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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UMASS LOWELL

INSOLCORP

Project Summary

Timeline:

Start date: April 01, 2020

Planned end date: March 31, 2023

Key Milestones

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).**

Budget:

Total Project $ to Date:

- DOE: $ 377,659
- Cost Share: $157,474

Total Project $:

- DOE: $1,394,121
- Cost Share: $ 558,894

Key Partners:

InsolCorp LLC

Industrial Advisory Board:

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

Project Outcome:

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.

Project Team

UML Faculty:

Dr. Jan Kośny
Project PI,
Research Professor,
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.**

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

- 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.

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

- 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.**

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

- 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:

INSOLCORP

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

- InsolCorp LLC. is the **U.S. largest manufacturer and supplier of inorganic PCM systems** for buildings with over 3 million square foot 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

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UML Students:

Jay Thakkar – Ph.D. student at the Department of Plastics Eng.

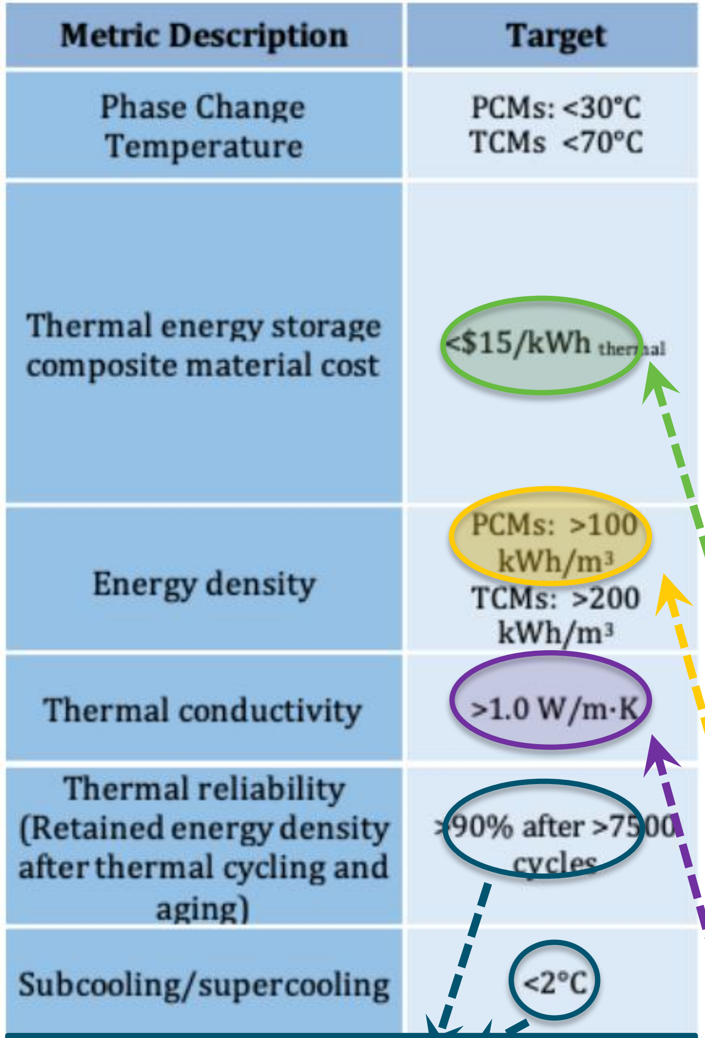
- .PCM chemical formulation work
- Analytical chemistry & material testing
- Thermal & durability analysis of PCMs
- PCM packaging & conductive plastics

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

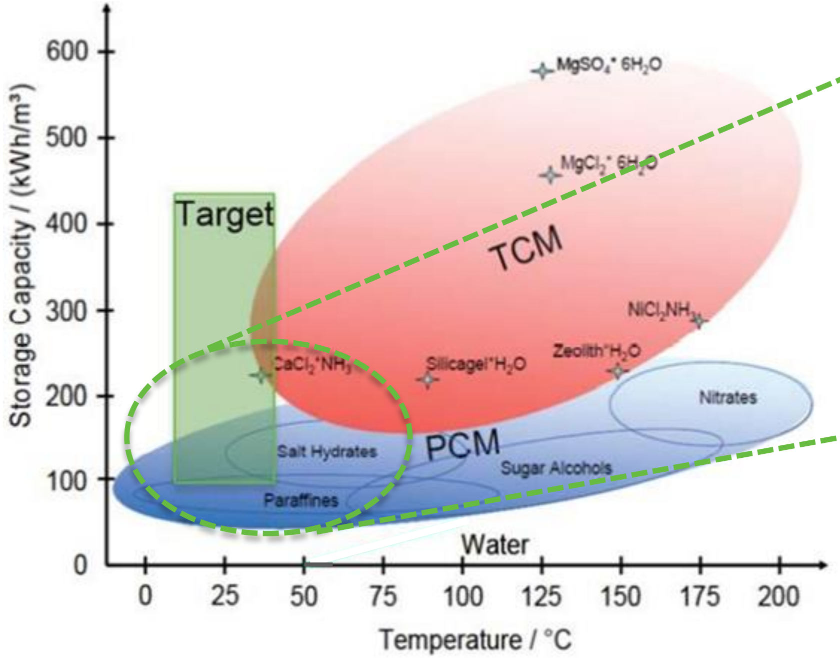
- **Ben Amuta – grad student at the Dept. of Mechanical Engineering** – PCM product design, SolidWorks design, material testing
- **Nick Bowen – undergrad student at the Dept. of Plastics Engineering** – PCM testing, thermal analysis, material durability testing

Performance Challenges *- DOE BTO Performance Targets & Limitations in Material Selection*



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.



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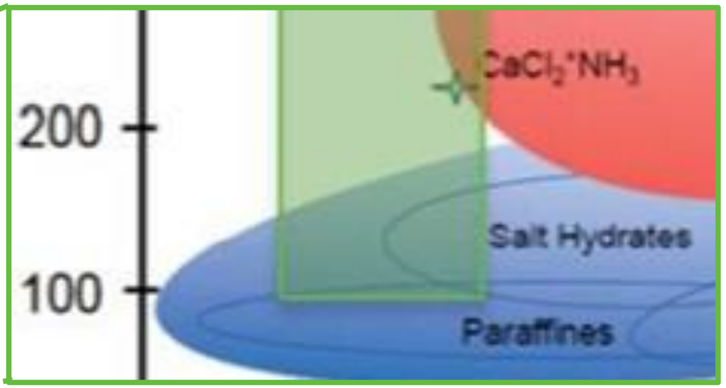


Practically, only salt hydrates can meet both DOE temperature range and energy storage density targets.

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.

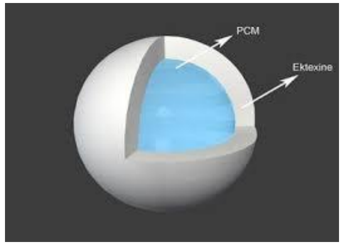
PCM Associated Challenges *- Leading to Formulation of the PCM-Related Approach*

- **Key organic PCM issues include:** **1**) flammability, **2**) low energy storage density because of low density of <1000 kg/m^3, **3**) low thermal conductivity (<0.3 W/m-K) causing incomplete phase cycling in building applications, **4**) common toxicity, and **5**) compatibility with enclosure materials, causing odor, corrosion, and/or leakage concerns.
- Our research has shown that even the lowest-cost organic PCMs, made of bio-waste, may not be cost-effective in buildings, with **payback time of >10 years**, (energy savings for U.S. climates https://www.nrel.gov/docs/fy13osti/55553.pdf)
- In contrast, **inorganic salt hydrates** often exhibit phase change **enthalpies of 180 - 300-J/g**, are non-toxic, **nonflammable**, significantly **less expensive than organic PCMs**, and due to their higher density (~1,500–2,500 kg/m^3), they have higher potential to exceed volumetric energy density of 100 kWh/m^3 in a cost-effective way.
- However, **salt hydrates have also several technical challenges:** **1**) significant subcooling caused by slow rate of crystallization, **2**) incongruent melting because of loss of hydration water upon phase cycling, and **3**) phase separation of salt hydrate into a phase with lower water hydration number which changes the phase transition temperature, compromising the overall efficacy and often energy storage capacity.

