Thermal Energy Storage Devices

Mike Pauken, Nick Emis
Jet Propulsion Laboratory

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Why Thermal Energy Storage?

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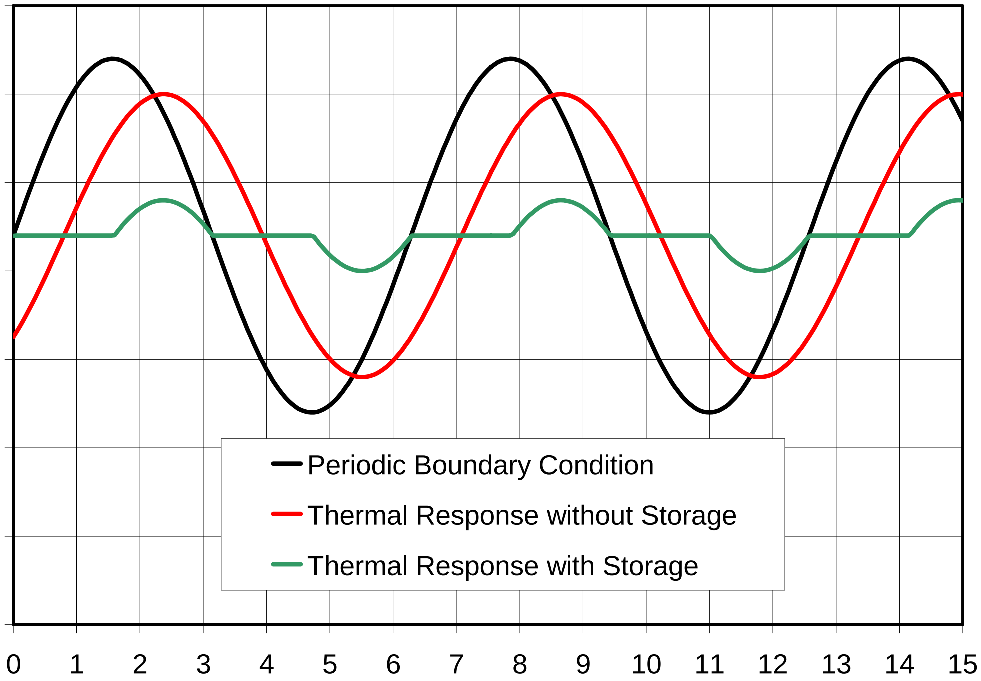
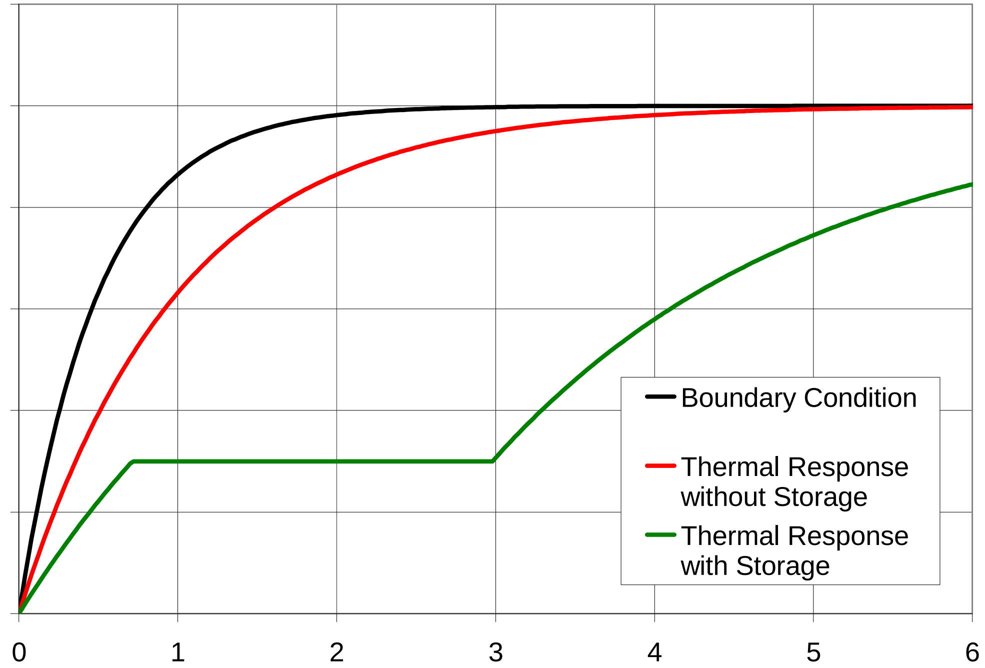
- Dampen effects of periodic boundary conditions on low thermal mass objects.
  - Spacecraft on orbit
  - Spacecraft on planetary surfaces such as Mars
  - Terrestrial Applications



Why Thermal Energy Storage?

