The Future of Building Materials:
Passive Design Utilizing the Energy Storage Capability of Phase Change Materials

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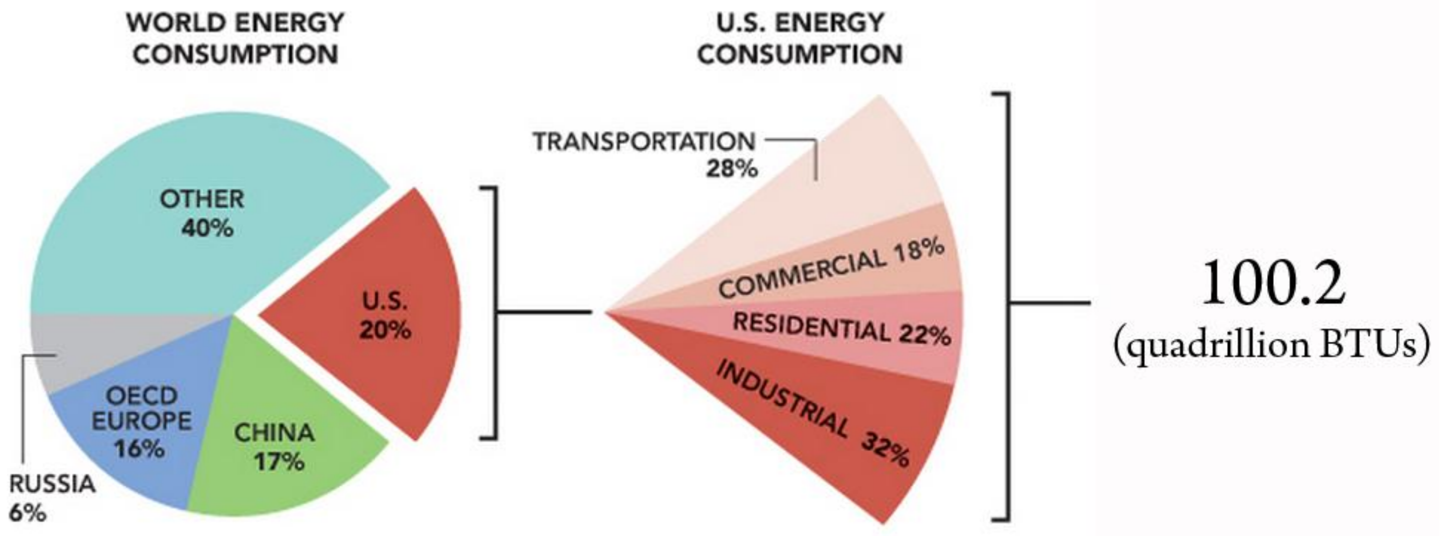
Outline

- Introduction / Phase Change Materials (PCM)
- Integration of PCM in buildings
- Cost of PCM
- Development of design guidelines
- Materials research on solid-solid PCM

Energy Consumption

Energy is fundamental for today's society: Nuclear, Fossil Fuel, Wind, Solar, Hydropower, etc



- United States Primary energy consumption per sector. (*2010 Buildings Energy Databook*, US. DOE, March 2011)

1 Quadrillion British Thermal Unit (BTU) = 8 Billion Gallons of Gasoline = 50 million tons of coal.

50 Million tons of coal = a pile 10 feet thick, one mile wide and 3.3 miles long.

Energy Consumption

1.1.4 2008 U.S. Buildings Energy End-Use Splits, by Fuel Type (Quadrillion Btu)	Natural Gas	Fuel Oil (1)	LPG	Other Fuel(2)	Renw. En.(3)	*Site* Electric	*Site* Total	*Site* Percent
Space Heating (5)	4.96	0.78	0.26	0.11	0.56	0.71	7.37	36.9%
Lighting						2.01	2.01	10.0%
Space Cooling							1.78	8.9%
Water Heating							2.58	12.9%
Refrigeration (6)							0.86	4.3%
Electronics (7)							0.78	3.9%
Ventilation (8)							0.53	2.7%
Computers							0.39	2.0%
Cooking							0.67	3.3%
Wet Cleaning (9)							0.37	1.8%
Other (10)							1.43	7.1%
Adjust to SEDS (11)							1.24	6.2%
Total	8.22	1.11	0.67	0.15	0.59	9.27	20.00	100%

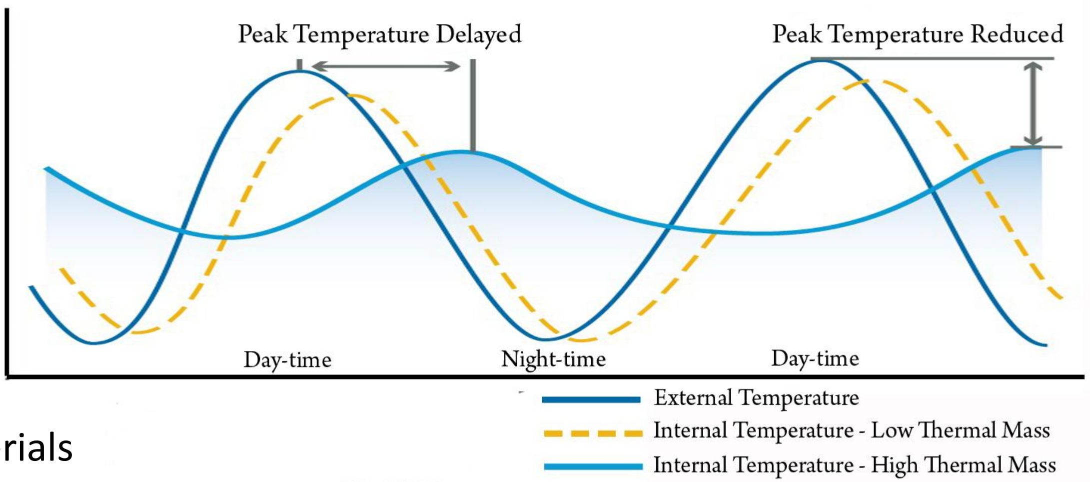
Opportunities for solar energy

But it's not easy!

2008 "site-to-source" electricity conversion = 3.16 (*2010 Buildings Energy Databook*, US. DOE, March 2011)

Energy Storage

- Use "heavy" materials to **absorb** extra heat when available, **store** it, and **release** it when needed.
- Heavy materials (stones, concrete, bricks)
- The process is reversible and also works for passive cooling.
- Terminology:
  - Energy storage, heat storage
  - Thermal mass
  - Thermal inertia
  - Activation of thermal mass
  - Latent heat vs. sensible heat
  - Phase change materials (PCM)
  - Evaporation
  - Heat capacity, specific heat of materials

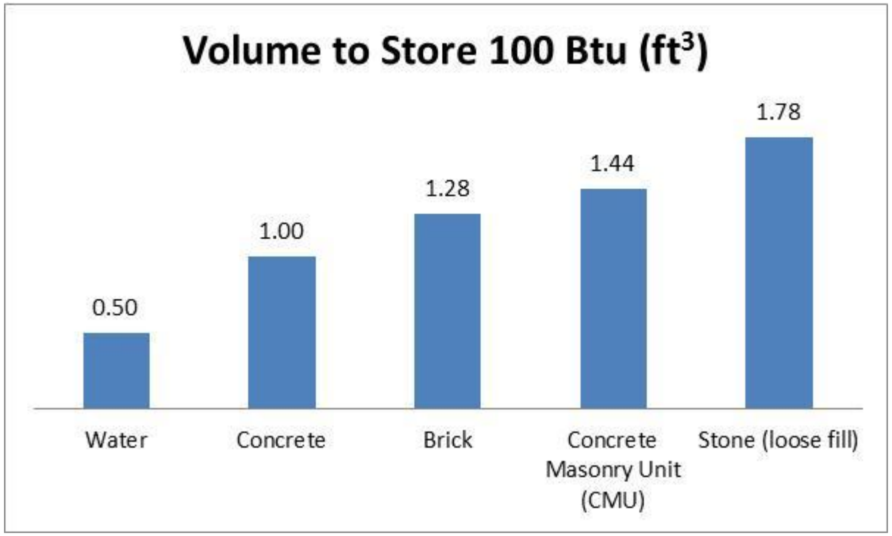


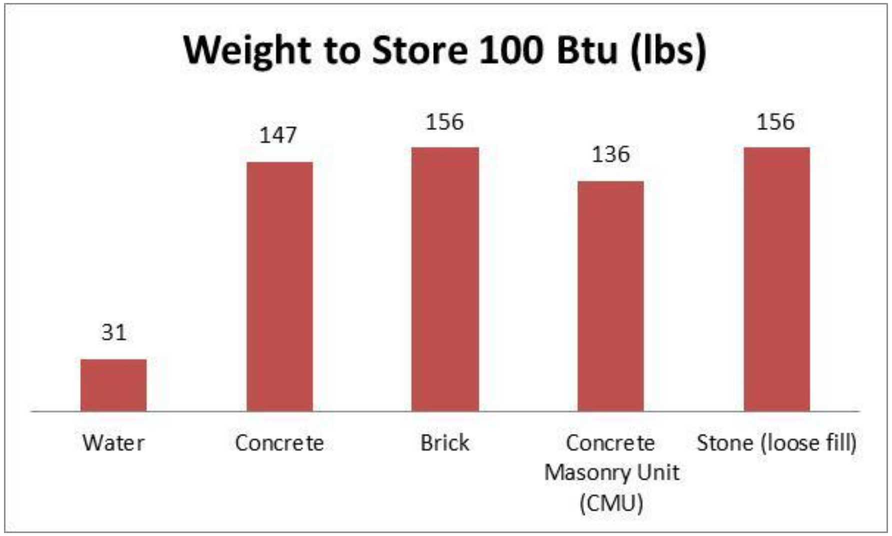
Two ways to store energy

- Sensible heat: energy is stored in the form of heat by raising the temperature of the storing material.
  - stones, concrete, and bricks
- Latent heat: energy is stored in the form of a change of phase of the storing material. Examples:
  - water absorbs a lot of energy when evaporating (i.e., changing phase from liquid to vapor) and releases a lot of energy when condensing (i.e., change phase from vapor to liquid)
  - phase change materials absorb heat when changing phase (usually from solid to liquid)
- Both ways are used in buildings for passive heating and cooling. Sensible heat is used all the time. Use of latent heat is not as popular because it is not as straight forward and usually requires more expensive materials.

Typical Thermal Mass Storage Materials

Material	Typical thickness (in)	Volume to store 100 Btu (ft^3)	Weight to store 100 Btu (lbs)	Comments
		Temperature increase: 1ºF		
Water	N/A	0.50	31	Inexpensive, container required
Concrete	2-18	1.00	147	Also structural
Brick	4-18	1.28	156	Also structural
Concrete Masonry Unit (CMU)	12-18	1.44	136	Also structural
Stone (loose fill)	4-12	1.78	156	Inexpensive, container required





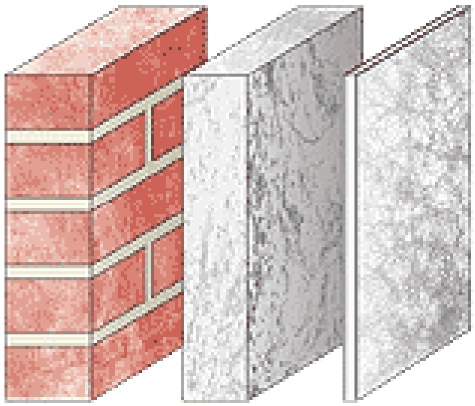
Phase Change Materials

Benefits

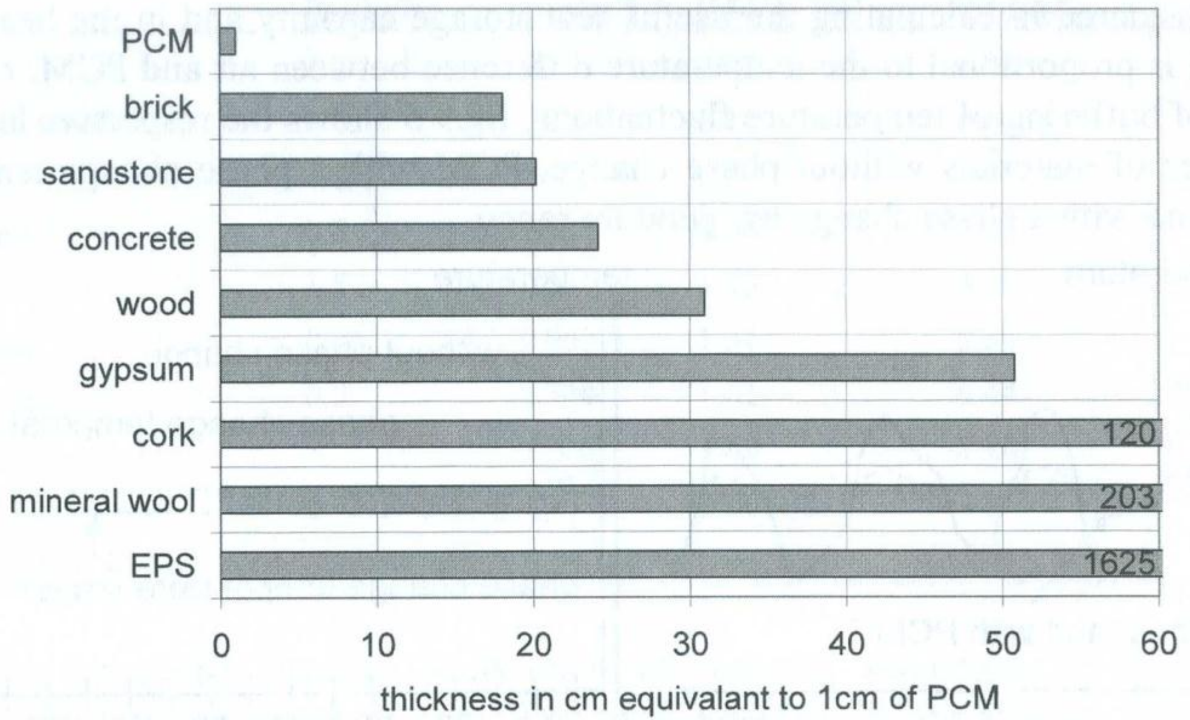
High heat storage capacity to weight ratio

High heat storage capacity to thickness ratio

Greater architectural freedom



½”-thick gypsum board (drywall) with 25% PCM (right) can store as much energy as a 4”-thick brick wall of same surface area

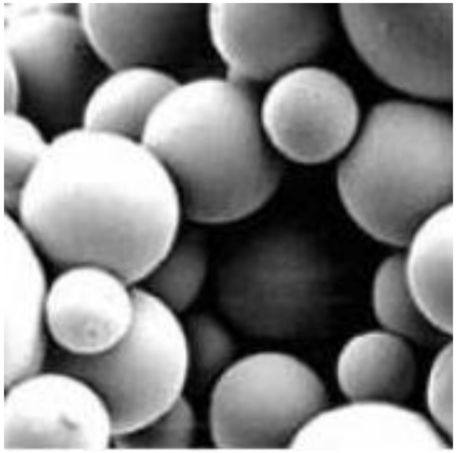


Phase Change Materials

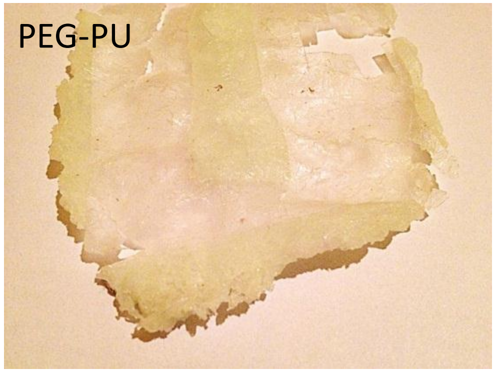
Three Types

Macro-encapsulation

Micro-encapsulation



Form-stable PCMs


PEG-PU

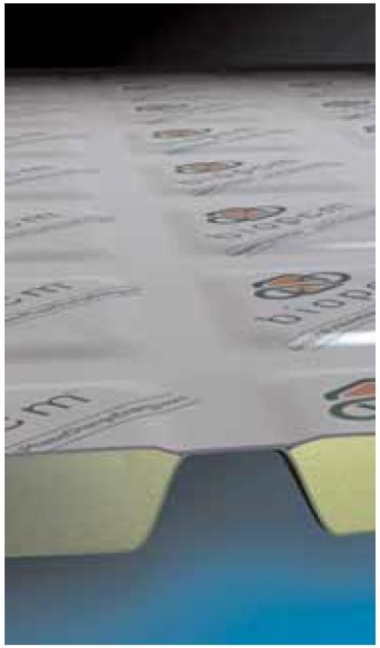

PEG-CDA

Phase Change Materials

Three Types

Macro-encapsulation

BioPCM™ layered on top of insulation in a standard wood frame structure.

