THERMOPHYSICAL STORAGE BREAKOUT

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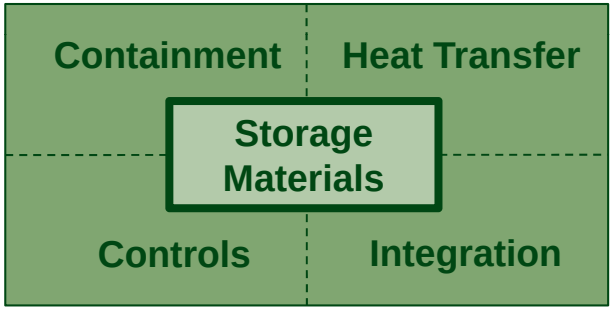
BASIC THERMAL STORAGE CONSIDERATIONS

Key Metrics of Performance	Example Units	Material Property	System Property
Storage Energy Density	MJ /kg, MJ /L	✔	✔
Transfer Power Density	MJ /kg•hr, MJ /L•hr	✔	✔
Operating Temperature	ºC	✔	✔
Cycle Life	# Cycles	✔	✔
Self-Discharge Rate	% /hour		✔
Roundtrip Efficiency	%		✔
Cost	$/MJ	✔	✔

Thermal Storage System



- Several important metrics to consider
- Both materials and system level considerations are important
- Properties may be complex or coupled, for instance:
  - e.g. power capability may change as heat is extracted and reactions proceed
  - e.g. power capability may degrade after several cycles

PRIMARY APPLICATIONS OVERVIEW

Buildings
Impact Objective: Dramatically reduce building energy consumption by storing and redeploying heat or cold to match building loads or optimize time of electricity use

Solar Thermal Power Generation
Impact Objective: Enable widespread deployment of solar thermal power by firming and extending the time window of output power generation

Industrial waste heat capture and storage
Impact Objective: Dramatically reduce industrial energy consumption by storing and redeploying waste heat for processing and manufacturing

Operational Mode(s)	Current Solution(s)	R&D Needs
Buildings: diurnal load shifting	water tanks, ice, embedded building materials…	• Energy density • Power density • Longer storage time and less loss • Thermal cycling stress • Reaction reversibility • Cost
Buildings: seasonal load shifting	soil, sand, water, concrete…	
Buildings: storage coupled to CHP	water, oil, organic phase change materials…	
Solar thermal storage	molten salts	
Industrial waste heat capture and storage	High temp sensible and latent systems	

