A novel multi-functional plate-like lamination that combines a thermal energy storage capability with a structural capability is described. The lamination consists of a paraffin impregnated porous graphitic core (the energy storage volume) encapsulated between rigid graphite/epoxy composite plates and ribs to form a two-dimensional box structure. Heat storage is via solid-liquid phase transition of the paraffin. Stacked laminations form a sandwich structure.

A thermal response model shows that the graphite foam is an effective thermal conductivity enhancer to the imbedded paraffin. Furthermore, the foam can accommodate the relatively large specific volume change that accompanies paraffin phase transition. However, it does so at the expense of reduced thermal performance.

Nomenclature

- **Ac**: Cross section area
- **h**: Conductance or latent heat
- **k**: Thermal conductivity
- **ke**: Effective thermal conductivity
- **mc**: Thermal capacity
- **MC**: Eq. (14b)
- **P**: Perimeter or length
- **Pe**: Length
- **q**: Heat transfer rate
- **Rk**: Eq. (15b)
- **Ri**: Interfacial resistance
- **S, So**: Shape factor
- **t**: Thickness
- **T**: Temperature
- **W**: Width
- **x**: Coordinate
- **Greek**:
  - **β**: Specific surface area
  - **δ**: "melt" region extent
  - **ε**: Volume fraction
  - **τ**: Time
- **Subscripts**:
  - **f**: Rigid plate
  - **i**: Interfacial
  - **p**: TES-volume

Introduction

A Thermal Energy Storage (TES) capability incorporated into the temperature control system of an electronics module having a variable heat dissipation rate will improve system reliability and allow for smaller, less-power-consuming module coolers. A system that possesses dual functionality, such as thermal storage together with structural functionality, will save weight and space in an avionics system. For example, TES-composites that combine the heat storage function with a structural function can be configured into a system as structural elements while at the same time they are part of the temperature control system.

Typically three methods are used for heat storage: sensible heat storage, thermochemical heat storage and latent heat storage. In latent heat storage, reversible phase transitions can be grouped according to their phase: solid-to-solid, solid-to-liquid and liquid-to-vapor. Solid-liquid PCM’s for electronics temperature control include: salt hydrates, paraffins, certain hydrocarbons and metal alloys. Systems utilizing PCM’s that undergo solid-liquid transition present material expansion and containment problems, so some sort of bellows mechanism must be incorporated into the design. In addition, their performance when the PCM is in the liquid phase could be sensitive to system orientation or g-loading due to buoyancy driven convection effects. Furthermore, except for the metallic PCM’s, these materials are generally poor heat exchange materials, with low thermal conductivities and correspondingly low thermal diffusivity. Therefore, the TES-package must be engineered to accommodate specific volume changes; immobilize the PCM when it is in liquid state; and, facilitate heat transfer to the PCM without excessive temperature increases.
Pai and Joshi\textsuperscript{6} used a honeycomb structure; and, O’Connor and Weber\textsuperscript{5} employed foam metal to enhance conduction in the PCM mass. Xavier et al\textsuperscript{9} experimented with a compressed expanded-particle natural graphite porous media as liquid immobilizer and conductivity enhancer. Fossett and co-workers\textsuperscript{1} used micro-encapsulated paraffin powder; and, Wirtz et al\textsuperscript{8} employed an immobilizing agent, SEBS, to inhibit paraffin liquid motion.

A process for producing slabs of thermally conductive graphitic foam is developed by Klett\textsuperscript{4}. This process provides open-cell foam from a mesophase or isotropic pitch. The foam has a uniform pore size distribution (400 - 600 µm) and a porosity that can range from 70 - 90%. Approximately 95% of the pores are interconnected, providing an open-cell porous structure. The thermal properties of graphite foam are investigated by Gatès and Faber\textsuperscript{2}. Thermal conductivities as high as 150 W/m\(\text{K}\) are measured in the z-direction. Thermal conductivity increases as a function of density from 10-50 W/m\(\text{K}\) in the x,y direction.