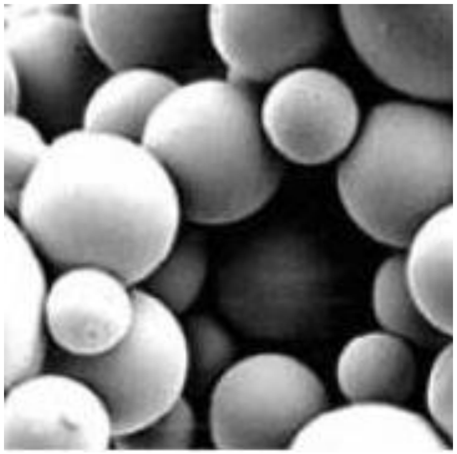


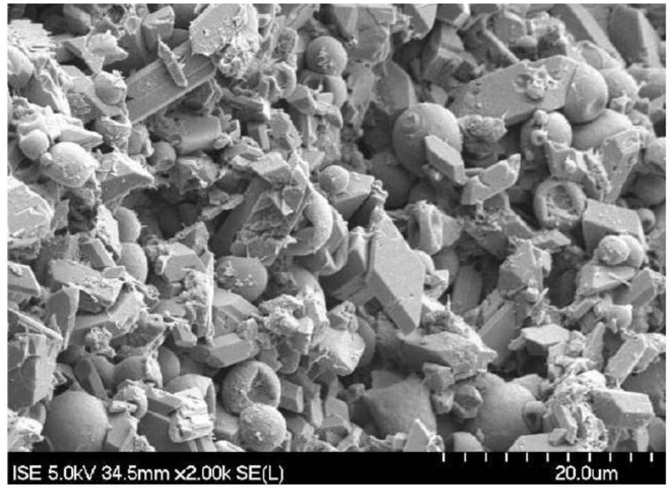
BioPCM™ is affordable, earth-friendly and easy-to-install. It's the next generation of high-performance energy savings material.

Phase Change Materials

Three Types

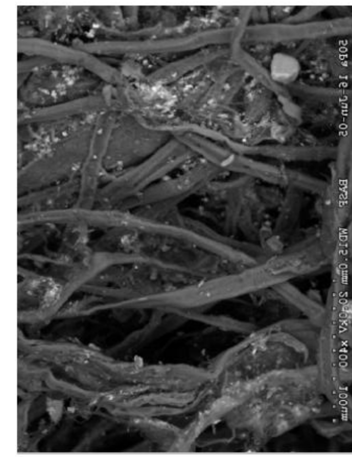
Micro-encapsulation

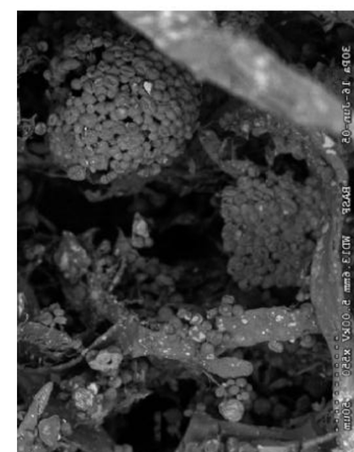


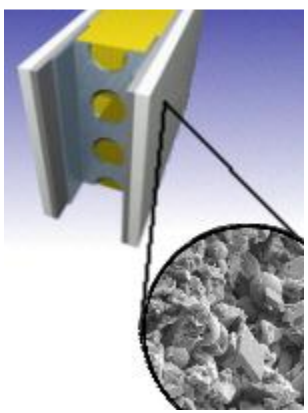


Mixed in plaster

Mixed in cellulose insulation







Mixed in spray foam

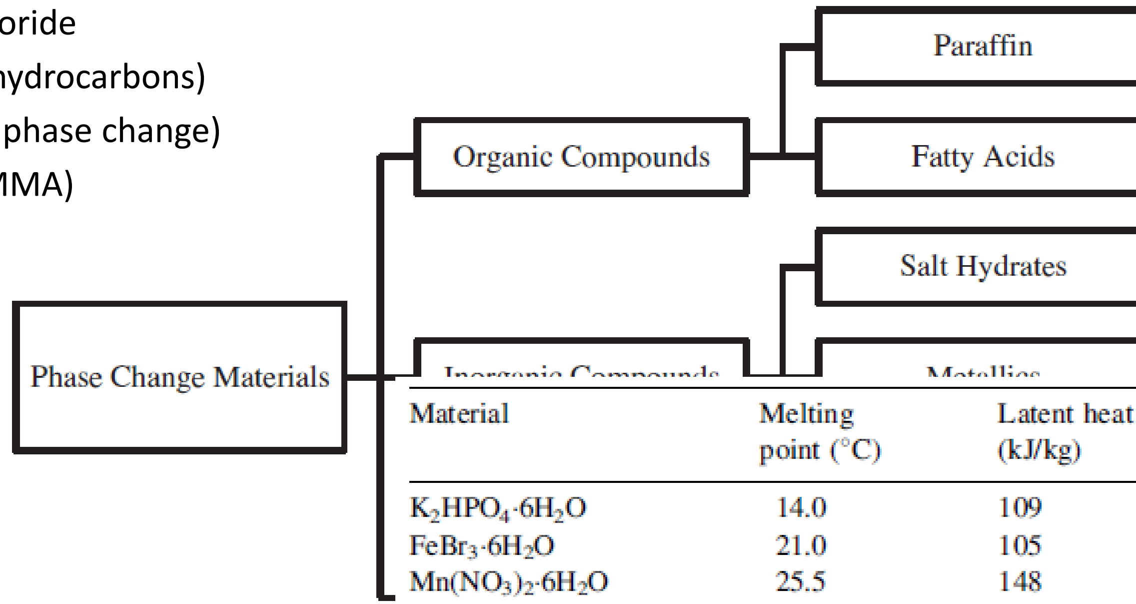
Phase Change Materials

PCM materials

~2000 materials reported in literature

~200 materials appropriate in building

- Perlite embedded with hydrated calcium chloride
- Paraffin compounds (linear crystalline alkyl hydrocarbons)
- Polyalcohols (do not leak but volatile during phase change)
- Fattic acid with polymeric encapsulation (PMMA)
- Polyethylene glycol (PEG)



Material	Melting point (°C)	Latent heat (kJ/kg)
$K_2HPO_4 \cdot 6H_2O$	14.0	109
$FeBr_3 \cdot 6H_2O$	21.0	105
$Mn(NO_3)_2 \cdot 6H_2O$	25.5	148
$FeBr_3 \cdot 6H_2O$	27.0	105
$CaCl_2 \cdot 12H_2O$	29.8	174
$LiNO_3 \cdot 2H_2O$	30.0	296
$LiNO_3 \cdot 3H_2O$	30	189
$Na_2CO_3 \cdot 10H_2O$	32.0	267
$Na_2SO_4 \cdot 10H_2O$	32.4	241
$KFe(SO_4)_2 \cdot 12H_2O$	33	173
$CaBr_2 \cdot 6H_2O$	34	138
$LiBr_2 \cdot 2H_2O$	34	124
$Zn(NO_3)_2 \cdot 6H_2O$	36.1	134
$FeCl_3 \cdot 6H_2O$	37.0	223

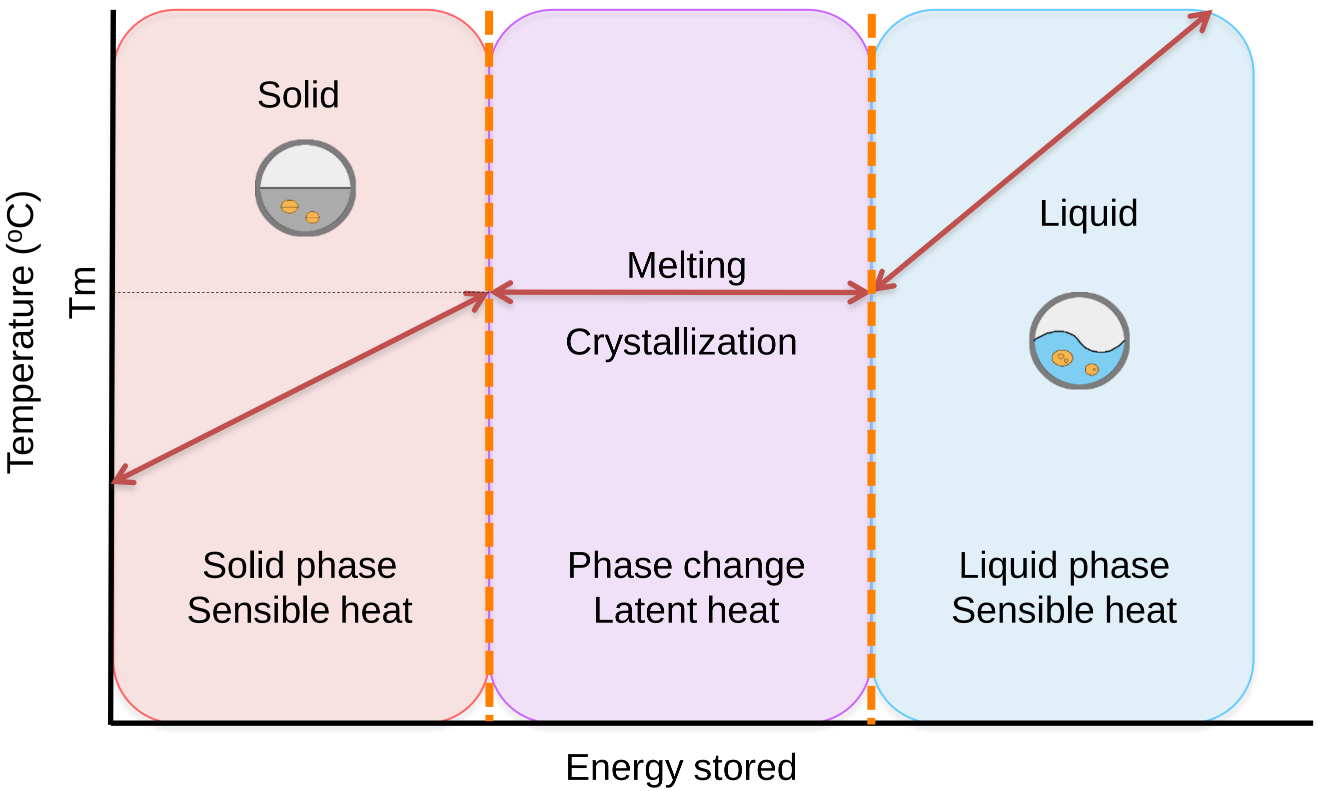
Latent heat capacity

50kJ/kg - 200kJ/kg.

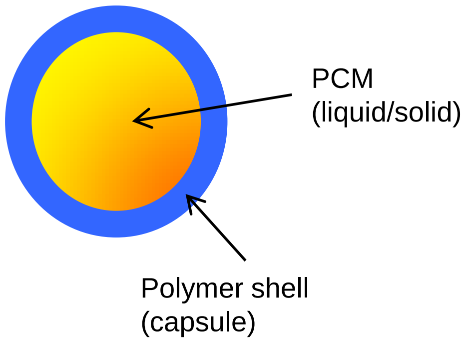
25kJ/kg and 50kJ/kg when mixed in construction m

200 kJ/kg = 100 BTU/lb = 25,000 cal/lb

How do they work?



Encapsulated PCM



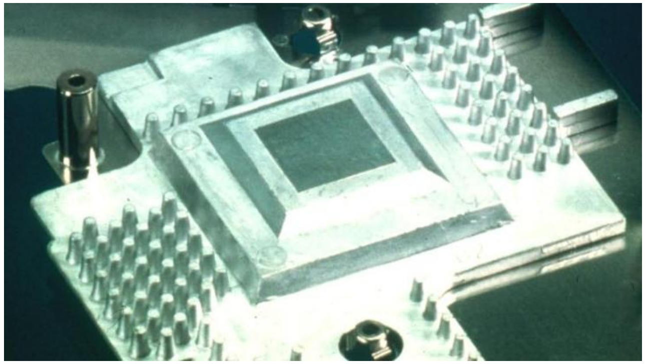
Melting temperature T_m is between 15ºC and 30ºC depending on the application. There exist different PCM materials for any desired melting temperature.

The process is 100% reversible. The temperature decreases as the energy is released.

Use of PCM

Purpose: Temperature regulation

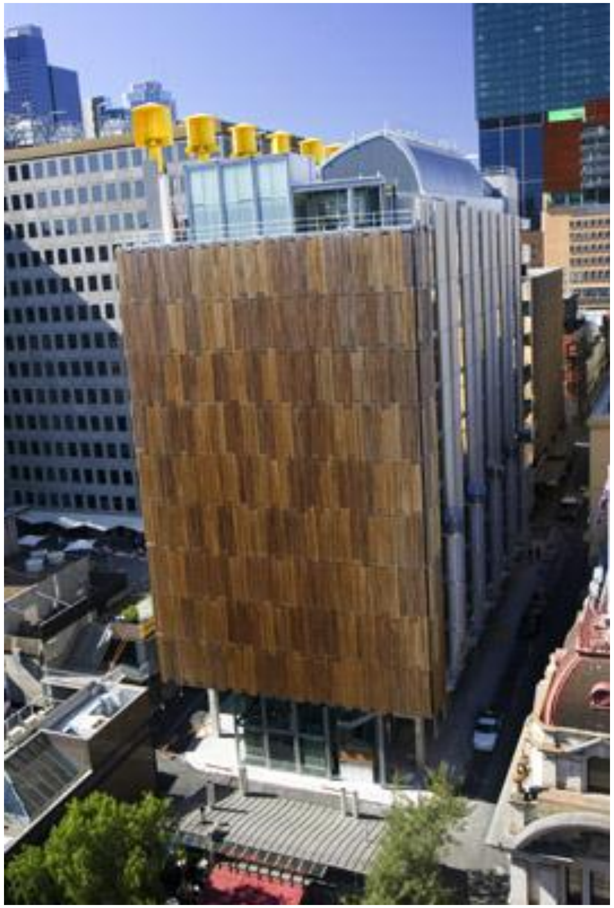
- Buildings
- Transportation
- Electronics
- Clothing



Examples of Buildings with PCM

Dover House, MA, 1947

(source: Sherburne, 2009)



City of Melbourne's Council House

<u>Setup</u>

- PCM – Glauber's Salt (Na_2So_4. $10H_20$)
- Melt temperature: 89^{o}F
- 18 solar collectors, 21 Tons of PCM.
- $20,000
- "Complete Comfort" for two winters without a fuel bill
- PCM stratified during the third winter.

