and non-flammable PCMs, as well as on state-of-the-art packaging methods. They were developed in the muti-disciplinary research effort focused on (i) development of PCM formulations, (ii) simultaneous development of the PCM packaging and functional shape of PCM products, (iii) development of fabrication technology and fabrication demonstration, and (iv) system scale installation demonstration, field testing, and performance analysis. As presented in Table 2, the project workplan included seven major tasks, which were originally planned for a 36-months' time-period. It is worth mentioning that during this three-year time, all project milestones and Go-No-Go requirements were fulfilled. However, during the third year, the project was extended to 45 months, to allow additional development of low-temperature PCM formulations, and continuation of technology field testing. This project was completed in December 2023.

Table 2. Project Time Schedule *(M = Milestone, G=Go/NoGo Decision Milestone)*

Project Tasks/ Project quarters	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
1. Selection of PCM compounds, design of PCM Blends				*G*								
2. Design of the PCM carrier, packaging shape and packaging method				*G*								
3. Performance optimization and lab fabrication of 10 to 15 PCMs												
4. Performance optimization and lab fabrication of PCM carriers and 3 PCM packaging products								G				
5. Analysis supporting Technology to Market Plan (1)												
6. Fabrication of final designs of PCM products and system-scale installation and performance demonstrations												
7. Analysis supporting Technology to Market Plan (2)												

1.3. Project Team

To realize work tasks planned for this project, the University of Massachusetts Lowell (UML) formed a team consisting of researchers from InsolCorp (only N. American manufacturer of inorganic PCM systems for building applications). The main goal was to develop a universal/multipurpose, simple-to-manufacture and cost-effective PCM technology. During the course of the project, a significant portion of research work was performed by a diversified group of undergraduate, graduate, and doctoral students. Our research team was also supported by a group of distinguished industrial advisors who helped in (i) planning of research approach, (ii) analysis of performance and cost data, and (iii) advised in technology commercialization effort.

Project research team:

Dr. Jan Kośny, Project PI, is a research professor at the Department of Mechanical Engineering at UMass Lowell. He is former associate professor at Technical Univ. of Rzeszow, Poland, senior research staff member at ORNL, and Director of Building Enclosures and Material Program at Fraunhofer CSE in Boston, MA. He has over 40 years of experience in building physics, external envelopes, and novel thermal insulations, through work in academia, national lab, and research institutes. He is well known for his decades-long work on Thermal Mass and Phase Change Materials. Dr. Kośny is a founder and first Executive Director of North American PCM Manufacturers Association. He has authored over 150 research publications, technical reports, and several patents in this area. In 2009, Dr. Kośny received the R&D 100 Award for the development of flame resistant PCM-enhanced thermal insulation.

Dr. Margaret Sobkowicz-Kline, project co-PI, is a professor in Plastics Engineering at UML. She holds B.S. and Ph.D. degrees in chemical engineering from Columbia University and Colorado School of Mines, respectively. She was awarded a National Research Council postdoctoral fellowship to study polymer photovoltaics at NIST. She received an NSF CAREER award to investigate reactive twin screw extrusion of biobased polymer blends. Her research is focused on plastics sustainability and clean energy. Active projects in her group include research on plastics recycling, biobased plastics, reactive extrusion, thermally conductive composites, and polymer electronics. Dr. Sobkowicz-Kline contributed to this project on the tasks associated with materials characterization, packaging, and polymer processing.

Dr. Cordula Schmid – project co-PI, is associate professor in the Department of Electrical and Computer Engineering, UML. Dr. Cordula Schmid's experience demonstrates the ability to manage complexities of this scale and larger. She was the program manager of the DOE-funded Plug and Play PV project which involved 3 years of managing 14 partners and an $8M budget, including: prototype development, construction, testing and full-scale demonstration. Prior to becoming a Research Associate Professor at UML, she managed the PV Technologies team at the Fraunhofer Center for Sustainable Energy CSE since 2016 and served as a member of technical staff for the Fraunhofer organization since 2004. She focused on the reliability related assessment of module materials and the mechanical and electrical testing of modules. She obtained her Doctor of Engineering Degree from the Karlsruhe Institute of Technology in Germany. Dr. Schmid contributed to this project on the tasks associated with system performance analysis, cost analysis, and technology commercialization.

Dr. Juan Pablo Trelles – project co-PI, professor in the Department of Mechanical Eng. UML. (Ph.D. in Mechanical Eng. - Univ. of Minnesota). His research encompasses: Sustainable Energy Engineering, Heat and Mass Transport, Plasma Science and Engineering, and Computational Transport Phenomena. Research sponsors: NSF, DOE, DOD, NASA, private companies. Awards: NSF CAREER Award -2015, DOE Early Career Research Award -2017. Dr. Trelles contributed to this project on the tasks associated with numerical performance analysis, design of PCM packaging, and system efficiency.

Mr. Peter Horwath serves as a CEO of InsolCorp LLC, U.S. manufacturer of PCMs, and PCM-based technologies – project industrial partner. He is also a president of North American PCM Manufacturers Association. InsolCorp LLC. is the U.S. largest producer of inorganic PCM systems for buildings with over 3 million ft^2 of installed products. In the project, their primary focus is on the technological PCM systems' design, testing and commercialization of inorganic, salt hydrate based PCM formulations, as well as the development, field testing, market introduction, and complete commercialization of PCM products. Their work extends beyond simple PCM formulations, and continues into development of encapsulation and materials science, as well as manufacturing, sales, and marketing.

2.0. Summary of Project Accomplishments & Milestones' Fulfillment:

As discussed in earlier sections, the key project objectives included:

- The development and performance/durability demonstration of a suite of low-cost, multipurpose, and durable inorganic PCM formulations with phase transition temperatures encompassing typical building applications (between +5°C and +55°C).
- The development of high-performance, easy-to-manufacture, and simple to install PCM packaging/encapsulation designs.
- Presentation of the scaled-up fabrication process and system scale demonstration of developed PCM technologies, combined with performance validation under field conditions.

The following sections summarize basic project achievements for each year of the project.

2.1. Year 1 - Summary of Project Accomplishments & Milestones' Fulfillment.

During Q1, Q2, Q3, and Q4 the project team's work was focused on Tasks 1 and 2 – see descriptions below. The project team performed the search work on available, described in literature, low-cost inorganic PCM precursors and formulations with phase transition temperatures between +5°C and +55°C (because most of PCM formulations have slightly different phase transition temperatures from original precursor compounds, the top temp. is little bit higher from what is listed in the SOPO). For this purpose, extensive laboratory analytical work was initiated. The UML team performed a significant amount of formulation development work and the enthalpy analysis of about 20 PCM formulations and formulation modifications. Furthermore, during Q3-Q4, the test equipment development work was performed on non-conventional equipment, which became essential later during the project. This, for example, included the unique water bath T-history testing apparatus for analysis of PCM enthalpy and subcooling effect.

Furthermore, the initial study was made on computational methods, that were later used during Q4 and Y2 for numerical performance analysis, design, and optimization of the shape and configuration of new PCM products. In addition, the project team worked with our industrial partners and the project advisory board on selection/modification/development of the highly conductive barrier materials. The project team reviewed/evaluated several PCM packaging methods and membrane materials used by different industries, including materials used by InsolCorp and other PCM companies. Several non-conventional marked-available products for PCM packaging were identified.

They were tested during Q3 and Q4. UML also worked on the development of the Teaming Contract and the Intellectual Property Management Plan (IPMP) with 3M, our industrial advisor at that time, and potential team member. In addition, during Q3, the Cost-Performance Analysis started with a collection of the cost data for typical chemical components (inorganic) used by the PCM industry.

As listed below, at the end of the Y1, the task realization progress met the initial plans in 100%. No significant delays were recorded for both Task 1 and Task2. Table 2 presents a list of realized project milestones with included subtasks' completion rates:

Task 1.0 – [Selection of PCM Compounds, Design of PCM Blends, Performance Analysis]:

Subtask 1.1- Review of PCMs and initial performance verification.

Subtask 1.2 - Performance enhancement and lab fabrication trials of selected 25 to 30 "most-promising" PCM compounds/formulations.

Task 2.0: – Design of the PCM carrier, packaging shape, and packaging method

Subtask 2.1: Design of the PCM carrier

Subtask 2.2: Development of the PCM packaging barrier membrane

Subtask 2.3: Functional, and shape design of three PCM products

Table 3. Y1 Milestones Status

Milestone	Type	Status	Completion Date
M1.1 - *Selection of 25 - 30 "most-promising" inorganic PCM compounds with phase transition enthalpy > 180 J/g and density between 1500–2500 kg/m³, which should lead to achieving the volumetric energy storage density of ~100 kWh/m³*	Technical	Complete	10/01/2020
M1.2 - *Down-selection of 10 to 15 of "most-promising" PCM compounds/formulations with phase transition enthalpy > 200 J/g and volumetric energy density > 100 kWh/m³*	Technical	30% Complete* Complete	03/31/2021 04/30/2021
M2.1 - *Selection/development and testing of 3 PCM carriers. This will include at least 2 types of membranes and one material candidate for the shape stabilized PCM application*	Technical	Complete	03/31/2021

M2.2 - *Development and testing of a prototype barrier membrane with apparent thermal conductivity between (1.0 - 10.0 W/mK)*	Technical	Complete**	03/31/2021
M2.3 - *Finalize designs of three PCM packaging application options. This included 2 types of arrays of PCM pouches, and one shape-stabilized application were PCM represented > 70% to 80% by weight and > 65% by volume of the application area*	Technical	Complete***	03/31/2021
Go/No-Go - *Successfully achieving prototype 2 targets for PCM*	Go/No-Go	60% Complete Complete****	03/31/2021 04/30/2021

**Supply of chemical compounds took longer than planned. This delay affected planned thermal performance testing of PCM formulations.*

***Required target thermal conductivity was achieved. However, the prototype production of the custom high thermal conductivity membrane was abandoned with DOE BTO approval. Major reasons were (i) required high content of carbon fillers (affecting the cost), (ii) too high vapor permeability, and (iii) associated high material density causing problems with extrusion. Instead, aluminum laminated vinyl membrane was used in follow-on fabrication of test prototypes.*

****This Milestone led to the development of a new design of PCM packaging for InsolCorp with significantly increased PCM load, and consequently, thermal storage capacity.*

*****Small delay due to chemical supply problems – see Milestone 1.2*

2.2. Year 2 - Summary of Project Accomplishments & Milestones' Fulfillment.

During Q5, Q6, Q7, and Q8 the project team's work was focused on completion of Task 1, as well as Tasks 3. 4. and 5. The project team continued the development work on preselected, low-cost inorganic PCM formulations with phase transition temperatures between +5°C and +55°C (because most of PCM formulations have slightly different phase transition temperatures from original precursor compounds, the top temperature is little bit higher from what is listed in the SOPO). For this purpose, the laboratory analytical work was initiated. We performed a significant amount of formulation development and verification work, using either UML's developed data or information available from scientific literature. The UML team also perfomed enthalpy analysis of about 12 PCM formulations and formulation modifications.

During Q5-Q8, we also continued the development/optimization work of the PCM board and flat heat exchanger products. We evaluated several packaging materials for PCM products. Furthermore, we analyzed, and numerically optimized the PCM panels' shapes and configurations of the PCM products (stackable assemblies). We performed this analysis using steady-state and transient heat transfer modeling and CFD numerical analysis, utilizing Comsol Multiphysics software for this purpose. The project team worked with our industrial partners and the project advisory board on selection/modification/development of thermally conductive barrier materials for PCM packaging.

We also evaluated several PCM packaging methods and membrane materials, including materials used by InsolCorp, other PCM companies, vacuum panel manufacturers, PV module manufacturers, as well as some products used by the food industry. In addition, several unconventional marked-available and proprietary thermally conducting products for PCM packaging were tested. One of the examples is PVC membrane laminated with aluminum foil. Furthermore, the UML team developed, and lab tested several formulations of conductive plastics to be used for PCM packaging. Finally, we worked on the Cost-Performance Model. This development/analysis was combined with collection of cost data for typical chemical components (inorganic) used by the U.S. PCM industry. During Y2, the Technology to Market Analysis was further advanced, with the main goal to support the market implementation and adoption of our PCM technologies developed during the project.

Below there is presented a list of currently realized project tasks with included the milestones completion information:

Task 3.0 – Performance optimization and lab fabrication trials of selected 10 to 15 PCM compounds/formulations, (M13-M24)

Subtask 3.0- Laboratory performance testing and performance optimization of selected 10 to 15 PCM compounds/formulations.

Task 4.0: – Performance optimization and lab fabrication trials of the PCM carrier materials and 3 types of PCM packaging products, (M13-M24)

Subtask 4.1: Laboratory performance testing and performance optimization of selected PCM carrier materials

Subtask 4.2: Fabrication trials, performance optimization, and laboratory performance testing of earlier-developed PCM packaging forms/products

Task 5.0: - Analysis Supporting Technology to Market Plan (1) (M13-M24)

Subtasks 5.1: Develop the Preliminary Cost-Performance Model (PCPM)

Subtask 5.2: Develop the Technology to Market Plan

Subtask 5.3: Manufacturing and Scalability Analysis

Subtask 5.4: Thermal performance analysis of specific PCM applications supporting the Technology to Market Plan

Milestones Status: Table 4 below shows the advancement status for all Y2 milestones. Only insignificant delays were recorded for Task 4, and Task 5. Please note that Task 3 was extended for the entire duration of the project. Additional workload was added to Task 3 to allow analysis of low-temperature PCM formulations.

Table 4. Y2 Milestone Status.

