A MULTI-FUNCTIONAL GRAPHITE/EPOXY-BASED THERMAL ENERGY STORAGE COMPOSITE
FOR TEMPERATURE CONTROL OF SENSORS AND ELECTRONICS

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Abstract
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 skins. 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. It will effectively immobilize liquid paraffin so that the thermal storage process will be unaffected by up to a 10g load. 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.

Structural analysis shows that graphitic foam has a low strength and elasticity modulus, and the material displays tension-compression asymmetry. The paraffin fill is shown to increase the compressive ultimate strength and elasticity modulus. The use of carbon fiber/epoxy skin greatly enhances the overall strength of the structure.

Nomenclature

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Introduction
Either many multi-chip modules and sensors are operated intermittently or they are variable power devices. Consequently, conventional module/sensor coolers must be designed for peak power operation, or an active control system must be incorporated into the cooler to accommodate variations in heat loading. Incorporation of a Thermal Energy Storage (TES) mechanism into the module cooler will allow for a smaller, less power consuming cooling system that is sized for some intermediate heat load. Then, heat is stored in the TES-system during periods of high power operation, and it is subsequently released from the system during periods of reduced power operation. Materials formulated to undergo phase transition at key temperatures can provide this load-leveling capability via the latent heat effect.

Space limitations often preclude the incorporation of this technology into electronics thermal control systems so that TES-systems must be such that they add no
mass (or volume) to existing systems. TES-systems having multiple functionality can satisfy this constraint. For example, TES-composites that combine the heat storage function with a structural function can be configured. These composites can be incorporated into the system as structural elements while at the same time they are part of a temperature control system.

Typically three methods are used for heat storage: sensible heat storage, thermochemical heat storage and latent heat storage. Sensible heat storage is often considered the least efficient method since much less thermal energy is involved in raising the temperature of the material compared to breaking and reforming chemical bonds or melting of a compound. Thermochemical heat storage involves the forward and reverse thermochemical reaction of the medium. As the heat involved in chemical reaction is generally large, this method has the advantage of allowing for a more compact system with high storage capacity. However, repetitive reversible reactions are difficult to control, so this method in generally limited to “one shot” applications.

In latent heat storage, reversible phase transitions are grouped according to their phase: solid-to-solid, solid-to-liquid and liquid-to-vapor. A major design issue related to liquid-to-vapor transition is the dramatic specific volume change that accompanies transition. On the other hand, certain molecular crystals undergo solid-state crystal transformations that absorb sufficient heat so they may be used for practical heat storage applications. The absence of a liquid or vapor phase precludes natural convection within the TES-volume so that system performance is insensitive to g-loading or TES-volume orientation. Wirtz et al, Bauer and Wirtz, and Zheng and Wirtz characterize TES-systems that utilize polyalcohol-based solid-solid PCM’s.

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. In addition, their performance when the PCM is in the liquid phase could be sensitive to system orientation or g-loading. Paraffin is used in the current study since there is available a wide range of stable and light-weight compounds that undergo transition over the near ambient-to-100°C temperature range with latent heats ranging up to 285 j/gm. However, in addition to natural convection issues when the PCM is liquid, these organics are poor heat exchange materials, with thermal conductivities of approximately 0.26 W/mK and correspondingly low thermal diffusivity. Furthermore, relatively large specific volume changes accompany solid-liquid transition. 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. O’Connor and Weber used aluminum foam and fin structures as conductivity enhancers. Xavier et al experimented with a compressed expanded-particle natural graphite porous media (CENG) as liquid immobilizer and conductivity enhancer.

In this paper, we describe a plate-like lamination that combines a thermal energy storage (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. 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 gives the lamination structural functionality.

A process for producing slabs of thermally conductive graphitic foam is developed by Klett. This process provides open-cell foam from a mesophase or isotropic pitch. A section of foam is shown in Figure 1. 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 Gaies and Faber. Thermal conductivities as high as 150 W/mK are measured in the z-direction. Thermal conductivity increases as a function of density from 10-50 W/mK in the x,y direction.