Wirtz et al\textsuperscript{7} describe a plate-like lamination that combines TES capability with a structural capability. The lamination consists of a PCM-impregnated porous graphite core (the TES volume) encapsulated between carbon fiber/epoxy composite skins. A thermal response model shows that the graphite foam is an effective thermal conductivity enhancer to the imbedded paraffin. They also show that due to the small pore size of the foam, liquid paraffin is effectively immobilized so that the thermal storage process will be unaffected by up to a 10g load. Furthermore, they find that the foam can accommodate the relatively large specific volume change that accompanies paraffin phase transition. However, it does so at the expense of reduced thermal performance. Furthermore, tension/compression and bending experiments conducted for this structure reveal poor mechanical characteristics. The poor strength is on account of the simple sandwich structure, as well as the low elasticity modulus and strength of the graphitic foam.

In this paper, we describe a structurally enhanced plate-like lamination that combines a TES-capability with a structural capability. The lamination consists of a paraffin impregnated porous graphitic core (the TES-volume) encapsulated between carbon fiber/epoxy composite skins and ribs, which form a two-dimensional box structure. The graphitic foam acts as a thermal conductivity enhancer and immobilizer of liquid paraffin, so that devices performance is g-load insensitive. The carbon fiber/epoxy skin/rib structure gives the lamination improved structural functionality.

In Part I of this paper, we describe a thermal response model for this TES-system configuration. The fabrication methodology and structural characteristics of the composite are described in Part II.

**Description of Laminate Structure**

Fig. 1 shows a 2-D structure of length \(P_e\), which consists of parallel carbon fiber/epoxy plates of thickness, \(2t_s\) (structural ribs) alternately placed between segments of the TES-volume (PCM-impregnated graphitic foam) of width \(W\) and thickness \(2t_p\). Additional carbon fiber/epoxy plates of thickness \(t_f\) (rigid plates) enclose the TES-volumes, forming a 2-D rectangular box structure.

Figure 2 shows top and edge views of a plate-like TES-structure that incorporates the laminate structure described in Fig. 1 into the overall design. The heat storage volume, of thickness \(2t_p\), is contained between rigid plates, each of thickness \(t_f\). The figure shows two laminates stacked together to form a composite sandwich structure. Heat input/output is via thermal interfaces (TI). The TI’s are presumed to be in thermal contact with a heat source or sink, so the temperature of

\[ x \]
the source/sink will be directly related to the TI temperature. The configuration shown has a series of straight, rectangular TI’s of thickness \(x_o\) imbedded in the sandwich structure (two TI’s are shown in the figure). The in-plane periodicity of the TI’s is 2\(P\) where \(P = P_e + x_o\). In storage mode, excess heat flows into the thermal interface, and then outward (in the x-direction) from the TI through the conductive heat spreader plates and to the TES-volume. In the heat release mode of operation, stored energy flows back to the heat spreader plates, inward toward the TI, and then to the heat sink of the system. We assume the TI’s make no contribution to the structural characteristics of the system.

Table 1 summarizes the thermophysical properties of the components of a graphite-based composite structure where the PCM is paraffin. It tabulates values of graphite volume fraction, density, in-plane conductivity and thermal diffusivity of individual components of the TES composite (rigid plates/structural ribs and the TES volume). The graphite foam density and in-plane thermal conductivity vary linearly with the graphite volume fraction. The correlation is best expressed by the linear equation,

\[
\frac{ke}{ke_o} = 0.865 \cdot (1 - \varepsilon) - 0.135
\]

where, \(ke\) is the effective thermal conductivity of graphite foam; \(\varepsilon\) is the porosity of the graphitic foam and hence \((1 - \varepsilon)\) is the graphite volume fraction; and, \(ke_o = 510 \text{watt/mK}\) is the zero-porosity extrapolated conductivity of the material tested. It is observed that the PCM impregnated foam has the same effective thermal conductivity as the unladen foam (\(k_p \approx ke\)). This is due to the very low thermal conductivity of paraffin. This implies that heat flow from the TI to the paraffin will be primarily via the foam ligaments. Note that due to the relatively large specific heat of paraffin, there is an approximate 3.5-fold reduction in thermal diffusivity of the foam/paraffin relative to unladen foam.