Milestone	Type	Status	Completion Date
M3.1 - *Successful completion of literature search, formulation adjustment experiments, fabrication trials, and a series of laboratory tests. Technical report discussing, the selection of 7 to 8 of "best-performing" PCMs of target energy storage density >100kWh/m³*	Technical	Complete*	12/31/2021
M3.2 - *Completion of PCM fabrication trials and durability (cycling) tests. Technical report discussing the results of long-term durability testing of 7 to 8 of "best-performing" PCMs. PCM's achieve at min. 90% of initial phase change performance (>100kWh/m³) after 500 phase change cycles.*	Technical	Complete*	03/31/2022
M4.1 - *Successful pilot fabrication of one or two fully developed PCM carrier materials for shape-stabilized applications. Limited mech. and installation testing.*	Technical	95% Complete Complete**	12/31/2021 03/31/2022
M4.2 - *Thermal, CFD, and mechanical strength modeling, allowing thermal performance/design optimization of developed PCM packaging systems. The system-scale installation and performance trials of developed PCM technologies. Fabrication and testing of three mechanically robust, impermeable, and thermally conductive PCM packaging forms/products.*	Technical	80% Complete Complete**	03/31/2022 05/31/2022
M5.1 - *Preliminary Cost-Performance Model including a simple process flow diagram, indicating input and outputs, a full bill of materials, and identifies key cost drivers.*	Technical	100% Complete	09/30/2021
M5.2 - *Initial Technology to Market Plan that outlines a roadmap for advancing BTO funded technology toward commercial viability and identifies key T2M factors for analysis.*	Technical	90% Complete Complete***	03/31/2022 05/31/2022
M5.3 - *Analysis of manufacturing and scalability risk, as well as future technology market implementation.*	Technical	75% Complete Complete***	03/31/2022 05/31/2022
M5.4 - *Literature review and numerical PCM performance analysis of PCM bldg. applications. Numerical simulations for both building envelope and mechanical system applications. This*	Technical	65% Complete Complete****	03/31/2022 06/30/2022

includes 3-D arrays of pouches used in open spaces and air duct applications, as well as concentrated board or multiple foil applications with different PCMs, for enclosed spaces and surface areas. Selection of the most promising PCM applications.			
Go/No-Go - *One or two fully functional and durable prototypes of PCM carrier materials achieving target performance – see Table 4 SOPO.*	Go/No-Go	85% Complete Complete**	03/31/2022 05/31/2022
GO/NO-GO - *Successful fabrication of three thermally conductive PCM packaging forms/products.*	Go/No-Go	Complete	03/31/2022

**To allow further development of low-temperature PCM formulations, Task 3 was extended on No-Cost-Bases. DOE BTO agreed to continue this Task till the end of the project.*

*** This delay was caused by limited market availability of PVC plastic membranes in the U.S., which caused delayed supply, and later-than-expected fabrication of test prototypes.*

**** During 2022, market prices of materials and chemical compounds used during the project changed several times. Both, economic analysis and commercialization plan had to be revised several times to incorporate these price changes.*

***** During Y2 of the project, following the results of numerical analysis and lab-scale tests, and reacting to the increasing prices of several components, the design of the PCM system was changed several times. This caused a slight delay in numerical analysis.*

2.3. Years 3 and 4 - Summary of Project Accomplishments & Milestones' Fulfillment.

During Q9, Q20, Q11, and Q12 the project team's work was focused on completion of Task 3, as well as Tasks 6 and 7. Project Y3 was dedicated to two major efforts which included:

- Continuation of the development work focused on low-temperature Glauber's salt (GS) based PCM formulations, and
- Field demonstration and performance analysis for wall and roof PCM technologies developed during the project,
- Technology Commercialization Works focused both on PCM formulations and PCM Products:
    - Technology commercialization, and financial investment analysis associated with the introduction of new products to the market,
    - Product cost analysis, as well as estimations of other fabrication, testing, and new equipment costs supporting the Technology to Market, Plan

During Y3 and extended Y4, we continued the PCM formulation development work. This effort was dedicated to filling the gaps in the following two temperature regions: (i) refrigeration temperatures between +5°C and +15°C, and completion PCM development and durability analysis work in (ii) the second temperature region between +40°C and +60°C. In the first case, our focus was on preselected, low-cost Glauber's Salt-based PCM formulations with phase transition temperatures in the refrigeration region between +5°C and +15°C. Our work on the second region included the development of SAT-based formulations (SAT - sodium acetate trihydrate). The majority of Y3 and Y4 PCM development work, however, was focused on GS-based formulation area. This fact is reflected by several prepared research publications, where most of the PCM formulation development and testing work was performed on GS-based mixtures containing different thickening agents. With respect to operational temperature region, we concentrated on filling the temperature gap between +5 °C and +15 °C. In addition to the PCM formulation work, the project team dedicated a significant amount of time to field demonstration of prototype PCM technologies which were developed during the project. For this purpose, three test huts were built and instrumented in Albemarle, NC, where wall, ceiling, attic, and roof technologies were tested in field conditions. As described in the Q9 - Q13 reports, the installation of several new PCM building products was demonstrated on the test scale construction buildings (8 x 10 x 8-ft test huts). The following four types of constructions applications were field validated: (i) internal wall surface application, (ii) suspended ceiling applications, (iii) top of the attic insulation application, and (iv) attic cavity application. During Q14, the UML team validated the fifth PCM application: (v) interior ceiling surface application. Finally, during Y3 and Y4, the project team worked on finalizing the technology cost estimates and development of the technology commercialization plan. Technology commercialization analysis included a series of discussions with largest PCM manufacturers in the U.S. about main implementation barriers which they identify for PCM products. From the perspective of PCM manufacturer companies, several key risks can be listed, which impact of the future of this kind of businesses, as well as the future U.S. implementations of dynamic thermal mass, and heat storage products. For about two decades both, U.S. PCM manufacturers and engineering/research society have been well aware about numerous problems which restrict the adoption of these technologies. They resonate with some resistance, which limits the large-scale acceptance of PCM technologies in U.S. buildings, mostly due to the dynamic nature of PCMs and lack of a full reflection of this fact in the existing building and energy codes. The current building industry is geared primarily to low thermal mass and high thermal resistance external envelopes and similarly, lightweight internal building fabric products. The current building and energy codes, as well as conventional construction approaches are centered around the steady-state R-Value or U-value performance labels, which in turn, are consequently, most often tested/analyzed using static test methods. That is why, technology commercialization approach was based on companies already having experience in introducing PCM-based products to the market. One of such contacts ended up with purchasing by Armstrong World Industries[1] a part of InsolCorp (including IP) – the project industrial partner company. This transaction

[1] https://www.armstrongceilings.com/commercial/en/performance/energy-saving-ceilings.html

was associated with commercialization of the ceiling and wall PCM panel technology utilizing several design elements, which were either developed or validated during this project.

Below there is presented a list of, realized during Y3 and Y4, project tasks with included the milestones completion information:

Task 3.0 – Performance optimization and lab fabrication trials of selected 10 to 15 PCM compounds/formulations, (M13-M24) - original work tasks and all deliverables were fully completed during Y2. However, this Task was extended till the end of the project.

Subtask 3.0- Laboratory performance testing and performance optimization of selected 15 PCM compounds/formulations.

Task 6.0 – Fabrication of final designs of PCM products and system-scale installation and performance demonstrations of developed PCM technologies, (M25-36)

Subtask 6.1 - Fabrication of final designs of PCM products - (M25-M27). The project team scaled up the fabrication process and produced three final designs of PCM products.

Subtask 6.2 - Construction of wall, roof, and ceiling mockups and system-scale installation demonstration of three developed PCM technologies - (M28-M30).

Subtask 6.3 - Seasonal system-scale field-exposure testing of selected PCM technologies was performed in NC climate. – (M25-M33).

Subtask 6.4 - Accelerated durability testing of three final PCM products (M28-M36).

Task 7.0 – Analysis Supporting Technology to Market Plan - (M25-M36)

Subtask 7.1 – completion of cost estimates of PCM formulations, product designs, and fabrication.

Subtask 7.2 - Refine the T2MP and Cost-Performance Model – The UML team refined the T2MP, which: (i) defined potential customers and their eventual needs; (ii) listed product basic requirements for specific target markets, and (iii) specified basic code requirements for specific applications.

Subtask 7.3 - Next-Stage Planning – Anticipated resource needs and potential follow-on funding sources for the next phase of technology developments.

Subtask 7.4 - Manufacturing and Scalability Analysis (MSA).

Subtask 7.5 – Final cost analysis of novel PCM products.

Milestones Status: Table 5 below shows the advancement status for all Y3 milestones, which were realized during Y3 and Y4. No significant delays were recorded. Please note that Task 3 was extended for the entire duration of the project. Additional workload was added to Task 3 to allow analysis of low-temperature PCM formulations, and durability testing of SAT based formulations.

Table 5. Y3 Milestone Status.

Milestone	Type	Status	Completion Date
M6.1 - *Fabrication of final PCM products - including 2-, or 3-dimmensional arrays of PCM pouches and one shape-stabilized or impregnated board/foil application.*	Technical	Complete	08/31/2022
M6.2 - *Construction demonstration of three system-scale mockups with six types of developed PCM technologies.*	Technical	Complete	08/31/2022
M6.3 - *Construction and instrumentation of three test huts in NC climatic location and performance test comparisons for at least 8 weeks.*	Technical	70% Complete* Complete	08/31/2022 06/30/2023
M6.4 - *Completion of accelerated durability testing of final designs of three PCM products prepared during the project.*	Technical	Complete	12/31/2023
M7.1 - *Revised Technology to Market Plan that outlines potential customer needs and requirements for target markets, potential market entry points, and refined cost-performance model.*	Technical	Complete	03/31/2023
M7.2 - *Analysis of next stage goals, resource needs, and potential next stage funding sources, outreach and engagement plan for partners/funders with actions, and associated timeline*	Technical	Complete	09/30/2023
M7.3 - *Scalability Risk Analysis that outlines the potential risks associated with technology market implementation and discusses potential technological complications impacting future scalability of the manufacturing process.*	Technical	Complete	03/31/2023
M7.4 – *Cost Performance Analysis of developed PCM formulations, their packaging methods, and comparison with competitive PCM products.*	Technical	Complete	09/30/2023
End-Of-Project-Deliverables *Development of minimum seven PCM formulations with Phase Change Temperatures between 5°C and 55°C; Cost <$15/kWh; Energy Density >100 kWh/m³*		Complete Complete *twelve PCM formulations were developed.*	03/31/2023 12/31/2023

Field demonstration of developed PCM technologies		Complete	09/30/2023

**Weather conditions in 2022 didn't allow collection of 8 weeks of summer season performance data. That is why the project was extended for Y4 to include early summer measurements.*

3.0. What was Accomplished under the Project Goals:

This project focused on developing low-cost enabling technologies, which will support in coming years the widespread implementation of high-energy density, and reliable latent heat storage technologies for building applications. This development was achieved by designing and integrating the following two technology components: 1) inorganic salt hydrate based PCMs that have high latent enthalpies, are low-cost, and are durable, and 2) PCM encapsulation (packaging) technology that maximizes PCM concentration and enhances heat transport characteristics. The packaging methods developed during this project allow both, implementation as a part of building envelope, internal building fabric, or as inner components of mechanical space conditioning systems, including different types of heat exchangers. As discussed in earlier sections, in this project, the research and development effort reflected the following three objectives:

Objective 1: To demonstrate a suite of low-cost, multipurpose, and durable inorganic PCM formulations with phase transition temperatures encompassing typical building applications (between +5°C and +55°C). The project's main goal was to design, fabricate, and experimentally validate a performance of inexpensive, durable, highly efficient, non-flammable, and easy to manufacture PCMs. To allow a variety of building applications, we focused on formulations that exhibit repeatable phase transitions between +5°C and +55°C. To follow the DOE BTO cost efficiency target without compromising thermal performance, we based our work on inorganic compounds (mostly salt hydrates) and their blends, which represented a fraction of the cost of most of organic PCMs with about twice as high density and significantly higher phase change enthalpy.

Objective 2: To develop easy-to-manufacture and -install packaging/encapsulation PCM product designs that are (i) a superior barrier to current state-of-the-art macro-packaging, which significantly reduces the risk of loss of hydration water and PCM leak, and (ii) optimal in enhancing the heat exchange rates with the surroundings and within the PCM core to ensure complete charging/discharging of the entire PCM within the product.

Objective 3: To scale-up the fabrication process to demonstrate installation on system-scale applications, and to validate the performance under field conditions.

3.1. **Objective 1** – Development of a family of low-cost and durable PCM formulations that exhibit phase transitions between +5°C and +55°C.

After extensive literature search, combined with lab synthesis, and experimental evaluation of over 200 formulations of inorganic PCMs, the project team successfully **developed twelve stable PCM formulations** with phase change temperatures between 10^{o}C and 58^{o}C. Compared to the project proposal and SOPO, this was the non-cost increase by four additional formulations. It is worth mentioning that PCMs developed during this projects are relatively easy to manufacture and require widely available chemical components. As shown in Table 6, most of them exhibit phase change enthalpies in the range between 170-J/g and 260-J/g. Only four low temperature PCMs have enthalpies between 130 and 140 J/g (#1 to #4 in Table 6). This Table lists major UML reports containing detailed information about development work and testing performed on specific formulations. In addition, these PCMs show either minimal (below 1^{o}C) or no subcooling. The prices of almost all of these formulations are well below the DOE BTO cost target of $15 per kWh. Within the whole group, the highest prices are for two formulations containing Sodium Tungstate Dihydrate (#11 and #12 in Table 6). They are just below the price of $15 per kWh. In most cases, these formulations have good chances to be commercialized after the completion of the project. All these formulations underwent 250-1000 phase change cycling to validate their long-term performance.

Table 6. List of best performing PCM formulations, developed during the project.

#	PCM Formulation	Tm [^{o}C]	Enthalpy [J/g]	Subcooling [^{o}C]	UML Report Reference
1.	Glauber's Salt - $Na_2SO_410H_2O$ (SSD) (80%), mixed with KCl (5.35%), NH_4Cl (9.65%) Borax (3%), SPA (2%)	10.0	136*	0.4	Rep. Apr.30th 2023 Rep. Jan.30th 2024
2.	Glauber's Salt - $Na_2SO_410H_2O$ (SSD) (80%), mixed with KCl (5.35%), NH_4Cl (9.65%) Borax (3%), SPA (2%)	9.8	140*	0.3	Rep. Apr.30th 2023 Rep. Jan.30th 2024
3.	Glauber's Salt - $Na_2SO_410H_2O$ (SSD) (80%), mixed with KCl (5.35%), NH_4Cl (9.65%) Borax (3%), SPA (2%)	10.0	141*	0.4	Rep. Jun.30th 2023 Rep. Jan.30th 2024
4.	Glauber's Salt - $Na_2SO_410H_2O$ (SSD) (80%), mixed with KCl (5.35%), NH_4Cl (9.65%) Borax (3%), CMC (2%)	10.2	130*	NA	Rep. Oct.30th 2023 Rep. Jan.30th 2024
5.	$CaCl_2.6H_2O$ mixed with Potassium Nitrate (KNO_3) and with 2% of Strontium Chloride Hexahydrate ($SrCl_2.6H_2O$), Potassium Bromide (KBr), and Water	22	195	0.5-1.0	Rep. Oct.31st 2021 Rep. Apr.31st 2022 Rep. Apr.30th 2023

6.	$CaCl_2.6H_2O$ mixed with 5% of KCl and 2% of Strontium Chloride Hexahydrate ($SrCl_2.6H_2O$)	26	174	NA	Rep. Oct.31st 2021 Rep. Apr.31st 2022 Rep. Apr.30th 2023
7	$CaCl_2.6H_2O$ mixed with 5% of NaCl and 2% of Strontium Chloride Hexahydrate ($SrCl_2.6H_2O$)	27.7	178	NA	Rep. Oct.31st 2021 Rep. Apr.30th 2023
8	75wt% of $Na_2HPO_4.12H_2O$ and 25wt% of $Na_2SO_4.10H_2O$, 2wt% of Borax	30	220	1.0 – 5.0	Rep. Jan.30th 2023
9	84-85wt% of Sodium Acetate Trihydrate ($NaCH_3COO*3H_2O$), 14wt% of Sodium Formate (NaHCOO), and 1 or 2wt% of Borax	50.7 to 51.8	182 to 206	NA	Rep. Jan.31st 2022 Rep. Apr.30th 2023
10	84wt% Sodium Acetate Trihydrate ($NaCH_3COO*3H_2O$), 14wt% Sodium Formate, and 2wt% of Sodium Tungstate Dihydrate ($Na_2WO_4*2H_2O$)	50.4	205.3	NA	Rep. Jan.31st 2022 Rep. Apr.30th 2023
11	98wt% of Sodium Acetate Trihydrate ($NaCH_3COO*3H_2O$), and 2wt% of Sodium Tungstate Dihydrate ($Na_2WO_4*2H_2O$)	58.8	238	NA	Rep. Jan.31st 2022 Rep. Apr.30th 2023
12	98wt% of Sodium Acetate Trihydrate ($NaCH_3COO*3H_2O$), and 2wt% of Borax	55.7	260	0.0 – 1.0	Rep. Jan.31st 2022 Rep. Apr.30th 2023