Enthalpy ~180 J/g

Source paraffin

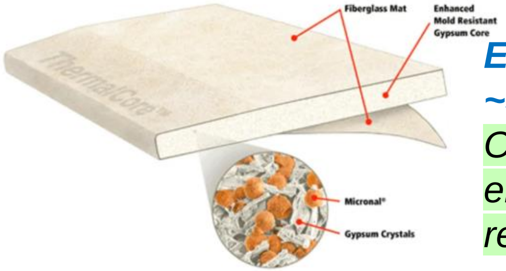
Microencapsulation



Microencapsulated PCM

Enthalpy ~110 J/g

PCM gypsum board production



Enthalpy ~35 J/g

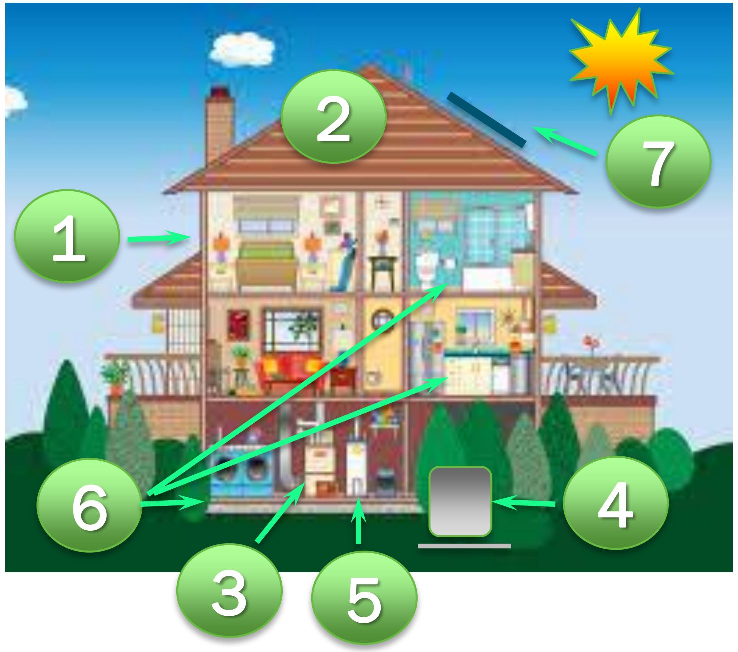
Over 80% of enthalpy reduction

- **PCM additives, modifiers, fire retardants, switchable temperature mechanisms, etc. reduce overall PCM enthalpy** - proportionally to their content (it may exceed even > **80% reduction** - https://doi.org/10.1016/j.rser.2017.01.159)

Further Challenges

Too Low Overall Heat Storage Density of Many PCM Technologies, Common PCM Temperature Mismatch, and Flammability Issues

Wide building market adoption of PCM products has been so far unsuccessful. Simply, these systems were often not effective enough, and had **relatively high prices**, which were even higher after common PCM encapsulation.



- 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°C to +30°C); (**2**) Roofs and Attics (+35°C to +55°C)
  - (**3**) Space Heating (+35°C to +55°C); (**4**) Cooling (0°C ice, and +5°C to +15°C - PCMs)
  - (**5**) Water heating (+50°C to +65°C); (**6**) Waste Heat Recovery (+5°C to +20°C)
  - (**7**) Building Integrated Solar Systems (+35°C to +70°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**
- Also, encapsulants and packaging materials take application space, **reduce overall product heat storage density, and compromise heat exchange**

Some PCMs (organic), as well as PCM packaging/encapsulation materials, and/or their polymeric additives can be flammable, which restricts their building applications

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

Some Key Conclusions Leading to Formulation of Our Approach

To reach the DOE BTO performance targets, PCM's enthalpy need to be at least ~200 J/g and it can't be compromised by too many additives

Local operational temperatures, in PCM system applications, need to be matched by PCM's phase change characteristics

In PCM system applications, PCM need to represent great majority of used materials (application volume) and proportionally, the heat exchange area

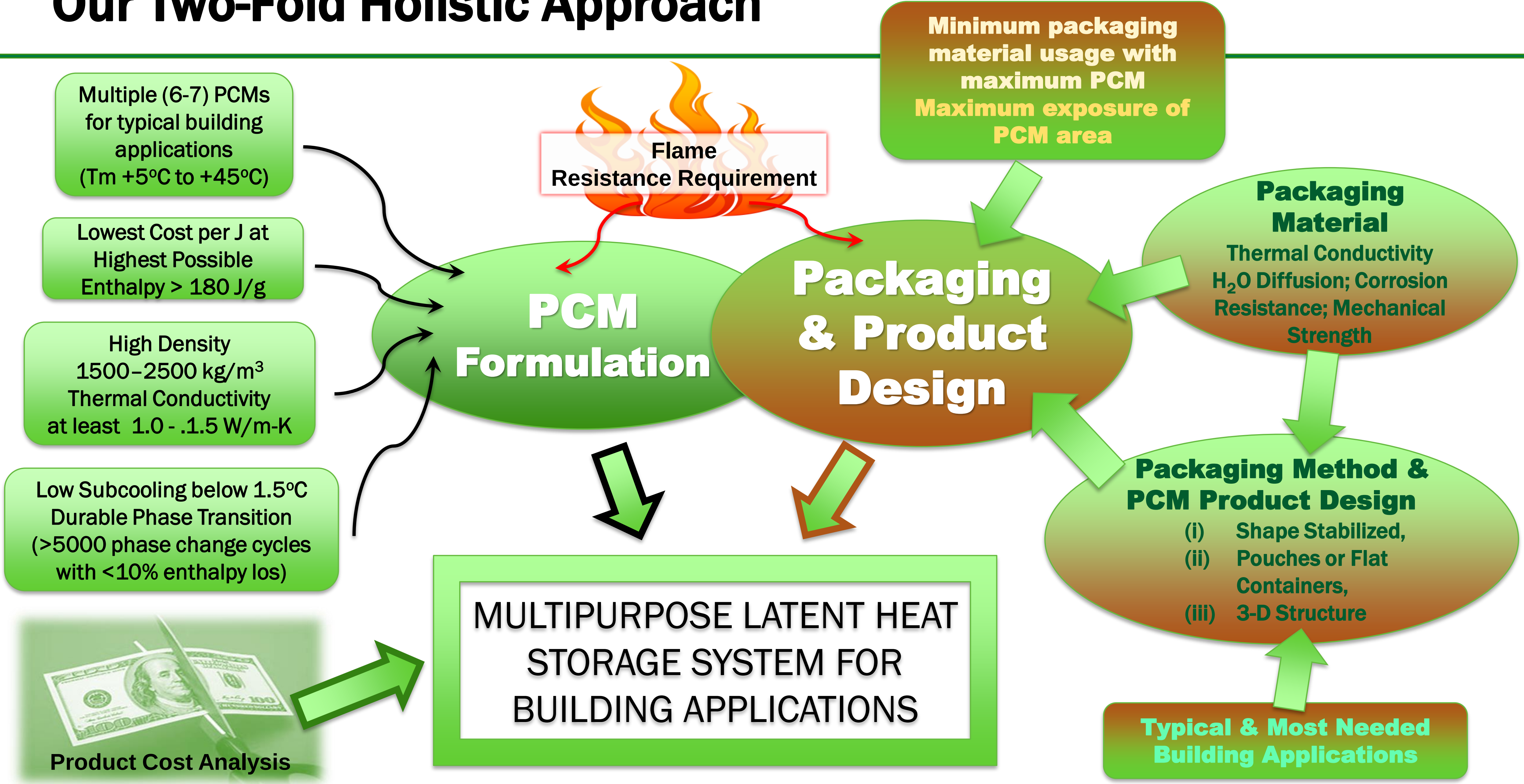
Successful implementation of a PCM system depends not only on properties of PCM. It primarily depends on performance and price of the entire system.

That is why our holistic approach includes a parallel development of both:

A family of low-cost PCM formulations with operational temperatures matching conditions in typical building applications

Three inexpensive product designs warranting high performance, easy installation, and a usage in typical building applications

Our Two-Fold Holistic Approach



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

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 1.5°C Durable Phase Transition (>5000 phase change cycles with <10% enthalpy los)

Product Cost Analysis

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*

PCM Formulations' Goals:

1. **Lower cost and superior fire resistance**, comparing to the existing PCMs
2. 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)
3. Developed PCMs are applicable in variety of building applications in temperature range between **+5°C and +45°C** with possible temperature adjustments of (+/- 5°C - 10°C)

Product Design and PCM Packaging:

1. **Simplicity of design** and **low-cost fabrication**
2. **Compatibility with U.S. structural systems**
3. **Three PCM packaging forms** allowing multiple applications: (a) shape stabilized or plastic channel boards, (b) membranes with PCM containers, and (c) 3-D PCM pouches
4. **Increased thermal conductivity** of plastic packaging materials (1.0 - 2.5 W/m-K)
5. **Added functionalities:** (a) moisture and air barrier, (b) reflective insulation, and (c) stackable heat exchanger

Goals for Complete PCM Products:

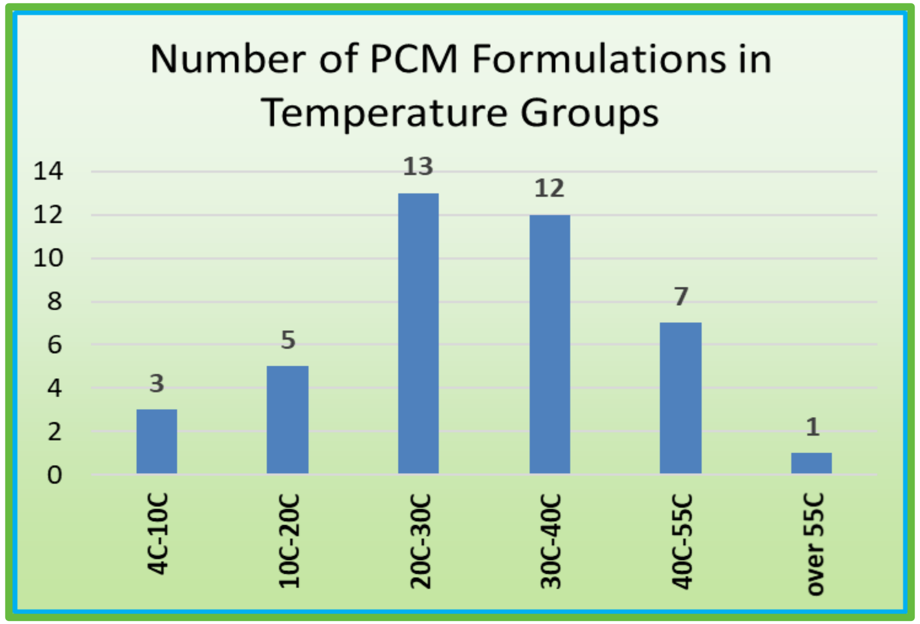
1. Superior performance comparing to the existing PCM applications: (a) **heat storage density of installed product**, (b) **fire resistance**, (c) **long term durability**, and (d) significant **cost advantage.**
2. Allow **implementations in variety of building applications** including: (a) building 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 and safety control in building integrated energy storage systems.