Modern manufacturing processes have allowed cellular cores to be affordably assembled and bonded to dense face materials representing a promising new alternative to the construction of high-performance structures.
Oliveira et al.\textsuperscript{10} conducted a multifunctional optimization for cellular materials. A cellular beam structure was fabricated to carry both mechanical and thermal loads. Optimizations were made based on the engineering outputs of interest (such as deformation, buckling load, and total heat transfer) as functions of load, material properties, and geometric parameters. McManus et al.\textsuperscript{8} developed a multifunctional structure for small satellite applications. The structure was made of an inner tube surrounded by an octagonal outer structure. The inner structure was designed to carry mechanical load and the article was attached directly to the tube wall. The octagonal outer structure’s primary function was to redistribute the thermal loads around the inner tube structure and provided an area to directly attach electronics. The inner tube was made of AS4/3501-6 graphite epoxy laminates separated by a thick low-density aluminum honeycomb structure. The octagonal outer structure had a composite sandwich configuration. The multifunctional structure led to dramatic weight and cost savings and resulted in a simpler and more reliable system for the satellite applications.

**Description of Laminate Structure**

Figure 2 shows top and edge views of a plate-like TES-structure. The heat storage volume, of thickness $2t$, is contained between rigid plates, each of thickness $s$. The figure shows four laminates stacked together to form a composite sandwich structure. Each lamination consists of a TES-volume of thickness $t$ bounded on one side by a plate of thickness $s$. The thermal storage volume consists of graphitic foam impregnated with paraffin. The graphitic foam acts as a thermal conductivity enhancer and immobilizer to inhibit liquid-phase paraffin motion. The rigid plate, which provides structural functionality, consists of a carbon fiber/epoxy composite.

Heat input/output to each lamination ($q_a$) is via thermal interfaces (TI). The TI’s are conductive media, presumed to be in thermal contact with a heat source such as a multi-chip module, so the temperature of the electronic module will be directly related to the TI temperature. The composite plate has a square array of cylindrical TI’s imbedded in the sandwich structure (four TI’s are shown in the figure). The in-plane periodicity of the TI’s is $2P$. In storage mode, heat flows into the thermal interface, and then radially outward from the TI through the conductive graphitic foam filaments to the paraffin that is imbedded in the foam. In the heat release mode of operation, stored energy flows back to the TI, and then to the heat sink of the system. Since the rigid (carbon fiber/epoxy) plates are relatively thin, with relatively low thermal conductivity, they do not have a significant impact on the heat transfer process.

Laminations are prepared by cutting sections of graphite foam (approximately 10 mm thick) and sanding to provide smooth and parallel surfaces. The carbon fiber/epoxy prepreg is used to cover the outside of the graphite foam in order to contain the paraffin and provide structural rigidity to the composite. A nitrogen-pressurized autoclave is used to cure the carbon fiber/epoxy prepregs, and insure good contact of the prepreg to the graphite foam core. The system operates at approx. 130°C and 5 atm to achieve adequate cure. One-ply skin samples were prepared. Cured graphite/epoxy skins are approximately 0.2 mm thick.

Paraffin impregnation is done by melting the paraffin and suspending the lamination above (and in contact with) the molten paraffin and allowing surface tension forces to draw the paraffin into the graphitic foam. Because of the excellent wetting of the graphite foam by the molten paraffin, filling by capillary action works quite well. Two grades of paraffin were used in the present study. A technical grade of paraffin whose properties are most similar to n-hexacosane ($T_{melt} \approx 56°C$) was used for the mechanical testing. Refined n-docosane ($T_{melt} = 43.9°C$) was used for the thermal response model benchmark experiments.

Table 1 summarizes the thermophysical properties of the components of the graphite-based composite. The tabulation shows that the graphitic foam density and in-plane effective thermal conductivity correlate nearly linearly with graphite volume fraction. Furthermore, the foam conductivity is approximately three-times that of the carbon/epoxy that forms the rigid skin of the composite. The TES-volume (paraffin impregnated foam) has the same effective thermal conductivity as...
the unladed foam. However, 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 unladed foam.

