Experimental and Numerical Energy Performance Analysis of PCM-Enhanced Building Envelope Products and Systems

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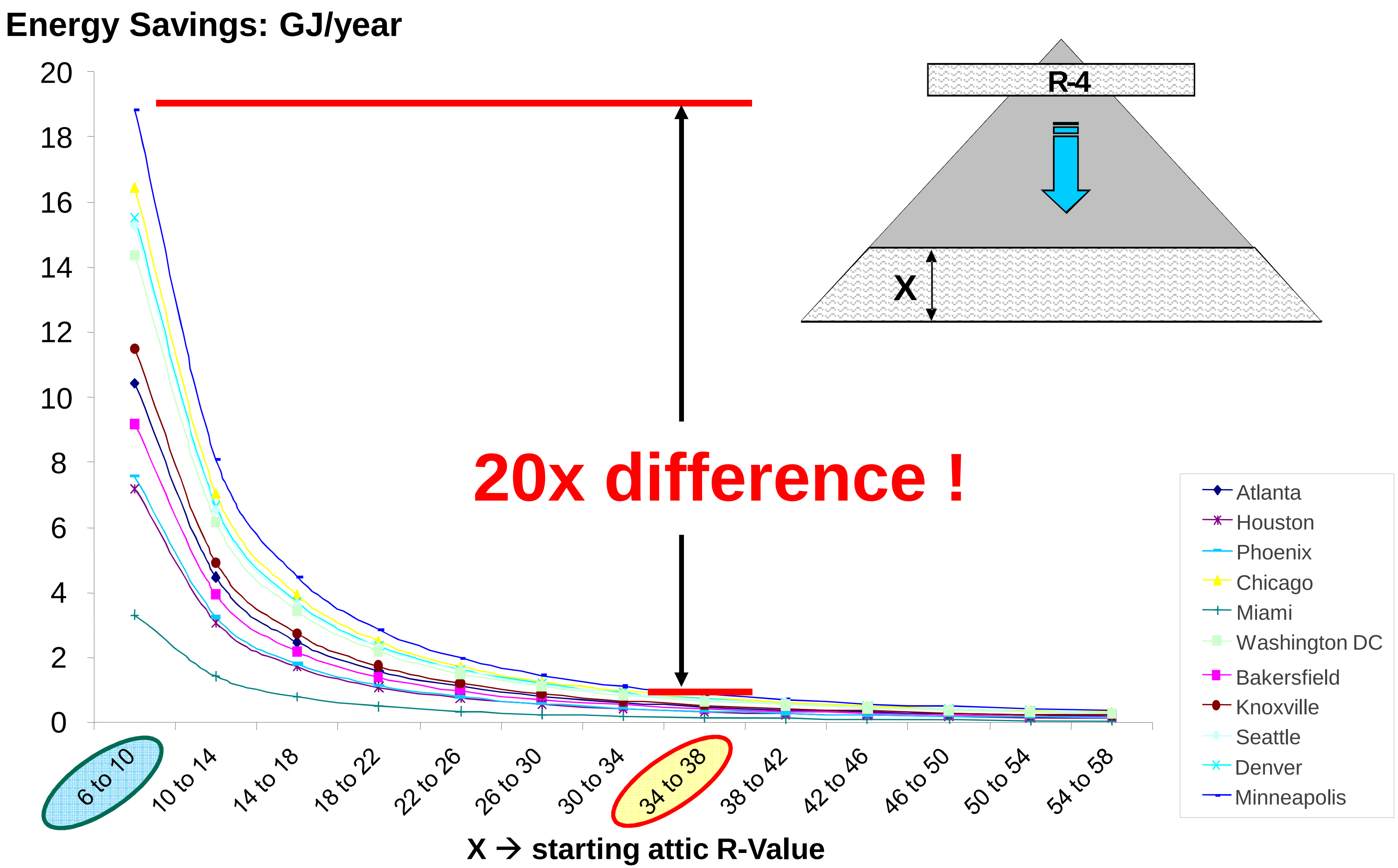
CESBP 2013
Tuesday, Sept. 10, 2013
Vienna, Austria

Agenda

- Introduction: A need for proper performance data for PCMs used in building applications – Major Motivation
- PCM Application Tactics
- Laboratory Testing of PCM Thermal Characteristics
- Challenges with Computer Simulations
- Whole building Energy Analysis of PCM Attic Insulation
- Conclusions

Major Motivation:
Performance Problems of Conventional Insulation

Insulation Effectiveness Drops Quickly with Initial Assembly R-Value



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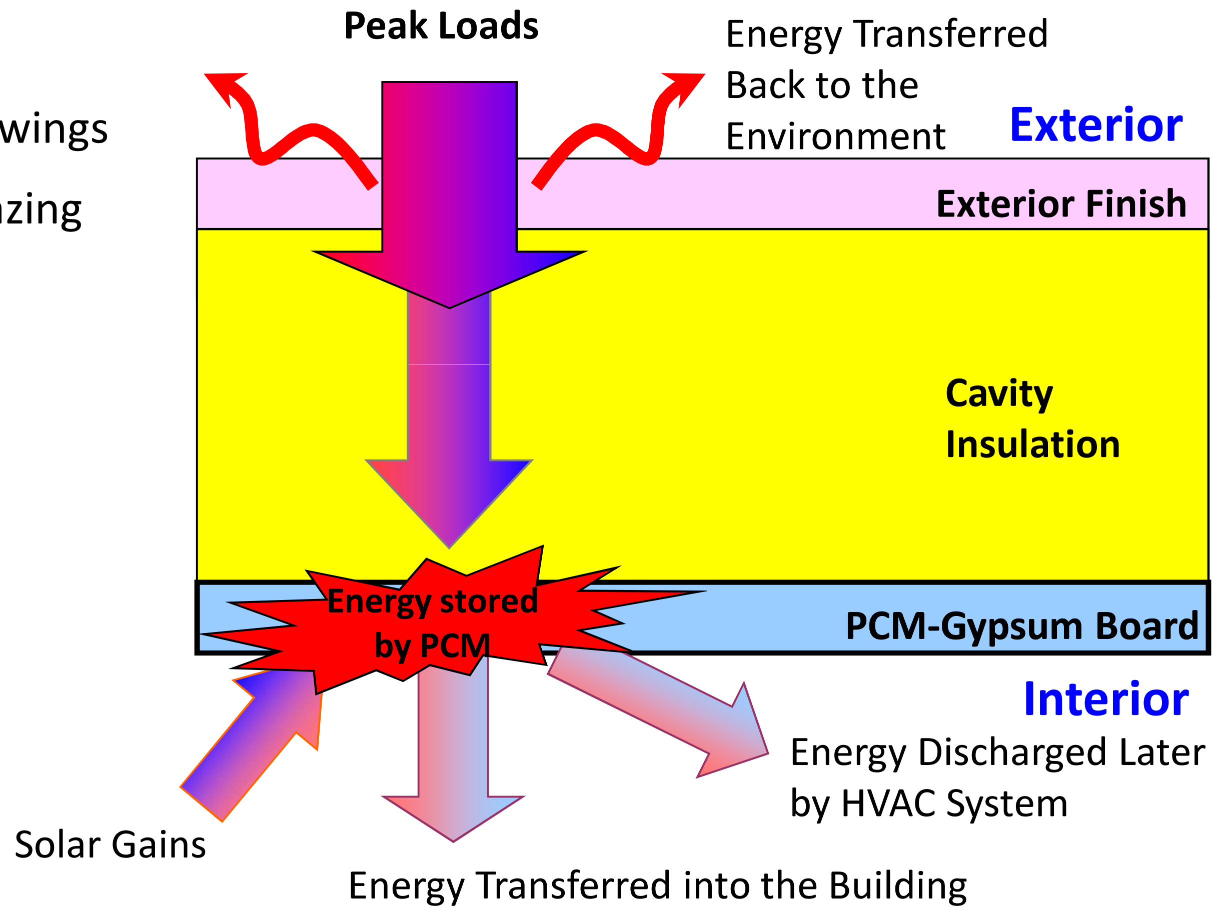
PCM Application Tactics:

Different PCM Configurations

European Approach – PCM Impregnated Gypsum Board

- PCM Charged by:
  - Interior temperature swings
  - Solar gains through glazing
- PCM Discharged by:
  - Building HVAC system