An operable unit cell for analysis of the configuration shown in Fig. 2 is shown in Fig. 3. It consists of a single segment of the laminate of edge length \(P\) and width \(W\). Carbon fiber/epoxy plates of thickness \(t_f\) and \(t_s\) bound the periphery of the TES-volume (graphitic foam/paraffin). One half of the TI is located at one end \((x = 0)\). Due to symmetry, all external surfaces of this unit cell, except the “heat input” surface of the TI, are adiabatic. The heat transfer to/from the TI segment is \(q_{in}(\tau)\) where \(\tau\) is time.

Since \(k_p\) is much larger than \(k_f\) or \(k_s\); and \(t_p\) is much larger than \(t_f\) or \(t_s\), the ratios of in-plane conductances of the rigid plates and the structural ribs to the in-plane conductance of the PCM-laden foam is small,

\[
\frac{k_f \cdot t_f}{k_p \cdot t_p} \ll 1 \quad \text{and} \quad \frac{k_s \cdot t_s}{k_p \cdot t_p} \ll 1
\]

Consequently, the rigid plates and structural ribs are primarily structural members, playing no significant role in the heat transfer process. In fact, the structural ribs act as insulators, so that heat flow is channeled down the TES volume in the x-direction.

Since the thermal conductivity of the graphite foam is much larger than that of paraffin, heat flow is from the TI to the foam ligaments, and then from the ligaments...
Concentric Tube Thermal Response Model

We can capture the essential characteristics of this process by consideration of the concentric tube unit cell shown in Fig. 4. It consists of a TI of thermal mass \((mc)\) attached to a hollow cylindrical heat spreader (tube) that encapsulates the TES-volume. The heat spreader has length \(P_e\), cross sectional area \(A_c\) and thermal conductivity \(k_c\). The interfacial contact conductance between the TI and heat spreader is \(h_i\). The encapsulated TES-volume has length \(P_e\), diameter \(2r_o\), cross sectional area \(A_{cp}\), thermal conductivity \(k_p\), volumetric latent heat \(h_v\) and transition temperature \(T_{tr}\). The spreader tube and TES-volume have interfacial perimeter, \(P_0 = 2\pi r_o\). Heat transfer to the concentric tube TI is

\[
q_i(\tau) = q_{rof}F(\tau)
\]

where \(q_{rof}\) is a reference quantity. Heat flows from the TI, down the axis of the heat spreader, and then radially into the TES-Volume.

The TI is characterized by its sensible heat capacity \((mc\text{-product})\) and its temperature is assumed to be spatially uniform. An energy balance gives

\[
mc\frac{dT_{TI}}{d\tau} = q_i(\tau) - q_{f,0}
\]

where \(T_{TI}\) is the TI temperature and \(q_{f,0}\) is the heat transfer rate from the TI to the heat spreader tube. Assume \(k_pA_{cp} \ll k_cA_c\). Then heat flow is primarily from the TI along the heat spreader tube, and then into the PCM, so

\[
q_{f,0} = h_iA_c\left(T_{TI} - T_{f,0}\right)
\]

where \(T_{f,0}\) is the spreader temperature at \(x = 0\), and \(h_i\) is the TI-to-heat spreader interfacial contact conductance. Assume the sensible heat capacity of the spreader tube and TES-volume is small compared to the latent heat capacity of the TES-volume. Then, the thermal response of the spreader and TES-volume are both quasi-steady. An energy balance on an \(A_c\) volume of spreader gives

