Phase-Change Composite TES for Nickel-Hydrogen Batteries

Date: November 19, 1992

Presented at: NASA Aerospace Battery Workshop, MSFC

Presented by: Richard A. Meyer
Energy Science Laboratories Inc. (San Diego, CA)

† Contract No: F29601-92-C-0065 (USAF SBIR Phase I)
Technical Monitor: Mary Corrigan (PL/VTPT)
Prin. Investigator: Timothy R. Knowles (619/552-2034)
CONTENTS

Ni-H2 Thermal Control Problems
Passive Thermal Control with TES

Phase-Change Composites (PCC)
Candidate Materials
Design Options
Fabrication & Freeze-Melt Cycling

Thermal Modeling
System Benefits
Applications
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.

\[
\tau = RC = \frac{(C/A)^2}{kc}
\]

Thermal flux

\[ F \propto \frac{1}{\tau} \propto kc \]

Flux / Weight

\[ \frac{F}{W} \propto \frac{kc^2}{\rho} \]

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>( \frac{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

\[
\begin{align*}
\text{thick fins} & \quad \text{thick fins} \\
\text{solid} & \quad \text{thin fins} \\
\text{liquid} &
\end{align*}
\]

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

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

\( k = \text{thermal conductivity} \)
\( c = \text{specific heat} \)
\( \rho = \text{density} \)
\( H = \text{latent heat} \)
SHRINKAGE VOIDS, STRESS RELIEF

High capacity PCMs generally have large volume changes \( \sim 10\% \) 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]

\( thick\ fins \quad thin\ fins \)
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 (H₂O, D₂O)
  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; ρ = 0.92 g/cm³, ice @ 0°C

- n-TETRADECANE (C₁₄H₃₀)
  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; ρ = 0.763 g/cm³ @ 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

\( \Rightarrow \) 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 = tetradecane, 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
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>Total 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
GEO Equinox Battery Temperature

- (1) $A = 0.97 \text{ m}^2$
- (2) $A = 2.40 \text{ m}^2$; 200 W heat
- (3) $A = 0.97 \text{ m}^2$; $C = 400\%$

Battery heat (200 W avg)
Heater power (200 W avg)

TIME FROM START OF ECLIPSE (hr)

TEMPERATURE (deg C)

POWER (W)
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

TIME FROM START OF BURST (hr)
TEMPERATURE CHANGE FROM AVERAGE (°C)
HEAT DISSIPATION (W)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
-20 -15 -10 -5 0 5 10 15 20
4500 4000 3500 3000 2500 2000 1500 1000 500 0
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