Distribution of Heating and Cooling Loads in Old PCM Applications



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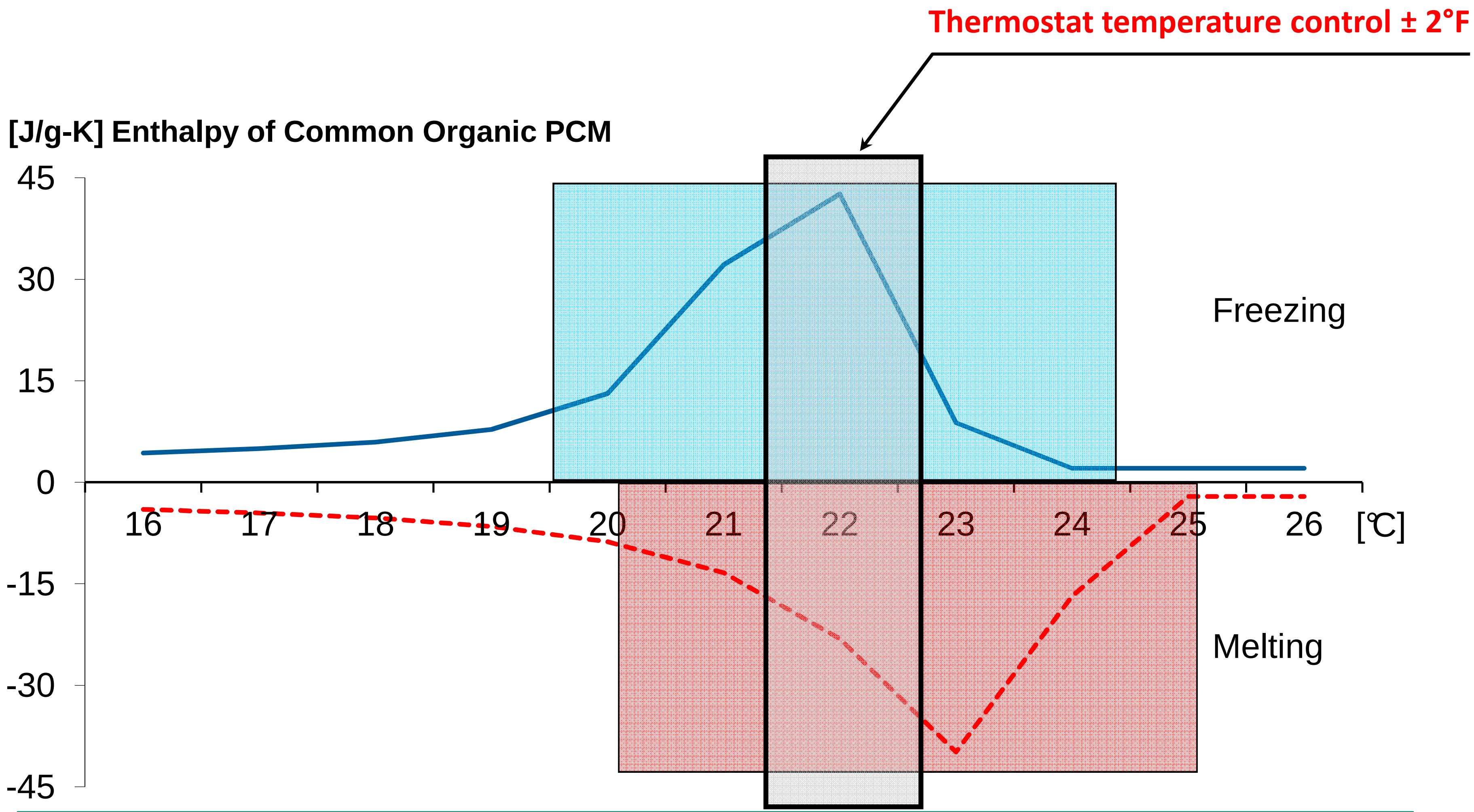
Problem with PCM Gypsum Board in Air Conditioned Buildings



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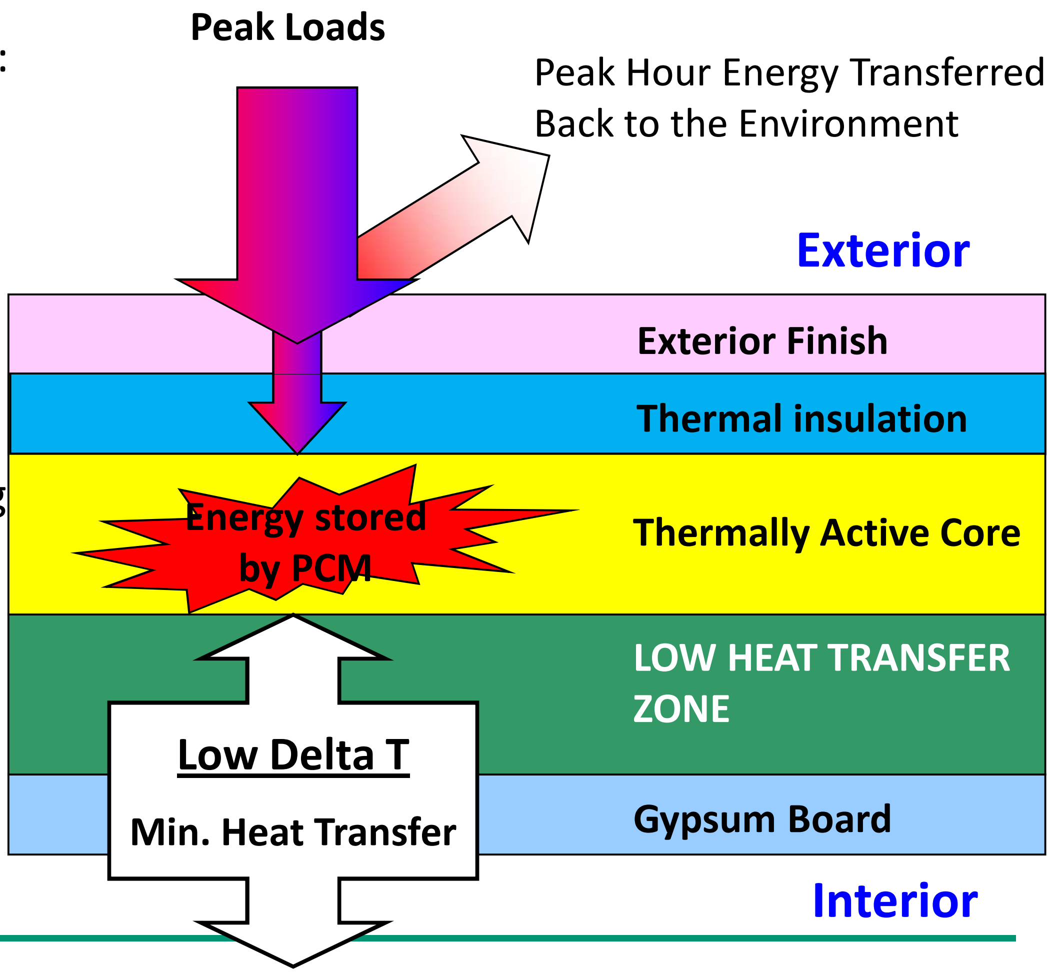
New Approach for PCM Installations in the U.S.

- PCM Charged and Discharged by:
  - Fluctuations in exterior temperature
  - Solar radiation

- PCM materials must be able to fully charge and discharge during 24-hour dynamic cycle.