Examples of Buildings with PCM

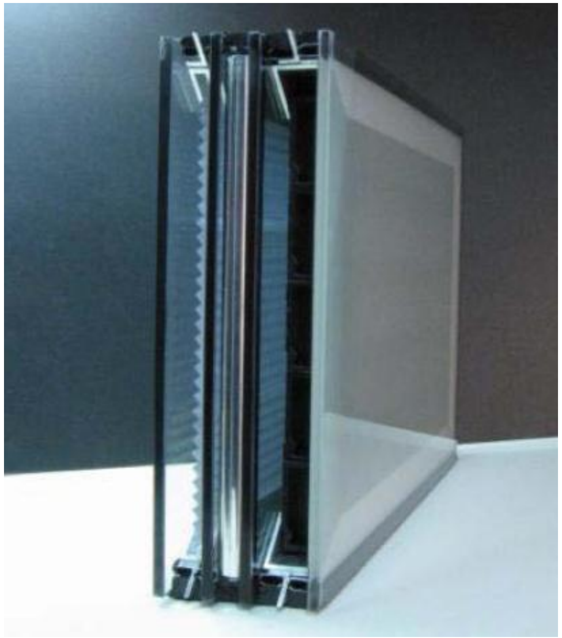
Steve Glenn's Santa Monica house, first house platinum LEED

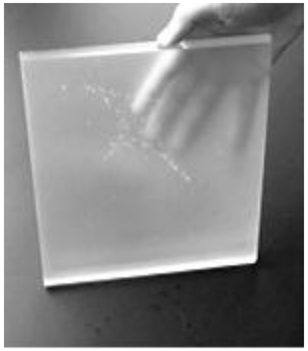
First Place 2007 Solar Decathlon: Technische Universität Darmstadt

2009 Solar Decathlon

Penn State

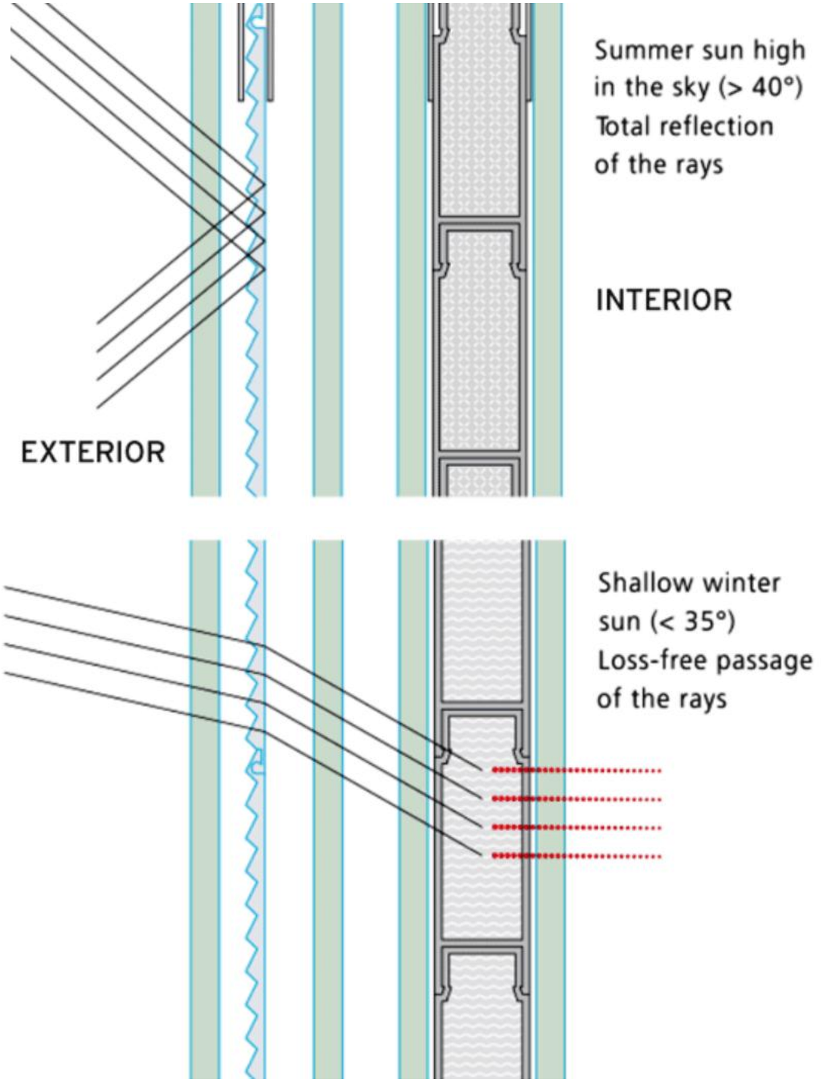
New Products





GlassX Crystal - Quadruple-glazed window includes PCM

Prismatic filter



http://glassx.ch/index.php?id=578

Increased Insulation vs. PCM

Increasing Insulation is known to be beneficial

The higher the R-value, the low the heat gain/loss

HOWEVER, not proportional!

$Q = A(T_{out}-T_{in})/R$

where Q = heat gain or loss

A = surface area

T_{out}, T_{in} = Temperatures

R = R-value

The benefit of additional insulation decreases with the amount of insulation.

Increased Insulation vs. PCM

Benefits of PCM

Most studies found that PCM improve building energy performance

- by reducing peak-hour cooling loads
- by shifting peak-demand time.

Can reduce heat and cooling load between 10 and 30%

Financial payback period is 5 to 10 years

Energy payback period is 5 to 10 years

Save $ since save heat and cooling energy

Save $$ if on-peak/off-peak billing cycle is adopted but does not help the planet

Cons of PCM

New technology

No guidelines exist / limit knowledge

Reliable durability is still uncertain

Example of Cost of PCM

Standard 2,434 sq ft house with 730 sq ft Basement, Gas Furnace, Central Air-conditioning

Heating and cooling cost per yr. Location: Louisville KY[ii]	
1643 therms Natural Gas @ average retail price of $1.30 per therm[iii]	$2136.00
10623 kWh @ average retail price[iv] 9.45	$1004.87
Yearly Total	$3140.87
Monthly expenditure	$ 262.67

PCM 2,434 sq ft house with 730 sq ft Basement, Gas Furnace, Central Air-conditioning

Heating and cooling cost per yr. Location: Louisville KY	
1150 therms Natural Gas @ average retail price of $1.30 per therm[v]	$1495.00
7436 kWh @ average retail price[vi] 9.45	$702.70
Yearly Total	$2197.70
Monthly expenditure	$ 183.14

Yearly Energy Savings for home with PCES BioPCM =$ 943.17

http://www.phasechange.com/whitepages-page.php

Some Additional Benefits from the use of BioPCM sheet:

- Tax benefits
- Lower cost for HVAC equipment
- Lower construction costs
- Energy Efficient Mortgage
- Reduced energy costs

Most beneficial with different billing cycle:

$0.12 /kWh during day

$0.07 /kWh during night

Research Project

National Science Foundation

Research Goal

• Increase knowledge by developing design guidelines for integrating PCM in buildings.

Research Questions

- For any given climate, what are the optimum:
    - PCM melting temperature
    - amount of PCM
    - location of PCM

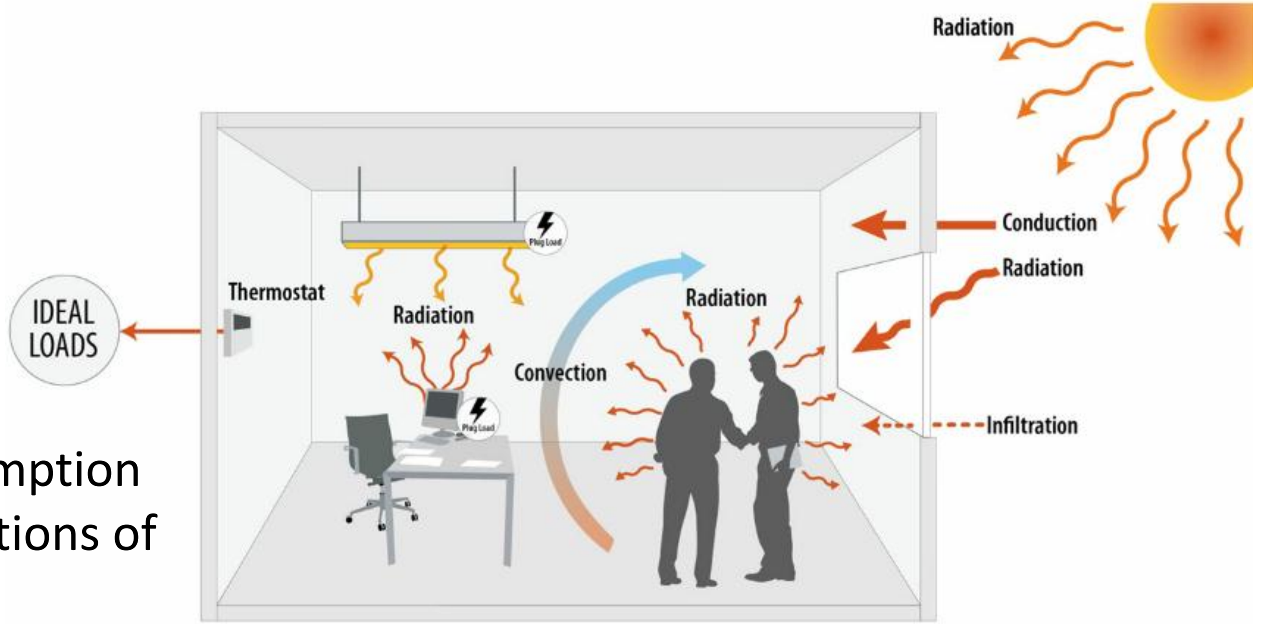
- What other parameters affect the integration of PCM.

Research Project

Experimental Design

1) Control
   - Annual Energy Consumption without PCM

2) Treatment
   - Annual Energy Consumption with different combinations of PCM
     a) melt temperature
     b) energy storage capacity
     c) location within the walls
     d) location within the room



Data collection

Finite Element Analysis (FEA)

Computational Fluid Dynamics (CFD)

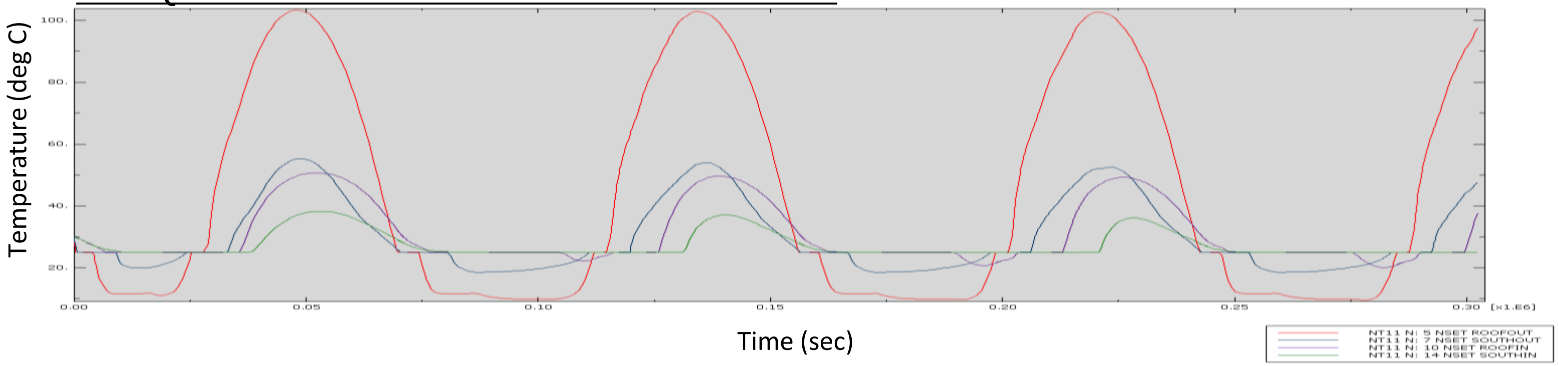
Whole building energy modeling software - EnergyPlus

Research Project

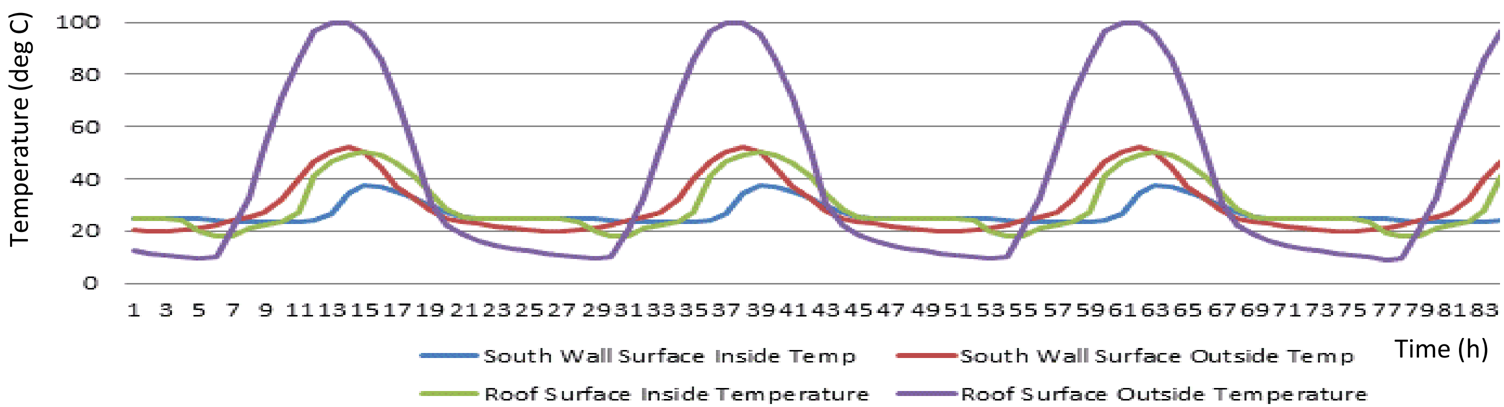
Numerical modeling

Modeling the thermal behavior of PCM in building is validated by comparing results obtained by different techniques: Abaqus (FEA) vs. EnergyPlus (FD)

ABAQUS – Finite Element Numerical Scheme

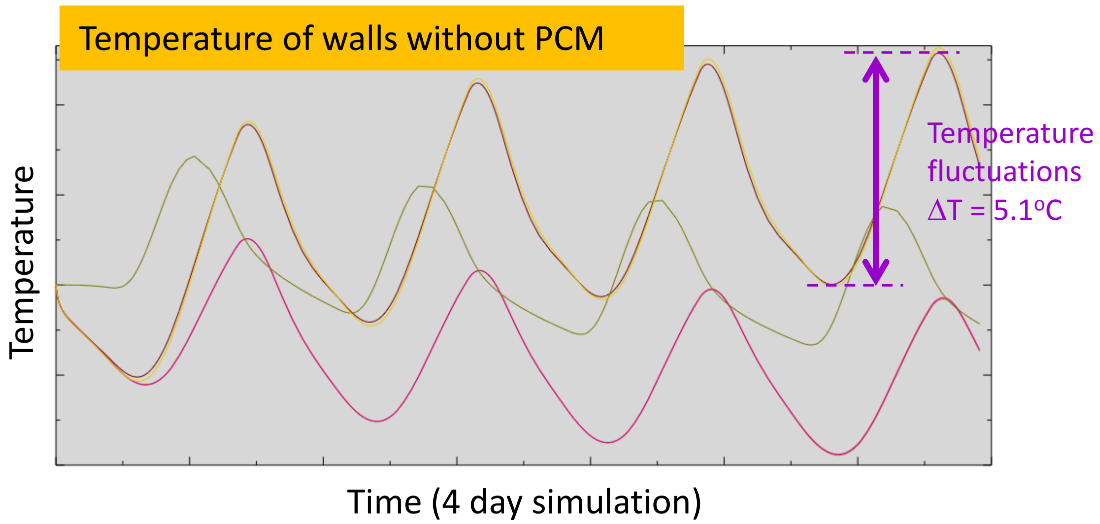


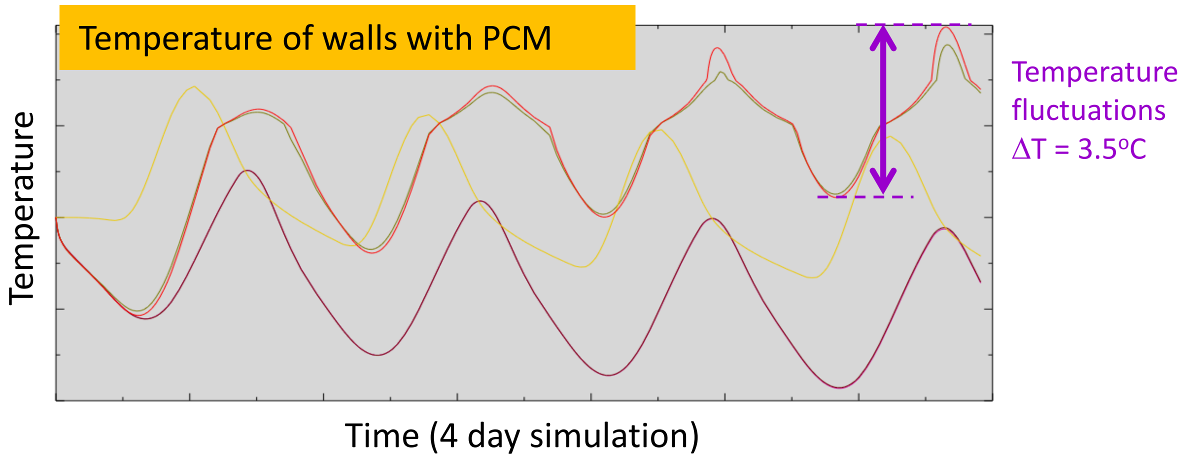
EnergyPlus – Finite Difference Numerical Scheme

