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EMI Shields Made From Intercalated Graphite Composites

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EMI SHIELDS MADE FROM INTERCALATED GRAPHITE COMPOSITES

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ABSTRACT

Electromagnetic interference (EMI) shielding typically makes up about twenty percent of the mass of a spacecraft power system. Graphite fiber/polymer composites have significantly lower densities and higher strengths than aluminum, the present material of choice for EMI shields, but they lack the electrical conductivity that enables acceptable shielding effectiveness. Bromine intercalated pitch-based graphite/epoxy composites have conductivities fifty times higher than conventional structural graphite fibers. Calculations are presented which indicate that EMI shields made from such composites can have sufficient shielding at less than twenty percent of the mass of conventional aluminum shields. EMI shields provide many functions other than EMI shielding including physical protection, thermal management, and shielding from ionizing radiation. Intercalated graphite composites perform well in these areas also. Mechanically, they have much higher specific strength and modulus than aluminum. They also have shorter half thicknesses for x-rays and gamma radiation than aluminum. Thermally, they distribute infra-red radiation by absorbing and re-radiating it rather than concentrating it by reflection as aluminum does. The prospects for intercalated graphite fiber/polymer composites for EMI shielding are encouraging.

KEY WORDS: Electromagnetic interference shielding, graphite fiber composites, intercalated graphite

1. INTRODUCTION

With increased reliance on electronic controls in aerospace applications EMI shielding requirements are becoming ever more important. Present technology uses metallic shielding boxes to provide this function, but the densities of metals are high compared to those of plastics and composites. In commercial communications satellites, saving a few ounces in the structure could enable an additional channel to be installed, or enough fuel could be added to extend the lifetime by years. In aircraft and automobiles, weight savings translates directly into increased fuel efficiency and longer range. Weights could be dramatically reduce by replacing metallic components, which have densities ranging from 2.7 - 8.9 g/cm^3, with composites having densities of about 1.8 g/cm^3. Typically, 15 to 20 percent of the mass of the power and electronics systems of a satellite resides in the EMI shielding cover boxes. About 30 percent of the mass of the electronics systems is in the supporting structure. Thus, a large weight savings in these areas, by replacing metallic parts with composite parts, would result in a significant weight savings in the power system.

The limit to mass reduction in present shielding is not its shielding effectiveness, but its mechanical characteristics, such as strength and stiffness. Metal foils, for example, may have sufficient shielding capability, but they do not have the structural integrity to permit their use in building spacecraft components. Foil shielding boxes would collapse under handling loads and launch stresses. The intrinsic shielding need not be as high as aluminum, it need only be sufficient to meet the shielding requirements.

Carbon fiber composites are commonly used to reduce weight in structural components. For example, a shielding box made from a single ply of 0 - 90° carbon fiber/epoxy composite would have less than 12 percent of the mass of a standard 2 mm (80 mil) aluminum shielding box of equal strength. Unfortunately, conventional carbon fiber/epoxy composites are not sufficiently electrically conductive to provide adequate shielding. Foils, paints, and platings on such composites can be used, but reliability problems caused by poor scratch resistance, poor adhesion, and oxidation can result.

Another approach to making composites more highly electrically conducting is to use intercalated graphite fibers. Intercalation is the process of inserting guest atoms or molecules between the graphene layers. The guest species can contribute carriers (either electrons or electron holes) to the graphite lattice, and thus increase its conductivity significantly[1] without seriously degrading its mechanical properties[2]. Although most intercalation compounds are unstable in air at the temperature needed to cure epoxy resins, the residual intercalation compounds which use bromine as the guest molecule have been shown to be quite stable[3]. Laminar composites have been fabricated using bromine intercalated fibers which show enhanced electrical conductivity[4].

EMI shields serve other critical functions in addition to shielding the electronic components from EMI. The shield must also act as a mechanical guard so that the components are not damaged during handling, launch, and deployment of the spacecraft. The shield must not interfere with the flow of heat generated by the protected component to a radiative surface. Lastly, the EMI shield must also act as at least part of the radiation shield. The sun is a time varying source of high energy particles and radiation. During times of peak solar activity radiation fluxes as high as 10^{13} MeV/cm^2-day are present[5], and many electrical components are sensitive to those levels of radiation. The purpose of this study was to assess whether intercalated graphite composites would have a combination of electrical, mechanical, thermal, and shielding properties that would result in more weight efficient EMI shields.

2. METHODS AND MATERIALS

2.1 EMI Shielding Effectiveness Calculation Methods For the purposes of this discussion EMI will be defined as any electromagnetic radiation, periodic or random, that has a disturbing influence on devices exposed to it. Only radiation which is propagated through space will be considered. Disturbances which travel along the power or ground paths, is purposefully excluded since shielding from such disturbances involves the installation of filtering devices (such as isolation transformers) rather than passive materials.

The discussion that follows, and the shielding effectiveness calculations used, were adapted from a NASA special publication by Taylor[6] though there are several other sources available. An inherent assumption about these equations is that the conductivity of the shielding material is isotropic. It is recognized that this assumption is not valid for highly conducting fibers embedded in an insulating matrix, but it will be used to develop a first approximation of the EMI shielding effectiveness of these materials.