Distribution of Heating and Cooling Loads in PCM-Enhanced Envelopes



Laboratory Testing of PCM:
Thermal Characteristics

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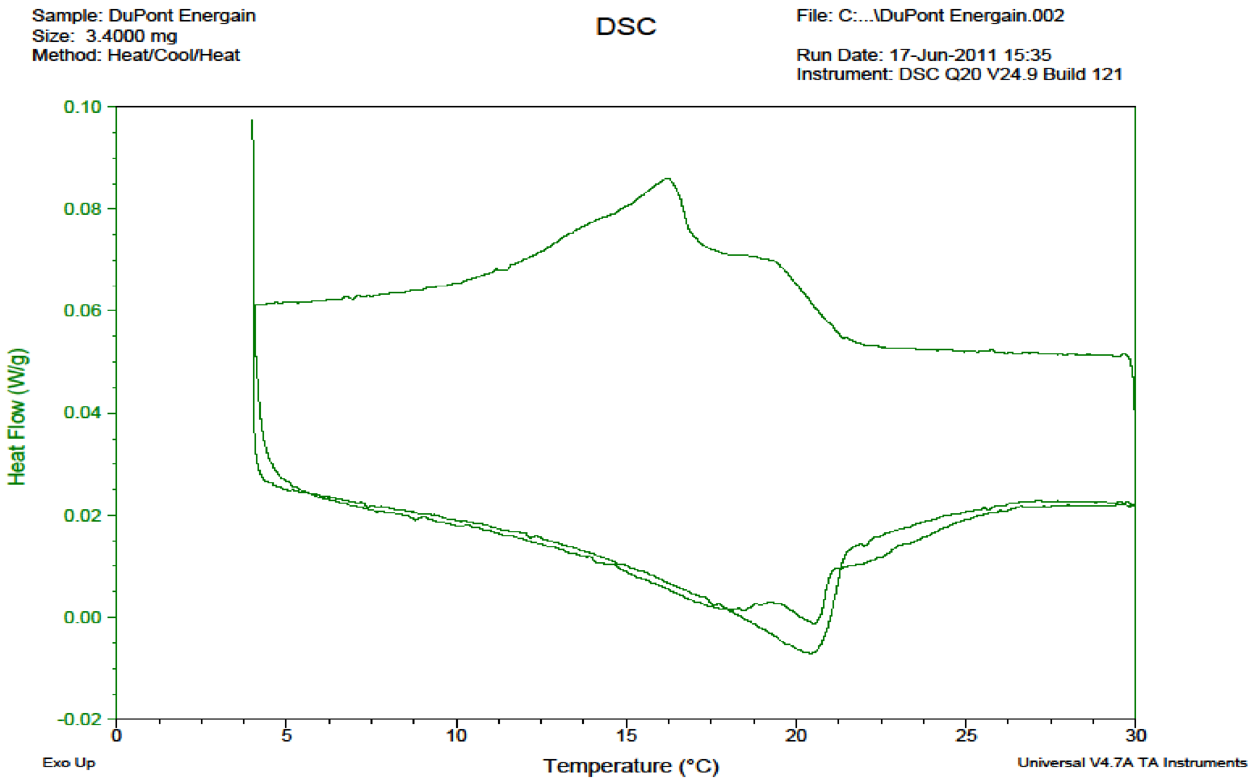
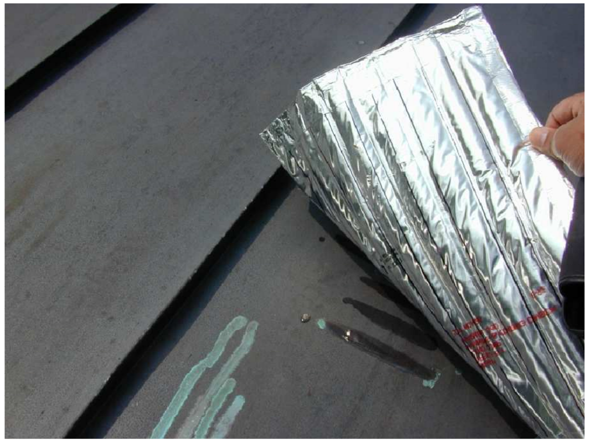
Numerous Dynamic Test Methods are Used Today in Analysis of Complex PCMs and PCM-enhanced Products

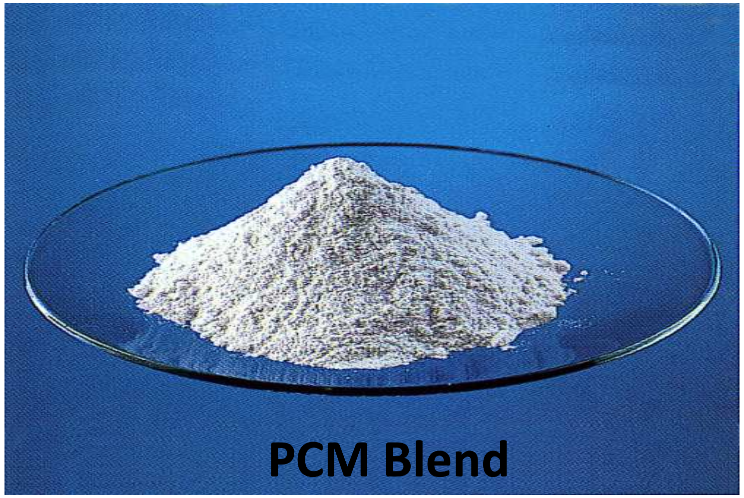
- DSC – only for uniform PCMs
- T-history method
- Dynamic Heat Flow Apparatus
  - Symmetrical Process
  - Non-symmetrical Process
- Dynamic Guarded Hot Plate Method (speculation so far)
- Dynamic Hot Box Method

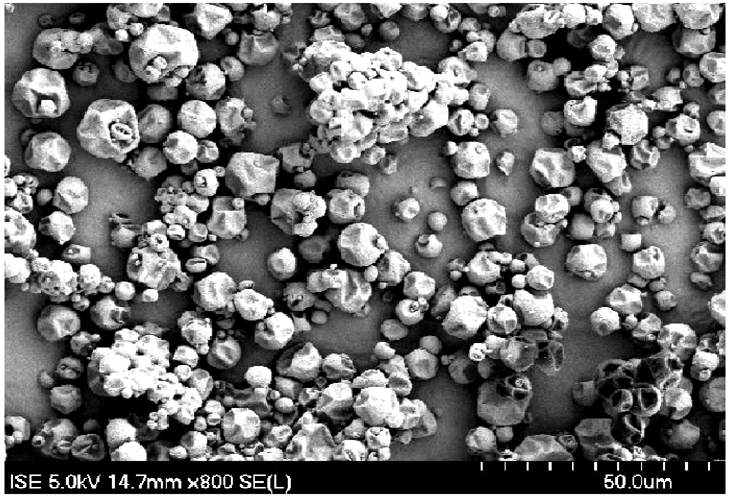
DSC Method is Most Commonly Used but Has Limitations



Large Selection of Non-Uniform PCMs Cannot be Tested by Differential Scanning Calorimeter (DSC)





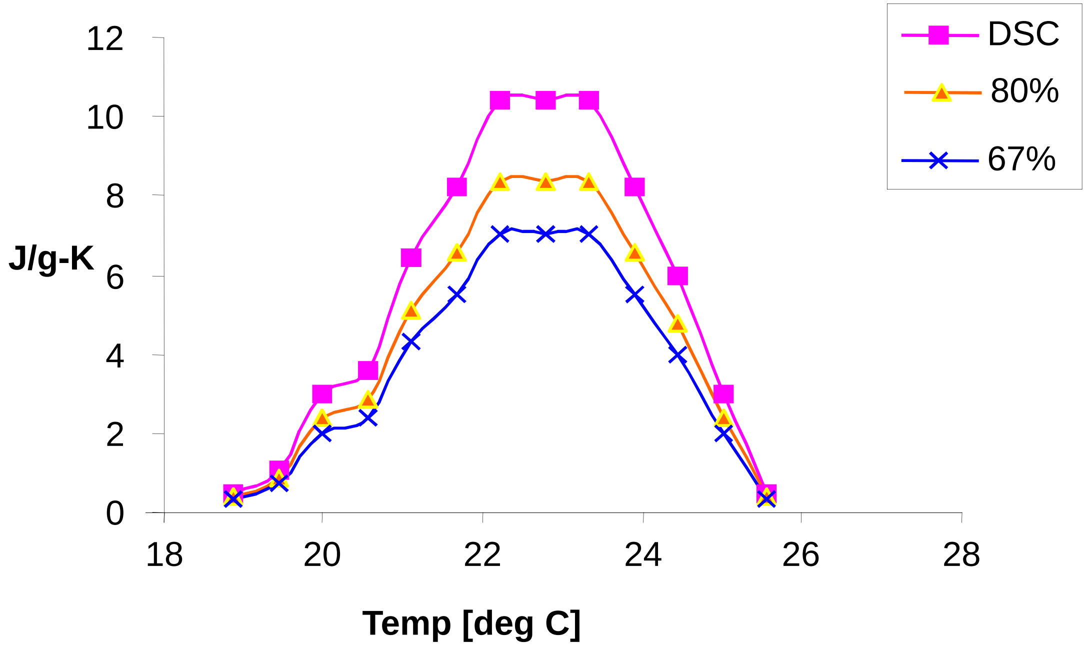


Major Thermal Analysis Problem for PCM Systems:

DSC data generated for pure (uniform) PCMs is often used in analysis of complex PCM products or PCM blends.

Need for Development of Enthalpy Charts for PCM-Enhanced Materials and Systems

- Initial DSC testing results for pure PCMs or PCM microcapsules can be misleading
- Additives to PCM-blends make a difference: Fire retardants, Adhesives, Non-functional PCM pellets



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Basic Heat Transfer Equations

The one-dimensional heat transport equation for such a case is as follows:

$$\frac{\partial}{\partial t}(\rho h) = \frac{\partial}{\partial x}\left[\lambda \frac{\partial T}{\partial x}\right]$$

ρ = density
λ = thermal conductivity
T = temperature
h = enthalpy per unit mass

Heat flux *q* is given by:

$$q(x,t) = -\lambda \frac{\partial T(x,t)}{\partial x}$$

Effective heat capacity is given by:

$$c_{eff}(T) = \frac{\partial h}{\partial T}$$

c_{eff} = effective heat capacity

For a blend of insulation and PCM, effective heat capacity may be expressed as:

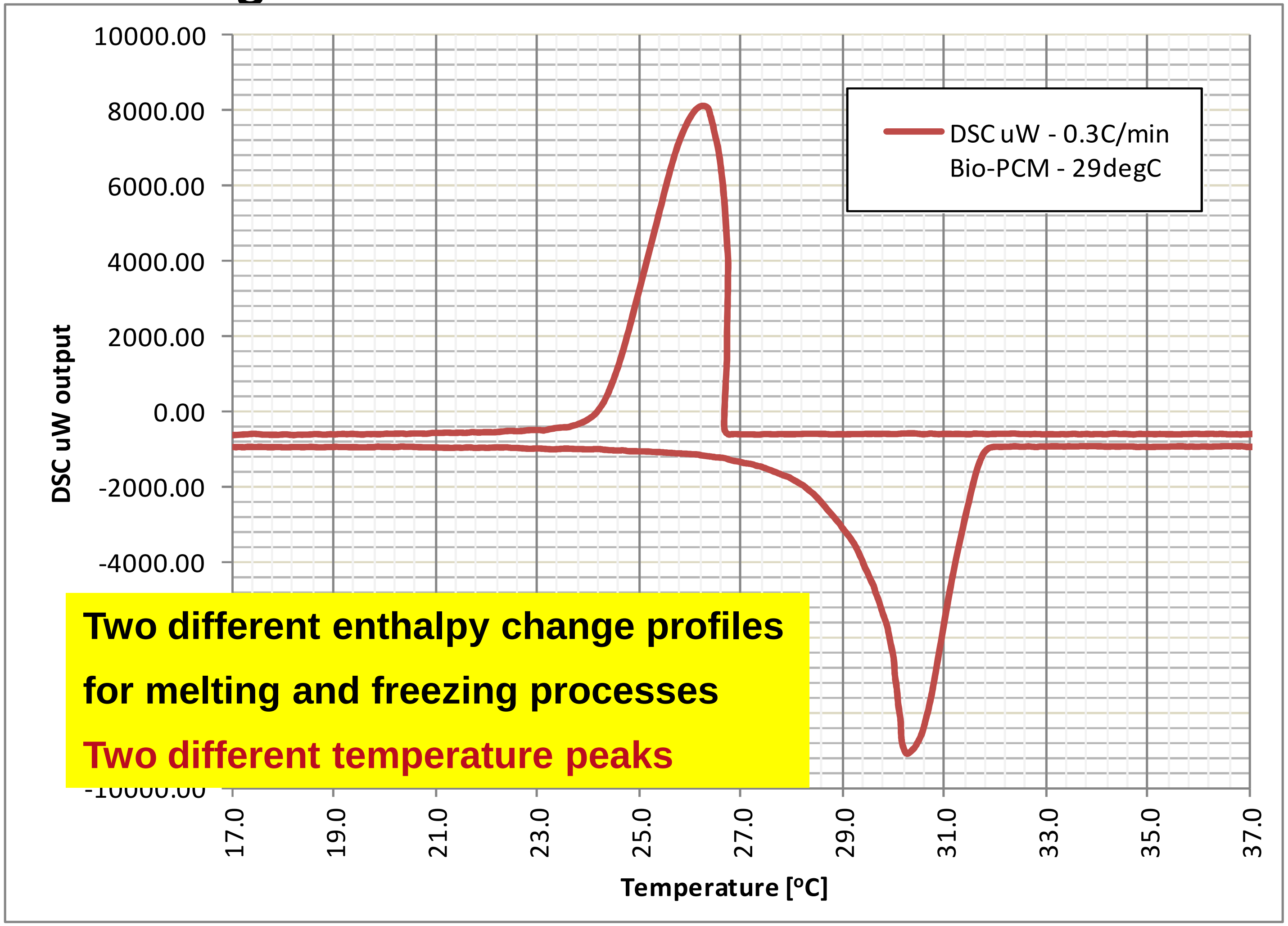
$$c_{eff} = (1-\alpha)c_{ins} + \alpha c_{effPCM}$$

α = percent of PCM

c_{ins} = heat capacity of pure insulation

c_{effPCM} = effective heat capacity of PCM

DSC Output for Bio-Based PCM. Melting and Freezing Cycles Show sub-cooling of 5°C



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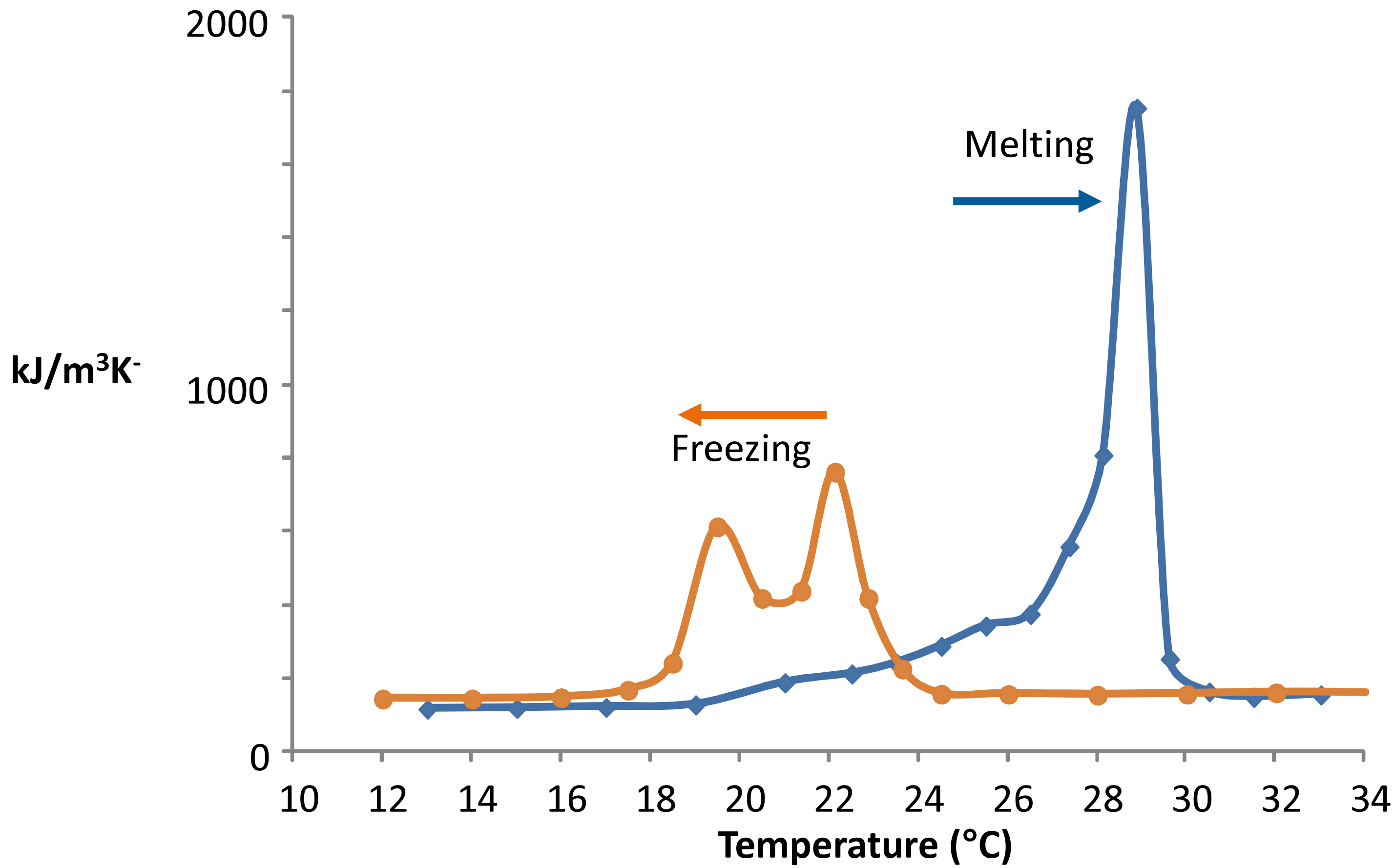
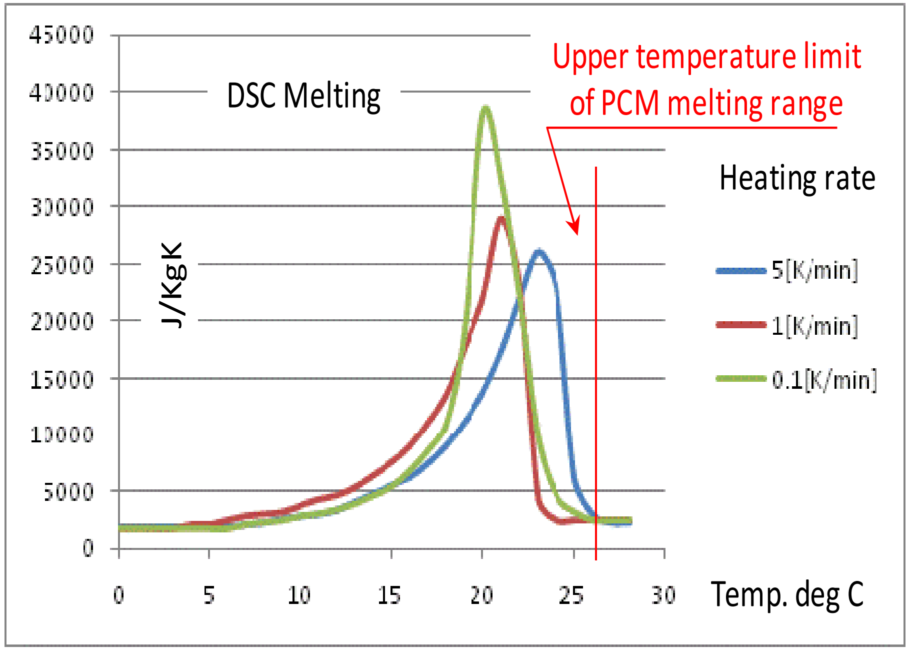
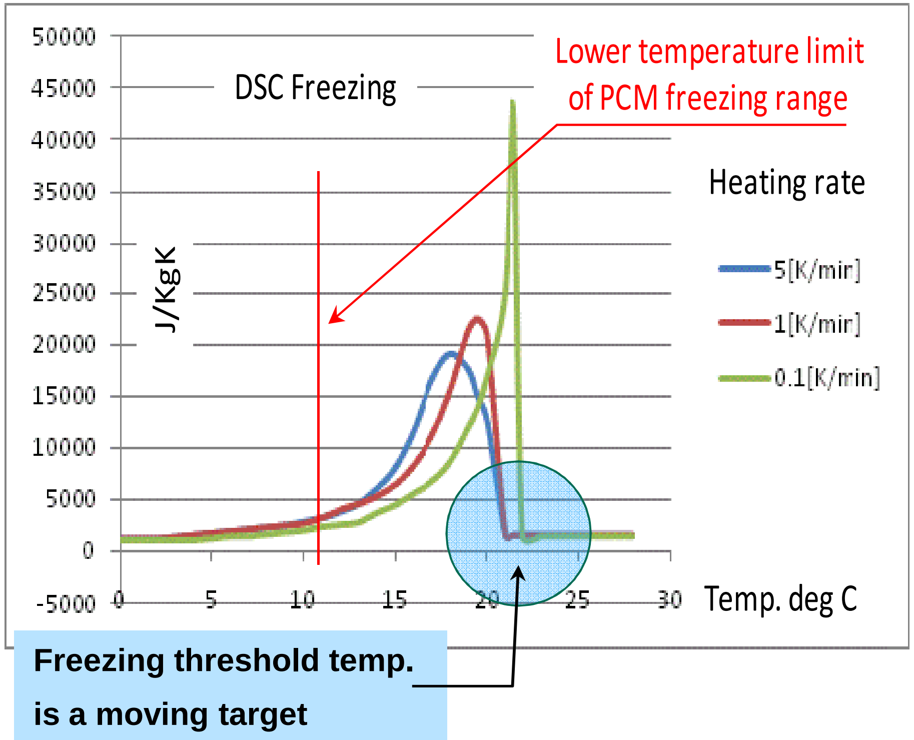
Volumetric Heat Capacity for Cellulose-PCM Insulation Sample using Bio-Based Micro-encapsulated PCMs



