Applications for Phase Change Material (PCM) Heat Sinks

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Presented By
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Agenda

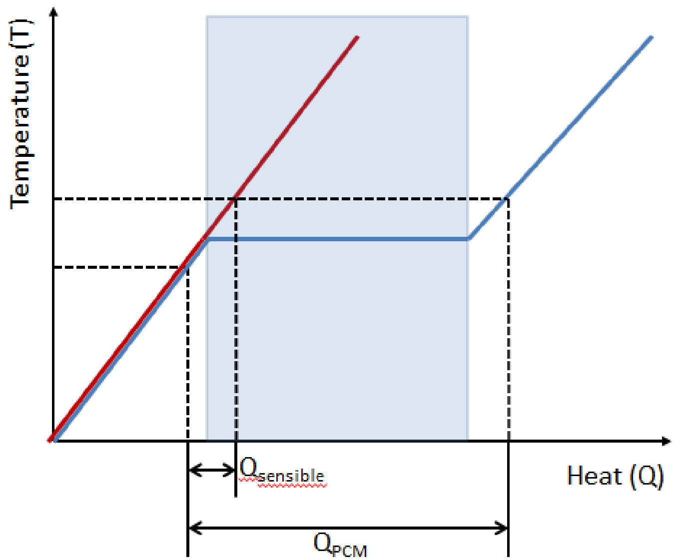
- PCM Overview
  - General Functionality
  - Common PCMs
- Thermal Storage with Venting Systems
- Real World Applications

Technology Overview

- PCM absorbs thermal energy and stores it during a solid to liquid phase transition
- This allows temperature to be maintained near the melting point of the PCM

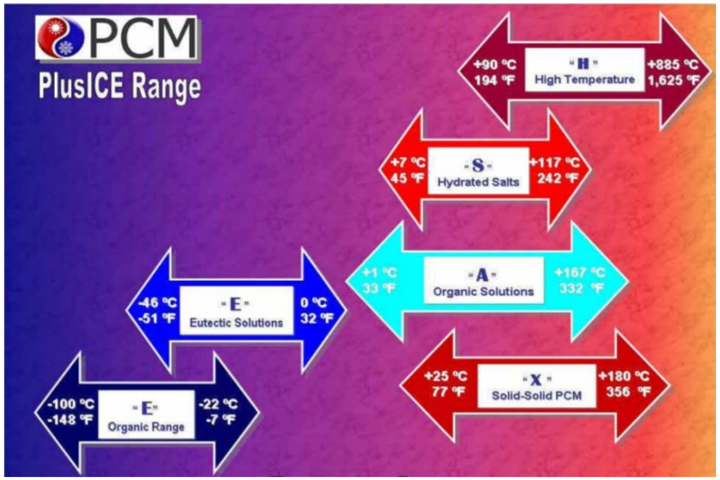
Basics

- Phase Change Material (PCM) utilizes latent heat of fusion to absorb energy
  - Typically 1-2 order of magnitudes higher storage than specific heat of common materials



- Benefits:
  - Heat storage
  - Weight
  - Compatibility
  - Reliable
  - Passive
    - No Moving Parts
- Limitations
  - Low Thermal Conductivity (<1W/m-K typically)
  - Cost – Paraffins (Long Chain Hydrocarbons)

PCM Selection



- Things to keep in mind:
  - Melt range(s)
  - Compatibility with base metal
  - Type of PCM
  - Purity
  - Capacity
    - Driven by latent heat
- Once down-selected, compare the storage capacity based on the latent heat using design parameters for fin thickness, volume, etc.

PCM	Melt Temperature Range (°C)	Fin Volume (%)	Latent Heat (kJ/kg)	PCM Mass (kg)	Heat Storage (kJ)
A	60 - 62	10	240	2.1	504
B	61 - 63	10	230	2.0	460
C	60 - 62	10	266	1.8	478.8

Types of PCM

Property or Characteristic	Paraffin Wax	Hydrated Salt	Metallics
Heat of Fusion	High	High	Med.
Thermal conductivity	Very Low	High	Very High
Melt Temperature (°C)	-20 to 100+	0 to 100+	150 to 800+
Latent Heat (kJ/kg)	200 to 280	60 to 300	25 to 100
Corrosive	Non-Corrosive	Corrosive	Varies
Economics	$ to $$	$ to $$	$$ to $$$
Thermal Cycling	Stable	Unstable over Repeated Cycles	Stable
Weight	Medium	Light	Heavy

Common Paraffin Wax

- Paraffin are most common PCM for significant life
  - Chemically compatible with metals
  - Large latent heat
  - Wide operating range
- List below shows a few PCMs with melt range favorable for most electronics.
- List of available PCMs is much more extensive based on melt temperature.