There are two distinct realms of EMI shielding; far-field shielding, where the source-to-shield distance is large compared to the wavelength of the radiation; and near-field shielding, where the distance is small compared to the wavelength. In the near-field case, the electromagnetic wave may be dominated by its electric component (in high-voltage, low current sources) or by its magnetic component (in low-voltage, high current sources). The shielding effectiveness for all three cases was considered in the study.

The total attenuation of EMI is the sum of three terms (in decibels), absorption, reflection, and multiple internal reflections within the shield. In figure 1 the contribution of each of the three components of the total far field shielding is shown for the shielding afforded by a 1 mm thick copper sheet. The shielding can be dominated either by the reflective term (at low frequency) or by the absorptive term (at high frequency). High frequency absorption is a much more efficient shielding mechanism, so the lower the frequency where the absorption term dominates, the larger the frequency range for effective shielding.

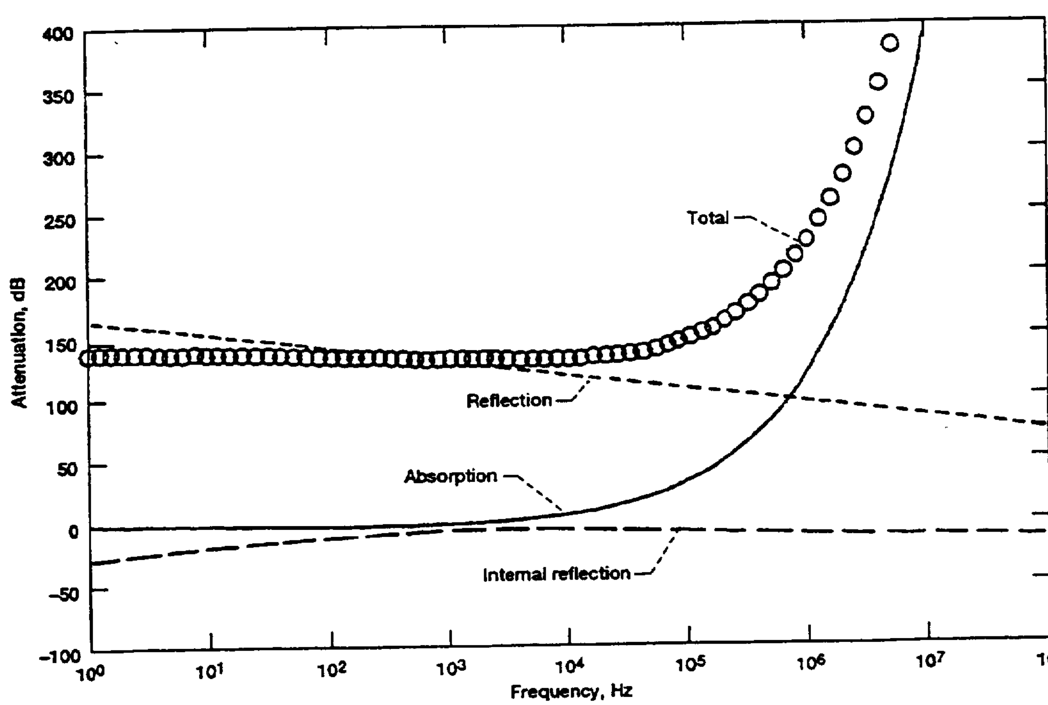

Figure 1. -- Contribution from absorption, reflection, and internal reflection to the total far-field shielding effictiveness of 1 mm of copper as a function of frequency.

2.2 Possible EMI Shielding Materials The search for improved EMI shields began with a review of the properties of candidate materials. Such a list is presented in Table 1. Materials are listed in order of decreasing density, so at first look, materials located towards the bottom of the list are the most desirable. Secondarily, the strength and modulus will be important since mechanical properties are often the limiting factor. Third, the resistivity is important to the shielding effectiveness, and must be below some limiting value which will differ with the application.

TABLE 1 -- PROPERTIES OF SHIELDING MATERIALS

Material	Density g/cm^3	Resistivity $\mu\Omega$-cm	Strength MPa	Modulus GPa
Copper	8.96	1.8	420	110
Iron	7.86	10	200	200
Al Alloy	2.80	10	520	71
Aluminum	2.70	2.8	210	60
Beryllium	1.85	4.0	620	290
P-100+Br/epoxy	1.78	90	840	430
P-100/epoxy	1.72	460	840	430
T-300/Epoxy	1.51	5000	3200	228

The first candidate considered was PAN-based carbon fibers in an epoxy matrix. It has the lowest density and the highest strength of the candidate materials. Unfortunately, it has been found that the resistivity of this material is too high to give adequate shielding for most applications. Beryllium has been used where weight was extremely critical, but this material is not only expensive and difficult to work with, but also highly toxic. This discussion will center on the materials located between beryllium and PAN-based fiber composites, pitch-based graphite fiber/epoxy composite, and bromine intercalated pitch-based graphite fiber/epoxy composite. Three grades of pitch-based fiber will be considered, Amoco P-55, P-75, and P-100, along with their respective residual bromine intercalation compounds. P-100 is the most highly graphitized fiber, and has a nominal tensile modulus of 100 msi. As the modulus designations decrease so does the graphitization, though even P-55 is significantly more graphitic than PAN fibers.

