PCM COMPOSITE COLD PLATE

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Final Report

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13. Supplementary Notes

14. Abstract This Phase I SBIR project has investigated a lightweight packaging design for phase change materials (PCMs) used in thermal management. To control expansion stress, conventional PCM heat sinks have strong encapsulation that weighs more than the PCM they contain. The objective of this work is to develop PCM heat sinks configured as thin sandwich plates, in which the mass of the encapsulation is a small fraction of the PCM mass. The design is based on a lightweight carbon fiber core that has suitable mechanical, thermal, and capillary properties. PCM composite plates were fabricated with dimensions 15x15x0.6 cm^3 and with a dodecan, sealed, and successfully tested in thermal-vacuum environment. No performance degration was observed after 100 deep thermal cycles in air. A lightweight design incorporating heat pipes was demonstrated. It appears feasible to fabricate such plates with thickness 1-10 mm and with organic PCM mass fractions exceeding 75%. Thick heat sinks may be formed by laminating thin plates.

15. Subject Terms Phase-change, PCM, Composite, Heat capacity, Heat pipe, Thermal management, Heat sink, Sandwich construction

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ESLI staff who participated in this project are: Michael G. Carpenter, Victor A. Ashford, Brett M. Ellman, Y. Robert Yamaki and Timothy R. Knowles (Principal Investigator).

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Nomenclature

A	area [m^2]
c	volumetric heat capacity [$J/K\text{-}m^3$]
D	fiber diameter, thickness of fiber core [m]
k	thermal conductivity [W/K-m]
T	temperature [K]
ϕ	fiber packing fraction, fiber volume fraction
PCM	phase change material
TES	thermal energy storage

1 PROJECT SUMMARY

Background - Thermal storage devices based on phase-change materials (PCMs) have traditionally been box-like structures with robust walls and low PCM volume fractions <60%. The bulkiness and weight of such devices limits their usefulness in aerospace thermal control systems. Satellites have thermal transients driven by periodic environmental and traffic loads, and thermal inertia can be used to moderate the resulting temperature variations. A useful configuration for PCM thermal energy storage (TES) is thin (1-5 mm) PCM plates that can be readily integrated into instrument enclosures, electronic racks, focal planes, panels for radar and photovoltaic arrays, and laser-hardened radiators. By laminating a number of thinner plates, thick PCM heat sinks can be fabricated. Prior PCM art does not teach how to achieve both PCM containment and structural stability in thin plate structures.

The innovation - This project develops a PCM packaging concept based on sandwich construction. A novel lightweight "fibercore" material is fabricated by electrostatic positioning of short carbon fibers to form a microtruss architecture that has good mechanical, thermal and capillary pore features. Capillary effects control the void distribution and effectively eliminate expansion stress, permitting the use of thin facings on the sandwich. Structural core having 95% open porosity with pore size less than 50 μm, and thin aluminum or composite facings enable packaging with up to 90% PCM volume fraction. Using an organic PCM, where the typical density is less than 0.8 g cm^{-3}, the mass density of the PCM composite plate can be less than that of water, yet the effective heat capacity for a typical electronic application can be ten-times higher than aluminum.

The fibercore is compatible with the inclusion of miniature heat pipes whose thermal connection to the facings is mediated by conductive carbon fibers. Such design may enable lightweight heat sink plates whose effective thermal conductivity is higher than that of copper.

Work done - PCM Composite plates were fabricated with dimensions 15x15x0.6 cm^3 and with a PCM mass fraction of 60%. The structural plates were vacuum backfilled with dodecane (melting point -10°C) sealed and tested. No performance degradation was observed after 100 deep thermal cycles between -90°C and +30°C in air. Also fabricated was a 15 cm cubical enclosure consisting of six plates one of which incorporated an interior thermosyphon-type heat pipe. This complete enclosure was tested in thermal vacuum environment where it performed successfully and in agreement with thermal modeling.

Conclusions - The sandwich design with a carbon fiber core is an effective structural design well suited for PCM Composite plates. It appears feasible to fabricate flat or contoured PCM Composite plates with thickness 1-10 mm and with organic PCM mass fractions exceeding 75%. PCM Composite plates may be preferable to aluminum plates on the basis of their heat capacity, thermal conductivity, weight and strength. The plate configuration is suited for integration in into electronic racks, instrument enclosures, panels and space batteries.

2 INTRODUCTION

2.1 Phase-Change Thermal Energy Storage

The problem - A number of PCM thermal energy storage devices have been used in satellite thermal control [1-6]. They are thick-walled aluminum boxes with cavities to contain the PCM, usually with some aluminum filler to enhance heat transfer in PCMs that have low thermal conductivity. Typical shapes are rectangular or cylindrical solids with a characteristic dimensions of 2-20 cm. The PCM volume fractions are rather low, typically less than 50%. A recently built PCM device is the 120 K BETSU PCM canister fabricated by Grumman Aerospace (17.1% PCM mass fraction) and Swales is currently developing a cryogenic PCM device for use near 60 K. The reason such stout design dominates is that PCMs can develop large expansion stresses during phase change, and the containers are built to withstand those forces. This project concerns an alternative design in which expansion forces are eliminated by control of void distribution, and lightweight thin-walled PCM packaging can be used.

If PCM plates were only 1-7 mm (0.040-0.25") thick, then they could be readily integrated into electronic racks, instrument enclosures, cryogenic focal planes, radiators, and the supporting panels for radar and photovoltaic arrays. Such plates could provide enhanced heat capacity for temperature control of transients common in LEO spacecraft and other applications. Fighter plane avionics have ~200 module plates with total volume of several liters. Such a volume of PCM could provide a valuable temperature control function needed during supersonic flight when air cooling is not possible. Conventional PCM packaging with its bulky metallic encapsulation understandably has been rarely used in such applications.

ESLI PCM composites - ESLI has investigated "PCM composites" in which thin conductive foil materials are dispersed in PCM matrices [5,6]. Two principal benefits were found: (i) capillary retention of PCM that controls void distribution and thereby reduces stress and (ii) good conductive heat transfer for fast charge & discharge. With sufficiently small capillary pore size, liquid PCMs will not migrate allowing the shrinkage voids to aggregate (**Fig. 1**). The origin of stress in a wax PCM, for example, is the separation of the shrinkage voids from the solid wax

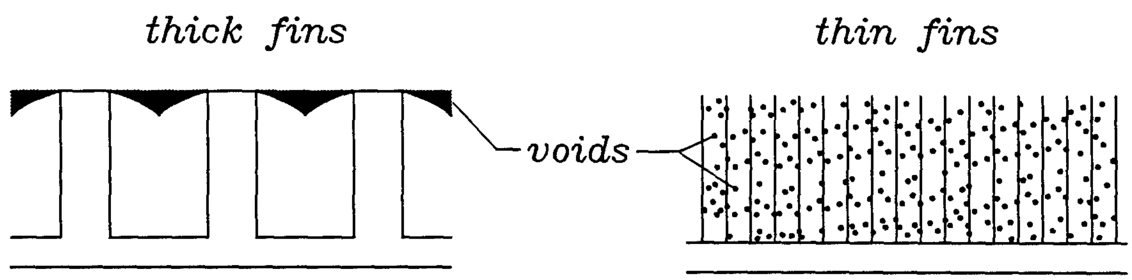

Fig. 1 Capillary structures cause PCM to fracture on contraction, distributing voids throughout.

during freezing so that access to this void space is blocked during remelt when the wax needs to expand. The PCM composite work enabled lightweight thin-walled PCM canister designs to be used, but the original foil designs did not lend themselves to thin plate fabrication. ESLI models from that work would call for micro-cellular honeycomb (with 50-micron cell diameter and 3-micron foil thickness) for use in a 3-mm thick plate. Such a micro-cellular honeycomb has not been practical.

2.2 PCM Composite Cold Plate Concept

This project investigates a PCM packaging concept in which PCM saturates the core of a sandwich structural plate. A novel fiber core material is used that consists of short carbon fibers that are bonded at the nodes where fibers touch forming a "microtruss" structure (**Fig. 2**, **Fig. 3**). Capillary effects retain adhesive at the nodes providing rigidization that is highly efficient for the added weight, typically a small fraction of the total fiber mass. The porosity of the core may be very high ~99% or much less depending on the fiber fraction and the degree of infiltration with solid rigidizing materials. Typical values of porosity are 85-95%.

The fibercore is multifunctional, providing all three features necessary for effective PCM Composite: good capillary control, through-thickness thermal conductance and reasonable strength in spite of high porosity. Carbon fiber is readily wetted by organics, including the PCMs of interest, and pitch-derived carbon fibers have high thermal conductivity if required for short-duration higher flux applications. For enhanced thermal conductivity parallel to the plate miniature heat pipes may be employed. To achieve adequate thermal conductance through the limited surface area of such pipes, radial carbon fibers may be used (**Fig. 4**). The microtruss architecture of the fibercore is expected to have good specific mechanical properties (on a per weight basis) derived from the carbon fibers. In this design there are no long carbon fibers: it is expected that the average fiber free length (between points of contact with other fibers) is on the order of 0.2 mm (0.008"). Since buckling strength varies inversely with the free length, we expect reasonable compressive strength properties.