Approach/Progress

Development of 6 to 7 PCM formulations that are durable and operate efficiently in the building temperature range ($5^{o}C$–$45^{o}C$)

Part I

- **Review of pre-selected 41 known/published in literature salt hydrate-based PCM formulations**, with phase change temperature range between $+5^{o}C$ and $+55^{o}C$.
- Fabrication trials, performance testing, and down selection to 12 most promising formulations:
  - Successful component mixing, reversable phase changes, and small or no material separation
  - Enthalpy around or over 200 J/g (min. 180 J/g)
  - Max. component cost below $800 per ton
- **Development of “REAL” recipes for selected 12 formulation and enhancement of their fabrication methods.**
- Selection/optimization of formulation stabilizers and nucleators
  - Good material mixing and chemical stability
  - Achieving target melting temperatures
  - Repeatable congruent phase changes, and stable enthalpy over first 15 freezing-melting cycles
  - Reduction of subcooling to below $5^{o}C$
- Durability cycling testing (500 freezing-melting cycles), T-history and DSC testing at the beginning and at the end.



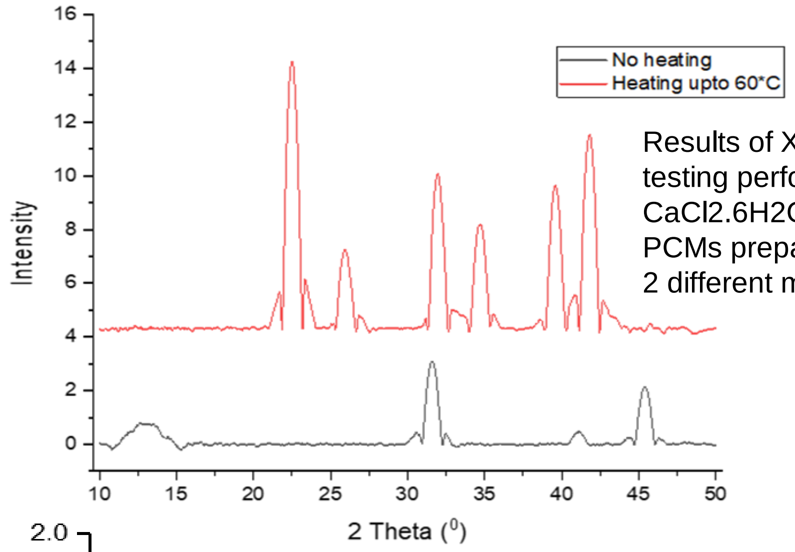
PCM compound, or PCM Formulation	Melt Temp C^{o}	Fuzion Heat kJ/kg
$NaOH + Na_2Cr_2O_7*2H_2O$+H20+ Kaolin Clay	5	250
$CaCl_2*6H_2O + CaBr_2*6H_2O$	9	188
K2HPO4-4H2O	18.5	231
$CaCl_2 + NH_4NO_3 + SrCl_2*6H_2O + KBr + H_2O$	18	220
$CaCl_2. + KNO_3 + SrCl_2*6H_2O + KBr + H_2O$	22	219
$CaCl_2*2H_2O.\ MgCl_2*6H_2O.\ KCl\ \ SrCl_2*6H_2O.\ Na_2WO_4*2H_2O. H_2O$	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

Approach/Progress

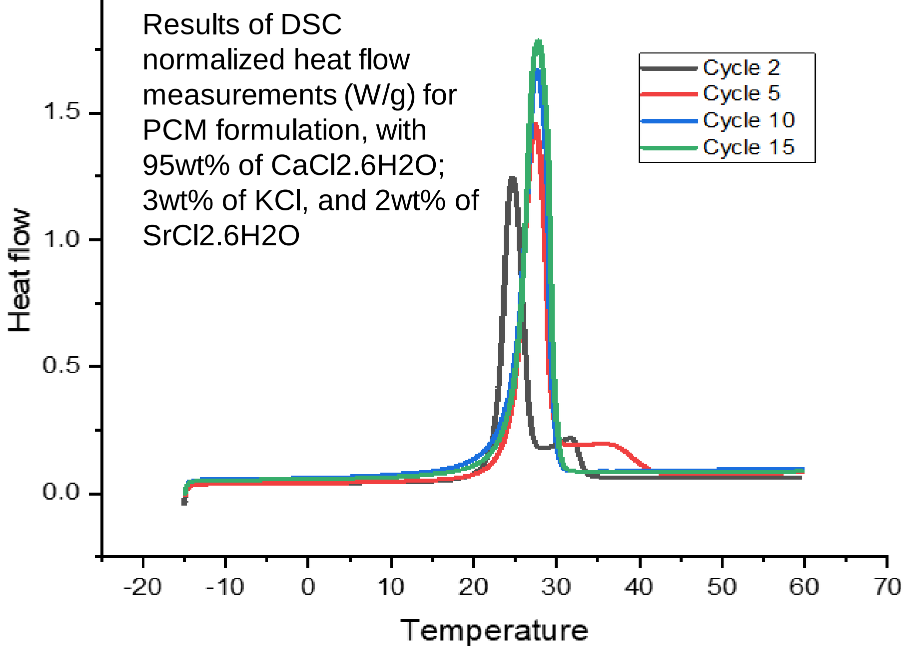
Development of 6 to 7 PCM formulations that are durable and operate efficiently in the building temperature range (5^{o}C–45^{o}C)

Part II

- Further optimization of recipes for **12 selected formulations**, durability cycling testing (1-15 freezing-melting cycles and 500 cycles), XRD analysis of mixing efficiency and crystallization, T-history and DSC testing at the beginning and at the end.
  - No development of lower hydration number components
  - Less than 10% of enthalpy loss over 500 cycles
  - Reduction of subcooling to below 2^{o}C (completed for 2 PCMs)
- Fabrication trials, performance testing, and down selection to **6 best performing groups of formulations**:
  - Calcium chloride dihydrate (CaCl2.2H2O) based PCMs (18-22^{o}C; 172-193 J/g)
  - Calcium chloride hexahydrate CaCl2.6H2O, combined with CaCl2.6H2O, with NaCl and/or KCl, and SrCl2.6H2O (22-26^{o}C; 170-204 J/g)
  - Glauber's salt (Na2SO4.10H2O) (27-31^{o}C; 171-215 J/g)
  - Sodium hydrogen phosphate dodecahydrate (Na2HPO4.12H2O) mixed with Glauber's salt (Na2SO4.10H2O): (30-35^{o}C; 188-207 J/g)
  - Sodium hydrogen phosphate dodecahydrate (Na2HPO4.12H2O (33-35^{o}C; 189-222 J/g)
  - Sodium Acetate Trihydrate (NaCH3COO*3H2O) based PCMs. (42-54^{o}C; 190-220 J/g)



Results of XRD testing performed on CaCl2.6H2O based PCMs prepared with 2 different methods



Results of DSC normalized heat flow measurements (W/g) for PCM formulation, with 95wt% of CaCl2.6H2O; 3wt% of KCl, and 2wt% of SrCl2.6H2O