To assess the impact of substituting intercalated graphite fiber composites for aluminum shielding boxes, consider first a typical electronics package found aboard a communications satellite. A 5 kg electronics package is covered by a 2 mm (80 mil) thick aluminum cover which measures 30 cm x 30 cm x 8 cm. Assume first a simple substitution of the cover of bromine intercalated P-100 epoxy composite of equal thickness, and the weight of the cover is only 66 percent of the aluminum cover. This yields a system weight savings of 6.7 percent (see Table 2). But the composite cover is not only less dense it is also stronger. An equal strength cover would only need to be 0.35 mm (14 mil) thick and would weight less than 12 percent of the mass of the aluminum cover. This would lead to a system weight savings of nearly 18 percent.

TABLE 2 -- MASS SAVINGS FROM EMI COMPOSITE SUPPORT STRUCTURE

	Aluminum	P-100+Br/epoxy	P-100+Br/epoxy
Thickness, cm (mil)	0.20 (80)	0.20 (80)	0.035 (14)
Strength, MPa-cm^2/g	78	470	83
Density, g/cm^3	2.70	1.78	1.78
Shield Mass, g	1000	662	116
Total Mass, kg	6000	5662	5116
Mass Savings, percent	0	6.7	17.7

TABLE 3 -- SPACECRAFT WEIGHT BREAKDOWN OF INTERPLANETARY PIONEERS

System	Weight lb	Weight percent	w/GIC Covers lb	w/GIC Covers percent
Communications	27.6	22.0	22.4	17.7
Electrical system	15.8	12.6	12.8	10.2
Remaining Systems	62.3	49.5		
Payload	20.0	15.9	28.2	22.4

What effect would the saving of nearly 18 percent of the electrical system weight have on the total spacecraft? Table 3 shows the spacecraft weight breakdown of the interplanetary Pioneers, of the type that were flown to Venus, Jupiter, and Saturn[7]. It is assumed that twenty percent of the weight of the communications system and electrical system is made up of aluminum EMI shielding covers. If those covers were exchanged for intercalated graphite composite covers 3.7 kg (8.2 lbs) could have been saved. If this mass were to be added to the experiments payload, the payload mass could have been increased by more than 40 percent! Although there may be reasons (i.e. radiation shielding ability) why this full margin could not be realized, it is obvious that a simple swap-out of covers, leaving the rest of the aluminum base structure intact could lead to a substantial increase in payload mass.

Since the supporting structure represents an additional 30 percent of the power system mass, if it were also made from similar composite materials the weight savings would be even more dramatic. A 6.0 kg conventional power package would weigh a mere 3.6 kg, a 40 percent savings.

2.3 Thermal Conductance Determination The thermal conductance was determined by measuring the temperature of a shield placed in front of a thermal load. The thermal load was a resistance heater brazed onto a copper block which was then bolted to a copper box with a window into the box, and a hole through the box. The result was a heat source with a very uneven temperature distribution. Test samples were mounted in front of the heater assembly, touching the assembly, but not in intimate thermal contact. The vast majority of the heat transfer was judged to be radiative. The samples were allowed to come to thermal equilibrium (no changes in the temperature profiles) before the data were recorded.

The heat source was mounted in a vacuum bell jar which was evacuated to approximately 10^{-5} Pa (10^{-7} torr). This vacuum is similar to that experienced in low earth orbit, and the gas pressure is below that which would support significant convection. An Inframetrics Model 600 Infra-Red Scanner sensitive to 8 μm radiation was used to record the data through a zinc selenide window. Absolute temperature readings may be somewhat in error because of the effects of different emittances of the sample surfaces. Temperature data are best considered to be semi-quantitative, though the trends were clear.

2.4 Ionizing Radiation Shielding Half thickness measurements were made using a 40 μCi ^{210}Pb source and a NaI (Tl) detector interfaced to a Nuclear Data ND2400 multi-channel analyzer. Both the 13.0 keV x-ray and the 46.5 keV γ-ray were monitored three times each over 10 sec intervals. Stacks of one to nine 1 mm thick composites were placed between the source and the counter to directly measure the absorption. The thickness and density of each of the composite samples were determined using a micrometer and an analytical balance.

3. RESULTS AND DISCUSSION

3.1 **Calculated EMI Shielding Results** The total far-field shielding afforded by copper, aluminum, and composites made from pristine or intercalated graphite fibers are shown in figure 2. At low frequency there is little absorption, and the frequency dependence of the reflection and the internal reflection tend to cancel. The result is that there is a constant shielding effectiveness up to some characteristic value, after which rises steeply due to the absorptive component.