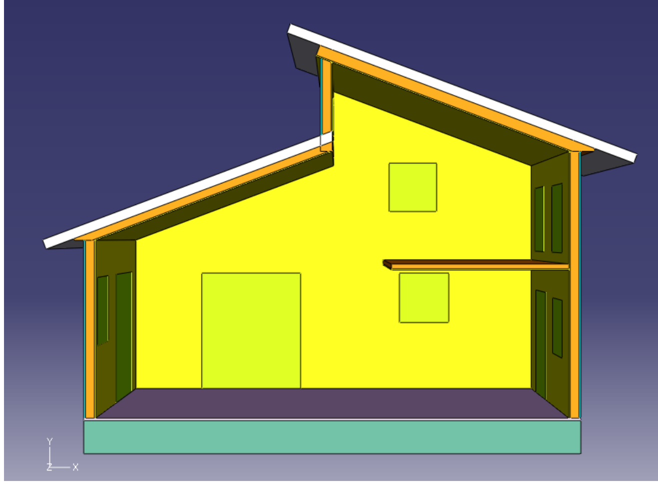


Example numerical simulation

Latent heat of PCM: 20 kJ/kg







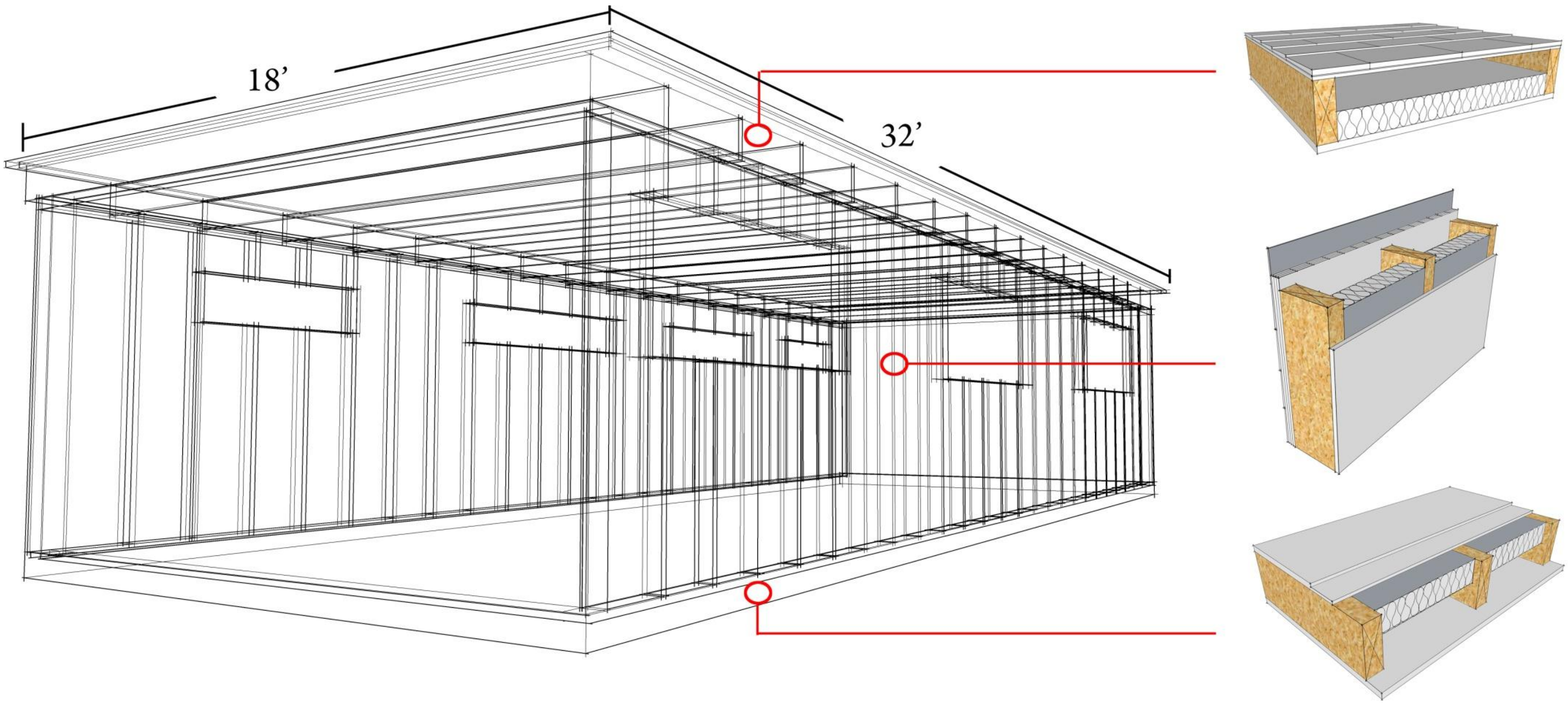
Benefits of PCM:

- Smaller temperature fluctuations
- Smaller duration at extreme temperatures
- Reduced cooling/heating load

Research Project

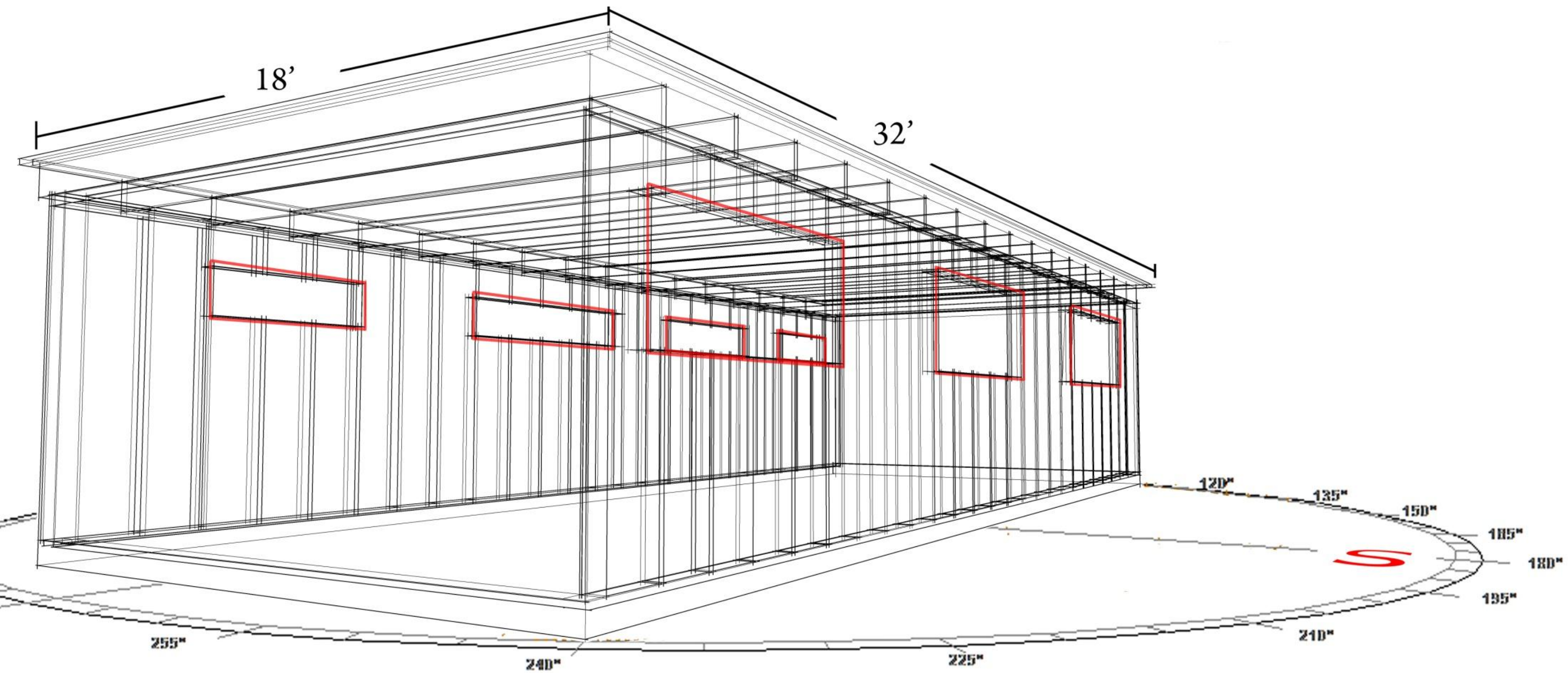
Base Building Model - ANSI/ASHRAE/IESNA Standard 90.1/90.2 – 2004
- ASHRAE – Advanced Energy Design Guides

a) Floor Area: 576 Sq ft.
Lightweight construction



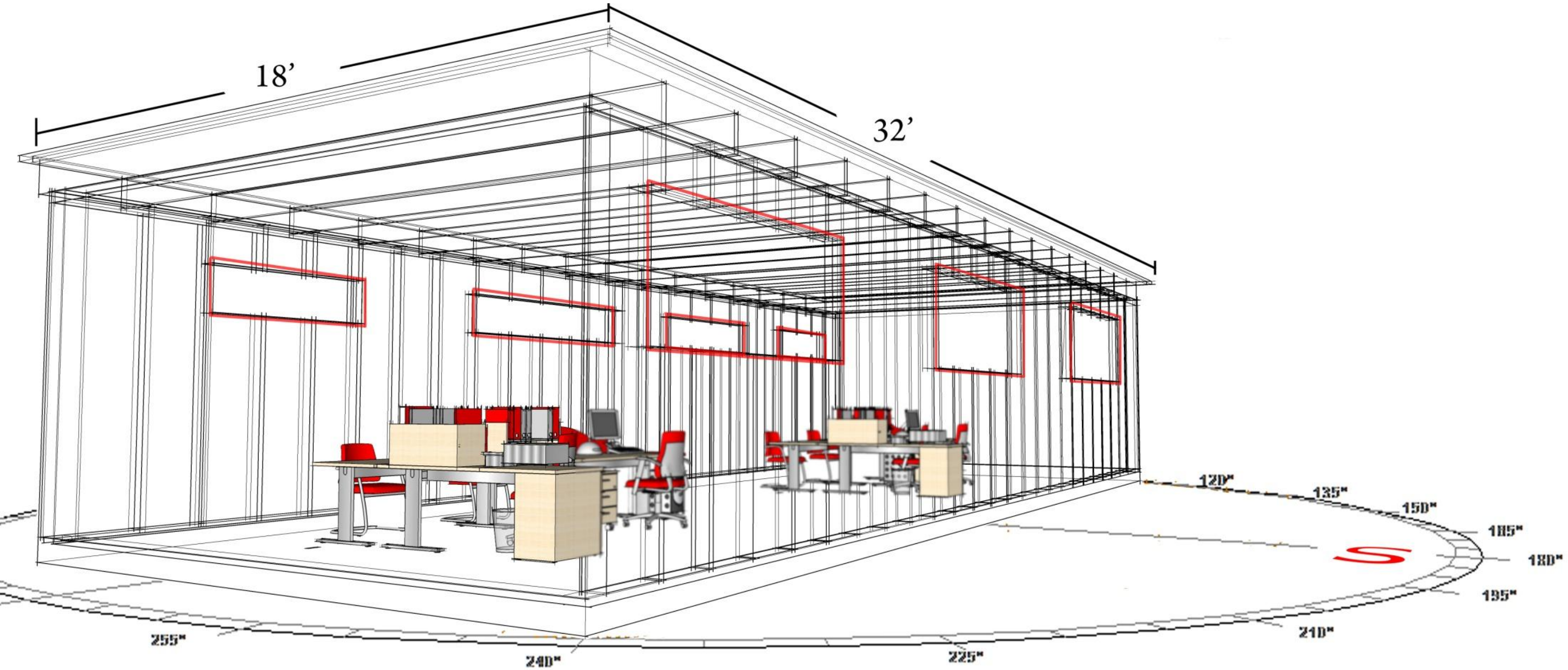
Research Project

b) 30% window/wall ratio
East/west orientation



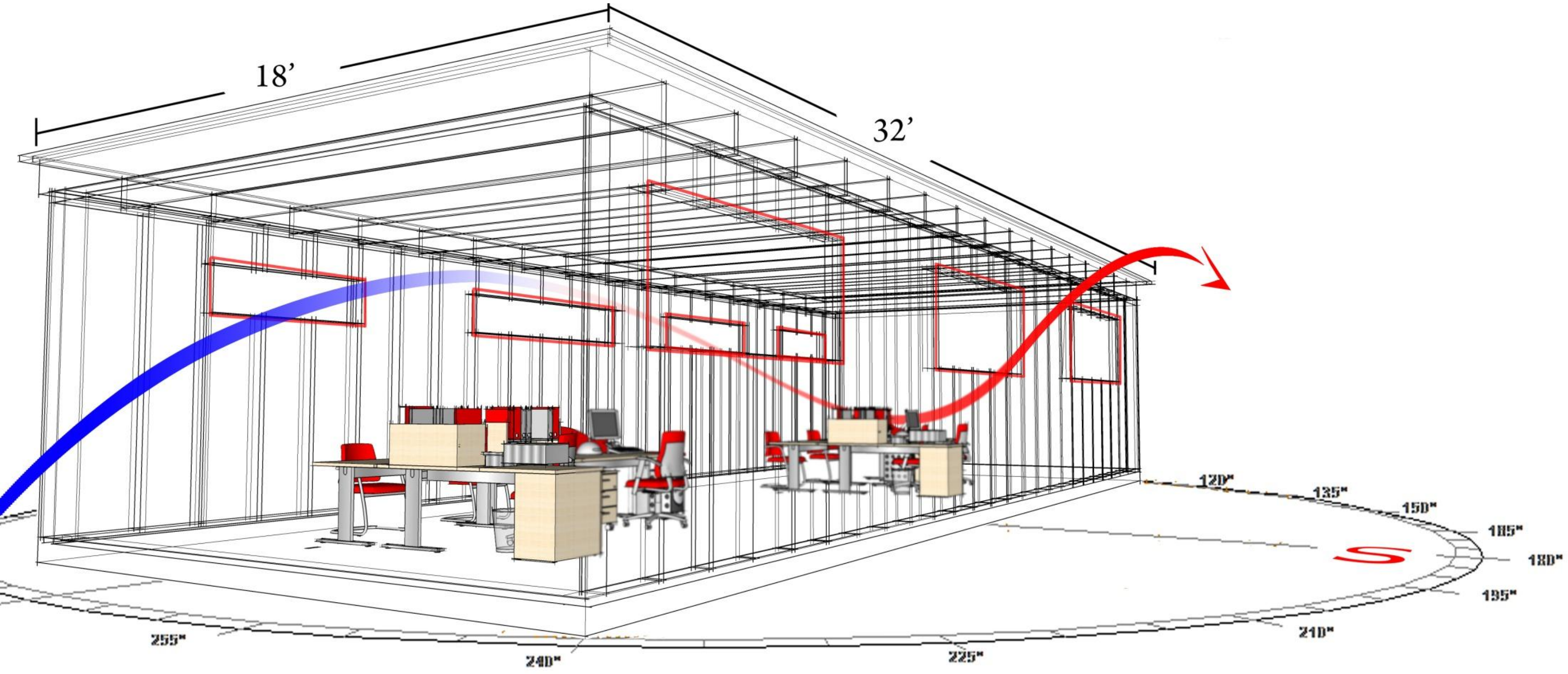
Research Project

c) Internal Loads
Computers
Lights
People



Research Project

d) Minimum Air Change Rate
0.35 AC/H



Research Project

Dependent Variable

Annual Energy Consumption (Y)

