ESLI

Phase-Change Composite TES for Nickel-Hydrogen Batteries

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Ni-H2 THERMAL CONTROL PROBLEMS

Ni-H2 thermal characteristics:

- cycle life sensitive to temperature control
- need lower temperatures (\(\approx 0^\circ C\)) than NiCads (\(\approx 21^\circ C\))
- high T transients at end of charge and during discharge
- T gradients in cell & across battery are detrimental

Cold-bias design is typical for aerospace battery thermal control

- radiators sized for larger than average heat dissipation
- high T transients remain
- heaters needed to prevent excessive low T
- option = VCHP, louvers also used to reduce heating

Passive high-heat-capacity option:

- thermal inertial reduces high and low T variations
- the heating needs are reduced
- the radiator may be sized for average load with low heating
PASSIVE THERMAL CONTROL WITH TES

Add thermal energy storage (TES) to the battery
- reduce temperature variations, both hot and cold
- time-average the heat delivered to the radiator

A phase-change material (PCM) makes TES light weight
- PCMs have 20x-40x higher specific heat than batteries

Phase-change composite (PCC) = PCM matrix + conductive fins
- high heat conductance and high heat capacity
- capillary gaps control position of fluid and voids

Potential benefits of PCC-TES are
- improved battery temp control, efficiency, cycle life
- reduced battery heater power
- reduced radiator area and system weight
PHASE-CHANGE COMPOSITES (PCC)

Composite a high conductivity (k) material with a high heat capacity (c) material for high speed TES = thermal capacitor. Figure of Merit for a TES material is the kc-product.

- Thermal time constant: \( \tau = RC = (C/A)^2 / kc \)
- Thermal flux: \( F \propto 1/\tau \propto kc \)
- Flux / Weight: \( F/W \propto kc^2 / \rho \)

where \( R = L/kA, \ C = cLA, \ c = \rho c_p, \ \rho = \) density, \( L = \) TES thickness, \( A = \) heat transfer area

**TABLE:** Combine high-k and high-c materials (illustrative values)

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>k</th>
<th>c</th>
<th>F ( \propto ) kc</th>
<th>( \rho )</th>
<th>F/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>high-k (metal, carbon)</td>
<td>100</td>
<td>1</td>
<td>100</td>
<td>3</td>
<td>33</td>
</tr>
<tr>
<td>high-c (PCM)</td>
<td>1</td>
<td>100*</td>
<td>100</td>
<td>1</td>
<td>10,000</td>
</tr>
<tr>
<td>50-50 composite (PCC)</td>
<td>50</td>
<td>50*</td>
<td>2,500</td>
<td>2</td>
<td>62,500</td>
</tr>
<tr>
<td>25-75 composite (PCC)</td>
<td>25</td>
<td>75*</td>
<td>1,875</td>
<td>1.5</td>
<td>93,750</td>
</tr>
</tbody>
</table>

* effective over a limited temperature range around the phase-change temperature
PCC STRUCTURE

Performance is best when homogeneous, with planar isotherms

\[\text{thick fins}\quad \text{thin fins}\]

Requires fins so thin that the thermal resistance across the PCM layer is less than the thermal resistance along the fin.

Fin widths required: <10 microns, for 5 mm TES thickness.

PCC thermal properties obey simple rule of fractions

\[
\begin{align*}
thickness \quad & k_{PCC} = k_F x + k_{PCM} (1 - x) \\[\text{parallel}\\] \quad & c_{PCC} = c_F x + c_{PCM} (1 - x) \\
\quad & \rho_{PCC} = \rho_F x + \rho_{PCM} (1 - x) \\
\quad & H_{PCC} = H (1 - x)
\end{align*}
\]

F = fin

x = fin volume fraction

\rho = density

H = latent heat
SHRINKAGE VOIDS, STRESS RELIEF

High capacity PCMs generally have large volume changes ~10% during solid-liquid phase change causing expansion stress.

Fine capillary structure in PCC prevents expansion stress
- capillary forces > gravity forces for small gaps
- shrinkage voids are finely distributed
- expansion into distributed voids avoids stress
- light weight encapsulation is adequate

![Diagram of thick and thin fins with voids](image)
CANDIDATE MATERIALS

Many PCMs are available between -20°C and 10°C

Encyclopedia of Organic Chemistry cites 975
Aldrich Chemical Company offers ~440

Two candidates currently under study are:

• WATER (H$_2$O, D$_2$O)
  high latent heat, but high stress potential
  MP = 0 - 3.8°C (range); BP = 100-101°C;
  H = 334 J/g; c = 4.19 J/g-K; $\rho = 0.92$ g/cm$^3$, ice @ 0°C

• n-TETRADECANE (C$_{14}$H$_{30}$)
  a benign paraffin that wets carbon fiber
  MP = 5.6°C; BP = 254°C; FP = 99°C; MW = 198.4
  H = 227 J/g; c = 2.21 J/g-K; $\rho = 0.763$ g/cm$^3$ @ 20°C
PCC DESIGN OPTIONS

PCC-TES LOCATION OPTIONS
- cell sleeve: good thermal control; simple retrofit
- cell interior: recommended for Common Pressure Vessels
- pockets: use open space between cells
- baseplate: interferes with wiring, heat pipes, fasteners

SLEEVE LINER OPTIONS
- thin metal: good heat transfer; corrosion?
- fiber composite: light weight; reliable encapsulation?