- Reduce heating rates of light weight, high powered devices on short duration missions to extreme environments
  - Landing on Venus Surface
  - Atmospheric probes to the Gas Giant Planets



Back-of-the-Envelope Analysis

- Five basic equations describe Thermal Energy Storage Performance:
  - Conservation of Mass
    - Mass of Phase Change Material, Filler Material and Casing
  - Conservation of Energy
    - Maximum energy storage capacity
  - Temperature Range Constraint
    - Temperature gradient between component and melting temperature
  - Computation of Equivalent Conductance
    - Net conductance of filler plus PCM.
  - Additive Area Relationship
    - Heat flow cross-sectional area of PCM and filler materials

Back-of-the-Envelope Analysis

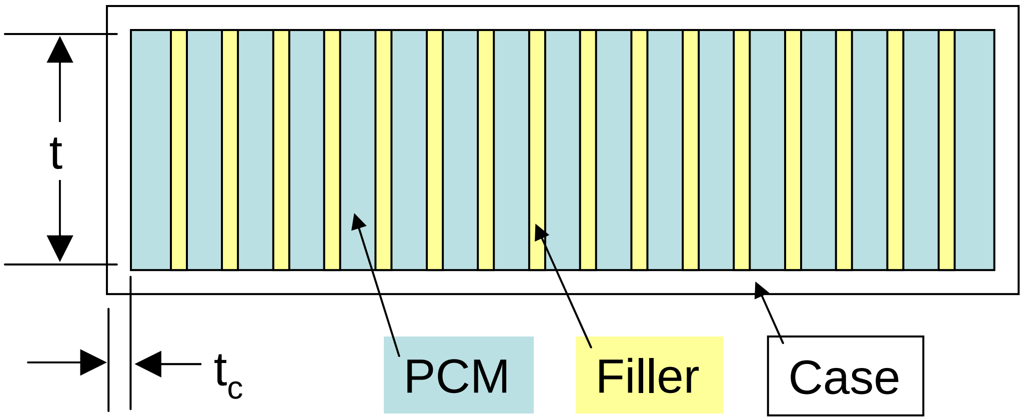
{1} Mass = $(\rho_{PCM}A_{PCM} + \rho_F A_F)t + \rho_C(2A_T + 4tA_T^{0.5})t_C$

{2} $E_{MAX} = \rho_{PCM}A_{PCM}\cdot t\cdot h_f + [\rho_F A_F C_{P\text{-}F} + \rho_{PCM}A_{PCM}C_{P\text{-}PCM}]t/2(T_{comp} - T_{melt})$

