MULTIPURPOSE LATENT HEAT STORAGE SYSTEM FOR BUILDING APPLICATIONS

Development of Low-Cost, High-Performance, Easy-to-Apply, Non-Flammable, Inorganic Phase Change Material (PCM) Technology - DE-EE0009156

University of Massachusetts, Lowell

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Project Summary

Project Objectives and Outcomes:

The project aims at developing a low-cost, high-energy storage, and a reliable PCM technology that will meet the following target metrics: (i) energy storage density of over 100 kWh/m^3, and (ii) thermal energy storage cost below $15/kWh. The PCM technology is realized by formulating and integrating following two technology components:

- Inorganic salt hydrate based PCMs that have high latent enthalpies and are low-cost and durable,
- PCM encapsulation (packaging) technology that maximizes PCM concentration and enhances heat transport characteristics in the product and with the external environment/materials.
- **Development of Low-Cost, non-Flammable PCM formulation of enthalpy between 300 J/g - 520 J/g and GWP of 0.5**

Key Partner: InsolCorp LLC

Industrial Advisory Board:

Representatives of 3M, Cold Chain Technologies, RAL, and R&D Services

Timeline: Start: April 01, 2020, End date: March 31, 2023

Six month, No Cost Extension (completion of field testing)

Budget: DOE: $1,394,121 Cost Share: $ 558,89

All Project Milestones have been already fulfilled

1. Selection of 10 to 15 best-performing PCM compounds/formulations **(M12)**
2. Designs of three packaging/geometrical options of PCM products **(M12)**
3. Successful fabrication and testing of three mechanically-robust, impermeable, and thermally conductive PCM packaging forms/products **(M24).**
4. Whole-Building Field Testing (M36)

Problem

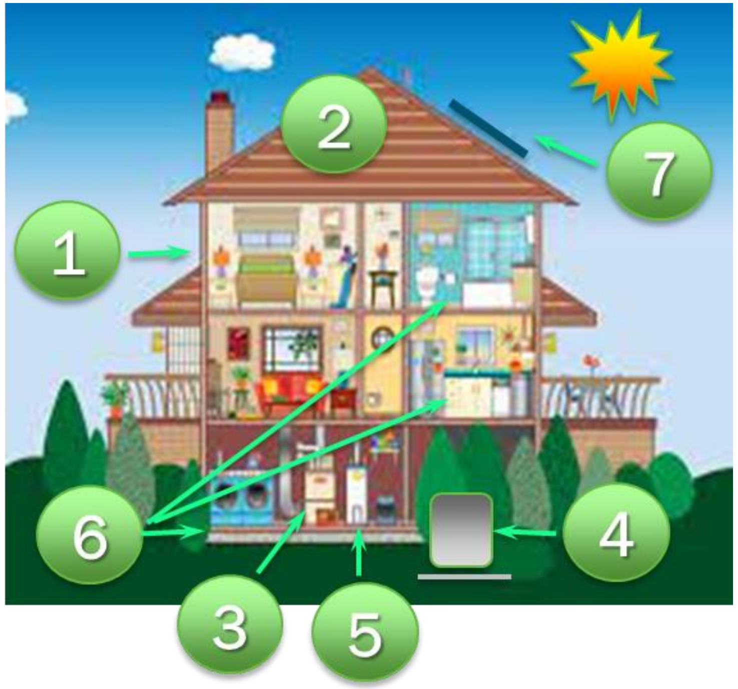
Building market adoption of PCM products has been so far unsuccessful. **These systems are often not effective enough**, and have **relatively high prices**, which become even higher after necessary PCM encapsulation.

Also, many organic PCMs, as well as packaging/encapsulation materials are flammable, which restricts their building applications

https://mospace.umsystem.edu/xmlui/bitstream/handle/10355/6252/research.pdf?sequence=3

Key Factors:

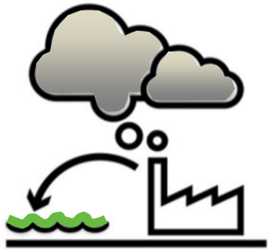
PCM System Design, Service Temperature Selection, & Location Choice



- PCM systems, to be fully functional, need to operate in PCM temperature ranges
- In building envelopes, **operational temperature is a function of location**
- Buildings with many thermal processes, and communities (seasonal heat storage) require **many PCMs serving in different temperatures:**
  - (1) Vertical Envelopes (+15^{o}C to +30^{o}C); (2) Roofs and Attics (+35^{o}C to +55^{o}C)
  - (3) Space Heating (+35^{o}C to +55^{o}C); (4) Cooling (0^{o}C ice, and +5^{o}C to +15^{o}C - PCMs)
  - (5) Water heating (+50^{o}C to +65^{o}C); (6) Waste Heat Recovery (+5^{o}C to +20^{o}C)
  - (7) Building Integrated Solar Systems (+35^{o}C to +70^{o}C)
- **Single PCM (even with switchable temp) may not serve well, even in a single application, where different placements are possible (large temp gradients)**
- **Better solution – well tuned PCMs for temperature at each use and location**
- Additives, encapsulants, and packaging materials not only take application space, **reduce overall heat storage density**, but also **significantly increase price!**