Examples of Paraffins	$C_{36}H_{74}$	$C_{32}H_{66}$	$C_{30}H_{62}$
Density$_{solid}$ (kg/m^3)	857	809	810
Latent Heat (kJ/kg)	223	261	249
T_{melt} (°C)	72 to 76	66 to 70	59 to 66

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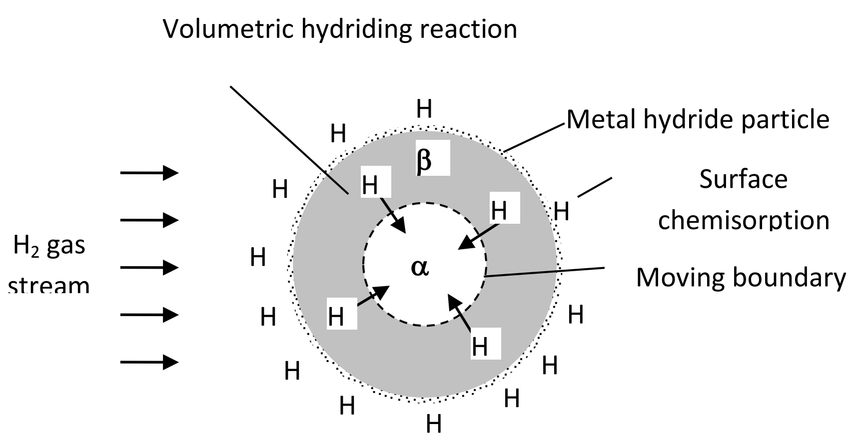
- PCM Overview
- Thermal Storage with Venting Systems
    - Sublimators
    - Vapor Venting
    - Hydrides
- Real World Applications

Thermal Storage – Vapor Venting

- Solid/liquid phase change is the preferred method when there are multiple thermal cycles
- Thermal storage with liquid/vapor phase change often is superior with heat rejection with one-two applications per mission
  - Vapor is normally vented
- Sublimators are often used in manned spacecraft during ascent and descent, when no external heat sink is available
  - Liquid-Ice-Vapor transition
  - Works only at high altitudes, with atmospheric pressure below the triple point.
- Other fluids with higher vapor pressure required for applications close to earth
  - Methanol works well
  - Latent heat ~ 1100 kJ/kg, vs. ~ 250 kJ/kg for waxes

Hydride Thermal Storage

- Hydrides can also be used for thermal storage
  - Absorption of hydrogen releases heat
  - Heating hydride with hydrogen releases hydrogen, an endothermic reaction
  - Takes advantage of the fact that hydrogen easily permeates into metals



$$M + \frac{x}{2}H_2 \underset{\text{dehydriding}}{\overset{\text{hydriding}}{\rightleftarrows}} MH_x + \Delta H_f$$

- Hydrides have a much higher thermal storage per unit volume than PCM
  - LaNi5, has a theoretical heat storage capacity of 1200kJ/liter
  - Paraffin wax PCM has a heat storage capacity of 160-200kJ/liter.

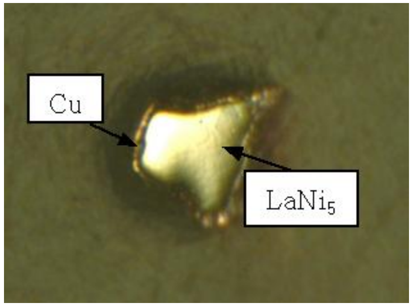
Hydride Thermal Storage

- With multiple hydriding/dehydriding cycles, high volume strains lead to "decrepitation" (or pulverization) of metal hydrides
  - Micron size particles
  - Very low thermal conductivity, ~ 0.1 W/m K)
- Can micro-encapsulate hydrides to prevent pulverization
  - Increases thermal conductivity to 3 to 5 W/m K
  - Hydrogen permeates easily through the copper

