Energy Science Laboratories, Inc.
Thermal Composites Division

ESLI

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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 (≈0°C) than NiCads (≈21°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 $R = L/kA$, $C = cLA$, $c = \rho c_p$, ρ = density, L = TES thickness, A = heat transfer area

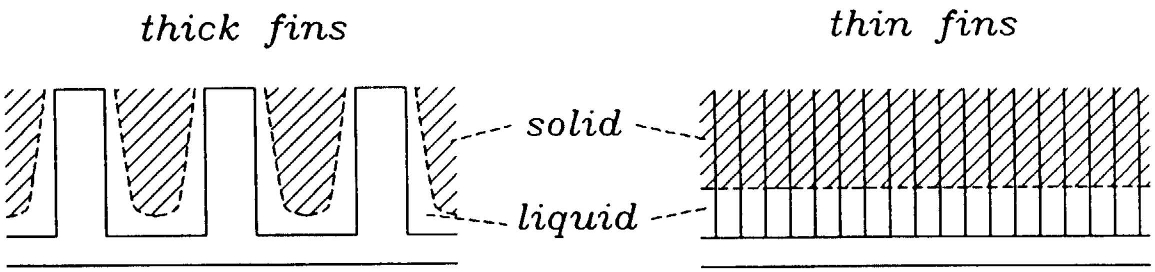
TABLE: Combine high-k and high-c materials (illustrative values)

MATERIAL	k	c	$F \propto kc$	ρ	F/W
high-k (metal, carbon)	100	1	100	3	33
high-c (PCM)	1	100*	100	1	10,000
50-50 composite (PCC)	50	50*	2,500	2	62,500
25-75 composite (PCC)	25	75*	1,875	1.5	93,750

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

PCC STRUCTURE

Performance is best when homogeneous, with planar isotherms



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

$k_{PCC} = k_F\,x + k_{PCM}\,(1 - x)$ (parallel)

$c_{PCC} = c_F\,x + c_{PCM}\,(1 - x)$

$\rho_{PCC} = \rho_F\,x + \rho_{PCM}\,(1 - x)$

$H_{PCC} = H\,(1 - x)$

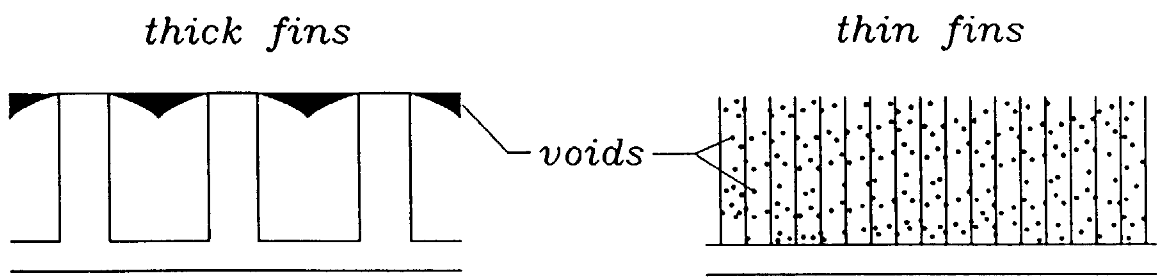
F = fin
x = fin volume fraction
ρ = density
H = latent heat

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



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_2O, D_2O)
  - 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/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; ρ = 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