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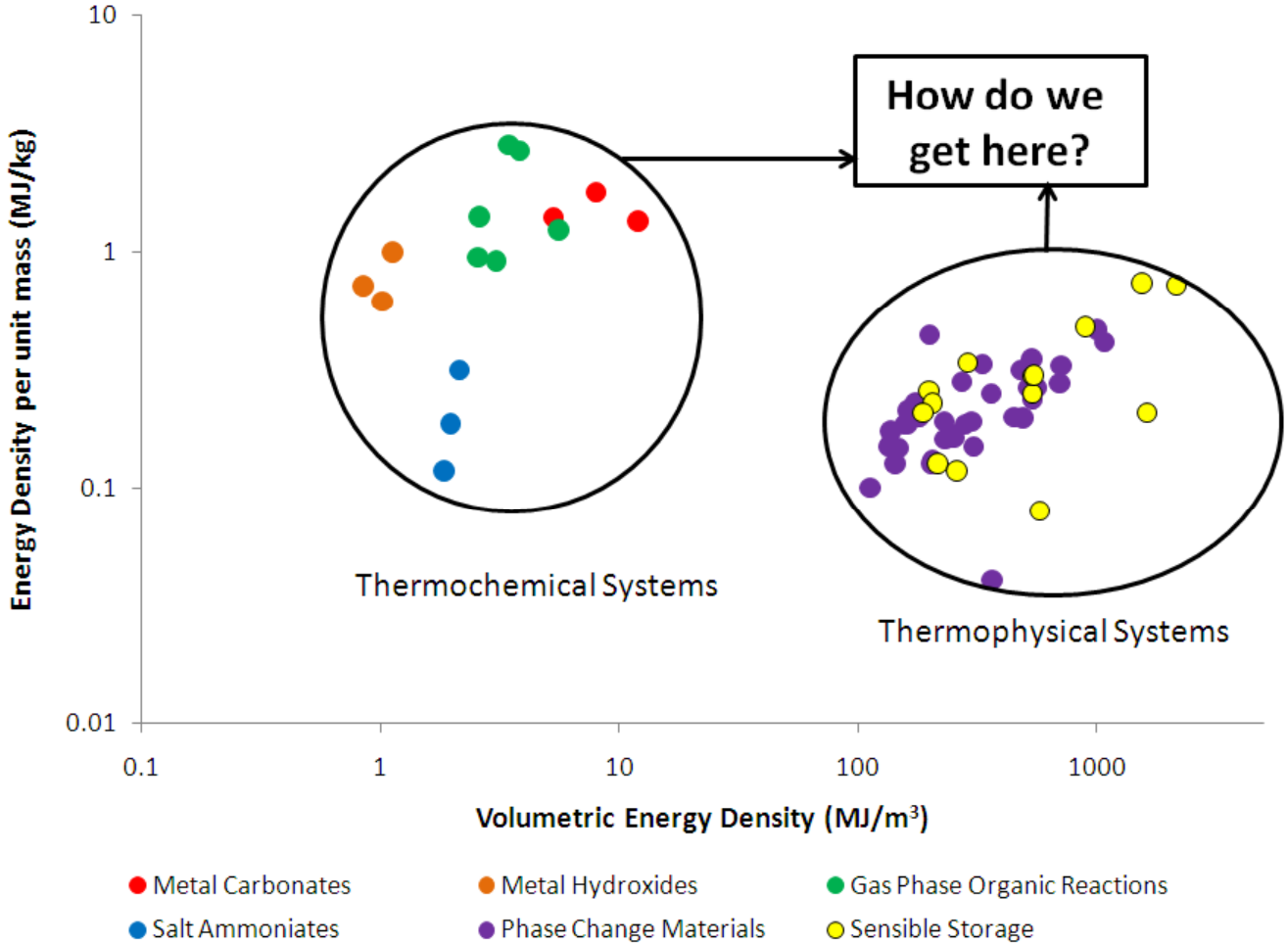