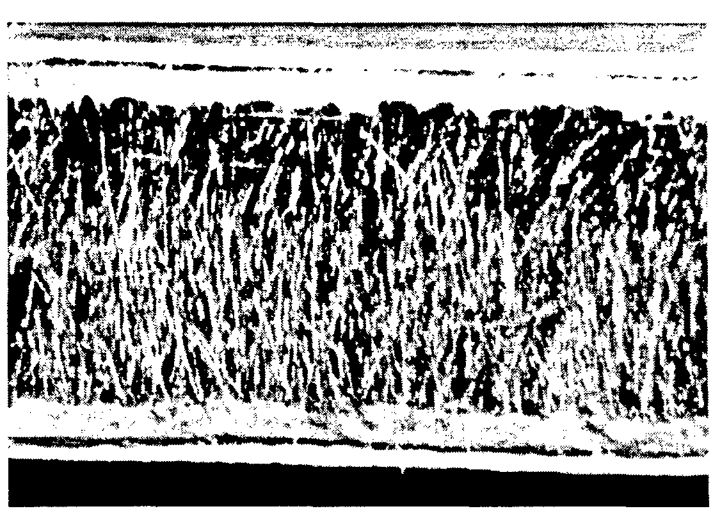

Fig. 2 Carbon fiber core sandwich structure, rigidized with an adhesive washcoat.

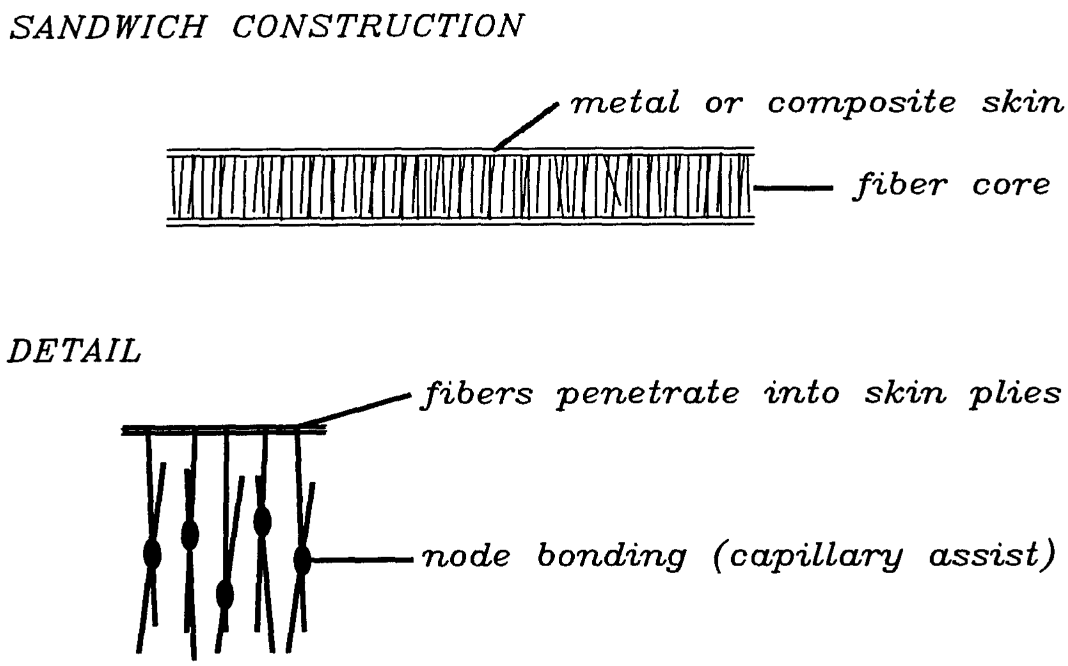

Fig. 3 Microtruss concept with node-bonded fibers and facing sheets that may be metal, polymer or reinforced composite.

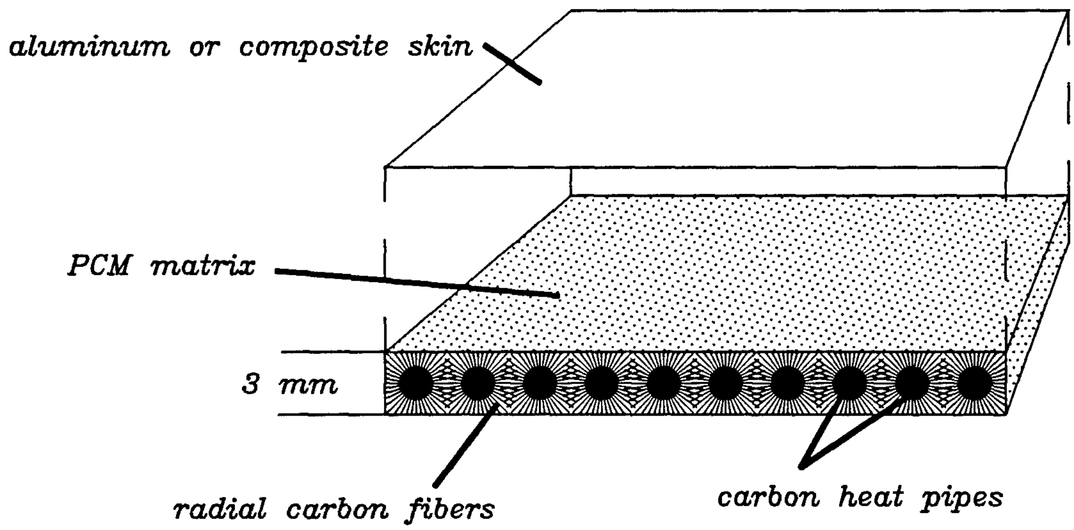

Fig. 4 Concept high conductance composite plate with miniature heat pipes and a fiber thermal interface.

2.3 Phase 1 Objectives

The primary Phase 1 objective is to demonstrate fabrication and use of PCM composite plates based on the carbon fiber microtruss core concept. Repeated deep thermal cycling should reveal prominent failure modes. At issue is whether lightweight PCM composite plate design will have reasonable mechanical properties (for example, to meet the requirements of an avionics cardrack) and will successfully avoid failure induced by the thermomechanical stress during phase transition. The proposed tasks were

Task/Objective	Effort
1. Define requirements and select materials	10%
2. Fabricate four PCM Composite plate test articles	30%
3. Obtain cycling and thermal response data	30%
4. Obtain mechanical strength data	10%
5. Assess benefits and design for applications	10%
6. Reporting	10%

Essentially all proposed tasks were successfully completed, vacuum-compatible PCM composite plates with 60% PCM mass fraction were fabricated and thermally cycled without failure (Section 3).

Early in the project ESLI received a Purchase Order from the Jet Propulsion Laboratory (Pasadena, CA) to perform a preliminary demonstration of a PCM Composite Warm Electronics Enclosure for the Mars Exploration Technology program. The fact that ESLI had this SBIR project was an important consideration for JPL. In order to accommodate that application, the peel testing intended in Task 4 was replaced by demonstrating the compatibility of PCM composite plates with vacuum.

3 PCM COMPOSITE COLD PLATE DEVELOPMENT

3.1 Materials

3.1.1 PCM Selection

There are many organic PCMs that cover cryogenic, ambient and high temperature applications. Organics such as straight chain paraffins, C_nH_{2n+2}, are benign, reliable materials available in suitable purity from, for example, Aldrich Chemical Company. The available melting points cover a range that includes subambient and moderate warm temperatures suitable for many electronics applications (**Fig. 5**). Note that the apparent deficit in the trend for carbon numbers 22-29 is the result of solid-solid transitions occurring just below the melting point and not included in these latent heat data. Paraffins such as hexadecane, octadecane and eicosane have been used in various heat sink studies at ESLI. For this project hexadecane was selected for wetting and capillary height studies, because it is molten at room temperature. Dodecane was selected for most of the PCM composite plate studies because it melts near -10°C which is suited for certain Mars exploration applications.

It might be added that water (and heavy water) are good candidate PCMs for thermal control near 0°C. Water has high heat capacity: approximately 100% higher than that of alkanes and its latent heat of fusion is approximately 50% higher than that of alkanes. An application is thermal

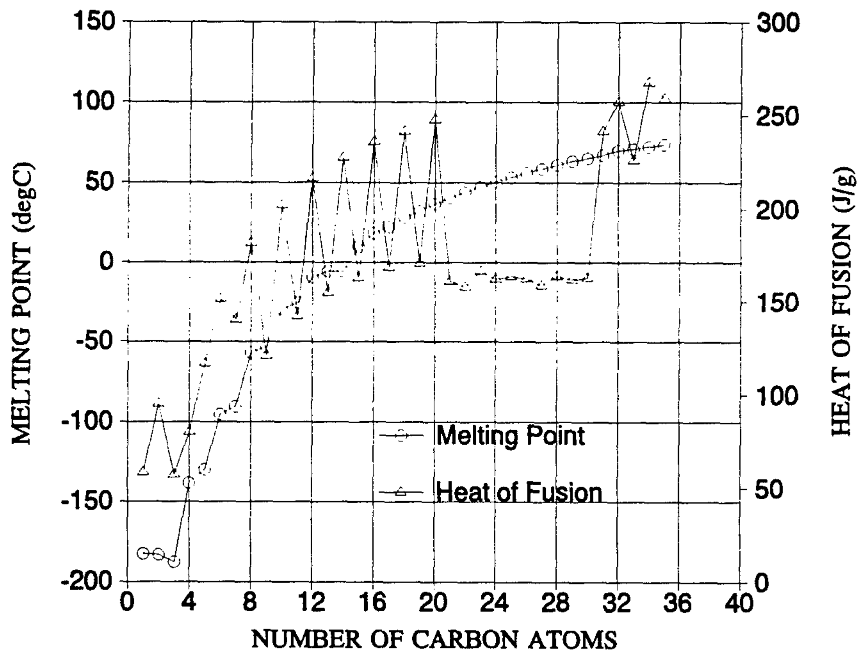

Fig. 5 Melting point and latent heat of normal (straight-chain) alkanes.

management in nickel-hydrogen spacecraft batteries. However, water can develop enormous expansion stress, as witnessed by burst water pipes during freezing weather. It is an interesting challenge to demonstrate adequate control of stress in water-based PCM composite plates. This may be investigated in a future effort.