DSC Rate of Temperature Change Affects Enthalpy Profiles

Due to lack of clear eng. guidelines or code regulations, incorrect DSC data is very often used in whole building computer simulations





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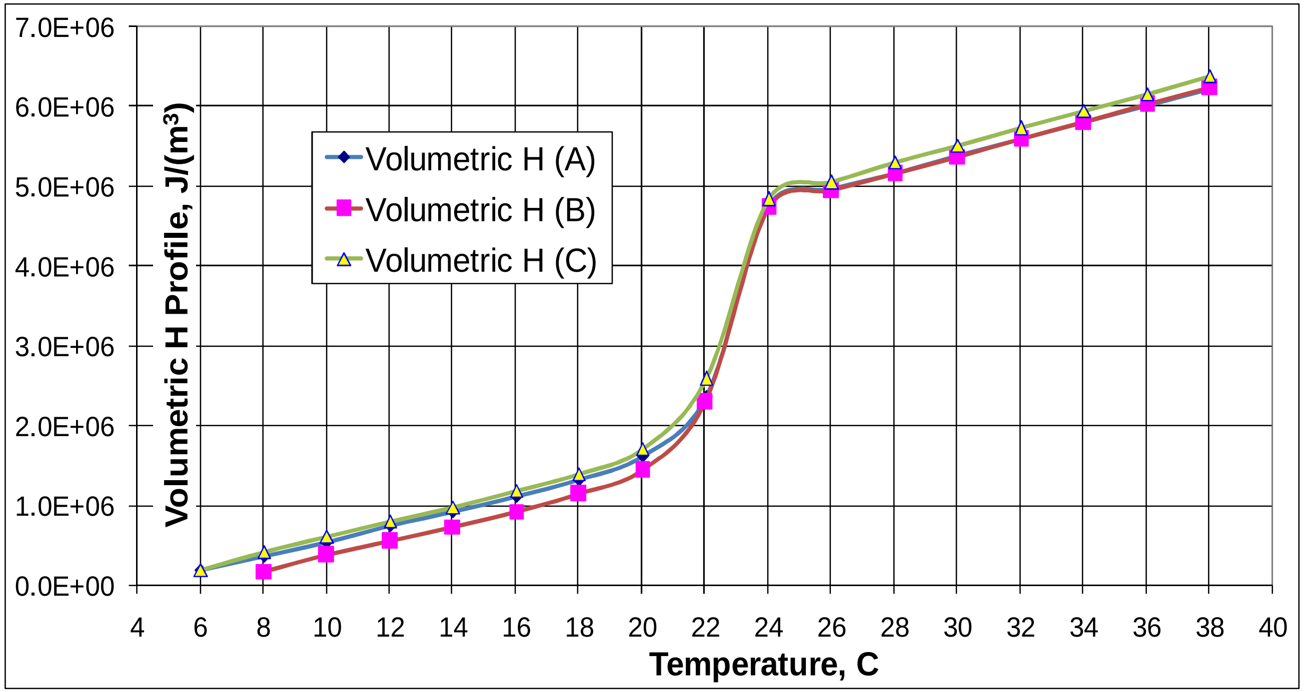
A Standard Heat Flow Meter Apparatus (HFMA) Can Be Modified To Perform Dynamic Testing of PCM-enhanced Products

Normally the HFMAs are used to measure the apparent thermal conductivity of materials as specified in ASTM C518.



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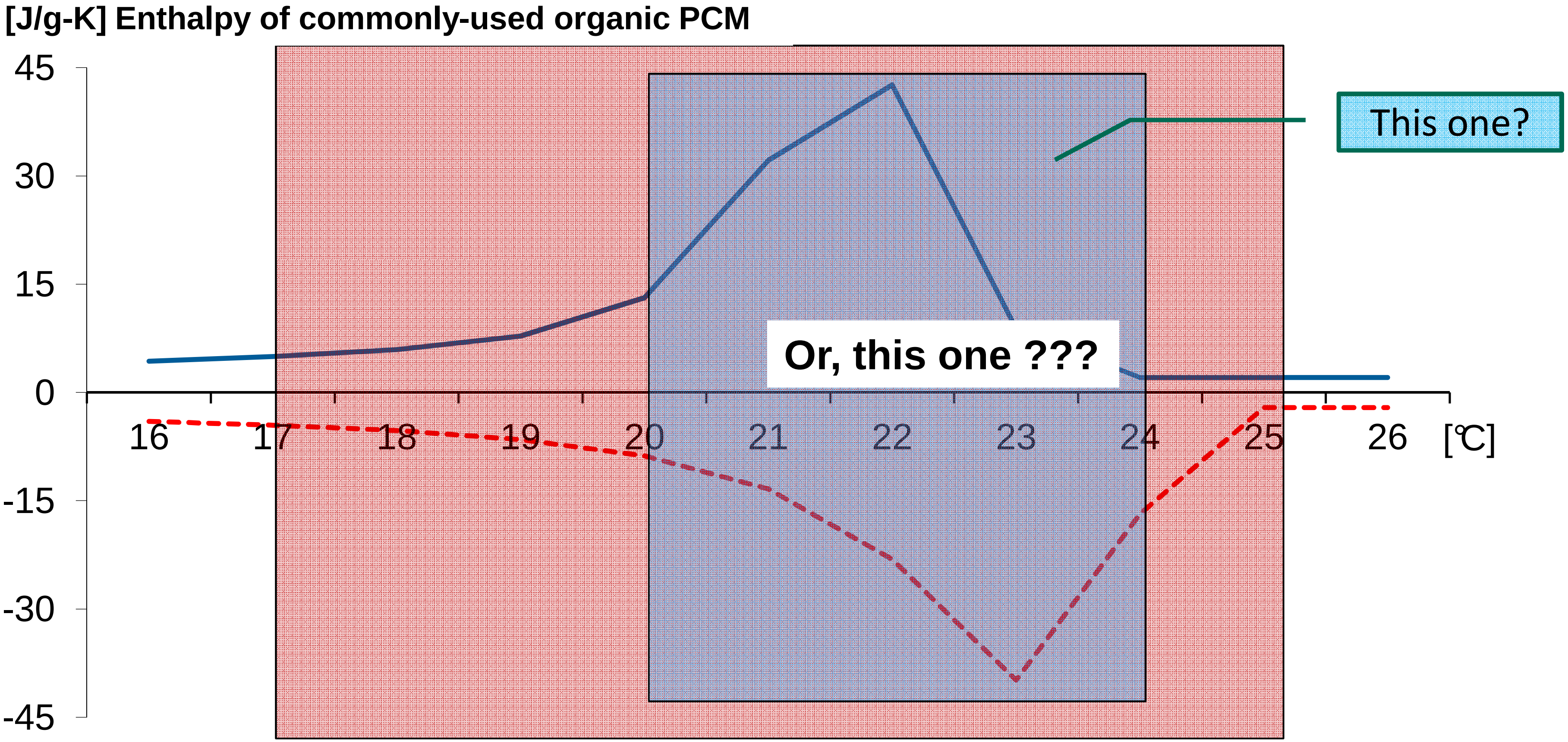
M-value – New Energy Performance Label for PCM-Enhanced Products