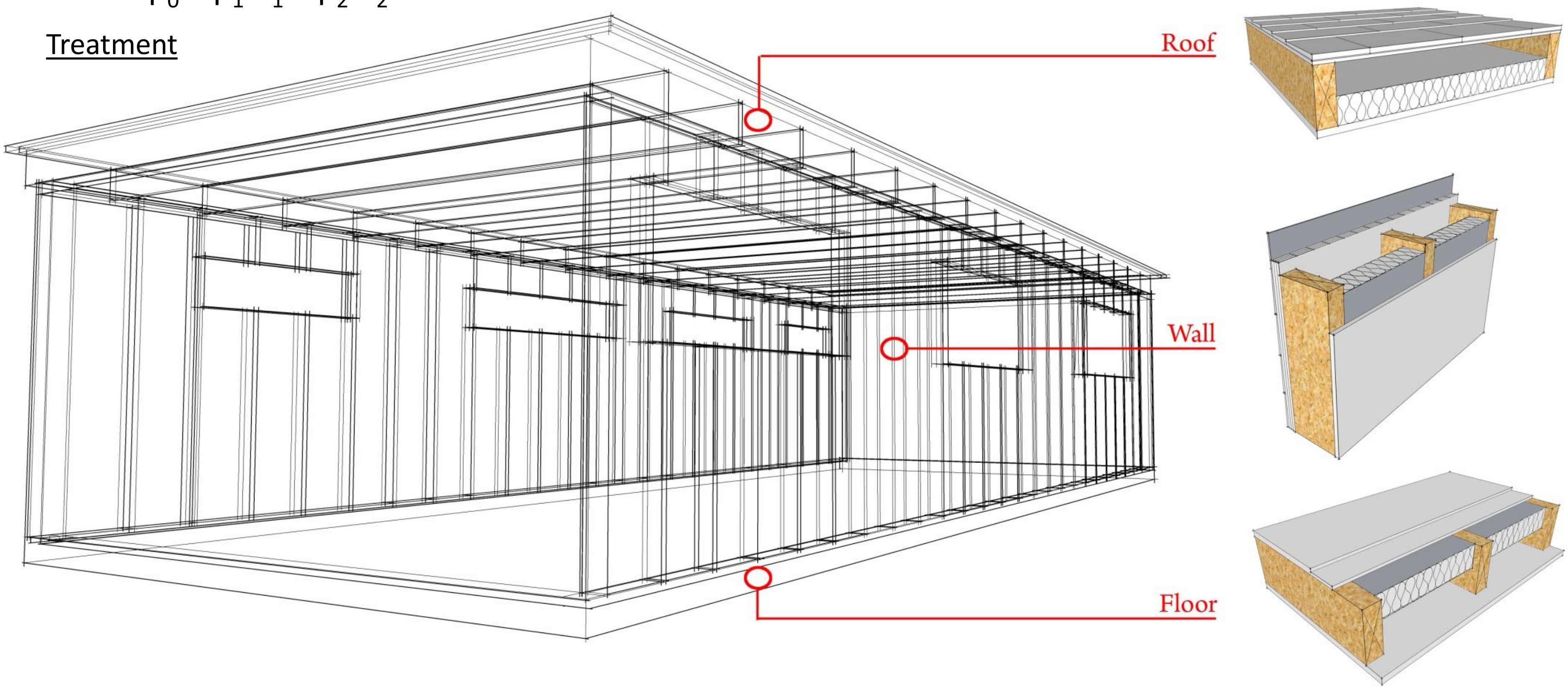
Regression Model

$$Y = \beta_0 + \beta_1.X_1 + \beta_2.X_2$$

Treatment

Independent Variables:

a) PCM Melting Temperature (X_1) – 18-29 degrees
b) PCM Enthalpy (X_2) – 50, 100, 150 KJ/Kg



Dependent Variable

Annual Energy Consumption (Y)

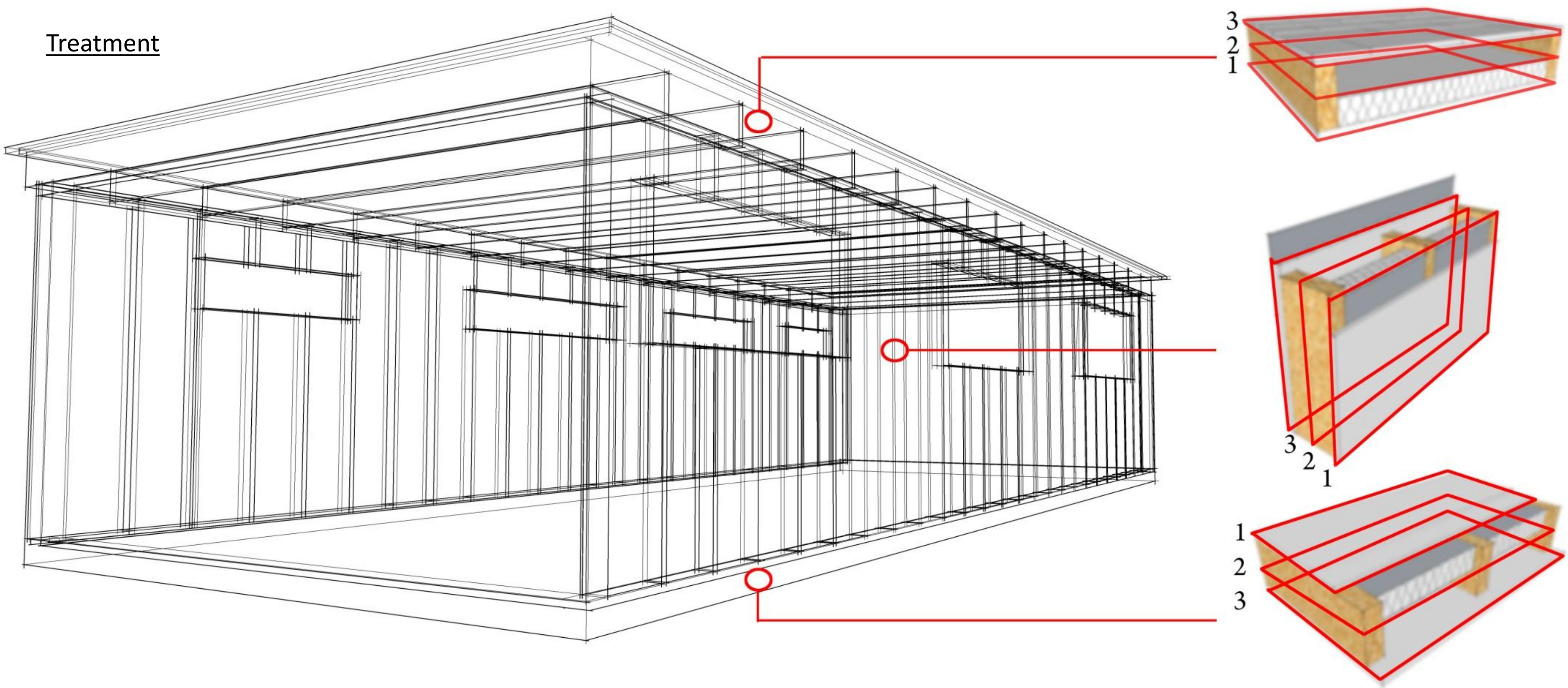
Regression Model

$$Y = \beta_0 + \beta_1.X_1 + \beta_2.X_2 + \beta_3.X_3$$

Independent Variables:

a) PCM Melting Temperature (X_1) – 18-29 degrees
b) PCM Enthalpy (X_2) – 50, 100, 150 KJ/Kg
c) Layers (X_3) – Interior, Interstitial, Exterior

Treatment



Dependent Variable

Annual Energy Consumption (Y)

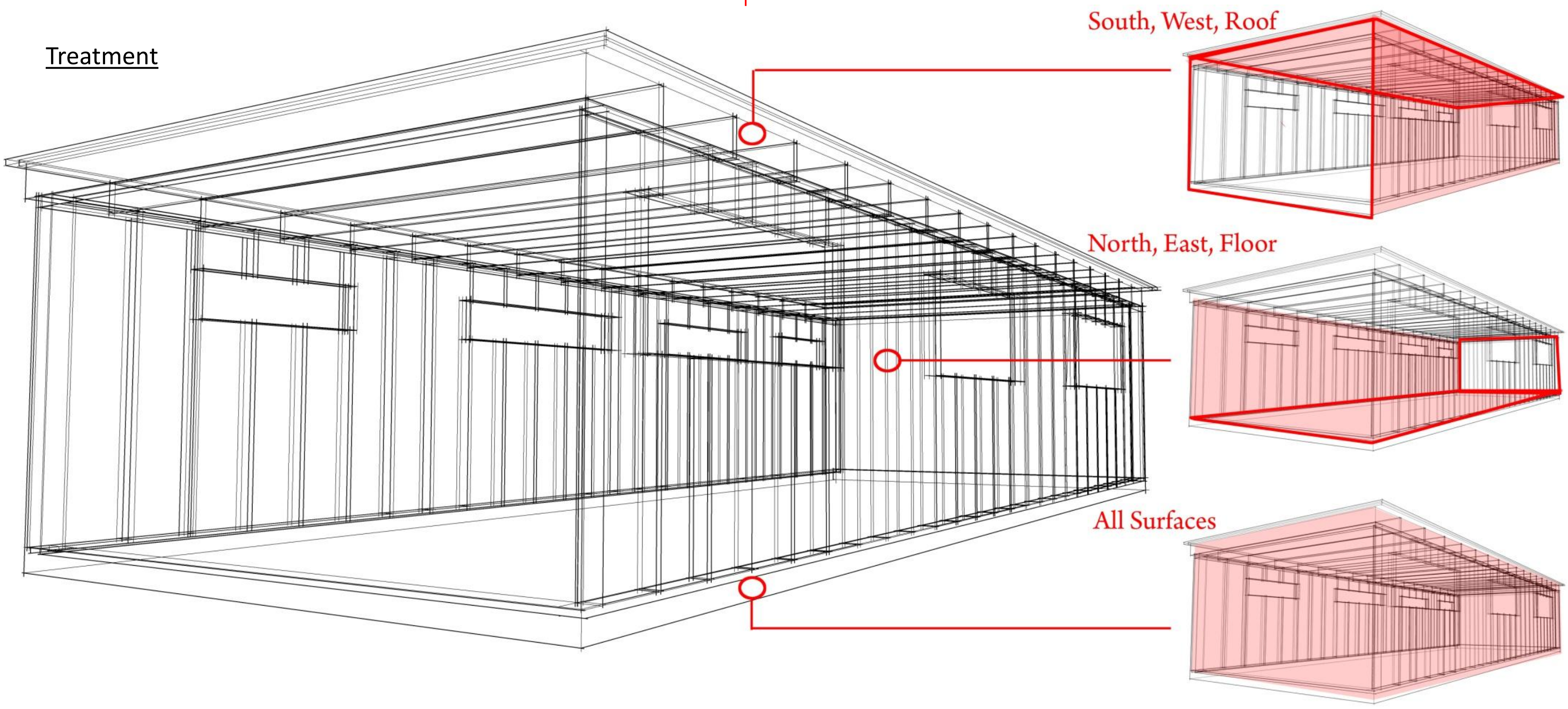
Regression Model

$$Y = \beta_0 + \beta_1.X_1 + \beta_2.X_2 + \beta_3.X_3 + \beta_4.X_4$$

Independent Variables:

a) PCM Melting Temperature (X_1) – 18-29 degrees
b) PCM Enthalpy (X_2) – 50, 100, 150 KJ/Kg
c) Layers (X_3) – Interior, Interstitial, Exterior
d) Surfaces(X_4) – High Radiation, Low Radiation, All Surfaces

Treatment



Dependent Variable

Annual Energy Consumption (Y)

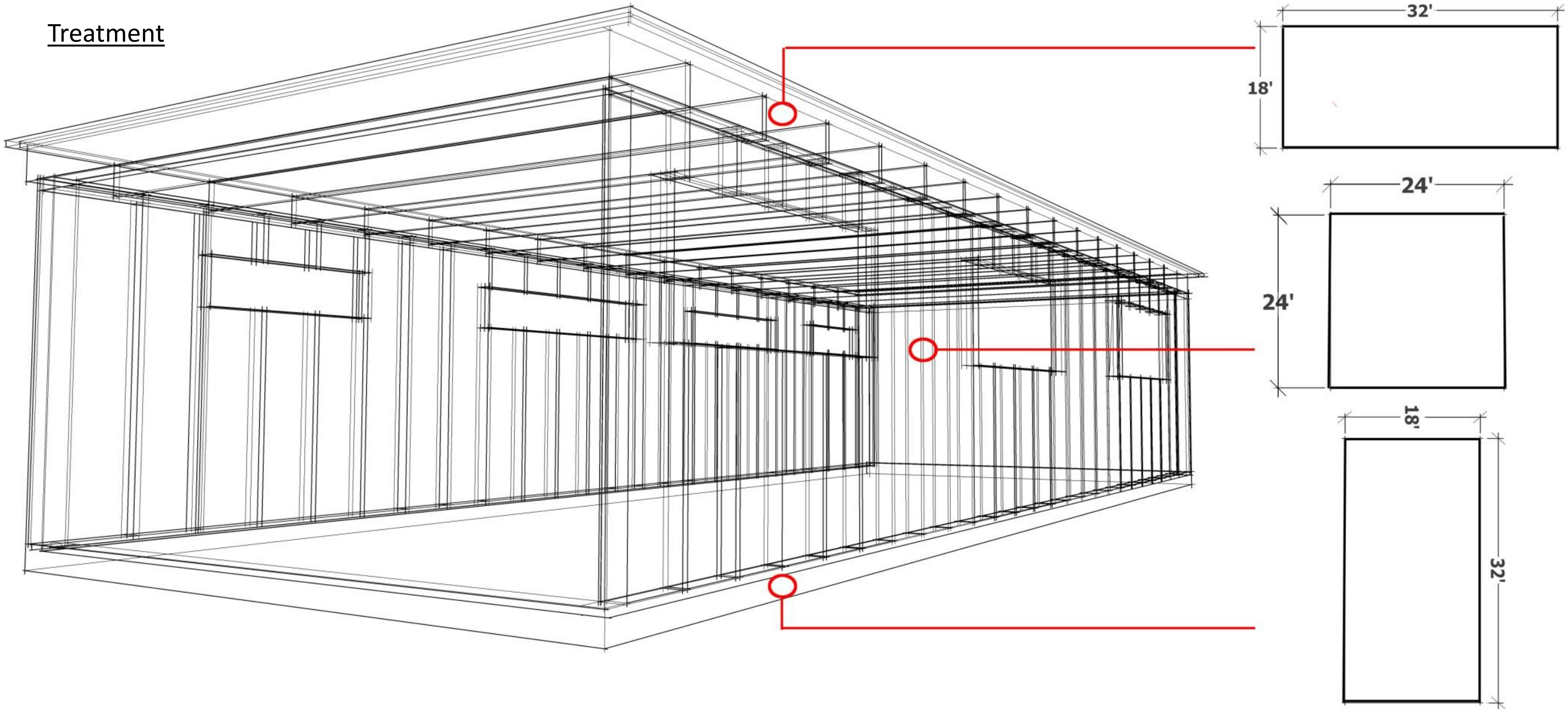
Regression Model

$$Y = \beta_0 + \beta_1.X_1 + \beta_2.X_2 + \beta_3.X_3 + \beta_4.X_4 + \beta_5.X_5$$

