HEXCEL

MEMO #14

COMPOSITE REFLECTOR PANELS FOR THE SAO SUBMILLIMETER ARRAY

KEY ISSUES AND THE APPROACH TO THEIR SOLUTION

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INTRODUCTION

A graphite/epoxy faced honeycomb sandwich is being evaluated as a candidate material for the reflectors of the Smithsonian Astrophysical Observatory's Submillimeter Array. Most existing reflectors are aluminum structures that are adequate for wavelengths longer than submillimeter. The SAO's operation requirements of wavelengths as low as 300um require materials and structures with much greater thermal and dimensional stability than aluminum. Graphite/epoxy's very low coefficient of thermal expansion and honeycomb sandwich structure's high stiffness-to-weight ratio makes this system ideal for this type of structure. These types of structures and materials are commonly used in the aerospace industry with proven success in their environment. Their history as precision reflectors is limited. Their use for this application is entirely feasible based on the data base built up by the aerospace industry over a 15 year period and the developing data base by JPL/NASA for space bound segmented reflectors.

This design study will discuss the key issues in evaluation of these materials

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for precision structures. Approaches to their solution are discussed. Analytical and empirical solutions are proposed.

PANEL CONFIGURATION

The general panel type is a graphite/epoxy skin and aluminum honeycomb cored sandwich structure. The individual skins are 8 plies of graphite fiber in an epoxy resin matrix at a thickness of 0.040 inches (1.0 mm). The core is a full hard 5052 aluminum alloy honeycomb with a Flexcore[R1] cell configuration at a thickness of 2.00 inches (50.8 mm). The panels are proposed to have a nominal overall thickness of 5.3 cm. This will yield a sectional Moment of Inertia of $I = 0.0832$ in^4/in (1.37 cm^4/cm) [1]. The bare panel weight, excluding close-outs, mounting fasteners, or coatings would be in the 7-8 kg/m^2 range.

Each graphite/epoxy ply of unidirectional tape is 145 gm/m^2 areal weight of graphite fiber with a 35-40% by weight epoxy resin content. The proposed graphite fiber is a 6K or 12K tow size, 34 msi (234 Gpa) modulus, 470 ksi (3.28 Mpa) tensile strength fiber [2]. The epoxy is a toughened 250^0 F cure 0.47 msi (3.28 Gpa) modulus resin system [3]. When stacked in a balanced 8-ply quasi-isotropic lay-up the in-plane laminate modulus is 7.6 msi (53 Gpa), with a strength of 110 ksi (768 Kpa), and a CTE (coefficient of expansion) of 3 to $4x10^{-6}$/degree C [4,5,6].

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1. Registered trademark of Hexcel Corporation

The high modulus of the graphite/epoxy facings in this honeycomb sandwich structure yields a plate stiffness coefficient D=632,000 in^2lb/in width [7], equivalent to a 7/8 inch thick plate of aluminum but at only 13% of the weight of the plate.

The honeycomb core is manufactured from a full hard 5052 aerospace grade aluminum alloy. The patented cell configuration allows the core to drape over very tight spherical or parabolic contours with extremely low residual stress making it ideal for this type of precision component. Aluminum provides a rapid heat transfer between skin facings to reduce transient local thermal distortions. Each cell is vented through machined slots to prevent distortion from pressure gradients within the honeycomb. The modulus of the core in the plane of the facings is negligible to prevent thermal expansion strain. The primary thermal expansion direction is axial to the cells or perpendicular to the panel surface. Any large (for example greater than 10 micron) temperature induced distortions in the radial direction can be corrected by slight focus changes.

SEGMENT CONFIGURATION

The ability to replicate precision composite reflectors up to 0.9 meters in diameter at better than 4 micron RMS room temperature surface accuracy has been demonstrated [8,9]. These parts are tested and measured as manufactured, with no subsequent polishing, from a polished ceramic tool. It is believed that larger parts could be fabricated to similar precision. A reasonable goal is 1.5 to 2.0 meter parts in the range of 8 micron RMS surface accuracy. Parts of this size will be fabricated in 1991 or 1992 as part of an ongoing joint technology program between NASA/JPL and Hexcel. 1.75 meter parts are a reasonable design value for the SMA reflector segments at this point in the technology development.

