THE DEVELOPMENT OF LIGHTWEIGHT ELECTRONICS ENCLOSURES FOR SPACE APPLICATIONS

Matthew T. Fenske
Janet L. Barth, Jeffrey R. Didion, Peter Mulé
NASA Goddard Space Flight Center
Greenbelt, MD 20771

ABSTRACT

This paper outlines the end to end effort to produce lightweight electronics enclosures for NASA GSFC electronics applications with the end goal of presenting an array of lightweight box options for a flight opportunity. Topics including the development of requirements, design of three different boxes, utilization of advanced materials and processes, and analysis and test will be discussed. Three different boxes were developed independently and in parallel. A lightweight machined Aluminum box, a cast Aluminum box and a composite box were designed, fabricated, and tested both mechanically and thermally. There were many challenges encountered in meeting the requirements with a non-metallic enclosure and the development of the composite box employed several innovative techniques.

KEY WORDS: Spacecraft Electronics, Applications-Space, Thermally Conductive Materials

1. INTRODUCTION

The use of electronics enclosures for housing specialty electronic boards for space flight has undergone several recent advancements. The NASA Goddard Space Flight Center set forth an effort to improve these structures for increased efficiency through the use of new technologies in materials, fabrication and design optimization. This paper outlines the effort to produce lightweight electronics enclosures for GSFC electronics applications with the end goal of presenting an array of lightweight box options for a flight opportunity. Three different boxes were developed independently and in parallel: a lightweight machined Aluminum box, a cast Aluminum box and a composite box.

2. DESIGN

2.1 Requirements

The housings themselves need to satisfy three simple functional requirements: must provide sufficient structure to mount the card assemblies and survive launch loads; must provide sufficient thermal path to dissipate component generated heat; must provide method for the precise connection of card assemblies to a motherboard or backplane as well as input/output connections in and out of the box. To quantify these functional requirements, a multi-disciplinary team produced a set of specific requirements that contained the necessary electrical, mechanical and thermal details from which to design, and an interface drawing that provided information regarding the size, interface considerations and electronic connection. This package was a significant achievement in the overall optimization process because it allowed the three different box developments to start from the same set of requirements. For the sake of brevity, the requirements list is shown in outline form in Figure 1. Each of the requirements sets were developed to meet the nominal expected values for upcoming missions. It is important to note that an interface drawing was also developed with this set of requirements that contains detailed tolerance, envelope, and interface information. Due to the fine details on such a drawing, it is not presented here. However, it is important to note that while the information in the drawing did have a large impact on the details of the boxes, it is not requisite to understand the nature of each of the enclosures.

Electrical	
- Grounding	2.5 mΩ
- EMI	One 90° Turn (no line of sight)
- Radiation	None
Mechanical	
- Loads	
Quasi-Static Qualification Loads	15 G per axis individually
Random Vibration	14.1 Grms
- Card Size (Heat Sink)	24 X 22 cm (9.5 X 8.7 in)
- Card Spacing	3.18 cm (1.25 in) center to center
- Max Deflection of Card (at midpoint)	1.27 mm (0.050 in)
- Max Weight of Single Card	1.5 kg (including Heat Sink)
- Nominal Weight of Single Card	1.0 kg
- Max Weight of Single Component	670 g
- Frequency	Decoupled from Cards (~200 Hz) Decoupled from ELV (>50 Hz)
Thermal	
- Max Heat Load per Card	20 W
- Nominal Heat Load per Card	5 W
- Mounting Sink Temperature	-10 to +50 °C

Qualitative or Functional Requirements

- Scalable Range of Cards from 6 to 14
- Single Card Accessibility
- Front and Back Covers Removable
- Must meet thermal requirement for two individual modes of heat transfer:
    1: Conduction through the base
    2: Radiation from the top
- No Generation of Particulate
- Must Provide a Faraday Cage for EMI Protection

Figure 1: Outline of mechanical, electrical and thermal requirements for the lightweight electronics enclosure.

With the requirements and interface drawing in hand, each of the box types was designed through its own material specific design philosophy. The final details of the design and manufacture were then rested on the companies who produced the hardware itself. As a result, each of the boxes looks very different, however, they all satisfy the initial set of requirements.

2.2 Machined Aluminum Enclosure

The most traditional of the three boxes is the lightweight machined Aluminum box. It is very similar to the box it replaced in the style of fabrication and construction. It is a basic six sided enclosure with each side individually machined and assembled with fasteners as shown in Figure 2.