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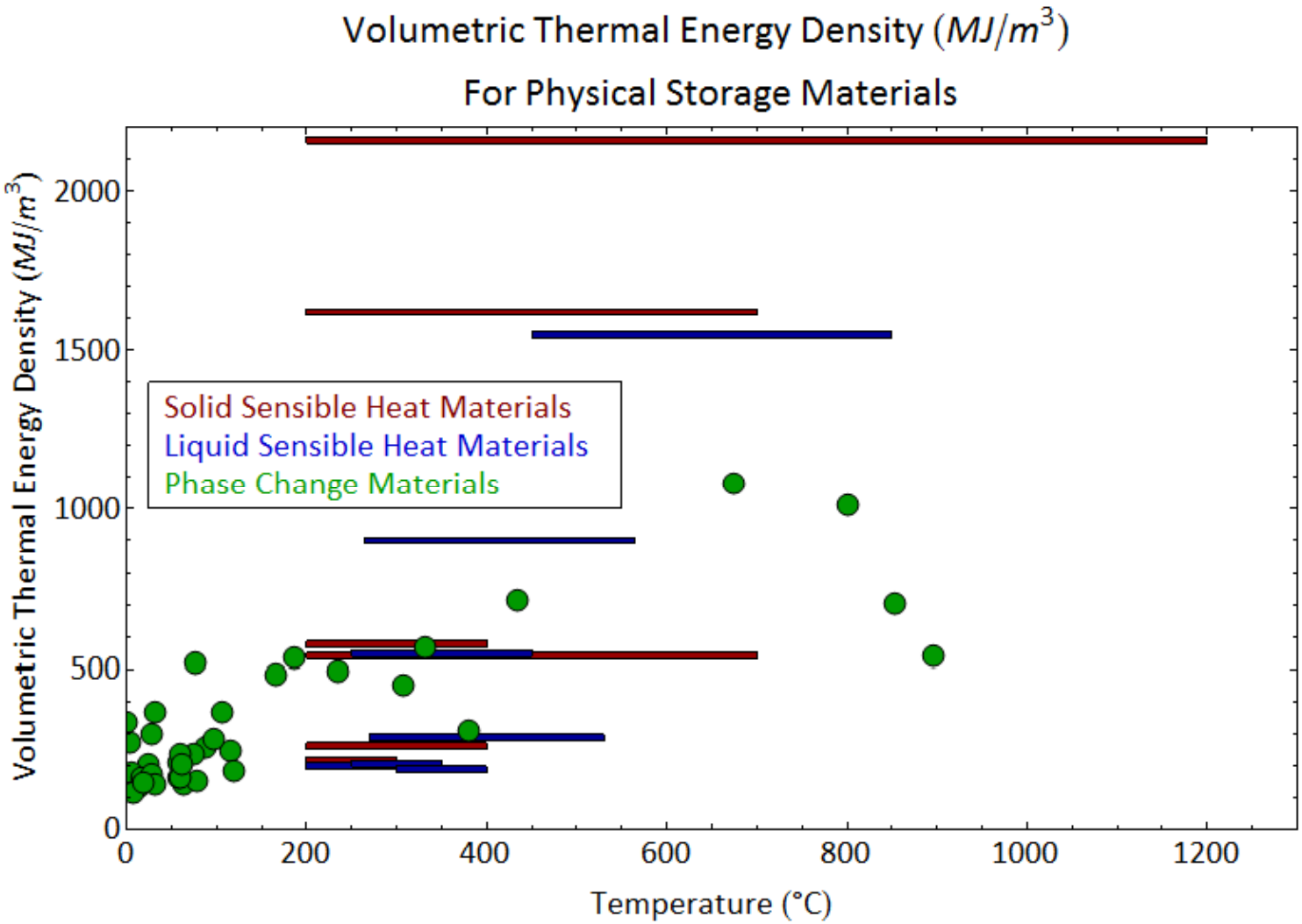
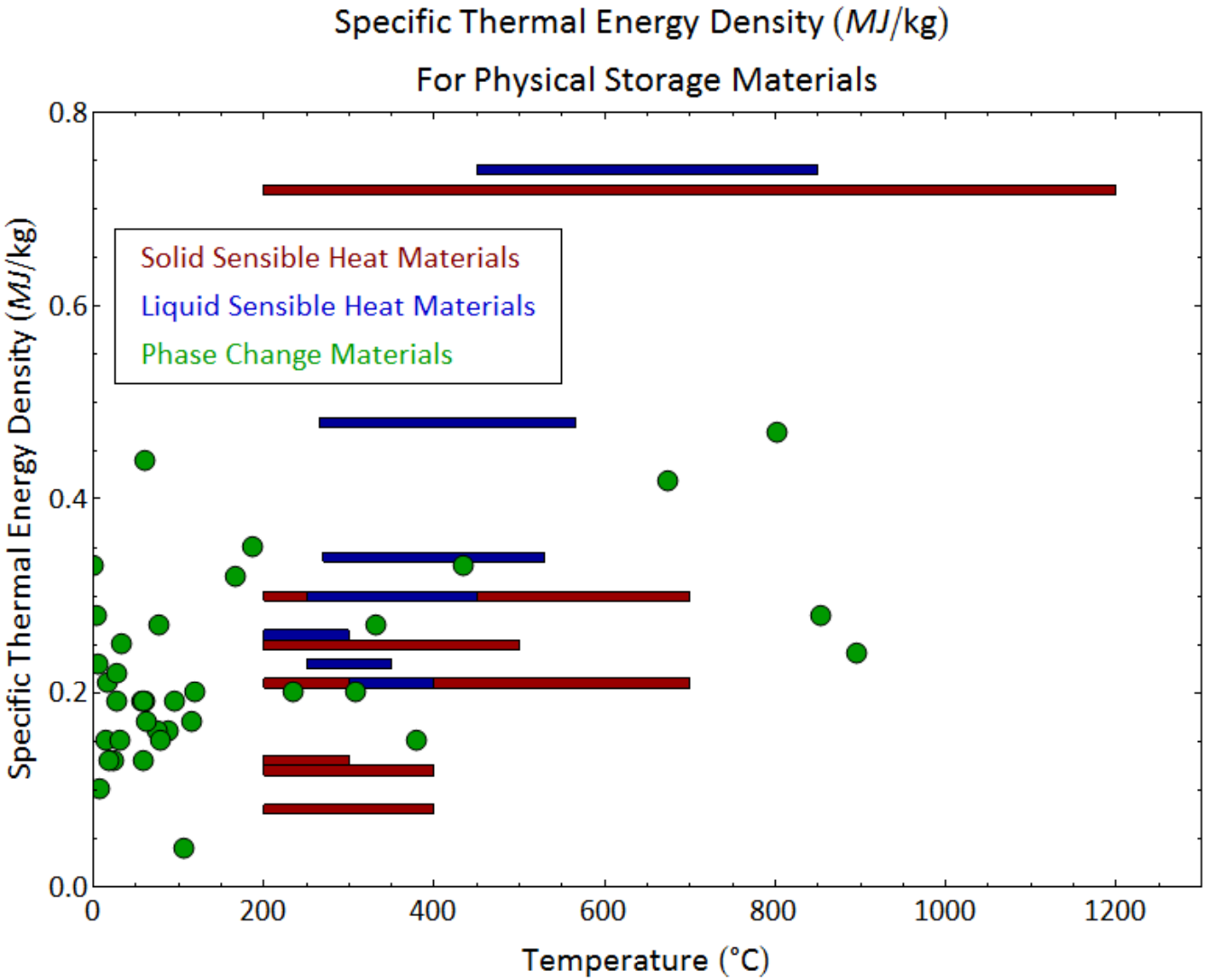
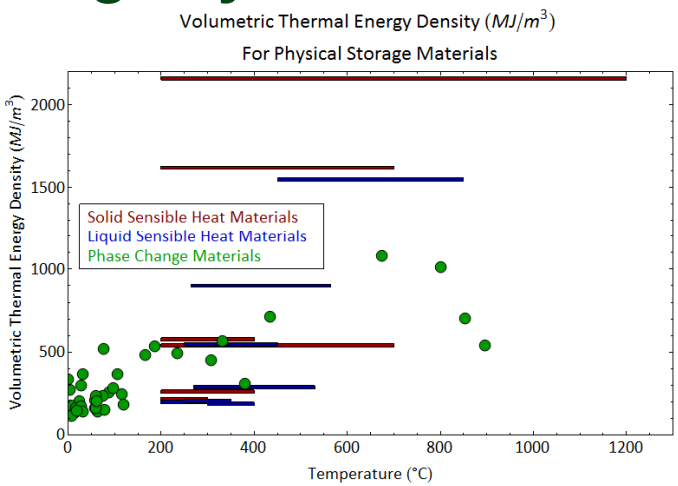