Expresses only the phase-change related enthalpy change

Potential Misuse of Experimental Performance Data of PCM-enhanced Products (likely for marketing purposes)

For what temperature range should PCM enthalpy be calculated if c_p-related effects are included together with phase transition–related effects?



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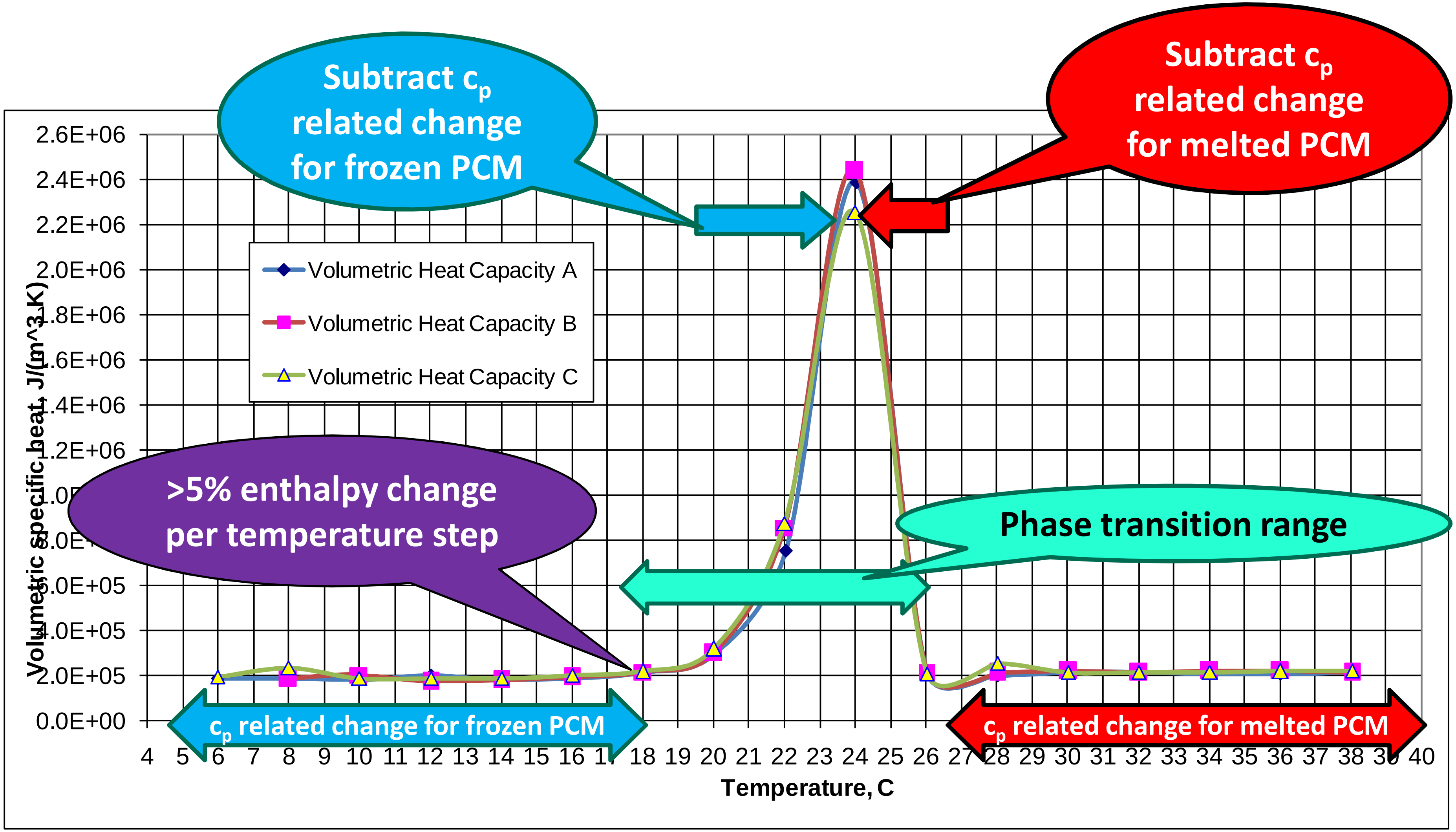
Proposed Energy Performance Label for PCMs

M-value ➔ $$M_{T_L}^{T_U} \quad [J/g]$$

T_U – upper temperature limit of the phase transition

T_L – lower temperature limit of the phase transition

Practical Determination of M-value

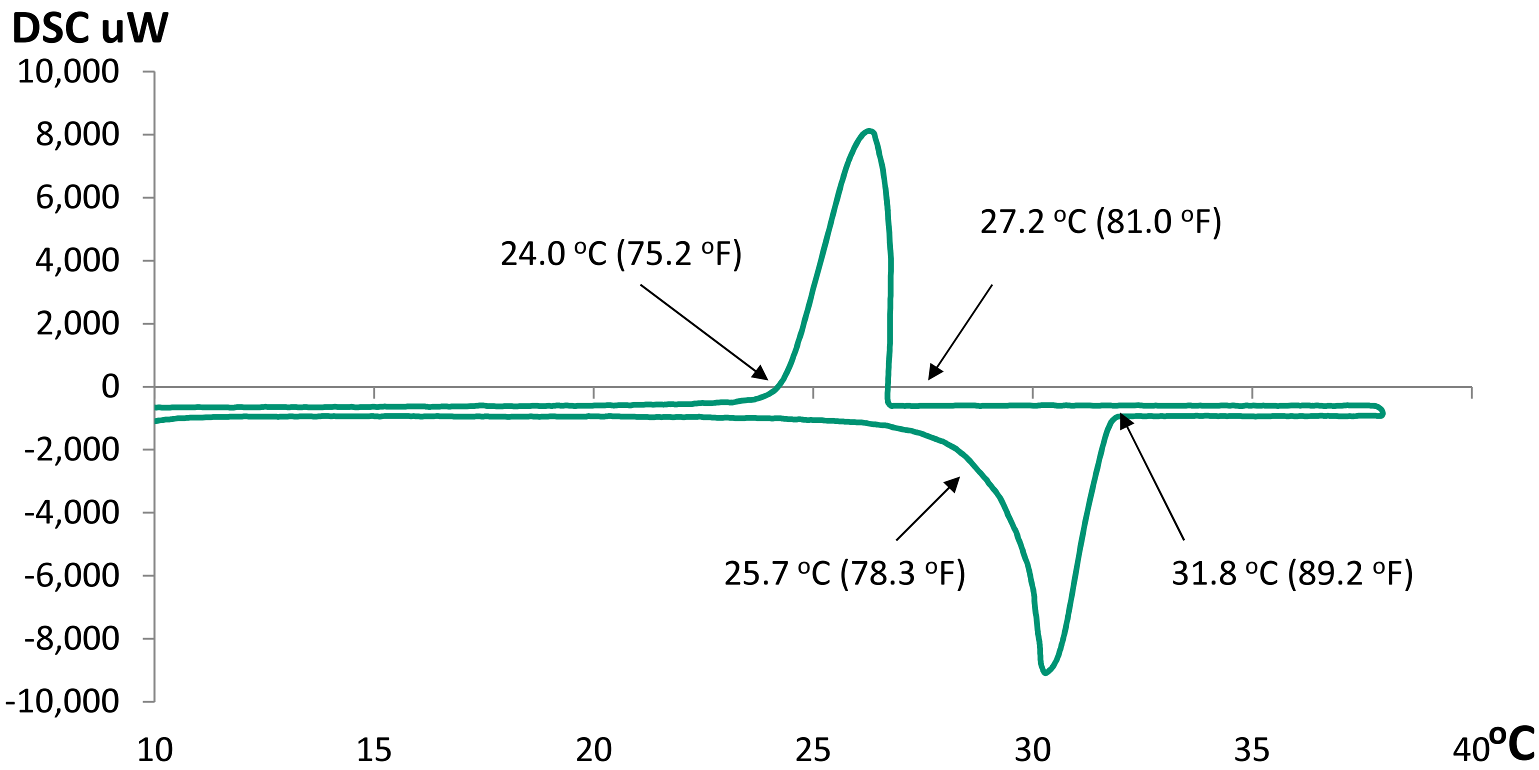


Computer Simulation Challenges

Most whole building simulation tools use **one** simplified enthalpy curve (usually for melting)

PCM Subcooling Effect is Not Properly Represented

Two independent enthalpy curves and upper and lower temperature limits generated by DSC tests for PCM-enhanced materials or composites still cannot be used today in whole building energy simulations (organic PCM data shown).