The box was manufactured and assembled by Litton Amecom SSO in College Park, MD. The components were machined from Aluminum 6061-T6 and fastened together with screws and shear pins. Simple measures such as reducing the wall thicknesses to the minimum that could be feasibly machined (1.27 mm or 0.050 inch) and reducing the fastener count were taken. In addition, mechanical and thermal analyses were performed to give bounds to material thicknesses and stiffnesses as well as the placement of structure and fasteners. It should be noted here that the final box accommodates only 14 cards and an additional manufacturing effort would be needed to produce another box to accommodate a different card count. Due to the use of traditional Aluminum construction, many of the requirements are satisfied by default such as the Faraday cage and grounding. The EMI requirement was met through the use of small overhangs on the edges of each component that met together at assembly creating a step thereby eliminating the line of sight holes. A detail of the corner of the box with the cover removed is shown in Figure 3. The lightweight machined Aluminum box is an excellent example of how weight can be removed from a traditional structure through the examination of requirements and thoughtful design and analysis.

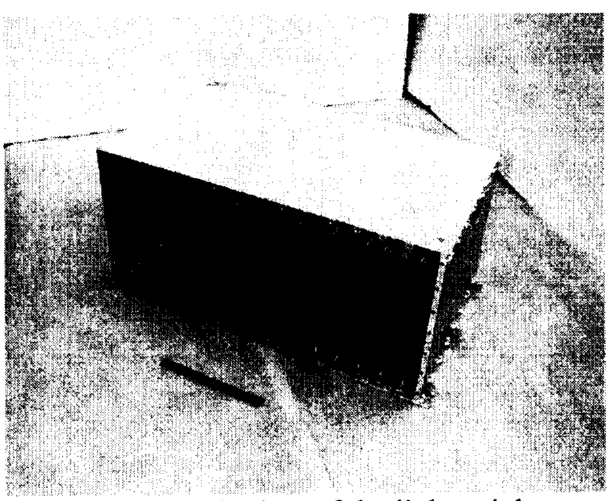

Figure 2: Overall view of the lightweight machined Aluminum enclosure

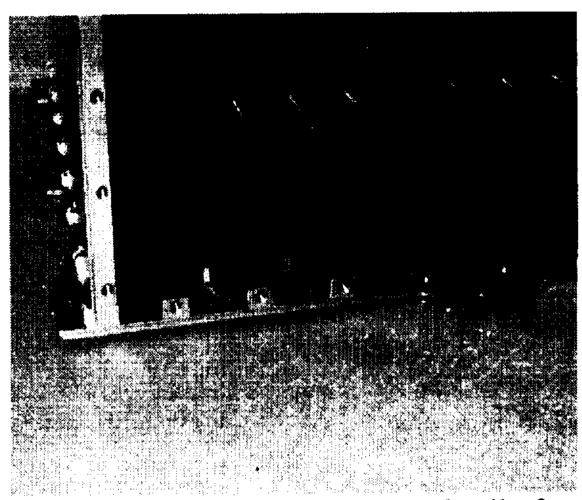

Figure 3: Close-up of the corner detail of lightweight machined Aluminum enclosure

2.3 Cast Aluminum Enclosure

The second type of construction is the cast Aluminum Enclosure. While still constructed of Aluminum, this box is an achievement of specialized casting. The box is a one-piece, four-sided unit with separate front and back removable covers. A picture showing the whole box with the front cover removed is shown in Figure 4.

The box was designed and fabricated by NuCast Inc. in Londonderry, NH through their proprietary investment casting or "lost wax" process. The detailed shape of the box was made into a wax mold through an injection molding process. It is important to note here that the mold used to create the wax forms is adjustable so that boxes can be created to accommodate a range of 6 to 14 cards with a minimum of effort. The wax mold is then transformed into a ceramic mold in which the part is cast. Several heat treating and post-cast finishing operations are performed to complete the part. Among these steps was a machining stage where the detailed tolerances were met through precise machining of the critical areas.

There are several features of this box that are directly related to the design being specifically tailored for the casting process. The corrugated appearance of the sides allows for improved thermal transfer from the heat sinks to the structure as well as higher mechanical stiffness. However, the key area to the success of this process in the production of the enclosure was the thin walls. A very thin wall section is difficult to cast, however, a 1.5 mm (0.060 in) wall thickness was attained with very good accuracy. Also the tolerances were met through the post machining of the critical areas. Some of the other requirements were met by virtue of the Aluminum enclosure and similar techniques as was used in the machined box such as the white paint on the top and the use of edges for EMI protection. A close-up of the corner detail can be seen in Figure 5.