For spacecraft, far field shielding is important for frequencies above about 10^8 Hz. The absorption of the metals, P-100+Br, and P-75+Br composites cause the shielding to rise sharply below 10^8 Hz. P-100 and P-55+Br shielding rises near 10^8 Hz, but the shielding for P-75, P-55, and PAN composites does not rise until higher frequencies. It has been shown that PAN composite shielding is not effective, and one would expect that the shielding effectiveness of P-55 and P-75 would also be marginal. The resistivity required for adequate shielding, however, depends on the exact application.

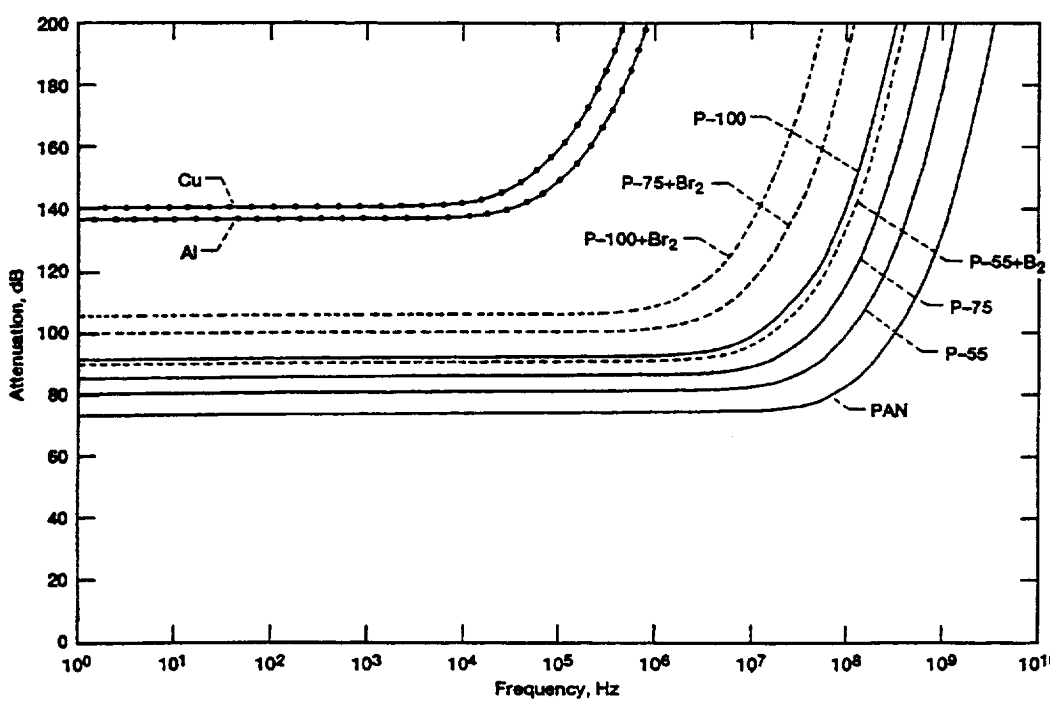

Figure 2. -- Far-field EMI shielding effectiveness.

The near-field high-voltage low-current shielding is shown in figure 3. At low frequencies the absorption is insignificant, the reflective attenuation decreases as the cube of the frequency, and the internal reflection term increases as the square of the frequency. The result is that the total shielding in this region decreases proportionately to the log of the frequency. At 1 Hz the shielding for all of the materials is about 300 dB, so at low frequency the shielding is effective. At high frequency the absorptive attenuation is high, so the only concern is the intermediate frequency region.