**Low temperature PCMs represent slightly lower enthalpy compared to other PCMs developed during this project. However, they exhibit higher thermal conductivity and density than competitive organic PCMs with the same operational temperatures. Correspondingly, their energy storage density is similar as in the case of the best organic products, at significantly lower price.*

In addition to the project quarterly reports, the above development of PCM formulations was documented in several reviewed research papers, conference presentations, and Ph.D. dissertation. The short list of publications includes:

1. Jay Thakkar (Dec. 2023) – "Optimizing Design of Salt Hydrate Phase Change Materials for Building and Cold Chain Efficiency Applications" Ph.D. Dissertation Submitted to the Francis College of Engineering, University of Massachusetts Lowell, in partial fulfillment of the requirements for the degree of PhD Plastics Engineering.
2. Jay Thakkar, Nicholas Bowen, Allen C Chang, Peter Horwath, Margaret J Sobkowicz, Jan Kośny (2022) – "Optimization of Preparation Method, Nucleating Agent, and Stabilizers for Synthesizing Calcium

Chloride Hexahydrate (CaCl2.6H2O) Phase Change Material." MDPI BUILDINGS, 2022, 12(10), 1762; https://doi.org/10.3390/buildings12101762

3. Thakkar J., Sobkowicz M.J., Yarbrough D., Horwath P., Kośny J. (2022) "Dynamic Heat Flow Meter Method for Evaluating Phase Change Material Performance," Proceedings of the 35th International Thermal Conductivity Conference and the 23rd International Thermal Expansion Symposium, Lowell, MA, August 2023, DEStech, Publications, Inc. ISBN – 978-I-60595-688-6.
4. Jay Thakkar, Sai Bhargav Annavajjala, Margaret J. Sobkowicz, Jan Kosny (2024) – "Influence of Carboxymethyl Cellulose as a Thickening Agent for Glauber's Salt Based Low Temperature PCM." MDPI MATERIALS – approved for publication Apr.26th.2024.
5. Jay Thakkar, Sai Bhargav Annavajjala, Jan Kosny, Margaret J. Sobkowicz (2024) – "Stabilizing a Low Temperature Phase Change Material based on Glauber's Salt," Journal of Energy Storage
6. Volume 91
7. , 30 June 2024, 111936

3.2. **Objective 2** – Development of easy-to-manufacture and -install PCM packaging/encapsulation designs.

The second major project goal was to develop easy-to-manufacture and -install packaging/encapsulation designs that were 1) a superior barrier to current state-of-the-art macro-packaging, which significantly reduces the risk of loss of hydration water and PCM leak, and 2) optimal in enhancing the heat exchange rates with the surroundings and within the PCM core to ensure complete charging/discharging of the entire PCM within the product. Depending on desired PCM application, different packaging or encapsulation methods of PCM are utilized. The project team reviewed and evaluated numerous recent packaging methods that involved micro- and nano- encapsulation as well as more advance deposition techniques (i.e. growth of crystalline PCMs, by molecular beam epitaxy, sputtering, pulsed laser deposition, cold sintering, etc.), and 3D printing. However, we found that most recently tested advanced methods are still at the proof-of-concept stage, and they add significantly to the product cost, making technology scalability questionable. That is why the project team focused on low-cost and simple-to-manufacture technologies that hold better chances to be successful in the building construction market. Our, main considerations were that (i) North American construction market is traditionally extremely sensitive to the cost, and (ii) that low-cost commodity thermal insulation types are the benchmark for building related energy saving measures.

3.2.1. Panel Design, Laboratory Thermal Testing, and Performance Optimization

Work Focused on Improvement of Panel Design and PCM Packaging – Conductive Membranes and Foils: During Y1 and Y2, the project team worked on material selection and fabrication trials and testing of PCM carrier materials. Following the initial results from Y1 investigation, the project team continued material component selection, combined with the development, and testing of the effective, laboratory-scale thermos-forming method for polymeric blends containing thermally conductive powders. Please note that, due to our plans for fast commercialization, our packaging material-related work was focused on the design of two new PCM products that can be quickly implemented by InsolCorp. For this purpose, we primarily utilized as a base the already used by InsolCorp PVC membrane products. However, we also performed a development and validation of custom thermally conductive plastic formulations (as discussed in the April 2021 report), as well as we investigated barrier films of increased thermal conductivity, used by other industries – see Figure 1. One of the fabrication methods considered for packaging of PCM products is Compression Molding, which produces strong molded parts with high structural stability. Durable, corrosion resistance products can be produced easily through this process and flexibility in design.

Figure 1. Process for compression molding (left). Carver, compression molder used during the project (center). Thermally conductive plastic molds, developed during the project (right).

For this project, two following commercial thermally conductive plastic resins from Celanese were evaluated:

- Coolpoly E5101 is a poly(phenylene sulfide) (PPS) carrier resin with carbon and glass fillers.

- Coolpoly D8102 is a thermoplastic elastomer (TPE) carrier resin with boron nitride fillers, designed to be electrically insulating.

Temperature depended thermal conductivity was measured using ASTM C518 test standard for two different set points, 10-20 °C and 20-30 °C. The results of the thermal conductivity are shown in Table 7.

Table 7. Thermal conductivities of the PPS and TPE conductive plastic samples, as measured by the FOX 50 Heat Flow Meter Apparatus.

Material	Sample no.:	Platen 1 Temp	Platen 2 Temp	Cycle Time	Thermal Conductivity (W/mK)

PPS	1	580°F	580°F	20 min	0.68
	2	580°F	580°F	30 min	0.72
	3	580°F	580°F	40 min	0.9
TPE	1	570°F	570°F	30 min	1.16
	2	570°F	570°F	40 min	1.2

In addition, the project team validated processing Coolpoly E5101 resin using injection molding. It was found that a short shot molding progression reveals the tendency of this resin to jet due to freeze-off of the melt front. The resulting chaotic flow yields incompletely filled mold features. So, a significant amount of time needs to be involved in setting up the temperature and the speed of processing, to achieve molds of satisfactory quality.

The general conclusion from both described above experiments is that as much as it is possible to fabricate material samples of required thermal conductivity and mechanical strength, it is difficult to fabricate thin impermeable membranes (project reports from April and August 2021). Furthermore, the required high load of conductive fillers significantly complicates the forming process and increases the fabrication cost. Based on these experiences, and in consultation with DOE BTO, the project team decided to abandon this direction of development of packaging materials and concentrate more on plastics laminated with aluminum foil for increased surface conduction rates and minimized permeability.

In addition to development of thermally conductive materials and work dedicated to the upgrade/improvement of InsolCorp panels, several other commercially available packaging membranes, films, and sealing tapes were evaluated for potential usage in fabrication of prototype PCM panels. The initial testing included analysis of their vapor permeance. Limited mechanical performance testing also included the ASTM D6862- Standard Test Method for the 90 Degree Peel Resistance of Adhesives – important for panel sealing design. With this effort, we analyzed seven types of plastic sheeting membranes with different chemical compositions. This included: 2 Nylon foils, PET, PVC, OPP, LDPE, and a HDPE multilayer aluminized foil. Another main tested component of a panel seal was a type of adhesive. We tested the 3M Acrylic Structural Plastic Adhesive DP8010 Blue.

In this testing, the Instron 3365 machine was set to a separation speed of 10-in/min; and according to the ASTM D6862 standard, each sample needed at least 3-in of separation within the testing range. For tested plastic foils and for used 3M's DP8010 Blue adhesive, peeling test results were between 1.75 lbf/in and 11.33 lbf/in. The highest measured peeling force, however, was over 19 lbf/in. But, because of the rupture of the foil sample, before reaching the 3-in. separation limit, this test was not considered correct – following the ASTM D6862 criteria. This indicates that for this combination of the foil and adhesive, in real life situations, the first material which may fail will be the plastic foil. Figure 2 shows from the left side: (i) installed for the testing Nylon foil, (ii) rupture of the Nylon foil, (iii) black PET foil installed for the testing, and (iv) aluminized HDPE foil after the testing. A similar series of testing was continued during Q6 for additional types of foils and different adhesives.

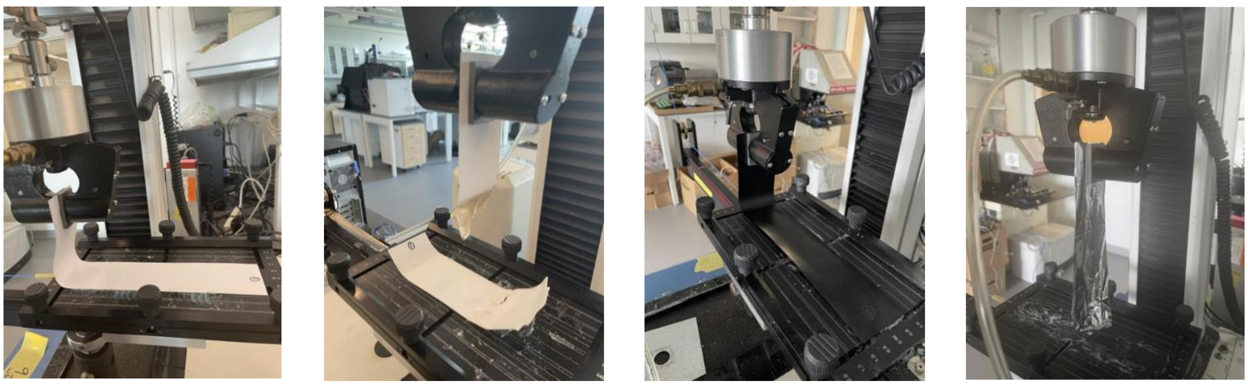


Figure 2: Peel test of the foil samples - from the left side: (i) installed for the testing Nylon foil, (ii) rupture of the Nylon foil, (iii) black PET foil installed for the testing, and (iv) aluminized HDPE foil after the testing.

Work Focused on PCM Packaging – Fabrication trials, performance optimization, and laboratory performance testing of PCM packaging forms and encapsulation products: Based on analytical work performed during Y1, it was presumed that packaging materials should meet the following performance requirements: (i) Have high strength, flexibility, and thermal stability, (ii) Have the ability to be thermally formed and sealed, (iii) Are excellent barrier to moisture, air, oxygen, and CO_2, (iv) Are stable under the UV exposure and environmental conditions, (v) If possible, exhibit increased thermal conductivity, (vi) Are not corrosive and do not react with PCMs,

For sealing purposes and for fabrication of PCM pouches, we evaluated the usage of commercially available barrier films utilized for food and/or pharma product packaging, or materials used by PV and VIP industries. Materials with reflective metallic surfaces are considered, as well. During this project, both UML and InsolCorp, as well as a group of other industrial partners and material suppliers performed a substantial work effort on the selection/modification/development of the PCM packaging, barrier materials.

Following our plans for quick commercialization, in the follow-on developments we primarily analyzed the already existing barrier film products, and we performed the analytical work focused on the design of new PCM products that could be commercialized by InsolCorp. This development and design effort was concentrated on two new types of panels containing different shapes of PCM pouches. For both packaging designs, we considered the usage of the PVC sheets (with the option of surface lamination with aluminum film) and thermo-forming method for fabrication of panels. This approach an advancement/modification of the existing InsolCorp's design and, for economic reasons, it followed their manufacturing processing.

The team's goal was to develop a new product design, which would have at least 30%-40% higher aerial heat storage capacity compared to the current InsolCorp's products and would also fulfill this FOA requirement of volumetric energy density > 100 kWh/m^3.   Our plan was to achieve it through, (i) about 5%-10% increase of the PCM load area, (ii) adding additional support reinforcing ribs, and (iii) increasing the thickness of the PCM containing space by about 30% to 40%. Consequently, we created a rigid panel that could easily hold up to 40% (in the future production 50%) more PCM than the existing InsolCorp packaging design – without adding more than 5% of extra packaging material cost. Figure 3a shows modifications of the existing InsolCorp's panel design. Figure 3b shows assembly of prototype PCM panels.

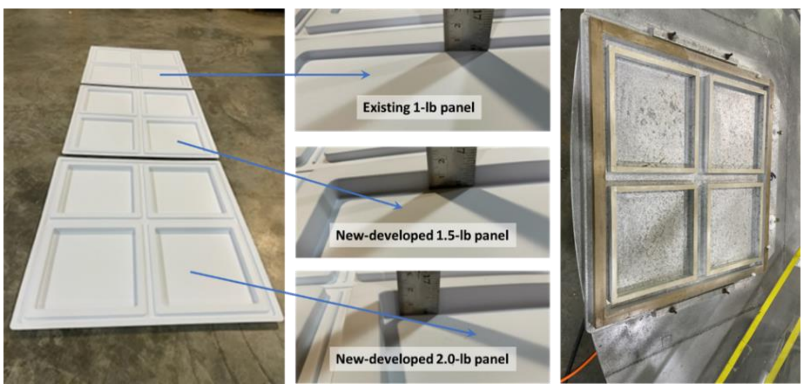


Figure 3a: Performance enhancement of the existing InsolCorp panels made of PVC (top), by increasing the PCM volume through the addition of the panel thickness – 50% increase (center), and 100% (bottom). On the right side, the new tooling developed for production of these panels.

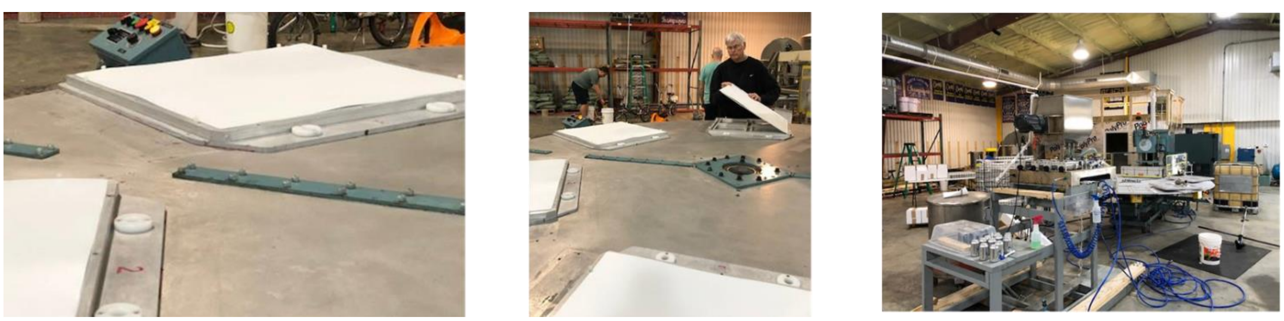


Figure 3b: Assembly of prototype PCM panels.

As it was reported in the April 2021 project report, the first set of modifications of the PCM panel design was completed, and drawings for necessary new tooling were prepared and reviewed by InsolCorp and manufacturer of the tooling equipment. Final designs of experimental panels were manufactured in early 2022 and installed in the test huts during July-August 2022.

In addition to work focused on modification/improvement of InsolCorp PCM panels, the project team also valuated other PCM packaging methods. This included (i) used by Rubitherm (German Manufacturer of PCM systems) metal flat panel containers, (ii) shaped stabilized cellular plastics, (iii) impregnated concrete like materials, (iv) extruded channel boards made of plastics or metal and (v) used by many PCM manufacturers arrays of plastic/composite/metal pouches for PCM. As illustrated in Figure 4, all these technologies were evaluated from the following five perspectives:

a) Capability to carry maximum volume of PCM, per volume used by application,
b) High thermal conductivity of packaging material
c) Technology resistance to water and liquid PCM leaks
d) Low application cost
e) Technology ability to be easily trimmed at least in one direction (this function is critical both for new construction and building retrofit applications).