Since the whole reflector is a 6 meter part it will be necessary to use more than one replicating tool to keep the segments in the 1.75 meter optimum dimension range. In an effort to reduce the total program cost by reducing the number of ceramic tools an inner and outer ring of petal segments is proposed (see Figure 1). Each segment within a ring would be identical for a parabolic shape. It is possible that the inner ring could be a one piece annular structure. Segment size fabrication limitations may require 4 petals of 90^{0} arc angle for the inner ring. In either case the outer ring would be made up of 18 petal segments of 20^{0} arc angle for a total of 19 or 22 independent segments, respectively. Surface accuracy is predicted to be on the order of 10 micron RMS per segment, or better, at room temperature.

If a single inner ring is used it will have a diameter of 2 meters with outer petals 2.0 meter x 1.04 meter chord length inclusive (see Figure 2). This represents the maximum feasible size for part fabrication at this time which may require a proof-of-concept or prototype evaluation first. This requires the largest tools of all the concepts with the associated fragility, heat mass, and cost.

A reflector configuration with four inner ring petals will have smaller segments. The four inner ring segments could be quarter circle segments of radius 1.25 meter, including the secondary cutout, by 1.77 meter chord. The outer segments would be 1.75 x 1.04 meter chord (see Figure 3). No dimension would be larger than 1.8 meter and both segments would have an equal maximum dimension. Optimization will be addressed from both part geometry and tooling considerations in phase two of the design study.

ATTACHMENT SYSTEMS

Several types of attachment systems warrant investigation. The true merit of any system will be its effect on the reflector surface accuracy under mechanical and nonmechanical strain induced by mechanical, thermal, or moisture loads. Any attachment will create a hardened or stiffened region on the back surface. The question is the control of and effect these hard points have on the reflective surface.

Penetrating the structural sandwich panel must be avoided to prevent discontinuities. Following are three possible designs to be evaluated in the second phase of this study. First, adding an additional laminate "doubler" to bond a mating fastener to the panel surface is preferred over actually penetrating the graphite/epoxy skin. In this case the laminate doubler is in the same plane as the back facing so all expansion/contraction will match the structural facing (see Figure 4). The bending stiffness of the laminate will be increased locally, however. This effect on the panel or reflective surface performance is unknown.

A second method is to orient a graphite/epoxy laminate perpendicular to the facing as a mounting surface (see Figure 5). This will result in lower localized stiffening but will reduce the radial CTE over a planar oriented doubler.

A third method would be to bond a second honeycomb panel at the attachment points to isolate the reflector from the support structure with its honeycomb core. A low CTE honeycomb could be utilized for this purpose (see Fig 6).

Panels modeling these concepts can be fabricated on existing optical ceramic tools and thermally tested with a laser interferometer for attachment induced distortion for the second phase of this study.

SHORT-TERM ENVIRONMENTAL EFFECTS

The two principal environmental causes of distortion in precision composite structures are thermal changes or gradients and strain due to moisture absorption in the epoxy matrix of the graphite/epoxy laminate. In both cases the principal strain is in the laminate thickness. However with a laminate thickness of 1.0 mm the deflection is minor and considered correctable by slight focus changes.

The primary concern is the in-plane laminate dimensional change from thermal and moisture expansion/contraction. The in-plane direction coincides with the extremely high mechanical and thermally stable properties of the laminate thereby minimizing gross effects. The in-plane laminate CTE is 3 to 4×10^{-6}/degree C and the maximum in-plane laminate strain under maximum moisture content is 160 to 300 microstrain (strain $\times 10^{-6}$) for typical graphite/epoxy laminates (see Table 1).

The final on-tool cure temperature of the panel segments will be approximately 25°C, representing T_0. The temperature extremes in service are -30°C to +40°C representing a maximum temperature gradient, T_0-T_1, of $\Delta T = 55°C$. This represents an in-plane dimensional change on the order of 150 microns from the center to edge of a 1.5 meter segment. The effects of this type of laminate deflection on the panel will be studied both analytically and empirically in the second phase of the study. Analysis can be compared by simple geometrical arguments and FEA. Empirical tests can be performed with current spherical parts built in conjunction with JPL and tested on one of several available laser interferometer test facilities built for just that purpose [10].