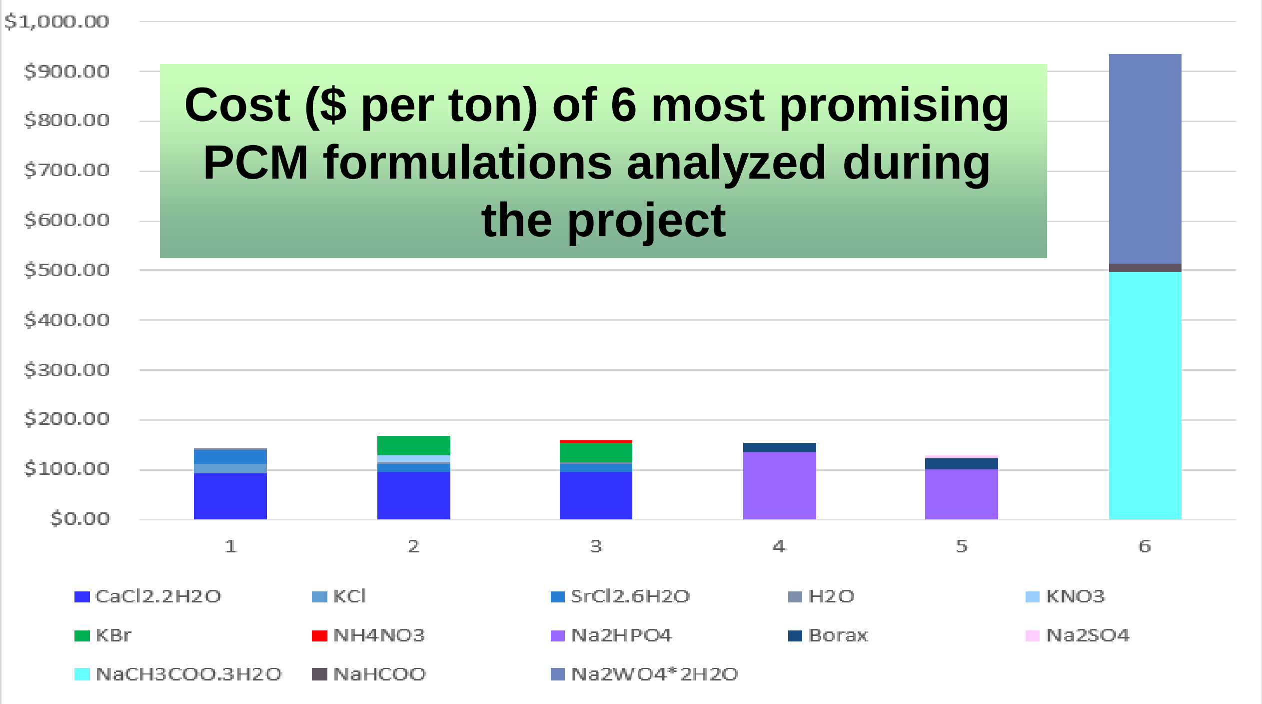
Approach/Progress

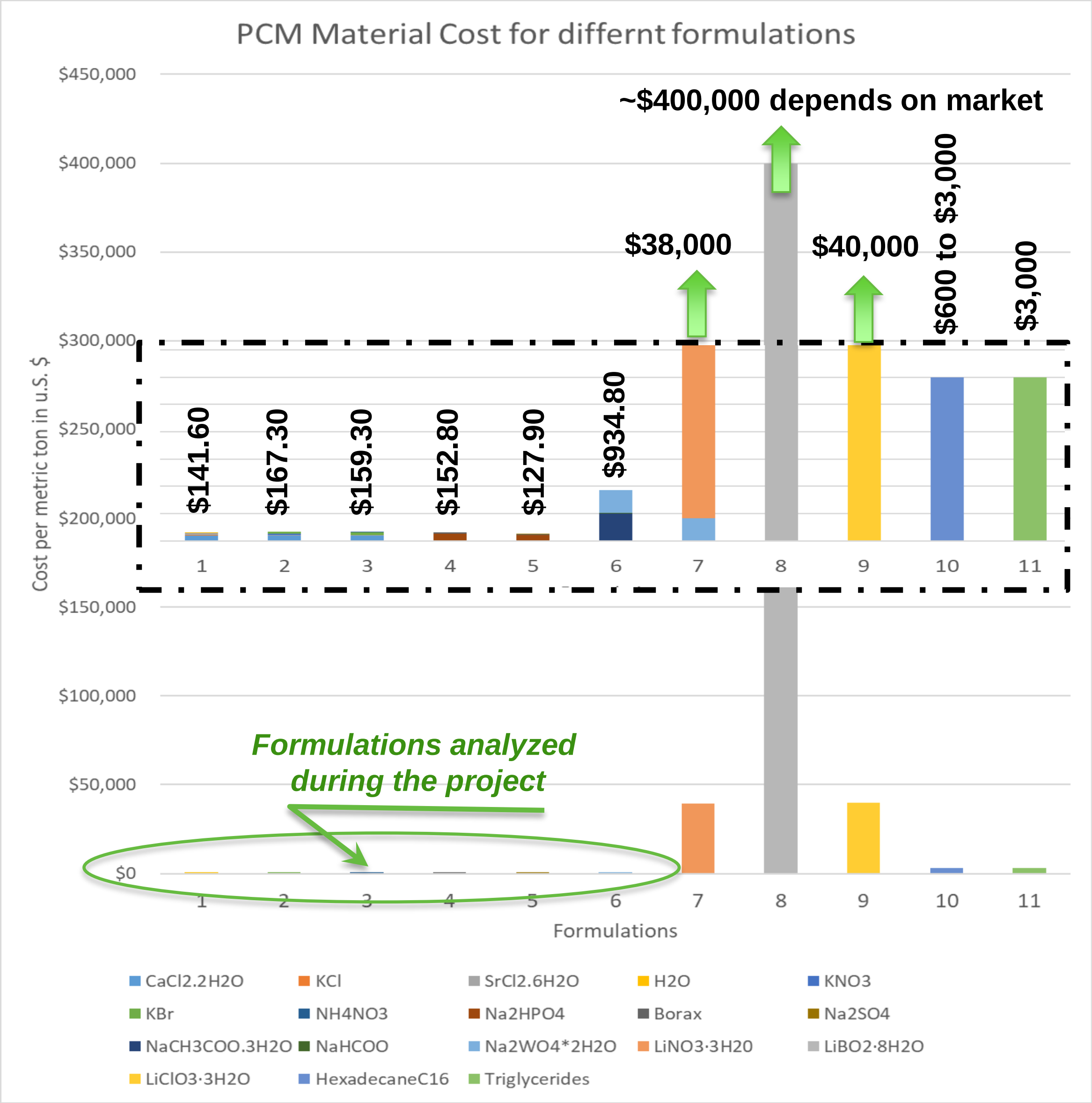
Development of 6 to 7 PCM formulations that are durable and operate efficiently in the building temperature range (5°C–45°C)

Part III

Cost Analysis:

- We evaluated most-promising PCM formulations.
- We also analyzed costs of several competitive PCMs
- Physical characteristics, chemical stability, phase change process reversibility, and overall costs were verified.
- Material prices were received from industrial partners and from international scientific sources.


Cost ($ per ton) of 6 most promising PCM formulations analyzed during the project



Approach/Progress

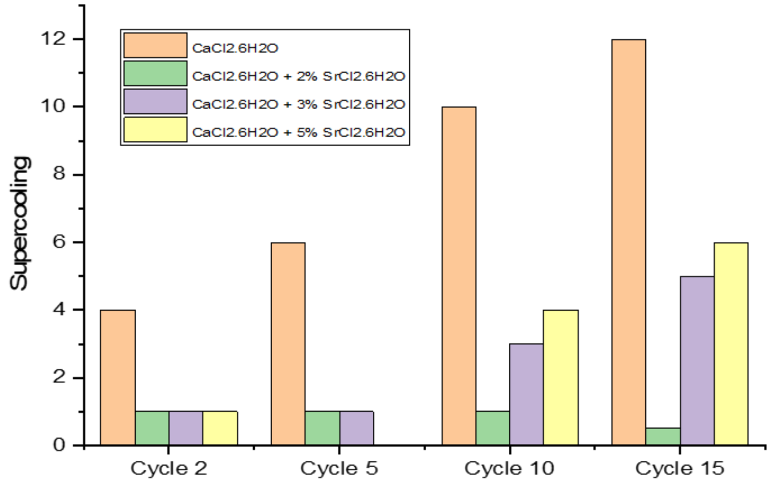
Development of 6 to 7 PCM formulations that are durable and operate efficiently in the building temperature range (5°C–45°C)

Part IV

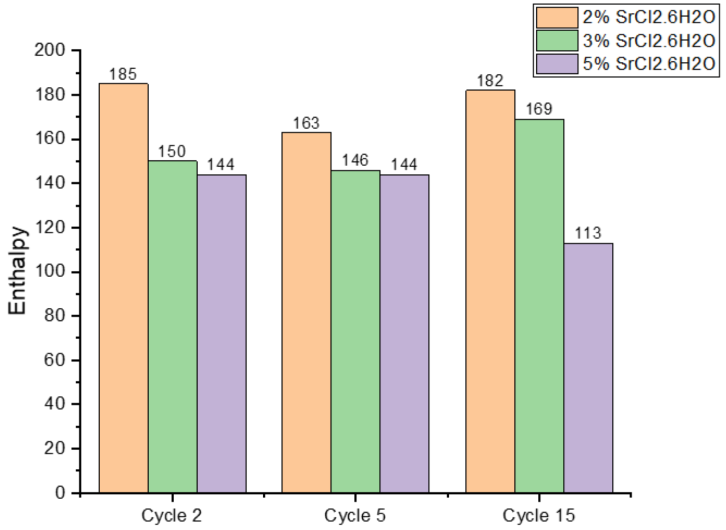
- Further reduction of subcooling to below 2°C for 6 **selected groups of formulations** (already very advanced for 2 groups)
  - Optimization of used amounts of stabilizers and nucleating agents to keep maximum level of enthalpy – see the charts on the right
  - Use of conductive powders (expanded graphite and carbon black) for PCM stabilization and for improvement of thermal conductivity
- Preparation of highly conductive, solid, shape-stabilized PCM “cakes” to be used as inserts in the Insolcorp PCM panels – target density of 1,800–2,200 kg/m^3, conductivity 2.0 - 3.5 W/m-K
  - Development of material recipes fabrication and procedures for solid PCM panels made with a use of conductive powders and carbon fibers
  - Material performance testing .
  - Material fabrication and panel assembly trials

PCM Development Work Tasks Planned for Y2 and Y3

- Continuation of durability cycling testing (1-15 freezing-melting cycles, 500 cycles, and 1000 cycles for selected PCMs)
- Fabrication trials for 6 – 7 developed and tested PCM formulations
- Fabrication of 2 types of PCMs for panels needed for the Y3 field testing and lab long-term durability testing



Reduction of supercooling and optimization of the PCM enthalpy and amount of nucleator, shown on the case of CaCl2.6H2O based PCMs prepared with SrCl2.6H2O.