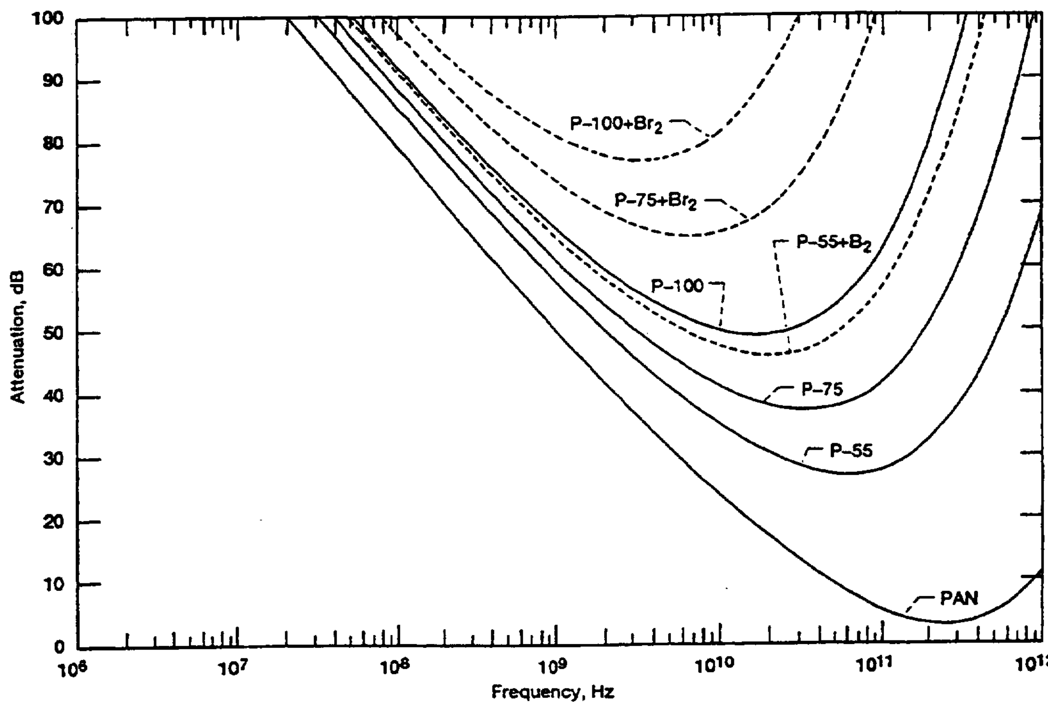

Figure 3. -- Near-field EMI shielding effectiveness: high-voltage - low-current

It is this region, which is highlighted in figure 3, that most dramatically shows the value of intercalation. Intercalation shifts the trough to lower frequency and raises the minimum value. P-100 has its low value of about 48 dB at about 2 x 10^{10} Hz. Intercalation raises the minimum shielding to 77 dB and shifts the minimum to 3 x 10^9 Hz. The geometry of spacecraft is such that near-field shielding is only required for frequencies less than about 2 x 10^{11} Hz. Intercalated graphite composites enable a range of frequency (1-200 GHz) which could not be shielded by conventional PAN composites.

The near-field high-current low-voltage shielding is shown in figure 4. For power components the frequency range of interest is usually less that 10^5 Hz, so this is the frequency range of interest for this type of shielding. In this range absorption is minimal. The reflected attenuation is also low, less than 30 dB for any of the materials considered. To compound the problem, internal reflection losses vary widely over this range, depending on the exact geometry of the source and shield. Thus, shielding is minimal under these conditions. Since the magnetic component is dominant under these conditions, only high permeability (ferromagnetic) materials make effective shields.

3.2 Experimental EMI Shielding Results Six formulations of composites were used for this study. Four-ply laminates 90.7 - 1.0 mm thick) of 0 - 90 weave cloth made up of Amoco Thornel P-55, P-75, P-100, and their respective intercalation compounds were fabricated. The properties of these laminate are summarized in Table 4, and the details of their fabrication and characterization are described elsewhere.[4]

Samples of five of the composites (all except P-55+Br) were evaluated at Ferro Corporate Research Facilities, Independence, OH. Far field tests were conducted in the frequency range of 30 - 1000 MHz using standard techniques which are described elsewhere.[8] In all five cases the shielding exceeded the limit of the equipment, which was 55 dB. In addition, the far-field attenuation of a P-100+Br composite sample was evaluated in the McDonnell-