\[
\frac{\partial}{\partial x^2}T_{f} - \frac{q_p'}{k_rA_c} = 0
\]

while a similar balance on the phase transition interface in the TES-volume (Fig. 5) gives

\[
\frac{\partial S}{\partial T_{f}} = \frac{Q_{p}'}{h_iP(\delta)}
\]

where \(\delta(x,\tau)\) is the extent of the “melt” region, and \(P(x,\tau)\) is the perimeter of the “liquid-solid” interface. \(q'_p\) is the heat transfer rate per length \((x)\) from the spreader volume to the TES-volume. Since the process is quasi-steady and the phase transition interface is at temperature \(T_{tr}\), it can be characterized in terms of shape factor, \(S\) as

\[
q_p' = k_pS(T_{f} - T_{tr})
\]

with

\[
S = \frac{S_o}{1 + R_S S_o}
\]

where

\[
S_o(\bar{\delta}) = \sqrt{\frac{2\pi}{\ln\left[\frac{1}{1-\bar{\delta}}\right]}}; \quad \delta = \frac{\bar{\delta}}{\delta_{max}} = \frac{r_o}{\delta_{max}}
\]
is the conduction shape factor normally associated with 2-dimensional conduction between concentric cylindrical isothermal surfaces, and

$$R_i = \frac{k_f}{h_i P_o}$$  \hspace{1cm} (11)

is the dimensionless spreader-to-PCM contact resistance. If the PCM in liquid phase fully wets the spreader surface, then $R_i \approx 0$.

Define the following dimensionless variables:

$$\bar{\delta} = \frac{x}{P_e}, \quad \bar{\tau} = \frac{\tau}{\tau_{ref}}, \quad \bar{q} = \frac{q}{q_{ref}}, \quad \bar{T} = \frac{T - T_p}{T_{ref}}$$  \hspace{1cm} (12a-e)

where

$$\tau_{ref} = \frac{Ac_P Pe h}{q_{ref}}, \quad T_{ref} = \frac{q_{ref}}{k_p P_e}$$  \hspace{1cm} (13a,b)

The reference time, $\tau_{ref}$ is the time to “melt” the PCM in the TES-volume (if $mc = 0$), and $T_{ref}$ is a convenient reference temperature. Equations (3) – (11) can be combined and summarized as follows:

$$MC \frac{d\bar{T}_{f,l}}{d\bar{\tau}} = F(\bar{\tau}) - \bar{\eta}_{f,0}, \quad MC = \frac{mc \cdot q_{ref}}{k_p P_e^2 Ac_p}$$  \hspace{1cm} (14a,b)

$$R_i \bar{\eta}_{f,0} = R_i (\bar{T}_{f,l} - \bar{T}_{f,s}), \quad R_i = \frac{k_f}{k_p Pe}$$  \hspace{1cm} (15a,b,c)

$$\frac{\partial^2 \bar{T}}{\partial x^2} - \bar{K}^2 \bar{T}_f = 0, \quad \bar{K} = \sqrt{\frac{S(\bar{\delta})}{R_i}}$$  \hspace{1cm} (16a,b)

$$\frac{\partial \bar{\delta}}{\partial \bar{\tau}} = \frac{S(\bar{\delta})}{F(\bar{\delta})} \bar{T}_f$$  \hspace{1cm} (17a)

$$\bar{P}(\bar{\delta}) = \frac{P}{P_o} = 1 - \bar{\delta}$$  \hspace{1cm} (17b)

Suitable initial and boundary conditions are:

$$\bar{T}_{f,l} (0) = \bar{T}_{f,0}, \quad \bar{T}(0) = 0$$  \hspace{1cm} (18a)

$$\bar{T}(0, \bar{\tau}) = \bar{T}_{f,0}, \quad \frac{\partial \bar{T}_f}{\partial x} |_{x=1} = 0$$  \hspace{1cm} (18b,c)