3.1.2 Fibercore Selection

Carbon fiber, rather than ceramic or polymeric fiber, is a natural choice for the core material because of its combination of suitable properties:

HIGH STRENGTH AND STIFFNESS: The ultrahigh-modulus fibers such as AMOCO P120 and K1100 are extremely brittle with strain to failure ~0.1%. For this project select PAN-derived carbon fibers were selected that have reasonably good modulus (~32 Msi), moderate strain to failure (~1.6%) and very high tensile strength (~500 ksi). They cost ~$100/kg.

GOOD THERMAL CONDUCTIVITY: High modulus fibers have high thermal conductivity exceeding that of copper, and PAN fibers have thermal conductivity k ~10-20 W m^{-1} K^{-1}, which is adequate for moderate flux applications in thin plate configurations. For use at higher heat flux and for thicker plates, suitable admixtures of high-k carbon fibers may be used to tailor the through-thickness conductance based on the rule of fractions and simple models of the thermal time constant or the thermal resistance.

CHEMICAL COMPATIBILITY: Carbon fibers are compatible with, and well wetted by many organic PCMs. They can be used also with high temperature PCMs, but fiber surface treatments may be needed for wetting or chemical passivation. For example metallization with nickel or copper enhances wetting by molten salts.

ESLI has considerable experience in the positioning of carbon fibers by various electrostatic, pneumatic and mechanical methods. Well oriented carbon fiber velvets (**Fig. 6**) can be fabricated over large areas. Such velvets can be mounted with epoxy or other adhesive layers on many different substrates, such as the aluminum or composite facings of a sandwich structure. Well oriented velvets can be inserted into one another forming sandwich structures, which, after rigidizing washcoats, become stiff, strong and well suited for PCM Composite cold plate fabrication.

The mass M of the velvet of area A_0 may be calculated according to

$$\frac{M}{A_o} = \rho\, \phi\, L = \rho\, \frac{D}{4}\, \frac{A}{A_o} \qquad \text{Eq. (1)}$$

where ρ = carbon fiber density. For example, 3-mm long carbon fibers having 7-μm diameter, ρ = 1.75 g/cm^3 and packing fraction ϕ = 5% will have an areal weight of 0.255 kg/m^2. The characteristic pore size in the flock may be estimated by dividing the total flock volume by the flock area: For example, Eq. (2) predicts that a 0.5% dense packing of 7-μm diameter fibers has a characteristic

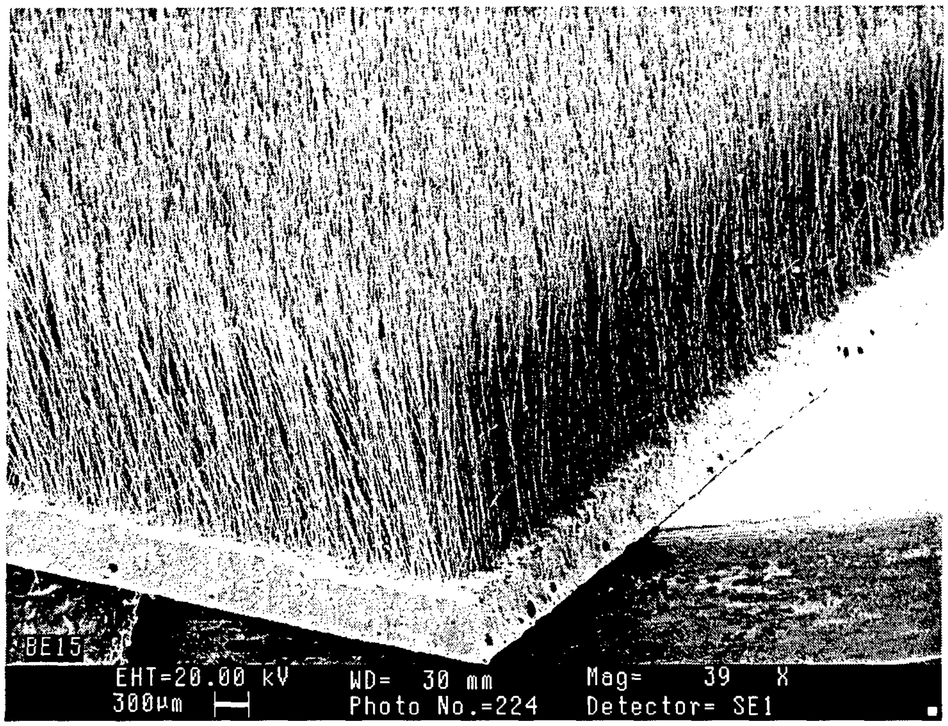

Fig. 6 Carbon fiber velvet formed with 7-µm diameter x 2.5 mm long PAN carbon fibers at packing fraction of 3%. These fibers are deeply embedded in a polymeric substrate.

$$D_{cavity} = \frac{volume}{area} = \frac{LA_o}{4\,\phi\,L\,A_o/D} = \frac{D}{4\,\phi} \qquad \text{Eq. (2)}$$

pore size of 350 µm, while a 5% dense packing has a characteristic pore size of 35 µm. The flock area enhancement, the areal mass and the characteristic pore size are shown in **Tab. 1**. These parameters are favorable for lightweight design with good pore size for capillary retention of PCM.

Tab. 1 Flock area, mass and pore size *vs* packing fraction (1-mm long, 7-µm diameter PAN carbon fiber).

packing fraction	area enhancement (m^2/m^2)	areal mass (kg/m^2)	pore size (µm)
0.01	5.7	0.018	175.0
0.02	11.4	0.035	87.5
0.03	17.1	0.053	58.3
0.04	22.9	0.070	43.8
0.05	28.6	0.088	35.0

3.1.3 PCM Composite Plate Design

As a simple example of the thermal design, consider a 3-mm (0.120") thick PCM composite plate 30*x*30 cm^2 (1 sqft) in area and operating between 40°C and 50°C. Assume 0.2 mm (0.008") thick aluminum skins, a carbon fibercore with fiber density ρ = 1.7 g/cm^3 at 5% packing fraction, and typical organic PCM properties (density = 0.75 g/cm^3, latent heat = 200 J/g, specific heat = 2 J/g). The effective specific heat capacity of the PCM composite is approximately 20-times higher than that of a simple aluminum plate (**Tab. 2**). The PCM mass fraction in this case is 63%.

The dominant non-PCM mass is in the facings because the fibercore is lightweight. Three candidate facing materials are (i) thin aluminum sheet, (ii) thin graphite epoxy laminate composite and (iii) thin polymer. Polymer facings are lightest, but also weakest and least conductive. Aluminum foils on the order of 0.1 mm thick (0.004") seem to be a good choice for lightweight design. Laminate composites would need to be made with very thin prepreg on the order of 0.05 mm (0.002") thick in order to compete on a weight basis. The PCM fraction achievable with 0.05 mm (0.002") thick aluminum skins on a 7 mm (0.28") thick plate is 81%wt-92%vol as broken out in **Tab. 3**. For facings that are 0.25-mm (0.010") thick, the PCM mass fraction drops to approximately 60%.

Tab. 2 Comparison of the specific heat capacity of PCM Composite plate and simple aluminum plate.

	PCM Composite plate	**Aluminum plate**
heat absorbed (W-hr)	13.0	1.80
weight (kg)	0.31	0.80
heat absorbed per pound (W-hr/kg)	41.9	2.25

Tab. 3 Weight distribution for a lightweight PCM Composite plate design.

PCM Plate Weight & Volume		
plate area =	232.2576	cm2
total plate thickness =	0.66	cm
=	259.8425	mils
skin thickness =	0.005	cm
=	1.97	mils
skin density =	2.7	g/cm3
adhesive thickness =	0.005	cm
=	1.97	mils
adhesive density =	1.5	g/cm3
fiber packing fraction =	0.06	-
fiber density =	1.7	g/cm3
PCM density =	0.7	g/cm3
surplus void =	0	
close out thickness =	0.005	cm
Weight distribution		
total mass =	131.654	g
total mass areal density =	**0.5668**	g/cm2
PCM mass areal density =	**0.4550**	g/cm2
PCM:	0.8027	
skins:	0.0476	
fibercore:	0.1170	
adhesive:	0.0265	
closeout:	0.0063	
Volume distribution		
total volume =	153.2900	cm3
total volume density =	**0.8589**	g/cm3
PCM volume density =	**0.7829**	g/cm3
PCM:	0.9115	
skins:	0.0152	
fibercore:	0.0582	
adhesive:	0.0152	
closeout:	0.0020	

3.1.4 High Conductance Design

For electronic cardrack applications there is a requirement for good thermal conductivity parallel to the plate, particularly in the direction toward the cardrails. Numerous projects in recent years have investigated the use of metal-matrix and carbon-carbon composite plates in an effort to provide good in-plane thermal conductivity in a lightweight rigid material.