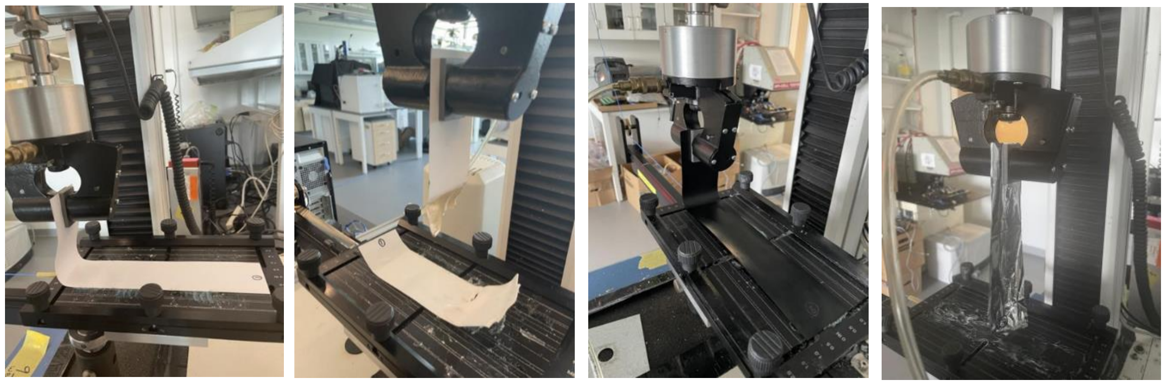


Approach/Progress

3 Product Designs and Development of PCM Packaging
#1a: PCM Extruded Channel Board

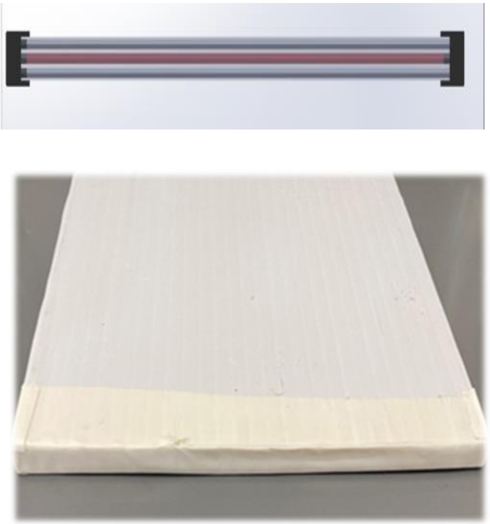
Part V

- Review of commercially available products and published in literature PCM product types, as well as encapsulation, and packaging methods
- Selection of three PCM packaging types for project work:
  - **#1.** **PCM Board Products:** (a) extruded plastic channel panels filled with PCM, and (b **solid shape stabilized PCM boards**
  - **#2.** **Plastic membranes** or panels containing arrays of PCM containers
  - **#3.** **3-D plastic panels** containing arrays of PCM pouches
- Analysis of available packaging materials (plastic membranes, thin sheets and extruded profiles) and selection of fabrication and panel sealing methods
  - Mechanical strength testing (membranes and adhesives)
  - Oxygen and H_2O transmission rates testing
  - Thermal conductivity analysis
- **Panel sealing testing** - extruded plastic channel board
- Fabrication trials with **plastics of enhanced conductivity**
- Initial fabrication of PCM board using extruded plastic channel board



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.

Filling the channel board with inorganic PCM



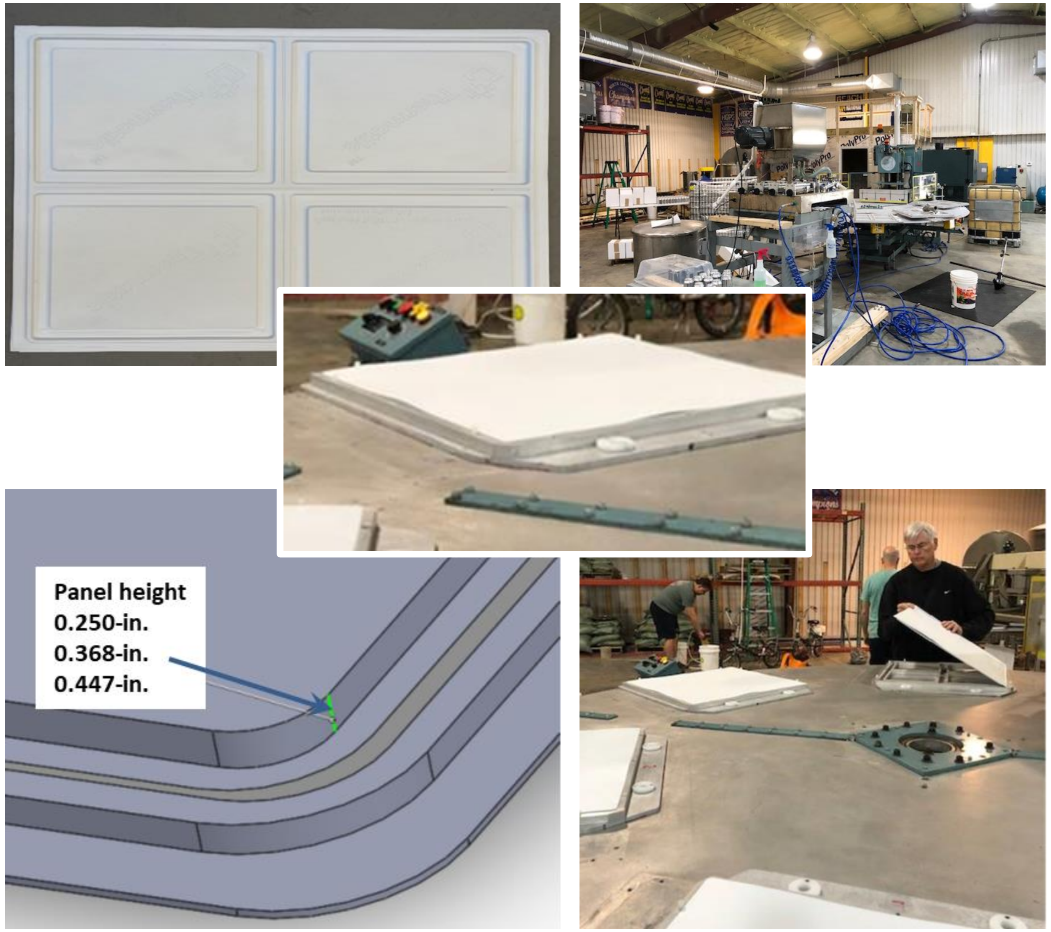
Sealed plastic channel board with inorganic PCM

Approach/Progress

3 Product Designs and Development of PCM Packaging #2: Plastic Panel with PCM Containers

Part VI

- **Design modifications of plastic panel caring PCM.**
- 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
- During Y1, we developed several **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 requirement of volumetric energy density > 100 kWh/m^3.
- The following panel modifications were made:
  - about 5%-10% increase of the PCM load area and the thickness
  - enlarging the PCM containing space by about 30% to over 60%.
  - adding additional support reinforcing ribs, and
  - adding predrilled holes for easy nail/screw installation, reducing potential for a damage
- We anticipate **only < 5% of extra packaging material cost**.
- This design was already consulted and priced by the tooling fabricating company. All necessary tooling has been already ordered and will be fabricated during Q6 and Q7.