Independent Variables:

a) PCM Melting Temperature (X_1) – 18-29 degrees
b) PCM Enthalpy (X_2) – 50, 100, 150 KJ/Kg
c) Layers (X_3) – Interior, Interstitial, Exterior
d) Surfaces(X_4) – High Radiation, Low Radiation, All Surfaces
e) Length to Width Ratio (X_5) – >>1, 1, <<1

Treatment



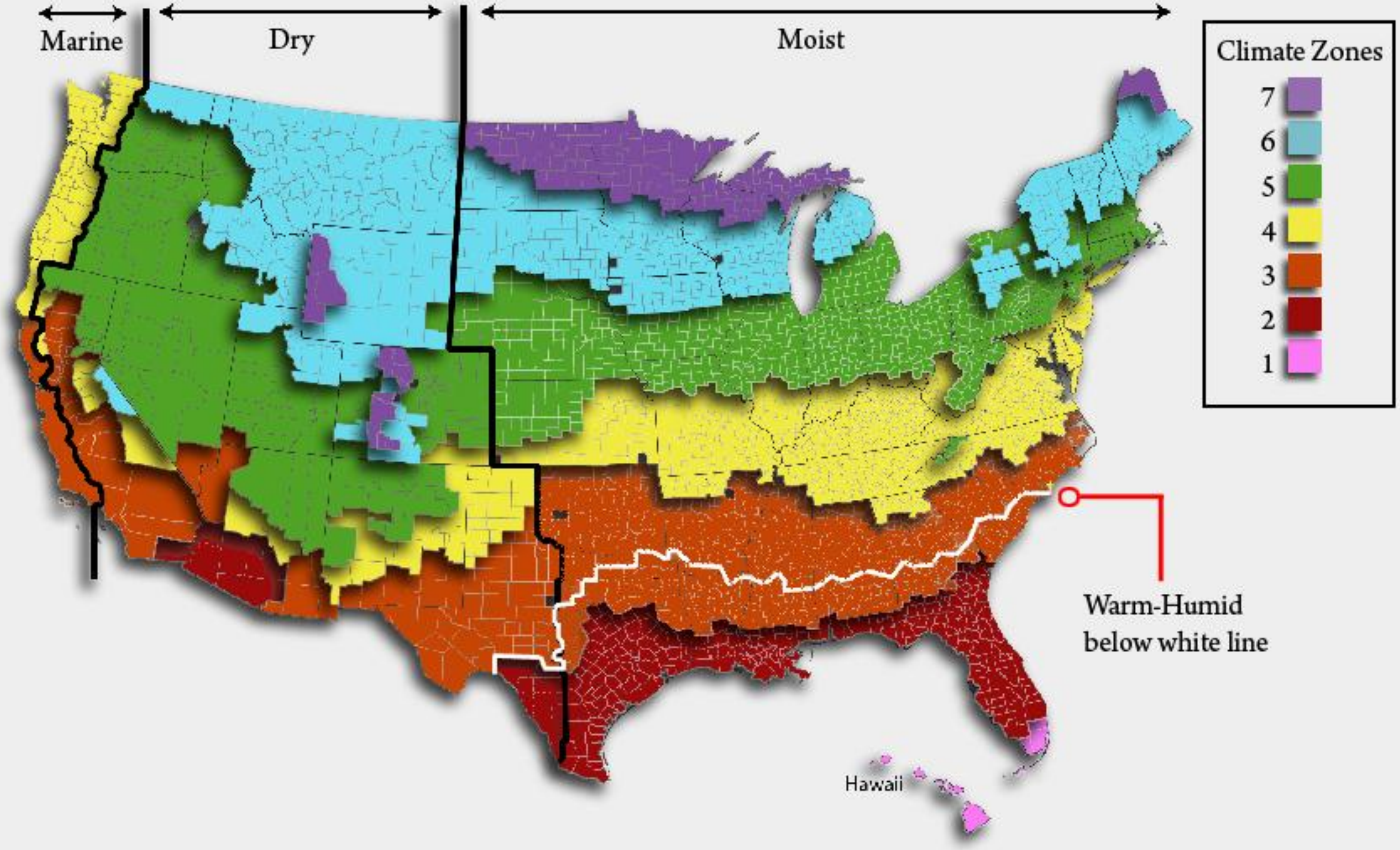
Factorial Design

Factors (Independent variables)	Levels
PCM Melt temperature	3 (18, 19, 20) (21, 22, 23) (24, 25, 26) (27,28,29)
Location in the room	3 (High Radiation, Low Radiation, All walls)
PCM enthalpy	3 (20 KJ/Kg, 30 KJ/Kg, 40 KJ/Kg)
Location within the wall	3 (Interior, Interstitial, Exterior)
Length to Width Ratio	3(>>1, 1, <<1)

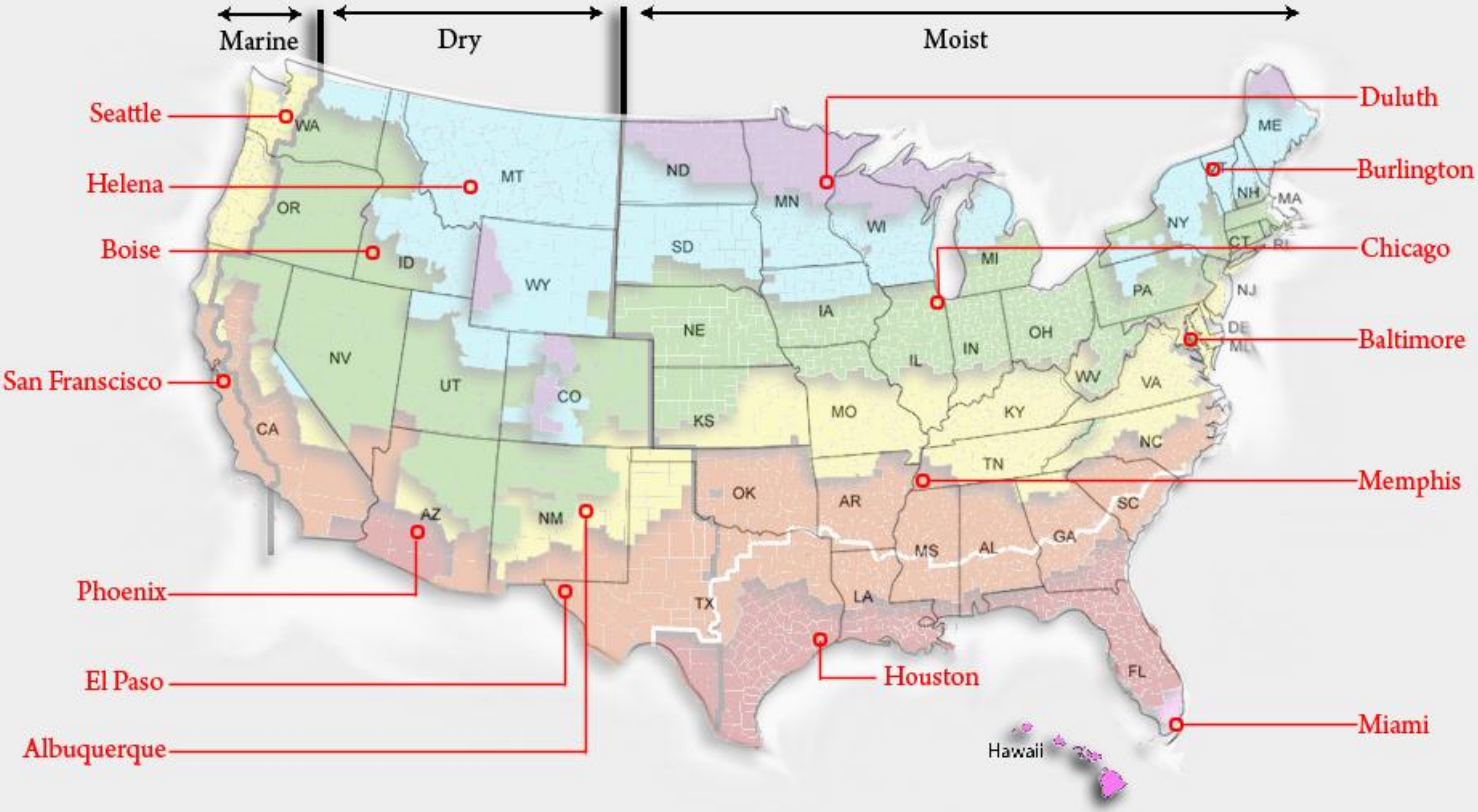
- **Control**: Building without PCM
- **Treatment**: Building with different combinations of PCM
- **Dependent Variable**: Annual Energy Consumption (Heating & Cooling)
- **Independent Variables**: 5 Factors - 3 levels each = 3^5 experiments = 243 experiments * 4= 972 Experiments (One Climate).

Goal: The development of response curves and design guidelines for the use of PCM in buildings.

U.S. Department of Energy: Climate Zones



U.S. Department of Energy: Representative Cities



972 experiments * 15 representative cities = 14580 experiments

Life Cycle Analysis of PCM

Life Cycle Analysis consists of analyzing all aspects of a product from craddle to grave in terms of cost, energy and environmental impact.

“Going green” is sometimes misleading when embedded energy is not considered.

Always beneficial for the owner but not always for the planet.

Macro-encapsulation → low embedded energy
Micro-encapsulated → large embedded energy

Copy of PCMMicroencapsulationprocess9-19 - Microsoft Excel

H58 =H57*H59

Step 1

Preparation of Melamine-Formaldehyde Precondensate

Input Energy	0.81	MJ/kg
Output Energy	0.002916	MJ
Mass	0.0036	kg
Molecular Weight	0.03003	kg km
Moles of Formaldeh	0.11988012	mol
aq. Formaldehyde (35-39%)		
Input Energy	3.2	MJ/kg
Output Energy	0.008	MJ
Mass	0.0025	kg
Molecular Weight	0.12612	kg km
moles of Melamine	0.01982239	mol
Melamine		
Input Energy	0.00162	MJ/kg
Output Energy	0.0000081	MJ
Mass	0.005	kg
Molecular Weight	0.018	kg/mo
Water		

Step 1:. 2.5g of Melamine is added to 3.6g of 37% Formaldehyde solution and 5g of Water. At 70°C, stir system at 600rpm for 1 hour.

Step 2: Cool system to 33°C

specific heat melamine	156.11	J/mol K
specific heat Formalde	36.69	J/mol K
specific heat H_2O	4.184	J/g K
$T_{initial}$1	20	(°C)
T_{final}1	70	(°C)
Reaction time	5400	seconds
Q1 Melamine	154.72	J
Q1 Formaldehyde	659.76	J
Q1 Water	1046	J
	=	
Q, Input Energy	1860.5	J
Pre-Energy	0.0109	MJ

density (formalde	1.09	g cm³
density (Melamir	1.573	g cm³
stirring rate, N³	1000	s⁻¹
N_p	4	
D_a⁵	5.905E-06	m
Mechanical Ener	0.0371536	Watts
Q, Input Energ	0.0018605	MJ
Mechanical Er	0.0002006	MJ
Pre-Energy	0.0109241	MJ
Sum	**0.01299**	**MJ**
Time	1.5	h
Heat Loss	0.0833333	assume 1
Added energy	0.0016232	MJ
Total Input En	**0.01461**	**MJ**

Preparation of Emulsion

Solution One — Prepare a solution of water and a hydrophillic colloid which becomes ionized in the water

Input Energy	1.42158	MJ/kg
Output Energy	2.11125743	MJ
Mass	1.48514851	kg
Molecular Weight	0.202	kg/km
Poly(Styrene-alt-Maleic Acid) Sodium Salt (Avg. MW 120,000,		
Input Energy	0.00162	MJ
Output Energy	0.00009315	MJ
Mass	0.0575	k g
Molecular Weight	0.018	kg/km
Water		

Step 1: Add 2.5g p(SMA)-[30% in H_2O MW= 120,000] to 57.5g of Water. Then adjust pH to 5

Reaction time	1800	seconds
stirring rate, N³	1000	s⁻¹
density	1.35	g cm⁻¹
N_p	4	
D_a⁵	6E-06	m
Mechanical Energy	0.0319	Watts
Pre Energy	2.1113	MJ

Pre Energy	2.1112574	MJ
Mechanical Er	5.74E-05	MJ
Sum	**2.11131**	**MJ**
Time	0.5	h
Heat Loss	0.0416667	assume
Added energy	0.0879715	
Total Input En	4.3105437	MJ

Solution Two — Prepare a second solution of water and hydrophillic colloid which becomes ionized in water with an electric charge opposite that of the colloid of the first solution

Input Energy	3.19881	MJ/kg
Output Energy	0.00047982	MJ
Mass	0.00015	kg

specific heat p(PG)	478.25	J/mol K
specific heat H_2O	4.184	J/g K
specific heat TDI	287.8	J/mol K

Density TDI	1.225	g cm⁻³
density PPG	1.004	g cm⁻³
N		

Step 2

Emulsification & Encapsulation

Add solutions 1,2,&3 at 31-33°C. to prepare emulsion solution Stir system at 2,0000 rpm for 10-15 min. Then slowly add droplets of the M-F precondensate solution

Energy Pre-conde	0.014608365	MJ
Energy solution O	4.310543698	MJ
Energy solution T	0.01519408	MJ
Energy solution T	2.974761164	MJ
Reaction time	900	seconds
$T_{initial}$1	20	(°C)
T_{final}1	33	(°C)
stirring rate, N³	37037.03704	s⁻¹
density	1.35	g cm³
N_p	4	
D_a⁵	5.9049E-06	m
Mechanical Energ	1.18098	Watts
Pre-Energy Step 1	7.315107308	MJ
Mechanical Energ	0.001062882	MJ
Sum	**7.31617019**	**MJ**
Time	0.25	h
Heat Loss	0.020833333	assum
Added energy	0.152420212	
Total Input Energ	**7.468590402**	**MJ**

After 15 minutes decrease stir rate to 400-600 rpm

Reaction time	900	seconds
stirring rate, N³	1000	s⁻¹
density	1.35	g cm³
N_p	4	
D_a⁵	5.9049E-06	m
Mechanical Energ	0.03188646	Watts
Mechanical Energ	2.86978E-05	MJ
Sum	**2.86978E-05**	**MJ**
Time	0.25	h
Heat Loss	0.020833333	assume 1/12 of heat is lost per hour
Added energy	5.97871E-07	
Total Input Energ	**2.92957E-05**	**MJ**

Total Emulsion Energy	7.468619698	MJ

St

Drying and Harden

specific heat melamine	156.11	J/m
specific heat Formaldehyde	36.69	J/m
specific heat H_2O	4.184	J/g
specific heat p(PG)	478.254519	J/m
specific heat n-paraffin	1.712	J/g
		J/m
$T_{initial}$	33	°C
T_{final}	80	°C
Reaction time	18000	sec
Total Mass		
Q n-paraffin	2413.92	J
Q_{Total} Input Energy	0.00241392	M

Insitu Condensation | U-M-F insitu polymerizatio | Insitu-Polymerization of UF | EE | Payback | XChemical | XElectricity | X | XComplex Coacervation

Ready | Page: 1 of 2

Copy of PCMMicroencapsulationprocess9-19 - Microsoft Excel

View

Wrap Text | General | Conditional Formatting | Format as Table | Euro | Standard_ecoin... | Temperaure | wissenschaft-... | Normal | Bad | Insert | Delete | Format | AutoSum | Fill | Clear | Sort & Filter | Find & Select