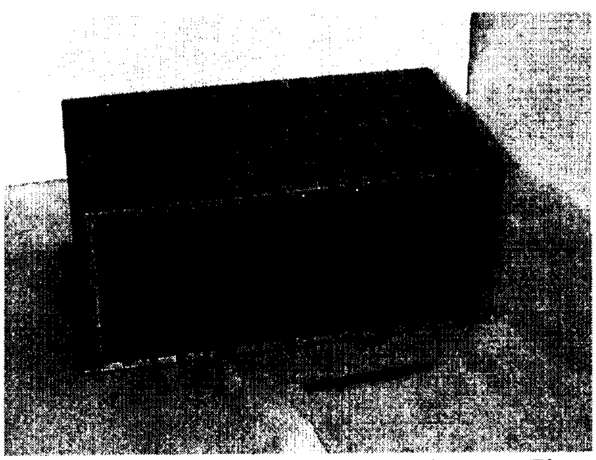

Figure 4: Overall view of the lightweight cast Aluminum enclosure

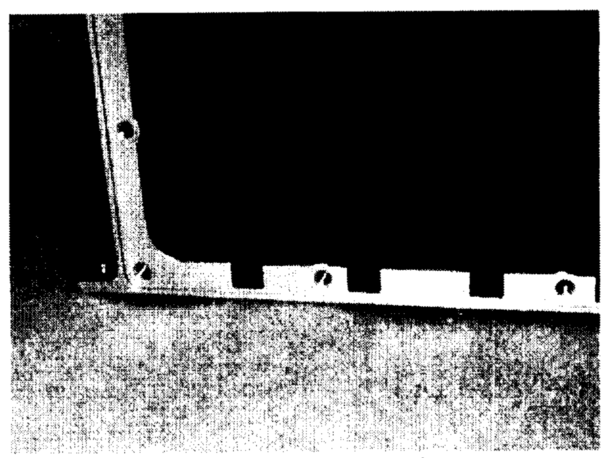

Figure 5: Close-up of the corner detail of the cast Aluminum enclosure

2.4 Composite Enclosure

The production of a composite electronics enclosure for space applications has been studied for many years, but progress has been limited. The primary advantages of composite materials are the high specific stiffness and high specific thermal conductivities of certain material systems. These advantages can be utilized in an electronics box to produce a very light chassis with the capability of handling a high thermal load. On the other hand, some of the properties of composite materials proved challenging to overcome for some of the requirements. The composite box is the most unique of the three due to its construction and materials as shown in Figure 6.

The composite enclosure was designed and fabricated by Composite Optics Inc. in San Diego, CA through their proprietary SNAPSAT™ technology. This technique allows for the construction of the box solely from flat laminates which are then joined in an assembly of mortise and tenon joints to produce a very stiff structure. Different configurations of flat laminates could be assembled to produce boxes that can accommodate from 6 to 14 cards, however, the 14 card version was produced for this study. The box is a double wall system designed to minimize cost and weight through the use of expensive high conductivity materials in certain areas and less expensive structural materials for the bulk of the chassis. The inner and outer walls are thin stiff laminates (M40J/CE) which surround heat spreading ribs (K1100/CE) that travel the entire distance around the box and frame out the structure. The cards interface with an Aluminum rail which is bonded to these ribs at the top and bottom. These ribs then transfer the heat around the box to the top or bottom. The top facesheet is also high conductivity material to maximize the radiative heat transfer mode. The box attaches to the spacecraft structure via Aluminum fittings that are bonded in between the ribs along the two sides. A close up of the corner detail is shown in Figure 7. The basic assembly is a very stiff structure and easily satisfies the structural requirements and the placement of the high conductivity material in the heat spreading ribs provides the thermal system.

Accommodating the electrical requirements, however, required some innovative techniques. The Faraday Cage was produced in the assembly by the configuration of the laminates that form the innermost wall of the structure. These laminates had a thin Aluminum foil cocured to one side and the joints were filleted with a conductive paste adhesive. While the foil and conductive adhesive system was adequate for the Faraday Cage, it was not sufficient for the grounding requirement. To meet the very small resistance allowable, it was necessary to electrically couple the Aluminum rails to the structures by adding thin Copper strips around the box in between the walls. The Aluminum rails and attachment fittings were Nickel plated and the strips were soldered directly to them creating a direct conductivity between the electronics and the spacecraft structure. Two separate strips were used for redundancy at only a slight weight penalty.