Uniform $\delta$ solution Wirtz et al$^8$ have shown that when $k_p Ac_p \ll k_f Ac_f$ melting of the PCM occurs at a spatially uniform rate so that $\delta = \delta(\bar{\tau})$ only. Then $\bar{K}$ is a function of time only, so Eq. (16) can be solved to give the spreader temperature distribution

$$\bar{T}_f(\bar{x}, \bar{\tau}) = \bar{T}_{f,0} \left(1 - \frac{\cosh(\frac{1}{\bar{K}}(1 - \bar{x}))}{\cosh \bar{K}}\right)$$  \hspace{1cm} (19)

The heat transfer rate at the TI-to-spreader interface is

$$\bar{q}_{f,0} = R_i \bar{K} \tanh(\bar{K} \bar{T}_{f,0})$$  \hspace{1cm} (20)

Since $\delta = \delta(\bar{\tau})$ only, Eq. (17a) must be written as

$$\frac{d\bar{\delta}}{d\bar{\tau}} = \frac{5}{P(\bar{\delta})} \bar{T}_{f,av}$$  \hspace{1cm} (21a)

$$\bar{T}_{f,av} = \int_0^1 T_f d\bar{x} = \frac{\tanh \bar{K}}{\bar{K}}$$  \hspace{1cm} (21b)

where $\bar{T}_{f,av}$ is the average spreader plate temperature (a function of time only). Then Eqs. (19 - 21) can be rearranged to give

$$\frac{d\bar{\delta}}{d\bar{\tau}} = \frac{5}{P(\bar{\delta})} \frac{S(\bar{\delta}) \bar{T}_{f,av}}{1 + R_i \bar{K} \tanh \bar{K}}$$  \hspace{1cm} (22)

$$\frac{d\bar{T}_{f,l}}{d\bar{\tau}} = \frac{1}{MC} \left(\bar{F}(\bar{\tau}) - R_i \bar{K} \tanh(JK[\bar{T}_{f,l}])\right)$$  \hspace{1cm} (23)

These two equations, together with Eqs. (9, 10a and 17b), can be solved using standard numerical techniques. Note, four parameters determine the solution: MC, $R_k$, $R_i$ and $R_{ip}$ (Eqs 14b, 15b, 15c & 11).

Negligible TI Thermal Mass and Internal Thermal Resistance Under these conditions (MC = $R_i$ = $R_{ip}$ = 0), $\bar{q}_{f,0} = \bar{q}_f$ and $\bar{T}_{f,l} = \bar{T}_{f,0}$. Then, from Eq. (23)

$$\bar{T}_{f,l} = \frac{\bar{F}(\bar{\tau})}{R_i \bar{K} \tanh(JK)}$$  \hspace{1cm} (24)

and Eq. (22) becomes

$$2\bar{\delta} - \bar{\delta}^2 = \int_0^{\bar{\tau}} \frac{\bar{F}(\bar{\tau})}{P(\bar{\delta})} d\bar{\tau}$$  \hspace{1cm} (25)

where one parameter ($R_k$) determines the solution.

Solution Characteristics Figure 6 plots the melt region growth ($\bar{\delta}$) and TI temperature response ($\bar{T}_{f,l}$) for the case of negligible TI thermal mass and internal thermal resistances. Heat input is via a unit step: $F(\bar{\tau}) = 1$.

The melt region growth rate accelerates as the solid/liquid interface recedes towards the center of the TES-volume. The TI temperature response is plotted for two values of $R_k$ (Eq. 15b). The plot illustrates the dramatic reduction in overall TI-temperature excursion that occurs with increases in the thermal conductivity.
ratio, $k_f / k_p$. An increase in this conductivity ratio leads to a more uniform heat spreader tube temperature (Fig. 7), so that more uniform heating of the PCM mass is facilitated.