Alignment and Impact

Impactful & Low-Cost Nation-Wide Applications - Alignment with the U.S. ambitious climate mitigation goals



Greenhouse gas emissions reductions

50-52% reduction by 2030 vs. 2005 levels

Net-zero emissions economy by 2050

Power system decarbonization

100% carbon pollution-free electricity by 2035

Energy justice

40% of benefits from federal climate and clean energy investments flow to disadvantaged communities

Sustainability Impact

- **Inorganic Non-Petroleum PCMs**
- **Low GWP PCM Formulations**

BEE Improvements

- Documented **10% - 15% thermal load reductions** in passive applications
- Documented up to **60% thermal load reductions** in dynamic applications

- PCM Systems Improve Buildings **Energy Dynamics Flexibility**
  - Demonstrated up to **6-hours peak load time shifting** ability
  - Documented up to **90% peak thermal load reductions** – see Dynamic Thermal Disconnect (DTD) systems
  - Documented Ability for **Thermal Load Alternating**

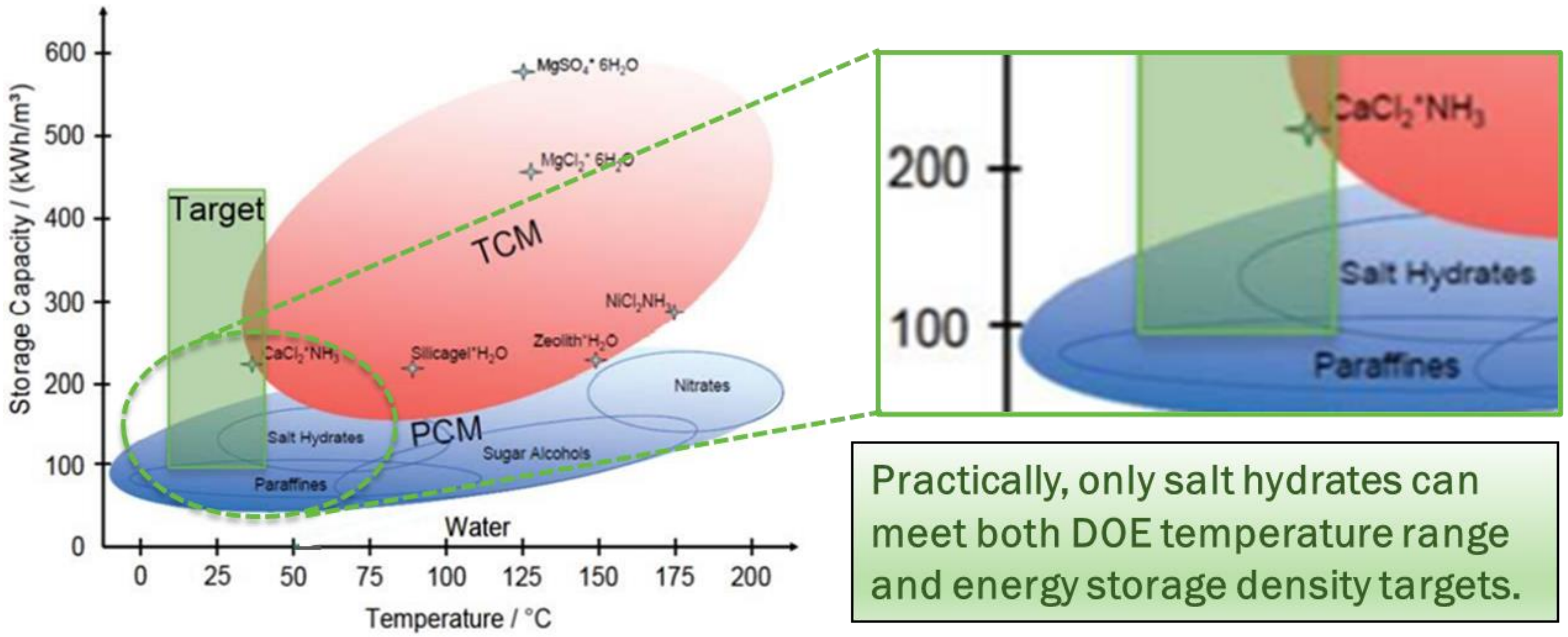
- Developed PCM formulations represent **fraction of the cost** of organic formulations
- Current commercialization allows almost **immediate market implementation**
- Developed PCM systems are easy to apply in existing buildings and **do not require any special expertise or tools**

Approach

To maximize performance and allow widespread adoption with minimal price and environmental impact

Metric Description	Target
Phase Change Temperature	PCMs: <30°C TCMs <70°C
Thermal energy storage composite material cost	<$15/kWh thermal
Energy density	PCMs: >100 kWh/m³ TCMs: >200 kWh/m³
Thermal conductivity	>1.0 W/m·K
Thermal reliability (Retained energy density after thermal cycling and aging)	>90% after >7500 cycles
Subcooling/supercooling	<2°C

Salt hydrates show incongruent phase transition & subcooling.