{3} $Q = k_T A_T(T_{comp} - T_{melt})/t$

{4} $k_T A_T = k_{PCM}A_{PCM} + k_F A_F$

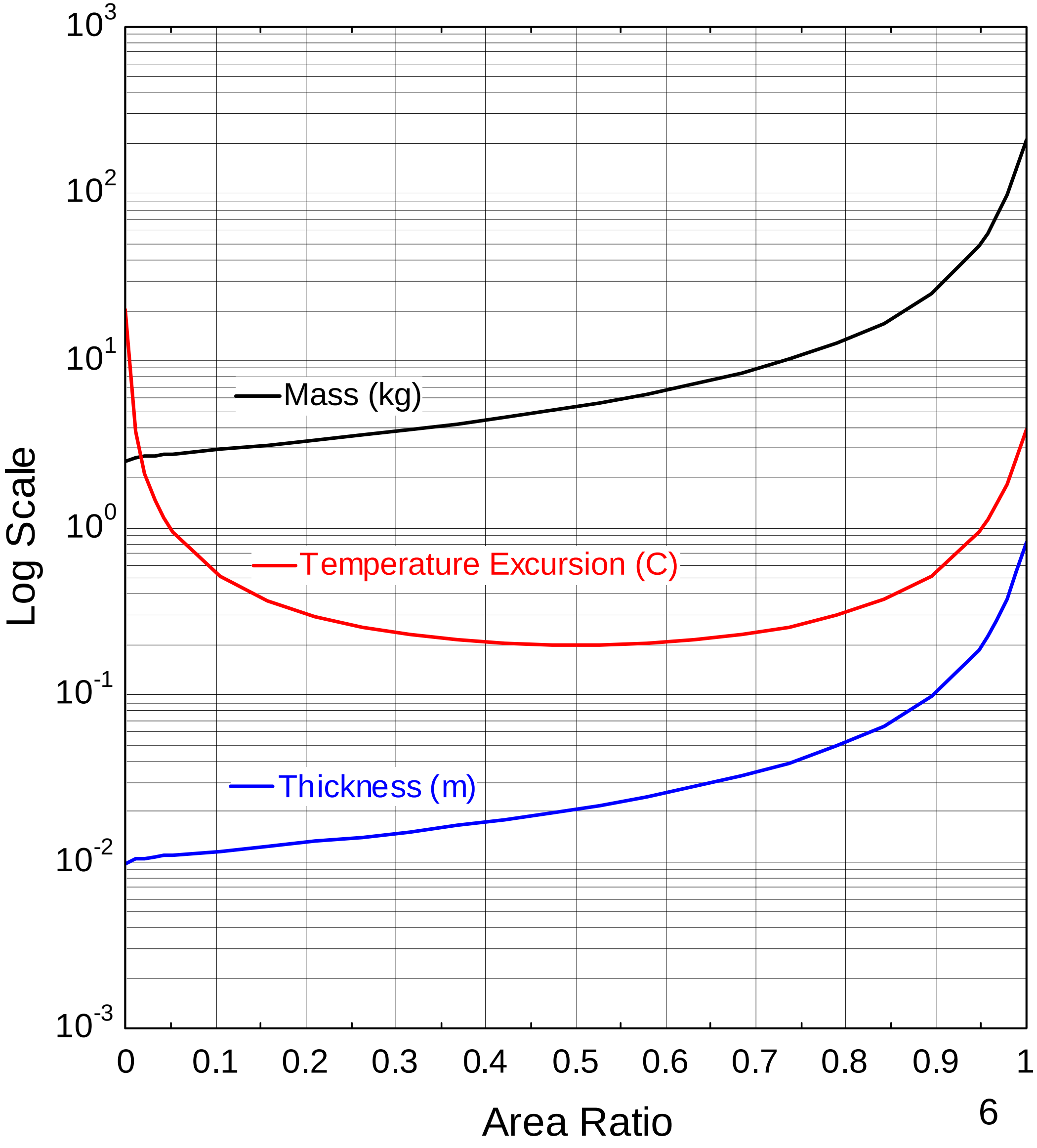
{5} $A_T = A_{PCM} + A_F$



Back-of-the-Envelope Analysis

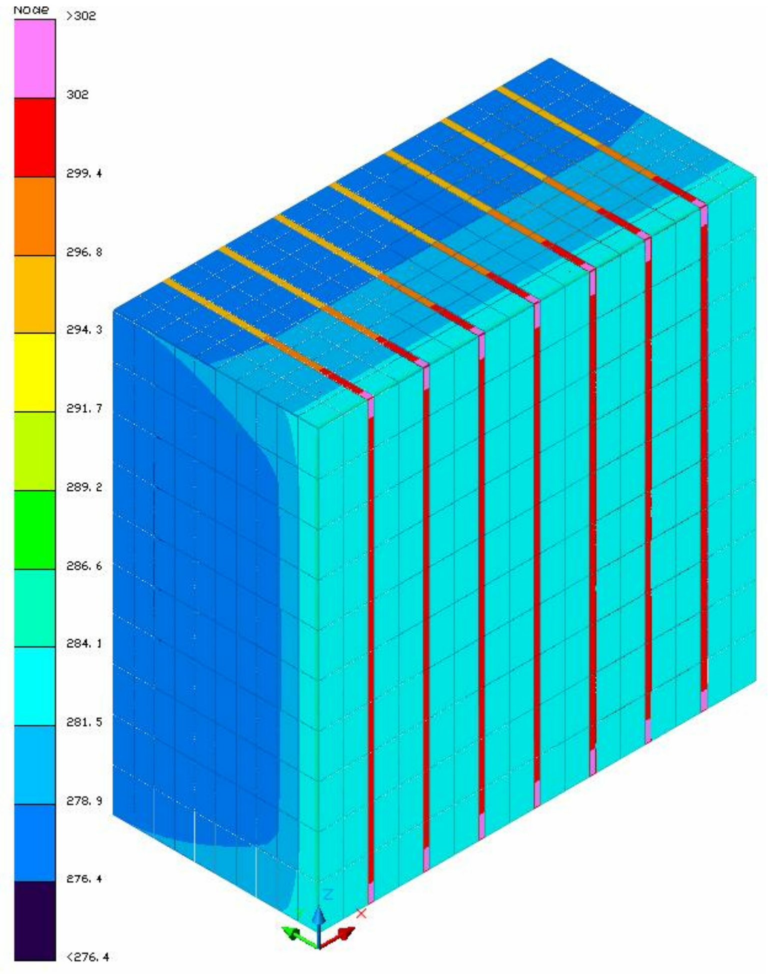
- Sample Results from Simple Analysis
- Area Ratio is:

Filler area/Total Area



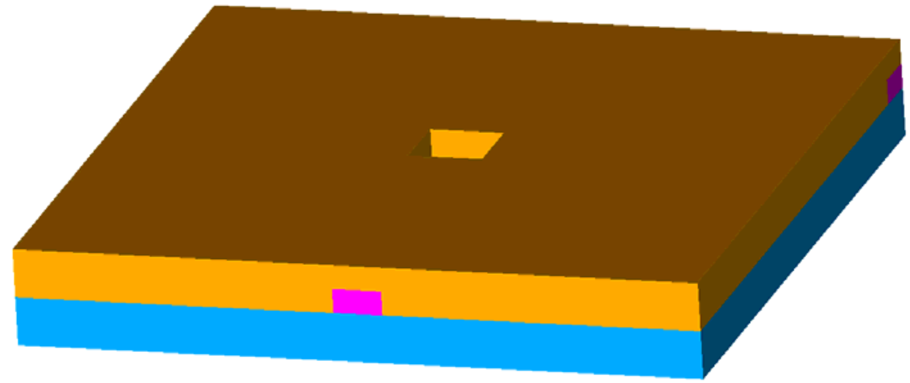
Thermal Modeling

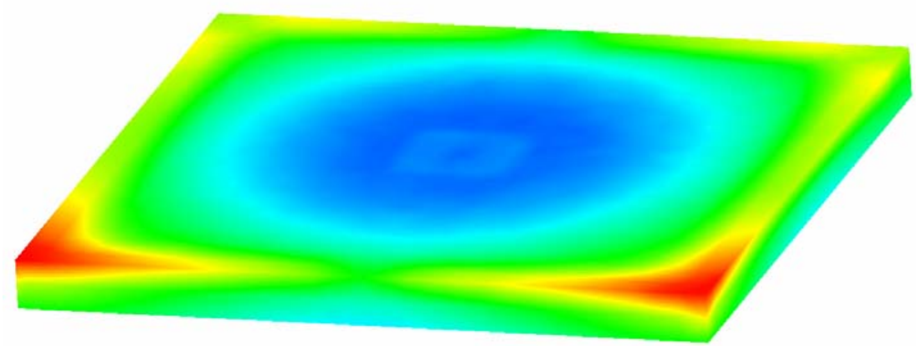
- Examine more complex shapes/geometry than rectangular boxes
- Evaluate 2-D and 3-D effects
- Utilize more accurate specific heat data (as a function of temperature and phase)
- Shown is a model of a simple unit with aluminum fins



Thermal Modeling

- Thermal models make it easy to model complex geometries or configurations.
- Module w/ graphite shell, Rubitherm-35 PCM and copper foam filler.
- Copper heater plate mounted on top





Phase Change Materials

- Conducted search of phase change materials with high heats of fusion.
- Paraffins are most common melt material.
- Lithium Nitrate has one of the highest heats of fusion and has a high density especially compared to paraffins.
  - Measured h_f for LiNO3 was ~287 kJ/kg
  - Most paraffins range from 170 to 230 kJ/kg
  - Density of LiNO3 is ~1.5 g/cc
  - Most paraffins are around 0.8 g/cc
- Implication: For a given container size, LiNO3 has more than double the heat capacity of a paraffin!