Figure 4 shows that after elimination of technologies which had two or more negative rates, extruded channel boards made of plastics or metal, and arrays of plastic/composite/metal pouches were selected for further development. Following this selection, during Y2, the project team performed numerical thermal performance analysis, followed, with several prefabrication trials leading to fabrication of fully functional PCM panels, which were necessary for dynamic thermal performance and durability testing.

Criteria:	Metal flat panel containers	Shaped stabilized cellular plastics,	impregnated concrete like materials	Extruded cha-nnel boards - plastics or metal	Plastic/com-posite /metal pouches for PCM
a) Capability to carry maximum volume of PCM	YES	NO	NO	YES	YES
b) High thermal conductivity of packaging material	YES	NO	Possible	Possible	Possible
c) Technology resistance to water and liquid PCM leaks	YES	NO	NO	Possible	YES
d) Low application cost	NO	Possible	YES	YES	Possible, NO for metal
e) Ability to be easily trimmed at least in one direction	NO	YES	YES	YES	YES
				Selected	Selected

Figure 4: Evaluation criteria used for selection of PCM packaging technologies.

Extruded plastic channels boards were found very attractive for PCM packaging because of their very low cost, low water permeability, corrosion resistance, and easy fabrication. Furthermore, low thermal conductivity of plastic and related low heat transfer between PCM and surrounding air or refrigeration fluids can be enhanced by lamination of the panel surface with aluminum foil. During Y2, the project team worked on panel edge sealing techniques and enhancement of panel thermal performance through surface lamination with plastic and aluminum foils. Later, foil was replaced by extruded plastic and aluminum profiles. Figure 5 shows all three stages of the edge seal preparation in the case of application of plastic foil.

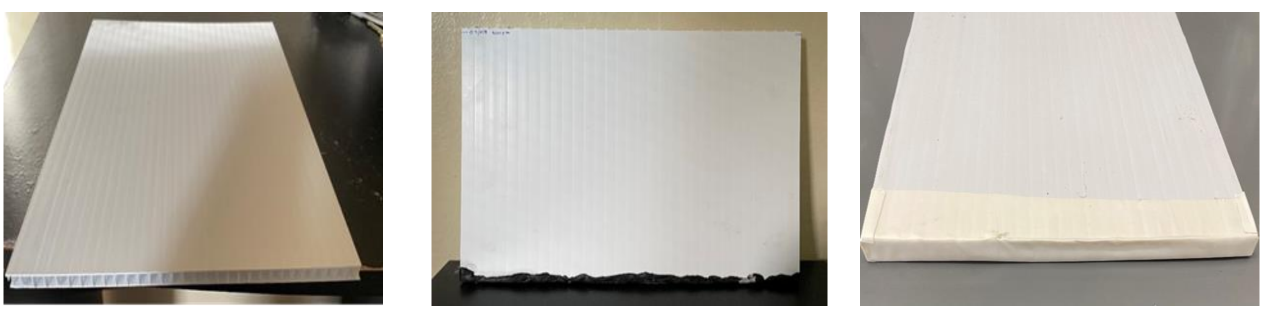


***Figure 5. Three stages of the edge seal preparation – from the left: (i) Cleaning, and sanding the board edge, (ii) Butyl rubber tape is installed as a primary seal, and (iii) Vycor Pro tape is used as a secondary finish seal*.**

In the following step, the quality of the edge seal was experimentally validated. The following steps were performed: (i) Channel board was filled with water, and (ii) Water level, time and date were marked on the channel board to compare the water level after every 24 hrs. These experiments showed that most of the designed edge sealing methods worked well in the short-term. During five days of testing, no water leaks were observed. During the follow-on work, the project team utilized thermal welding of a tape to the channel panel, and an application of extruded aluminum profiles for sealing the edges. The last of these methods was used in the panel prototype fabrication.

As shown in Figure 6, during prototype fabrication PCM was injected to the board channels with a use of a long pipette, which should reach to the end of the channel. During the PCM filling, the pipette is withdrawn from the channel. This method can be easily automated, and it allows easy removal of air from the channel. It was recommended by the project industry partners. We anticipate that during the technology commercialization on the industrial scale, an automatic needle manifold, filling the whole panel at once, will be used. We also attempted laboratory-scale gravimetric channel filling method using a long glass funnel and pouring from a beaker – see Figure 6.

Figure 6. Extruded channel panel is filled with PCM using a pipette and a lab funnel.

Following the development of these panel filling and sealing procedures procedure, the project team prepared several types of the PCM board prototypes, which were later used in lab-scale thermal performance analysis. Figure 7 shows Improved Insolcorp panels laminated with aluminum foil, extruded plastic panel, sealed with the tape, and extruded panel sealed with aluminum profile. Dynamic thermal testing in the heat flow meter apparatus was used for lab scale performance evaluations.

Figure 7. Examples of panel prototypes prepared during the project: Improved InsolCorp panel with added thermal storage capacity and aluminum foil lamination (left), Extruded channel panel sealed with plastic tape (center), Extruded panel sealed with aluminum profile (right).

3.2.2. Numerical Analysis Supporting Design of Modular PCM Container Panels:

During this project, a novel concept of modular stackable thermal storage system was developed - Figure 8 This work was dedicated to the PCM panel design that allows great variety of applications starting from passive thermal storage boards, elements of air distribution system, and ending in variety of heat exchanger applications. This work originated several ideas of passive and dynamic thermal storage technologies, which were presented to DOE, DoD, and industry. Two following innovations were developed by UML based on this part of the project:

- In January 2023, UML's team filled Invention Disclosure - UML: 2023-016, "Compact Liquid-Air Heat Exchanger Integrated with PCM Thermal Storage."
- In March 2024, UML's team filled Invention Disclosure - UML 2024-025, "Stackable Thermal Battery and Phase Change Material (PCM)-Air Heat Exchanger."

In addition, two research projects have been funded by DoD, which are partly based on this development, starting from 2022.

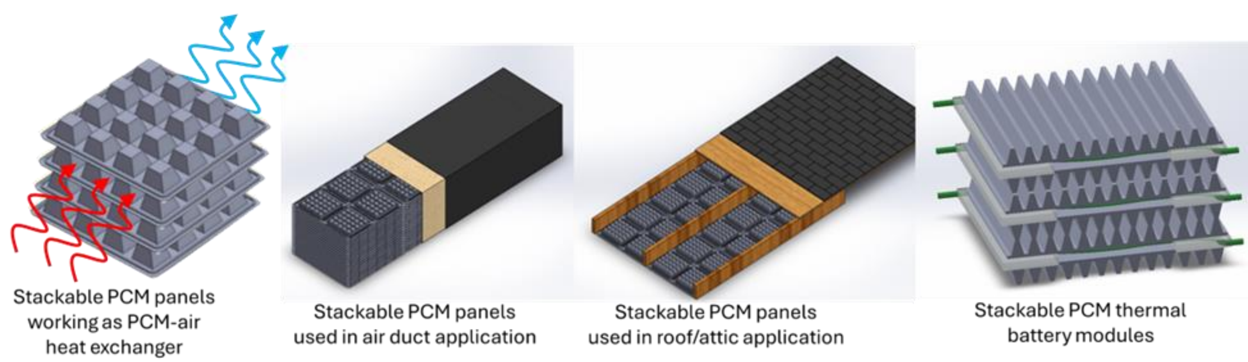


Figure 8. Modular, stackable 3D plastic panels containing PCM, working as a thermal storage and heat exchanger in passive, air moving, and heat exchanger applications.

<u>Numerical CFD Performance Analysis of the Container Panel:</u> Several configurations of 3D plastic or laminated plastic panels have been in development by UML since 2021. A low-cost, plastic manufacturing method utilizing thermoforming, is used to fabricate PVC sheets with integrated pockets for PCM. In this project, numerical optimization of the PCM panel design was performed. We used parametric CFD analysis for studying of temperature distribution, pressure drop, for various inlet air velocities have been investigated for the stacked PCM container panels. This allowed calculations of heat exchange efficiencies and optimization of the panel geometry as presented in Figure 9. Developed computer models supported both the panel, and the panel system designs, and helped in the development/validation of potential applications.

During Y2 and Y3 of the project, a series of CFD simulations of steady state incompressible flow of single-phase fluid has been performed. As illustrated in Figures 9 and 10, our main interest was in the pressure drop associated with air gap between PCM layers in stacked 3D plastic panels containing PCM. For this analysis, two main governing equations are conservation of momentum and mass:

$$\nabla\cdot(\rho\mathbf{u}\mathbf{u}) = -\nabla p+\nabla(\mu(\nabla\mathbf{u}+\nabla\mathbf{u}^{T}))+\mathbf{F} \qquad (1)$$

$$\nabla\cdot\mathbf{u}=0 \qquad (2)$$

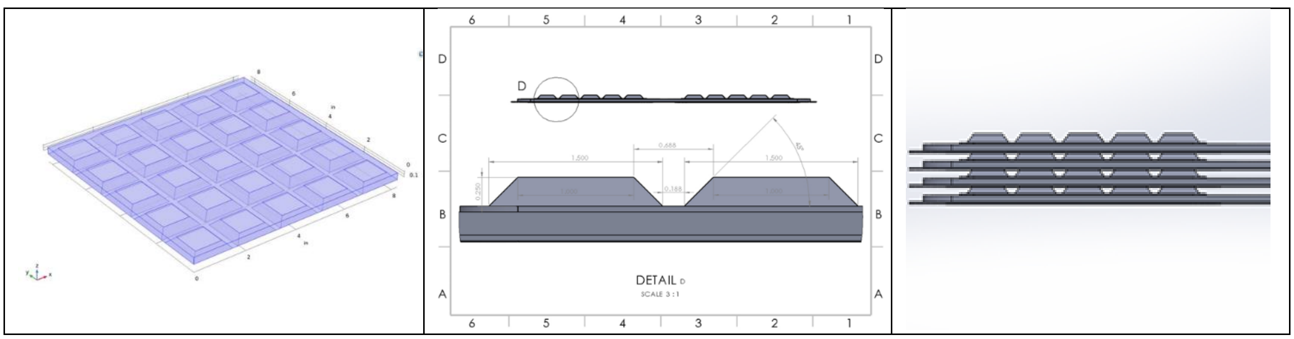


Figure 9. CFD modeling of air movement in gaps between PCM layers in stacked 3D plastic panels.

We used a 3-dimensional simulation domain in this analysis. It is schematically illustrated in Figure 10. It consists of one sheet of PCM material prototype that has two wall boundaries, Inlet and Outlet. Air enters the domain through inlet where the inlet velocity $\mathbf{u}_{\mathbf{inlet}}$ is specified. Air leaves through the outlet that has pressure set to $\mathbf{p}_{\mathbf{atm}}$. On all other surfaces, including PCM, the boundary conditions for velocities and pressure are set to zero gradient.

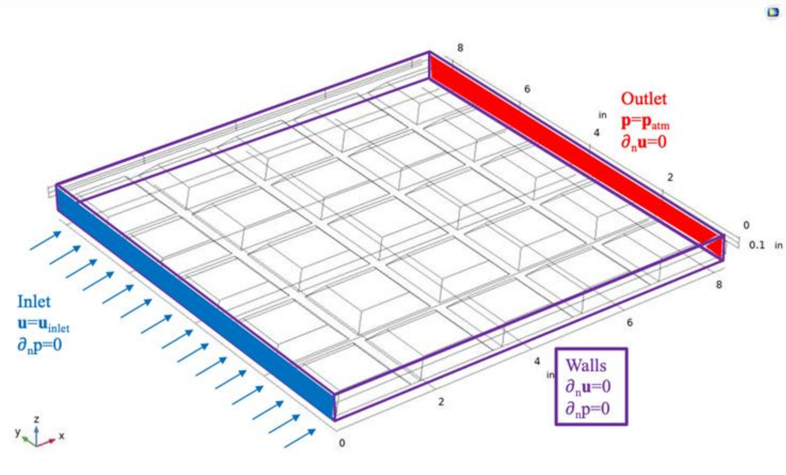


Figure 10. Numerical model schematic for CFD simulations of 3D plastic panels.

As illustrated in Figure 11, numerical mesh created for CFD modeling, consists of roughly 380000 tetrahedras, 55160 pyramids and 43760 quads. In this study, $\mathbf{u}_{\mathbf{inlet}}$ has been in the range from 0.4 to 2.0 m/s with a step of 0.4 m/s, while $\mathbf{p}_{\mathbf{outlet}}$ was kept at 0 Pa, and gravity effects were not accounted. All simulations have been performed with the use of the COMSOL Multiphysics Computation Fluid Dynamics software.

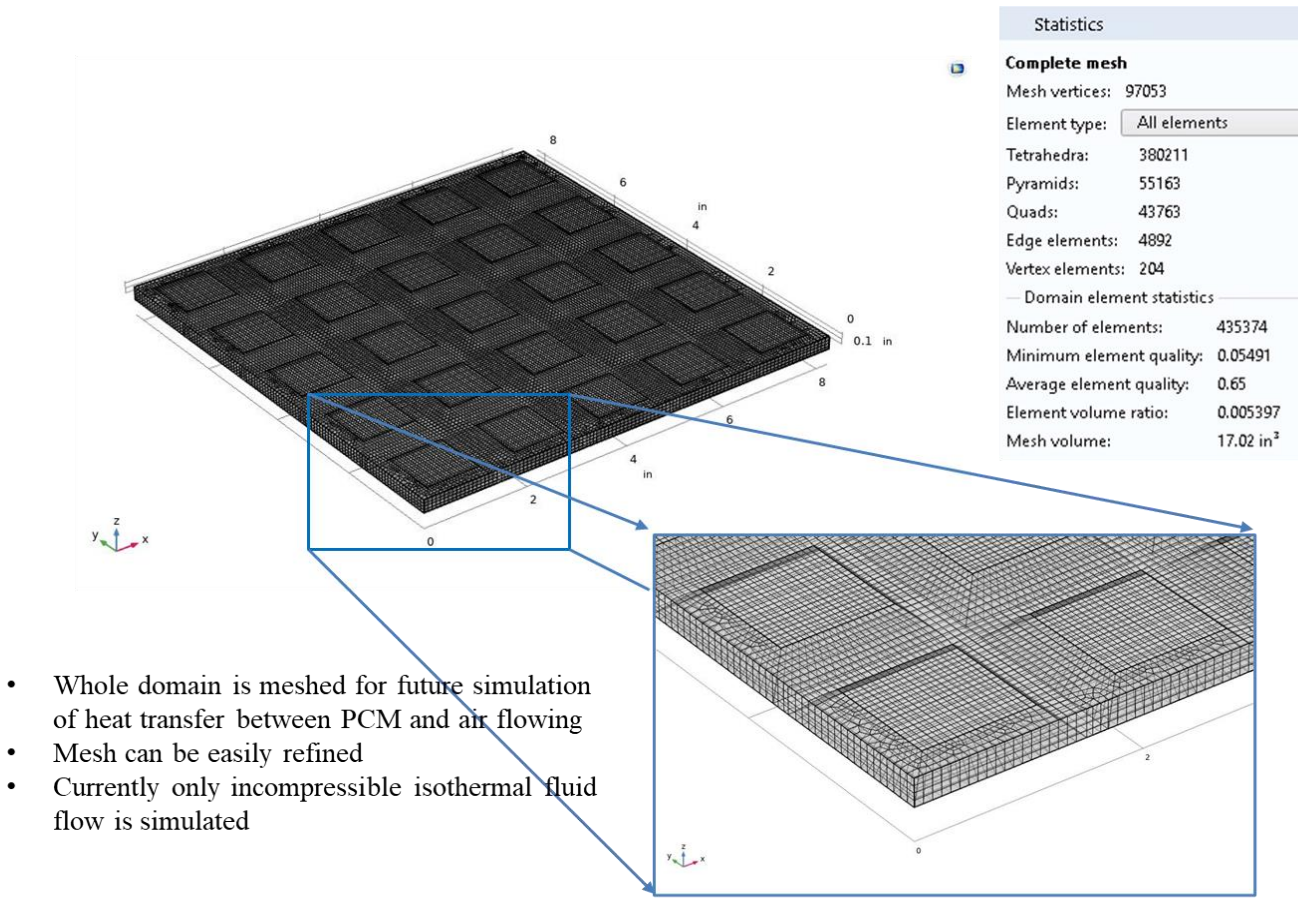


Figure 11. Generating a numerical mesh for CFD simulations of stacked 3D plastic panels.