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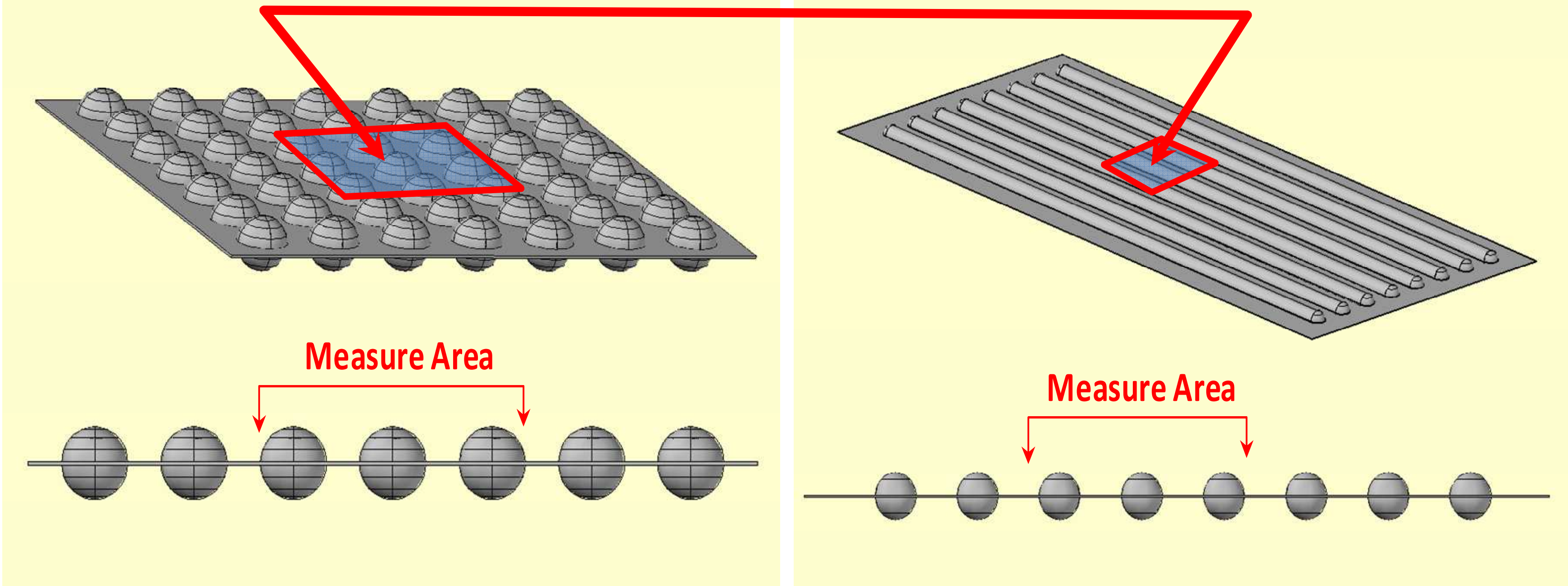
Computer Simulation Challenges

Most whole building simulation tools do not properly represent PCM thermal characteristics

Complex Arrays of PCM Containers Are Difficult To Test in Conventional Equipment, Even More Difficult Numerical Analysis

Example estimation of the measure area for arrays of PCM pouches

Measure area needs to contain representative geometry of the measured array of PCM containers

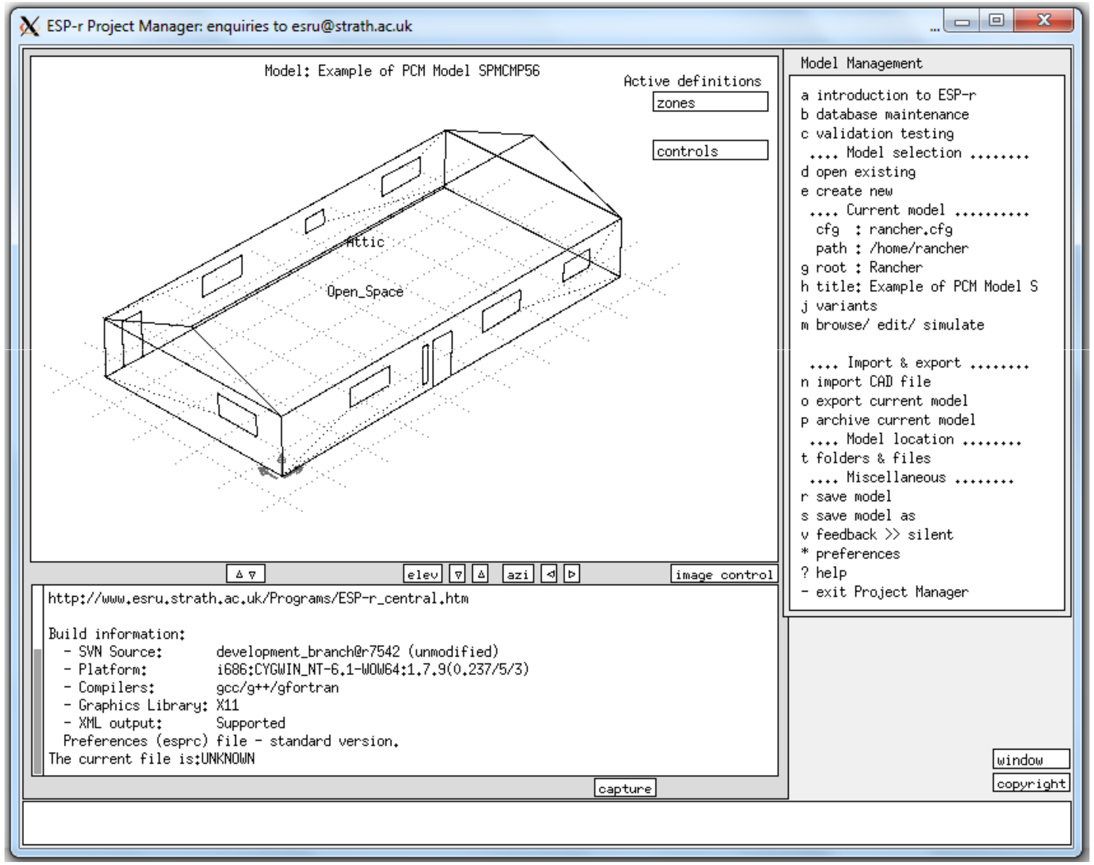


Computer Simulation Challenges

Complex 3D geometries for packaged PCM products are not properly represented by 1D algorithms used in whole building simulation tools.

Whole building Energy Analysis of PCM Attic Insulations

Single Story Residential Building Modeled Using ESP-r



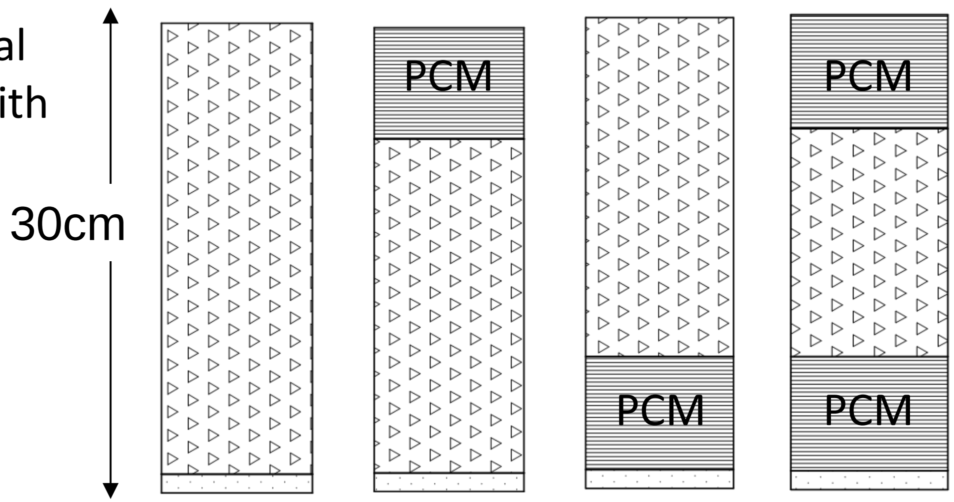
Four Simulation Configurations

As a case study to demonstrate a practical application of the ESP-r PCM model SPMCMP56, we modeled a residential single-story house in a hot climate with PCM-enhanced cellulose ceilings.