PCM composite design is compatible with miniature heat pipes that are located inside the plate. Heat pipes offer effective thermal conductivities on the order of 50,000 $W m^{-1} K^{-1}$ (**Fig. 7**), which is a specific thermal conductivity two orders of magnitude better than high-*k* graphite fibers. A panel in which 10% of the volume consists of such heat pipes could therefore have an effective thermal conductivity (parallel to the heat pipes) that is roughly ten-times higher than copper, or 20-times higher than aluminum. In order to be that effective however, it is critical to have good thermal coupling between small pipes and the surrounding medium.

One means of achieving high interfacial conductance is to use radial high-*k* carbon fiber pin-fins on the tube exteriors and then integrate with the fibercore of the sandwich structure (**Fig. 4**). This type of thermal interface is porous and does not displace PCM as would a conventional aluminum saddle.

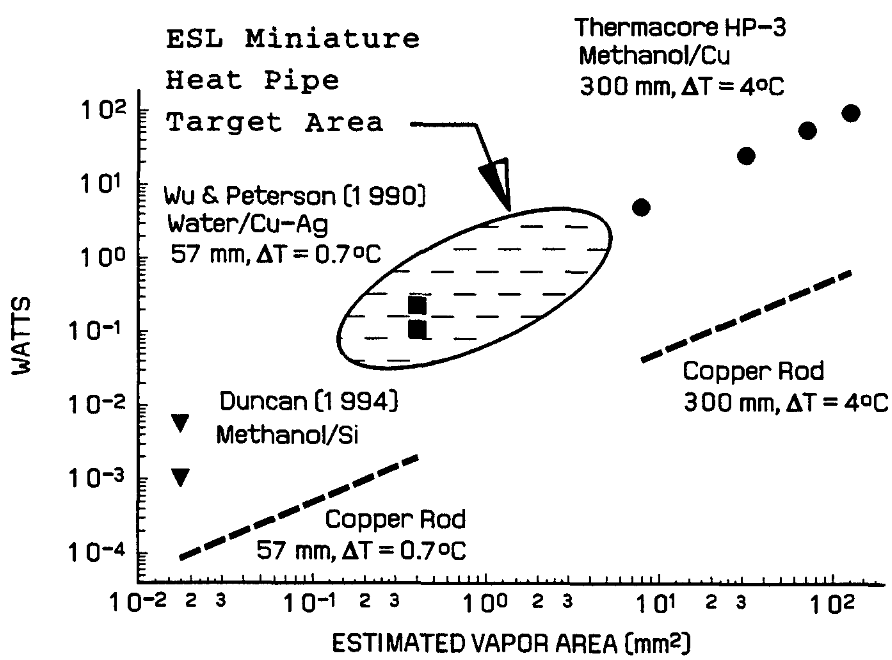

Fig. 7 Heat pipe transport capacity *vs* vapor area. The effective thermal conductivity is roughly 100-times higher than that of solid copper.

3.2 Fabrication

3.2.1 PCM Composite Plates

Structural sandwich plates were fabricated using electroflocking to position precision cut fibers vertically onto the aluminum facings with an epoxy adhesive. Two such plates are then plugged into one another like two sheets of velvet, and a thin adhesive washcoat is applied to rigidize the fiber structure. Capillary effects retain a small amount ~1%(vol) of adhesive at nodes where the fibers touch. The resulting microtruss structure containing approximately 5% fiber volume fraction has good specific strength and stiffness. Higher strength is achieved with greater amounts of adhesive, but the core weight also increases.

There are various ways to close out the edges of the sandwich plates. The most reliable is to shape the aluminum facings so that the they meet and can be welded by electron beam. A lower cost method is to fold and crimp the facings to one another similar to the methods used to seal aluminum beverage cans. As a simple, but less reliable method, one can bond aluminum sheet closeouts with an epoxy. This latter method was used for the test articles.

The sandwich plates were filled with PCM using a vacuum backfill technique in which the plates are first evacuated and then a valve is opened permitting molten PCM to flow into the core, filling it completely. The plate is then heated to the maximum use temperature to exude excess PCM and the fill hole is then sealed by either crimping the small fill tube or by cleaning and covering the hole with epoxy.

The resulting plates (**Fig. 8**, **Fig. 9**) were approximately 15x15x0.66 cm^3 in size and the average composition is given in **Tab. 4**, where it is seen that the PCM mass fraction of these components is approximately 60%. Six plates, in which one contained a butane thermosyphon (**Fig. 10**) were assembled into an enclosure box with simple aluminum tape joints (**Fig. 11**).

Tab. 4 Composition and mass fraction of PCM Composite plates fabricated for thermal testing.

Component	Material	Mass fraction
skins, edges	0.010" aluminum	23%
adhesive	epoxy	9%
core fiber	PAN carbon fiber	8%
core nodes	phenolic	2%
PCM	dodecane $C_{12}H_{26}$	58%

PCM Composite areal mass density = 0.68 g/cm^2.

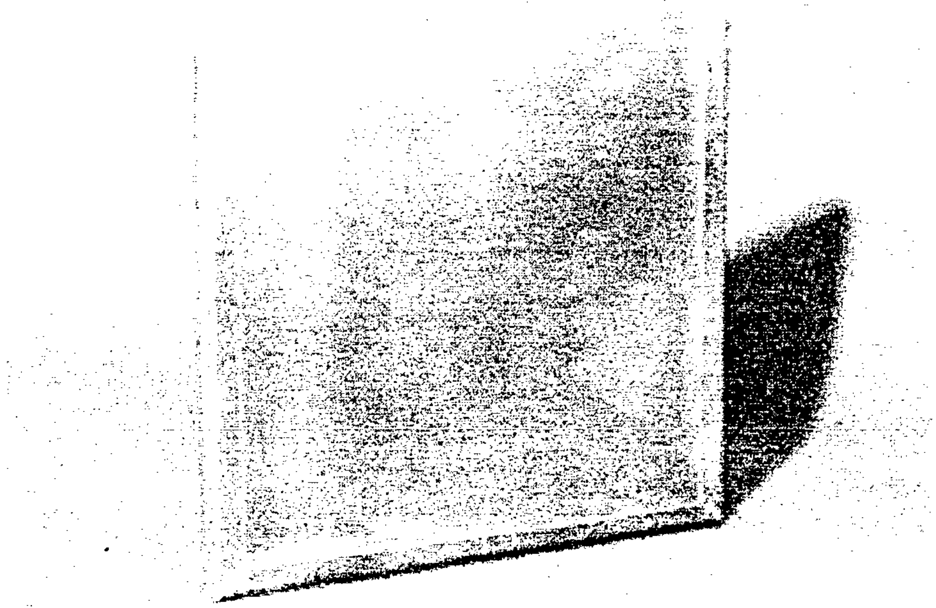

Fig. 8 PCM Composite plate, 15x15x0.566 cm^3.

Fig. 9 Cross-section of PCM Composite plate showing fiber core.

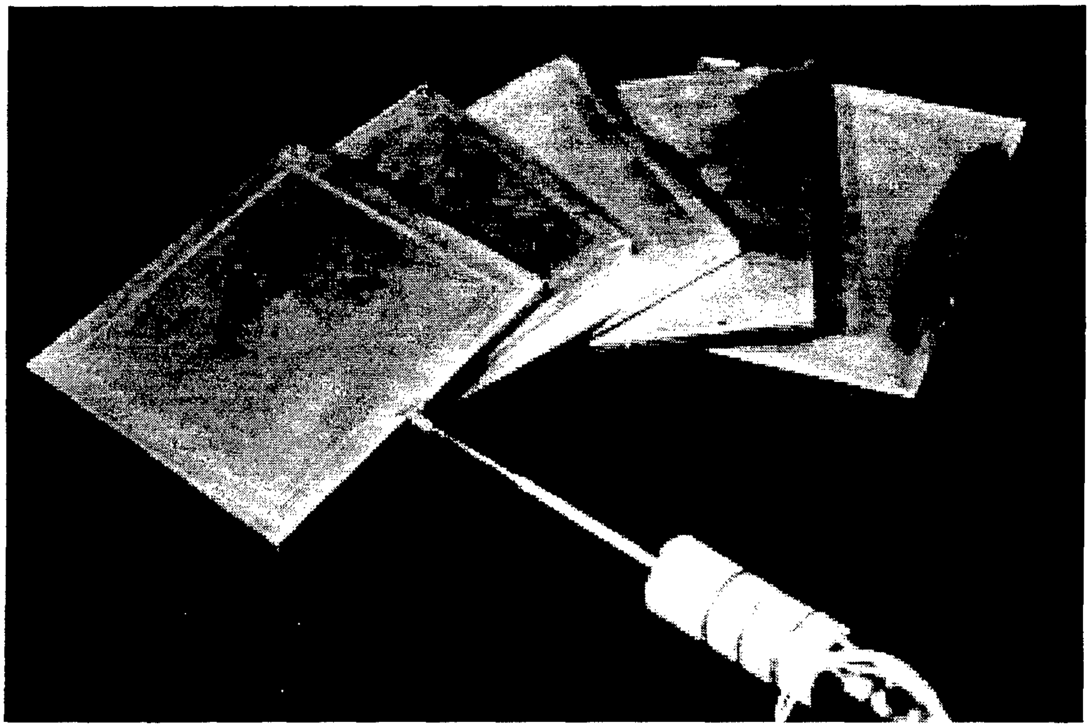

Fig. 10 Five of the PCM Composite plates, one of which has a butane heat pipe that passes through the middle of the plate.