**Thermal Response Model**

An operable unit cell for analysis of the configuration shown in Fig. 2 consists of a single laminate, of edge length 2P with the carbon fiber/epoxy rigid plate (thickness s) bounding one side of a TES-volume (graphitic foam/paraffin) of thickness t. The TI is located at the geometric center of the plan form. All external surfaces of this unit cell, except the exposed surface of the TI, are adiabatic. The in-plane radial conductance of the carbon fiber/epoxy plate is \( k_s \approx 0.003 \text{watt/K} \), whereas that for the storage volume is \( k_f \approx 0.3 \text{watt/K} \). Consequently, radial conduction from the TI is primarily via the graphitic foam, and the rigid plate is primarily a structural member; it plays no significant role in the heat transfer process.

Figure 3a shows a section edge-view of a TI/TES-volume unit cell. Our physical model has heat conducted from the TI radially outward along filaments of the graphitic foam, and then to pellets of paraffin contained in the foam pore structure. The volume of foam is

\[ V_f = A_c t \]  

\[ \text{(1)} \]

while that of the paraffin embedded in the foam is

\[ V_p = \varepsilon_f A_c t \]  

\[ \text{(2)} \]

where \( A_c = 4P^2 - \pi_o^2 \) is the cross section area of the TES-volume, and \( \varepsilon_f \) is the effective porosity of the porous foam (not all foam pores are filled with paraffin). In addition, the foam-to-paraffin contact area is

\[ A_{fp} = \alpha_f A_c t \]  

\[ \text{(3)} \]

where \( \alpha_f \) is the effective specific surface area of the foam.

Figure 3b shows an equivalent view consisting of stacked radial graphitic fins of thickness \( t_f \) interspersed with disks of paraffin of thickness, \( 2t_p \). In this case, the foam-to-paraffin contact area is

\[ A_{fp} (\text{equiv.}) = nA_c \]  

\[ \text{(4)} \]

where \( n \) is the number of sub-laminations (thickness \( t_f + t_p \)). For the two systems to be equivalent, \( A_{fp}(\text{equiv.}) = A_{fp} \), so the number of sub-laminations is

\[ n = \alpha_f t \]  

\[ \text{(5)} \]

The thickness of each component of each sub-laminate is

![Fig. 3 Section edge-view of TI/TES-volume.](image)
\[ t_f = \frac{t}{n} = \alpha_f^{-1} \quad \text{and} \quad t_p = \frac{\varepsilon_f t}{\varepsilon_f} = \frac{t}{\alpha_f} \] (6)

**Sub-laminate thermal response.** Consider one sub-laminate, consisting of a segment of TI, a graphitic annular fin of thickness \( t_p \), and a disk of paraffin of thickness \( t_p \). We transform this square plan form shape into the composite cylinder shown in Fig. 4. The transformed unit cell consists of the following elements:

1. A centrally located TI element of radius \( r_o \).
2. An annular disk graphitic fin of thickness \( t_p \) and outer radius \( r_e = \frac{4}{\pi} r_p \), and thermal conductivity \( k_f \) and
3. An annular disk of paraffin having thickness \( t_p \), effective thermal conductivity \( k_p \), and volumetric latent heat \( h_v \).

The temperature of the fin material is \( T_f \) and that of the TES-volume is \( T_p \). The figure shows the structure at some time, \( \tau \) during the heat storage mode (\( q_1 = q_0/n \) is the heat input to each sub-laminate) with a phase transition interface in the storage volume moving radially outward and downward. PCM below the phase transition boundary is in solid phase at the phase transition temperature \( T_c \), and PCM above the phase transition boundary is in the liquid phase at \( T_p > T_c \).

Define the thermal conductance ratio,

\[ R_k = \frac{k_f t_f}{k_p t_p} = \frac{k_f}{\varepsilon_f k_p} \] (7)

\( R_k \) characterizes the heat flow path from the TI in the radial direction. \( R_k \) is large by design \((k_f \gg k_p, \varepsilon_f < 1)\). Under these conditions, radial conduction is predominantly in the graphitic fin plate, then in the \( z \)-direction into the paraffin disk. Make the following assumptions:

- Heat flow in the fin is one-dimensional transient (\( r \)-direction); heat flow in the paraffin-disk is one-dimensional transient (\( z \)-direction).
- The sensible heat capacity of the TI, fin and PCM-disk is negligible compared to the latent heat capacity of the paraffin-disk.