Practically, only salt hydrates can meet both DOE temperature range and energy storage density targets.

Theoretical **material with enthalpy of 200 J/g and density of 1.8 g/cm^3 would need to cost lees than $830 per metric ton**, which eliminates some paraffins, esters, fatty acids, etc… (~$600 – $3,000 per ton) and all lithium-based salt hydrates (Li_2CO_3 costs between $14,500 and even $94,000 per ton – see: https://www.fastmarkets.com/commodities/industrial-minerals/lithium-price-spotlight.)

Material enthalpy over 200 J/g would need to have density over 1.8 g/cm^3, which is almost 50% - 80% higher from most typical organic PCMs.

Organic PCMs usually exhibit 3 to 5 times lower thermal conductivities.

Some Key Assumptions Leading to Formulation of Our Approach

- Serious cost-reducing, performance, and durability improving R&D works need to be performed on PCMs and PCM products, to make them adoptable by the U.S. building sector, and acceptable by U.S. customers
- To reach the DOE BTO performance targets, PCM's enthalpy need to be around ~200 J/g and it can't be compromised by too many additives.
- Local operational temperatures, in PCM system applications, need to be closely matched by PCM's phase change characteristics
- In PCM system applications, PCM need to represent great majority of the application space and proportionally, the heat exchange area
- Successful implementation of a PCM system depends not only on properties of PCM. It primarily depends on performance and price of the entire system.

Our Approach

- **Our holistic approach includes a parallel development of:**
  - A family of low-cost PCM formulations with operational temperatures matching conditions in typical building applications
  - Inexpensive product designs warranting high performance, easy installation, and a usage in typical building applications
- **To allow quick and easy technology commercialization market implementation we work closely with InsolCorp – Project Partner, and a group of industry advisors**
- **To allow a widespread market adoption we:**
  - Developed PCM technologies of notably lower prices
  - We demonstrated technology performance advantages
  - We developed easy to install products, compatible with existing building systems

Our Two-Fold Holistic Approach

Multiple (6-7) PCMs for typical building applications (Tm +5ºC to +45ºC)

Lowest Cost per J at Highest Possible Enthalpy > 180 J/g

High Density 1500–2500 kg/m^3 Thermal Conductivity at least 1.0 - .1.5 W/m-K

Low Subcooling below 1.5ºC Durable Phase Transition (>5000 phase change cycles with <10% enthalpy los)

Flame Resistance Requirement

PCM Formulation

Packaging & Product Design

Minimum packaging material usage with maximum PCM

Maximum exposure of PCM area

Packaging Material

Thermal Conductivity H_2O Diffusion; Corrosion Resistance; Mechanical Strength

Packaging Method & PCM Product Design

(i) Shape Stabilized,
(ii) Pouches or Flat Containers,
(iii) 3-D Structure

Typical & Most Needed Building Applications

MULTIPURPOSE LATENT HEAT STORAGE SYSTEM FOR BUILDING APPLICATIONS

Approach Details *- Solving Typical PCM Technology Problems & Allowing Variety of Building Applications*

Our Development Targets for Complete PCM Products:

1. Simplicity of design, Low-Cost Fabrication & Compatibility with U.S. structural systems
2. Superior performance comparing to the existing PCM applications: (a) **heat storage density of installed product**, (b) **fire resistance**, (c) **long term durability**, and (d) significant **cost advantage**.
3. Scale Effect – To allow implementations in variety of building applications including: (a) building envelopes and interior fabric, (b) HVAC systems, (c) water heating, (d) short-term and seasonal heat storage, (e) renewable energy and waste heat recovery systems, and (f) for temperature control and safety in building integrated energy storage.

PCM Formulations' Goals:

1. Enthalpies in the range between 180 and 280 J/g with congruent and durable phase changes, **density** of **1500–2500 kg/m^3**, and thermal conductivity of 1.0 - 1.5 W/m-K (possible increase to 5 W/m-K)
2. Lower cost and superior fire resistance, comparing to the existing PCMs
3. Developed PCMs are applicable in variety of building applications in temperature range between **+5°C and +55°C** with possible temperature adjustments of (+/- 5°C - 10°C)

Approach Details *– Elimination Barriers & Reducing PCM Technology Application Risks*

Elimination of Key Technology Application Barriers:

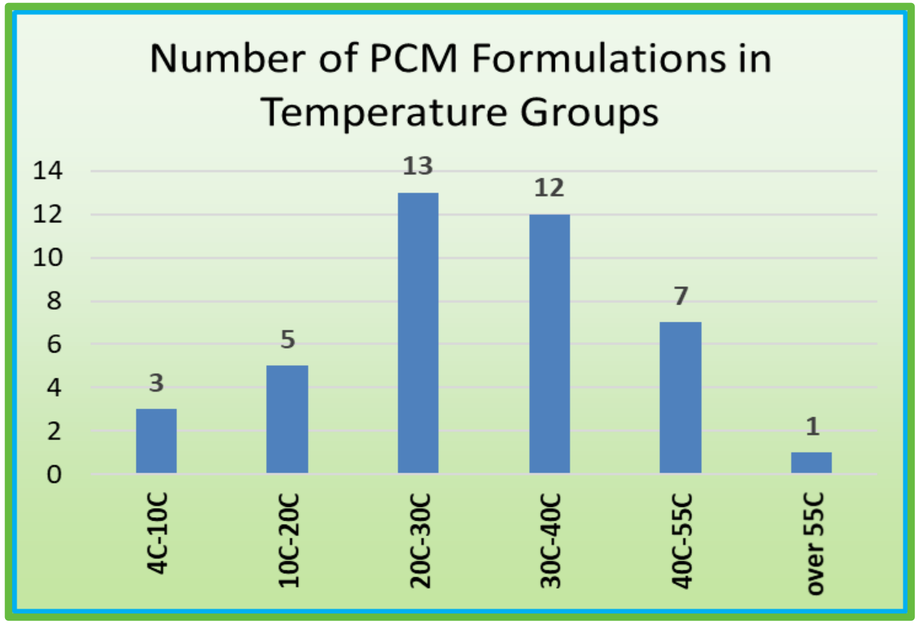
1. Superior thermal performance and documented PCM durability
   a) High enthalpy
   b) No Phase Segregation, Congruent and Durable Phase Changes - demonstrated during long-term cycling testing
2. Superior price, comparing with similar organic, and lithium-based products
3. Eliminated Flammability Hazard
4. Widely available components and easy and inexpensive manufacturing

Reduction of Application Risks through Improved Product Design and PCM Packaging:

1. **Simplicity of design, compatibility with U.S. structural systems,** and **low-cost fabrication/installation**
2. **Three PCM packaging forms** allowing multiple applications
3. **Added functionalities: (a) moisture and air barrier, (b) reflective insulation, and (c) stackable heat exchanger**

Progress and Future Work

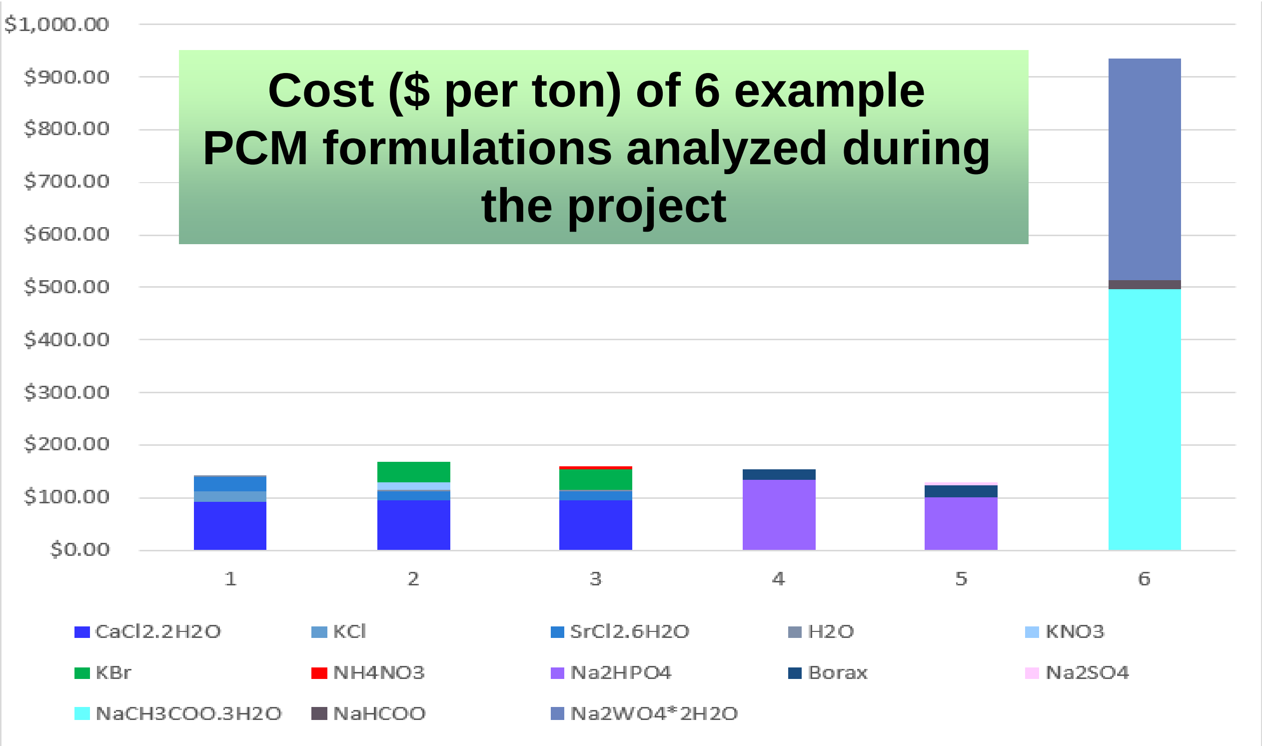
- **Review of pre-selected 41** known/published in literature salt hydrate-based **PCM formulations**, with phase change temperature range between +5ºC and +55ºC.
- **Development of "REAL" formulation recipes and fabrication methods for four major groups of PCMs.**
  - Two Groups of Glauber's Salt Based Formulations
  - Calcium Chloride Hexahydrate Based Formulations
  - Sodium Acetate Trihydrate based Formulations
- **Fabrication trials, performance testing** of most promising formulations:
  - Successful component mixing, reversable phase changes, and minimal or no material separation
  - Enthalpy around of around 200 J/g
  - Max. component cost below $800 per ton
- **Durability testing** (500-1000 freezing-melting cycles), T-history and DSC testing at the beginning and at the end.