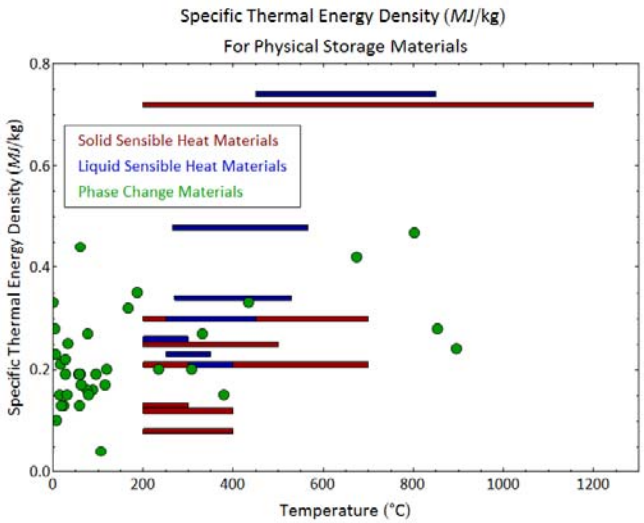
BASIC THERMOPHYSICAL STORAGE CONSIDERATIONS



QUESTIONS

1. What are the 5 most impactful energy applications of physical thermal storage? What has been the bottleneck in the adoption of physical storage systems?