Raw

Copper-Plated

Cross-Section



Agenda

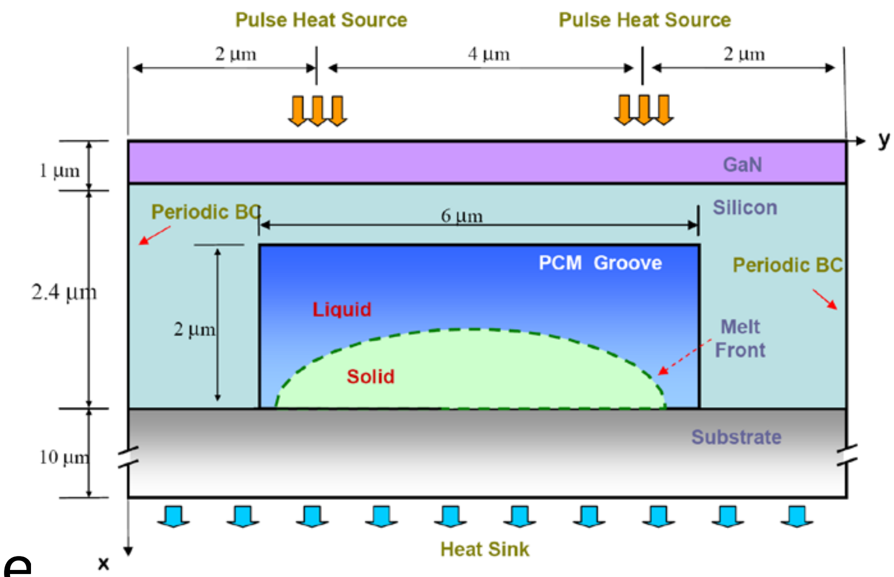
- PCM Overview
- Thermal Storage with Venting Systems
- Real World Applications
  - On-chip PCM for pulsed power
  - Electronics heat sinks, particularly during loss of coolant
  - PCM heat exchangers
  - Vapor Venting Systems
  - Hydride Thermal Storage

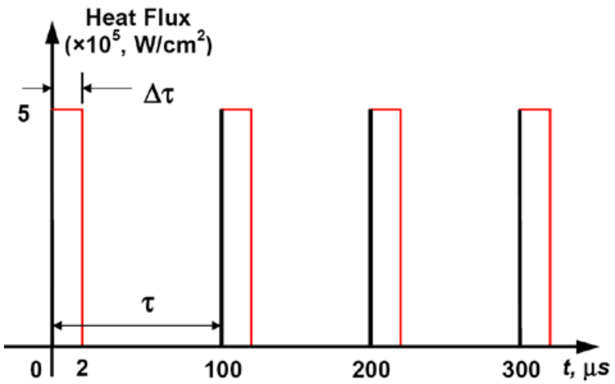
PCM Applications

- Types of applications include:
  - Storage for one-time use applications
  - Protection from momentary failure
  - Dampening of heat loads in pulse mode operation
- PCM is used for a variety of applications:
  - High powered electronics
  - Direct Energy Weapons (DEW)
  - HVAC
  - Primary or Redundant Thermal Management
  - Venting

On-Chip PCM for Pulsed Power

- High power semiconductors for communication often operate in pulsed mode
  - Rapid temperature transients are continuously experienced within the die.
  - Typical duty cycle of 2 to 10%
- Add PCM near individual gates to improve performance
  - PCM melts when operating, then refreezes
- Need to calculate minimum distance to avoid parasitic capacitance

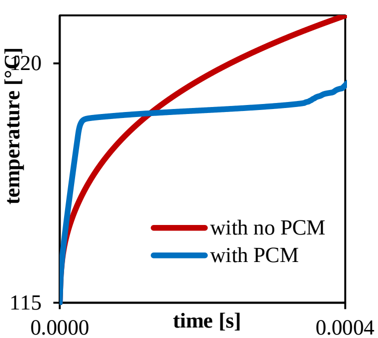




On-Chip PCM for Pulsed Power

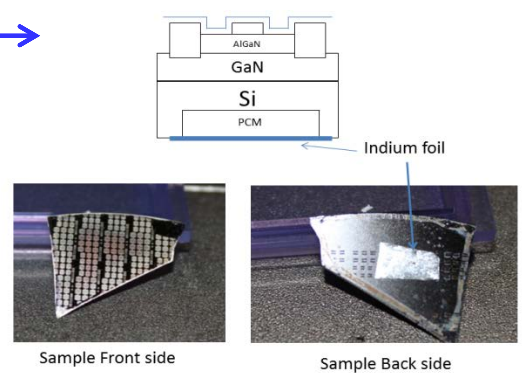
- High junction temperature is the biggest challenge in high powered pulsed RF device applications such as radar and communication applications
- Experiments - Successful integration of PCM in the HEMT substrate achieved improved electrical performance at high temperatures

Concept



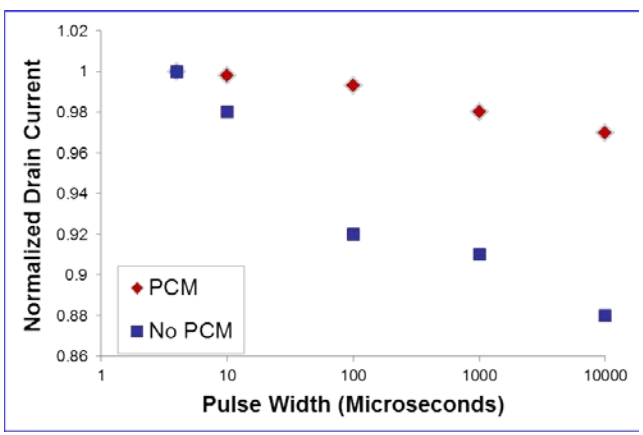
Computational Model Prediction

Fabrication



GaN Transistors with PCM filled grooves (capped with Indium)

