Product Development of Engineered Thermal Composites for Cooling Spacecraft Electronics

Edward M. Silverman
Northrop Grumman Space Technology

Northrop Grumman Space Technology, a world leader in the design and production of advanced space systems, has validated and implemented a breakthrough concept of encapsulated annealed pyrolytic graphite (APG) for thermally stressing spacecraft applications. This article presents the results of a 10-year effort, from 1995 to 2005, to find advanced thermal materials to meet future spacecraft thermal radiator subsystem needs. Our study focused on several next-generation thermal composite materials—including carbon-carbon composites and encapsulated APG—that possessed higher thermal conductivity than commercially available carbon polymer composites.

The alternative advanced materials were analytically and experimentally evaluated to verify their potential to cool future spacecraft high-density electronics. Each material was found to present specific technical challenges, such as mechanical and thermal property verification, product-design proof of concept following exposure to environmental loads, and vendor product availability. This article traces the favorable conditions that led to the breakthrough acceptance of the encapsulated APG: pathfinder testing, a multidisciplinary product team, and government contract research programs.

Introduction

Northrop Grumman Space Technology has been a world leader in the design and production of advanced space systems since the successful Pioneer I program in the mid-1950s. A vital part of the space vehicle design, the thermal control subsystem must maintain all components at or below specified allowable operational temperature limits when exposed to external thermal environments. Alternative advanced thermal materials are needed to meet future spacecraft thermal radiator subsystem requirements. To satisfy that need, we implemented a breakthrough concept of encapsulated annealed pyrolytic graphite (APG) for thermally stressing spacecraft applications.

We conducted material trade studies to identify performance gaps between the capabilities of commercially available carbon polymer composites and future thermal management requirements. We analytically determined the performance advantages of several next-generation thermal composite materials—including carbon-carbon composites and encapsulated APG—that possess higher thermal conductivity than commercially available carbon polymer composites. A multidisciplinary product team executed a pathfinder test program to verify the ability of a new material concept to meet performance requirements in an operational environment that included significant thermal cycles and vibration levels representative of launch loads. The result is a breakthrough engineered material concept that uses the high-performance thermally conductive APG material.

In the following section, we discuss the requirements of spacecraft thermal control subsystems and future mission needs, followed by a description of available design solutions. We then present the evolution of materials for thermal radiators, culminating in a detailed discussion of the engineering of APG and its performance. Our approach to pathfinder testing and test results is presented, the benefits of APG are summarized, and prospective future APG applications and other technologies are briefly discussed.

Spacecraft Thermal Control Subsystem and Future Mission Needs

A spacecraft thermal control subsystem must simultaneously accomplish the following:

- Maintain all components at or below specified allowable operational temperature limits.
- Dissipate heat at a radiator temperature of 40°C or higher to maximize thermal efficiency, i.e., minimize the thermal gradient between the chip and the radiator.
- Minimize the mass of components in the heat rejection path.

Table 1 lists typical spacecraft temperature requirements. A relatively cool, narrow operating temperature range extends the useful life of batteries. Propulsion systems, on the other hand, may need a warm environment to avoid freezing propellants, i.e., hydrazine. To meet long-duration space mission reliability requirements, junction temperature limits for the electronic components on the printed circuit boards are typically 105°C for silicon components and 125°C for GaAs components.

The heat generated by spacecraft components often presents difficult thermal design problems because of local high heat fluxes (typically expressed as W/in^2), high total power dissipation, and wide temperature changes over time (e.g., a satellite moving in and out of the sun's rays is subjected to large cyclic temperature extremes over short periods of time). Heat sources include communication system transmitters and receivers; spacecraft electronics, such as attitude control, electrical power, and telemetry and command; batteries; solar cells; and semiconductor chips.

The increasing need to fly larger, higher-performance payloads with higher-density microprocessors for longer periods of time has escalated power dissipation and heat flux at the silicon level. Future military communication satellites will have higher power density microelectronics packaging design concepts that will increase by five to ten times the data processing throughput, resulting in up to ten times the thermal density requirements, e.g., power dissipation will increase to 2 to 3 W/in^2 above the current level of 0.1 to 0.5 W/in^2. Consequently, the chip junction-to-unit base-plate temperature gradients can exceed 80°C

Table 1. Typical spacecraft temperature requirements

Component	Temperature Range (ºC)
Chips	<125
Electronic equipment	0 to 50
Batteries	5 to 20
Propulsion tanks and lines (hydrazine)	5 to 50
Solar arrays	–100 to +75

if waste heat is not efficiently removed from the electronic devices and components. Electronics packaging designers must therefore increase component density and reject additional thermal dissipation, while improving component reliability and performance for such advanced chips as GaAs.

Passive thermal components—such as radiators, doublers, multilayer insulation, coatings, electronic chassis enclosures, and chip packaging—are often used to control the temperatures of electronic components. Required in all spacecraft, radiators are designed in several forms, such as structural equipment panels, flat-plate radiators mounted to the side of the spacecraft, and panels deployed after the spacecraft is on orbit.

Driven by future stringent weight and thermal performance requirements, the next generation of satellites will potentially use higher thermally conductive materials in the design of the electronics boxes, chip packaging, radiators, and heat-spreading doublers. The following sections identify the critical performance variables in the design of radiator and doubler thermal-control subsystems.

Thermal-Control Subsystem Design Solutions

Many factors influence thermal-control subsystem design requirements, notably:

- External environments (e.g., solar radiation, albedo, Earth-emitted infrared)
- Heat generated by the onboard equipment
- Physical design and mechanical loading environments of the spacecraft

Those factors influence the selection of materials that are used in radiators and doublers. Their thermal and structural properties—e.g., density, elastic modulus, yield strength, thermal conductivity, heat capacity, and coefficient of thermal expansion (CTE)—are exploited to meet the thermal and mechanical loads, as well as to establish doubler dimensions and the configurations of thermal control subsystem components such as radiators. In addition, the components must be thermally compatible with the structures to which they are attached, i.e., similar CTE. Next, we discuss the primary design drivers for radiators and doublers, especially their need for thermal compatibility.

Radiator Configuration Design Criteria. All of the waste heat dissipated by electronics is radiated to space by passive "thermal radiators." Figure 1 illustrates body-mounted radiators on a typical communication satellite, with electronic equipment mounted inside a panel and waste heat rejected to space by the outside surface of the panel. Each electronic box or battery module generates a different heat load, e.g., Q_1. The panel inboard facesheets spread the heat out from the electronic base plates, radiating to the outboard facesheet surface, which is the primary heat-rejection path. The outboard surface is covered with thermal control coatings, silverized Teflon®, and/or second surface mirrors.