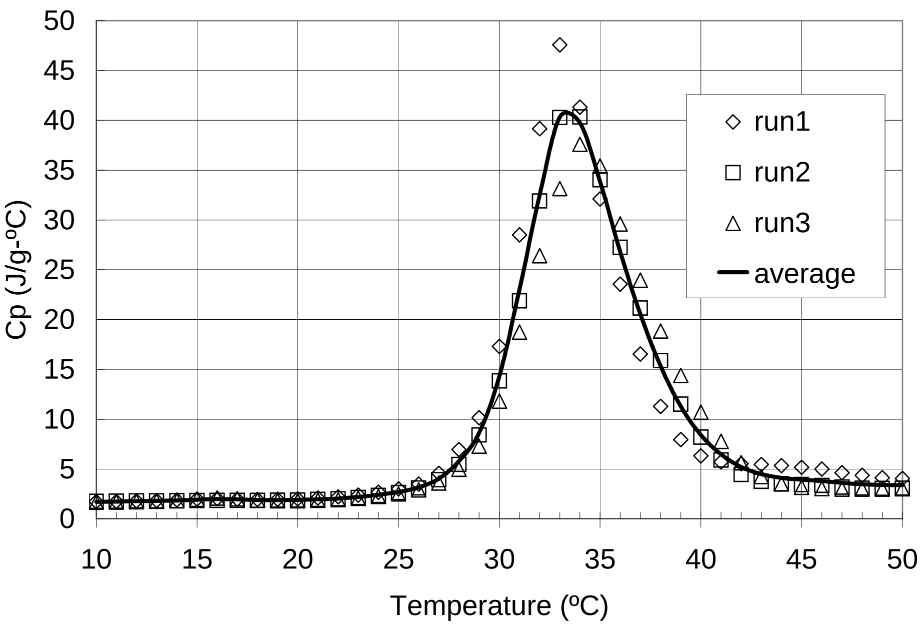
Lithium Nitrate Developments

- $LiNO_3$ is more difficult to handle than paraffins:
  - Must add water to it to form $LiNO_3$-$3H_2O$
  - It readily absorbs water from ambient air and reduces heat capacity.
    - Must keep it sealed until loaded into Thermal Storage Module
  - Melting point is about 30°C, freezing point is around -5°C.
    - This phenomenon is called subcooling.
    - Can be reduced with a catalyst: add 1% by weight of $ZnNO_3$
    - With catalyst, freezing point is around 28°C.
- $LiNO_3$ appears to be compatible with aluminum, no corrosion products have been observed.

Heat Capacity Measurements

- Heat capacity of $LiNO_3$ was measured because literature data in both solid and liquid phases were incomplete
- Measurements were made using Differential Scanning Calorimetry
  – This tends to produce broader melting temperatures than observed in bulk samples.

Specific heat measurements of $LiNO_3$



Filler Material Developments

- Aluminum fins have traditionally been used as the filler material for conducting heat into the melt material.
- Carbon foam, trademarked name “Pocofoam”, has been used successfully as a filler material with paraffin loaded storage modules by others.
- Carbon foam is hydrophobic and will not absorb water based materials such as $LiNO_3$-$3H_2O$.
- Adding a small amount of surfactant to $LiNO_3$-$3H_2O$ solves the absorption problem.

Pocofoam Testing

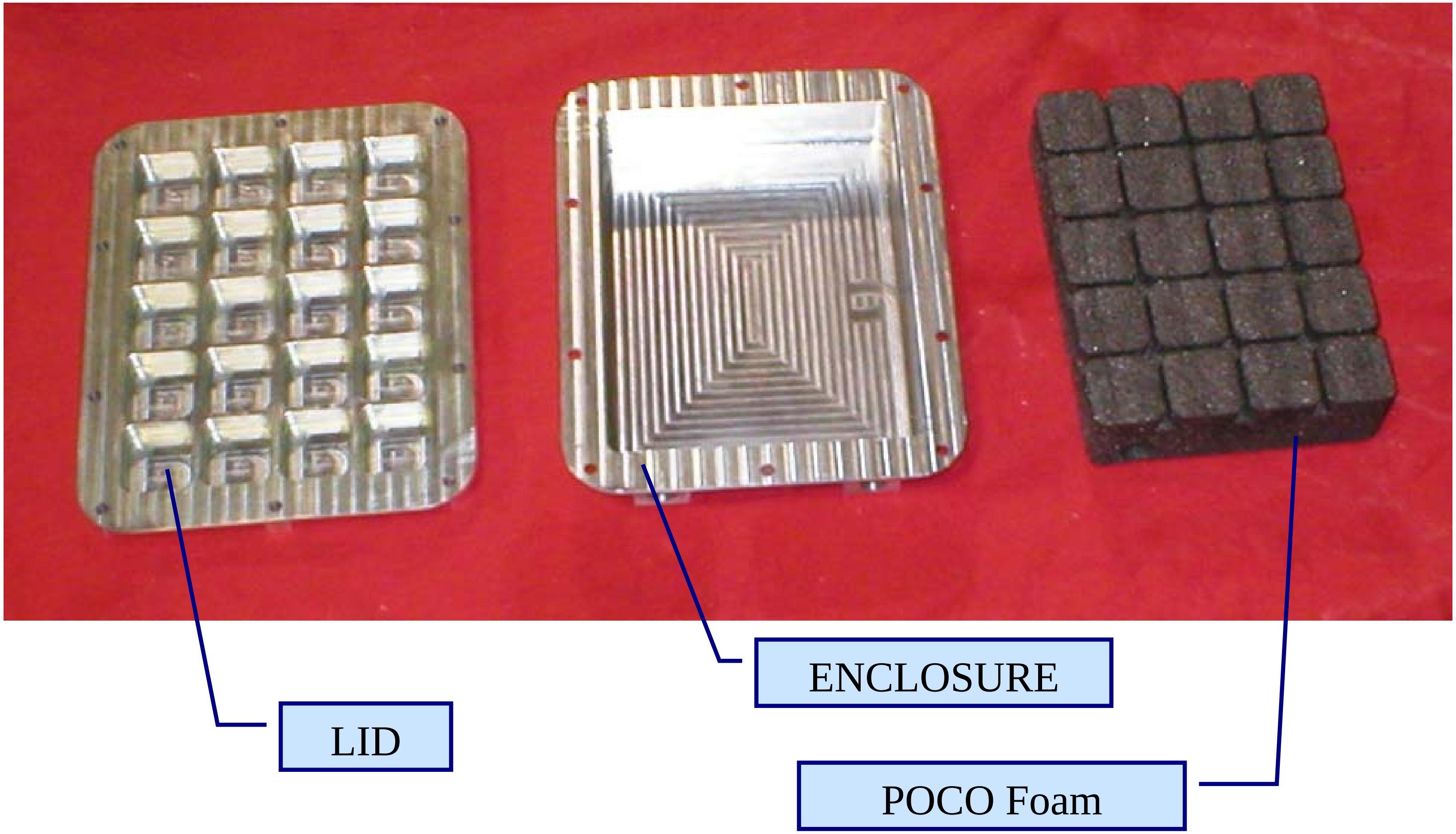
- Pocofoam floats in untreated water as shown in top photograph demonstrating hydrophobia.
  - This means LiNO3 would not be absorbed into Pocofoam