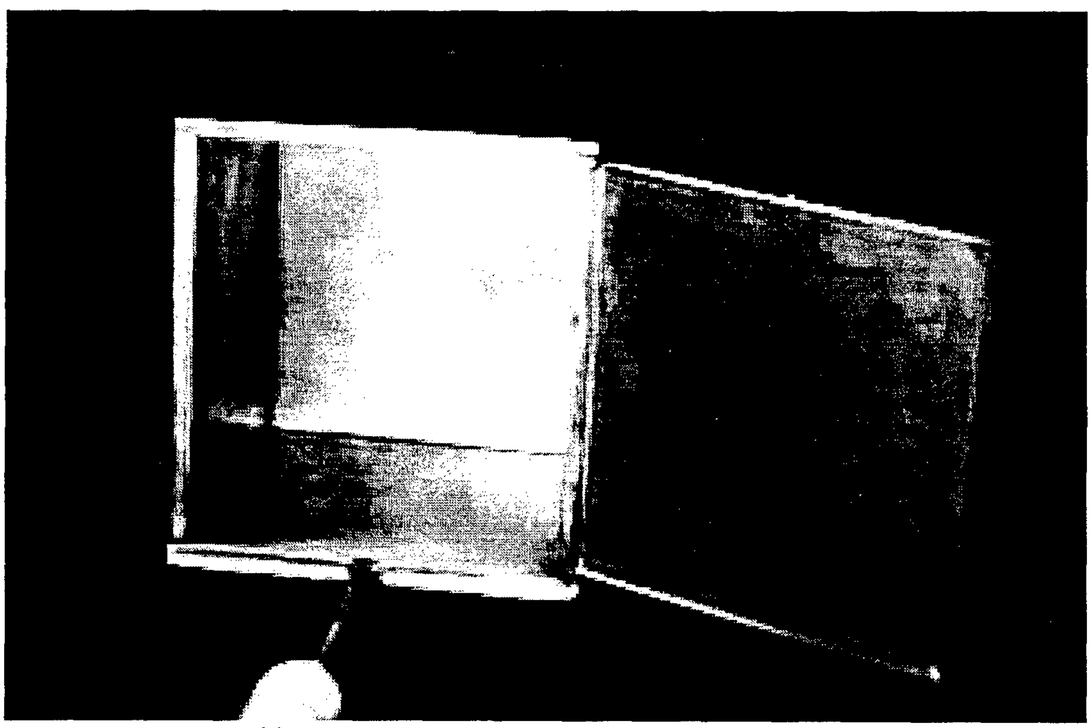

Fig. 11 Six-sided PCM Composite enclosure (15 cm edge).

3.2.2 Sandwich Plate with Large Diode Heat Pipe

A PCM composite plate was fabricated with a 4.5 mm diameter stainless/butane thermosyphon-type heat pipe (**Fig. 10, Fig. 12**). A pyrex section was incorporated to reduce conduction down the pipe and provide diode action useful for the Mars warm electronic enclosure application. This pipe was coated with radial carbon fibers before incorporating it into the fibercore of the sandwich plate and washing with a phenolic. The resulting attachment was strong and reliable.

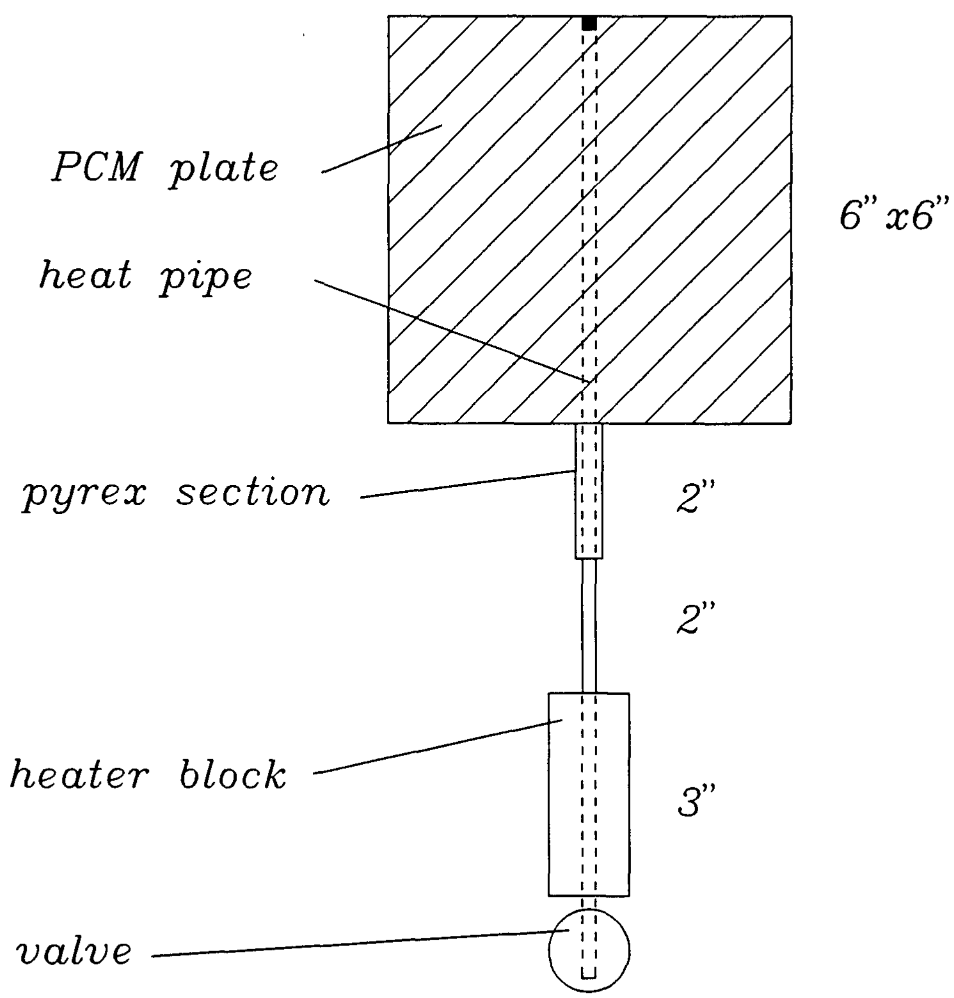

Fig. 12 PCM Composite plate with butane thermosyphon to serve as diode heat pipe in gravity.

3.2.3 Plate with Miniature Heat Pipes

A PCM plate with six interior heat pipes was fabricated (**Fig. 13**, **Fig. 14**). The heat pipes were copper/water "thermal pins" obtained from Noren Thermal Products (Palo Alto, CA). The pipes were first coated with radial carbon fibers, placed on the carbon velvet facing and then covered with a second carbon velvet facing. Note that the interlocking flock provides a lightweight "saddle" to thermally interface the pipe with the plate. The fibers used in this panel are PAN carbon fibers with $k \sim 20\ \mathrm{W\,m^{-1}\,K^{-1}}$ and therefore have limited heat transfer.

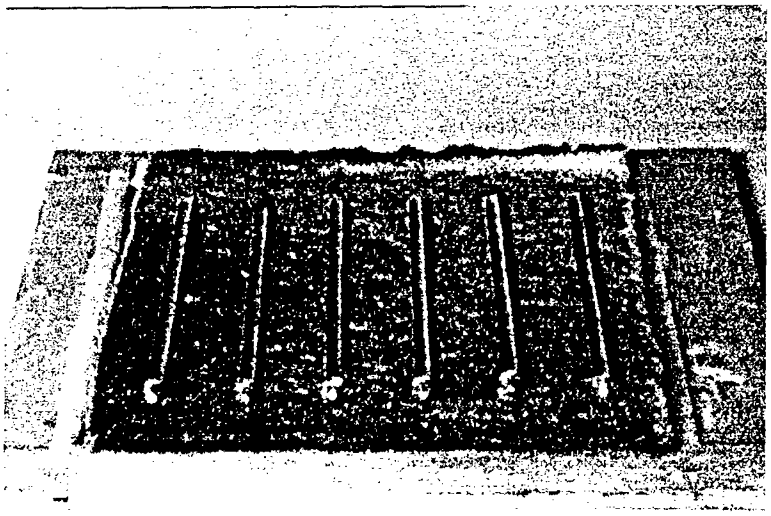

Fig. 13 Fiber-coated plate with widely spaced fiber-coated copper/water heat pipes.

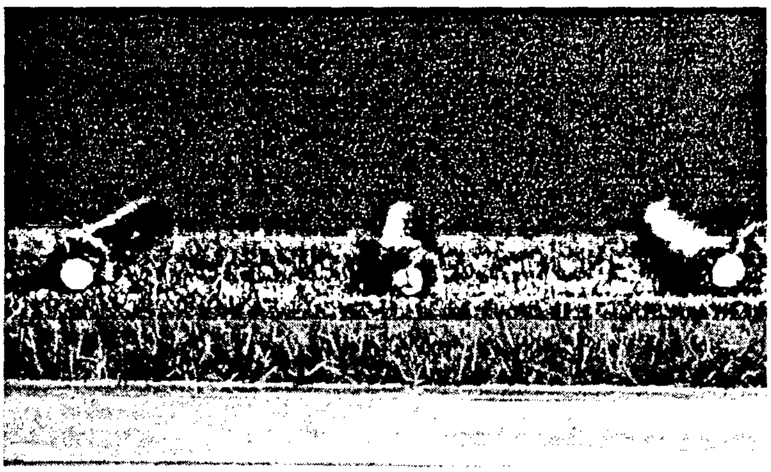

Fig. 14 Closer view of the heat pipes with fiber interface.