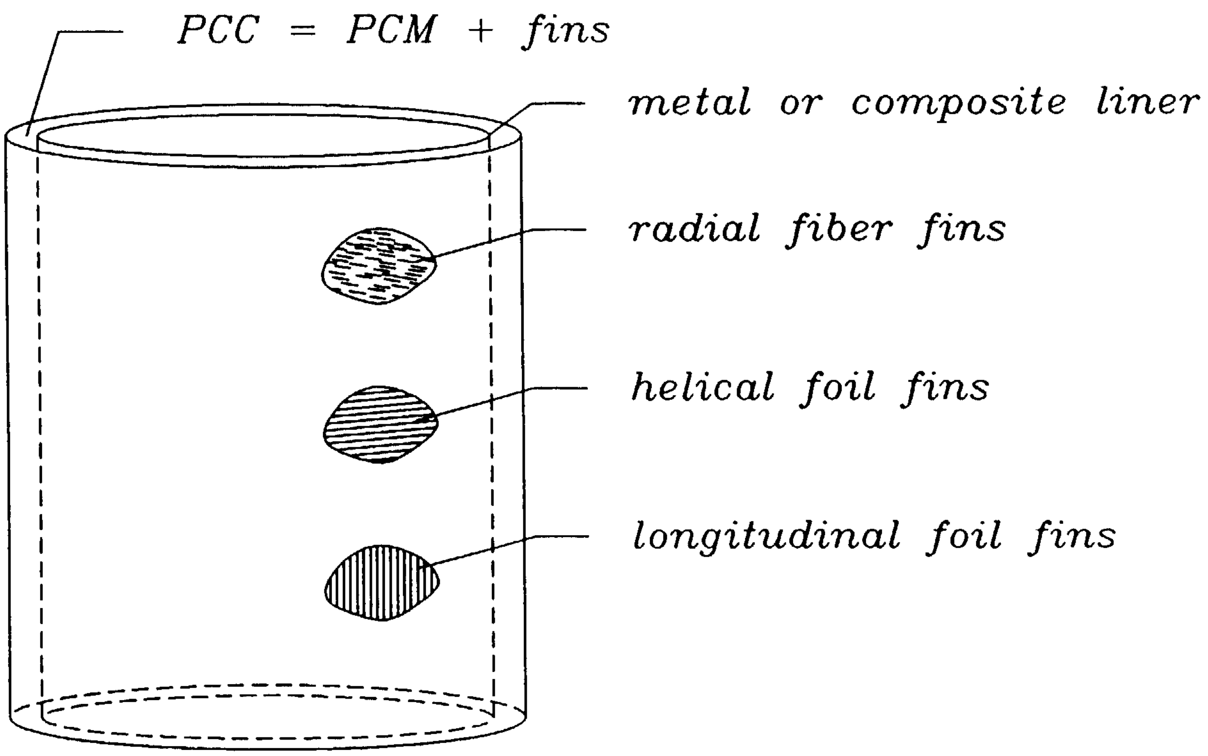
thin metal	good heat transfer; corrosion?
fiber composite	light weight; reliable encapsulation?

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:



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 ≈constant temp

- **☞ PCC-TES does NOT need thick conductive walls**

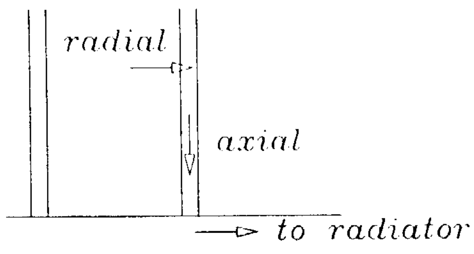


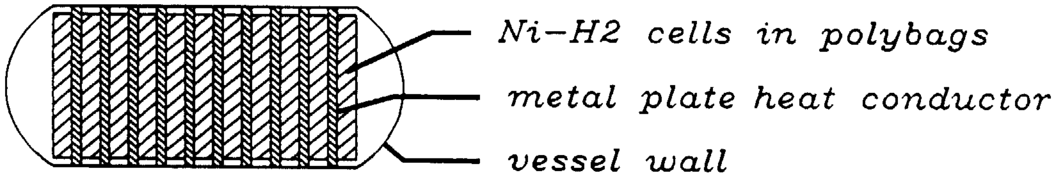
TABLE: Axial and radial sleeve thermal resistances.

	Axial	Radial
conventional 1-mm aluminum sleeve =	6.15	0.00010
3-mm water =	675.74	0.10365
2.75-mm PCC (361% of cell heat cap.) =	442.9	0.00207
PCC-TES: 0.25-mm Al + 2.75 mm PCC =	23.40	0.00178

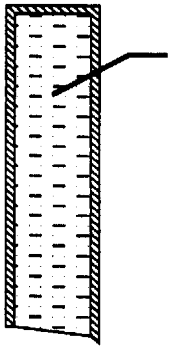
PCC PLATE FOR MULTICELL CPV

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

COMMON PRESSURE VESSEL (eg 22 cells)



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.