Two zones:

conditioned space and
unconditioned attic

Four Attic Assemblies:



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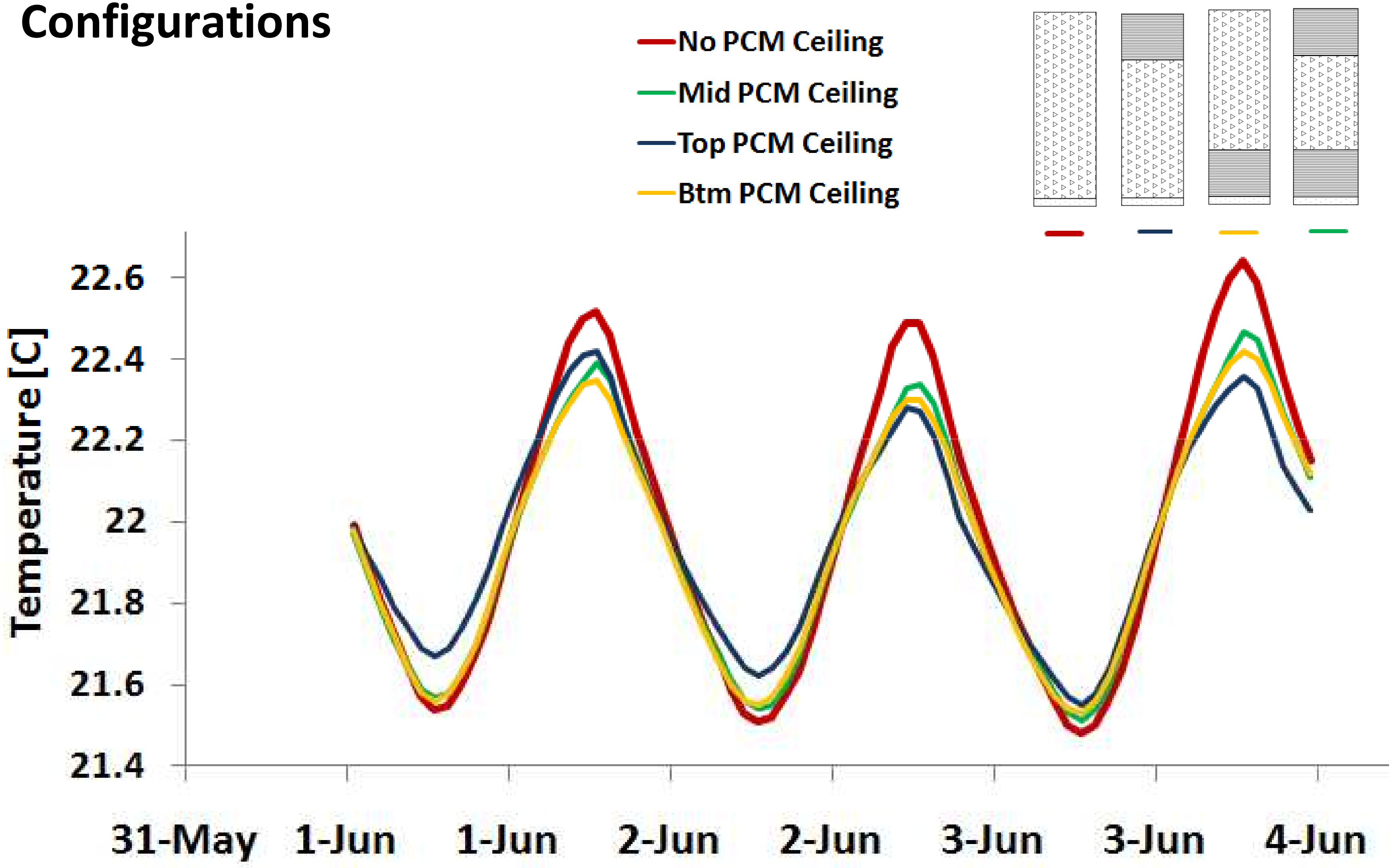
Underside Surface Temperature of Ceiling for Different PCM Configurations



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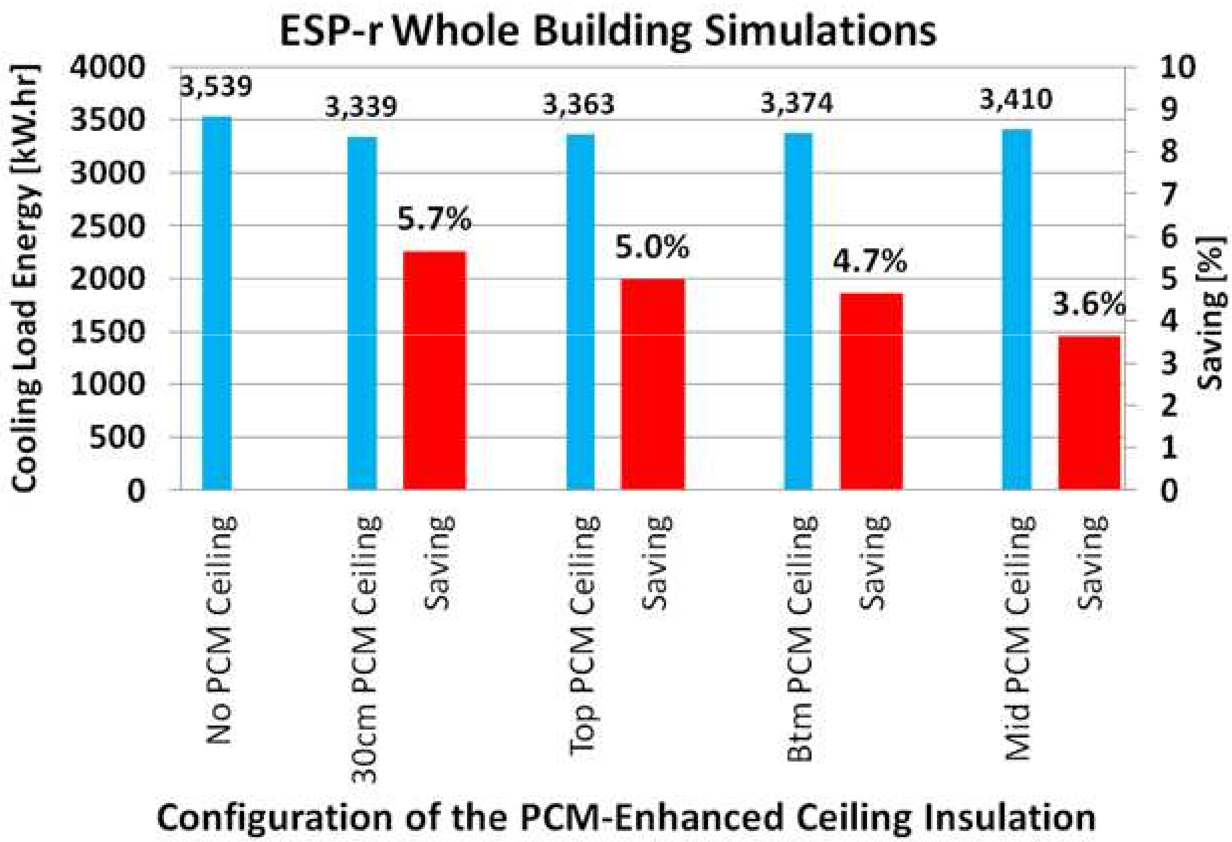
Annual Cooling Load Simulation Results
Savings Are Relative to the Non-PCM Ceiling Case



Conclusions

- During the last several decades, simple PCM applications like PCM-gypsum boards have dominated the thermal storage market for building envelope applications. Today the focus has slowly begun to shift to more complex PCM applications (i.e. PCM blends with insulations, PCM containers, etc.).

- A new dynamic testing procedure utilizing symmetrical step changes of temperature, and whole building energy simulations using ESP-r model were utilized in this paper.
- A conventional heat-flow meter apparatus was used to obtain transient heat flux data for fiber insulation material containing microencapsulated PCM.
- The routinely used DSC method for dynamic thermal property measurement of a PCM is valid only for small quantities of pure PCM and is not appropriate for large-scale PCM-enhanced building components
- In this work, we employed a novel method based on HFMA to measure dynamic thermal properties.
- In this PCM study, we used earlier validated ESP-r PCM model SPMCMP56, for the energy modeling and PCM performance analysis.
- Simulation result showed PCM-enhanced cellulose yields a whole-building cooling load energy saving from 3.6% to 5.7% depending on the PCM configuration for the Phoenix, AZ climate. These savings correspond to approximately a 38.0% to 47.5% reduction in the attic-generated cooling loads.

Thank You!

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