- Adding surfactant to the water causes immediate absorption by the Pocofoam as shown in bottom photograph and sinks.
  - Same trick works for water spiders!

Prototype Design Features

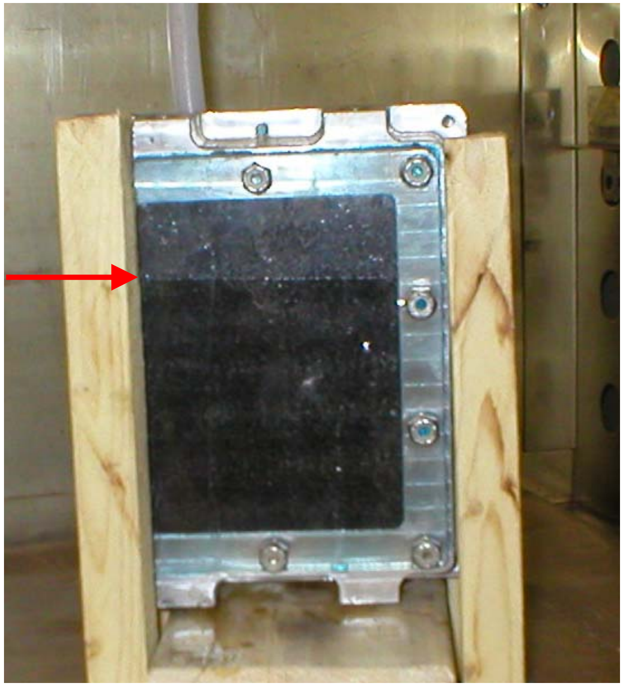
- A phase change thermal energy storage module was designed with the following features:
  - A stiff lid to make a stable mounting surface for accommodating electronic components (we just used a heater for testing).
  - A thin backplate to act as a diaphragm to reduce pressure variations as LiNO3 changed phase.
  - Carbon foam filler core
  - $LiNO_3$-$3H_20$ plus 1% zinc nitrate plus surfactant

Prototype Components

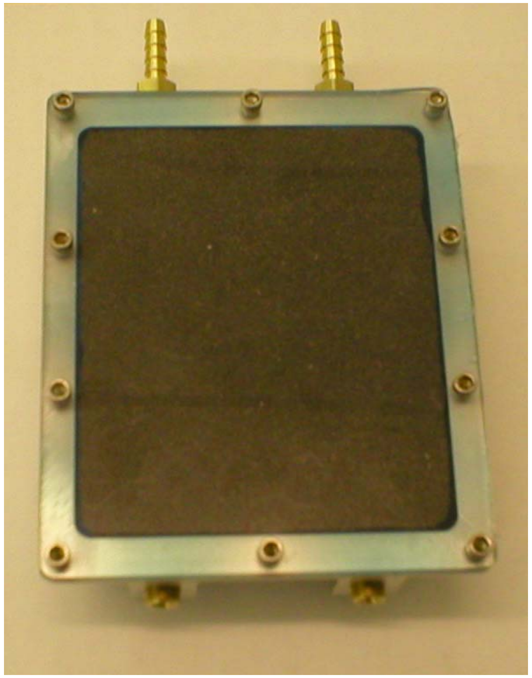


Plexiglas Model

- Before making the aluminum casing module, a Plexiglas unit was fabricated to verify filling because of the hydrophobic nature of Pocofoam.