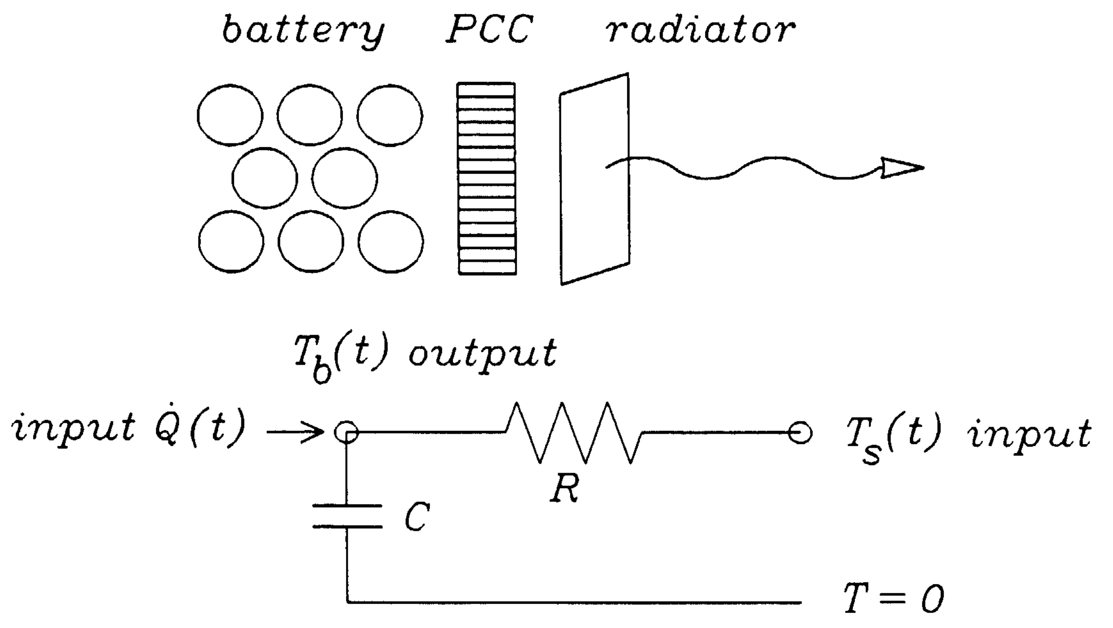
Phase 2 objectives

- 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**



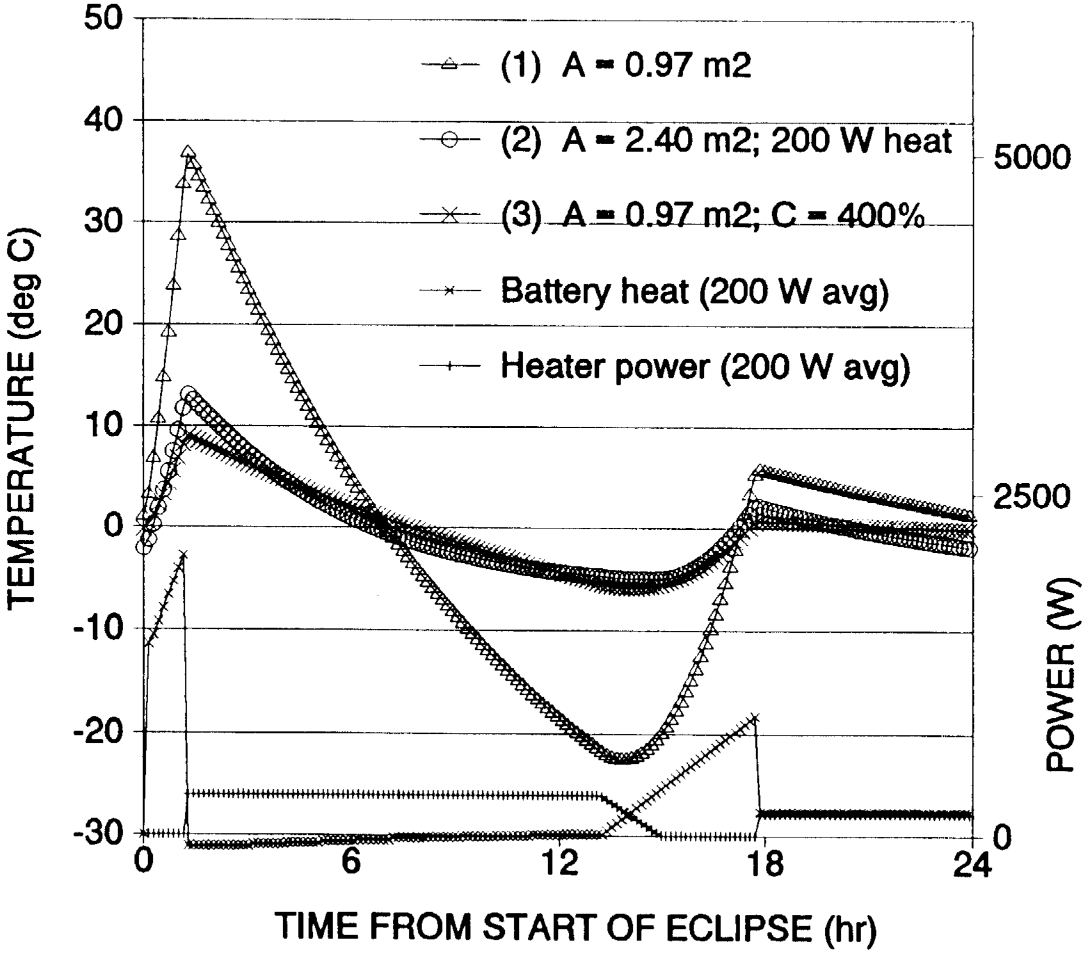
GEO Ni-H2 BATTERY TEMPERATURES

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

	COMPONENT WEIGHT (lbs)					
	Battery	Thermal Control System (TCS)				Battery + TCS
		Radiator + heat pipes	Heater subsystem	PCC-TES subsystem	Total TCS	