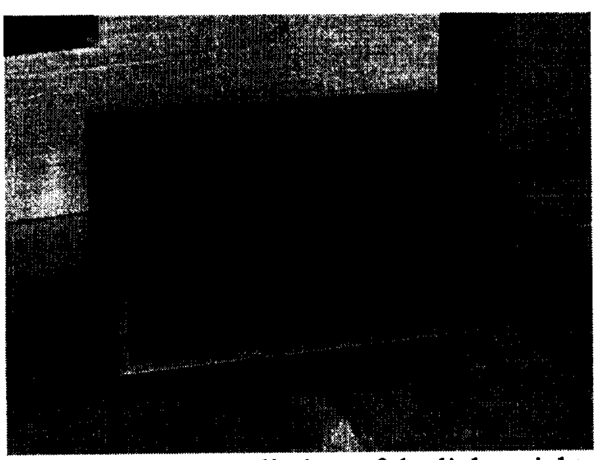

Figure 6: Overall view of the lightweight composite enclosure

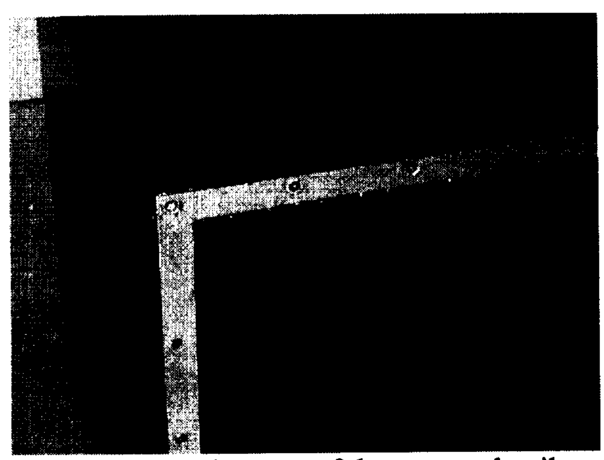

Figure 7: Close-up of the corner detail of the composite enclosure

2.5 Mass and Cost Considerations

The final considerations in the overall box designs are the weight and cost. Figure 8 outlines the weight comparisons with each of the boxes compared to the original machined Aluminum box. It is important to note that this original box was not designed to be lightweight, but rather as a robust all purpose enclosure. It is only through the efforts described in this paper that the new requirements and conditions of the box have been developed to allow for a lighter structure.

Box Type	Weight Kg (lbs)	Percent Savings over Original Machined Aluminum
Original Machined Aluminum	8.4 (18.5)	----------
Lightweight Machined Aluminum	4.4 (9.7)	48%
Cast Aluminum	4.5 (9.9)	46%
Composite	2.6 (5.8)	69%

Figure 8: Weight comparison of Lightweight Electronics Enclosures

Figure 9 outlines the end use cost comparison between the boxes for a nominal figure of $10K per pound to orbit. The point of this figure is to show the cost effectiveness that comes with saving weight. Significant cost considerations in each of the box developments are not shown here, however, it can easily be seen that the final end use cost difference is significant. This cost difference shows the importance of the application of resources up front to achieve a lightweight and cost saving product down the road. Often times, this savings is larger than the non-recurring cost of developing the product.

Box Type	Weight Kg (lbs)	Launch Costs at $10K/lb
Original Machined Aluminum	8.4 (18.5)	$185 K
Lightweight Machined Aluminum	4.4 (9.7)	$97 K
Cast Aluminum	4.5 (9.9)	$99 K
Composite	2.6 (5.8)	$58 K

Figure 9: End use cost comparison of each of the box types.

3. STRUCTURAL ANALYSIS AND TESTING

3.1 Description of Analyses

The thrust of the analyses conducted for this effort fell into two different areas: box modeling and card modeling. In previous box designs, the stiffening effect of the heat sink was not included in the analysis for conservatism. It was decided early on that since the deflection of the heat sinks was the critical parameter and that they were rigid structures themselves, they would be considered as part of the box structure. This did not represent a departure from conservative design, but rather the realization of how the structures behave that permitted a more accurate model of the problem.

The card models used in the overall box analysis were the result of a number of independent studies on the modeling of electronic components, circuit boards, connectors, and card guides [1]. In addition, several tests were conducted on boards of different material and boundary condition in an effort to hone the card model. The use of unique elements such as torsional springs in the card guides were developed and compared with test results and were found to give very good agreement. Accurate and realistic card modes proved to be very important in the overall box analysis.

A detailed finite element analysis was performed on each of the box types. Card models were place inside the box and results were used to correlate to experimental values. For example, the final machined Aluminum FEM consisted of approximately 6500 plate, beam, and spring elements. A detailed stress analysis resulted in positive margins throughout the housing and identified marginal areas such as the mounting flanges, where changes could be made to improve future designs. Frequency response analysis gave excellent comparison with test results for the box and the cards within.

3.2 Test Configuration, Levels and Results

Each of the boxes was subjected to the same compliment of mechanical testing as outlined in Figure 10. A typical test setup is shown in Figure 11 with the Lightweight Machined Aluminum Box on the shaker table. Typical electronic cards were simulated with mockups representing the range of potential configurations from the heat sink only to distributed and point masses. Figures 12 and 13 show a distributed mass and a point mass mockup. In all cases the card guides and connectors were kept the same as are used in flight type boards and the masses reflect the values given in the requirements. The total mass of the 14 card mockups was 15 Kg (33 lbs).