Performed series of thermal and CFD modeling helped in optimization of the shape and placement of PCM pouches both from the perspective of maximum thermal storage (max PCM content) as well as from the perspective of the air-PCM heat exchanger. Example of simulation results is shown in Figures 12 – 16, where pressure drops for different inlet velocities are indicated. In general, air velocity values are highest in the mid 2 channels with flow developing towards the domain outlet.

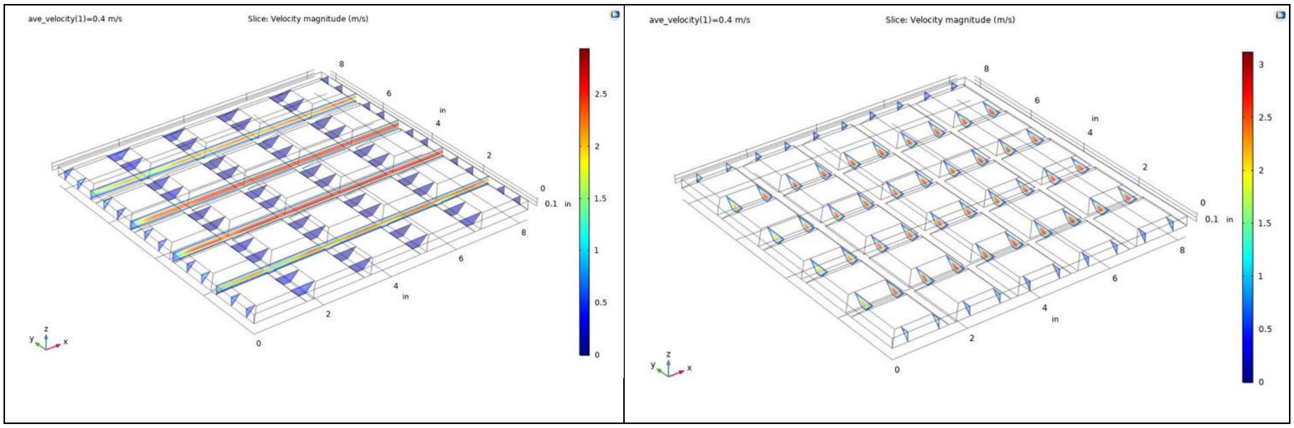


Figure 12. Simulated velocity magnitudes' slices in zx and yz planes for u_{inlet} = 0.4 m/s

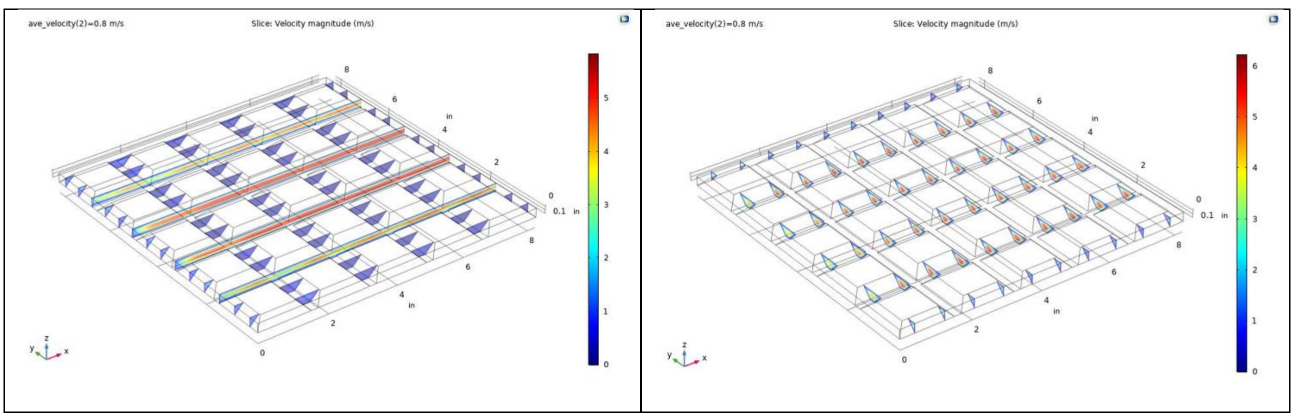


Figure 13. Simulated velocity magnitudes' slices in zx and yz planes for u_{inlet} = 0.8 m/s - *Highest magnitude is in the mid 2 channels with the value of ~ 6 m/s.*

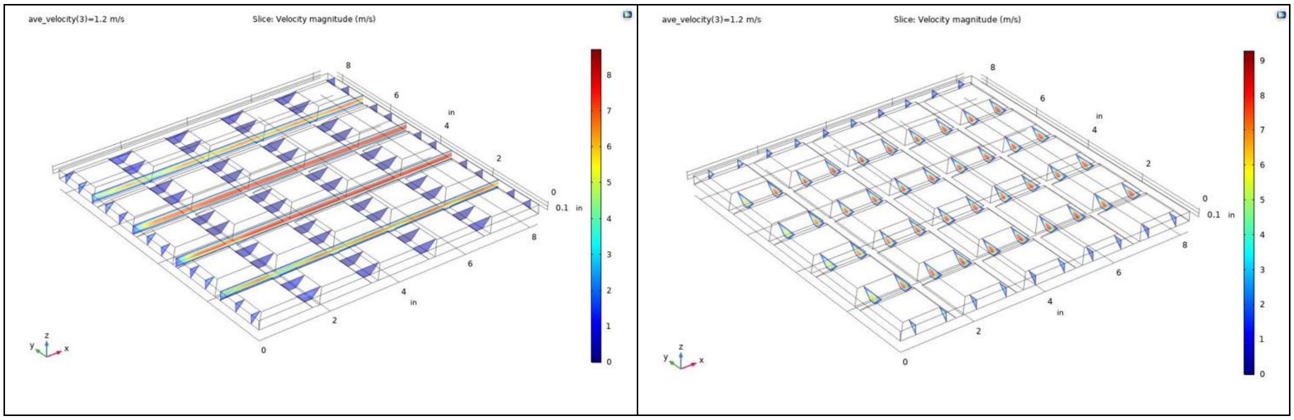


Figure 14. Simulated velocity magnitudes' slices in zx and yz planes for u_{inlet} = 1.2 m/s - *Highest magnitude is in the mid 2 channels with the value of ~ 9 m/s.*

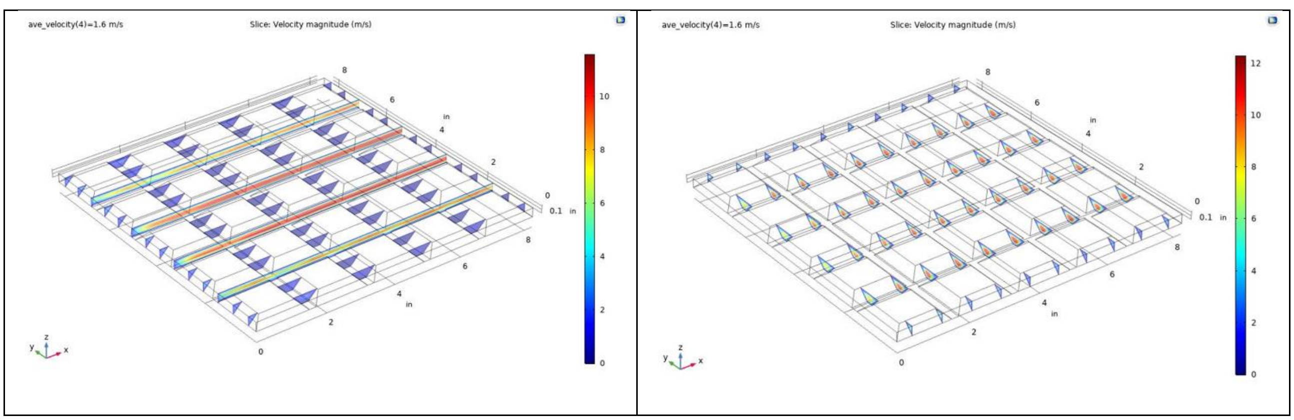


Figure 15. Simulated velocity magnitudes' slices in zx and yz planes for u_{inlet} = 1.6 m/s - *Highest magnitude is in the mid 2 channels with the value of ~ 12 m/s.*

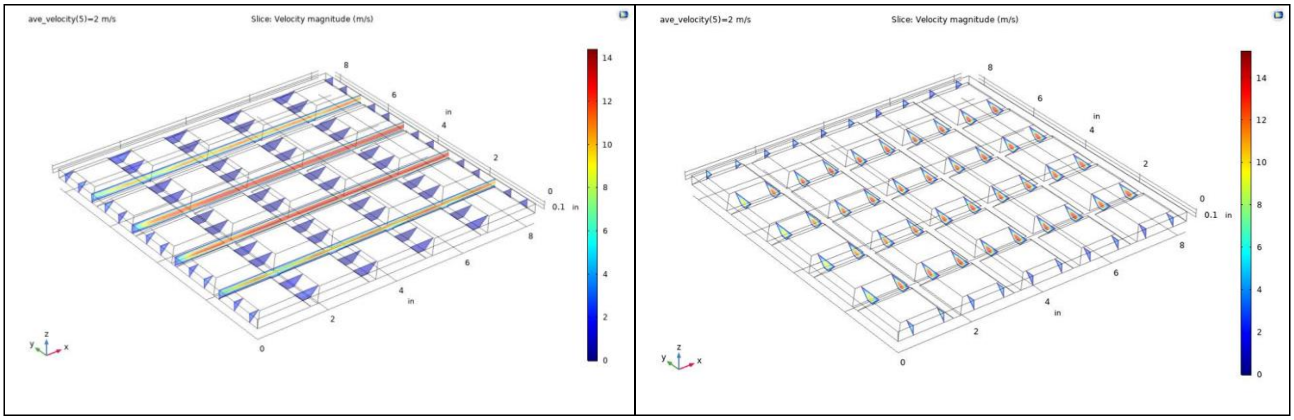
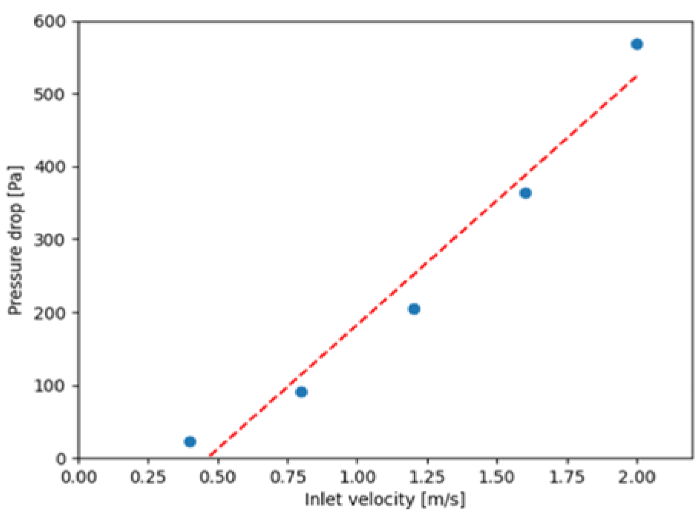


Figure 16. Simulated velocity magnitudes' slices in zx and yz planes for u_{inlet} = 2.0 m/s - *Highest magnitude is in the mid 2 channels with the value of ~ 14 m/s.*



The pressure drop across a single panel was analyzed for $\mathbf{u_{inlet}}$ between 0.4 and 2.0 m/s. It can be concluded from the summarizing Figure 17, that with increasing $\mathbf{u_{inlet}}$ the pressure drop that occurs is increasing almost sixfold, as expected, reflecting the increase of air velocity. Based on this finding the initial conclusion can be derived that 3D panels may function better in low-velocity applications. However, the whole picture will be better known after planned full-scale/full-effect simulations, which will include heat exchange and phase change processes.

Figure 17. Simulated pressure drop relation with panel inlet velocity.

In addition to the project quarterly reports, the above development of PCM panel designs was documented in several reviewed research papers, conference presentations, and Ph.D. dissertation. The short list of publications includes:

1. Kośny J., Thakkar J., Kamidollayev T., Sobkowicz M.J., Trelles J.P., Schmid C., Phan S., Annavajjala S., Horwath P. "Dynamic Thermal Performance Analysis of PCM Products Used for Energy Efficiency and Internal Climate Control in Buildings" – MDPI Buildings, (2023) vol. 13, issue 6, p.1516
2. Kamidollayev T., Trelles J.P., Thakkar J., Kośny J. "Parametric Study of Panel PCM–Air Heat Exchanger Designs" - MDPI Energies, (2022), vol 15, issue 15, p. 5552
3. Kośny J., Miller W.A., Yarbrough D., Kossecka E., Biswas K. "Application of Phase Change Materials and Conventional Thermal Mass for Control of Roof-Generated Cooling Loads" Applied Sciences, Special Issue Phase Change Materials in Buildings, Appl. Sci. 2020, 10(19), 6875; - 30 Sep. 2020; https://doi.org/10.3390/app10196875
4. Thakkar J., Sobkowicz M.J., Yarbrough D., Horwath P., Kośny J. "Dynamic Heat Flow Meter Method for Evaluating Phase Change Material Performance," Proceedings of the 35th International Thermal Conductivity Conference and the 23rd International Thermal Expansion Symposium, Lowell, MA, August 2023
5. Kośny J. (2023) "Mitigation of Building Energy Dynamics – Great Opportunity for Reflective Insulation combined with Thermally Massive Systems." - 2023 International Reflective Insulation Manufacturers Conference (I-RIM Conference), May 23-25, Rome, Italy.
6. Doctoral dissertation by Tlegen Kamidollayev (2023) "Computational Modeling of Reactive Species Interphase Transport in Plasma Jet Impinging on Water." The Francis College of Engineering, Department of Mechanical and Industrial Engineering, University of Massachusetts, Lowell, April 4, 2023.

3.3. **Objective 3** – To scale-up the fabrication process to demonstrate installation on system-scale applications, and to validate the performance under field conditions.