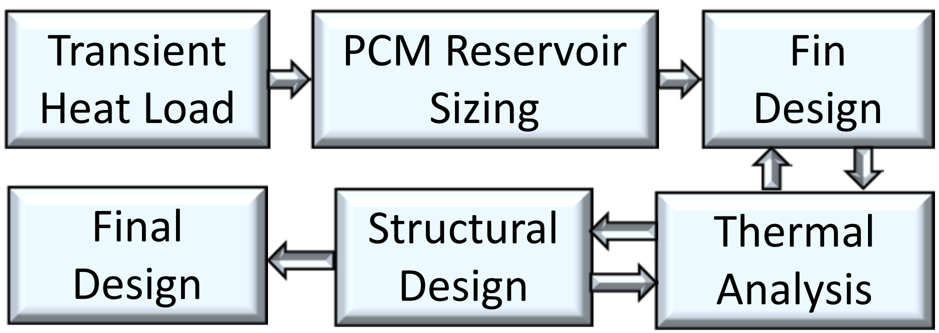
Electrical Testing



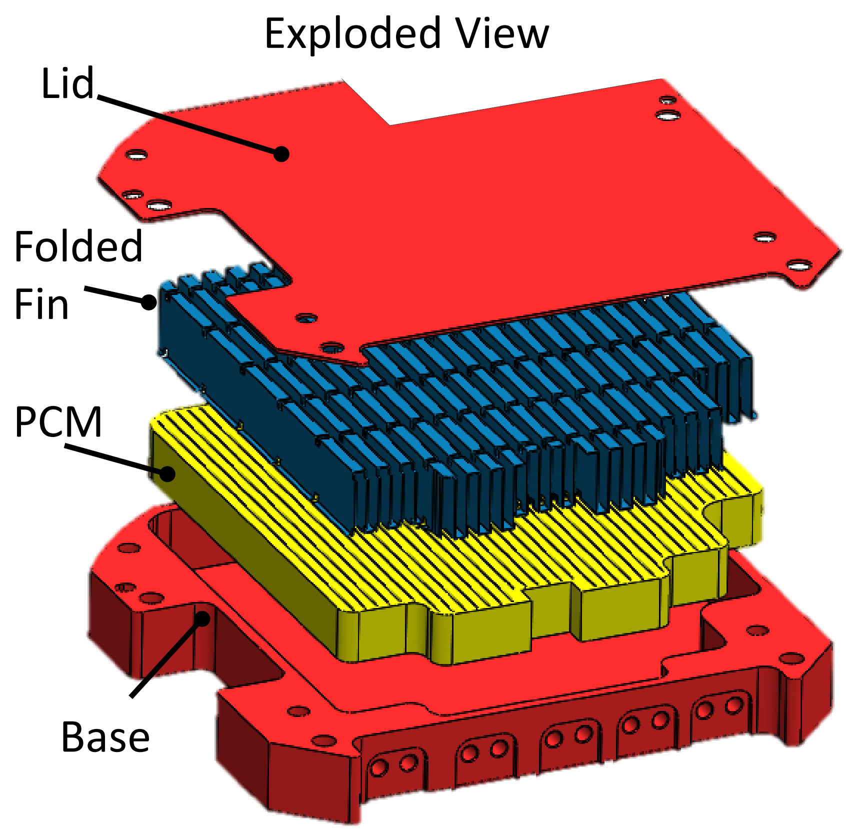
Normalized drain current remains stable at high pulse width for GaN devices with PCM filled grooves

Electronics Heat Sinks

- Electronics operating with transient heat loads or one-time-use can benefit from PCM
- Design Process