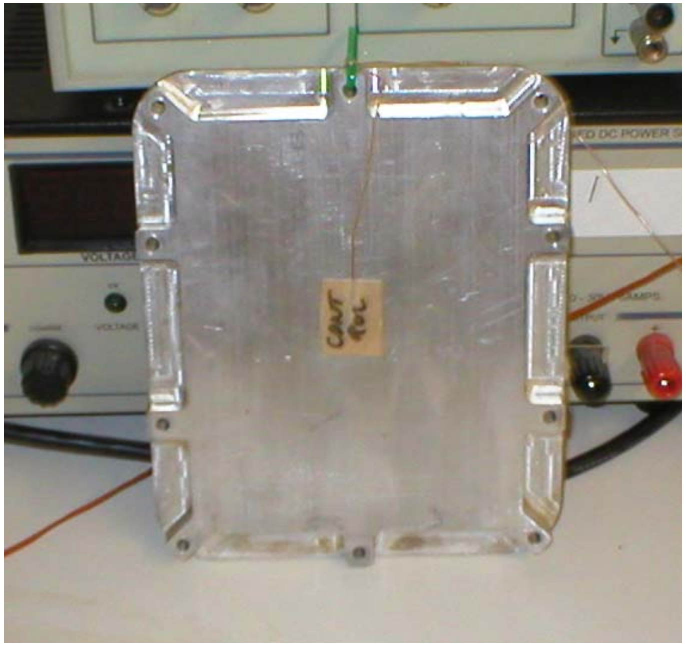
Liquid line evident during filling

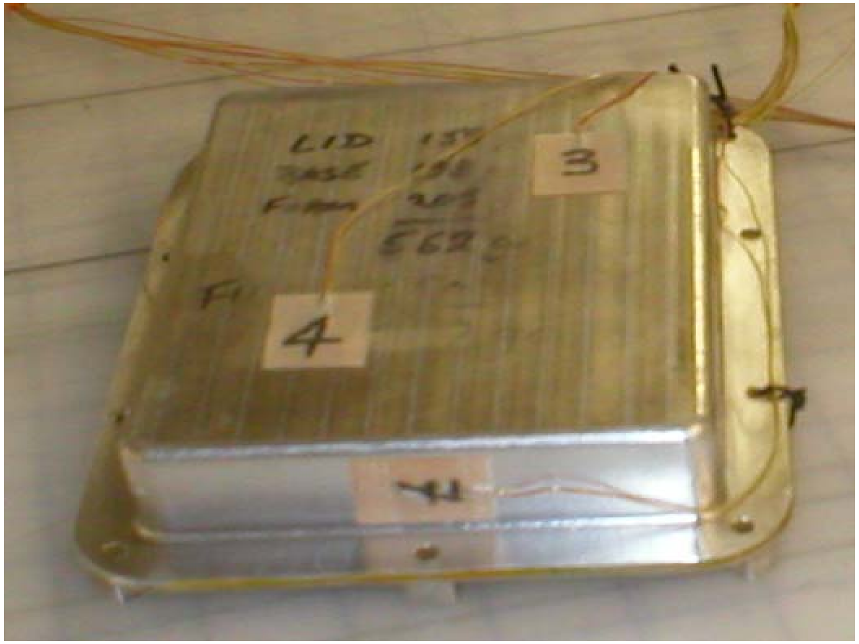


Completely filled module

Aluminum Casing Prototype

- Photographs of the completed phase change module





Thermal Testing of Prototype

- Power levels applied to unit: 15, 30, 60 and 90 watts
- Tests ran from 0 to 90ºC
- Tests repeated 5 times each to check consistency
- Module was placed inside insulated box to reduce heat leaks.
  - Observed approximately 8 watts of heat leak through insulation