Moisture absorption effects occur over a much longer time scale than thermal effects [11]. A 1.0 mm thick uncoated graphite/epoxy laminate will take weeks to equilibrate in a constant humidity and temperature environment. Under normal ambient conditions a steady state or equilibrium condition might be reached on the order of a year or more. Once steady state equilibrium is reached the major changes would be more seasonal in nature. However tests by Springer [12] indicate these changes around the steady state moisture content to be negligible under fluctuating ambient conditions. Tests done on aircraft structures with their rapidly cycling environmental extremes show very little fluctuations around steady state.

The real concern is to determine the strain induced in the panel at steady state. If it were determined to be significant the skins could be conditioned to steady state before the final bonding into the precision configuration thereby locking the panel shape in under steady state moisture induced strain. Typical graphite/epoxy laminates have a maximum moisture absorption of 1.4 to 1.8 % under constant 100% humidity conditions [13]. Ambient conditions would result in a much lower steady state value. The actual moisture content is fairly linear to the actual constant humidity. According to Wolfe [14,15]the actual maximum strain of graphite\epoxy laminates under maximum moisture content is 160 to 300 microstrain (strain x10^{-6}). This represents an in-plane dimensional change on the order of 150 microns from the center to edge of a 1.5 meter segment for an average steady state moisture induced 200 microstrain. On a positive note this dimensional change will have negligible fluctuation once the steady state moisture content is reached. The effects of this type of deflection will be studied analytically after generating specific laminate data experimentally in phase two of this design study.

LONG-TERM ENVIRONMENTAL EFFECTS

Longer term environmental effects include continuous thermal cycling effects on the laminate, freeze-thaw cycle effects on the surfaces, UV radiation, and environmental induced mechanical impact such as blowing dust, ice, hail, and rain erosion. These types of stresses and degradation cannot be analytically quantified. Graphite/epoxy and aluminum honeycomb sandwich structures are proven aerospace materials able to survive the rigors of flight and space environments. Their application in precision structures is not so well documented. Phase two of this design study will address and quantify these effects as they pertain to this unique application.

Special coatings are required to achieve the specular reflectance required in the submillimeter range and to protect the panel from environmental stresses. Tests to quantify relative merit of coatings will be performed in phase two. There are several ASTM specifications for evaluating environmental durability that can be utilized. For mechanically initiated degradation, a specific impact can be imparted by a gauged object such as a 1/8 inch steel ball. The "damaged" panels built with different coatings and reflective surfaces can then be put through the appropriate environmental tests. A relative merit system will be used to judge which is best. A control based on existing surfaces that have not been successful will be used if they can be properly characterized.

CTE COST/PERFORMANCE TRADE-OFF

The major material cost driver in the graphite/epoxy and aluminum honeycomb sandwich structure is the graphite fiber. A broad range of graphite fibers are available classified primarily by their modulus and strength. In general the higher the modulus the higher the cost, as an exponential function. Graphite fibers have the property of a low negative CTE value while the matrix resin has a high CTE value (-0.1 to -1.4×10^{-6}/degree C vs $+43$ to 70×10^{-6}/degree C [16,17]). It is the selection of fiber by modulus that determines the CTE of the laminate since the modulus of the matrix varies little by resin type. The low cost "low" modulus graphite fibers will yield in-plane CTEs of $3\text{-}4 \times 10^{-6}$/degree C in a quasi-isotropic layup. A CTE value at or even below zero is possible with the high modulus fibers. However doubling the modulus to 60 msi (419 Gpa) to achieve a near zero in-plane laminate CTE requires high modulus fibers with an associated 10-fold minimum cost premium (see Table 2).

The operating environment and surface accuracy requirements of the SMA may not require the CTE laminate values of high modulus fibers. The thermal analysis will be able to determine the panel performance based on CTE and hence the fiber requirement. There will always be a cost/benefit tradeoff for very low CTE performance. Phase two of this study could cover analysis of specific fibers and their effect on the structure as a function of CTE if a CTE less than $3\text{-}4 \times 10^{-6}$/degree C is required.

INSPECTION METHODS

The inspection program is more complicated than conventional reflector fabrication. Since the parts are replicated off a convex parabolic surface, the tool must be verified before production begins. Verifying the concave paraboloid surface of the replicates (parts) represents the more conventional inspection problem. Current methods of inspection will be studied during phase two to determine actual tool and part test methods. Definition of first article inspection that might include surface accuracy and reflector performance as a function of thermal and mechanical loads must also be addressed.