3.3 Mechanical Testing

3.3.1 Flexural Stiffness

The flexural stiffness of the fibercore sandwich plate (without PCM) was measured. A flexure test fixture (**Fig. 15**) was designed in accordance with ASTM Standard C 939-62, "Flexure Test of Flat Sandwich Constructions", and in its present configuration, is suitable for specimens up to one inch wide and from 1/8 inch to 1/4 inch thickness. Load is applied to the specimen through 3/16 inch diameter rods (this diameter determines specimen thickness limits per the standard), and the span is infinitely adjustable from 1-1/2 inches to 5 inches, in either half-span (3-point) or quarter-span (4-point) loading configurations. Span was set at 3 inches to obtain the subject test data. The span points are mounted on a beam comprised of a pair of 1 x 1 inch aluminum bars, between which the specimen-midpoint displacement-measuring device is mounted so that it contacts the bottom surface of the specimen. The current displacement-measuring device is a dial gage with .001" divisions (readable to nearest .0002 inch); it is anticipated that this will be replaced by a high-accuracy displacement transducer. Load is sensed by a 50-pound capacity load cell; for the subject data, the load cell conditioner was adjusted to yield a sensitivity of 30 millivolts/pound (readable to the nearest 0.1 millivolt). A 5-pound dead-weight calibration (to nearest 0.1 millivolt, or .0033 pound) to is employed prior to each testing session, and a jig is used to obtain proper alignment of fixture components.

Fourteen specimens were measured, including carbon fibercore with aluminum facings, carbon fibercore with fiberglass/epoxy composite facings, Duocell foams with aluminum facings and, as a control specimen, a solid aluminum specimen. The data are shown in Tab. 5.

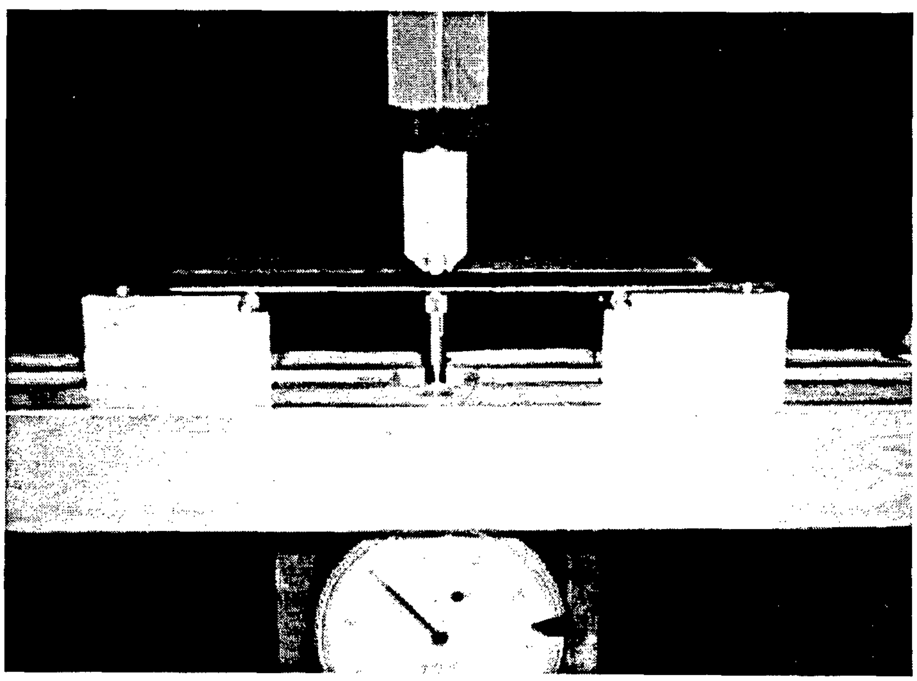

Fig. 15 Flexure test fixture.

Tab. 5 Flexure test data taken on sandwich composite materials. The highest stiffness-to-weight is observed with a carbon fibercore rigidized with phenolic.

SPECIMEN	thickness (inch)	mass density (g/cm^2)	(Load for 0.005" deflection) / (mass density) x 10^{-3}
MGC6-25, phenolic	0.157	0.21	10.2
MGC6-29.2, epoxy-1	0.157	0.17	3.4
MGC6-31, epoxy-1	0.157	0.17	3.3
MGC6-31.2, epoxy-1	0.157	0.17	4.3
MGC6-33, epoxy-2	0.157	0.17	6.1
YRY1-35.1, epoxy-2	0.145	0.229	6.4
YRY1-35.2, epoxy-2	0.143	0.226	6.1
YRY1-35.3, epoxy-2	0.144	0.229	7.1
YRY1-35.4, epoxy-2	0.144	0.230	9.2
YRY1-35.5, epoxy-2	0.143	0.227	6.1
YRY1-35.5, epoxy-2	0.145	0.226	6.6
Duocell, 10 ppi	0.125	0.28	5.9
Duocell, 40 ppi	0.125	0.28	5.3
Solid aluminum	0.14	0.90	6.3

3.3.2 Capillary Height

Capillary height was measured using molten octadecane. Selected sandwich panels were first loaded with the PCM by submerging them nearly horizontal and measuring the mass of PCM absorbed. The plate was then turned vertical and left to drain for approximately one hour in an oven at 40°C. The capillary height was determined gravimetrically by comparing the remaining PCM mass with the initial PCM mass and deriving the equivalent fill height. The capillary height derived in this way was 8.53 cm.

For comparison, the capillary height in 4-mm thick Duocell aluminum foam plates obtained from ERG (Oakland, CA) was measured in the same manner and found to be 2.0 cm for the foam described as 10 pores-per-inch and 2.3 cm for the foam described as 40 pores-per-inch.

3.3.3 Vacuum Compatibility

The PCM composite plates were observed to be leak tight during vacuum backfill with PCM. After filling and sealing the fill holes the plates were placed in a vacuum chamber and it was pumped down to less than 10 Pa pressure. No deflection or other effect was observed by exposure to vacuum. In one case out of eight a failure was observed where the facing blistered away from the core, presumably just a poorly bonded facing. The compatibility of the composite plates with the vacuum environment indicates that the fibercore and the facing bondline have a reasonable tensile strength. Adhesively bonded aluminum close-outs were tested and found to be leak tight.

3.4 Thermal Testing

3.4.1 Cycling

The first plate fabricated (CP-001) was a fibercore sandwich structure with dimensions 15x15x0.66 cm^3, where the thickness includes two 0.025 cm (0.010") aluminum skins. No edge closeouts were used. The plate was loaded with octadecane (MP 28°C) and the resulting composition was

aluminum skins	31.12 g	
adhesive	20.80 g	
carbon fiber (P120)	12.31 g	7.9%(wt), 4.0%(vol)
epoxy resin	07.07 g	
PCM	84.80 g	54.3%(wt)
TOTAL	**156.10 g**	
AVERAGE DENSITY	1.067 g/cm^3	

The weight fraction of the skins+adhesive is 33.3% which is likely to be higher than needed for structural purposes.

Approximately one hundred cycles were run over the course of several days in both horizontal and vertical orientation. No structural fatigue or failure was detected (**Fig. 16** and **Fig. 17**). In the vertical orientation PCM drained; after 20 cycles 8.23 cm of PCM height remained which is within 4% of the value observed after the one-hour static drain mentioned above. We conclude that cycling does not tend to drive out the PCM.

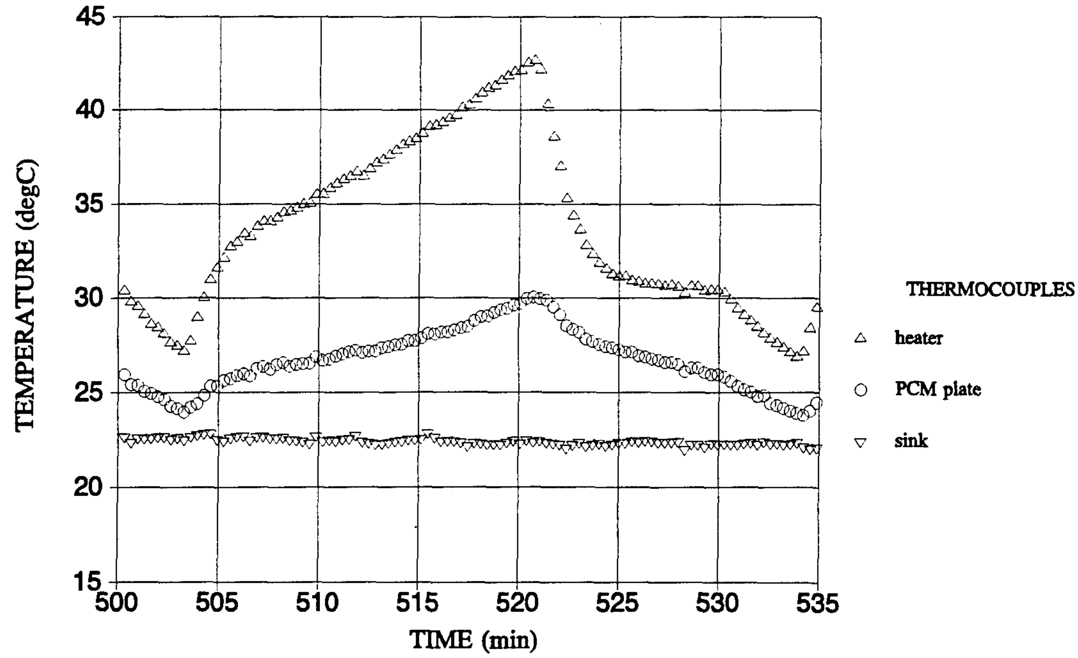

Fig. 16 Temperatures during cycle of plate CP-001.