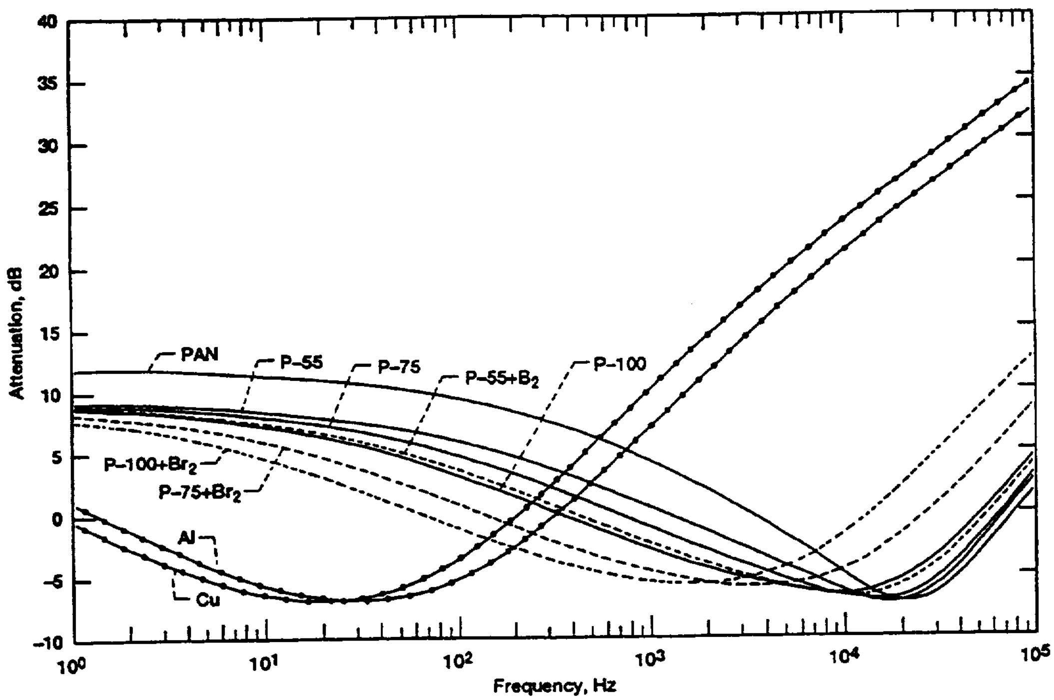

Figure 4. -- Near-field EMI shielding effectiveness: high-current - low-voltage

Douglas, St. Louis, MO, mixed mode chamber in the frequency range of 1 - 12 GHz. The shielding attenuation also exceeded the range of this instrument, 70 dB. The measurements are consistent with the calculation made above from the far field measurements, figure 5. Preliminary capacitively coupled near-field shielding tests were also carried out at Ferro Corporation in the 30 - 1000 MHz range[9]. These data indicated a complex structure in their frequency dependence which casts doubt on their accuracy, but they do show that intercalation improves the shielding characteristics of the composites. The actual shielding effectiveness was somewhat lower than predicted by the theory, and given the anisotropic nature of the material, perhaps that is reasonable. But more data are required before firm conclusions can be made.

TABLE 4 -- PHYSICAL PROPERTIES OF LAMINAR COMPOSITES

	P-55	P-55+Br	P-75	P-75+Br	P-100	P-100+Br
Fiber volume percent	56.2	54.0	58.7	58.8	64.0	48.0
Resin weight percent	28.0	31.0	27.6	30.6	24.3	38.7
Void volume percent	6.5	3.8	5.0	0.0	2.9	0.0
Fiber density, g/cm^3	2.182	2.214	2.059	2.141	2.039	2.293
Resin density, g/cm^3	1.265	1.265	1.265	1.265	1.265	1.265

3.3 Thermal Conductance Results There were five regions whose temperatures were monitored for each sample. Region 1 is the heater block, rectangular in profile, to which the heater itself was brazed. Region 2 is the surface of the face of the copper box. Region 3 is a cavity made up of a circular hole through the box face, a window through which the temperature of the interior of the box can be measured. Region 4 was a hole through the box which was made up of two circular holes aligned through the front and back faces of the box. A target placed 2 cm in front of the box was labeled Region 5.