Since the sensible heat capacity of the PCM-disk is neglected, the transient temperature profile is linear and the \( z \)-direction heat flux in the liquid-phase region is

\[ q_p''(r, \tau) = \frac{k_f (T_f - T_i)}{\delta(r, \tau)} \] (8)

where \( \delta(r, \tau) \) is the thickness of the liquidous region. An energy balance on the liquid-solid phase interface gives

\[ \frac{\partial \delta}{\partial \tau} = \frac{q''_p(r, \tau)}{h_v} \] (9)

Since the graphitic fin sensible heat capacity is negligible, the temperature response is quasi-steady. Then an energy balance of the graphite fin gives

\[ \frac{\partial T_f}{\partial r} = \frac{q''_p(r, \tau)}{k_f t_f} \] (10)

**Uniform \( \delta \) Solution.** \( R_k \) is large and \( t_p << r_o \), so except near the TI, the phase transition interface will be a nearly horizontal plane and \( \delta(r, \tau) \approx \delta(\tau) \) only. Under these conditions, the average heat flux into the storage volume is \( q_p'' = q/A_c \). Then Eq. (9) may be integrated to give the average penetration depth

\[ \delta_{avg}(\tau) = \frac{q_0 \tau}{h_v A_c} = \frac{q_0 \tau}{\alpha_f h_v A_c \tau} \] (11)

and, Eqs. (8, 10 and 11) may be combined to give

\[ \frac{\partial \theta}{\partial \tau} - \beta^2(\tau) \nabla \theta = 0 \] (12)
with
\[
\theta(\bar{r}, \bar{\tau}) = \frac{T_I(\bar{r}, \bar{\tau}) - T_{e}}{T_{TI}(\bar{r}) - T_{e}}, \quad \bar{\tau} = \frac{\tau}{\tau_{ref}} \tag{13} \]
where \(T_{TI}\) is the TI temperature, and
\[
\beta(\bar{r}) = \sqrt{\frac{B}{\bar{r}}} \quad B = \frac{1}{Rk} \left( \frac{r_e}{t_f} \right)^2 \tag{14} \]
\[
\bar{\tau} = \frac{\tau}{\tau_{ref}} \quad \tau_{ref} = \frac{\epsilon_f h A_k}{\alpha_f q_f} \tag{15} \]
\(\tau_{ref}\) is the time interval to melt all of the PCM.

Equation (12) may now be integrated with respect to \(r\).

The general solution (Bessel’s equation) is:
\[
(13a,b) \quad \text{and} \quad (14a,b) \quad \text{and} \quad (15a,b) \tag{16} \]

Suitable boundary conditions are
\[
\theta(\bar{r}_e, \bar{\tau}) = 1, \quad \frac{\partial \theta}{\partial \bar{r}_e} \bigg|_{\bar{r}_e} = 0 \tag{17} \]
give
\[
C_1(\bar{r}) = \frac{K_1(\beta(\bar{r}))}{D(\bar{r})}, \quad C_2(\bar{r}) = \frac{I_1(\beta(\bar{r}))}{D(\bar{r})} \tag{18} \]
\[
D(\bar{r}) = I_1(\beta(\bar{r}) \bar{r}_e): K_1(\beta(\bar{r})): I_1(\beta(\bar{r}) \bar{r}_e) \tag{19} \]

Then, the dimensionless temperature response of the TI,
\[
\Delta T_{TI} = \frac{T_{TI} - T_{e}}{\tau_{ref}}, \quad T_{ref} = \frac{q_f}{k_f t_f} = \frac{q_n}{k_f t} \tag{20} \]
can be calculated as
\[
\Delta T_{TI}(\bar{r}) = \frac{1}{2\pi \bar{r} \beta(\bar{r})} \left[ C_2 K_1(\beta(\bar{r}) \bar{r}_e) - C_1 I_1(\beta(\bar{r}) \bar{r}_e) \right] \tag{21} \]

Figure 5 plots graphitic fin temperature profiles at three different times. A characteristic of the present laminate configuration (with a centrally located TI) has relatively large temperature gradients at the TI/TES-volume interface. The relatively large temperature gradients at \(F \rightarrow \bar{F}_o\) are the result of the small peripheral area of the TI, giving rise to high heat flux and consequent high temperature gradients near the TI. Consequently, there is a relatively large temperature drop from the TI to the outer periphery of the unit cell \((r = r_e)\). An increase in \(r_e/P\), at the expense of reduced storage volume, reduces this. This is shown in Fig. 6 where the TI temperature response is plotted for three values of \(r_e/P\). Each doubling in \(r_e/P\) brings about a decreasing-returns reduction in the final TI temperature excursion. A similar result obtains with increases in \(Rk\) and decreases in \(\alpha_f P/\epsilon_f\).