FIN STRUCTURE OPTIONS
- radial fibers: good heat transfer, void control; low cost
- axial fins: too conductive, higher cost metal fabrication
- helical fins: good heat transfer; adequate stress control?
- helical tubing: poor heat transfer; low stress in poly tubing
PCC SLEEVE FOR IPV

Retrofit PCC-TES sleeves on IPVs. Increase volume 10%.
Sleeve conductivity design options:

\[ PCC = PCM + \text{fins} \]

- metal or composite liner
- radial fiber fins
- helical foil fins
- longitudinal foil fins
SLEEVE THERMAL RESISTANCE

Conventional aluminum sleeve needs thick walls for heat conductance, and is 11% of battery weight.

PCC-TES sleeve stores heat, then releases it at \( \approx \) constant temp. 
- PCC-TES does NOT need thick conductive walls.

**TABLE:** Axial and radial sleeve thermal resistances.

<table>
<thead>
<tr>
<th></th>
<th>Axial</th>
<th>Radial</th>
</tr>
</thead>
<tbody>
<tr>
<td>conventional 1-mm aluminum sleeve</td>
<td>6.15</td>
<td>0.00010</td>
</tr>
<tr>
<td>3-mm water</td>
<td>675.74</td>
<td>0.10365</td>
</tr>
<tr>
<td>2.75-mm PCC (361% of cell heat cap.)</td>
<td>442.9</td>
<td>0.00207</td>
</tr>
<tr>
<td>PCC-TES: 0.25-mm Al + 2.75 mm PCC</td>
<td>23.40</td>
<td>0.00178</td>
</tr>
</tbody>
</table>
PCC PLATE FOR MULTICELL CPV

CPV has same heat generation in more compact geometry. Interior PCC-TES plates reduce transients, average heat release.

**COMMON PRESSURE VESSEL** (eg 22 cells)

- Ni-H2 cells in polybags
- metal plate heat conductor
- vessel wall

**OPTION: PCC-TES Plates**

- high capacity
- low weight
- improved Temp control
- reduced GEO heating requirement
FABRICATION & TESTING

Phase 1 progress: fabrication of subscale sleeves and demonstration of freeze-melt survival for limited cycling

- Sleeve size = 10 cm long, 2.3 cm ID, 3.9 cm OD.
- Aluminum liner, polymer encapsulation.
- PCMs = tetradeacne, water
- Fin material = high-k carbon fiber felt

Without fins, expansion stress causes fracture and leak during first freeze/melt cycle. Fin structures have been developed for which no fracture or leak has occurred in all 16 cycles run.

PCMs encapsulated in polyethylene also can survive freeze/melt cycling, but the heat conductance is too low.

Phase 2 objectives

- PCC-TES prototype development
- Reliability testing
THERMAL MODELING

For qualitative system study use two-node RC model
  • lump battery and TES capacity into single node
  • couple node to space node via radiator resistance
  • input cell heat record and space temperature
  • predict battery transient temperatures

\[ T_b(t) \text{ output} \]
\[ \text{input } Q(t) \rightarrow \text{RC} \rightarrow T_s(t) \text{ input} \]
\[ C \]
\[ T = 0 \]
**GEO Ni-H2 BATTERY TEMPERATURES**

Calculate temperature response of battery using 2-node model for different heater, radiator and TES configurations.

<table>
<thead>
<tr>
<th>Case</th>
<th>Battery</th>
<th>Thermal Control System (TCS)</th>
<th>Battery + TCS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Radiator + heat pipes</td>
<td>Heater subsystem</td>
</tr>
<tr>
<td>Case 1</td>
<td>450</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>450</td>
<td>65</td>
<td>66</td>
</tr>
<tr>
<td>Case 3</td>
<td>450</td>
<td>26</td>
<td>0</td>
</tr>
</tbody>
</table>

PCC-TES option (case 3) offers improved temperature control and 62 lb weight saving = 47% weight reduction of the TCS
LEO Ni-H2 SURGE POWER BATTERY TEMPERATURES

Calculated temperature response of battery with 1 m² radiator, compared with temperature response for 400% capacity.

Burst Power in LEO
Battery temperature response

Legend
- Baseline
- 4x capacity; 2x resistance
- Heat
SYSTEM BENEFITS SUMMARY

Potential system benefits:
- Improved cell temp control during high rate discharge
- Improved temperature uniformity across the battery
- Smaller, lighter radiator sized for average load
- Less heater power required
- Less reliance on active louvers, VCHPs
- More options for high rate, deep discharge use
- Less satellite repositioning for thermal control
- Fewer active control functions
- More satellite resources available for primary function

HIGH-C thermal control (PCC-TES) is best for short transients.
LOW-R thermal control (heat pipe radiators) is best for steady state.

Ni-H2 batteries do benefit from HIGH-C option, but PCC-TES components are not space qualified.
POTENTIAL APPLICATIONS

Retrofitting Ni-H2 for Ni-Cd batteries
- TES lowers peak load to radiator and may allow existing NiCad radiator area to be used for Ni-H2

GEO communications and data relay satellite
- TES may reduce battery temperature transients, reduce heater requirement, and reduce radiator size.

Multicell CPV batteries
- TES inside the vessel may reduce temperature gradients and reduce heat flux through vessel wall

LEO satellite surge battery power
- TES may lower peak battery temperatures in mobile telephone satellites over high traffic centers
- TES may lower peak battery temperatures in Space Based Radar

Other battery applications
- Na-S, Ni-MH2