Figure 8 illustrates how increases in TI thermal mass, and TES-system internal thermal resistances affect system thermal response. The bold solid line is the case of negligible TI thermal mass and internal thermal resistances ($R_k = 0.3$). The light solid line shows how an increase in $(mc)$ further stabilize temperature. The two dashed lines show that non-zero internal thermal resistances lead to significant increases in system temperature excursion.

**2D Box Laminate Thermal Response**

Consider a PCM impregnated foam TES-segment and TI (of thermal mass mc) with dimensions $P_e \times W \times a$ ($a = 2t_p$ in Fig. 1). The heat transfer rate into the segment is $q_{seg}$. Given $(\varepsilon, \beta, \text{ke})$ of the foam and the thermophysical properties of the PCM ($\rho_p, k_p, h_v$, etc), key dimensional characteristics of the segment can be determined:

$$A_{c_p} = \varepsilon a W, \quad A_{c_f} = \left(1 - \varepsilon\right) a W \quad (26a,b)$$

$$P_o = \beta a W \quad (26c)$$

At the PCM-particle in foam-ligament level, heat transfer is three-dimensional. We can capture essential characteristics of this process by recourse to the Concentric Tube model described in the previous section. Replace the TES-volume with $n_{tube}$ concentric tube units (Fig. 4, 5) such that the total $A_{c_p}, A_{c_f}$ and $P_o$ are

$$A_{c_p} = n_{tube} \pi r_o^2, \quad A_{c_f} = n_{tube} A_{f,tube} \quad (27a,b)$$

$$P_o = n_{tube} 2\pi r_o \quad (27c)$$

Equating Eqs 26 to 27 gives

$$r_o = \frac{2\varepsilon}{\beta}, \quad n_{tube} = \frac{aW\beta^2}{4\pi\varepsilon} \quad (28a,b)$$

Fig. 6 Concentric Cylinder TES-unit cell response. $F(\tau) = 1$.  

Fig. 7 Heat spreader temperature distribution.  

Fig. 8 Concentric cylinder TI temperature response.
\[ Ac_{f,tube} = \frac{(1 - \varepsilon)AW}{\nu_{tube}} \]  

and the coefficients, Eqs. (14, 15b,c and 11) are

\[ MC_{tube} = \frac{mc \cdot q_{ref}}{\nu_{tube} k_p h_v Pe^2 Ac_p} \]  

\[ R_{k,tube} = \frac{ke_f Ac_f}{\nu_{tube} k_p Pe^2} \]  

\[ R_{i_{tube}} = \frac{ke_f}{h_i Pe}, \quad Ri_{p,tube} = \frac{\nu_{tube} ke_f}{h_{i,p} P_o} \]  

(31a,b)

The heat transfer rate into the tube unit becomes

\[ q_i = \frac{q_{set}}{\nu_{tube}} \]  

(32)

**Thermal Response Model Benchmark Experiments**

**Test Article Characteristics** Figure 9 shows a 2D box structure that consists of paraffin-impregnated graphite foam (Poco Graphite Inc.) reinforced with carbon/epoxy heat spreader plates and structural ribs (Hexcel Composites, W3T282-F155). The 2D Box structure is made of seven 5.6mm square cross section rods of graphite foam/paraffin. We measure the in-plane effective thermal conductivity of the graphite as \( ke = 50 \text{W/mK} \) (Table 1). The mean cell size of the foam is 500\( \mu \text{m} \); and, the porosity is approximately 0.75. The graphite foam was charged with 9.5 gm of n-docosane (\( T_{tr} = 43.9 \degree \text{C}, k_p = 0.28 \text{ W/mK}, h_v = 189 \text{ joule/cc} \)), so the volume fraction of n-docosane in foam is \( \varepsilon = 0.71 \). For each paraffin impregnated segment of foam, \( R_{k,tube} = 0.815 \)

Graphite-epoxy spreader plates and structural ribs are single ply, approximately 0.2mm thick. The measured in-plane, x- direction effective thermal conductivity of the spreader plates/structural ribs is 12 W/mK. So, the conditions of Eq. (2) are clearly satisfied.