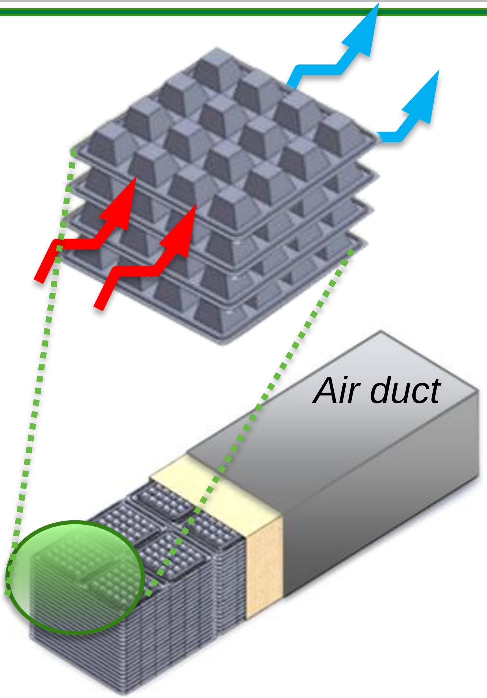
Existing PCM panel design (top left), panel fabrication line (center and right), panel height modifications bringing up to 60% increase in the aerial heat storage capability (bottom left).

Approach/Progress

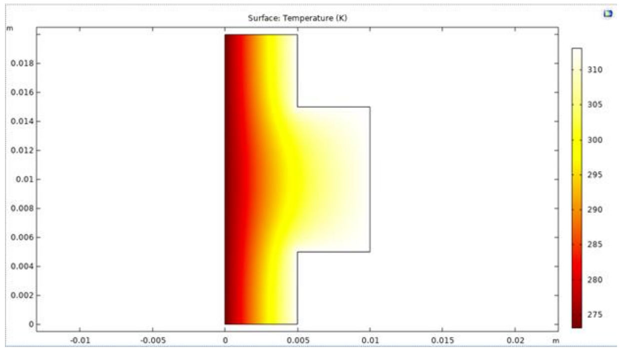
3 Product Designs and Development of PCM Packaging
#3: Plastic 3-D Arrays of PCM Pouches

Part VII

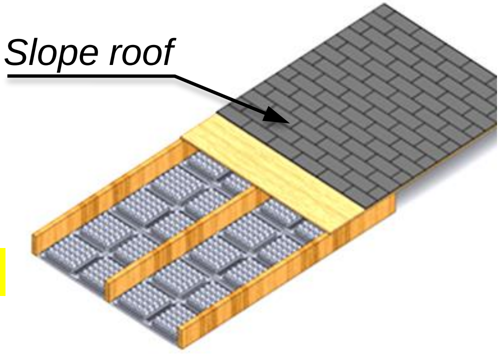
- Development of **3D Stackable PCM Panels**: Several 3D plastic panels designs are in development since Q2.
- These panels will contain one flat PVC sheet or low permeability barrier membrane, which will be laminated to the second thermoformed sheet containing 3D pouches/containers.
- They **can be either utilized as a single layer** in small air cavities, or, when **stacked together, used as dynamic heat exchangers containing significant heat storage capacity**
- Plastic manufacturing methods, and thermally conductive plastics, combined with thermoforming, will be utilized to laminate sheets with integrated pockets for PCM.
- Series of **heat transfer and CFD simulations** were performed to analyze the dimensions of the 3D panels. This included:
  - Thermal optimization of panel dimensions
  - Analysis of an impact of increased heat conduction in plastic skin - boundary heat flow (intensity of heat exchange) is increasing **2 times after the replacement of conventional plastics (0.2 mK/W) with conductive plastics (1.5 mK/W)** . Higher conductivity increase is not that effective (**from 1.5 mK/W to 15 mK/W → 2.4 times increase**)
  - CFD heat exchange and air flow and pressure distribution analysis

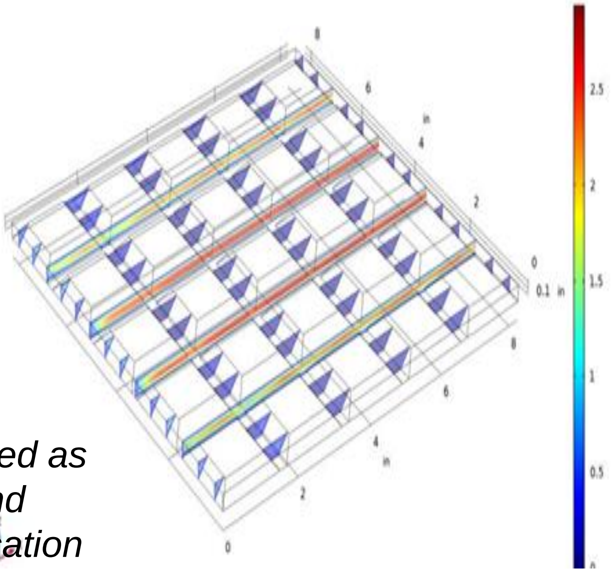


2-D thermal analysis of a single PCM pouch



CFD air flow analysis of a section of the panel





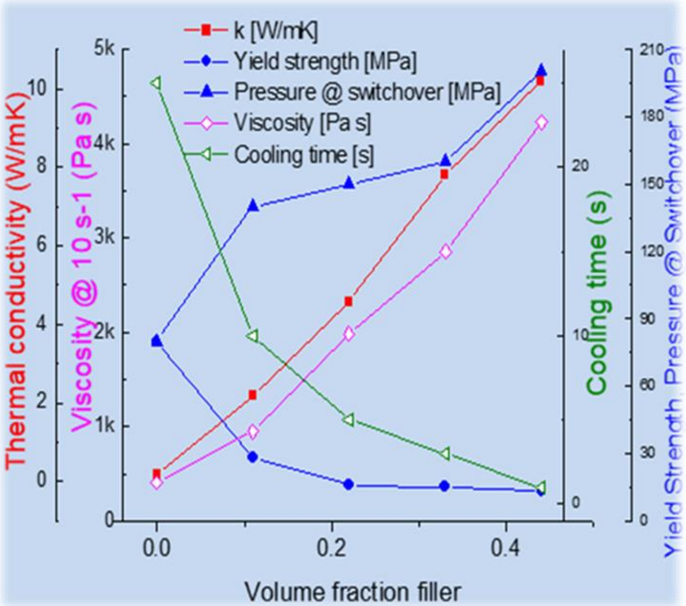
Stackable 3D PCM panels used as an air-duct heat exchanger and roofing thermal storage application

Approach/Progress

3 Product Designs and Development of PCM Packaging
Enhancement of Plastic Thermal Conductivity

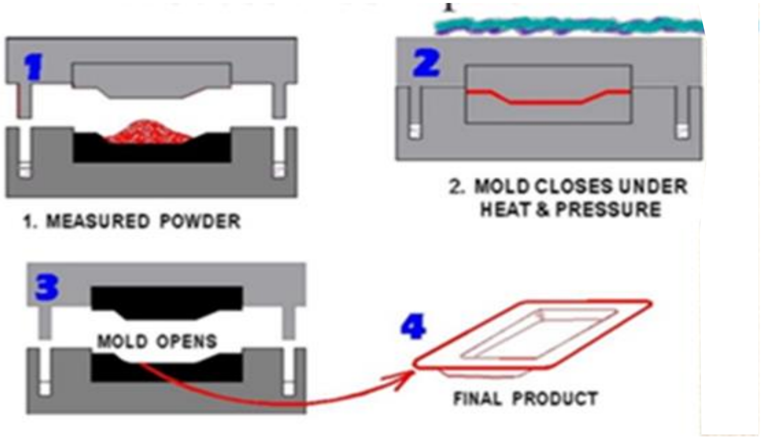
Part VIII

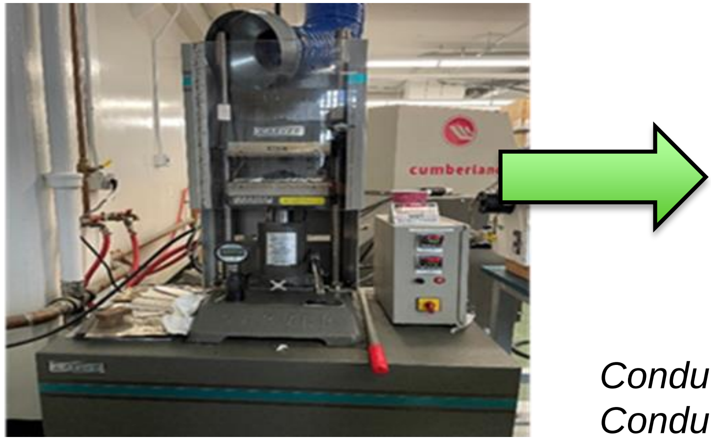
- During Q4, we reviewed several types of **thermally conductive plastics**
- Highly conductive plastics require even up to about 20%- 40%of load of powder additives. That is why they are relatively difficult to extrude (because of extra load of highly conductive additives which increase viscosity).
- Production of thin conductive films/sheets can be very difficult and very expensive. **Highly conductive plastics are at least an order of magnitude more expensive**, when compared to conventional plastic films
  - Conductive plastics: $25 to $90 per kg, depends on density and conductivity
  - Conventional plastic films: $1.20 - $1.60 per kg
  - High-end multilayer barrier films - $2.50 - $3.50 per kg – or even - $6-$7 per kg
- **Product design optimization will be performed to avoid the increase in overall cost of the PCM product**



Relation between the conductive filler load and thermal conductivity of plastics

Thermoplastic Elastomer (TPE)