Are there regions on this plots that would enable new applications? At what cost?

5 m → 10 m → 15 m

QUESTIONS

2. A physical storage system consists of a number of elements:

- **Storage medium**
- **Insulation**
- **Charge/discharge method**
- **Pressure vessel/encapsulation**

Which of these areas presents a need and opportunity for advancement? (poll)

5 m | 10 m | 15 m

QUESTIONS

3.For the <u>storage medium</u>: Are there additional materials or phenomena that we have not yet considered? For example

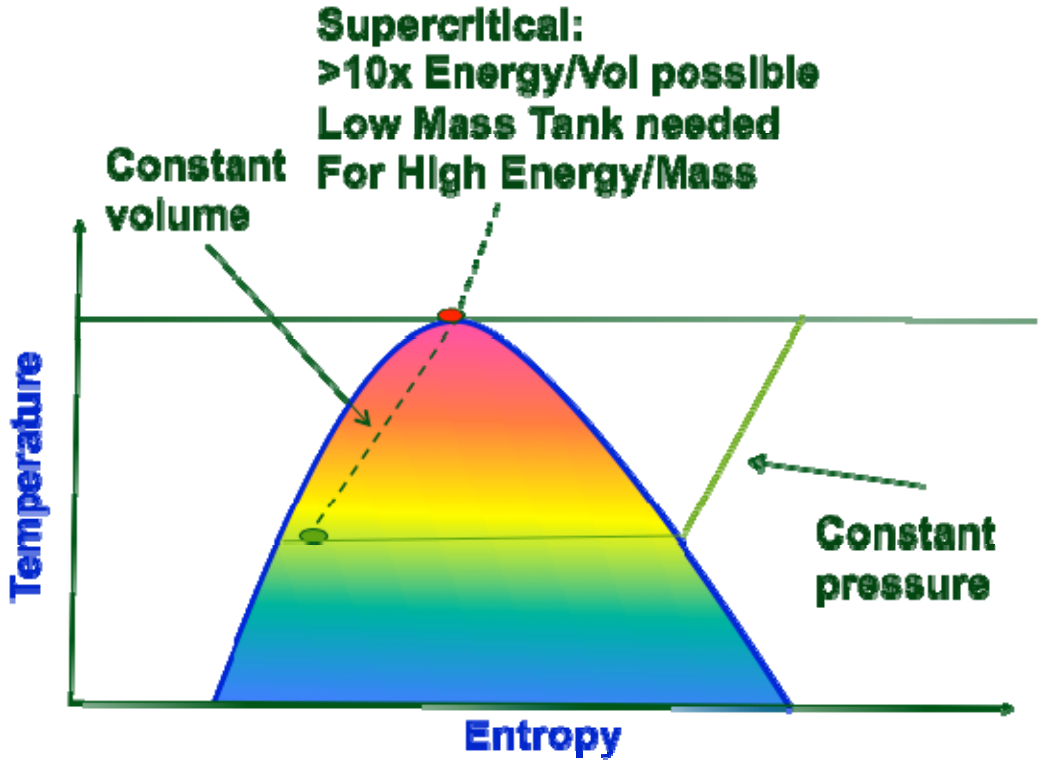
a) Why have supercritical states not been widely considered for thermal storage? How can pressure vessel cost be significantly reduced?

b) Can self-assembly of nanostructures and molecules be used for thermal storage?

c) How can nanotechnology and molecular engineering be used for altering thermodynamic properties?

d) Can second-order phase transitions (e.g. magnetic phase transitions) be used for thermal energy storage?

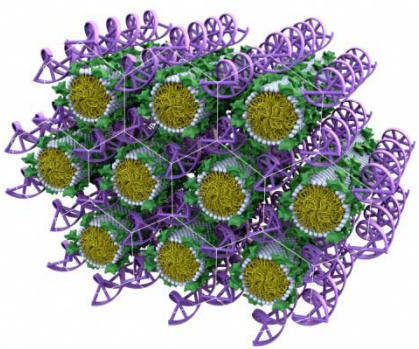
SUPERCRITICAL ENERGY STORAGE

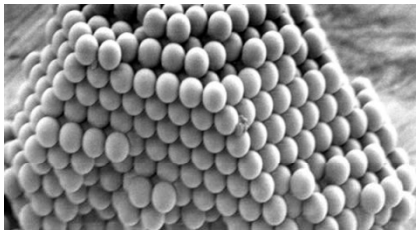


	Pressure (bar)	Temperature (oC)	Kj/kg	Mj/m3
Critical	220	374	1049	330
Super heated	28	374	2214	14.5
Ice		0	330	330