Current trends toward increasing power dissipation and mounting density of electronic equipment will require larger radiator areas or higher thermal efficiencies to reject higher heat fluxes. The amount of heat that can be emitted or radiated from the radiator panel surface is governed by the Stefan-Boltzmann heat-transfer-rate equation for radiation:

$$Q = A\sigma\varepsilon\,(T_r^4 - T_s^4) \quad , \tag{1}$$

where

Q is the thermal dissipation plus thermal environment input,

A is the cross-sectional area (m^2),

σ is the Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2-K^4,

ε is emissivity, with

–Maximum emissivity = 1.00 (black charcoal surface),

–Minimum emissivity = 0.06 (shiny gold surface),

T_r is the radiator temperature (K),

T_s is the sink temperature (K), i.e., space environment.

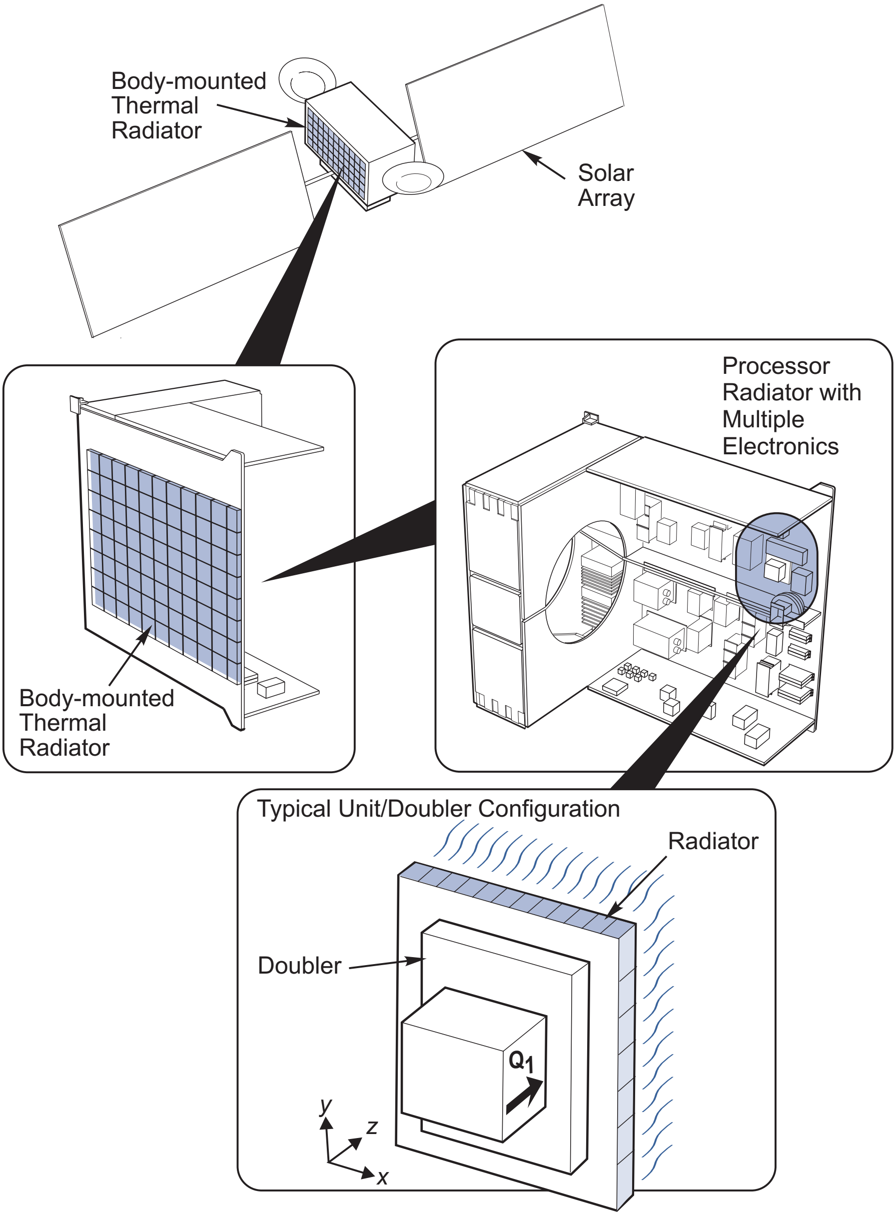

Figure 1. Body-mounted radiators on typical communication satellite

Hence, for higher power dissipation of the electronic components, i.e., high Q_1, it is beneficial to have a structural radiator with a large surface A radiating heat at a high radiator temperature T_r. The volume constraints of the spacecraft and weight-saving goals tend, however, to limit the allowable radiator area. Furthermore, the high thermal density of the electronic equipment tends to cause the radiator to operate at a low temperature, owing to the larger temperature drop within the electronics unit.

Thermal Doublers for Efficient Radiator Designs. An important issue in the design of the thermal control subsystem is the localized concentration of heat dissipation. Traveling wave tubes and many other temperature-sensitive electronic components have a very high heat density over a small footprint area to the radiator panel. The inadequate surface area prohibits maximal energy transport to heat-sinking radiators.

In such instances, power-dissipating components will be mounted onto lightweight sheets called *thermal doublers*. The thick, thermally conductive sheets distribute highly concentrated heat, dissipated by the electronic units, over a larger area than the base of the unit itself. Hence, a larger surface area for transporting heat generated by the component or equipment is available for conduction into the heat sink—i.e., the radiator, which reduces the formation of a large thermal gradient. A typical unit/doubler configuration is shown in Figure 1.

The doubler is a two-dimensional fin that spreads the dissipated energy of an electronic unit over an area large enough to maintain acceptable unit temperatures. The rate of heat conduction within the doubler is governed by Fourier’s Law of Conduction for heat transfer by a steady, unilateral flow:

$$dQ/dt = -kA(dT/dx) \quad , \tag{2}$$

where

dQ/dt	is the rate of heat conduction (W) along the x-axis through a defined cross-sectional area A,
k	is thermal conductivity (W/m-K), i.e., the intrinsic property of a material that relates its ability to conduct heat,
A	is the area of the path (m^2),
dT/dx	is the temperature gradient along the path.

Hence, the rate of heat flow dQ/dt through a homogenous solid is directly proportional to

- The area A of the section at right angles to the direction of heat flow
- The temperature difference along the path of heat flow dT/dx
- The material’s thermal conductivity k

The primary objective of the thermal doubler is to maintain the temperature of the dissipating component at or below a specified operating temperature; an important secondary goal is to minimize the thermal subsystem mass. A thermally efficient doubler will allow smaller radiators to enhance heat-rejection efficiency by operating at higher temperatures. In general, metals that are good heat conductors, i.e., have a high inherent thermal conductivity, also make good heat sinks. Aluminum is a good example of a heat sink widely used on spacecraft.