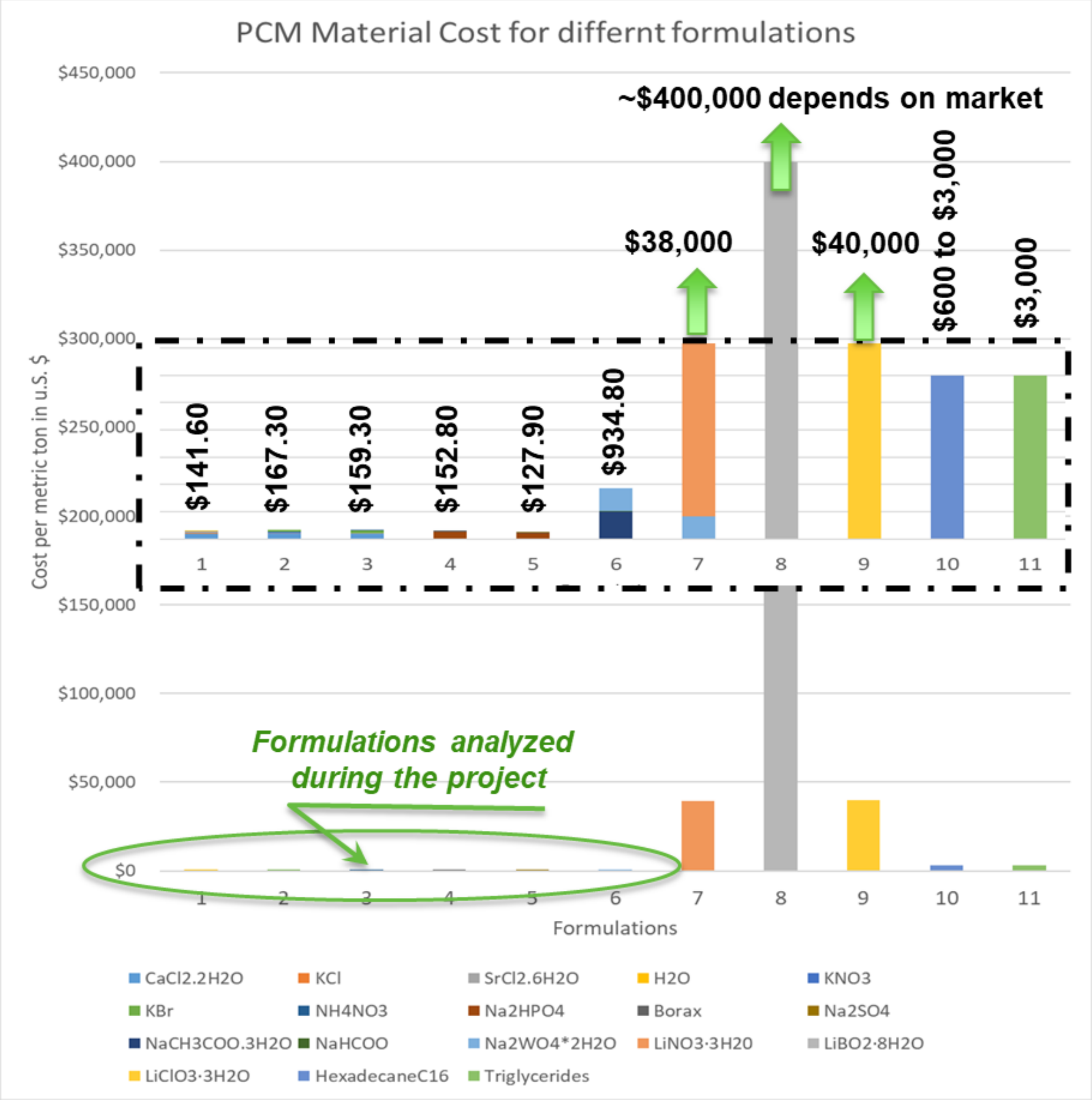


PCM compound, or PCM Formulation	Melt Temp Cº	Fuzion Heat kJ/kg
NaOH + $Na_2Cr_2O_7$*$2H_2O$+H2O+ Kaolin Clay	5	250
$CaCl_2$*$6H_2O$ + $CaBr_2$*$6H_2O$	9	188
K2HPO4-4H2O	18.5	231
$CaCl_2$ + NH_4NO_3 + $SrCl_2$*$6H_2O$ + KBr + H_2O	18	220
$CaCl_2$. + KNO_3 + $SrCl_2$*$6H_2O$ + KBr + H_2O	22	219
$CaCl_2$*$2H_2O$. $MgCl_2$*$6H_2O$. KCl $SrCl_2$*$6H_2O$. Na_2WO_4*$2H_2O$. H_2O	24	185
$CaCl_2$ + KCL + $SrCl_2$*$6H_2O$ + H_2O	29	185