**Model Verification.** Benchmark experiments were performed to test the accuracy of the above-described analytical model. The test article consists of a 101 mm diameter x 14.1 mm thick \((r_e = 50.5 \text{ mm}, t = 14.1 \text{ mm})\) docosane impregnated disc of graphitic foam having an average density of 0.615 gm/cm\(^3\) and effective thermal conductivity of 50.2 watt/mK. A 27.9 mm diameter aluminum cylindrical TI, with small cartridge heater, was interference fit at the center of the foam disk. The disk was loaded with 48.6 gm of docosane \((T_I = 43.9^\circ \text{C}, h = 242 \text{ j/gm, } \rho = 0.778 \text{ gm/cc})\), so that \(\epsilon_f = 0.6\) and \(Rk = 270\). Type T thermocouples monitor the TI temperature and the mid-plane TES-volume temperature at \(r = 25.4 \text{ mm and } 38.1 \text{ mm (two T.C’s at each location). Temperatures are monitored with a data logger having an accuracy of } \pm 0.2^\circ \text{C. The voltage drop}
and electrical resistance across the TI cartridge heater is monitored with a DMM having a ±0.1% accuracy.

The test article is surrounded with rigid fiber insulation and placed in an oven, which is maintained at 43.5°C. When all temperatures are steady at 43.5°C, power is applied to the TI heater, and temperatures are recorded as a function of elapsed time. Figure 7 plots the temperature response of the test article for an experiment where the heat input rate is $q_0 = 25$ watts. Open symbols are every 40-th recording of the TI temperature (circles) and the two mid-plane TES-volume temperatures at $r = 25.4$ mm and $38.1$ mm (squares and diamonds, respectively). The solid line is the predicted TI temperature response (Eq. 22). The dashed lines are predicted foam temperatures at $r = 25.4$ mm and $38.1$ mm. The measured foam temperatures are lower than the corresponding analytical prediction (dashed lines) since the thermocouples measure an average temperature of the foam and paraffin, whereas the model predicts only the foam temperature.

The effective foam-to-paraffin contact area is not known a priori. Its value is selected to give the best fit of the TI temperature response data shown in Fig 7. A value, $\alpha_f = 310 \text{ m}^{-1}$ appears to work best, resulting in a final TI temperature rise of $\Delta T_{TI} = 9.5$ °C at $\tau_{ref} = 471$ sec. The “best fit” value of $\alpha_f$ is considerably smaller than expected, based on the foam structure shown in Fig. 1. Assume the foam is made up of interconnected spherical cells ($d_f = 500 \mu$m) where holes that interconnect adjacent cells represent 33% of each spherical cell surface area. Then the foam specific surface area is given as

$$\alpha = 0.67 d_{sphere} = 0.67 \left( \frac{1 - \varepsilon_f}{d} \right) = 3200 \cdot \text{m}^{-1} \quad (22)$$

A light-solid line (lower part of Fig 7) depicts the TI temperature response that would occur if $\alpha_f = 3200 \text{ m}^{-1}$. In this case, the final TI temperature rise at $\tau_{ref} = 471$ sec would be $\Delta T_{TI} = 1.2$ °C. This is approximately eight times smaller than shown in Fig. 7.

We believe the reduced effective contact area ($\alpha_f = 310 \text{ m}^{-1}$) 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 10% - 15% of the surface of each paraffin particle is in direct contact with its containing cell wall. In support of this argument, it is noted that the graphitic foam used in the benchmark experiments has a nominal porosity of approximately 73% while when fully charged with docosane, weight measurements indicate the volume fraction of paraffin is $\varepsilon_f = 0.6$. The difference (0.73 – 0.60 = 0.13) accounts for this shrinkage. Therefore, while the foam graphite matrix can accommodate the specific volume change that accompanies phase transition without fracture, it does so at the cost of a reduced ability to maintain the TI at a nearly constant temperature.