Random Vibration Test Levels (Qualification Duration = 120 seconds)

Axis	Frequency (Hz)	Qualification Levels
X, Y, and Z	20	0.026 G^2/Hz
	20-50	+6 dB/octave
	50-800	0.16 G^2/Hz
	800-2000	-6 dB/octave
	2000	0.026 G^2/Hz
	Total	14.1 G_{rms}

Sine Burst Loads Test Levels (Minimum of 5 Cycles at Full Level)

Axis	Frequency (Hz)	Qualification Level
X, Y, and Z	20	15 G

Sine Sweep Levels

Axis	Levels	Frequency (Hz)	Sweep Rate
X, Y, and Z	0.25 G	20-2000	4 octave/minute

Figure 10: Lightweight Electronics Enclosure Test Levels

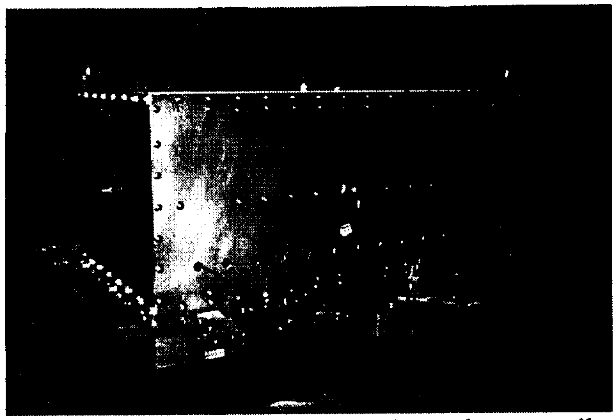

Figure 11: Lightweight Machined Aluminum box on vibration table

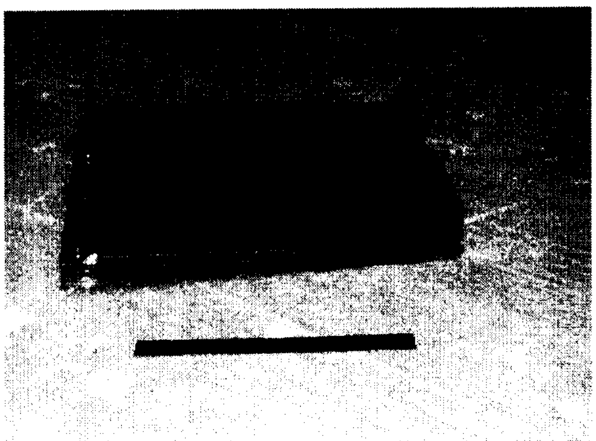

Figure 12: Distributed Mass Mockup

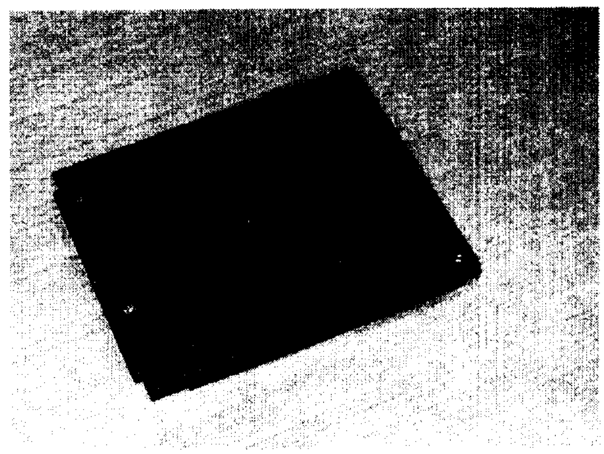

Figure 13: Point Mass Mockup

The results of the mechanical testing show that each of the boxes survived the test sequence with no detectable damage. Low level sine sweeps were performed before and after testing in each axis as a tool to detect structural changes through variations in sweep signature. As an additional method of damage detection on the composite box, thermal test were run before and after mechanical testing to identify any conductivity or other thermal effects. In addition, the models predict positive margins everywhere.

The three lightweight designs performed almost identically and show good correlation to analytical models. In the axis out of plane of the cards the housings all had primary resonance frequencies of approximately 800 Hz. This response is well enough above typical card frequencies of 200 Hz to prevent coupling. Card performance, based on frequency response, was also identical proving the housing designs all provide equivalent support to the cards.

4. THERMAL ANALYSIS AND TESTING

In addition to the structural testing, each of the boxes was modeled and tested from a thermal standpoint. Models of each of the boxes were constructed and solved through traditional finite difference solving techniques to develop predicted temperatures and gradients. These analytical results were compared to the test results to evaluate the box's thermal performance.

Each box was tested in a conduction mode and a radiation mode in a controlled thermal chamber. In the conduction mode, the box was insulated around its outside and bolted to a platen with a .38 mm (0.015 in) thick layer of carbon to facilitate heat transfer with 14 10-32 screws at 25 in-lbs. torque. In the radiation mode, each box was set on 1 inch high G-10 stands and radiated to the heat sink held at the appropriate temperature. The box radiator was painted with Chem glaze A276 white paint. Card mockups were installed in the box with various heaters attached to represent circuit components in both a concentrated and distributed configuration as seen in Figures 14 and 15.