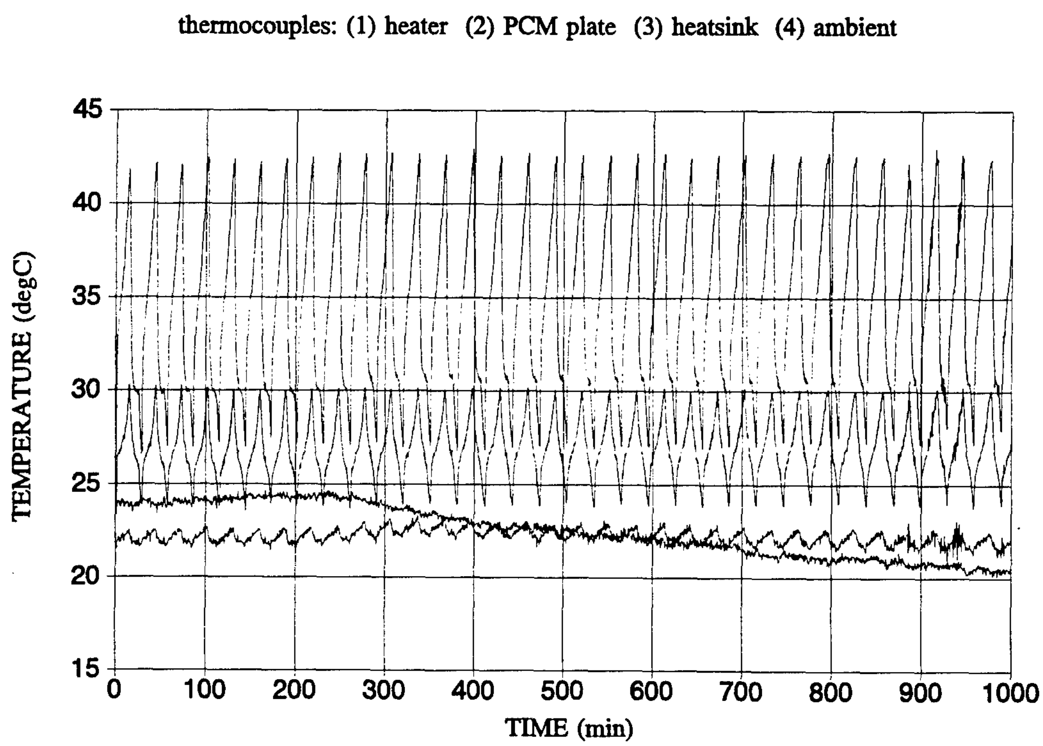

Fig. 17 Typical temperature data cycling plate CP-001 in horizontal orientation.

3.4.2 Diode Heat Pipe Plate Test

The diode heat pipe panel was tested by insulating the panel with 1" thick Rohacell foam insulation and placing it vertically in an ultralow-temperature freezer set to -90°C. The diode heat pipe protruded beyond the insulation and was exposed to the freezer temperature. Type-E thermocouples were applied to the pipe and the plate in various locations. Power was applied to a resistance heater taped to a cylindrical mass attached to the lower end of the butane heat pipe.

The temperature data (**Fig. 18**) show that the heat pipe functioned well under the 5 W heat load. The highest temperature curve is the heater, the next is a location up the pipe, etc. and the cluster of similar temperatures were locations on the PCM plate. (Note: The National Instruments LabView data acquisition program used in this test had a peculiar calibration curve for type E thermocouples, whereby it would report no temperature lower than -60°C, even, for example, when the thermocouple was immersed in liquid nitrogen. For temperatures above -60°C it appeared to report correctly).

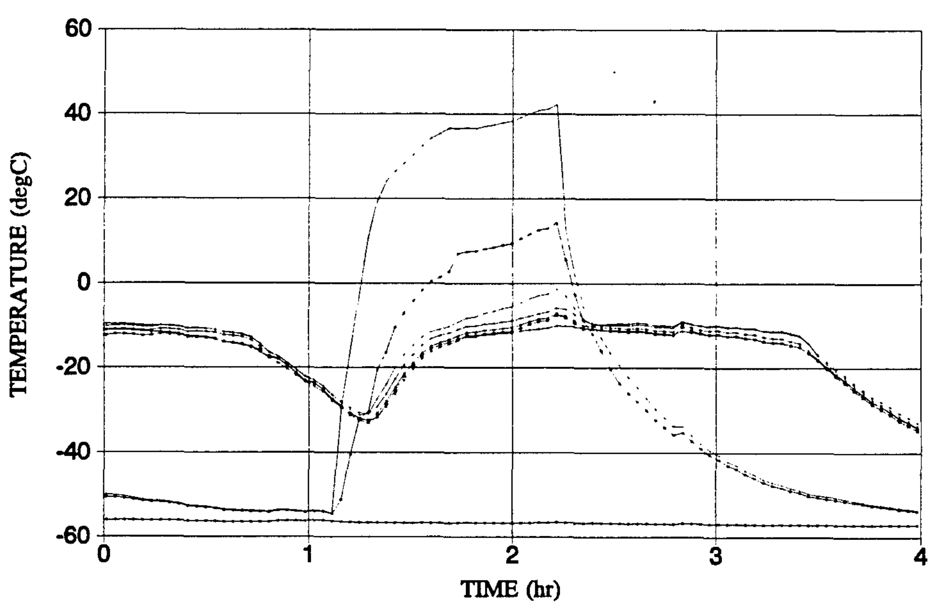

Fig. 18 Temperature data showing response of PCM plate to heat applied at the lower end of the butane heat pipe.

3.4.3 Thermal-Vacuum Test

The cubical electronics enclosure consisting of six 6"x6"x1/4" PCM composite plates **(Fig. 11)** was tested in a preliminary fashion at ESLI. Tests were performed using an ultralow-temperature freezer set to -90°C. There was no attempt to simulate the Martian atmosphere which consists of approximately 10 torr carbon dioxide. Sixteen thermocouples were used to monitor the temperature of the box interior, exterior and the freezer ambient. These various temperature records are shown in summary fashion in **Fig. 19** and the power applied is shown in **Fig. 20**. The group of temperatures that show the "shoulder" features are the box interior, and the shoulders are the characteristic arrest in temperature rise or fall caused by the PCM at its phase-change temperature (MP = -10°C).

JPL thermal-vacuum testing - The enclosure was tested in Mars-relevant thermal-vacuum conditions at JPL and compared with a similar enclosure not containing PCM [7]. The resulting thermal data are shown in **Fig. 21** for the PCM case and **Fig. 22** for the non-PCM case. JPL engineers explain that predictions based on their thermal modeling is in agreement with these observations [Manvi, 1996].

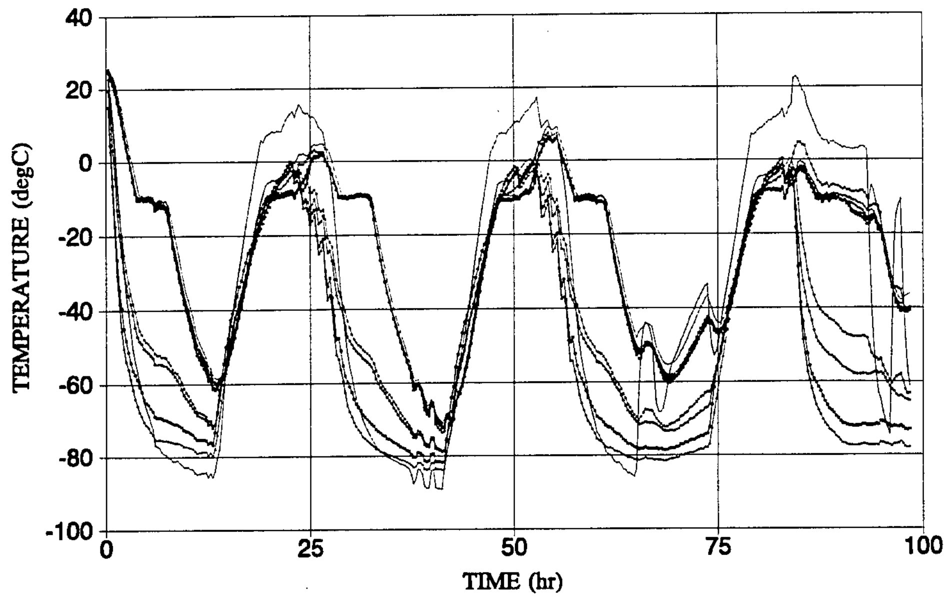

Fig. 19 ESLI performance test of PCM composite enclosure at ambient pressure.