NANOSTRUCTURES & SELF-ASSEMBLY FOR THERMAL ENERGY STORAGE

Organized
Low Temp State





Heat In
Molecules Unfold

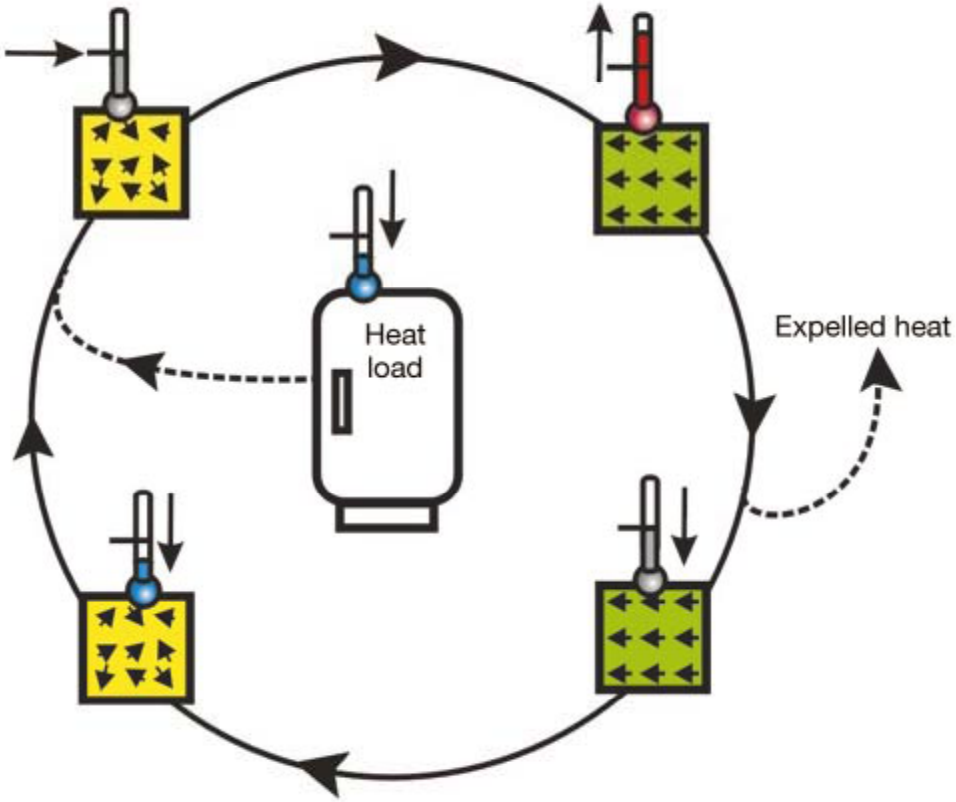
Disorganized
High Temp State

Energy Recovery
Heat Removal
Molecules Refold

How much energy can we store?

Is chemical degradation an issue?