For each of the test modes, the box heat dissipation load varied from a relatively common 20 W to an unusually high power level of 72 W. Card power levels varied from 4 W to 20W and temperatures at various places on the cards and box were monitored with thermocouples. A test configuration for the composite box in the conduction configuration is shown in Figure 16. For the conduction case, the heat was transferred to a sink at –10 °C and another case where the sink was 30 °C. For the radiation case the sinks were –170 °C and –10 °C. In each configuration the cases were run to steady state.

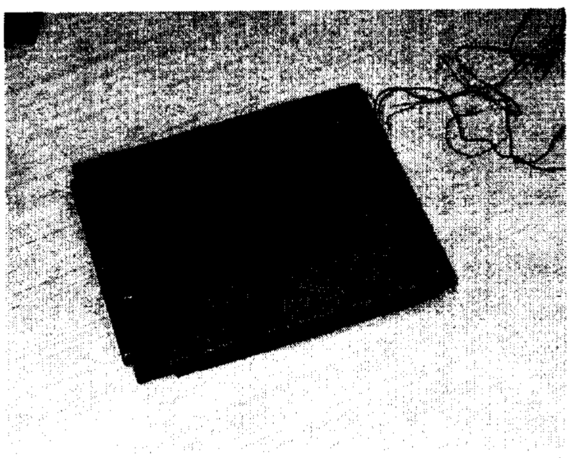

Figure 14: Concentrated Power card mockup

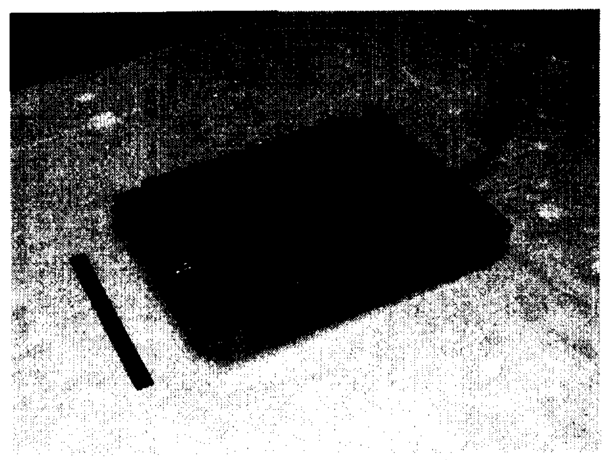

Figure 15: Distributed Power card mockup

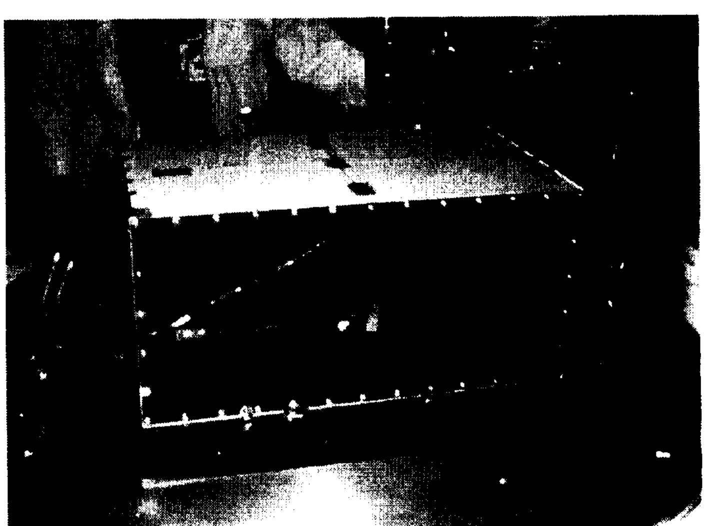

Figure 16: Composite Box in thermal conduction configuration (without insulation)

In general, the candidate enclosures performed without major surprises. Due to its construction, the composite box displayed the highest temperature gradients both within the box surfaces and in transferring heat from the box to the heat sink. The aluminum and cast box performed similar to each other and the system resistances were determined for each box. The boxes' instrumentation permitted determination of the resistance from the card rails to the heat sink; thus, the thermal resistance due to box construction was calculated. All the results are summarized in Figure 17. Clearly, for boxes with high power dissipations the selection of composite boxes may present a significant thermal design consideration. Further studies may be performed to determine the maximum power each box can accommodate in each configuration given an allowable component temperature or predicted operating temperature range.