REFLECTIVE SURFACE MATERIALS

Several types of reflective surfaces are possible for this application. They include vapor deposition, co-curing or post curing a reflective film or foil, and embedding a reflective material in or above the exterior ply. All have known general advantages and disadvantages. The cost/benefit tradeoff and relative performance and durability merit for this application can be determined by analysis and test in phase two.

Vapor deposition of a reflective material such as aluminum is a standard method of applying a reflective film. The major benefits are accurate highly reflective and durable surfaces which allow easier part fabrication. The major drawback is the projected high cost. The graphite\epoxy surface may need an intermediate film deposited or co-cured with the laminate to enhance aluminum film adhesion. The aluminum is very delicate and may require a protective coating such as SiO_2. All of these steps can be very costly for precision parts of this size. A cost analysis will be done in phase two to compare this with other options.

A low cost method of applying a reflective coating is to bond a reflective coated thermoplastic film to the part. Both the film and the thermoplastic are not considered durable against mechanical damage. It is noted that this method has been tried in the past with unsatisfactory results. Possibly thicker films and more durable surface layers could be utilized to achieve a workable low cost system. Evaluation of this approach will be performed in phase two based on comparative merit.

Bonding a thick foil (e.g. greater than 25 micron) as a reflective surface is also possible. Stretching that foil to the surface configuration to avoid wrinkles, waves, folds or tears is required with the associated tooling costs. This would make an excellent moisture resistant coating for the laminate outer surface. The relatively thick layer of such a high modulus moderate CTE material's affect on the panels thermal performance needs to be analyzed and tested. Galvanic isolation between the graphite fiber and the aluminum is necessary and readily accommodated. The feasibility and cost of this approach will be evaluated in phase two.

Another approach is to embed a reflective material into the exterior ply of the graphite\epoxy laminate. This technique is successfully utilized for EMI shielding, static charge dissipation, and lightning strike protection of composite structures. These types of materials are all conductive and therefore offer the possibility of being sufficiently reflective in the submillimeter range. The crudest materials are aluminum coated fiberglass and actual woven or expanded metal mesh. More sophisticated materials include Nickel mattes, Nickel coated carbon fibers, and conductive polymers.

The actual reflective surface of these materials must be within the operational RMS surface accuracy regardless of the accuracy of the physical part surface. Small laminates can be easily fabricated on a precision glass tool and evaluated for reflectance in the appropriate wavelengths. As a part of the phase two study a method of protecting the epoxy surface from UV degradation without interfering with the reflective material must be evaluated if this system looks promising.

DISTORTION DUE TO MECHANICAL LOADS

Distortion due to mechanical loads can be determined analytically and by Finite Element Analysis. The two primary mechanical loads in terms of operational performance are the parts own weight and wind loads. Survivability conditions include higher than operational wind loads plus snow and ice loads. This will be fully analyzed in phase two of the design study.

PANEL CLOSE OUTS

The panel close out must obviously be designed to protect the panel, in particular the honeycomb core, from damaging environmental conditions plus mechanical/human abuse. It must also allow venting of the panel interior to the atmosphere including a mechanism for condensation moisture drainage. Cells with large amounts of water that has frozen could damage the panel structure enough to permanently compromise performance.

In addition the closeouts must not "harden" the edges so as to create an edge effect around each segment that becomes exaggerated in thermal cycling. Thermal testing will be performed on design concepts in phase two.

COST AND LEAD TIME

The cost is estimated at $200,000 R.O.M. per 6 meter diameter 18 segment circumferential ring plus a 4 segment inner ring reflector. This assumes one tool for the inner segments and one tool for the outer segments but does not include the cost of the tools. Material costs are based on a low cost carbon fiber. The price includes 3 mounting pads, simple closeouts, and a weather resistant paint on all but the reflective surface. The reflective surface cost is not included. The reflective surface cost will be determined in phase two along with a more accurate total cost including tooling.