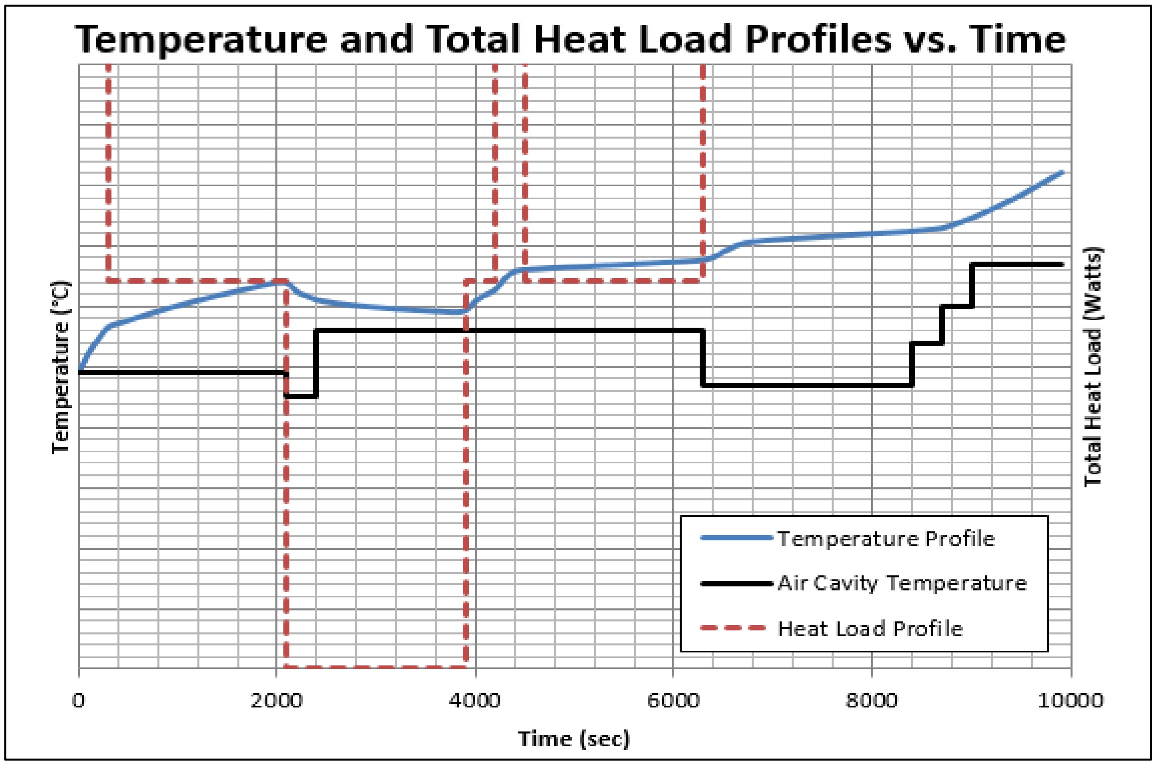


- Transient thermal modeling is used to confirm heat sink design
  - Captures heat transfer to PCM
  - Melt front vs. time
  - System ΔT

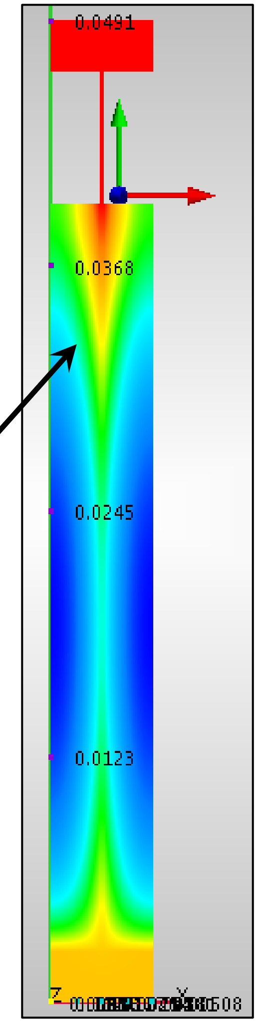


Electronics Heat Sinks

- Results (blue) plotted against heat load (red) and varying ambient (black)