MAGNETOCALORIC MATERIALS



Tegus et al. Nature, 2002

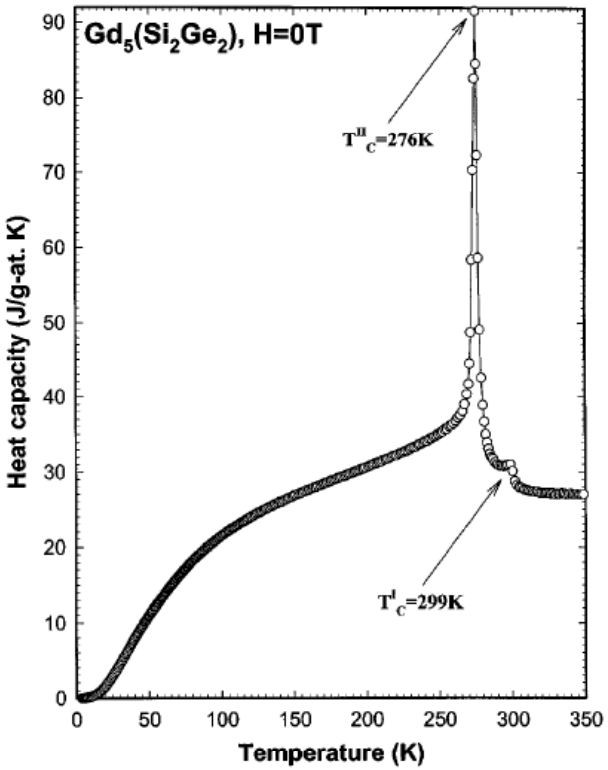


FIG. 1. The zero magnetic field heat capacity of $Gd_5(Si_2Ge_2)$ from 3.5 to 350 K. The arrows point to heat capacity anomalie due to a second order paramagnetic ↔ ferromagnetic (I) transformation at 299 K and a first order ferromagnetic (I) ↔ ferromagnetic (II) transition at 276 K.

Pecharsky et al. PRL, 1997

QUESTIONS

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b) Can self-assembly of nanostructures and molecules be used for thermal storage?

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d) Can second-order phase transitions (e.g. magnetic phase transitions) be used for thermal energy storage?

QUESTIONS

4. Is it possible to beat ice by 2X for low temperature systems in volumetric and mass energy density without dramatically increasing the cost?

Phase Change: 334.00 MJ/m^3, 0.33 MJ/kg
Specific heat capacity, ice: 2.108 kJ/kg-K
Specific heat capacity, water: 4.187 kJ/kg-K
Specific heat capacity, water vapor: 1.996 kJ/-kgK

QUESTIONS

5. For the <u>charge/discharge</u>: What are the special challenges related to:

- **a) Solid sensible heat materials**
- **b) Liquid sensible heat materials**
- **c) Phase change materials**
- **d) Others**

What research areas can overcome these challenges?

Is it important to separate out metrics for both $/MJ$_{th}$ and $/W$_{th}$?

5 m → 10 m → 15 m

QUESTIONS

6. What advances are needed for <u>thermal insulation</u>?

a) Can it be made switchable with very high conductivity contrast?

b) Can we have reliable low cost vacuum insulation?

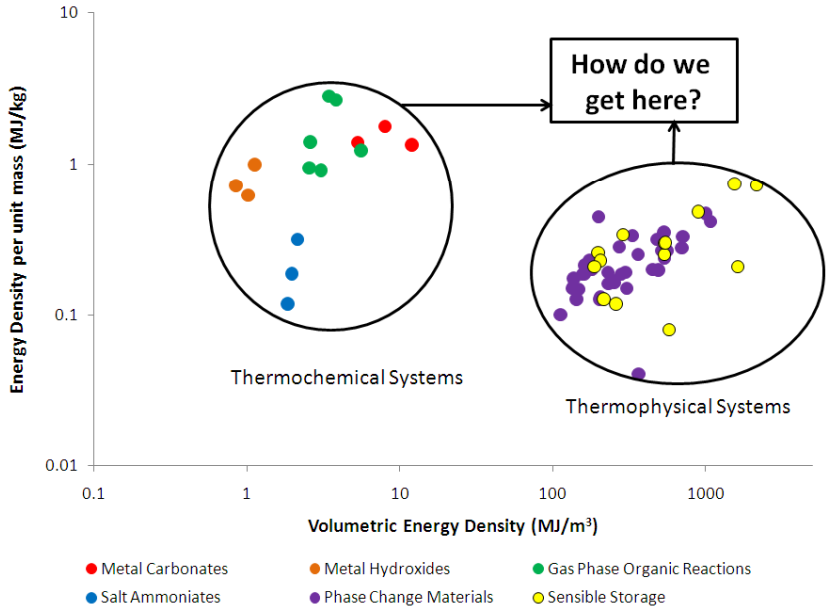
c) Can physical storage systems be used for long distance thermal energy transmission?

d) What would be the key impacts of these advances?