Box Type	Overall System Resistance (°C/W)		Individual Box Resistance (°C/W)	
	Conduction	Radiation	Conduction	Radiation
Aluminum	2.294	1.247	1.106	.125
Composite	3.888	2.478	2.254	.810

Figure 17: Thermal Test Results

5. RADIATION CONSIDERATIONS

The development of lightweight electronics enclosures is occurring simultaneously with increased reliance on commercial-off-the-shelf (COTS) components and emerging technologies to meet mission objectives. The implication is that we are using significantly more radiation sensitive components with less shielding against the hazards of the natural radiation environment. Structural shielding is a critical parameter for defining the radiation hazard in space. Depending on the radiation effect, the hazard is typically defined as the number of particles emerging behind a specified thickness of aluminum or as the dose received by a component behind an aluminum shield. The dependence of the level of radiation effects on shielding is illustrated in Figure 18.

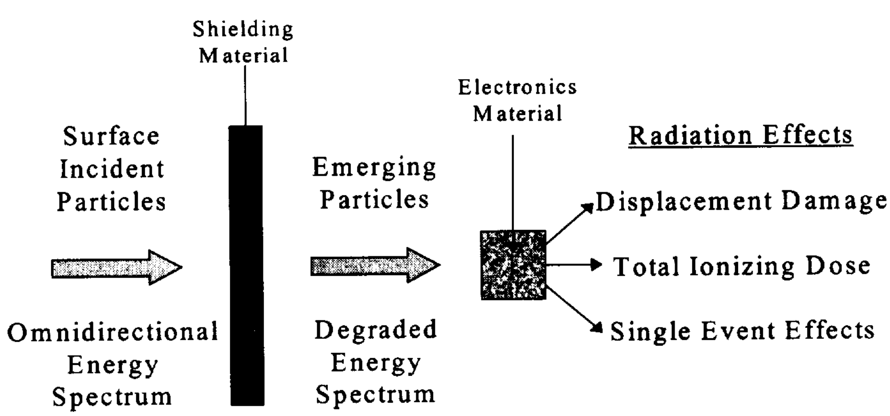

Figure 18: The characteristics of the shielding material are critical for determining the level of radiation effects on electronics.

Figure 19 shows the dependence of the radiation effect on the shield thickness, in this case, total ionizing dose for a two-year mission. In the past, radiation requirements were usually set by adding together the thicknesses of the aluminum spacecraft skin and walls of the electronics enclosure and using this estimate to calculate the level of exposure. For example, the estimated thickness would be used with the curve in Figure 19 to determine the total dose for a mission.

With the desire to fly more radiation sensitive components, it is now more common to determine radiation requirements by taking into account as much shielding as possible. Developing a three-dimensional radiation model of the electronics enclosures and their contents and/or the spacecraft structure accomplishes this. Once the model is defined, the predicted levels of energetic particles for the mission are transported through the model to a specified sensitive location in the enclosure. This degraded particle spectrum can be converted to a total ionizing dose value. This method produces a radiation requirement that is up to a factor of ten lower than the estimate obtained by the old method. Setting a requirement at 10 krad-si is significantly more desirable than at 100 krad-si.

The evaluation of the shielding offered by spacecraft structures includes consideration of the type of material, the material thickness, the order of the material layers, and the geometry of the arrangement of the material surrounding the radiation sensitive component. Structures that are important for radiation shielding are bus structure, equipment panels, electronic box chassis, heat sinks, board stiffeners, solar cell backing, etc. Increasingly these structures are built using lightweight materials, including composites. Composites are especially problematic. They are composed of carbon and epoxies and, therefore, provide less protection than aluminum. Also, composites are difficult to model in shielding analyses because they are non-homogeneous and little theoretical or empirical information of basic radiation transport through composites exists.