$CaCl_2$ + $SrCl_2$*$6H_2O$ + H_2O	29	188
Na_2SO_4*$10H_2O$ + Na_2HPO_4*$12H_2O$	32	175
Na_2SO_4*$10H_2O$	32.4	254
Na_2HPO_4*$12H_2O$	35	265
$NaCH_3COO$*$3H_2O$ + NaHCOO	47	200

Progress and Future Work - Detail Cost Analysis at Each Step

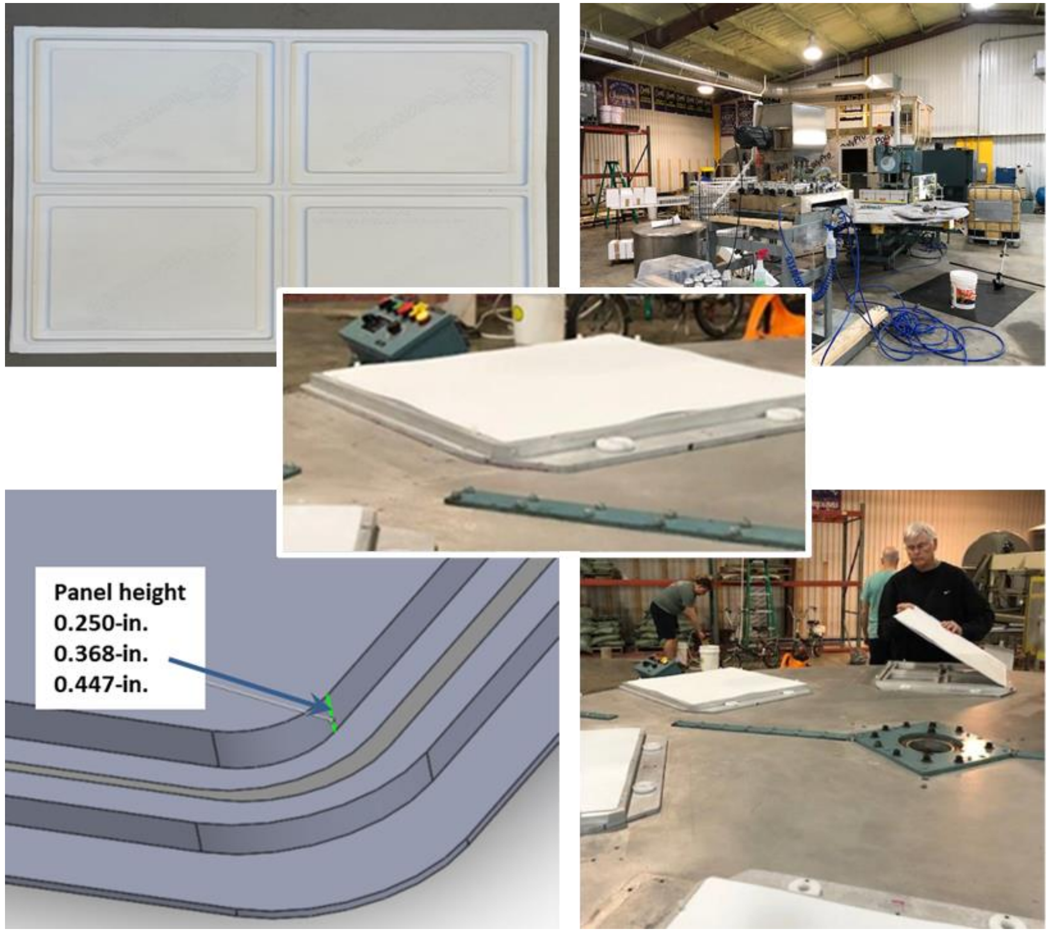
- We evaluated each promising PCM formulation,
- We also analyzed costs of several competitive PCMs,
- Material prices were received from industrial partners and from international scientific sources.