Conductive TPE plastic Conductivity - 1.2 W/mK

Impact - *Energy sector Impact and Technology Advantages*

- PCMs can be used to **store heat or cold and regulate local temperatures in buildings, as well as in solar, shipping, food, pharma, and medical applications**.
- Publicly available results from numerical simulation and field demonstration studies have already demonstrated, that **PCMs can reduce whole-building space-conditioning energy consumption by 5%–35%,** as well as they significantly improve the internal building thermal comfort.
- Furthermore, according to the recent LBNL/NREL research data, there is **a potential for 38% to 61% reductions of enclosure generated loads for the switchable/tunable and thermally massive technologies utilizing PCMs.**
- We conservatively estimate the primary energy saving potential for PCM technologies (installed in building envelopes and interior building fabric) to be around 0.7–1.1 quad (=15% to 25% x [2.5 quad for residential + 2 quad for commercial sector]) - compared to equivalent lightweight applications.
- Growing rate of renewable energy applications, electrification of building systems, and e-mobility are significantly **increasing the demand** for high performance thermal storage systems (such as PCMs).
- **PCMs can mitigate building energy dynamics through the shaving and time-shifting of building thermal peak loads**. PCMs enable modification/control of dynamic energy response of whole buildings. This supports the **dynamic integration of buildings with the power grid, energy storage systems, and renewable energy resources**.

Impact

PCM technology will become accessible and easy applicable

Application platform, local governments, technical resources, labor force,

- **Our approach expands traditional thermal storage R&D beyond typical energy density optimization** to include a holistic PCM thermal storage and building system designs, and adding supplementary product functionalities
- **Variety of potential applications (use cases)** include dedicated thermal storage, equipment integrated thermal storage, building envelope integration, building integrated solar system, community scale seasonal storage, etc.…
- **This technology uses maximum available heat storage density of PCMs** with only minimum amounts of chemical additives and optimized packaging materials
- Technology is **fire resistant** and enables **widespread, inexpensive, and easy to install building thermal storage applications**
- This approach is matching typical building structural characteristics (dimensions, installation methods, etc…).
- **Our approach allows precise determination of the system's operational temperature, based on specific needs/requirements for particular application.**
- This work develops an **integrated heat storage platform of building systems/envelope design**, which includes materials science, measurement science, and integration science for thermal storage R&D:
  - **Technical:** Thermal energy storage and control materials optimized for integration at the building and community scale.
  - **University Scale Competencies:** Capabilities accessible to the private sector, and local Government (MassCEC, NYSERDA), DoD, academia, and national labs for discovery, integration, and characterization of next generation thermal energy control and storage materials.
  - **Workforce Development:** Partnerships with InsolCorp, 3M, Office of Navy Research, North American PCM Manufacture Association, and industry partners collaborating through the Project Industry Advisory Team enable a next generation of multi-discipline thermal storage engineers, building scientists, and building system designers.

Stakeholder Engagement

- This project is almost in the **mid stage** now. Current preparation of one **patent application.** One **research paper** has been already published, with one or two extra journal research papers are on the way.
- UML **Ph.D. and graduate students** are involved. Four **full time faculty** with extensive range of expertise, from chemistry, thermal sciences, plastics engineering, building technologies, and building science.
- **Industrial companies** participating in the project are regularly informed about the progress of work and some of them actively participate in the project related R&D. Also, major, project findings have been already discussed individually with the members of the project **Industrial Advisory Team**.
- Most of project theoretical assumptions and lab **developments will be demonstrated and field validated** later in the project (Y2 and Y3), with external stakeholders to ensure that we are on the right track
- At the end of this project, **we plan to apply for BTO Phase II, SBIR and/or STTR funding for further development of the 3D panel design and fabrication of necessary** tooling – **which will support the product commercialization.**
- We also anticipate a beginning of **patenting/licensing negotiations leading to technology commercialization** – this will include selected technology components developed by the team.
- We plan to actively engage with **building professionals and the broader scientific community** both, through the building conferences (Buildings Envelops Conference, ACEEE, Advanced Building Skin, etc.), as well as through non-traditional buildings conferences like TechConnect and Materials Research Society.
- **Non-proprietary project results** will become publicly available for U.S. industry through presentations and meetings with members of the N. American PCM Manufacturers Association, and at the Professional Associations Meetings (including ASHRAE and ASTM), as well as for building designers and state government officials.

Remaining Project Work *- Y2 Work Plan – Main Tasks*

PCM Development

1. Complete the development and lab testing of 6-7 PCM formulations
    a) Chemistry work leading to stable, congruent phase changes with subcooling below 2 ^{o}C
    b) Complete short-term cycling testing 15 cycles and durability testing with 500 cycles
    c) Fabricate enough PCM for preparation of testing panels for the lab dynamic thermal testing

Panel Design and Development

2. Complete the design of modified plastic panels with PCM containers for InsolCorp
    a) Verify the tooling design sizing with InsolCorp and the tooling fabricator
    b) Order the tooling
3. Complete numerical design of the 3-D PCM panels
    1. Optimize the panels and pouch sizing using CFD analysis
    2. Optimize thermal conductivity of the enclosure materials
    3. Design tooling for fabrication

Fabrication and Testing

4. Develop technology for fabrication of solid, highly conductive panels made of expanded graphite, graphite fiber, and PCM – they will serve as inserts in modified InsolCorp panel design.
    a) Fabricate test panels
    b) Test these panels using dynamic heat low meter measurements
5. Fabricate extruded channel panels for Lab testing and for the test hut testing during Y3
6. Fabricate and test the new modified panels (InsolCorp) – add radiant barrier functionality
7. Complete the design of test panels for Y3 field and lab testing

Thank You

University of Massachusetts, Lowell and InsolCorp llC

Prof. Jan Kośny
Ph #: 978.934.1903.   Email: JAN_KOSNY at UML.EDU

REFERENCE SLIDES

Project Budget

Project Budget:

- Year 1 Actuals DOE = 275,134 Cost Share = 137,253
- Year 2 Actuals DOE = 102,525 Cost Share = 20,221
- Total Project to date DOE = 377,659 Cost Share = 157,474
- *These values are through 8/5/2021.*

Cost to Date: ~27%

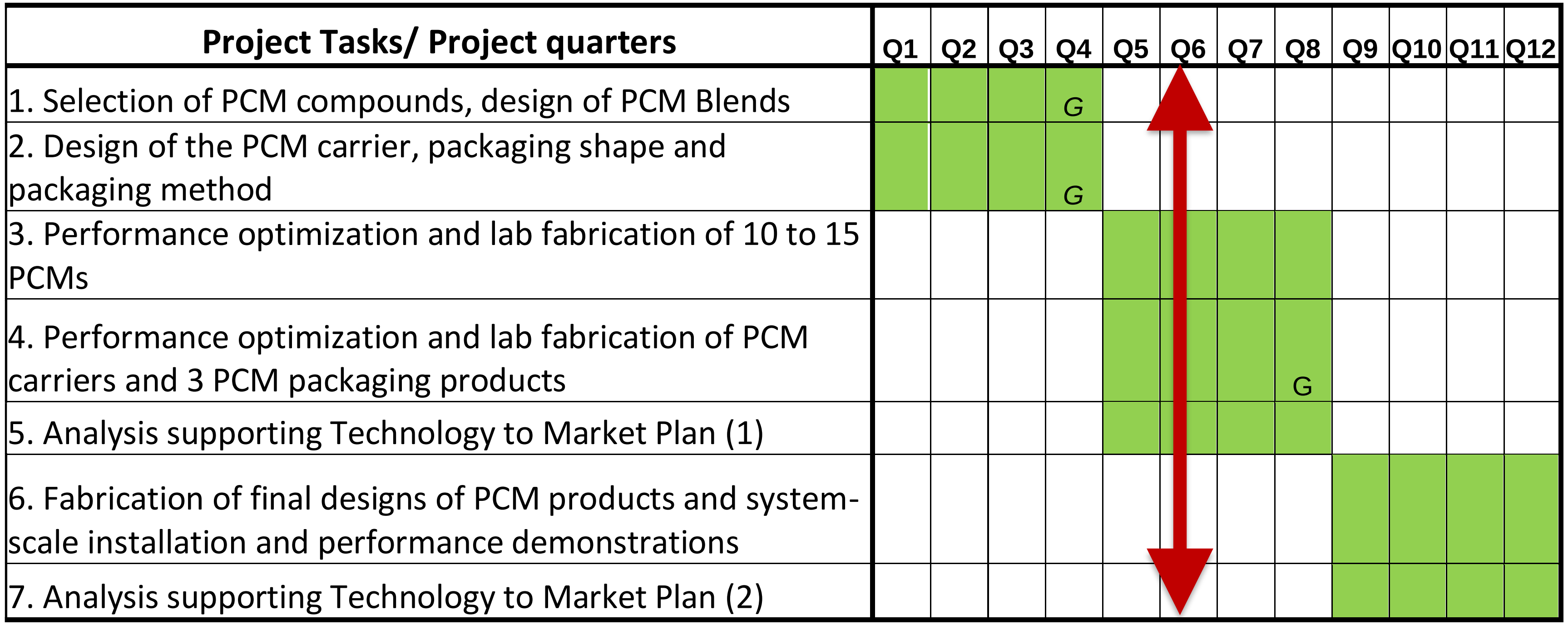
Additional Funding: NA

Budget History					
Apr. 01. 2020 – FY 2020 (past)		FY 2021 (current)		FY 2022 – March 31. 2023 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
404,388	170,833	498,243	196,406	491,491	191,655