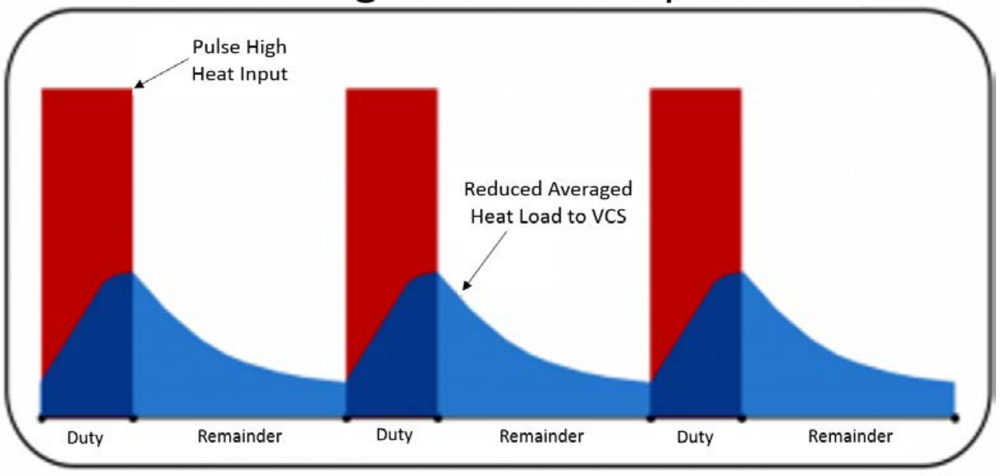
Melt Front



PCM Heat Exchanger

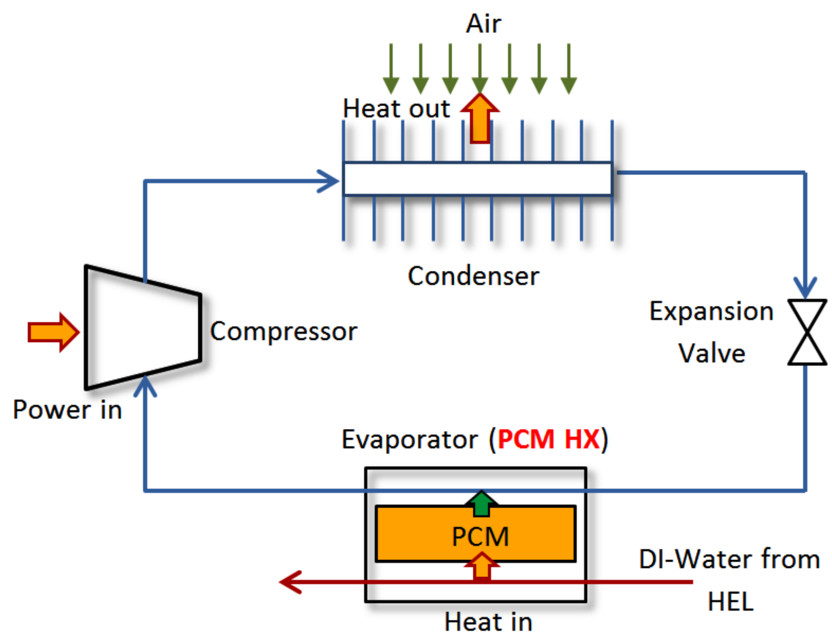
- PCM Heat Exchangers are used to dampen pulsed operation in order to design a heat sink for average power.
- No matter what the ultimate sink is, this method can reduce size/weight for duty cycle operation

Smoothing Out Pulsed Operation



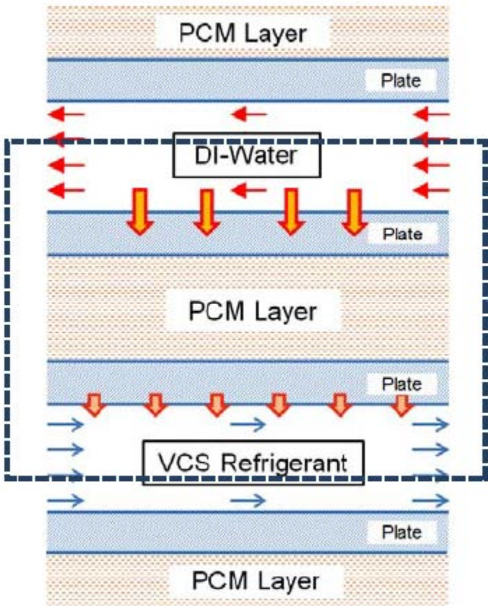
Heat Exchangers for DEW

- Directed Energy Weapon (DEW) systems require tight temperature control near 25°C – Vapor Compression System (VCS)
- Duty Cycle Operation typically less than 40% “on” time
- PCM exchanges heat between the hot fluid coming from the lasers and ultimate vapor compression heat sink.
- Similar design considerations
  - Determine volume based on duty cycle and heat load
  - Minimize gradient during melt
  - Ensure VCS refreezes the PCM during the “off” time



Heat Exchangers for DEW

- Two Loop Cooling System with an intermediate PCM heat exchanger
- PCM heat exchanger has series of 3 layers
  - PCM layer between each coolant loop and refrigerant layer absorbs heat duty pulse loads
  - Heat released to VC refrigerant over the entire cycle time
  - Series design allows design to scale
- Significant potential for system level volume and mass reduction
- ACT has manufactured sub-scale systems cooling up to 30 kW_t.