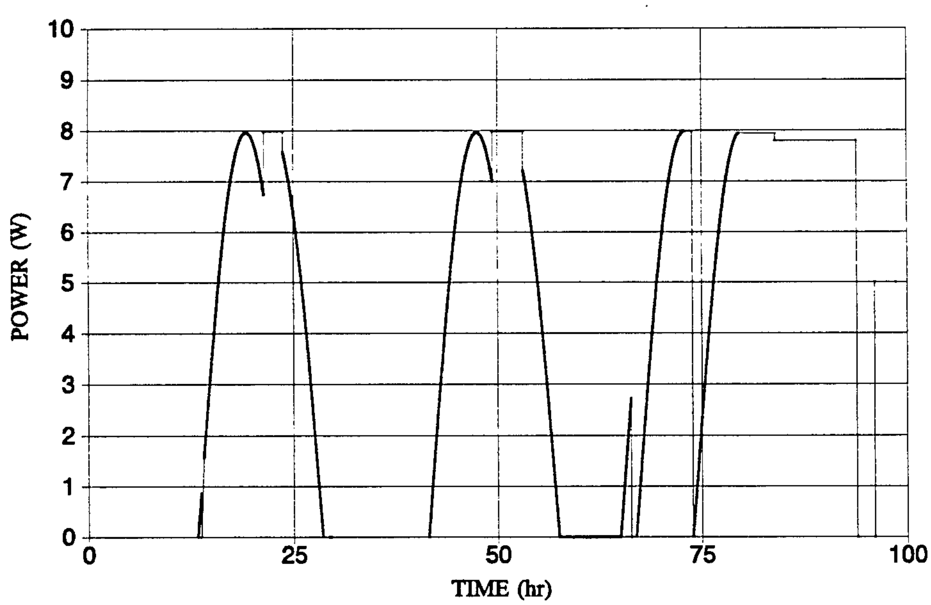

Fig. 20 ESLI thermal test heat load.

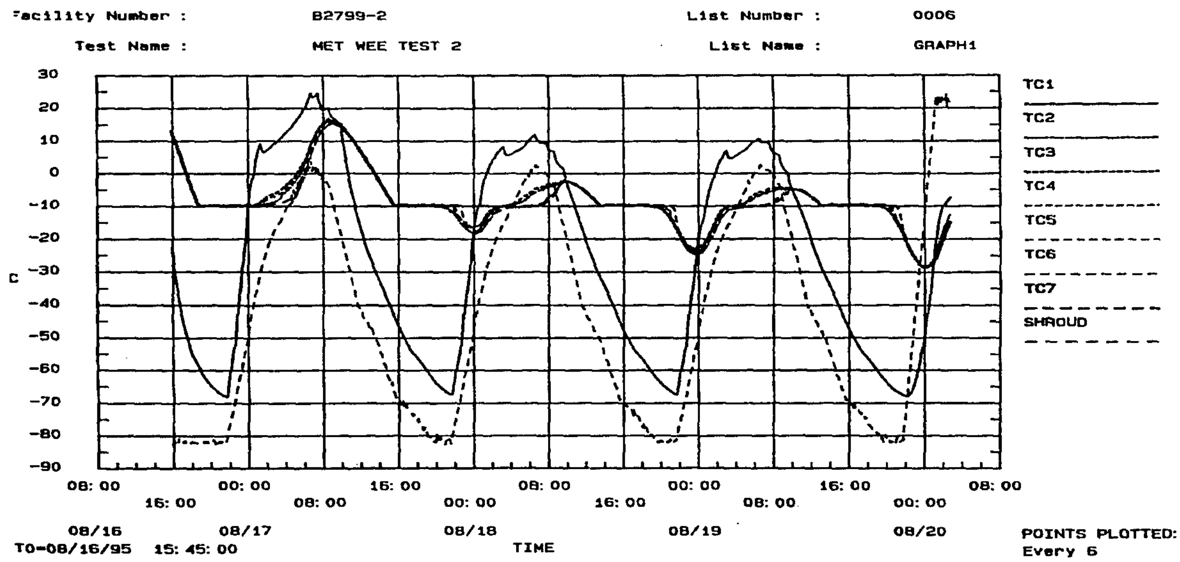

Fig. 21 JPL temperature data taken on the Warm Electronics Enclosure (WEE) fabricated by ESLI. Note the shoulders caused by the phase-change latent heat.

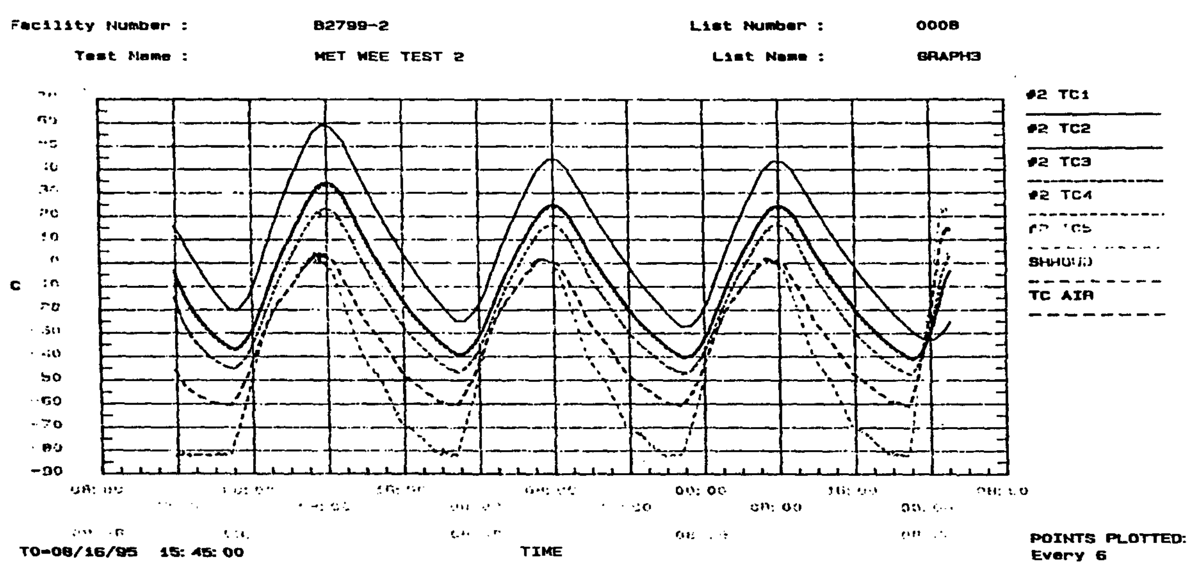

Fig. 22 JPL temperature data obtained with the non-PCM enclosure.

4 CONCLUSIONS

4.1 Phase 1 Achievements

Phase 1 effort demonstrated the feasibility of fabricating PCM Composite plates and that these plates have the following characteristics:

1. The STRUCTURAL sandwich based on carbon fibercore is structurally efficient and may achieve a higher strength-to-weight ratio than other foam and honeycomb cores. The plates can be pumped on and survive evacuation. After PCM fill they survive being placed in a vacuum chamber.
2. The WICK function of the fibercore is effective at controlling PCM and void distribution. A capillary height of 8 cm was observed and it appears feasible to achieve significantly higher values.
3. PCM MASS FRACTION of 60% was demonstrated using 0.25 mm (0.010") facings on a plate 6.6 mm thick. With thinner facings and more efficient use of adhesives, PCM mass fractions up to 80% appear feasible.
4. CONDUCTANCE FEATURES of the fibercore are favorable for good through-thickness heat transfer. High-*k* pitch carbon fibers can be admixed if required for higher-heat-flux applications. A lightweight heat pipe saddle concept was demonstrated in which radial fibers enhance heat transfer between the pipe and the facing. It appears feasible to incorporate 10% volume fraction of miniature heat pipes to greatly increase the in-plane thermal conductance.
5. THERMAL TESTING and CYCLE TESTING demonstrated that the plates exhibit high PCM heat capacity and have shown no sign of degradation during 100 deep thermal cycles.

It appears possible to fabricate PCM Composite plates that, compared with solid aluminum plates of the same size, have one-half the density, ten-times higher heat capacity (over 10 K range), ten-times higher thermal conductivity, and equivalent strength and stiffness. Such plates would have broad application in electronic thermal control instrument enclosures.

4.2 Applications

Based on our experience with PCM thermal storage devices since 1980, the sandwich plate design appears to be an outstandingly useful PCM configuration for a variety of thermal management applications. In addition, the fabrication method is lower-cost than prior methods based on highly dispersed metal foils or foams. Specific potential applications are:

Government

- spacecraft thermal management (heat sinks, PCM-enhanced doublers)
- spacecraft electronics
- spacecraft batteries (nickel-hydrogen, sodium-sulfur)
- space-based radar arrays
- spacecraft sensors, cryogenic focal planes
- aircraft avionics modules and racks (supersonic flight, radar)
- missile guidance electronics
- thermal protection systems

Commercial

- electronics
- instrument enclosures
- refrigerators/freezers
- automotive batteries
- passive solar thermal energy storage

4.3 Recommendations

Further development of PCM Composite Cold Plate should address the following:

1. Develop fibercore sandwich materials, seeking
   - higher strength and lighter weight
   - stronger capillary effects
   - improved skin-to-core bonding
   - other facesheet materials options
   - thick plate options
   - reliable sealing and close-outs
   - cylindrical and other shapes

2. Investigate other PCMs
   - water, high temperature salts
   - liquid-vapor transitions
   - obtain corrosion data

3. Develop thermal conductivity options
   - incorporate miniature metallic heat pipes
   - investigate saddle conductance

- investigate nonmetallic heat pipes
- demonstrate high-k electronics module plate

4. Characterize PCM Composite Plate performance
    - obtain structural data
    - obtain thermal conductance data
    - perform vibration test
    - perform extended thermal cycling, determine failure modes

5. Fabricate Prototype demonstration articles for specific applications
    - electronic module plates with thermal interface
    - composite electronics rack
    - freezer/refrigerator drawers, shelves
    - cryogenic focal plane
    - nickel-hydrogen battery thermal control plates

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