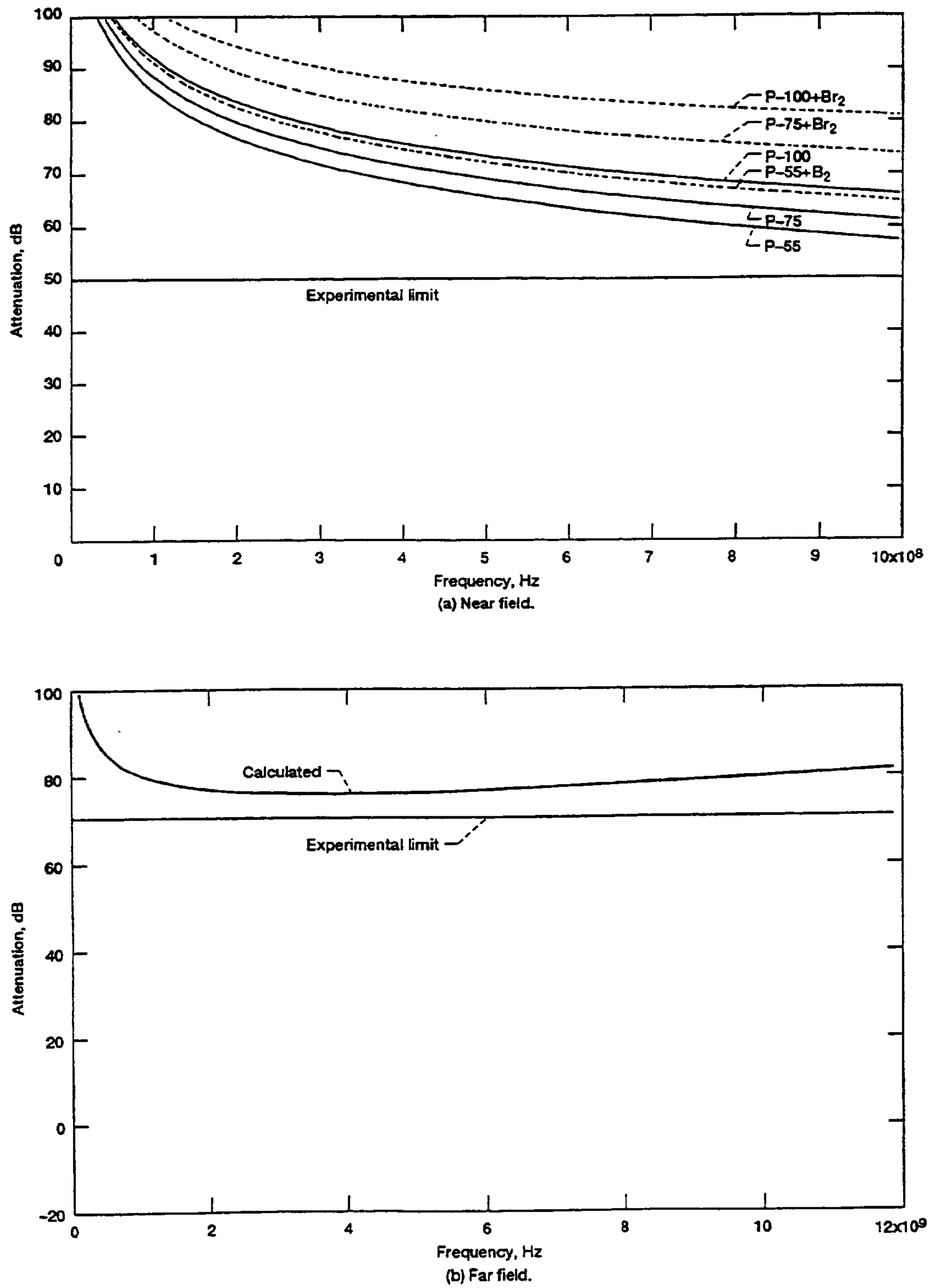

Figure 5. -- Comparison of calculated shielding effictiveness with experimental limits for (a) composites samples in the far field up to 100 MHz and (b) P-100 + Br composite samples up to 12 GHz.

Table 5 lists the temperatures measured at each of the five regions for the heater itself, for the heater with an aluminum shield, and for the heater with six different composite shields. Note the wide variation in the temperatures of the unshielded heater. The heater block itself and the cavity temperature were nearly the same, about 95 °C. The face of the block itself was 45 °C cooler, the hole through the heater cooler still, and the probe in front of the heater was warmed to about 36 °C.

TABLE 5 – TEMPERATURES RECORDED THROUGH EMI SHIELDING MATERIALS

Material	Heater	Block	Cavity	Hole	Target
no shield	95. °C	50. °C	93. °C	43. °C	36. °C
Al	21	21	21	21	24
P-55	46	47	46	47	35
P-75	46	46	46	46	36
P-100	46	47	46	47	33
P-55 + Br	38	39	38	37	29
P-75 + Br	47	48	48	48	37
P-100 + Br	47	47	47	47	38

The aluminum shield was measured to be much cooler, a uniform 21 °C, when placed in front of the heater. Aluminum is very reflective in this region of the infra-red, and as a result most of the heat was simply reflected back off of the sample. The high thermal conductivity of aluminum (220 W/m-K) evened out temperature variations as high as 50 °C impinging on the aluminum to less than 1 °C emitted. The probe outside of the shield (region 5) showed only a slight increase in temperature, 24 °C. It is likely that the probe and the shield were at nearly the same temperature, and that the 3 °C differences are due to emissivity differences between the two surfaces.

The graphite fiber/epoxy composite shields all acted similarly. Like the aluminum shield they evened out the temperature variations to within one degree celsius. However, the equilibrium temperature was well above room temperature. The temperature of the surface corresponds approximately to the weighted average temperature emitted by the heater. Whereas the aluminum shield reflected most of the infra-red radiation, the graphite epoxy composites absorbed the radiation, conductively evened out the thermal variations, and then emitted the radiation. This is also seen in the probe which was placed outside the shield which had a temperature increase similar to that when no shield was present.

There seemed to be no measurable differences in the thermal performance of composites made from different grades of graphite fiber. The heat conduction mechanism proposed here involves three steps, absorption of the IR, conduction of the heat to average out temperature variations, and emission of IR. Although the thermal conductivity of the best conducting (P-100) fibers is 5 times better than the thermal conductivity of the worst (P-55)[10], all are sufficiently conductive to average out temperature gradients in this experiment. The optical properties of the three types of fibers, at least in this spectral region, are indistinguishable. This study is further proof of their similarity.

There also seems to be no measurable effect due to the bromine intercalation. Bromine intercalation of P-100 fibers has been shown to have little effect on the thermal conductivity[11], and the optical properties in this spectral region are not affected. Thus, one would not expect to see large changes due to bromine intercalation.

The bromine intercalated P-55 fiber composites seem to be anomalous. Although the temperature gradient is within 1 °C, the temperature of both the shield and the probe outside the shield are anomalously low. Although a systematic error, such as a mis-setting of the emissivity, is suspected, facility renovation prevented a repeat of this experiment, and a more definitive answer to this issue.

In a spacecraft electronics package the aluminum and composite shields would distribute the heat generated very differently. An aluminum shield would tend to protect components exterior to the box from high temperatures, but the component itself would run hotter, due to the reflected infra-red radiation bouncing around in the box. Thus, the impact of aluminum boxes is to create islands of high temperature within the structure. Composite shields would tend to homogenize the temperature within the spacecraft. In this test the probe placed outside the box experienced temperatures equivalent to those when no shield was present. Whether a relatively cooler spacecraft with a few hot spots, or a relatively warmer spacecraft of uniform temperature is more desirable is dependent on the specifics of the spacecraft and its mission.

3.4 Ionizing Radiation Shielding Results The half-thickness of pristine fiber/epoxy composites for absorption of 46.5 KeV γ-rays and for 13.0 KeV x-rays are shown in Table 6. There were no substantial differences among the various grades of fibers. This is not surprising since all of them are essentially pure carbon. The half thicknesses were substantially greater than the half-thickness measured for aluminum for the same radiations, which was measured to be 7.5 and 4.2 mm for the γ-ray and x-ray respectively. This is to be expected since the atomic number for carbon is less than that of aluminum. The composite half-thickness will be dependant on the fiber fraction in the composite, but not strongly dependent since the resin itself is made up of carbon, hydrogen, and oxygen, and so has an average atomic number similar to the carbon fiber.