	System with PCM HX	System without PCM HX
Compressor	40 kg	180 kg
Condenser	146	379
Heat Exchangers	79	7.5
Total	265 kg	576 kg
Weight Reduction	311 kg (54%)	

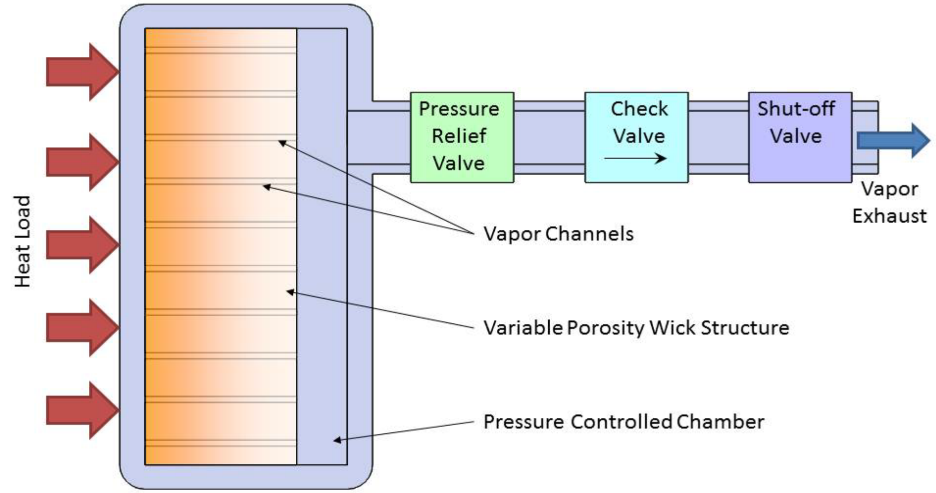
Power Plant/ECU Dry Cooling

- ACT is developing a PCM Supplemental Cooling System for power plants for ARPA-E, to enhance the overall efficiency
  - PCM melts during the hottest part of the day, providing additional cooling without using water
  - PCM is refrozen during the cooler night hours
- Under an Army Phase II SBIR, ACT is also developing an Environmental Control Unit (military air conditioner) with integrated thermal storage
  - Objective is to reduce fuel consumption on military bases
  - PCM provides additional cooling for several hours during the hottest part of the day, when the ECU is least efficient
  - Again, refreeze at night when the ECU is most efficient
- Both programs use hydrated salts due to their significantly lower cost
- Both Programs are still in the early stages

Vapor Venting Systems

When would you use liquid-vapor phase change thermal storage?

- Several cycles per mission (can be recharged)
- Volume and weight constrained systems
- High heat load and short time durations
- Large lateral and normal g-loading environments
- Long duration storage
- Liquid stored in a variable porosity wick structure
- Hydrides can also be used

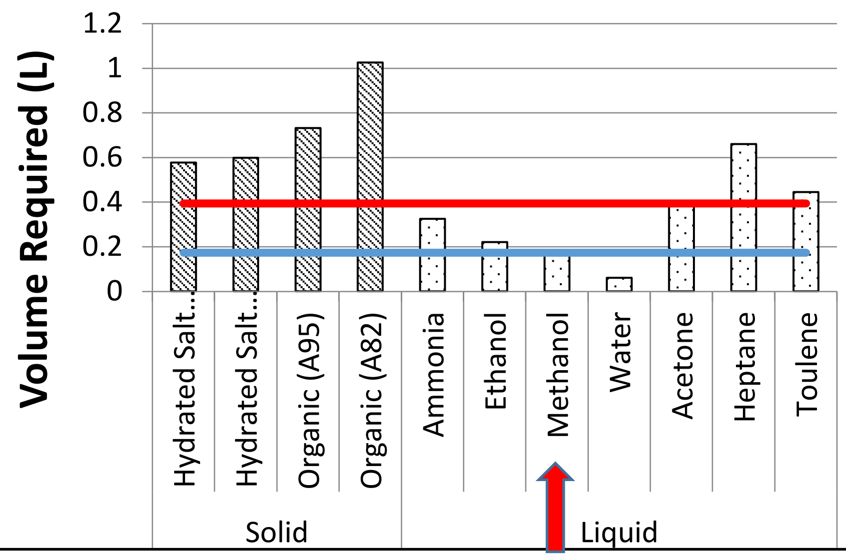


Vapor Venting- Latent Heat Storage

- The following equation was used to determine the necessary volume for latent heat storage:

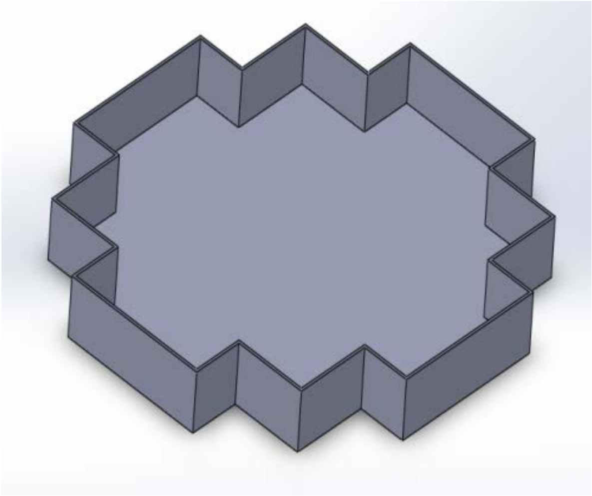
$$Q = mh_{fg}$$

- Four of the materials investigated for latent heat storage are capable of fitting in the available volume (red line).
- However, a wick structure and supporting posts must be fitted inside the casing which reduces the available volume (blue line)
- Methanol selected (needs to operate when water is frozen)
- Smaller volume than PCM



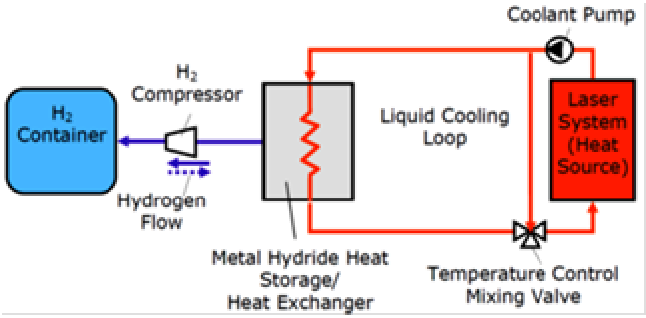
Vapor Venting

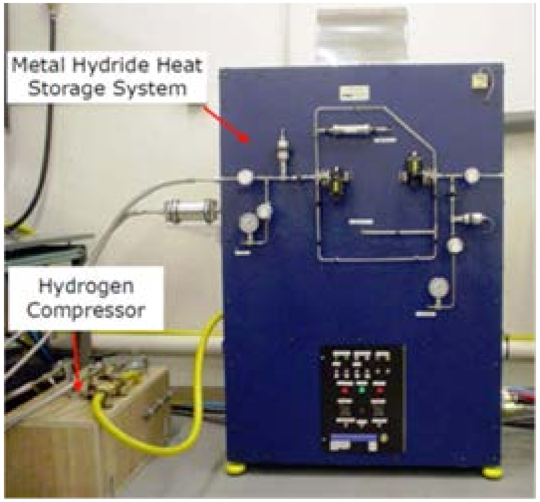
- Cold plate capable of dissipating 1 kW for 120 seconds
- High g-loading
- Maximum weight: 1.5 lbs.
- Limited Volume: 0.4 L
- Copper wick
- Engineering units have been fabricated and tested at ACT
- Easy to vent for testing, and then refill
- Significant weight reduction if use carbon wick, but requires development.



Hydride Thermal Storage

- ACT developed and successfully tested a hydride thermal storage system capable of multiple cycles in an SBIR
  - Micro-encapsulated hydrides
  - Compressor to recompress hydrogen to drive into hydride
  - Not practical
  - Compressor weight too high





Hydride Thermal Storage

- Hydrides more suited for single use system
  - Eliminates storage tank and compressor
  - Can easily be recharged.
- Technology Readiness Level ~ 4
- Further Development Needed
  - Hermeticity for long shelf life. The hydride system must be hermetic, particularly for low temperature storage. Cannot allow air to leak in.
  - Structural stability under high g-loading, shock, and vibration.
  - Heat collection from the electronics into the hydrides.
  - Methods to increase metal hydride thermal conductivity.

Comparison of Mass/Volume

- Estimated masses and volume
  - Rough rule of thumb for the PCM that the enclosure and conductivity enhancements double the mass and volume
  - Methanol with a copper wick weighs more than the PCM system, but 1/4 of the volume
  - Methanol with carbon wick: 1/3 the mass, 1/4 of the volume
  - Hydrides have 1/2 the mass, but 7% of the volume of the PCM

Heat Energy	System	Mass	Volume
1 kW for 120 sec = 0.12 MJ	PCM	1.5 kg	2.0 liter
	45% Copper	2.36 kg	0.54 liter
	45% Carbon	0.52 kg	0.54 liter
	$LaNi_5$	0.78 kg	0.13 liter

Conclusions

- Applications include on-chip cooling, electronics heat sinks, heat exchangers for DEW system, power plants, HVAC, and one/two use per mission
  - Energy storage ranges from mJ to GJ
- PCM can be used for
  - Thermal storage device
  - Heat exchanger to dampen duty cycle electronics
- Technology Readiness Level ranges from 4 (hydrides) to 9 (electronics cooling, sublimation)
- PCM selection depends on component max operating temperature and boundary conditions of your system
  - Temperatures from below 0°C to hundreds of °C

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