Merge & Center | $ % , | Alignment | Number | Styles | Cells | Editing

M	N	O	P	Q	R	S	T	U	V	W	X	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ

p 1

maldehyde Precondensate

t melamine	156.11	J/mol K	density (formalde	1.09	g cm³
t Formalde	36.69	J/mol K	density (Melamin	1.573	g cm³
t H_2O	4.184	J/g K	stirring rate, N³	1000	s⁻¹
	20	(°C)	N_s	4	
	70	(°C)	D_a^5	5.905E-06	m
			Mechanical Ener	0.0371536	Watts
e	5400	seconds	**Q, Input Energ**	0.0018605	MJ
			Mechanical Er	0.0002006	MJ
			Pre-Energy	0.0109241	MJ
e	154.72	J			
ehyde	659.76	J	**Sum**	**0.01299**	**MJ**
	1046	J			
	=		Time	1.5	h
nergy	1860.5	J	Heat Loss	0.0833333	assume 1
			Added energy	0.0016232	MJ
y	0.0109	MJ	**Total Input En**	**0.01461**	**MJ**

Step 2

Emulsification & Encapsulation

Add solutions 1,2,&3 at 31-33°C. to prepare emulsion solution Stir system at 2,0000 rpm for 10-15 min. Then slowly add droplets of the M-F precondensate solution

Energy Pre-conde	0.014608365	MJ
Energy solution O	4.310543698	MJ
Energy solution T	0.01519408	MJ
Energy solution T	2.974761164	MJ
Reaction time	900	seconds
$T_{initial}$1	20	(°C)
T_{final}1	33	(°C)
stirring rate, N³	37037.03704	s⁻¹
density	1.35	g cm³
N_s	4	
D_a^5	5.9049E-06	m
Mechanical Energ	1.18098	Watts
Pre-Energy Step 1	7.315107308	MJ
Mechanical Energ	0.001062882	MJ
Sum	**7.31617019**	**MJ**
Time	0.25	h
Heat Loss	0.020833333	assum
Added energy	0.152420212	
Total Input Energ	**7.468590402**	**MJ**

Step 3

Drying and Hardening of Capsule Shell

specific heat melamine	156.11	J/mol K
specific heat Formaldehyde	36.69	J/mol K
specific heat H_2O	4.184	J/g K
specific heat p(PG)	478.254519	J/mol K
specific heat n-paraffin	1.712	J/g K
		J/mol K
$T_{initial}$	33	°C
T_{final}	80	°C
Reaction time	18000	sec
Total Mass		
Q n-paraffin	2413.92	J
Q_{Total} Input Energy	0.00241392	MJ

stirring rate, N³	1000	s⁻¹
density	1.35	g cm³
N_s	4	
D_a^5	5.9E-06	m
Mechanical Energy	0.03189	Watts
Emulsion Energy	7.46862	MJ
Mechanical Energy	0.00057	MJ
Input Energy	0.00241	MJ
Sum	**7.4716**	**MJ**
Time	5	h
Heat Loss	0.41667	assume 1/12 of heat is lost per hour
Added energy	3.11317	MJ
Total Energy Consum	**10.585**	**MJ** for 30 g of PCM
for 1 kg of PCM	320.751	MJ
	0.32075	BJ
	0.00032	TJ
solar radiation	200	W/m2
roof	150	m2
	30000	W
	864	MJ
Wall	400	m2
Wall 1 cm	4	m3
	4000	kg
30% PCM	1200	kg
Manufacturing energy	384901	MJ
Savings % due to PCM	0.1	%
	86.4	MJ per day
	4454.87	days
PAY BACK	**37.12**	**years**

of Emulsion

rophillic colloid which becomes ionized in the water

e	1800	seconds	**Pre Energy**	2.1112574	MJ
N³	1000	s⁻¹	**Mechanical Er**	5.74E-05	MJ
	1.35	g cm⁻¹	**Sum**	**2.11131**	**MJ**
	4				
	6E-06	m			
Energy	0.0319	Watts	Time	0.5	h
			Heat Loss	0.0416667	assume 1
	2.1113	MJ	Added energy	0.0879715	
			Total Input En	**4.3105437**	**MJ**

After 15 minutes decrease stir rate to 400-600 rpm

Reaction time	900	seconds
stirring rate, N³	1000	s⁻¹
density	1.35	g cm³
N_s	4	
D_a^5	5.9049E-06	m
Mechanical Energ	0.03188646	Watts
Mechanical Energ	2.86978E-05	MJ
Sum	**2.86978E-05**	**MJ**
Time	0.25	h
Heat Loss	0.020833333	assume 1/12 of heat is lost per hour
Added energy	5.97871E-07	
Total Input Energ	**2.92957E-05**	**MJ**

Total Emulsion Energy	7.468619698	MJ

nd hydrophillic colloid which becomes ionized in
e that of the colloid of the first solution

t p(PG)	478.25	J/mol K	Density TDI	1.225	g cm⁻³
t H_2O	4.184	J/g K	density PPG	1.004	g cm⁻³
t TDI	297.8	J/mol K	N	4	

For 33 g				
Oc 2.974761164		MJ	2820	BTU
PC 10.5847774		MJ	10034	BTU

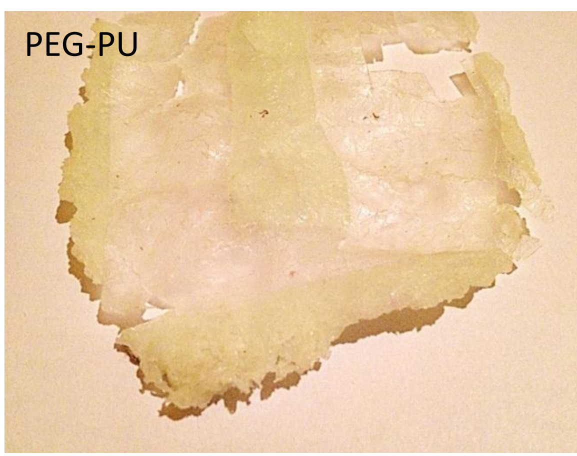
Insitu-Polymerization of UF | EE | Payback | XChemical | XElectricity | X | XComplex Coacervation

68%

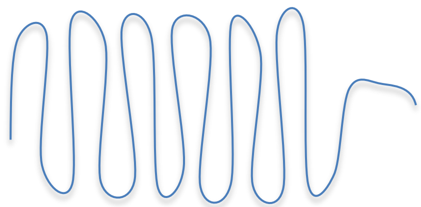
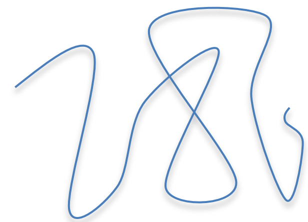
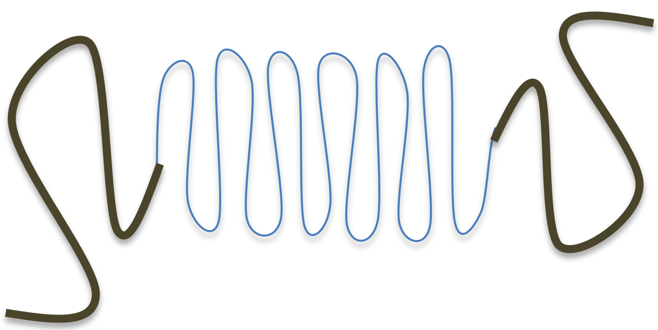
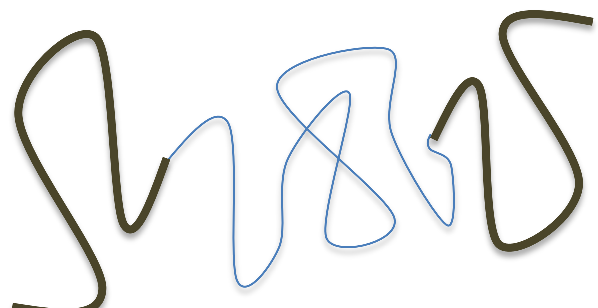
Synthesis and Characterization of Solid-Solid PCM

Background

- Solid-liquid PCM require encapsulation, are costly and have high embodied energy.
- Solid-solid PCM (SSPCM) are expected to be better alternatives.
- PEG-PU is a PCM polymer made of Polyethylene Glycol (PEG) and a polyurethane polymer (PU) or cellulose diacetate (CDA).
- Energy storage and release are due to change of phase from the semi-crystalline phase to the amorphous phase of PEG.
- When grafted to a backbone polymer, the amorphous PEG remains solid at high temperature.



Solid-Solid Phase Transformation by cross-linking

	Semi-crystalline state (lamellae)	Amorphous state
Pure PEG		 (macro-fluidity → liquid)
Cross-linked PEG		 Remains solid

Increase temperature →

Synthesis and Characterization of Solid-Solid PCM

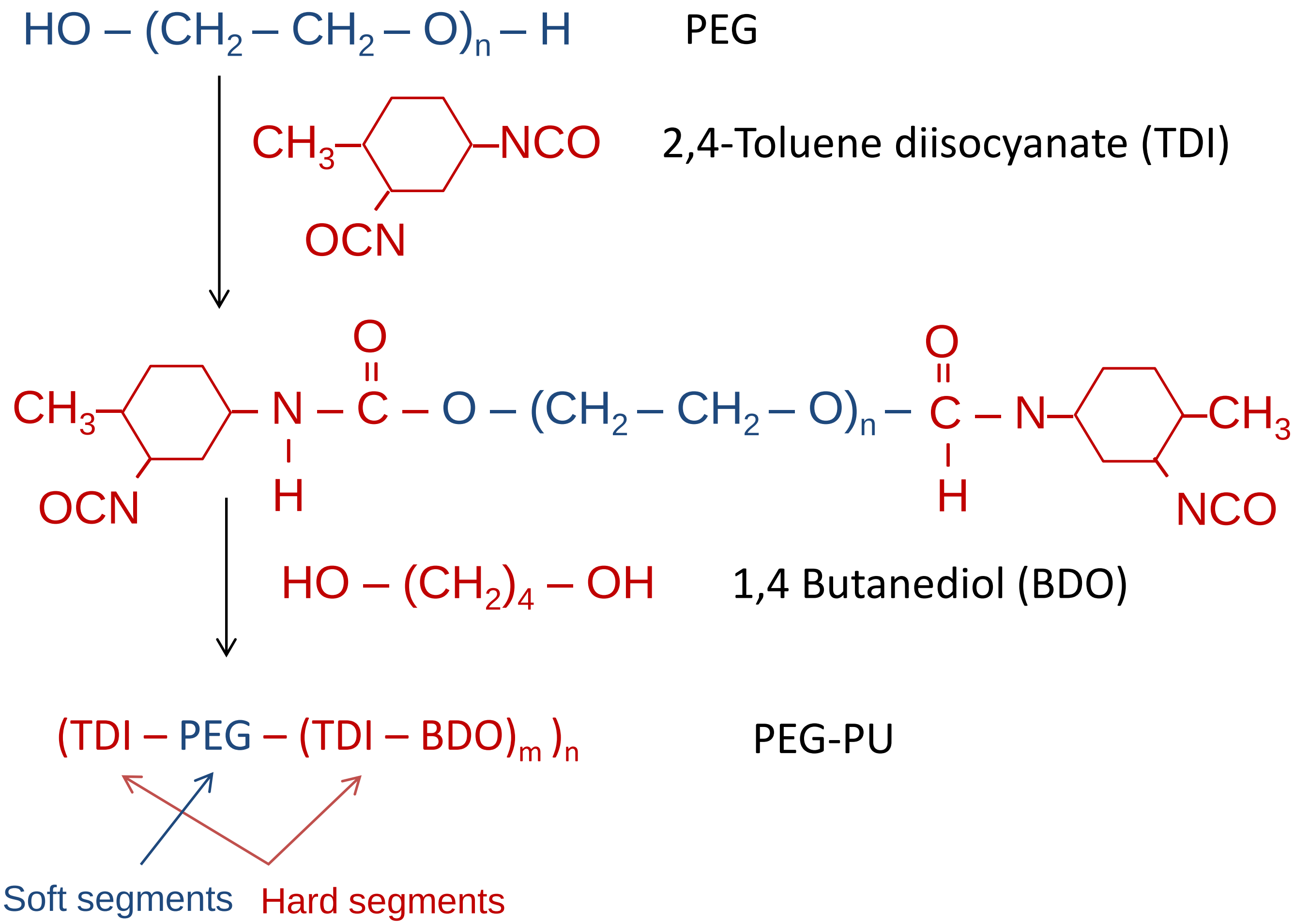
Research goals

- Understand the synthesis process of PEG-PU and PEG-CDA.
- Characterize thermo-mechanical properties.
- Understand the phase change process in order to control the phase change temperature, maximize enthalpy, optimize mechanical properties, and minimize environmental impact.

Why focus on Polyethylene Glycol (PEG) as a PCM polymer?

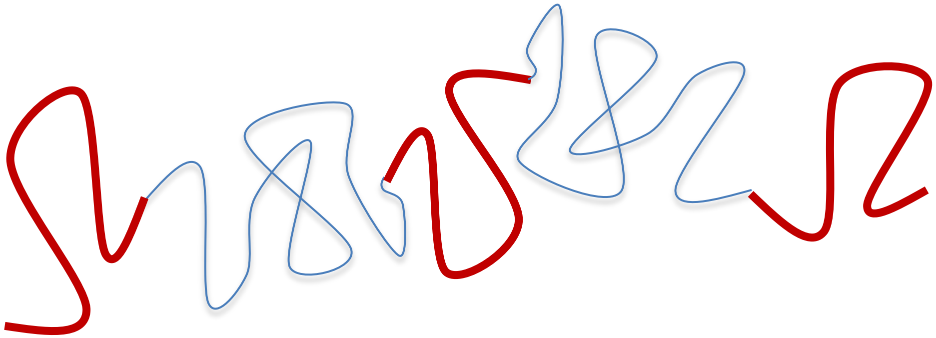
- Non-toxic, biocompatible and biodegradable
- Hydrophilic
- -OH end groups allow easy chemical modification
- Crystallizes easily thanks to simple linear polymer chain
- Ample production at various molecular weights from 0.3 to 10,000 kg/mol

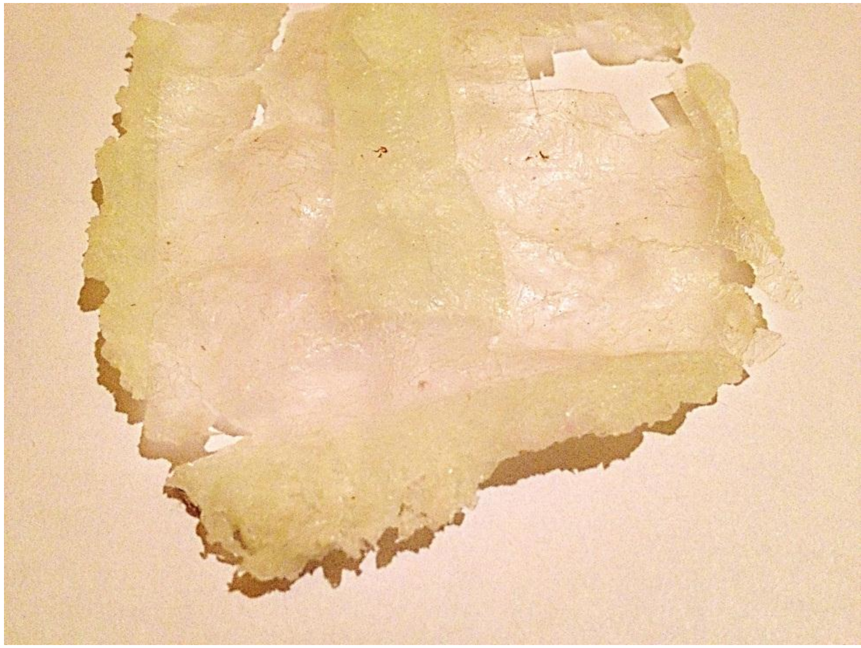
Synthesis


HO – (CH2 – CH2 – O)n – H
PEG
CH3 NCO OCN
2,4-Toluene diisocyanate (TDI)
CH3 OCN N – C – O – (CH2 – CH2 – O)n – C – N CH3 NCO
O
H
HO – (CH2)4 – OH
1,4 Butanediol (BDO)
(TDI – PEG – (TDI – BDO)m)n
PEG-PU
Soft segments
Hard segments