Higher thermally conductive polymer composites are also being used, as discussed below (page 6). Doublers are commonly paired with heat pipes to assist in spreading the heat. (The heat pipe is a semiactive device suited to space applications in which a large amount of heat must be transferred from one area to another or when a stable isothermal condition is required in an area subject to hot and cold spots.)

Based on prior trades and analyses, we found that thermal doublers are needed to diffuse heat fluxes (power dissipation per unit area) greater than 0.3 W/in^2 over a large area for rejection into space. As the thermal density increases 5 to 10 W/in^2 for high-powered traveling wave tube amplifiers (TWTAs), doubler thickness and area increase proportionally. In addition, electronic units requiring very thick thermal doublers are likely to be degraded by use of a material—such as a polymer composite—with poor conductivity in the direction normal to the doubler, i.e., the *z*-direction.

Structural Compatibility. The design of large spacecraft structures constructed with more than one material must give careful attention to the mechanical loads introduced by the thermal growth resulting from dissimilar CTEs. Hence, structural compatibility is a prime driver in material selection because

- Aluminum and polymer composite materials have different CTEs
- The structure may be subjected to wide temperature extremes (–40°C to +71°C)

Thus, it is unlikely that a thermal doubler composed of a particular material can be bonded onto a structural panel of a different material without inducing internal thermal loads. Similarly, for a GaAs semiconductor die attached to a heat spreader, a CTE range of 6 to 9 ppm/°C is the prevailing heat spreader design criterion used to closely match the CTE of the semiconductor material.

The increasing use of composite platforms for the precision pointing of scientific instruments and reflectors has highlighted the difficulty of embedding aluminum heat pipes in a carbon-fiber-reinforced composite spacecraft bus. The problem results from the mismatch of associated CTEs. Several industry efforts have attempted, with limited success, to embed aluminum heat pipes in composite panels. A more thermally efficient radiator would obviate the need for heat pipes.

Evolution of Materials for Thermal Radiators

In developing and selecting innovative materials to improve spacecraft thermal management subsystems, a number of factors must be considered, especially the following:

- Identifying gaps between the performance capabilities of currently used materials and future spacecraft system requirements helps define the performance requirements of the next-generation advanced materials.
- In addition to mechanical and thermal properties, the selection criteria for the advanced materials must include their ability to withstand vibration launch loads and the extremely variable thermal environment, manufacturing lead time, and product costs, availability, and reproducibility.

Multifunctional Carbon Polymer Composites. Because weight is at a premium on a spacecraft, lightweight polymer composites have been targeted to replace aluminum for such structural components as struts, boom, spacecraft-to-booster adapter sections, and other key structures for which stiffness is a critical design parameter. In the late 1980s, the development of a high-modulus, highly thermally conductive K1100 carbon fiber embedded in a polymer matrix led to the replacement of aluminum radiator facesheets and doublers.

Previously, low-modulus polyacrylonitrile (PAN)-based carbon fibers, such as T-300 with its 33×10^6 psi modulus, were not intended to address heat-conduction issues, owing to their low thermal conductivity in the range of 5 to 10 W/m-K. Now, the new mesophase pitch-based carbon fibers, such as K1100, are more graphitic and have demonstrated a 130×10^6 psi modulus and 1100 W/m-K thermal conductivity. Such materials are interesting because designers can use them to create structures that perform more than one function, e.g., a multifunctional material offering both structural and thermal performance.

Figure 2 summarizes the trends in material performance for spacecraft, beginning with isotropic metals, such as aluminum, and transitioning to carbon polymer composites and next-generation carbon-carbon and APG. The figure presents a comparative performance map of specific stiffness (modulus E divided by density ρ) as a function of specific thermal conductivity (in-plane thermal conductivity, k_{xy}, divided by density, ρ) between conventional metals and polymer composites incorporating those fibers. The thermal conductivity of the composite material is a combination of that of the polymer matrix and the reinforcing carbon fiber.

For example, by a volume weighting of properties, a unidirectional 0-deg lay-up K1100 carbon polymer composite, with 60% fibers by volume, has a conductivity of 595 W/m-K in the direction of the fibers and 1 W/m-K in the other orthogonal directions. The high specific thermal conductivity of the composite materials permits replacing aluminum in radiator panels, resulting in significant weight savings [1,2]. For comparison, aluminum has a thermal conductivity of 180 W/m-K, only a fraction of the K1100 carbon fiber polymer composite's conductivity.

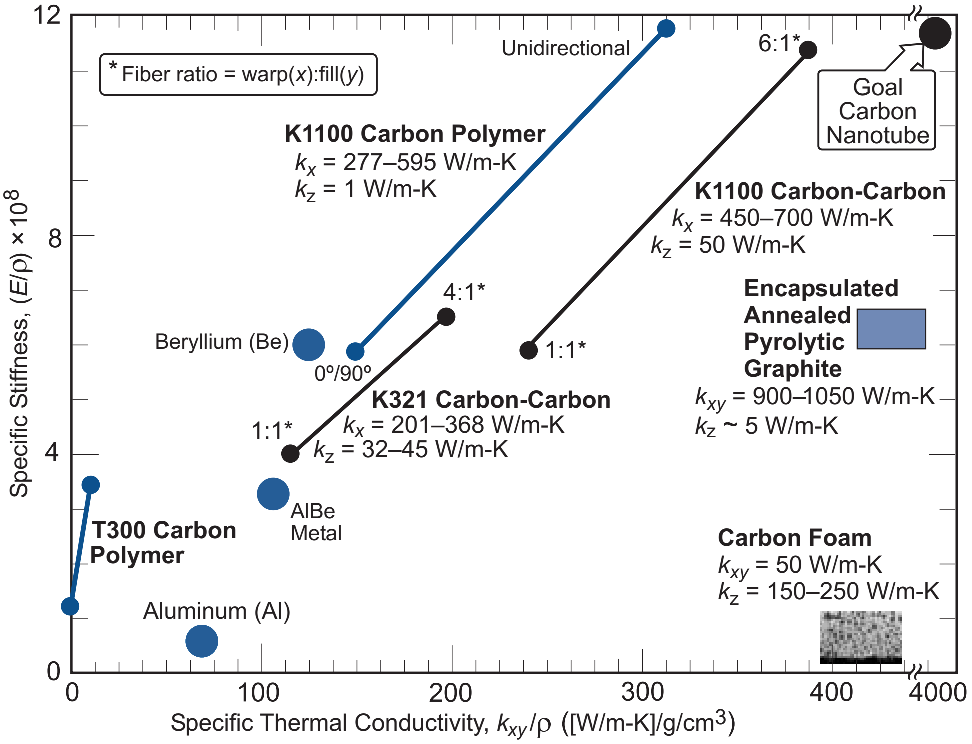

Figure 2. Trends in material performance for spacecraft

K1100 carbon fiber polymer composite material served the thermal management needs of the spacecraft designed in the 1990s, such as doublers for the Aura and Aqua EOS bus structures. However, materials with higher thermal conductivities are needed for the next-generation spacecraft higher-power-density electronics for the following reasons:

- Innovative lightweight electronic packaging/panel concepts with higher *xy*-direction thermal conductivity must be developed to provide the thermal environment required to ensure device reliability and payload accommodation for the higher-dissipating components.
- The shortcoming of the carbon polymer composites is their poor thermal conductivity in the direction normal to the fibers, i.e., the *z*-direction. Flat plates constructed of that material are highly anisotropic. Electronic units requiring very thick thermal doublers (~0.25 in. or more) would not meet the allowable operational temperature requirements, because of the low through-the-thickness, *z*-directional conductivity of 1 W/m-K for carbon polymer composites.

Thermally Conductive Carbon-Carbon Composites. In 1995, the Air Force Research Laboratory and the National Aeronautics and Space Administration (NASA) funded several studies to assess the potential for improving spacecraft thermal management efficiency (e.g., reduced weight, reduced radiator area) by using advanced carbon-carbon composites on future spacecraft thermal management radiators [3,4]. Carbon-carbon composites, a generic class of materials similar to polymer matrix composites, comprise a carbon fiber, such as K1100, in a carbonaceous matrix. The matrix can be formed through the curing and carbonization of a resin-impregnated carbon preform, followed by several cycles of densification using the chemical vapor deposition (CVD) of carbon from a hydrocarbon to the carbon fiber preform.

Carbon-carbon composites based on K1100 carbon fiber are predicted to have enhanced thermal conductivity in both the *x* and *y* directions, as well as in the through-the-thickness *z*-direction, compared with laminates of K1100 carbon fiber polymer composites detailed in Figure 2. Table 2 compares the thermal properties of aluminum with those of carbon polymer and carbon-carbon composites [5–7]. Consequently, a radiator can be designed with no heat pipes by using laminates of K1100 (6:1, fiber ratio of warp to fill) carbon-carbon composites with a maximal thermal conductivity of 700 W/m-K in the fiber-warp-

Table 2. Comparative properties of aluminum and advanced composites

Material	Fiber Lay-up Orientation	Fiber Volume (%)	Density (gm/cm^3)	Thermal Conductivity (W/m-K)		
				x	*y*	*z*
Aluminum 6061	Isotropic	N/A	2.70	170	170	170
K1100 carbon polymer	Unidirectional	60	1.84	595	1	1
K1100 carbon polymer	0º/90º	60	1.84	277	277	1
K1100 carbon-carbon	6:1[a]	55	1.80	700[b]	55[b]	50
K1100 carbon-carbon	1:1[a]	55	1.80	450[b]	450[b]	50
K321 carbon-carbon	4:1[a]	50	1.75	368	97	45
K321 carbon-carbon	1:1[a]	50	1.75	201	200	32

[a] Fiber ratio = warp(*x*):fill(*y*)
[b] Calculated from rules of mixtures

aligned *x*-direction [5]. Significant cost savings are associated with the elimination of integration and testing of heat pipes.

In addition, carbon-carbon composites can potentially enhance doubler thermal efficiency, owing to their higher *z*-direction thermal conductivity, compared with that of polymer composites—50 W/m-K versus 1W/m-K, respectively. The higher thermal conductivity leads to smaller thermal gradients across the radiator panel, and that reduction increases the effective radiator heat-rejection temperature, while maintaining or increasing the electronic base-plate temperature.

Although recent studies have shown the advantages of carbon-carbon composites for spacecraft applications [8–10], limiting factors affect the increasing use of carbon-carbon composites: prohibitive product expense and long-lead manufacturing times due to slow, complex carbonization and densification steps. A commercially acceptable carbon-carbon composite is based on a low-modulus and lower cost K321 carbon fiber.

The material supplier's attempt to develop a less-expensive carbon-carbon composite process resulted in a lower thermal conductivity—368 W/m-K measured versus the 700 W/m-K predicted (Figure 2)—which restricted the utility of carbon-carbon composites in stressing spacecraft thermal management applications. Hence, affordable, more thermally conductive materials are needed to meet future thermal density requirements.

Engineering a New Material for Enhanced Thermal Capability: Annealed Pyrolytic Graphite. In the mid-1990s, the k Technology Corporation patented a new thermal material concept that encapsulates low-strength pyrolytic graphite material within a high-strength structural shell material such as aluminum or a carbon polymer composite [11]. APG is a highly ordered crystalline material with a thermal conductivity over 1500 W/m-K, but with fragile strength properties (detailed in the adjacent sidebar, "Annealed Pyrolytic Graphite," pages 11–12). The patented concept permits intimate contact between an encapsulant and the APG core, while decoupling the thermal and mechanical interdependence of the constituent materials. That is, as Figure 3 shows, no shear force is transferred across the encapsulant/APG interface.

The versatility of such a material is that an encapsulant such as aluminum or carbon polymer composite, though mechanically decoupled from the APG insert because of the

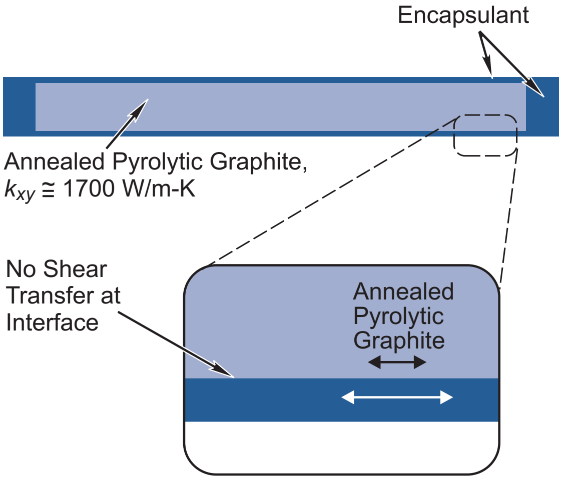

Figure 3. Encapsulated annealed pyrolytic graphite: No shear transfer at interface

zero-shear transfer interface, is thermally enhanced by the APG insert up to five times the thermal conductivity of the baseline aluminum, i.e., 1050 W/m-K versus 180 W/m-K, respectively. In contrast, the APG cannot impart a shear load onto the encapsulant because of its low strength in its crystalline *c*-direction. Therefore, any thermal-expansion-induced strains between the encapsulant and the APG insert will not impart stresses to the assembly. That is, the CTE and other structural properties of the assembly are controlled solely by the encapsulation material.