CONCLUSION

A graphite/epoxy and honeycomb sandwich structure is a possible candidate for the reflectors of the Smithsonian Astrophysical Observatory's Submillimeter Array. It has been utilized as a reflector structure in the past and is undergoing full evaluation by JPL/NASA as the structure of choice for the PSR segmented reflector Space Telescope on the Space Station. Reflector segments have now been routinely produced that exceed the surface accuracy requirements of SAO. The mechanical and physical properties of the material elements combine to produce the stiffest, lightest, and most thermally stable structures reproducible for this application. In large structures of multiple elements this technology also offers to be the least expensive.

PHASE TWO DESIGN STUDY ELEMENTS

Phase two of the design study will include but not be limited to the following areas:

1) Optimization of the segments based on part geometry, tooling considerations, and their impact on overall cost. This would include their interface with the backup structure.

2) Analysis of different attachment methods and their impact on the panel and reflective surface performance. This would include small panel fabrication and testing.

3) The thermal effects will be studied both analytically and empirically. Analysis can be compared by simple geometrical arguments and FEA. Empirical tests can be performed with current spherical parts built in conjunction with JPL and tested on one of several available laser interferometer test facilities built for just that purpose.

4) The effects of moisture absorption induced deflection will be studied analytically after generating specific laminate data experimentally.

5) Long term environmental tests will be conducted on small laminates or panels to quantify the relative merit of different coatings and reflective surfaces. Resistance to mechanical damage will also be evaluated. A relative merit system will be used to judge which is best.

6) Current methods of inspection will be studied to determine actual tool and part test methods.

7) The cost/benefit tradeoff and relative performance and durability merit (per item 5) for different reflective surfaces will be evaluated.

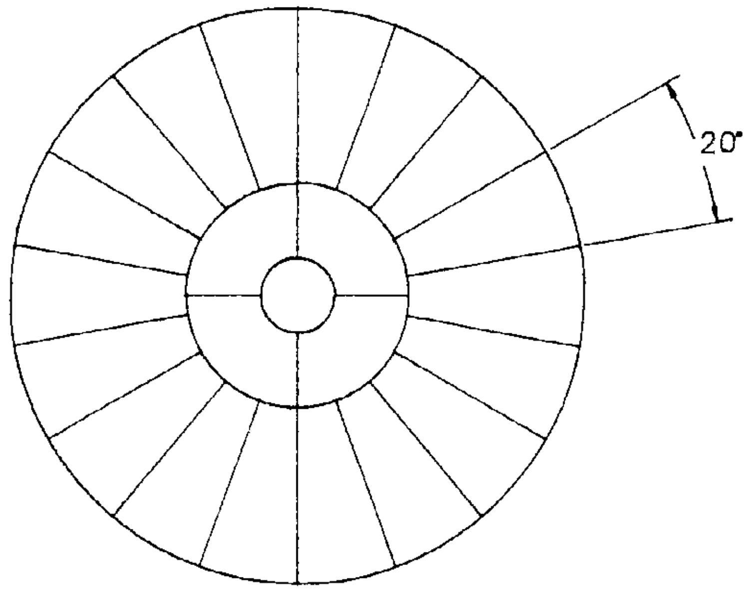
8) Analyze the deflection due to mechanical loading.

9) Fabricate small sample panels and thermally test close out designs.

10) Evaluate possible sources for the ceramic tools required for this program.

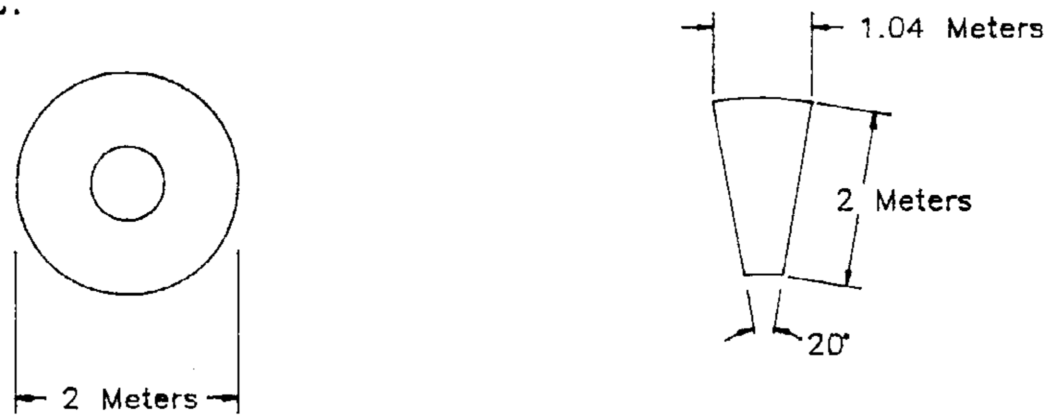
11) Make a final recommendation for part design including a ROM cost and manufacturing time schedule.