The test article has $\tau_{ref} = 471$ sec while the data of Fig 7 indicate that the heat storage process is essentially over at about 350 sec. Two conditions may contribute to this:

1. Impurities in the paraffin/graphitic foam composite (small graphite particles) together with the small particle size of solid paraffin particulary near the end of the melting process, will shift and broaden the phase transition temperature interval, effectively reducing the volumetric latent heat at 43.9°C.

2. Small paraffin particles near the end of the melt process are effectively insulated from the conductive foam by a layer of imobile liquid paraffin ($k_p = 0.26 \text{ watt/mK}$). Thus, they do not participate effectively in the thermal storage process.

**Liquid Paraffin Immobilization.** Consider a $d_p = 250 \mu$m diameter solid paraffin particle that is melting inside a $d_f = 500 \mu$m diameter cell. A 125 µm thick layer of liquid paraffin surrounds the solid particle. Assume a $\Delta T_{p} = 5$ °C temperature difference between
the cell wall and the paraffin particle. The natural convection Rayleigh number is
\[
Ra = g \cdot C_{Te} \cdot \Delta T \left( \frac{d_f - d_p}{2} \right)^3 = 0.12g
\]
where \( \nu_p = 4 \times 10^{-6} \text{ m}^2/\text{sec} \), \( \lambda_p = 1.4 \times 10^{-7} \text{ m}^2/\text{sec} \) and \( C_{Te} = 9 \times 10^{-3} \text{ K}^{-1} \) are the kinematic viscosity, thermal diffusivity and coefficient of thermal expansion of paraffin, respectively. Thus, at 10g, the Rayleigh number is O(1), and convection effects are negligible. We confirmed this (at 1g) by repeating the benchmark experiments described above with the test article in different orientations with no discernable difference in the recorded temperature data.

**Mechanical Characterization**

Tension, compression, and bending experiments were conducted for graphitic foam, graphitic foam filled with paraffin, and graphite-based sandwich structures at room temperature. Major mechanical properties under tension and compression are summarized in Table 2. All the experiments were conducted using an INSTRON 8500 load frame and a low force hydraulic material testing system equipped with computer control and data acquisition. Specimen designs followed the ASTM standards.

Figures 8 and 9 show the compression test results for porous graphitic foam, graphitic foam filled with paraffin and graphitic sandwich structures. The graphitic foam has a very low elasticity modulus and strength. One characteristic of the graphitic foam, as shown in Fig. 8, is the wavy stress-strain curve after yielding. This property is a result of the buckling failure mode of the graphitic foam under compression which occurred layer by layer. It was experimentally observed that the wave length in the load-deflection curve is equal to the cell size of the foam. The results shown in Figure 8 indicate that paraffin filled into graphitic foam enhances the compressive strength. The paraffin fill and the graphitic skin added transverse constrains in the structure, thus retarding buckling and increasing strength. It is noticed in Figures 8 and 9 that the addition of the graphitic skin does not increase the Young’s modulus under compression due to the fact that the thin skin cannot carry compressive load. Furthermore, the influence of porosity on the Young’s modulus for graphitic foam and filled graphitic foam follows a parabolic

### Table 2 Mechanical properties of carbon fiber-epoxy/graphitic foam-paraffin laminates.

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<thead>
<tr>
<th>Property</th>
<th>Sandwich Structure**</th>
<th>Rigid Plate(^*) (s = 0.22 \text{ mm})</th>
<th>TES Volume(^*) (\varepsilon_f = 0.73)</th>
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<td>Material</td>
<td>Carbon/Epoxy-Paraffin/Foam</td>
<td>Carbon/Epoxy</td>
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<td>Tensile Strength [Mpa]</td>
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Notes: Handbook/vendor supplied values, ** Measured values
relationship (Figure 9).