The decoupling permits each component to be optimized independently. In other words, the encapsulation material's properties govern the structure (strength, stiffness, CTE), whereas the APG core governs the thermal conductivity. That feature is particularly useful for electronic packaging applications where a heat sink must have both a high thermal conductivity and a low CTE. The resulting engineered material now has a high thermal conductivity of ~1050 W/m-K, greater than the 700 W/m-K thermal conductivity previously predicted for a carbon-carbon radiator panel design with no heat pipes.

APG Breakthrough Performance Benefits. A carbon-polymer-composite-encapsulated APG doubler with an assumed thermal conductivity of ~800 W/m-K was analytically determined to provide significant cost, weight, and risk savings for future programs that need to embed aluminum heat pipes in composite panels to enhance the heat spreading capability of spacecraft radiators containing high-power-density units, e.g., TWTAs. A carbon polymer encapsulant was chosen for that application because its near-zero CTE property matches that of the carbon polymer composite bus structure, providing weight savings and dimensional stability not achieved with aluminum bus construction.

A comparative steady-state conduction analysis comparing a baseline K1100 carbon polymer composite 30 × 30 in. doubler design with a redesigned carbon-polymer-composite encapsulated APG doubler points to enhanced performance without the need for embedded aluminum heat pipes in polymer composite radiator panels.

Using the next generation of an encapsulated APG doubler to replace heat pipes would achieve additional weight savings. Equally important, the CTE mismatch problem inherent in combining composite facesheets with aluminum heat pipes would be avoided, hence eliminating the risk of a structural debonding failure. Table 3 summarizes those benefits.

Table 3. Comparative advantages of annealed pyrolytic graphite versus conventional radiation design

Doubler Material (30 × 30 in.)	Number of Radiator Heat Pipes	Traveling-Wave-Tube-Amplifier Temperature (ºC)	Doubler + Heat-Pipe Weight (lbm)[a]	Recurring Cost ($K)[b]
Carbon polymer composite/annealed pyrolytic graphite	None	41[c]	6.7	38
K1100 carbon polymer	9	61	16.7	152

[a] 10-lb panel weight savings due to heat-pipe elimination translates into launch cost savings

[b] 75% recurring cost savings over heat-pipe radiator panel due to elimination of heat-pipe fabrication and integration costs, as well as elimination of expensive K1100 doublers

[c] 41ºC base-plate allowable temperature for traveling-wave-tube amplifiers

Annealed Pyrolytic Graphite: A Breakthrough Material for Spacecraft Thermal Control

Annealed pyrolytic graphite (APG) is a crystallographic carbon deposited on a substrate via the pyrolysis of a hydrocarbon gas—methane or acetylene—over a high temperature range of 1750°C to 2250°C in a vacuum furnace. Pyrolytic graphite, when removed from a substrate (such as a flat graphite panel), is not a fibrous material but a crystalline carbon sheet that replicates the base on which it has been deposited.

APG consists of tightly bonded, hexagonally arranged carbon layers held together by weak van der Waals forces. The result is a crystal that is remarkable in its anisotropy, being almost isotropic within the basal plane but with *c*-direction properties, i.e., between the basal planes, which differ by orders of magnitude from those within the basal plane. Figure S1 shows the atomic structure of graphite, a crystalline lattice.

The highly aligned crystalline graphite in the figure has an in-plane thermal conductivity of ~1700 W/m-K, four times greater than that of copper, but a *z*-directional thermal conductivity of less than 5 W/m-K. In addition, bonds within the chicken-wire-like sheets are very strong, but interactions between the sheets are weaker and can easily be broken, thus explaining why APG is a soft, brittle substance.

Hence, the mechanical properties of APG make it difficult to use directly for electronics cooling applications. The stiffness, i.e., Young's modulus, of APG is 2.9×10^6 psi, a quarter

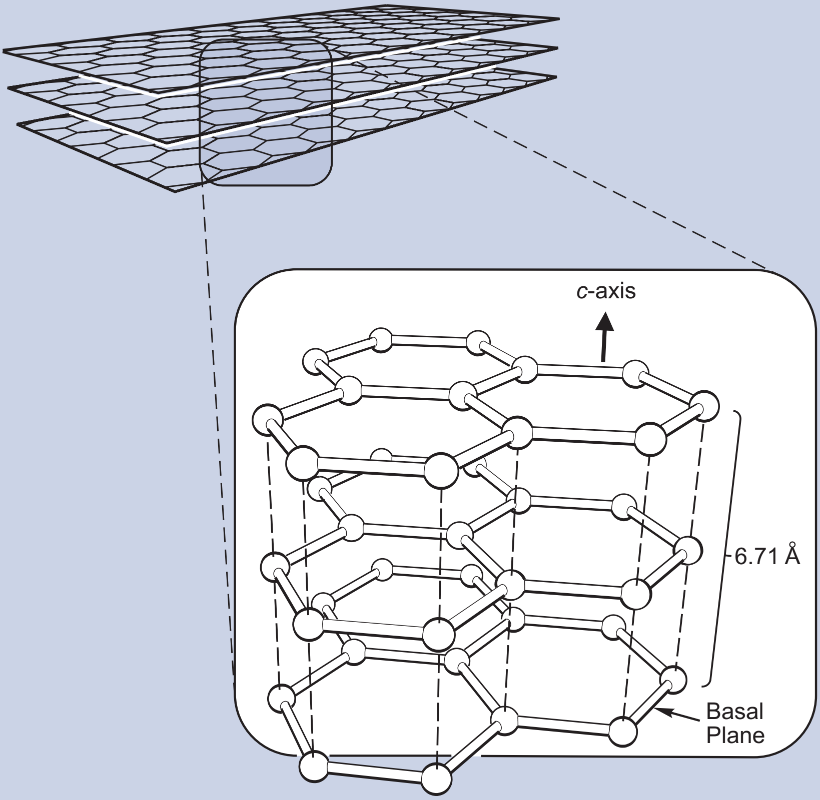

Figure S1. Atomic structure of graphite: Crystalline lattice

that of aluminum's 11.5×10^6 psi. Its tensile strength is 11.6×10^3 psi, just two-tenths that of aluminum's 58×10^3 psi. Overall, APG has poor mechanical properties because of the weak van der Waals forces that bond the lattice in the *c*-axis. Encapsulating APG within a structural shell overcomes that limitation.