Case 1	450	26	0	0	26	476
Case 2	450	65	66	0	131	581
Case 3	450	26	0	43	69	519

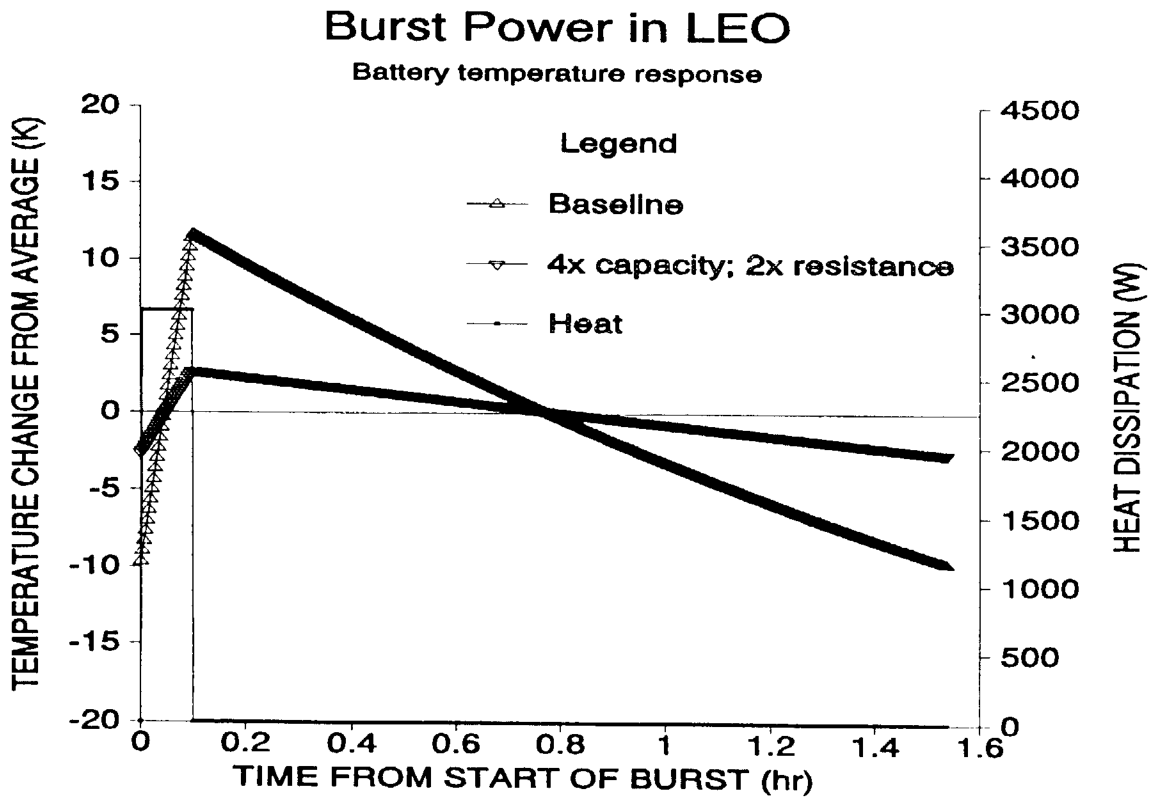
PCC-TES option (case 3) offers improved temperature control and 62 lb weight saving = 47% weight reduction of the TCS

GEO Equinox Battery Temperature



LEO Ni-H2 SURGE POWER BATTERY TEMPERATURES

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



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