5 m | 10 m | 15 m

QUESTIONS

7. How can the mass energy density of physical storage system be made as high as chemical energy storage system (> 1 MJ/kg) without compromising on the volumetric energy density (> 300 MJ/m^3)?



5 m → 10 m → 15 m

QUESTIONS

8. What will a very high impact research and development program look like for physical storage? What will be the composition of an ideal research team?

Is it enough to specify:

- **Cost metrics ($/kWh$_{th}$ $/W$_{th}$)**
- **Energy density metrics (MJ/kg MJ/m^3)**
- **Cycle life**
- **Roundtrip efficiency**
- **Storage times**

What should those metrics be? What targets should we be challenging researchers to achieve?

5 m | 10 m | 15 m

BASIC THERMOPHYSICAL STORAGE CONSIDERATIONS

Solid Media - Sensible Storage	Temperature (°C)	MJ/m3	MJ/kg	dT	Tc (°C)	Th (°C)
Sand-rock-mineral oil	250	216.00	0.13	100	200	300
Reinforced concrete	300	260.00	0.12	200	200	400
NaCl (solid)	350	540.00	0.25	300	200	500
Cast Iron	300	576.00	0.08	200	200	400
Cast Steel	450	1620.00	0.21	500	200	700
Silica fire bricks	450	540.00	0.30	500	200	700
Magnesia fire bricks	700	2160.00	0.72	1000	200	1200

Liquid Media - Sensible Storage	Temperature (°C)	MJ/m3	MJ/kg	dT	Tc (°C)	Th (°C)
Mineral Oil	250	198.00	0.26	100	200	300
Synthetic Oil	300	205.20	0.23	100	250	350
Silicone Oil	350	187.20	0.21	100	300	400
Nitrite Salts	350	547.20	0.30	200	250	450
Nitrate Salts	415	900.00	0.48	300	265	565
Carbonate Salts	650	1548.00	0.74	400	450	850
Liquid Sodium	400	288.00	0.34	260	270	530

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Phase Change Media	Temperature (°C)	MJ/m3	MJ/kg
NaNO3	308	450.00	0.20
KNO3	333	561.60	0.27
KOH	380	306.00	0.15
Salt-ceramics (NaCO3-BaCO3/MgO)	675	1080.00	0.42
NaCl	802	1008.00	0.47
Na2CO3	854	698.40	0.28
K2CO3	897	540.00	0.24
Water	0	334.00	0.33
CaCl2.6H2O	29	298.34	0.19
Na2CO3.10H2O	33	362.09	0.25
Ba(OH)2.8H2O	78	514.66	0.27
Mg(NO3)2.6H2O	89	252.34	0.16
MgCl2.6H2O	117	244.47	0.17
66.6%CaCl2.6H2O+33.3%MgCl2.6H2O	25	201.93	0.13
58.7%Mg(NO3).6H2O+41.3%MgCl2.6H2O	59	204.60	0.13
66.6%urea+33.4%NH4Br	76	231.84	0.16
68.1%KCl+31.9%ZnCl2	235	491.04	0.20
38.5%MgCl+61.5%NaCl	435	708.48	0.33
Paraffin-C14	6	174.80	0.23

Phase Change Media	Temperature (°C)	MJ/m3	MJ/kg
Paraffin-C16	18	161.12	0.21
Paraffin-C18	28	170.28	0.22
Paraffin Wax	64	137.46	0.17
Naphthalene	80	148.00	0.15
Polyethylene (CnH2n+2, n to 100k)	120	180.00	0.20
caprylic acid - CH3(CH2)6COOH	16	134.25	0.15
capric acid - CH3(CH2)8COOH	32	135.56	0.15
myristic acid - CH3(CH2)12COOH	58	160.15	0.19
palmitic acid - CH3(CH2)14COOH	61	157.25	0.19
D-Sorbitol -C6H8 (OH)6	97	281.20	0.19
D-Mannitol -C6H8 (OH)6	167	480.32	0.32
Galactitol -C6H8 (OH)6	188	533.52	0.35
PEG400	8	112.50	0.10
PEG600	20	143.00	0.13
PEG6000	60	230.28	0.19
tetrahydrofuran THF-C4H8O+H2O	5	271.60	0.28