Annealed Pyrolytic Graphite Pathfinder Testing: Technical Challenges

A pathfinder testing study was initiated to verify the product design concept of the new engineered material, whose hybrid construction differed considerably from that of the conventional carbon polymer composites already qualified for flight. The testing program addressed the following technical challenges:

- Although the components of the composite-encapsulated APG doubler are structurally decoupled, it has been assumed that an excellent thermal interface links the APG graphite insert and the encapsulant, resulting from the normal forces applied between those components during fabrication. However, the thermal performance of an APG doubler would be significantly degraded if a high interface resistance developed at that interface, e.g., debonding after thermal cycling or vibration testing.
- The effective thermal performance of a composite APG doubler is a function of the volume fraction of the APG insert and its in-plane thermal conductivity, >1500 W/m-K. Although APG has a low through-the-thickness conductivity of ~5 W/m-K, we assume that any reduction in its heat conduction capability is not significant for a heat-spreading doubler, because the length of the thermal path along the plane of the APG is large relative to the path normal to this plane. A lower-than-anticipated k_z thermal conductivity or a higher-than-anticipated interface resistance would, however, lower the overall performance of the APG heat spreader.
- Bolts and inserts attach numerous electronic assemblies to the radiator panels. With an AGP heat spreader, holes would have to be drilled through the structural composite frame and the APG material. Although the holes are subsequently epoxy-potted with bushings that tend to preserve the structural integrity of the heat spreader, any potential degradation in thermal performance must be verified.
- Verifying that the properties of the prototype doubler resemble those of previous procured coupons would mitigate the risk of future producibility issues associated with scalability.

Testing Objectives and Approach. A multidisciplinary product team was assembled to verify that a carbon-polymer-composite-encapsulated APG doubler could provide enhanced thermal performance and spacecraft system cost advantages on spacecraft composite panels with high-power-density electronic units [12,13]. Specifically, the following objectives were set:

- Evaluate the effects of thermal cycles, vibration, and life-cycle tests on the carbon-polymer-composite-encapsulated APG doubler thermal performance by comparing temperature profiles of the before-and-after thermal balance tests.
- Quantify the APG doubler thermal performance in terms of effective thermal conductivities by correlating the test results with the predicted results, based on test-panel thermal models and under identical test operating conditions.

To accomplish those objectives, a 35.5 × 25.5 in. APG doubler was bonded to a typical honeycomb panel using materials and dimensions identical to flight and power dissipation units representative of high-power TWTAs. The radiator/doubler panel had the following characteristics:

- The polymer-composite-encapsulated APG doubler panel comprised 100-mil-thick APG plates encapsulated between two polymer-composite facesheets. An overall effective thermal conductivity of ~1140 W/m-K was anticipated, based on a rule-of-mixture prediction. The doubler was adhesively bonded to a 30 × 42 in. honeycomb panel with an aluminum honeycomb core and carbon polymer-composite facesheets.
- The TWTA thermal simulator, representing the TWTA collector shape and dimensions, was bolted to the radiator doubler/honeycomb panel containing numerous bushings, as shown in Figure 4. (The bushings were installed using conventional drilling and potting techniques with no visual evidence of panel delamination.)
- Mass simulators representative of electronic black boxes and other hardware, such as batteries, were directly mounted to the inner surface of the panel for vibration testing, as shown in Figure 5.
- Thermocouples were mounted on the front of the doubler and on the back of the honeycomb radiator panel.

The radiator doubler/honeycomb panel underwent a series of test phases designed to measure changes in thermal performance due to thermal cycling and launch-load vibration environments representative of flight. The results cover five sets of hot and cold thermal balance tests. The test sequence was as follows:

- Hot and cold balance tests before eight thermal cycles between –50°C and +71°C
- Hot and cold balance tests before vibration
- Vibration
- Postvibration hot and cold balance tests
- Hot and cold balance tests after 50 and after 100 life cycles between –30°C and +50°C

Thermal Cycling and Vibration Loading Do Not Degrade Panel Temperature Profiles. The thermal performance for each hot/cold-balance test revealed no degradation in APG

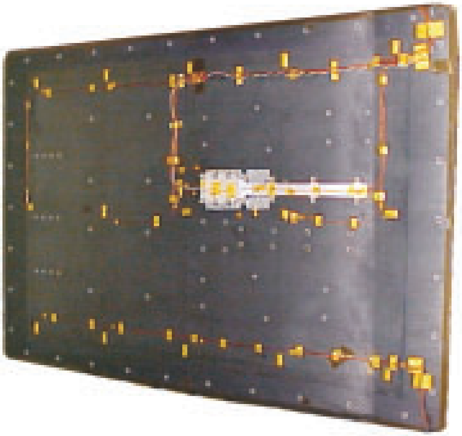

Figure 4. Doubler application with TWTA thermal simulator

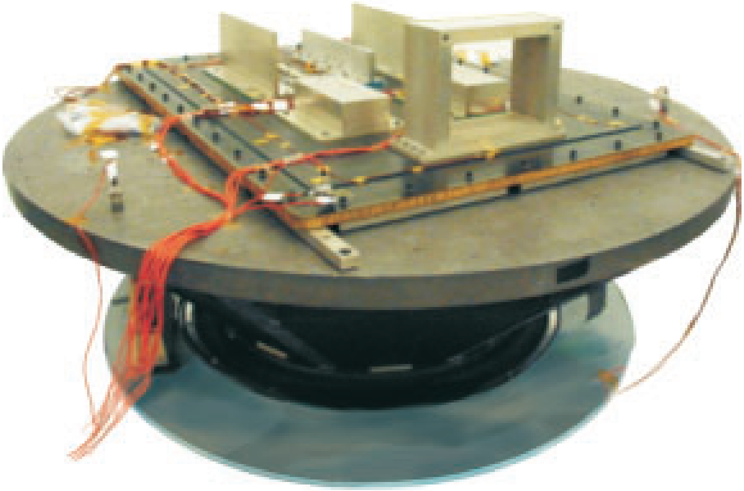

Figure 5. y-axis vibration fixture with doubler/honeycomb panel containing mass simulators

doubler thermal performance as a result of thermal cycling and vibration testing. Figure 6 plots measured temperature profiles against thermocouple number for all five hot-thermal-balance tests. Thermocouples 1 to 15 show the doubler temperatures; thermocouples 16 to 30 show the radiator temperatures. All profiles follow the same patterns, which exhibit no sign of thermal degradation; temperature spatial gradients were the same in each profile.