Fig. 1:



Two Rings Concept

Fig. 2:

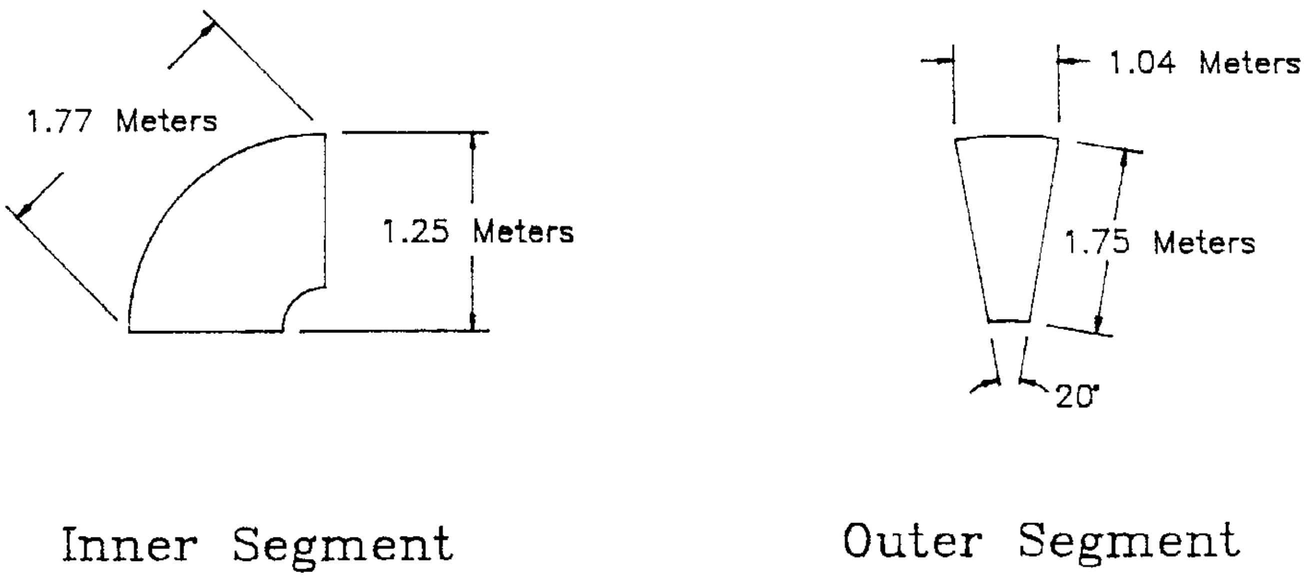


Inner Ring

Outer Ring Segment

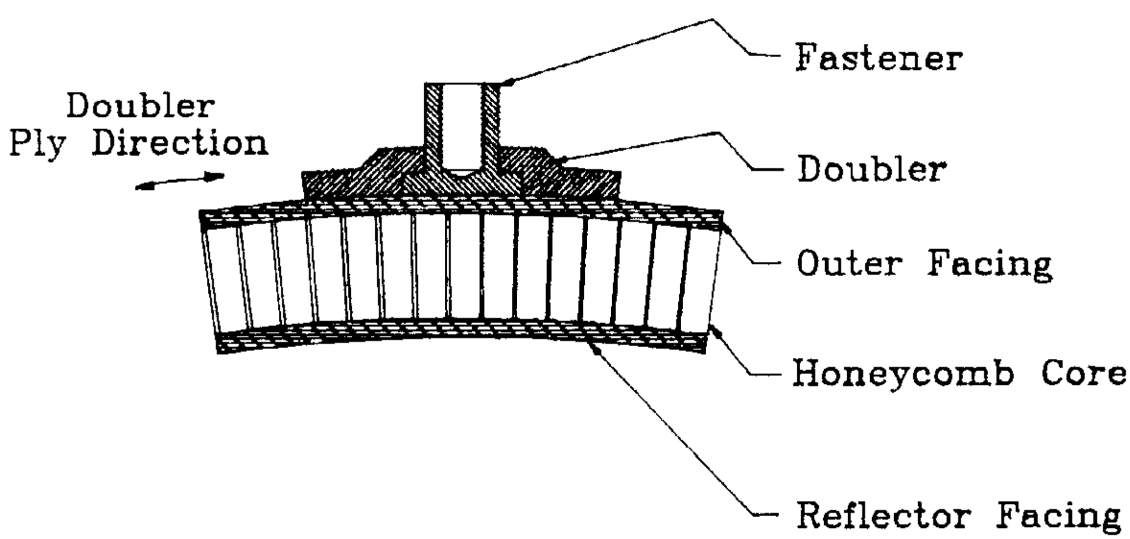
2 Meter Max Part Dimensions
Annular Inner Ring