3.3.1. Pilot scale fabrication trials of PCM panel:

Fabrication and Dynamic Testing of First PCM Panel Prototypes: During 2022, the UML project team fabricated the first experimental PCM panel prototypes, using extruded plastic channel boards. Following this development, prototypes of the PCM-liquid panel heat exchanger were fabricated. The first panel configurations were using extruded plastic channel boards. Photographs of panel prototypes are presented in Figure 7. These panels are right now used for dynamic thermal performance testing. Furthermore, InsorCorp experimented with lamination of PVC panels and fabrication of panel prototypes, where one of surfaces was laminated with aluminum foil. In the follow-0n step, experimental panels were tested in the heat flow meter apparatus using the ASTM C1784 standard test method - "Standard Test Method for Using a Heat Flow Meter Apparatus for Measuring Thermal Storage Properties of Phase Change Materials and Products" – Figure 8.

Thermal characterization was necessary for PCM technologies developed during the project to understand its thermal performance, allow numerical analysis, and to make thermal efficiency predictions. Basic material characteristics of PCMs are most often characterized in the laboratory scale using differential scanning calorimetry (DSC). In our case of PCM panels, dynamic heat flow meter testing had to be implemented. Typically, DSC testing is utilized for PCMs to measure the phase transition temperature, enthalpy, and supercooling. In DSC testing, the sample size is relatively small (5-10 mg), which makes analysis of non-homogenous samples difficult and may lead to hindered nucleation (due to low nucleation density). Furthermore, the DSC method is very sensitive for different speeds of phase transition testing. It may lead to misinterpretation of the impact of thermal lag due to temperature gradients across the sample.

In the case of PCM products, the DSC testing is not as relevant, especially when sample size is significantly different from that of the commercial application. The key parameters that influence the accuracy of DSC testing of salt-based PCM technologies include heating – cooling rate, small sample size and sample homogeneity. High heating rate reduces temperature resolution which leads to poor separation of peaks and sometimes no peak is observed. With a high heating rate, the results are often not representative of the whole sample. It results in broader peaks showing indistinct melting temperature because of larger thermal gradients. Cooling rate in DSC affects the crystallization behavior of the sample. High rate of cooling may show a “false” supercooling, which means delaying of the crystal formation, or lowering the solidification temperature. This is because salt crystals do not have enough time to grow at high cooling rates. In addition, sample sizes are small in DSC tests, which also affects the crystallization process and consequently the accuracy of the supercooling analysis. Achieving good sensitivity and high resolution in a single experiment is nearly impossible using DSC especially for non-homogenous PCMs products that include packaging and other components.

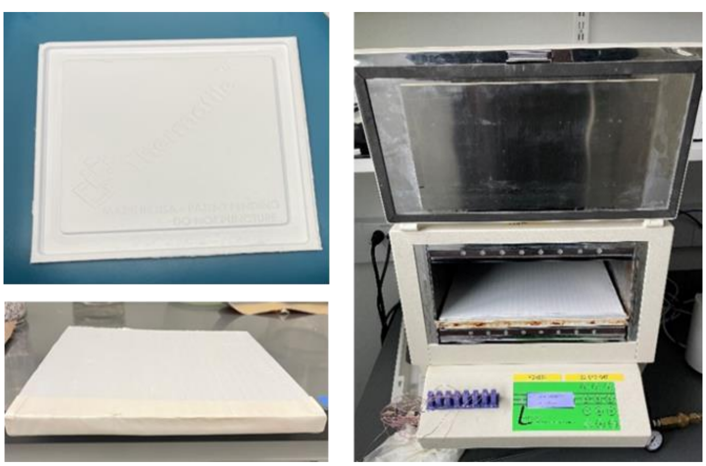
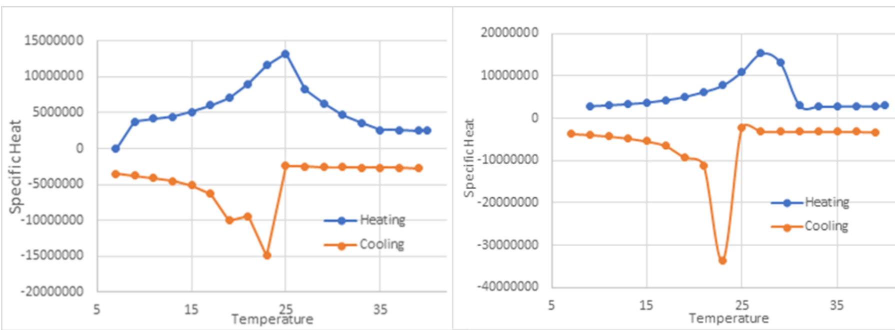


Figure 8. ASTM C1784 testing of PCM panel prototypes: InsolCorp PCM panel – left top; Sealed extruded channel panel with PCM – left bottom; PCM panel during the dynamic heat flow meter performance testing – right.

Thermal performance of PCM technologies does not only represent characteristics of PCM. It also includes impacts of packaging materials, PCM volume load, and internal thermal bridges, or areas of lower thermal conductivity (reduced heat transfer). That is why, in this project, thermal performance of PCM panels was most often characterized with a use of the ASTM C1784 standard test method. Figure 9 shows the example of the system heat storage measurements for extruded plastic PCM panels containing a blend of $CaCl_2.6H_2O$ with added KNO_3 and KBr. It can be observed that phase transition plots are different for the first and second melting-freezing cycles. Measured phase change enthalpies are noticeable different with the melting process. It was 143 J/g and 163 J/g, respectively for the first and second cycles. During DSC measurements, the latent heat for melting was around 170 J/g. During lab testing phase, each developed PCM system was characterized for up to 30 cycles.



DT	Thermal Cycle	Latent heat (melting) (J/g)	Latent heat (cooling) (J/g)
2°C	1	177	143
	2	178	163

Figure 9. Comparison of latent heat measurements for first two heating and cooling cycles for the PCM panel filled with modified $CaCl_2.6H_2O$.

During spring months of 2022, InsolCorp fabricated two series of new-developed PCM. This included: (i) a series of panels of increase PCM load, and (ii) a series of panels laminated with aluminum foil. Newly modified panels carried ½ lb and 1 lb more of the PCM formulation, consequently significantly increasing the overall system heat storage capacity by 50% and 100%. The right side of Figure 3a and Figure 3b show the new tooling equipment which was developed and manufactured during the project. This tooling allows fabrication of PCM panels of increased heat storage capacity.

In the second series of prototypes, performance of PCM panels was improved by installation of aluminum foil on the panel surface. Laminated aluminum foil improved the panel surface heat conduction and reduced the surface radiation heat transfer. These newly designed panels can be utilized as thermal storage radiant barriers in roofing and attic applications, both in commercial and residential buildings. Furthermore, this type of reflective panel can be utilized as a thermal storage in suspended ceilings and raised floors (computer rooms) applications. Figure 10 shows two variations of PCM panels containing reflective surface: (i) panels containing PCM of melting temperature 22°F, and (ii) panels containing PCM of melting temperature 29°F.

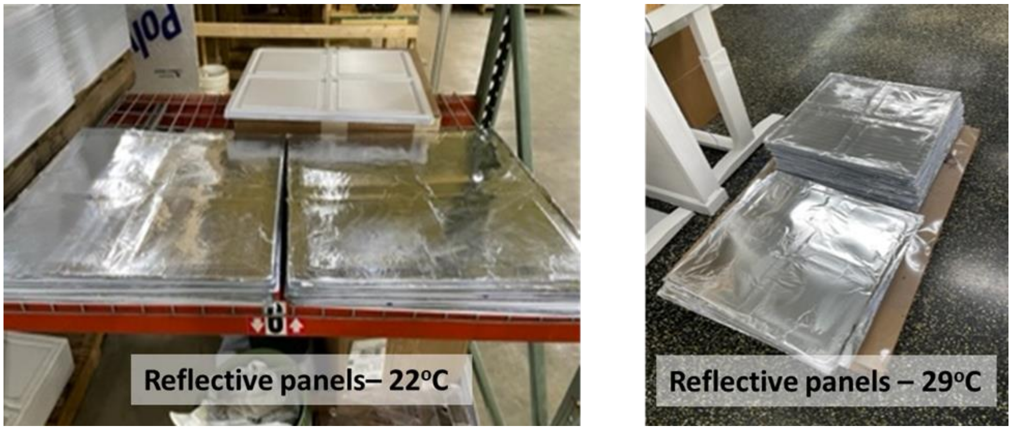


Figure 10. Prototypes of two types of PCM panels containing reflective surface: (i) panels with PCM of melting temperature 22°F, and (ii) panels with PCM of melting temperature 29°F.

3.3.2. Test hut construction, instrumentation, and installation of prototype PCM panels:

Initiation of PCM Field Testing in Albemarle, NC: During May-July 2022, three test huts were constructed in Albemarle, - in a moist, heating-dominated climate. For this location, three huts – two dedicated to testing of PCM systems and one control test hut (no PCM system) were constructed and configured for a longer-term field testing – Figure 11. In this field test facility, the installation of three novel roof, attic/ceiling types of panels, and one wall PCM application was demonstrated on the test scale construction buildings (8 x 10 x 8-ft test huts). Following this installation, test huts were instrumented, and thermal performance data was recorded for over 12 months (two summers).

Figure 11. Installation of three test huts (a). Ventilated attic with shown attic insulation on bottom (b). Attic ventilation (c).

PCM field tests were performed in Albemarle, NC in a moist, heating-dominated climate. For this location, three huts – two installed with PCM systems and one control test hut (no PCM system) were constructed and configured for a longer-term field testing (> 12 months). At the end of August 2022 thermal/energy data started to be collected. Analyzed PCM technologies were tested during two summer seasons – (i) end of summer/beginning of fall 2022, and (ii) early summer months 2023.

Figure 12. Installation trials of PCM wall panel application - PCM 22^{o}C (right), and PCM suspended ceiling installation - PCM 22^{o}C – bottom view, conventional appearance (center), and top view (right).

The following five types of PCM construction application were field validated: (i) internal wall surface application, (ii) suspended ceiling applications, (iii) top of the attic insulation application, (iv) attic cavity application, and (v) interior ceiling surface application. Figure 12 documents installation of wall and suspended ceiling PCM systems. Figure 13 shows two PCM attic applications. More information about test hut construction and instrumentation can be found in the project report from July 2022.

Figure 13. Installation trials of two PCM attic systems; (a) top of the ceiling installation - PCM 29^{o}C, (b) attic cavity installation - PCM 22^{o}C, (c) instrumentation of attic cavity below PCM, (d) instrumentation of comparative, conventional, baseline attic.

3.3.3. Field testing of prototype PCM panels:

As discussed in earlier section, five types of panelized PCM building products were demonstrated on the test scale construction buildings (8 x 10 x 8-ft test huts). For all three test huts, detail analysis based on performance data recorded during this testing is available in the following project reports:

- Rep. July 2022,
- Rep. Oct. 2022,
- Rep. July 2023.

In the following section, a short summary of thermal performance of the tested attic and roofing systems is only provided.

Peak temperature time-delay in all three test roofs: One of the most important features of dynamic roofs and attics (including systems containing PCM) is their ability to increase the amount of time which is necessary for thermal excitation to travel across all material layers of the entire building envelope. In attics A and B, two variations of Dynamic Thermal Disconnect (DTD) Systems (see: Kosny et al. 2010[2]) have been employed for this purpose. These systems incorporate a coordinated action of (i) thermal insulation, (ii) reflective insulation, (iii) air cavity, and (iv) PCM technologies. In dynamic thermal processes, thermal performance of DTDs is superior to any type of conventional thermal insulation, offering lower overall cost and significant space savings.

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

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

Conventional practice uses thermal insulations as a thermal disconnect. However, the typical problems associated with application of conventional insulations are common lack of space (for desired thermal insulation) and thermal bridging in locations where structural members penetrate thermal insulation.

[2] https://web.ornl.gov/sci/buildings/conf-archive/2010%20B11%20papers/199_Kosny.pdf

Introduced in 2010, the concept of DTD replaces the "statically" designed conventional building shells with novel, fully integrated, dynamically working envelope systems using active rather than conventional static thermal disconnects. To achieve maximum thermal performance, the following five major system components need to be considered during the design process of dynamic thermally disconnected envelopes:

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

As depicted in Figure 14 below, the summary of peak temperature time delays, which were recorded during the week of July 7th, 2023. Peak temperature time delays were estimated by comparison of the peak temperature of the roof surface and peak temperature of the bottom surface of the PCM heat sink – (note that temperature of the bottom layer of thermal insulation is strongly affected by the cycling internal temperature – due to AC turning on and off).

Figure 14 also demonstrates how effective is the PCM heat sink in keeping the entire bottom of the attic cool during the time of max. temperature excitation. The top layer of the PCM heat sink contains PCM which melting temperature of about 28-30 ^{o}C. It can be observed that during all example days, temperature of the top layer of PCM stayed below 30 ^{o}C for about 4-5.5 hours longer than the surface of the roof. It can be also observed a notable saddle in the temperature line for this surface at around 30 ^{o}C. It indicates that phase transition energy is absorbed by PCM – reducing local temperature.

To allow direct performance comparisons between tested envelope technologies, Table 8 summarizes dynamic performance data for DTD system used in test Attic A. For further evaluation, Table 9 provides general attic time delay information for test Attics B and C. Please note that Attic C doesn't contain the DTD system, it only uses thermal insulation.

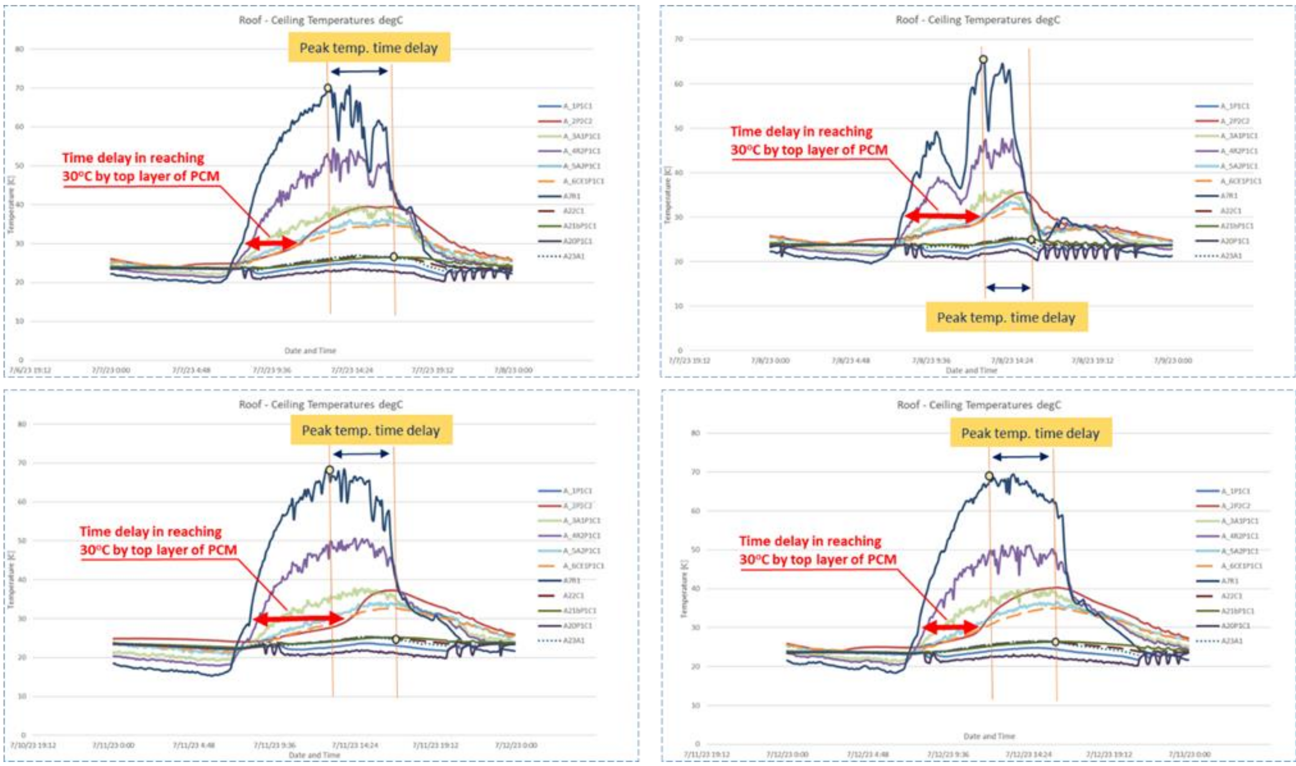


Figure 14. Temperature profiles recorded on Hut A attic and illustration of peak temperature time delays recorded during the recorded week of July 7th, 2023.