Besides concluding that the vibration testing had no deleterious effect on thermal performance, we determined that no loss in the structural integrity of the APG doubler occurred because of vibration that simulated expected launch loads (three-axis random vibration consisting of 24.3 Grms normal and 11.1 Grms in plane for three minutes). Similar test results were obtained for the five cold-balance tests. They follow the same pattern as the hot-balance test results with the same general conclusions.

Finally, we found that the temperature levels for the last three balance tests performed after the vibration test were lower by a couple of degrees centigrade. The difference could simply be due to greater heat loss through the multilayer insulation because a different blanket was used after the vibration test.

APG Doubler's Lateral Thermal Conductivity Correlates Strongly with Test Data. A thermal model of the test article was developed to correlate the effective lateral thermal conductivity k_{xy} of the APG doubler to the test data. Figure 7 shows the measured temperatures as a function of thermocouple numbers for the hot thermal balance measurements following initial thermal cycling and preceding the vibration test. Panel temperature predictions are also shown for different values of the composite-encapsulated APG doubler lateral thermal conductivity in the range of 345 to 1210 W/m-K.

By comparing the different panel predicted temperature profiles with the measured temperature profiles, one can see that the actual APG doubler k_{xy} thermal conductivity value falls toward the upper end of the range, i.e., between 882 and 1210 W/m-K—a value that concurs with the rule-of-mixture prediction of 1140 W/m-K. The maximum value for the doubler k_z of ~5 W/m-K was assumed for the panel temperature predictions, which matched the value based on the coupon test results reported in a previous coupon study.

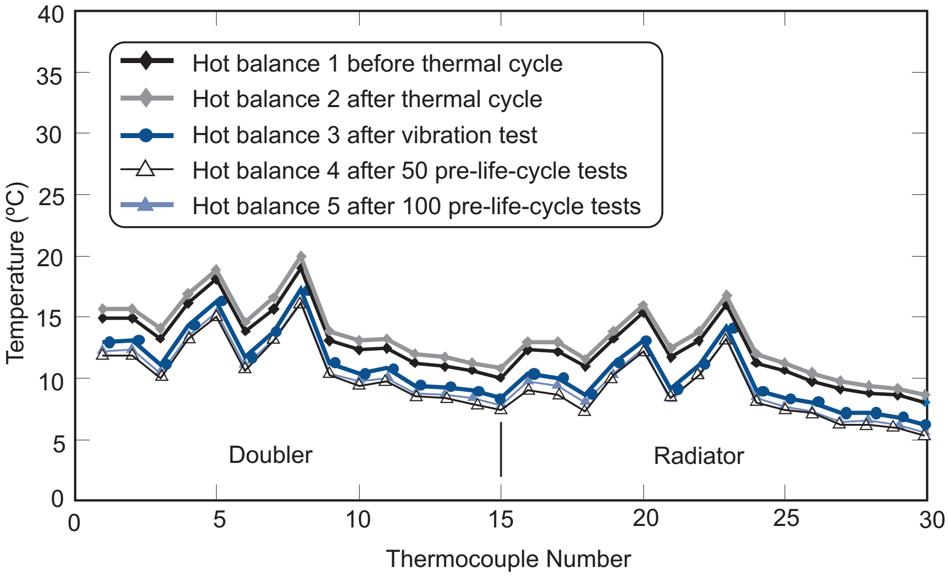

Figure 6. Hot-thermal-balance measured temperature profiles for various environmental tests

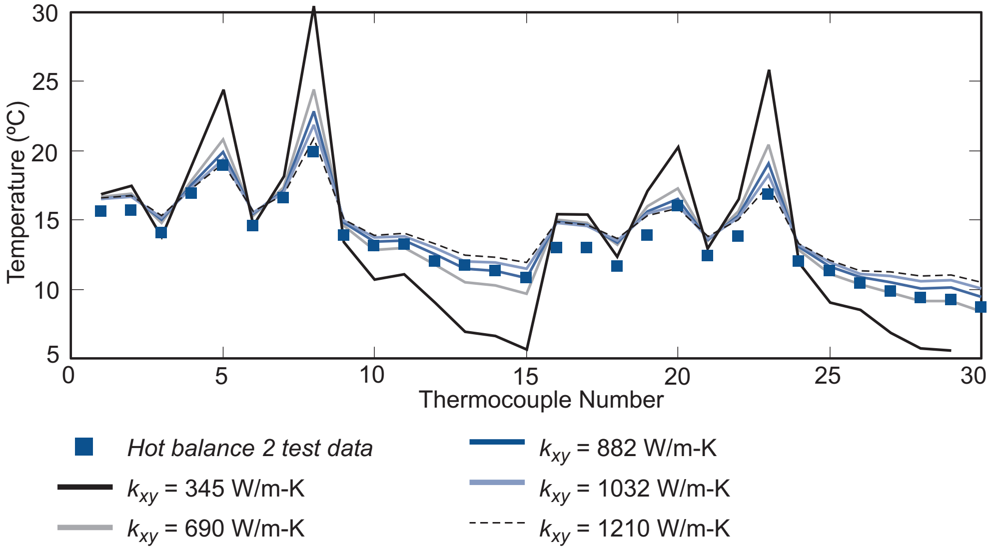

Figure 7. Measured hot-balance condition compared with range of predicted temperature profiles

Annealed Pyrolytic Graphite Performance Benefits Summary

All pathfinder testing study objectives were achieved:

- The APG doubler exhibited no evidence of degradation in its thermal performance when exposed to vibration and limited (100 cycles) life-cycle tests.
- Correlation of the test data with predicted values showed apparent APG doubler lateral thermal conductivity of >882 W/m-K and through-the-thickness thermal conductivity of ~5 W/m-K.

In addition, strong evidence of no change in thermal performance successfully addressed the following original technical challenges of the pathfinder testing (see page 12):

- The thermal interface between the APG graphite insert and the composite encapsulant is excellent.
- The low through-the-thickness thermal conductivity of ~5 W/m-K is not a significant factor in the overall lateral thermal performance of the heat-spreading doubler.
- The APG doubler experienced no structural degradation within the panel or within the vicinity of any bushings following exposure to simulated launch loads.
- The APG doubler’s properties are similar to coupon-generated properties.