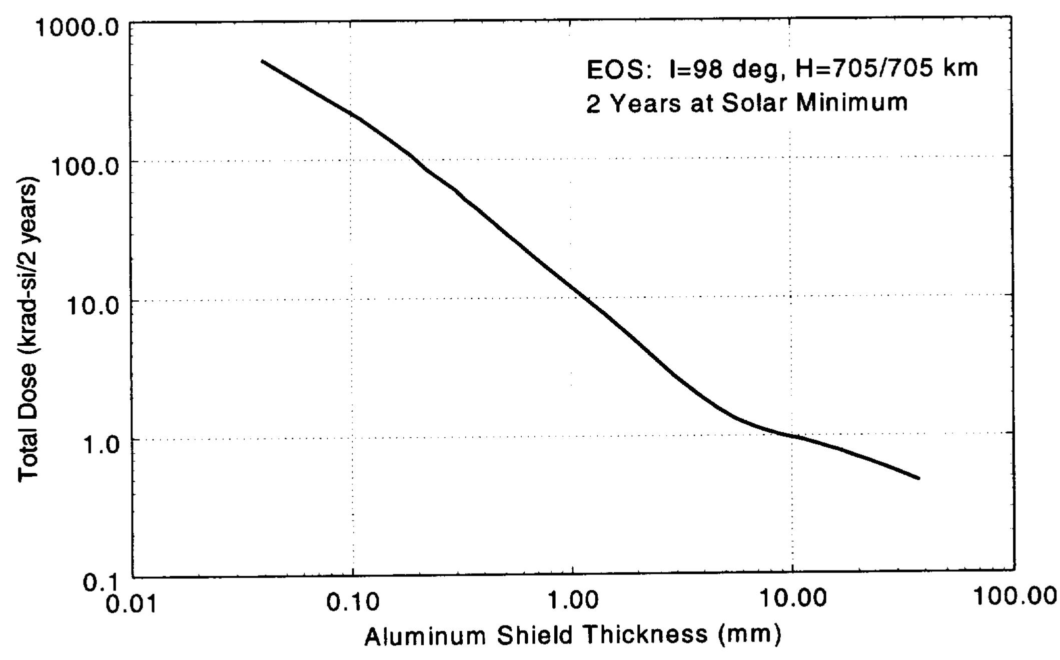

Figure 19: Total dose at the center of solid aluminum spheres for a low earth, polar orbit. The curve shows the importance of the shield thickness on total dose.

A joint Naval Research Laboratory (NRL) and NASA/Goddard Space Flight Center program investigated energy loss of protons in several sample composite materials through laboratory testing [2,3]. The results from the testing were compared with the energy loss models used in the transport codes. The findings were that, although small corrections to the energy loss models in the transport codes were required, the transport codes are valid for a wide range of composite materials. For composite shielding analysis, it is recommended that a transport code which can represent materials by composition and density be employed. The common practice of taking the ratio of the density of the composite to aluminum has no basis in the physics of particle transport and is inaccurate, especially for electrons [4].

It is difficult to make generalizations about the radiation protection offered by the three electronic enclosures described in this study because the levels of exposure inside the boxes are also dependent on the box contents, the spacecraft structure, and the location of the enclosure in the spacecraft. However, it is obvious that the cast aluminum enclosure will provide more radiation protection than the machined enclosure by virtue of the thicker aluminum walls (60 mils versus 50 mils). Also, we know that because composites are manufactured from less dense materials, their radiation performance will be inferior to aluminum. Previous work [2,3] has shown that when tungsten foils are co-cured with the composites, radiation protection is improved. Work by Jordan et al [5] showed that, for materials manufactured in layers, the order of the layers can optimize radiation protection in electron dominated environments. Therefore, it should be possible to manufacture electronics enclosures using composite materials with co-cured foils that have similar shielding performance of lightweight aluminum enclosures.

6. CONCLUSIONS AND FUTURE CONSIDERATIONS

The Lightweight Electronics Enclosure effort was a successful venture into the optimization of traditional structures through new technologies. Recent advancements in the areas of traditional machining, investment casting, and advanced composite materials and assembly enabled the development of three individual electronics housings. Each of the housings marked a significant weight savings over the existing design and passed the full compliment of structural and thermal testing. Each box satisfied the electrical, mechanical and thermal requirements derived for this new generation of electronics enclosures. This set of requirements proved reasonable in that each of the boxes was able to attain the proper features to satisfy the requirements without any significant cost or weight penalty.

The final step in this development and the only way to truly realize the cost saving measures is a space flight. Currently, none of the boxes are baselined for flight, however, several upcoming missions have noted the availability of the lightweight enclosures. Forthcoming insights into the radiation effects and some visibility may clear the way for these boxes into space.

7. REFERENCES

1. *Thermal and Vibration Tests of Composite Heat Sink Electronic Component Assemblies*, AM 149-0016 (155), August 16, 1996.

2. M. Stanton, W. J. Stapor, and P. McDonald, "Determination of Radiation Transport Characteristics of Selected Composite Materials," Naval Research Laboratory Center for Space Technology, SSD-TP-AS196, 4555 Overlook Avenue, SW, Washington DC., 20375, August 8, 1997.

3. J. L. Barth, E. G. Stassinopoulos, G. B. Gee, and M. C. Kilerlane, "Radiation Environment Predictions of Composite Shielding Materials for Selected NRL Orbits," X-900-97-005, NASA/Goddard Space Flight Center, Greenbelt, MD., August 1997.

4. J. W. Wilson, "Weight Optimization Methods on Space Radiation Shield Design," Journal of Spacecraft and Rockets, Vol. 12, No. 12, pp. 770-773, December 1975.

5. R. Mangaret, T. Carriere, J. Beaucour, and T. M. Jordan, "Effects of Material and/or Structure on Shielding of Electronic Devices," IEEE Trans. on Nuc. Sci., Vol. 43, No. 6, December 1996.