A 5.6 mm square by 39 mm long aluminum block with an imbedded cartridge heater and instrumented with 0.08 mm diameter type-T thermocouples served as the prototype’s TI. This unit is clamped to the end of the Box prototype. (mc) of this unit is estimated as 0.56 joule/K.

The box structure was instrumented with a series of 0.08 mm diameter type-T thermocouples with junctions located along the centerline of the foam rods. Temperatures are monitored with a data logger having an accuracy of \( \pm 0.2 \degree \text{C} \). The voltage drop and electrical resistance across the TI cartridge heater is monitored with a DMM having a \( \pm 0.1\% \) accuracy.

The test article is surrounded with rigid fiber insulation and placed in an oven, which is maintained at 43.5\( \degree \text{C} \). When all temperatures are steady at 43.5\( \degree \text{C} \), power is applied to the TI heater, and temperatures are recorded as a function of elapsed time.

**Benchmark Experiments** Figure 10 shows the measured temperature response for a case where \( q_{seg} = 0.59 \text{ watt} \). The power is 0.59 watt (every 50-th data point is plotted). Also shown is the prediction of the model. The figure shows that the predicted TI-temperature tracks the measurements quite well. Predicted heat spreader temperatures are generally higher than measurement since the thermocouples imbedded in the PCM/foam
30% of the surface of each paraffin particle is in direct contact with its containing cell wall. Wirtz et al [ref 7] observed a similar effect in their experiments with simple graphitic foam/epoxy laminations.

The TI-to-spreader (graphitic foam) interfacial conductance, $h_i$, is determined by extrapolating spreader temperature measurements at a particular time (say 400 sec) to $x = 0$, and then calculating the conductance as

$$hi = \frac{q_i}{(1 - \epsilon_i)W(T_{f,i} - T_{i,o}) \big|_{x=0}} = 3.5 \text{ W cm}^{-2} \text{K}$$

We do not know a priori the magnitudes of the specific surface area ($\beta$) or the foam-to-paraffin contact conductance ($h_{f,p}$). These quantities are adjusted to give the best fit of the model with data. We consistently find best fit values, $\beta \approx 300$ - 350 m$^{-1}$ and $h_{f,p} \approx 45,000$ watt/mK. This value of $h_{f,p}$ gives a graphite-to-paraffin thermal resistance of approximately 0.03 K/W ($R_{f,p} \approx 0.17$), indicating that liquid paraffin wets the foam surface.

The value of $\beta$ obtained is roughly 30% of what would be expected. For example if the foam cell structure were a cubic array of interconnected 500 µm diameter spherical cells with about 2/3rds of each cell an open interconnect with an adjacent cell, we would expect $\beta = 1150$ m$^{-1}$. Apparently, the reduced effective contact area ($\beta = 310$ m$^{-1}$) is due to the approximate 13% specific volume change that accompanies solid-liquid phase transition of paraffin. Graphitic foam is filled with liquid-phase paraffin. Upon cooling and solidifying, particles of paraffin shrink and pull away from the graphite cell walls so that only approximately 30% of the surface of each paraffin particle is in direct contact with its containing cell wall. Wirtz et al [ref 7] observed a similar effect in their experiments with simple graphitic foam/epoxy laminations.

Conclusions

A novel multi-functional plate-like lamination that combines a thermal energy storage capability with a structural capability is described. The lamination consists of a paraffin impregnated porous graphitic core (the energy storage volume) encapsulated between rigid graphite/epoxy composite plates and ribs to form a two-dimensional box structure. Heat storage is via solid-liquid phase transition of the paraffin. Stacked laminations form a sandwich structure.

A thermal response model shows that the graphite foam is an effective thermal conductivity enhancer to the imbedded paraffin. Furthermore, the foam can accommodate the relatively large specific volume change that accompanies paraffin phase transition. However, it does so at the expense of reduced thermal performance.

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