Intercalation with a high atomic number intercalate such as bromine might be expected to improve the radiation absorption ability, that is, to shorten the half-thickness. Since the fibers contain about 18 percent bromine by mass[12], that corresponds to about 3.3 percent by number. There is also a volume expansion of about 10 percent[13]. This leads to an increase of average atomic number of less than 10 percent, and leaves it well below the value of 13 for aluminum. Thus, it was somewhat surprising that the half-thickness of the bromine intercalated fiber composites were measured to be comparable to aluminum (Table 6). Apparently a few heavy atoms within a light matrix is a more efficient shield that a uniform, slightly heavier matrix. In addition, it is expected that there will be a stronger dependence of the half thickness on fiber volume, since only the fibers contain the heavy bromine atoms. This can be seen in the P-75+Br composite, which has both the highest fiber volume and the shortest half-thickness.

TABLE 6 – IONIZING RADIATION SHIELDING OF EMI SHIELDING MATERIALS

Material	46.5 KeV γ-Ray Half-Thickness, mm	13.0 KeV X-Ray Half-Thickness, mm
Al	7.5	4.2
P-55	32	17
P-75	33	17
P-100	30	17
P-55 + Br	6.9	5.6
P-75 + Br	6.6	5.6
P-100 + Br	6.5	4.1

The implication is that intercalation not only makes up for the deficit conventional composites have in shielding ionizing radiation from components, but actually has a shielding advantage over aluminum. This is important because the higher strength of composite shields allows them to be made thinner, but only if they can still perform ancillary functions, such as radiation shielding.

4. CONCLUSIONS

Calculations indicate that a substantial weight savings (over 85 percent) can be realized by replacing conventional EMI shielding covers with those fabricated from intercalated graphite composites, providing that mechanical properties are the limiting factor. This could result in decreasing the weight of the total spacecraft power system by nearly 18 percent. Depending on the individual spacecraft, the percent payload increase my be very high, over 40 percent in the case of the interplanetary Pioneers.

If the assumption can be made that composites shield in an analogous way to isotropic metals, then shielding attenuation can be calculated. These calculations indicate that intercalation can considerably enhance shielding effectiveness, and in fact may be an enabling technology in the frequency range between 10^6 and 10^9 Hz.

Preliminary experiments do not contradict the results of the calculations. Far field tests show attenuation of at least 55 dB in the 30 - 1000 MHz range, even for the case of P-55 composites. Bromine intercalated P-100 composites show at least 70 dB shielding in the 1 - 12 GHz range.

The thermal effect of an aluminum shield was to reflect the infra-red radiation coming from a heat source and to emit very little. The thermal effect of a composite shield was to absorb the heat from the IR radiation, average it over the surface of the shield, and re-emit it. The consequences for a spacecraft is that aluminum shields would lead to lower temperatures within most of the spacecraft at the cost of a few hot spots, whereas composite shields would lead to a warmer, but more uniform spacecraft temperature distribution.

Graphite/epoxy composites were found to have half-thicknesses for x-rays and γ-rays about four times that of aluminum, which could seriously limit their use in high radiation environments. However, bromine intercalation was found to reduce the half-thickness for x-rays and γ-rays to values comparable to those for aluminum. This is important if the mechanical characteristics of the composites are to be taken advantage of, enabling the use of thinner EMI shields that are presently used.

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Jennifer Terry is a senior Biology-Chemistry major at Manchester College. She was an intern at the NASA Lewis Research Center in 1993, and has worked under contract and grant for NASA since then. In addition to this work she has co-authored a paper on the kinetics of bromine intercalation of graphite fibers, and has two additional manuscripts in preparation in the area of graphite intercalation compounds. She will attend the Indiana University Medical School beginning in the fall of 1994.

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13. ABSTRACT ***(Maximum 200 words)***

Electromagnetic interference (EMI) shielding typically makes up about twenty percent of the mass of a spacecraft power system. Graphite fiber/polymer composites have significantly lower densities and higher strengths than aluminum, the present material of choice for EMI shields, but they lack the electrical conductivity that enables acceptable shielding effectiveness. Bromine intercalated pitch-based graphite/epoxy composites have conductivities fifty times higher than conventional structural graphite fibers. Calculations are presented which indicate that EMI shields made from such composites can have sufficient shielding at less than twenty percent of the mass of conventional aluminum shields. EMI shields provide many functions other than EMI shielding including physical protection, thermal management, and shielding from ionizing radiation. Intercalated graphite composites perform well in these areas also. Mechanically, they have much higher specific strength and modulus than aluminum. They also have shorter half thicknesses for x-rays and gamma radiation than aluminum. Thermally, they distribute infra-red radiation by absorbing and re-radiating it rather than concentrating it by reflection as aluminum does. The prospects for intercalated graphite fiber/polymer composites for EMI shielding are encouraging.

14. SUBJECT TERMS

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