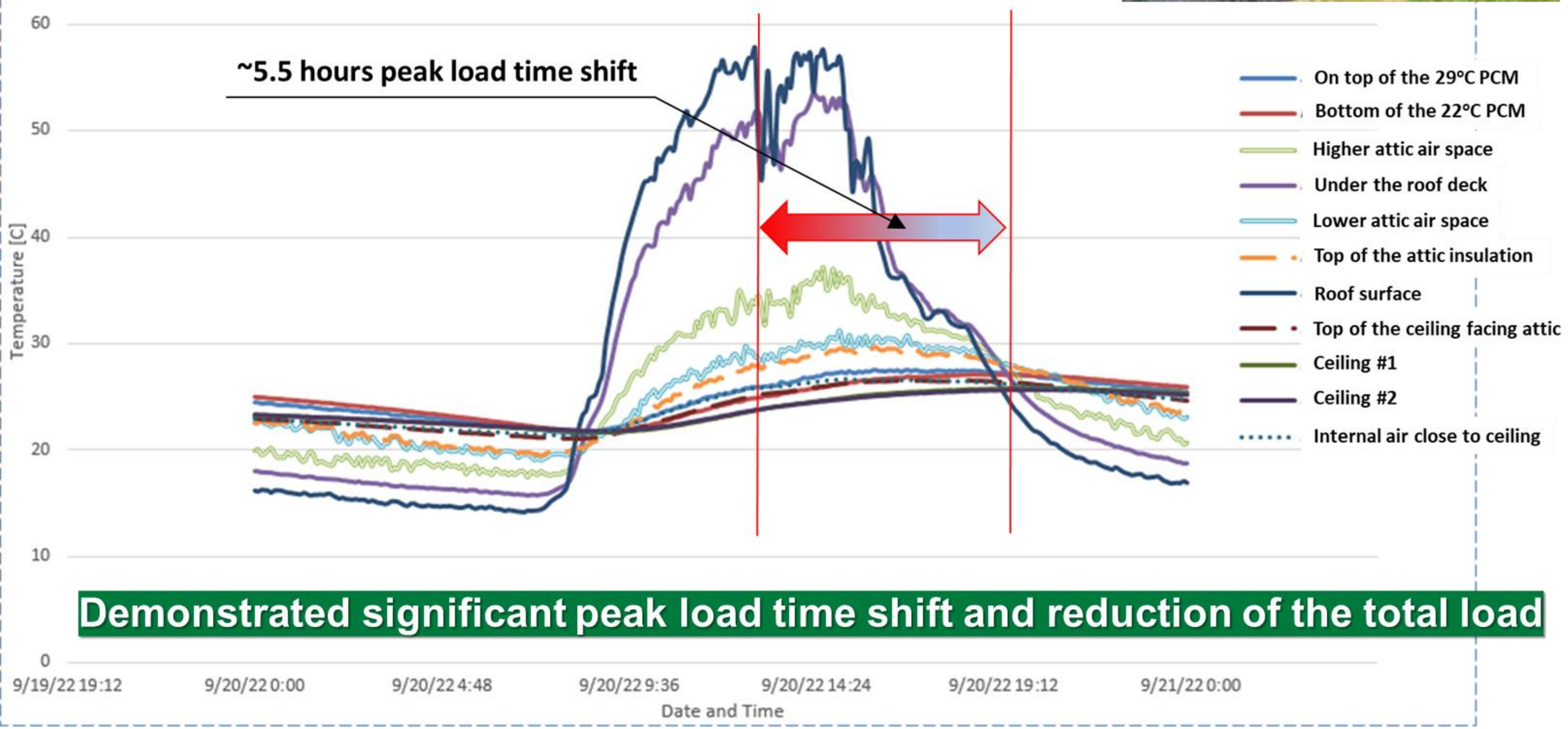
Progress and Future Work – PCM Product Developments

- **Design of <u>three groups of plastic panels caring PCM</u>.**
- We selected rigid thermoformable PVC because of its excellent barrier properties and ease in fabrication - density between 1.3-1.45 g/cm^3 and thermal conductivity ~ 0.14-0.28 W/mK. **PVC is already used by InsolCorp** in production of their PCM products
- New **designs of PCM panels with 30% to over 60% increase of the aerial heat storage capacity and radiant barrier surface functionality.** This technology fulfills this FOA's target of volumetric energy density > 100 kWh/m^3.
- **New Tooling Design** was developed and fabricated. <u>This tooling is already in use for fabrication of novel panels.</u>
- <u>New Panel Designs are undergoing field testing right now</u>
- Development of **3D Stackable PCM Heat Exchanger Panels**: Several novel 3D plastic panels designs were development during the project.
- Development of **Expanded Channel PCM carriers**



Existing PCM panel design (top left), panel fabrication line (center and right), panel height modifications bringing up to 60% increase in the aerial heat storage capability (bottom left).

Progress and Future Work – PCM Product Field Testing



Testing will be continued till the end of summer 2023.