Table 8. Summary of time delay data due to the DTD system used in test Attic A, as recorded during the recorded week of July 7th, 2023.

Peak Temperature Time Delay between top of the roof and bottom of the PCM heat sink	Hours of the process	Time delay [h, min]	**Time Delay in Reaching 30°C Local Temperature** between top of the roof and top of the PCM heat sink	Hours of the process	Time delay [h, min]
	13.00 – 17.35	**4,25**		7.45 – 11.35	**3,50**
	12.40 – 15.25	**4,45**		7.50 – 12.50	**5,00**
	12.45 – 17.25	**4,40**		8.10 – 14.05	**5,55**
	12.25 – 26.40	**4,15**		7.50 – 11.45	**3,55**

Table 8. Summary of time delay data due to the DTD system used in test Attic B, and time delay for no-PCM attic C, as recorded during the recorded week of July 7th, 2023.

Peak Temperature Time Delay for Attic B – measured between top of the roof and bottom of the PCM heat sink	Hours of the process	Time delay [h, min]	**Peak Temperature Time Delay for Attic C** – measured between top of the roof and bottom of attic insulation	Hours of the process	Time delay [h, min]
	13.00 – 16.50	**3,50**		13.15 – 14.45	**1,30**
	12.40 – 15.25	**4,45**		12.45 – 14.25	**1,40**
	12.45 – 16.25	**3,40**		12.50 – 15.05	**2,15**
	12.25 – 26.35	**4,10**		13.05 – 15.10	**2,05**

In addition to the project quarterly reports, the above performance analysis of PCM panels was documented in several reviewed research papers, and conference presentations:

1. Kośny J., Yarbrough D. (2023) - “Thermal Insulation and Radiation Control Technologies for Buildings,” Book, June 2023; Springer., ISBN: 978-3-030-98692-6
2. Kośny J., Thakkar J., Kamidollayev T., Sobkowicz M.J., Trelles J.P., Schmid C., Phan S., Annavajjala S., Horwath P. “Dynamic Thermal Performance Analysis of PCM Products Used for Energy Efficiency and Internal Climate Control in Buildings” – MDPI Buildings, (2023) vol. 13, issue 6, p.1516
3. Kośny J., Miller W.A., Yarbrough D., Kossecka E., Biswas K. “Application of Phase Change Materials and Conventional Thermal Mass for Control of Roof-Generated Cooling Loads" Applied Sciences, Special Issue Phase Change Materials in Buildings, Appl. Sci. 2020, 10(19), 6875; - 30 Sep. 2020; https://doi.org/10.3390/app10196875
4. Kośny J. (2023) “Mitigation of Building Energy Dynamics – Great Opportunity for Reflective Insulation combined with Thermally Massive Systems.” - 2023 International Reflective Insulation Manufacturers Conference (I-RIM Conference), May 23-25, Rome, Italy.

3.3.3. Development of the Technology to Market Plan:

Cost Analysis: The process of production of PCM panels requires integration of the following two major manufacturing paths: (i) Synthesis of PCM, and (ii) PCM packaging. Figure 15 below shows a process flow diagram describing the PCM manufacturing process. The preparation of PCM components and packaging components happen in parallel. Once the packaging is thermoformed, the mixed PCM material is filled into the packaging. A sealing and performance testing step follows this step.

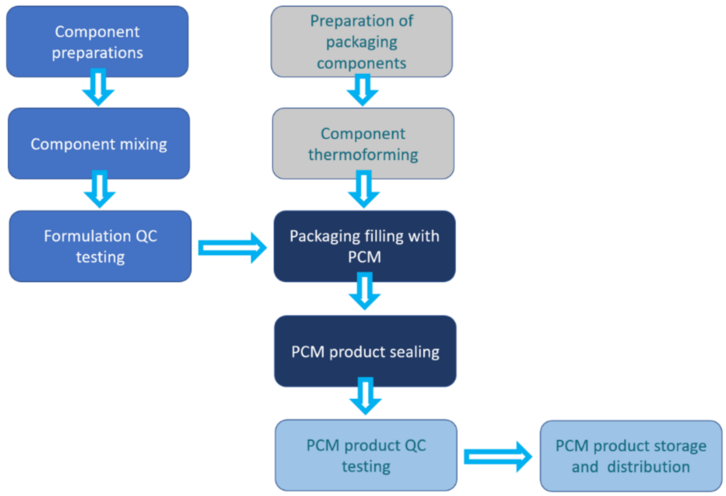


Figure 15. Process flow diagram for manufacturing PCM panel products.

Since of the project goals was cost reduction of PCM applications, each chemical formulation developed during the project, and each considered manufactured process were reviewed from the perspective of the cost efficiency. The following Table 8 includes the bill of materials for six different formulations, which were investigated during the project by the project team. The following Table 9 shows the cost per ton for materials used for the six different formulations currently under consideration.

Table 8: Bill of materials for 6 basic PCM formulations used during Y2.

Sr No	Formulation	Composition	Melting temp
1	CaCl2.2H2O + NaCl + SrCl2.6H2O + H2O CaCl2.2H2O + KCl + SrCl2.6H2O + H2O	62.42% + 5% + 2% + 30.58% 62.42% + 5% + 2% + 30.58%	24-26 °C
2	CaCl2.2H2O + KNO3 + SrCl2.6H2O + KBr + H2O	63.2 + 2% + 1.2% + 2% + 31.6	22 °C
3	CaCl2.2H2O + NH4NO3 + SrCl2.6H2O + KBr + H2O	63.2 + 2% + 1.2% + 2% + 31.6	18 °C

4	Na2HPO4 + H2O + Borax	38.81% + 59.19 + 2%	34-36 °C
5	Na2HPO4 + H2O + Na2SO4 + Borax	29.70% + 58.18% + 10.12% + 2%	30-32 °C
6	NaCH3COO.3H2O + NaHCOO	83% +14% + 3% Nucleator	47 °C

Table 9: Cost of materials per ton.

Material	$CaCl_2.2H_2O$	KCl	$SrCl_2.6H_2O$	H_2O	KNO_3	KBr	NH_4NO_3
Cost per ton	$150	$350	$1,500	$1.48	$700	$2,000	$300
Material	Na_2HPO_4	Borax	Na_2SO_4	$NaCH_3COO.3H_2O$	NaHCOO	$Na_2WO_4*2H_2O$	Na2HPO4
Cost per ton	$340	$1,000	$60	$600	$120	$100	$340

The diagram below shows the material cost for each of the six formulations under consideration – Figure 16. This graph shows dollar amounts assuming to produce one ton of PCM material. There are relatively moderate differences between five of the formulations with costs ranging between $128 for formulation number five and $167 for formulation number two. Formulation number six has a significantly higher cost of $935. The key drivers for this higher cost are the following two components: the Sodium Acetate Trihydrate, which is shown with the bright turquoise color and the Sodium tungstate dehydrate, which is shown in the light blue in the column six in the graph above – see: Figure 16.

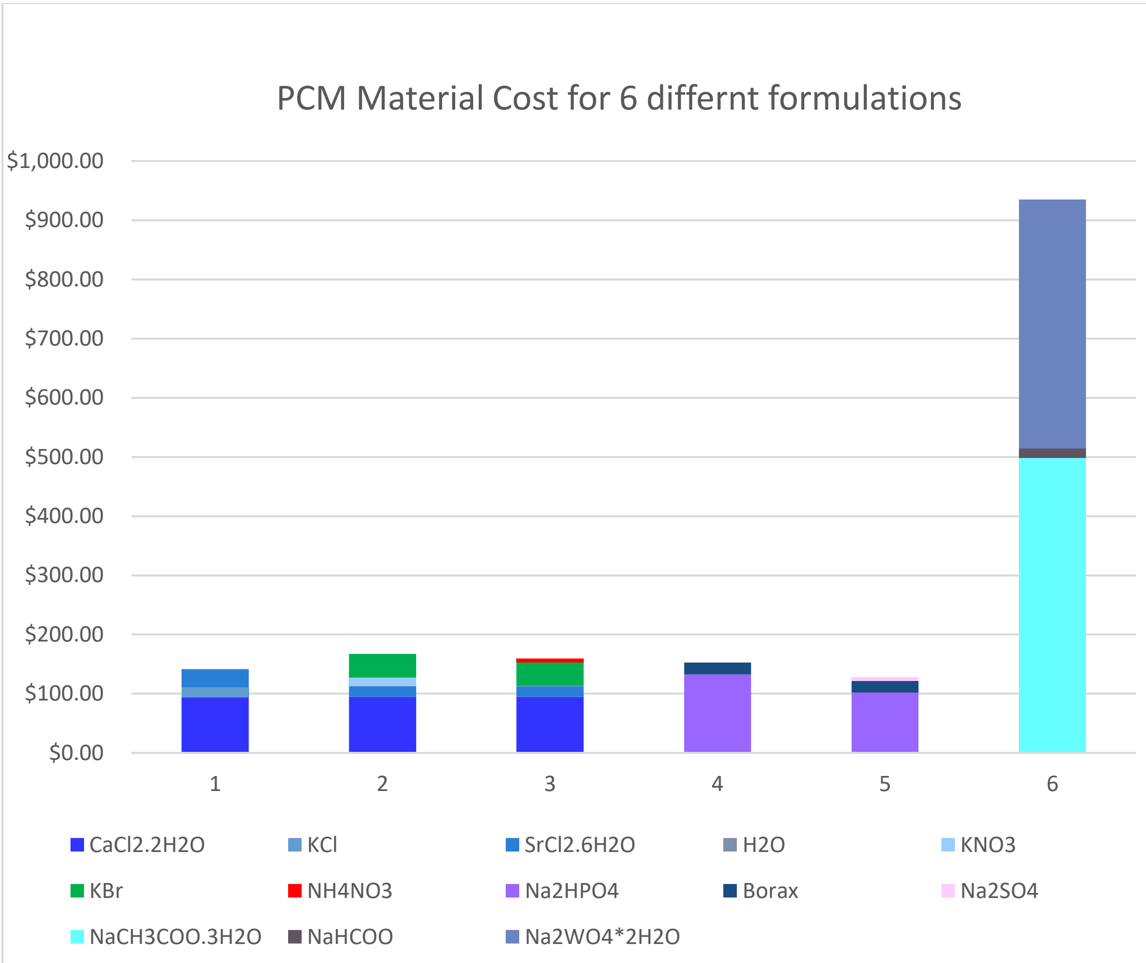


Figure 16. PCM material cost for six different formulations under consideration.

As shown in Figure 16, the sodium acetate (SAT) – sodium formate – nucleator formulation resulted in the highest absolute material cost among the six analyzed formulations. At the same time, it achieved one of the highest latent heat values of 250 J/g. When evaluated for the cost per Joule, this formulation achieved the best cost per Joule ratio among the high latent heat range (220-270 J/g) test formulations group. The ratio was $3.74 per Mega Joule. Based on these previous findings, the team continued to analyze additional sodium acetate (SAT) formulations with the objective to reduce cost, while maintaining superior latent heat performance.

Table 10 and Figures 17 and 18 provide an overview of the additionally developed and tested Glauber's Salt-based material formulations, including their demonstrated thermal performance. The nucleator material in the formulation was the major cost driver, so the strategy was to reduce the amount of nucleator and replace some of it with lower cost materials while maintaining the thermal performance.

Table 10: Bill of materials for four additional PCM formulations (1, 1a, 2a, 2b in addition to the previously developed and tested formulation 3).

Sr No	Formulation	Composition	Melting temp	Latent Heat
1	SAT* + Borax	98%+2%	57-60 °C	200-220 J/g
1a	SAT + Sodium tungstate dihydrate	98%+2%	57-60 °C	200-220 J/g
2a	SAT + Sodium formate + Sodium tungstate dihydrate	84-85%+14%+1-2%	48-51 °C	190-220 J/g
2b	SAT + Sodium formate + Borax	84-85%+14%+1-2%	48-51 °C	190-220 J/g
3	NaCH3COO.3H2O(SAT) + NaHCOO (sodium formate)	83% +14% + 3% Nucleator	47 °C	250 J/g

**SAT – Sodium Acetate Trihydrate*

When taking thermal performance into account and analyzing the cost per Mega Joule, the results showed, that three out of the four new formulations could achieve a lower cost per Joule. Considering formulation three, (developed and analyzed in the previous reporting period) as the baseline, the cost could be reduced by a relative percentage of 23% for formulation one, by 7% for formulation 2a and by 30% for formulation 2b. In this comparison Borax is a major cost-saving additive eliminating costly Sodium tungstate dihydrate.

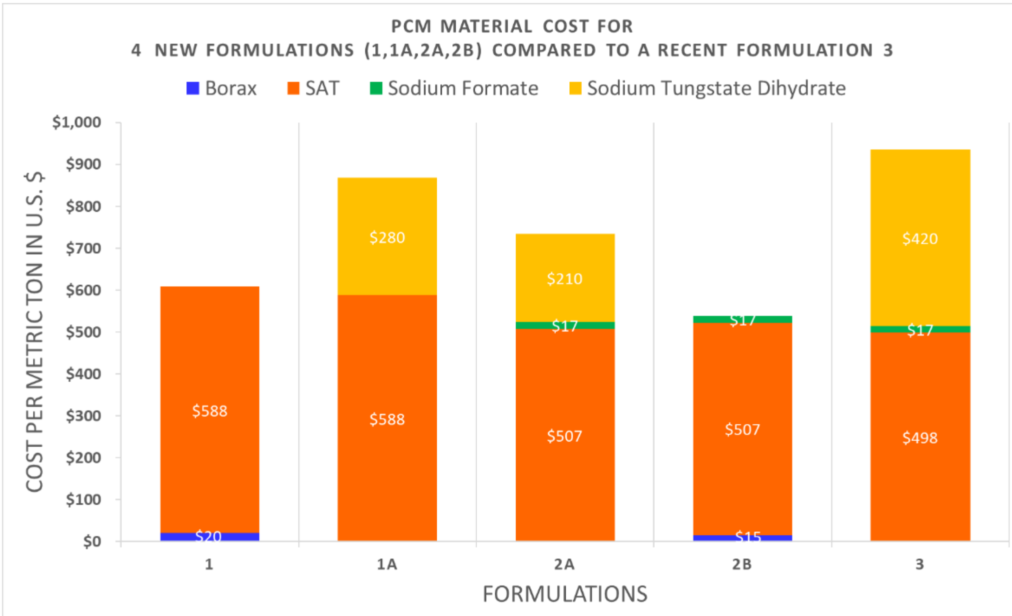


Figure 17. PCM material cost for four additional PCM formulations (1, 1a, 2a, 2b in addition to the previously developed and tested formulation 3).