PEG-PU Synthesis

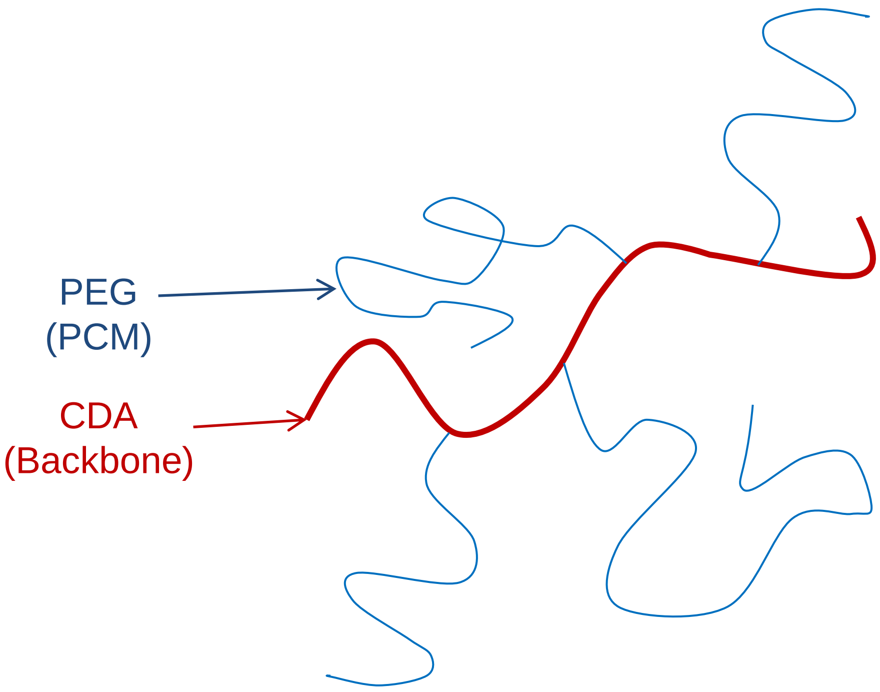
- PU includes isocyanate groups (NCO) and hydroxyl groups (OH)
- Dissolve PEG by 1/3 wt%
- Heat to 50-60˚C and purge with Nitrogen
- Add stoichiometric amounts of TDI and BDO
- Reflux for 30 minutes
- Before the gelation occurs pour into mold and either place in oven or hot press
- Let cool until sample gel hardens





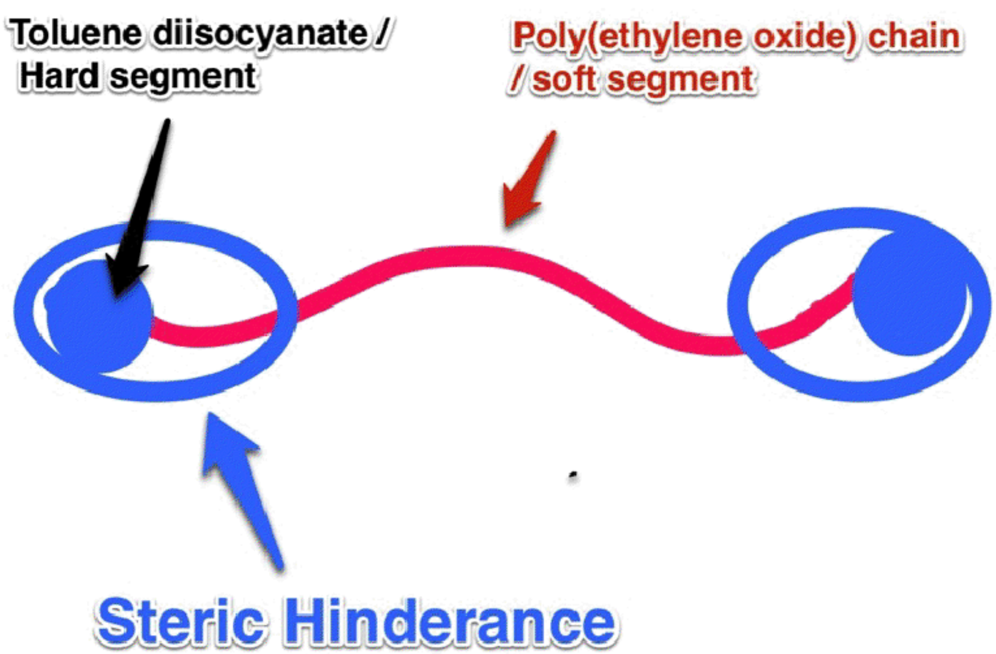
PEG-CDA

- PEG grafted onto the Backbone of Cellulose Diacetate (CDA)
- Cellulose Diacetate is a thermally stable polymer that remains intact above PEG melting temperature



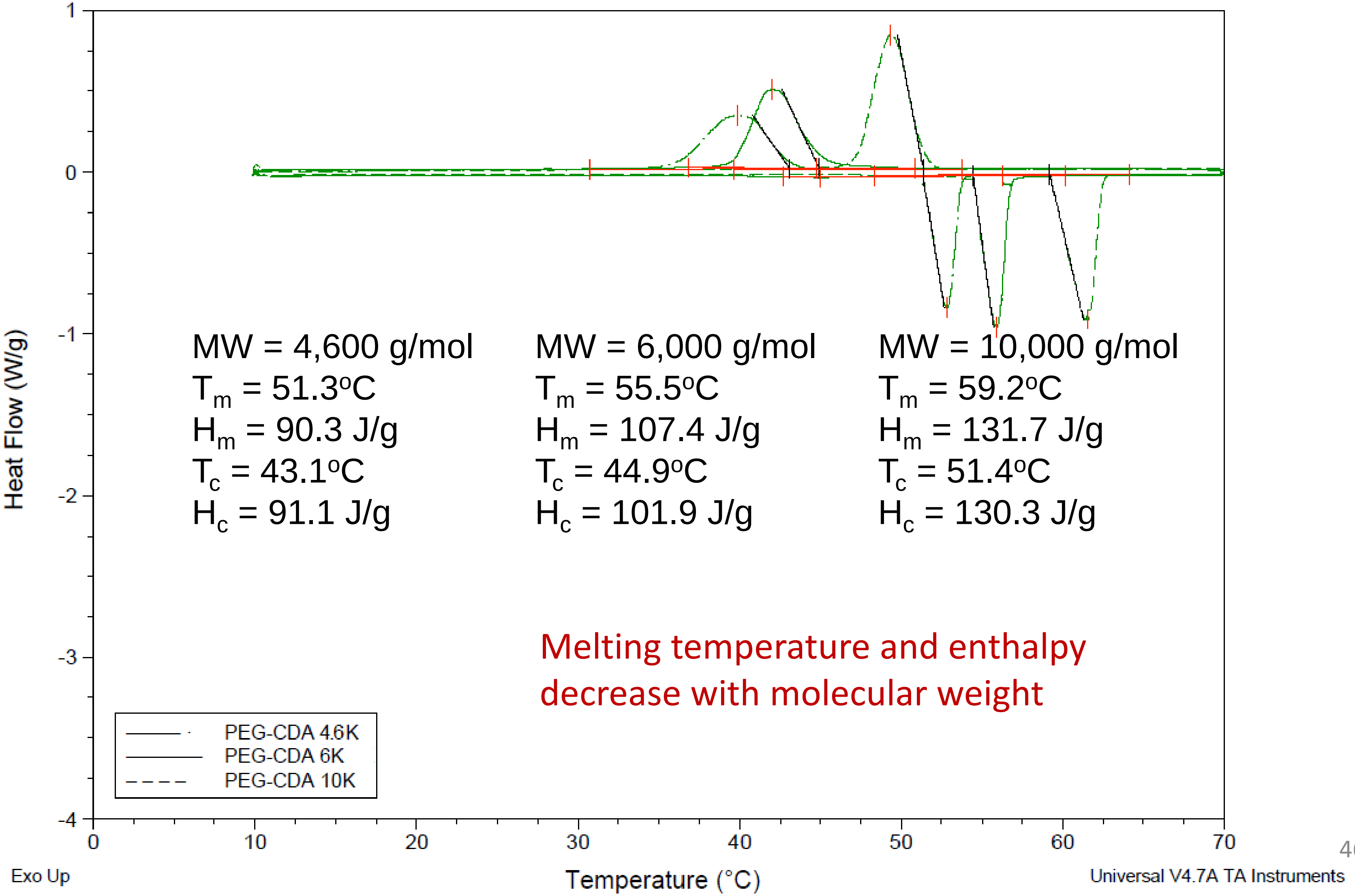
Length of chain and crystallization

- Smaller molecular weight of PEG leads to shorted chains
- Shorter chains result in lower phase change temperature (which is desirable)
- However, steric hinderance reduces length useful chain where crystallization occurs, which reduces the enthalpy / latent heat (which is not desirable)
- One goal is to reduce effect of steric hinderance



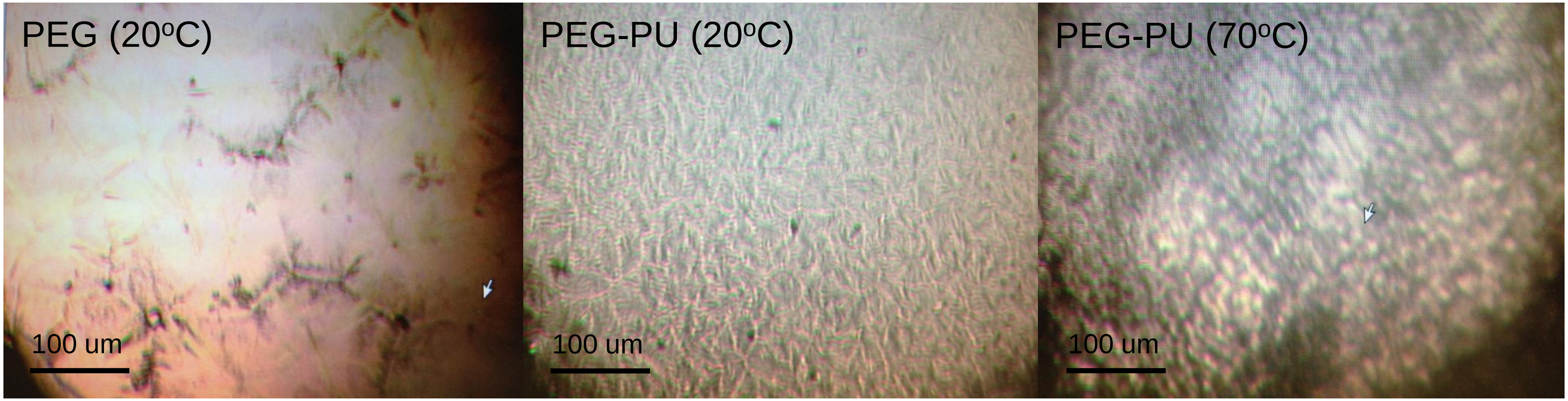
Differential Scanning Calorimetry (DSC)

- Measure melting and crystallization temperatures and enthalpy values



Polarized Optical Microscopy (POM)

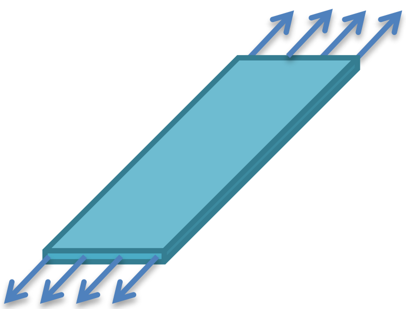
- POM is used to visualize and identify the crystal structure
- At room temperature, both pure PEG and PEG-PU show spherulites
- Spherulites in PEG-PU are smaller because hard segments interfere with PEG crystalline behavior
- At 70^{o}C, the spherulites disappear since crystals have melted

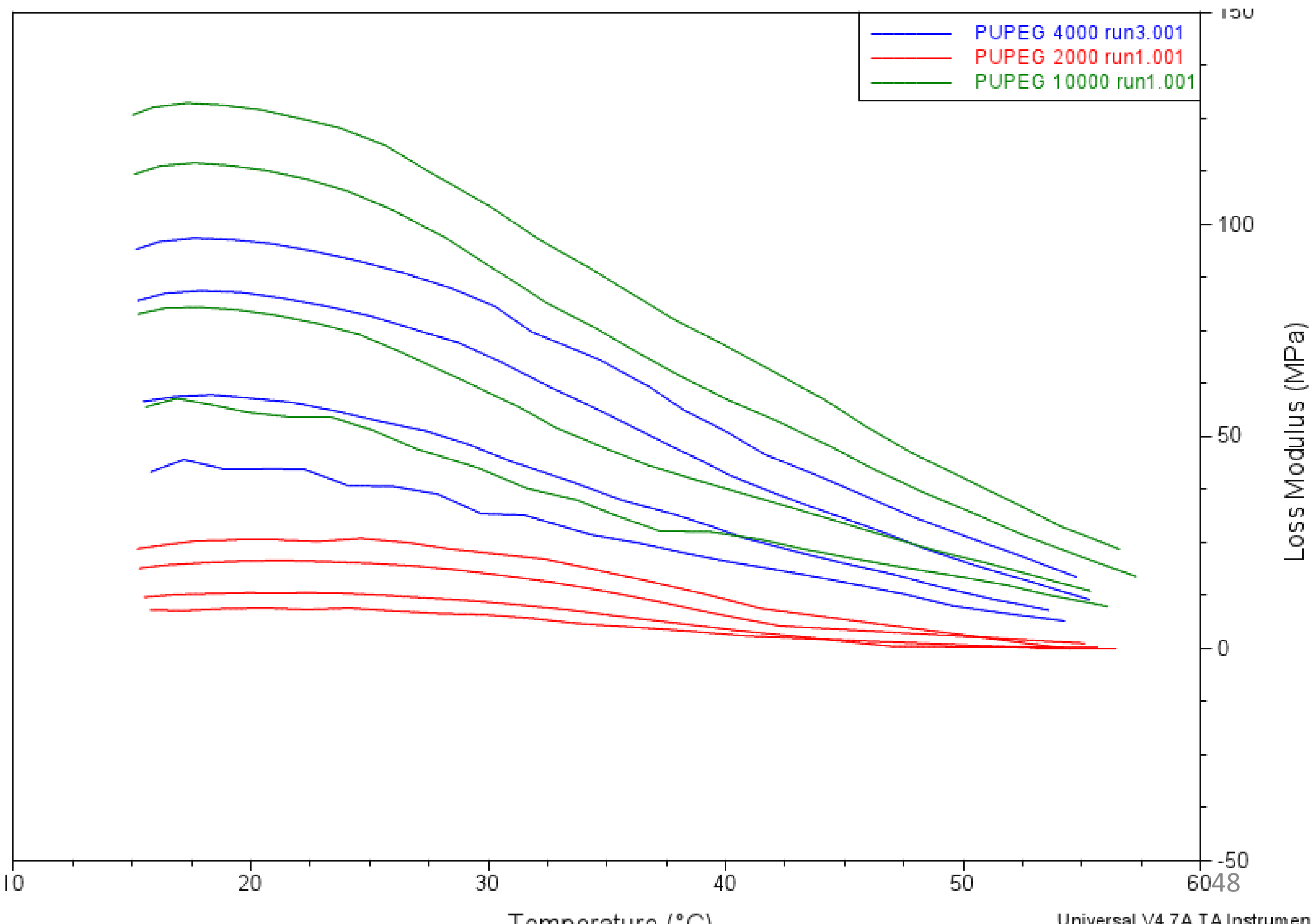


Dynamic Mechanical Analysis (DMA)

- DMA is used to characterize the viscoelastic behavior of PEG-PU over temperature range

Dynamic sinusoidal stress (1 Hz)





Summary

- Research project involving students and faculty from architecture and engineering collaborate to identify best materials and practice
- This on-going project has the potential to promote use of PCM by providing a unified set of design guidelines (reduced need of engineering studies)
- PCM can reduce the energy footprint of buildings. However:
  - PCM have high initial cost
  - Some PCM have large embodied energy
- PCM should be a common construction material in the future

Acknowledgement

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National Science Foundation

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