The testing project verified that an encapsulated APG radiator doubler will provide enhanced thermal performance, achieve weight savings by eliminating heat pipes, and provide spacecraft system cost advantages for carbon composite radiators containing high-power-density units. For example, the estimated cost and weight savings for 12 equipment radiator panels are $1.4 million and 120 pounds per spacecraft, respectively.

In addition, implementing APG doublers will accommodate future spacecraft high-density equipment panels that would otherwise require embedded heat pipes. The breakthrough engineered material concept exploiting an encapsulated APG material will enable spacecraft radiator subsystems to cool increased-density electronics while minimizing mass.

Future Space Applications and Materials

APG technology is being considered for other programs and applications. An aluminum-encapsulated APG product concept now under development will enable equipment panels to have adequate heat spreading without requiring oversized, weight-prohibitive aluminum doublers, hence accommodating higher-power-density equipment layout with improved thermal margins. In addition to radiator components, the APG technology is being considered for other thermal control components, such as advanced packages [14] that would reduce the thermal gradient from the heat source to the radiator.

The insight gained over the 10 years spent searching for higher-performance materials to meet anticipated thermal management control requirements tells us that it would be equally prudent to span the current technology horizon in search of even higher performing materials. As shown in Figure 2 above (page 7), the theoretical thermal properties of carbon nanotubes make them a compelling choice for current research efforts, as described in the adjacent sidebar, “Carbon Nanotubes.”

Carbon foam is being studied as a highly thermally conductive material for radiators [15], as well as a material solution for solid-state-laser thermal management applications [16]. Carbon foam’s low density (~0.5 g/cm^3) and thermal conductivity values (50 to 250 W/m-K) account for its attractive specific thermal conductivity property (Figure 2).

Carbon Nanotubes

A carbon nanotube was discovered in 1991 by the Japanese Ijima team. The team observed that nanotubes are closed, smooth, hollow tubes with a graphite structure (curved like a roll of chicken wire) and closed at both ends by a fullerene-type cap, i.e., containing pentagons (see Figure S1). Figure S1 shows the idealized version of the experimental nanotube [S1]. The cylinders can be a few microns or even millimeters long, with a diameter on the order of a nanometer—hence, their name. Several methods are employed to make nanotubes, including arc discharge, laser ablation, and the most promising method, chemical vapor deposition, which is usually conducted by reacting a carbon-containing gas with a metal catalyst particle at temperatures above 600°C.

Carbon nanotubes have properties that make them potentially useful in extremely small-scale electronic and mechanical applications. They are predicted to have unusual strength and unique electrical properties, as shown in Table S1, which compares material properties. Carbon nanotubes constitute the ultimate carbon fibers, with an exceptional tensile strength reported at ~9100×10^3 psi [S2] and a theoretical thermal conductivity of 6000 W/m-K [S3]. Thus, they could form the basis of a multitude of future high-performance materials.

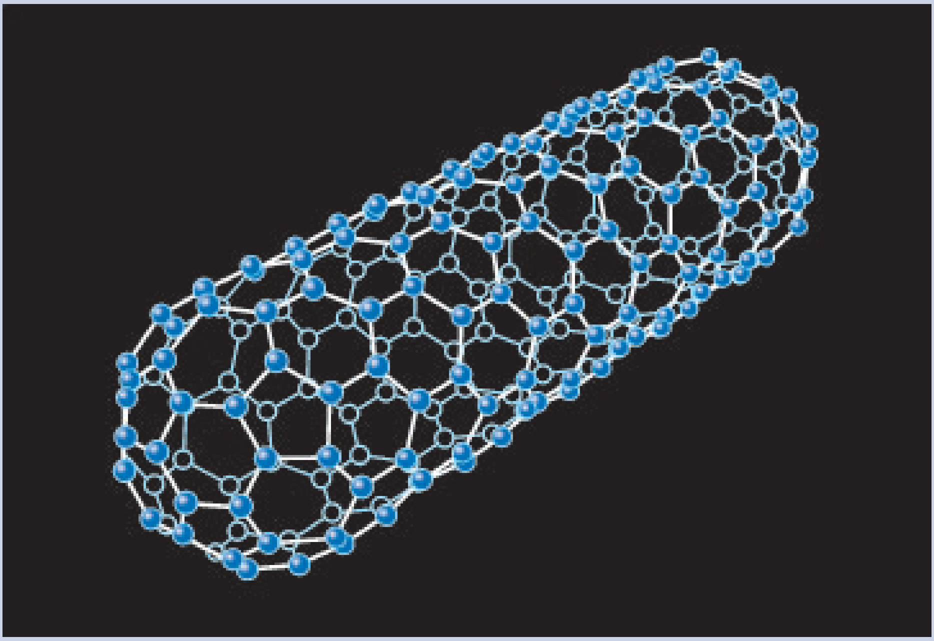

Figure S1. A nanotube: Cylinder with a graphite structure closed at both ends by fullerene-type cap containing pentagons

Table S1. Comparative properties of carbon nanotube and common spacecraft materials

Material	Specific Gravity (gm/cm3)	Strength (10^3 psi)	Modulus (10^6 psi)	Thermal Conductivity (W/m-K)	Electrical Resistivity (μΩ-cm)
Carbon nanotube	1.3	>9100	95 to 145	~6000	<100
Ultra-high-modulus carbon fiber	2.2	430	130	1100	220
Carbon polymer composite	1.8	4 to 200	10 to 30	50 to 400	2000
Aluminum	2.7	35	10	180	4.3
Steel	8.0	90	29	65	14

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Acknowledgments

The multidisciplinary team that conducted the research reported here was honored with Northrop Grumman Space Technology’s 2005 Innovation Award. The award-winning team members were Scott L. Kugler, Ray A. Manning, Jeffrey W. Nienberg, Hsiao-hu Peng, David A. Pohl, Gregg D. Potter, Michael B. Ryan, Fatollah Tehranian, and Garrett R. Wittkopp, in addition to the author.

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Author Profile

Edward M. Silverman is the advanced technology manager for advanced materials development at Northrop Grumman Space Technology. He is responsible for managing technology development programs and acquiring new businesses in spacecraft materials technology from commercial and government customers. As the program manager of two NASA contracts, he compiled two handbooks on design guidelines for composite spacecraft components and on space environment effects on spacecraft materials. He has led the development of new lightweight composite resin transfer molded joints, isogrid reflectors, and the APG thermally conductive material. His current interest includes the development of nanotechnology for aerospace applications. He has published more than 60 papers in scientific journals and conferences. He has received several awards for innovative research and development. He holds a Bachelor of Engineering in chemical engineering from City College of New York and a PhD in chemical engineering from Stanford University.

edward.silverman@ngc.com