Figure 10 summarizes the influence of porosity of the graphitic foam on the Young’s modulus under tension load. Tension and compression properties are different for the graphitic foam due to different failure mechanisms involved. Breakage of the cells causes the tensile failure. Both the graphitic skin and paraffin increase the tensile elasticity modulus significantly. Experimental results indicate that the ultimate strength of the skinned specimens was unaffected by porosity variations of the graphitic foam. Under tension loading the graphitic skin takes most of the tensile load since the elasticity modulus of the graphite/epoxy fabric is 58000 MPa and the tensile ultimate strength of the skin is 848 MPa (Table 2), much higher than those of the filled graphitic foam. The influence of porosity on elasticity modulus for graphitic foam and filled graphitic foam follow a similar trend as that for compression. One noticeable tensile property is that the ultimate strength of the skinned specimens is only marginally affected by the porosity of the graphitic foam. Due to the breakage failure mode of the cells under tension, the paraffin fill does not have a significant influence on the tensile ultimate strength.

Three-point bending experiments were conducted for the graphitic sandwich structures. The 6.4mm x 19mm x 130mm sandwich beam specimen consisted of layers of graphitic skin on top and bottom, and graphitic foam filled with paraffin in the middle. The gage length of the bending specimen was 100 mm. The thickness of the graphitic skin was 0.22 mm. The load versus mid-point deflection curves are shown in Fig.11. A finite element (FE) model and an energy method model were developed using the material properties obtained from the tension and compression experiments for the skin and graphitic foam (Table 1). The prediction results are compared with the experimental observations in Figure 11.

The energy method was developed based on the assumption that plane cross sections of the structure remain plane under bending, a condition that is valid for both nonlinear and linear materials. As a result, strain varies linearly over the cross section of the structure. The energy method uses the stress-strain relationship (material properties) obtained from the experiments. To apply the energy method, the structure was divided into finite volumes, and strain in each volume was considered to be identical. From the bending load applied, strains in every volume can be determined. Therefore, the stress in every volume can be obtained by using the stress-strain relationship. Once the stress and strain in each volume are known, the energy increase of the whole structure can be determined. By using the energy conservation law, the displacement increase at the load point can be obtained.

In the FE model, the sandwich structure was treated as a composite beam consisting of four different materials due to the tension-compression asymmetry of the material properties. The graphitic skin was assumed to display elastic behavior. The nonlinear elastic-plastic material properties of the filled graphitic foam was considered in the FE modeling. Due to the small variations in the porosity of the graphitic foam used and in the specimen dimensions, the three-point bending experimental results display a certain scatter. The predictions shown in Figure 11 represent the upper and lower bounds considering the variations in the specimens. Clearly the FE model and the energy method can adequately predict the deformation and failure for the carbon/epoxy-paraffin/foam graphite sandwich structure. The energy method is easier to implement.
Conclusions
A 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 TES-volume) encapsulated between graphite/epoxy composite skins. Heat input/output to each lamination is via a grid of thermal interfaces, presumed to be in thermal contact with a heat source such as a multi-chip module. The carbon fiber/epoxy skin gives the lamination structural functionality. Stacked laminations form a sandwich structure.

Analysis shows that the carbon fiber/epoxy skin does not participate in a significant way in the heat transfer process. On the other hand, the graphitic foam, with in-plane thermal conductivity that ranges to 50W/mK, acts as an effective thermal conductivity enhancer to the paraffin. In addition, the small cell size of the foam effectively immobilizes liquid paraffin so that the TES-composite thermal performance is expected to be insensitive to up to a 10g load. A thermal response model, which physically represents the TES-volume as a stack of annular graphitic fins interspersed with annular paraffin disks, shows that the paraffin-to-foam contact area is approximately eight-times smaller than the specific surface area of the graphitic foam. It is speculated that this is due to the approximate 13% specific volume reduction that accompanies paraffin solidification. Consequently, the graphitic foam is able to accommodate phase change related specific volume changes at the expense of reduced thermal performance.

The graphitic foam is found to have a low strength and elasticity modulus. It displays tension-compression asymmetry due to the different failure mechanisms that accompany tension versus compression loading. The paraffin fill increases the ultimate strength and elasticity modulus of the graphitic foam under compression loading. The use of the graphitic skin greatly enhances the overall strength of the sandwich structure. Finite element and conservation of energy models are shown to accurately capture the mechanical properties of the TES-laminate structure reasonably well.

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References