Project Plan and Schedule

- **Project original initiation date**: Apr. 1st. 2020
- **Project planned completion date**: Mar. 31st. 2023
- **Explanation for slipped milestones and slips in schedule**: NA
- **Current and future work**:
  - Patent work and SBIR and STTR applications based on this project and
  - Current 2-year project on “Thermal Control for Batteries with use of PCM”

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)									🟩	🟩	🟩	🟩

Y1 Schedule and Milestones

- **<u>BUDGET PERIOD 1</u>:**

- **Task 1.0: Selection of PCM Compounds, Design of PCM Blends, Performance Analysis (M1-M12)**
- **<u>Subtask 1.1:</u> Review of PCMs and initial performance verification - (M1-M6).** The team will review the preselected, and additional compounds and formulations from Insolcorp and literature with phase transition between +5 ^{o}C and +45 ^{o}C. Physical characteristics, chemical stability, phase change process reversibility, and overall cost will be verified.
- ***<u>Milestone 1.1</u>:*** Selection of 25 to 30 of "most-promising" initial compounds/formulations **(M6)**
- **<u>Subtask 1.2:</u> Performance enhancement and lab fabrication trials of selected 25 to 30 "most-promising" PCM compounds/formulations - (M7-M12).** We will work on optimizing initial chemical formulations of PCMs with focus on the thermal performance and long-term durability. Our goal is to allow, at the end of the first year, a down-selection to 10 - 15 best-performing PCMs, we will test enthalpy, sub-cooling effect, durability (500 cycles), toxicity, corrosion potential, and flammability.
- ***<u>Milestone 1.2</u>:*** Selection of 10 to 15 best-performing PCM compounds/formulations **(M12)**

GO-NO-GO Month 12
PCM prototypes 2 have been successfully fabricated, achieving target specifications in the SOPO Prototype Target for Prototypes 2.

- **<u>BUDGET PERIOD 1 cont.</u>:**
- **Task 2.0: – Design of the PCM carrier, packaging shape, and packaging method, (M1-M12)**
- **<u>Subtask 2.1:</u> Design of the PCM carrier - (M1-M9).** To maximize the inner heat conduction and minimize the PCM's ability to separate we will either: a) mix PCM with highly-conductive and thickening powders (traditional approach), and/or b) use a small amount of a highly-conductive carrier material (max. 20% by weight) such as: thermally-conductive open cell foam, a nonwoven material made of conductive fibers, and extruded lightweight skeleton.
- ***<u>Milestone 2.1</u>:*** Selection/development and testing of three PCM carrier materials – **(M9)**
- **<u>Subtask 2.2:</u> Development of the PCM packaging barrier membrane - (M1-M12).** UML will work with 3M on selection/modification/development of the highly conductive barrier material. We will design and optimize the PCM package/encapsulation material of high thermal conductivity (1.0 - 10.0 W/mK), which will provide: a) physical encasement of PCM, b) highly-conductive PCM enclosure enhancing the intensity of heat exchange, and c) protect PCM from leaking out and losing the hydration water.
- ***<u>Milestone 2.2</u>:*** Development and testing of a prototype of highly-conductive barrier membrane with thermal conductivity around 5.0 W/mK – **(M12)**
- **<u>Subtask 2.3:</u> Functional, and shape design of three PCM products - (M4-M12).** The project team will design three geometric forms/designs of PCM products, allowing a large range of future building applications: 1) highly-conductive, flexible, cut-able, and nail-through, thin membrane, 2) flexible/foldable membrane with array of 6-8-in.wide PCM pouches, and 3) stackable PCM system allowing multilayer applications.
- ***<u>Milestone 2.3</u>:*** Designs of three packaging/geometrical options of PCM products – **(M12)**

Y2 Schedule and Milestones

- **<u>BUDGET PERIOD 2</u>:**
- **Task 3.0: – Performance optimization and lab fabrication trials of selected 10 to 15 PCM compounds/formulations, (M13-M24)**
- **<u>Subtask 3.0:</u> Laboratory performance testing and performance optimization of selected 10 to 15 PCM compounds/formulations - (M13-M24).** The team will perform a series of fabrication trials and laboratory tests, to allow a down-selection to top-performing, physically/chemically-stable, and durable 6-8 PCMs of energy storage density of 100 kWh/m^3. This work will include a long-term durability testing and fire cone calorimetry testing.
- ***<u>Milestone 3.1</u>:*** Selection of final 6-8 of "best-performing" compounds/formulations of energy storage density higher from 100 kWh/m^3 and completion of fabrication trials **(M21)**
- ***<u>Milestone 3.2</u>:*** Long-term durability testing for final 6-8 "best-performing" PCM formulations – at min. 90% of initial phase change performance after 500 phase change cycles **(M24)**
- **Task 4.0: – Performance optimization and lab fabrication trials of the PCM carrier materials and 3 types of PCM packaging products, (M13-M24)**
- **<u>Subtask 4.1:</u> Laboratory performance testing and performance optimization of selected PCM carrier materials - (M13-M21).** We will perform the fabrication trials of PCM carrier materials, as well as impregnation/mixing trials with PCMs. One, or two physical forms of the PCM carrier will be evaluated for their thermal performance.
- ***<u>Milestone 4.1</u>:*** One or two fully-developed PCM carriers, allowing assembly of highly-thermally-conductive and durable composites/mixtures with PCMs **(M21)**

- **<u>BUDGET PERIOD 2 cont.</u>:**
- **<u>Subtask 4.2:</u> Fabrication trials, performance optimization, and laboratory performance testing of earlier-developed PCM packaging forms/products - (M13-M24).** This subtask will include fabrication of barrier membranes, creation of pouches/containers, an addition of PCM, and/or PCM with carrier material, sealing of the pouches, etc. PCM products will be tested for: a) mechanical strength of pouches and product and seals, b) overall heat transfer characteristics of the PCM packaging products, c) optical surface characteristics - in the case of IR coatings, d) long-term material permeability, and e) a life-span of the pouch seals.
- ***<u>Milestone 4.2</u>:*** Successful fabrication and testing of three mechanically-robust, impermeable, and thermally conductive PCM packaging forms/products **(M24).**
- **Task 5.0: – Analysis Supporting Technology to Market Plan (1) (M13-M24)**
- **<u>Subtask 5.1:</u> Develop the Preliminary Cost-Performance Model (PCPM) – (M13-M15).** During this subtask, the team will develop a Preliminary Cost-Performance Model (PCPM). The model will identify the key cost drivers for the proposed universal/multi-use PCM technology.
- ***<u>Milestone 5.1</u>:*** Preliminary Cost-Performance Model includING a simple process flow diagram, indicating input and outputs, a full bill of materials, and identifies key cost drivers. **(M15)**
- **<u>Subtask 5.2:</u> Develop the Technology to Market Plan – (M13-M18).** The team will develop the initial Technology to Market (T2M) Plan, which will outline a 3-year roadmap for advancing the universal/multi-use PCM technology toward commercial viability and potential for impact. The plan will explore and evaluate market, manufacturing, intellectual property, and next-stage resource factors. The team will also initiate the relationship with relevant industry advisors.
- **<u>Milestone 5.2</u>:** The T2MP that outlines a roadmap for advancing BTO funded technology toward commercial viability and identifies key T2M factors for analysis. **(M18).**

Y2 Schedule and Milestones

- **BUDGET PERIOD 2 cont:**

- **Subtask 5.3: Manufacturing and Scalability Analysis - (M19-M24).** The project team will perform the Manufacturing and Scalability Risk Analysis (MSA) and plan to mitigate factors that may significantly affect production costs and scale up. Analysis will reflect different complementary perspectives offered by the engaged industrial advisors.
- ***Milestone 5.3***: Manufacturing and 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. **(M24).**
- **Subtask 5.4: Thermal performance analysis of specific PCM applications supporting the Technology to Market Plan - (M13-M24).** The project team will perform the literature review (of typically used PCM applications), combined with the system-scale thermal performance simulations of specific PCM applications, and numerical analysis of whole-building energy consumption and dynamic load shifting and shaving abilities analysis in U.S. buildings located in different climatic conditions. This data will support the payback time analysis.
- ***Milestone 5.3***: Report summarizing results of literature review and numerical performance analysis of PCM building applications **(M24).**

GO-NO-GO Month 24

- Fully-functional and durable prototype of the PCM carrier material, achieving target specifications in the Prototype Target Table for Prototypes 4.
- Successful fabrication of three fully-functional, mechanically-robust, impermeable, and thermally conductive PCM packaging forms/products, achieving target specifications in the Prototype Target Table for Prototypes 4.