Test Set up at Vendor's facility

Test Results

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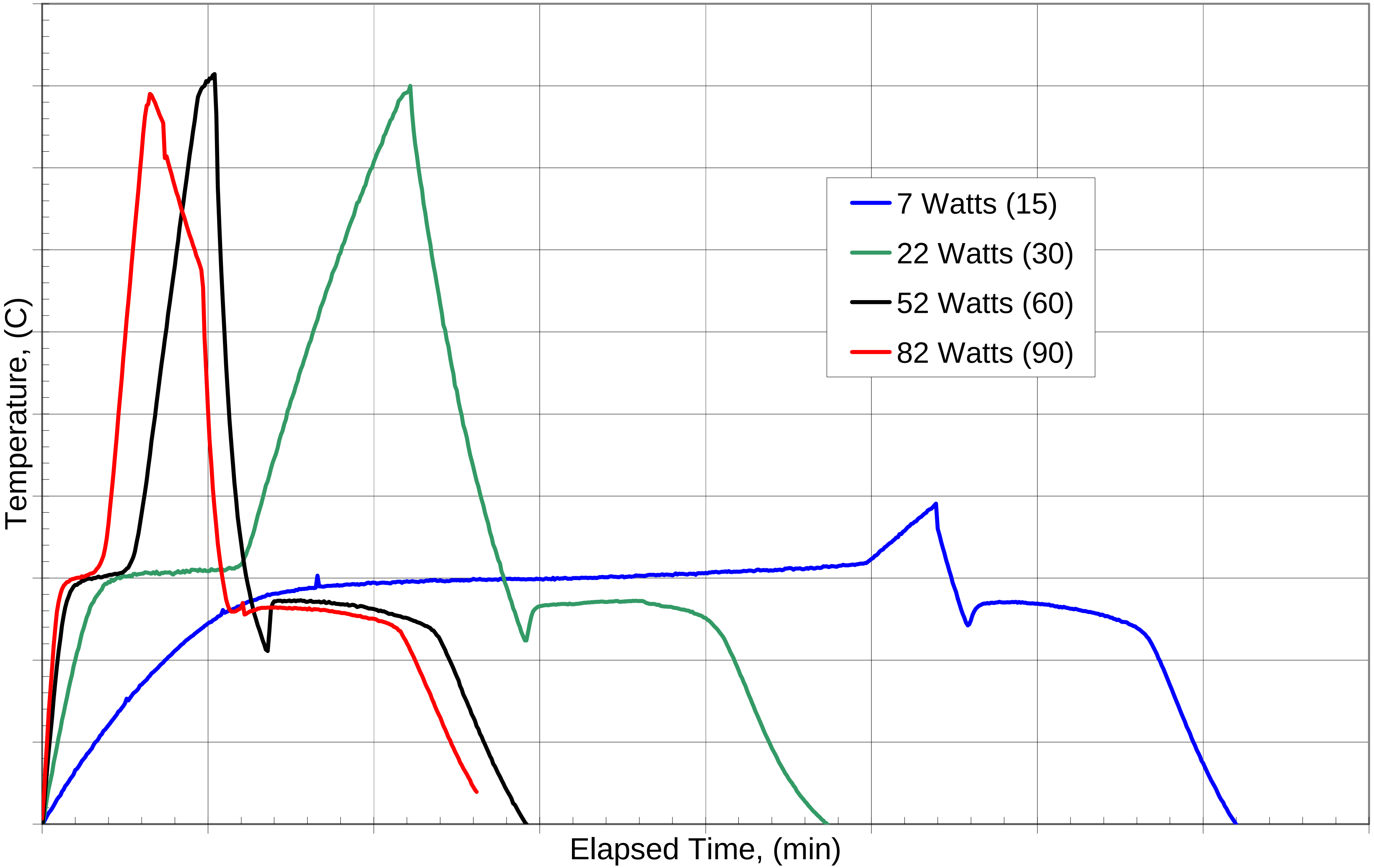
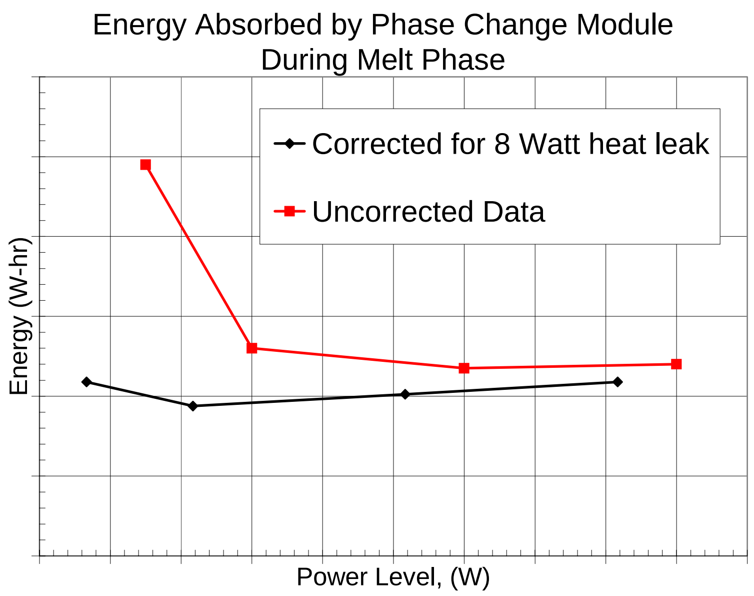
PCM Tests Comparing Different Heat Loads



Correction for Heat Leak

- Energy absorbed during melt should not change with power.
- Observed 15 Watt case took much longer to melt than expected.
- Estimated 8 Watt heat leak and corrected the melt energy to be around 40 W-hr/kg.
  - If paraffin were the melt material, melt energy would be around 20-30 W-hr/kg



Conclusions

- An improved Thermal Energy Storage Device suitable for spacecraft applications has been developed.
- The melt material was lithium nitrate and had a melt temperature around 30C.
- The freezing point subcooling was reduced to only 2C with the addition of 1% zinc nitrate.
- Pocofoam was used as the filler material, hydrophobic effects were eliminated using a surfactant.
- Energy storage capacity of unit is 30% to 100% greater than a paraffin filled unit.

Acknowledgments

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- Fabrication and testing of the thermal storage device was performed by XC Associates, Stephentown, NY.