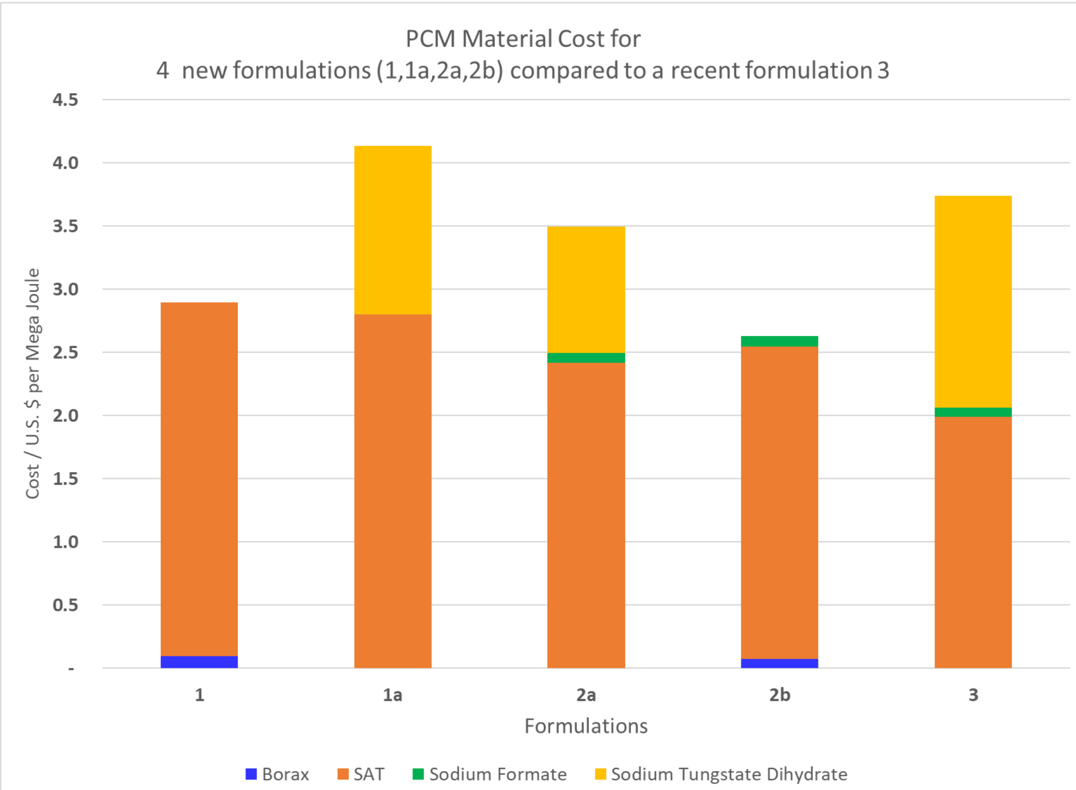


Figure 18.: PCM material cost per Mega Joule for four additional PCM formulations (1, 1a, 2a, 2b in addition to the previously developed and tested formulation 3).

Manufacturing and Scalability Analysis (SAT-PCM product assumption – InsolCorp perspective): In planning the PCM product commercialization, both selected PCM formulations as well as novel packaging methods/products need to be considered. For example, assuming the development of the SAT based PCM, from the PCM perspective, the commercialization process will most likely focus on formulation No. 1 from Table 10 above. The final product design will most likely consist of a 4' x 8' thermoformed plastic component containing a gelled inorganic PCM which is laminated to a sheet of insulation and a radiant barrier – Figure 19. In the future, this packaging product can be used for wall assemblies, exterior sheathing, and commercial roofing (with different PCMs). Utilizing a laminating process for combining the PCM (thermally active) component with the Thermally passive component (Polyisocyanurate foam Sheet) allows for multiple future product variations by changing the passive component to other materials and changing the order and type of materials laminated. For example, the polyiso sheet could be changed to gypsum board to create a PCM enhanced decking board similar to GP DensDeck. In addition, the FRB panel could be laminated on the opposing side to function as a finished surface for wall or ceiling applications.

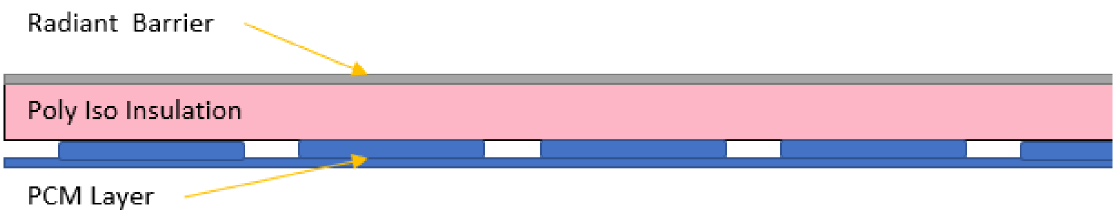


Figure 19. Schematic view of the cross-section of the product for the planned commercialization.

Cost analysis for commercialization components (manufacturing):

Benchtop fabrication setup and initial performance testing:

As part of the commercialization process, the team plan to fabricate in the close future about 40 prototypes on a small-scale benchtop fabrication setup. These prototypes will be used for the initial performance testing - including; (i) thermal performance product testing, (ii) long term durability testing, (iii) external exposure testing on test huts, (iv) moisture performance, etc…. The result of these tests will allow the improvements/adjustments of our current design. This work will be followed with commercial and residential building demonstrations.

Pilot scale fabrication line: After this optimization step, InsolCorp LLC will establish a pilot scale fabrication line. In order to establish this prototyping line, they will need to invest in the following equipment components:

- Chemical Mixing Tank ~ $30K
- 4’ x 8’ Thermo former ~ $225K
- 4’ x 8’ Radio Frequency Welder ~ $400K
- Multiport Filler ~ $80K
- Pneumatic Laminator ~ $45K

$780K

The total cost of equipment is expected to be around $780K at current prices (March 2022).

In addition to the equipment cost, InsolCorp will need to invest an additional $100K to provide the necessary facility infrastructure like electrical, pneumatic and vacuum supply. On this pilot scale fabrication line, InsolCorp will produce up to 2000 samples (64K ft^2) for further field whole-scale and lab testing. In this stage of commercialization, the testing will include:

a) Performance and installation demonstration:
   1500 samples will be used for a performance and installation demonstration in a relevant environment. The installation demonstration will include a roof demonstration on a commercial building and a wall sheathing demonstration.

b) Code relevant testing:
   Samples will be subjected to
   - Fire testing according to ASTM E84
   - Roof Assembly testing to NFPA 276
   - Wall assembly testing to NFPA 285

The expected cost for these tests is around $125K.

Timeline:

The expected commercialization timeline is dependent on available funding. With adequate capital InsolCorp could release the discussed above initial product (Figure 15) within 24 to 36 months. Furthermore, the flexibility of this design would also allow for multiple variants such as the decking board example above. As little or no additional equipment would be required for these new variants, time to market would be limited only by testing requirements. It is estimated that InsolCorp would be able to release new technology variants on an annual basis and that several new products would be developed that could be manufactured using the proposed manufacturing line.

Market introduction:

For the market introduction we envision the following steps:

- Pilot demonstrations
- Technical and Promotional material development
- Sales and end user training program developed and implemented
- Marketing campaign development and launch

Throughout this process we would be identifying potential large scale industry partners to assist with the process. The project team is currently working with several key building materials market players who may have a potential interest in these newly designed products.

The main target building markets include:

1. Commercial roofing (new and reroof): The total global roofing market size was valued at $102.4 billion in 2020, and is projected to reach $156.0 billion by 2030, it is estimated that commercial roofing insulation contributes in excess of 10% of this ~$10Billion. We believe a successful product could eventually comprise a large portion of this market.

2. Commercial construction (wall exterior sheathing): The global exterior sheathing market reached a value of US$ 7.7 Billion in 2021. The market expects to reach US$ 10.4 Billion by 2027. The superior performance expected by this product would allow for large market penetration for the proposed product.

4.0. What opportunities for training and professional development has the project provided?

The researchers in UML received systematic training to sharpen research skills. Across the course of the project,

- three Ph.D. students participated in work (two has already graduated),
- five graduate students participated in work (all graduated), and
- two undergrad students participated in work (all graduated).

From the InsolCorp industrial perspective, this project offered numerous opportunities for training and professional development for individuals involved in the project. Engineers, technicians, professors, postdocs, and students involved in the project could gain technical expertise in the analysis, design, selection, and installation of PCM panels. This includes understanding the principles behind PCMs, their thermal performance characteristics, and how to integrate them effectively into building structures. Professionals working on the PCM project had the chance to deepen their knowledge of material science and technology, especially in relation to advanced insulation and building envelopes. This involved learning about the manufacturing processes, properties, and performance considerations of PCM technologies. The project also provides an opportunity for professionals to enhance their understanding of building physics and energy efficiency. They learned how thermal storage can contribute to improving the thermal performance of buildings and reducing energy consumption, gaining insights into sustainable construction practices. Project managers involved in the project developed new skills in coordinating the work from different teams. This includes planning, scheduling, and overseeing the various aspects of the project, ensuring that it stays on track and meets its objectives. This project sparked an interest in ongoing learning and staying updated on advancements in thermal storage and insulation technologies. Students, faculty, and professionals took advantage of participating in conferences, workshops, and courses to continually enhance their knowledge in this evolving field. Both UML and InsolCorp team members received considerable professional development opportunities throughout the project. It also allowed them to advance professionally by collaborating with and being mentored by the PI and the co-PIs. The research activities undertaken inspired more new ideas and generated collective learnings that lead to publications. The research advances the subject area of PCM, thermal storage, and building energy efficiency, and this project increases the likelihood the PCM products can be applied in the built environment. The project presents a multifaceted learning environment that contributed to the professional growth of individuals involved in different capacities. This included technical knowledge, project management skills, interdisciplinary collaboration, and a broader understanding of sustainable and energy-efficient building practices.

5.0. How have the results been disseminated to communities of interest?

UML and InsolCorp and other members of the project team continued to engage in numerous discussions regarding this technology. These include insightful discussions with the industry experts (architects, engineers, and builders) on the materials and products desired in the industry. These discussions continue to generate a lot of interest in our materials. Disseminating the project results to communities of interest is crucial for sharing knowledge, promoting awareness, and facilitating the adoption of innovative technologies. Scientific and technical research papers published in journals, conferences, and industry publications. Project team members presented findings, methodologies, and outcomes related to the project in numerous conferences, and professional association meetings. For example, participated as an invited speaker in Saint-Gobain Building Efficiency Seminar in Aveiro, Portugal (2022), RIMA International Conference in Rome Italy (2023), as well as the DOE BTO Ambient Energy Meeting (2023), presenting results from this study, and listening to technology improvement suggestions, and meeting professionals, academics, and other stakeholders in the field. In addition, Ph.D. student Jay Thakkar presented project results at the 2023 Thermal Conductivity Conference in Boston MA. Presenting the project results at conferences, seminars, and workshops provides an opportunity to engage directly with professionals, practitioners, and researchers. These events allow for the exchange of ideas, discussions, and networking within the community. Working with relevant government agencies involved in building regulations, energy efficiency, or sustainable construction can help integrate the results into broader policy discussions and guidelines.

6.0. Products: What has the project produced?

6.1. <u>Conference papers, and presentations:</u>

1. Thakkar J., Sobkowicz M.J., Yarbrough D., Horwath P., Kośny J. (2022) "Dynamic Heat Flow Meter Method for Evaluating Phase Change Material Performance," Proceedings of the 35th International Thermal Conductivity Conference and the 23rd International Thermal Expansion Symposium, Lowell, MA, August 2023, DEStech, Publications, Inc. ISBN – 978-I-60595-688-6.

2. Kośny J. (2023) "Mitigation of Building Energy Dynamics – Great Opportunity for Reflective Insulation combined with Thermally Massive Systems." - 2023 International Reflective Insulation Manufacturers Conference (I-RIM Conference), May 23-25, Rome, Italy.

6.2. Books and Book Chapters:

1. Kośny J., Yarbrough D. (2023) - "Thermal Insulation and Radiation Control Technologies for Buildings," Book, June 2023; Springer., ISBN: 978-3-030-98692-6

6.3. Manuscripts of Journal Articles:

1. Jay Thakkar, Nicholas Bowen, Allen C Chang, Peter Horwath, Margaret J Sobkowicz, Jan Kośny (2022) – "Optimization of Preparation Method, Nucleating Agent, and Stabilizers for Synthesizing Calcium Chloride Hexahydrate (CaCl2.6H2O) Phase Change Material." MDPI BUILDINGS, 2022, 12(10), 1762; https://doi.org/10.3390/buildings12101762
2. Kośny J., Thakkar J., Kamidollayev T., Sobkowicz M.J., Trelles J.P., Schmid C., Phan S., Annavajjala S., Horwath P. "Dynamic Thermal Performance Analysis of PCM Products Used for Energy Efficiency and Internal Climate Control in Buildings" – MDPI Buildings, (2023) vol. 13, issue 6, p.1516
3. Kamidollayev T., Trelles J.P., Thakkar J., Kośny J. "Parametric Study of Panel PCM–Air Heat Exchanger Designs" - MDPI Energies, (2022), vol 15, issue 15, p. 5552
4. Kośny J., Miller W.A., Yarbrough D., Kossecka E., Biswas K. "Application of Phase Change Materials and Conventional Thermal Mass for Control of Roof-Generated Cooling Loads" Applied Sciences, Special Issue Phase Change Materials in Buildings, Appl. Sci. 2020, 10(19), 6875; - 30 Sep. 2020; https://doi.org/10.3390/app10196875
5. Jay Thakkar, Sai Bhargav Annavajjala, Margaret J. Sobkowicz, Jan Kosny (2024) – "Influence of Carboxymethyl Cellulose as a Thickening Agent for Glauber's Salt Based Low Temperature PCM." MDPI MATERIALS – approved for publication Apr.26th, 2024.
6. Jay Thakkar, Sai Bhargav Annavajjala, Jan Kosny, Margaret J. Sobkowicz (2024) – "Stabilizing a Low Temperature Phase Change Material based on Glauber's Salt," MDPI ENERGIES – in review.

6.4. Doctoral Dissertations - Ph.D.

1. Jay Thakkar (Dec. 2023) – "Optimizing Design of Salt Hydrate Phase Change Materials for Building and Cold Chain Efficiency Applications" Ph.D. Dissertation Submitted to the Francis College of Engineering, University of Massachusetts Lowell, in partial fulfillment of the requirements for the degree of PhD Plastics Engineering.
2. Doctoral dissertation by Tlegen Kamidollayev (2023) "Computational Modeling of Reactive Species Interphase Transport in Plasma Jet Impinging on Water." The Francis College of Engineering, Department of Mechanical and Industrial Engineering, University of Massachusetts, Lowell, April 4, 2023.

7.0. Inventions:

1. January 2023, UML's team filled Invention Disclosure - UML: 2023-016, "Compact Liquid-Air Heat Exchanger Integrated with PCM Thermal Storage."

2. March 2024, UML's team filled Invention Disclosure - UML 2024-025, "Stackable Thermal Battery and Phase Change Material (PCM)-Air Heat Exchanger."