Demonstrated significant peak load time shift and reduction of the total load

Progress and Future Work – Project Outcomes

- Four groups of experimentally validated and durable PCM formulations with service temperatures between +5 °C and +55 °C - *three new formulations planned to be commercialized after the completion of the project*,
- Three groups of PCM products, with several products already fabricated, and *their prototypes are already in field testing, ready for commercialization*.
- Outdoor field-testing facility with four test huts was developed in North Carolina
- Patents: Two Invention Disclosures have been already filled
- Publications and Presentations: One book chapter; Five journal papers; One keynote talk, Six conference papers
- Education: Two Ph.D. dissertations, seven graduate, and two undergraduate students participated in the project
- Faculty involvement: Four UML professors participated in the project
- DEI Effect: Two female faculty, one minority faculty, and two minority students were involved in the project

Progress and Future Work – Technology Impact & Prospective Works

National Research Impact:

- The DOE BENEFIT project, helped with the development of two federal funded and one industry funded, projects focused on inorganic PCMs
- The development of Low-Cost, non-Flammable PCM formulation of enthalpy between 300 J/g - 520 J/g and GWP of 0.5 has yielded the creation of a new research team with academic/industry/national lab collaboration – this team is preparing several research proposals right now

U.S. Industry Impact:

- **PCM formulations and products to be commercialized by two companies with target application in buildings, shipping, batteries, and military**
- **All non-proprietary basic PCM formulations developed during the project will become available for commercialization by U.S. companies, after the completion of this project**
- **PCM performance data developed during this project will become available in the form of research publications.**

Thank You

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REFERENCE SLIDES

Project Progress - Revised Timetable:

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 field performance demonstrations												
#7. Analysis supporting Technology to Market Plan (2)												

Extra PCM work on Tm below 15 degC

PCM field testing in NC

Project Team

UML Faculty:

Dr. Jan Kośny
Project PI,
Research Professor,
Dept. of Mechanical Engineering

Dr. Margaret Sobkowicz-Kline
Project co-PI,
Associate Prof.,
Dept. of Plastics Engineering

Dr. Cordula Schmid
Project co-PI,
Associate Prof|.
Dept. of Electrical and Computer Engineering

Dr. Juan Pablo Trelles
Project co-PI,
Associate Prof.
Dept. of Mechanical Engineering

Dr. Jan Kośny 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.

- **35 years of experience in building physics, external envelopes, and novel thermal insulations**, through work in academia, national lab, and research institutes.
- **Decades-long work on Thermal Mass and Phase Change Materials** 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.
- **R&D 100 Award** for the development of flame resistant **PCM-enhanced thermal insulation.**

- Key Research Expertise Areas:
  - Polymer blend and composite processing, and natural fillers
  - Polymers for energy and renewable applications
  - Thermal storage systems
  - Structure-property relationships, rheology
  - Polymer recycling
- In the project, prof. Sobkowicz-Kline is working on the optimization of **PCMs' chemical formulations and the development of thermally conductive plastics and composites for PCM carriers and/or packaging.**
- Her research has been funded by NSF, DOE, DOD, NASA, and numerous private companies.

- Key Research Expertise Areas:
  - PV Prototyping, Performance and Durability Analysis
  - Materials for Energy Applications
  - Failure Analysis and Fracture Mechanics
  - Technology Demonstrations and Field Testing
  - Technology Commercialization.
- In the project, prof. Schmid is working on **the development of Technology to Market Path, Cost Analysis** for newly developed PCM products**, Technology Commercialization, and Material Testing.** During Y3, she will lead the **product field performance testing.**

- Key Research Expertise Areas:
  - Sustainable Energy Engineering,
  - Computational Transport Phenomena,
  - Plasma Science and Engineering
- In the project, prof. Trelles is working on **computational system design and evaluation of the PCM carrier.**
- The approach is based on **2- and 3-D time-dependent Computational Fluid Dynamics models** describing the **sensible and latent heat exchange through PCM, product enclosure, and surrounding environment.**
- Research funded by NSF, DOE, DOD, NASA, and private companies.

Project Team

Industry Partners:

Mr. Peter Horwath
CEO - InsolCorp LLC
President - North American PCM Manufacturers Association

- InsolCorp LLC. is the **U.S. largest manufacturer 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.**

Industry Advisory Team:

Ms. Laura Nereng -
Business Development Director, Corporate Strategy at 3M

Dr. Milind Sabade
Sr. Manager – 3M
Strategic Technology and New Business Development

Dr. Dawn Smith – Director, Research & Development
Cold Chain Technologies, LLC

Mr. Ben Welter – RAL Quality Association PCM News website (former PureTemp)

DR. David Yarbrough – vice president R&D Services, former ORNL and Chair of Chemical Eng. ant Tennessee Tech University

UML Students:

Jay Thakkar – Ph.D. student at the Department of Plastics Eng.
- .PCM chemical formulation work
- Analytical chemistry & material testing
- Thermal & durability analysis of PCMs
- PCM packaging & conductive plastics

Tlegen Kamidollayev – Ph.D. student at the Department of Mechanical Engineering
- Dynamic heat transfer simulations
- Numerical CFD analysis of 3-D heat exchanger PCM products

- **Ben Amuta – grad student at the Dept. of Mechanical Engineering** – PCM product design, SolidWorks design, material testing
- **Nick Bowen – undergrad student at the Dept. of Plastics Engineering** – PCM testing, thermal analysis, material durability testing