Fig. 3:



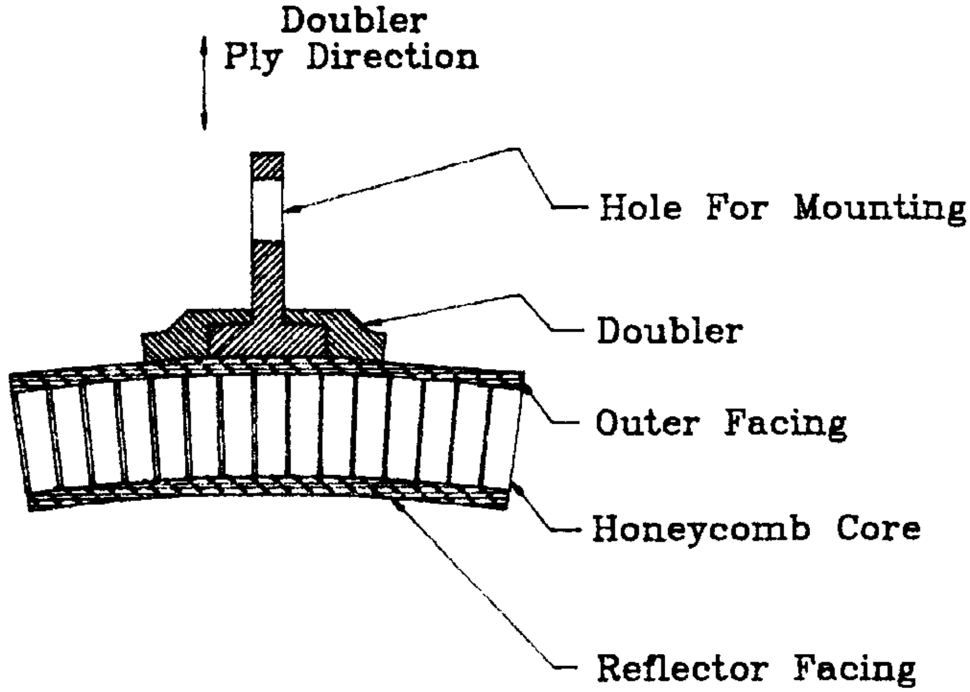
Equal Max. Part Dimensions

Fig. 4:



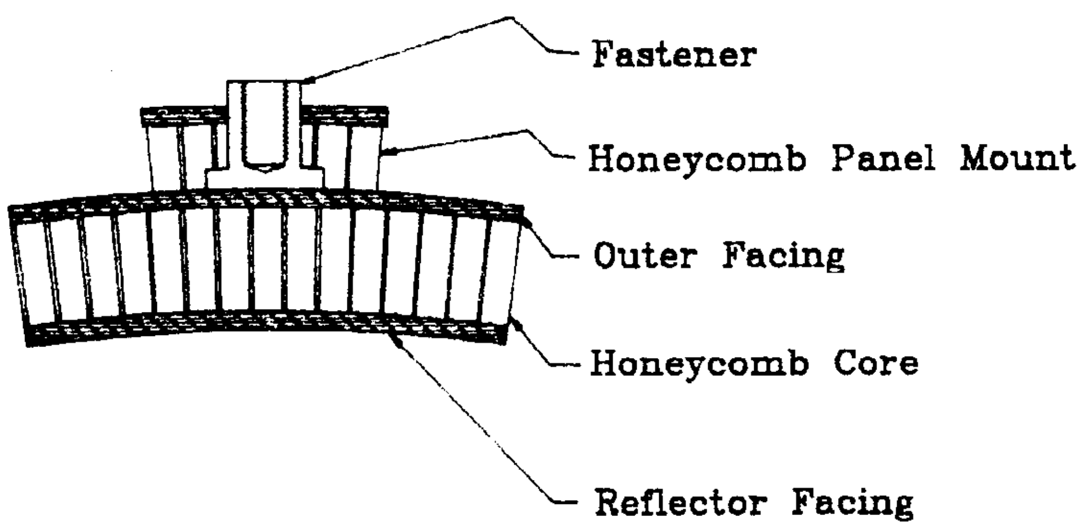
In-Plane Doubler

Fig. 5:



Perpendicular Mounted Doubler

Fig. 6:



Honeycomb Panel Mount Concept

TYPICAL GRAPHITE/EPOXY LAMINATE PROPERTIES
34 MSI FIBER, QUASI-ISOTROPIC LAMINATE

PROPERTY	VALUE
Tensile Modulus	53 Gpa
Tensile Strength	768 Gpa
Areal Density	0.009 lbs/sq foot/mil thick
CTE, Coeff Thermal Expansion	3-4 PPM/Deg C
CME, Coeff Moisture Expansion	160-300 PPM/%M
Maximum Moisture Content	1.4-1.8%
Maximum Moisture Strain	160-300 microstrain

TABLE 1

COST vs MODULUS of GRAPHITE FIBER

Supplier/Fiber	FIBER MODULUS	FIBER COST
Celanese/C12000	234 Gpa	$18/lb
Hercules/UHM	419 Gpa	$325/lb

TABLE 2

(1)Hexcel Corporation, TSB 124 Bonded Honeycomb Sandwich Construction, Hexcel Corporation, Dublin, Ca, 1989, p. 15.

(2)Celanese Corporation, Celion 12000 Carbon Fiber Data Sheet, Celanese Corporation Bulletin CFM4C, 1985.

(3)Hexcel Corporation, "Hexcel F155 Resin Systems Data Sheet", Hexcel Corporation, Dublin, Ca, 1988.

(4)Daniel R. Coulter and Paul B. Willis, "Materials Development for Precision Segmented Reflector Applications", JPL paper presented at SPIE Conference on Active Telescope Systems at Orlando, Florida, March, 1989, p. 5-6.

(5)Chris Porter, "Laminate Program", computation results.

(6)Introduction to Composite Materials, Stephen Tsai and H. Thomas Hahn, 1980, Technomics Publishing Co., general discussion of laminate analysis.

(7)Hexcel Corp, TSB 124, op. cit., p. 15

(8)Paul McElroy, "Composite Mirror Development at JPL for Antennas and Telescopes", JPL presentation at the Northern California Chapter of SAMPE 16th Annual Composites Workshop on January 26, 1990.

(9)E. B. Hochberg, "PSR Optical Test Report: Test of 7-11-89", JPL interoffice memorandum, July 12, 1989.

(10)R. G. Helms, et. al., "Lightweight Composite Mirror Analysis and Testing", JPL paper presented at SPIE Conference on Active Telescope Systems, Orlando, Florida, March, 1989, p. 5.

(11)George S. Springer, editor, Environmental Effects on Composite Materials, 1981, Technomic Publishing Co., p. 15-39.

(12)Ibid., p.109-124

(13)Ibid., p. 28.

(14)Ernest G. Wolfe, "Dimensional Stability of Graphite/Epoxy Composites", presentation at the Northern California Chapter of SAMPE 16th Annual Composites Workshop on January 26, 1990.

(15)Ernest G. Wolfe, "Polymer Matrix Composites: Moisture Effects and Dimensional Stability", rough draft, Department Of Mechanical Engineering, Oregon State University, 1990, Table V.

(16)George Lubin, editor, Handbook of Composites, 1982, Van Nostrand Reinhold Co., p. 225.

(17)David E. Bowles and Stephen S. Thompkins, Predictions of Coefficients of Thermal Expansion for Unidirectional Composites, Journal of Composite Materials, Vol. 23, April 1989, p. 376-377.