DESIGN AND MANUFACTURING CONSIDERATIONS FOR THE E-926 VACUUM VESSEL

William T. Emmet
Yale University
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1.0 Scope

The purpose of this report is to describe the design, development and manufacturing aspects of a low-visibility vacuum vessel for the proposed Brookhaven National Laboratory E-926 experiment. Specifically, the report will address mechanical design, materials, methods of manufacture and approximate costs associated with the project.

2.0 Introduction

One of the requirements for experiment E926 is a large evacuated volume through which a collimated beam will pass. The beam is expected to have horizontal and vertical divergence of 125 and 4 milliradians respectively. In addition, the evacuated volume will contain a large array of plastic scintillators. Table 1 shows the requirements for the vacuum chamber.

Parameter	Value
Vacuum	10^{-7} Torr
% Radiation Length	< 5%

There are numerous metallic alloys that are structurally adequate for use in the proposed vacuum vessel. Unfortunately, these alloys in the thickness required would exceed the radiation length target set forth in table 1. However, use of reinforced polymer-based laminate materials results in both superior structural performance and reduced radiation length percentages. In addition, these materials can be "engineered" through individual ply properties, the relationship between plies and the total number of ply layers. Table 2 shows the radiation lengths of various materials.

Material	Radiation Length (cm)	5% Radiation Length (cm)	Modulus/Rad. Length Ratio ($lb/in^2/in$)
Aluminum	8.9	0.445	2.85e+6
Steel	1.76	0.088	4.33e+7
Copper	1.43	0.072	3.02e+7
Polyethylene	47.9	2.40	5.30e+3
Graphite/epoxy laminate*	25.0	1.25	4.57e+3

*P75/954-3 graphite/cyanate ester unidirectional laminate (V_f=0.6)

However, there are some disadvantages associated with the use of fiber-reinforced polymer composites. The materials and associated tooling are relatively expensive. Furthermore, there is little experience in the use of composite materials for vacuum vessels, primarily due to outgassing and sealing issues. As part of this report, an extensive literature search was conducted and will be discussed in a subsequent section.

The report consists of discussions of previous work, the proposed design approach, sealing and outgassing issues, results of a preliminary structural analysis, and a cost estimate.

3.0 Literature Survey

Unfortunately, there is very little available in the public literature concerning the use of fiber reinforced plastic (FRP) composites for vacuum vessels. However, there has been extensive use of composites for lightweight pressure vessels. Common examples are oxygen tanks used by firefighters and scuba divers. The aerospace industry has also taken advantage of the high strength to weight ratio offered by FRP pressure vessels.[1] The common method used to fabricate such containers is filament winding over a thin metal liner. The liner acts as an impermeable barrier, while the FRP winding absorbs the structural load.

However, three examples of FRP composite vacuum vessels have been found. The earliest is described in the Journal of Vacuum Science and Technology of July/August, 1987[2]. Researchers at CERN fabricated graphite/epoxy beampipe sections up to 15 cm in diameter by 180 cm in length with wall thickness approaching 0.15 cm. Test sections were manufactured with and without aluminum foil (10-50 micron thick) liners. The sections with liners were able to support vacuums in the 10^{-10} Torr range with leak rates approaching 10^{-10} Torr liter/second. Outgassing was also minimal (2×10^{-12} Torr liter/second cm^2). Sections without liners initially leaked at a rate of 10^{-10} Torr liter/second. When sealed off, the internal pressure began to rise and residual gas analysis indicated water vapor. The authors found that moisture was migrating through the cylinder wall.

The test cylinders with liners were fabricated using two different methods. In the first, a thin foil piece was wrapped around a cylindrical mandrel with the foil's seam running parallel to the mandrel's axis of revolution. The graphite epoxy outer shell was then filament-wound over the foil. In the second method, the foil was spiral-wound around the mandrel with a 50 percent overlap. The outer shell was applied as in the first method.

The second reference is a proposal submitted by General Atomics to Lawrence Livermore National Laboratory for their fusion energy project[3]. The proposal provides some detail concerning the design of a large (10.2 meter diameter) spherical vacuum chamber to be constructed from graphite epoxy. A preliminary structural analysis is included. Unfortunately, no thought was given to outgassing or leakage concerns. Contact has been initiated with the project leader at General Atomics.

The third reference is a vacuum chamber[4] designed by Composite Solutions of Murray, Utah for MIT Lincoln Labs. This vessel is 12 feet long by 6 feet in diameter and is designed to test microwave antennae in a space (vacuum) environment while minimizing the material between the antenna surface and measurement apparatus. The vessel consists of a 2-inch thick honeycomb cylinder with fiberglass skins and 4-inch thick honeycomb/fiberglass flat endcaps. However, the vacuum does not have to be particularly good for this application. According to the chief engineer for this project, the honeycomb is not vented to the interior of the vessel.

4.0 Design Approach

Based on the data presented in table 2 and the fact that composites technology has matured to a stage where there are many companies capable of fabricating a structure of this size, a vessel of graphite reinforced plastic composite was decided upon. **Figure 1** shows the design concept. The central portion of the vessel is fairly straight forward in that it consists of two hemispheres (radii~1.25 m) joined by flanges to a central cylinder. The design challenges are with the configuration of the beampipes attached to each hemisphere, whether an interior coating is required to minimize outgassing and/or leakage, and how to apply such a coating during manufacture.

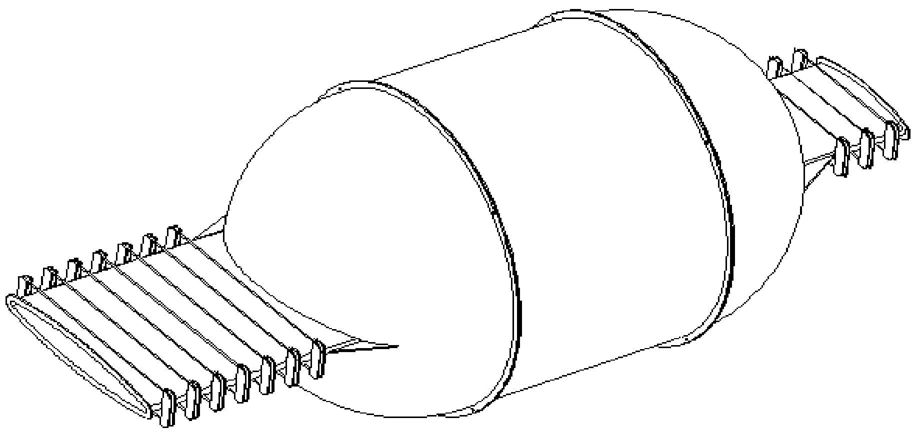

Figure 1: Isometric View of Proposed E926 Vacuum Vessel

Due to the relatively high ratio of horizontal to vertical beam divergence and the need to place detectors close to the beam, the beampipes up- and downstream of the main vacuum vessel need to have a large aspect ratio. Structurally, this results in an inefficient shape as compared to a perfect cylinder when loaded uniformly (external pressure). **Figure 2** shows two concepts of providing additional beampipe support while minimizing wall thickness. One is via external cables in tension which prevent the beampipe from collapsing. The second concept shows internal dividers (or septums) which are in compression and substantially reduce the unsupported span length. Internal support is simpler and more integral; however, external support interferes less with the beam. The external support option is being pursued at this time due to this fact and its further use as a means of mechanical support for the pre-radiator modules. The internal support approach is analyzed in this report solely as an alternative and as a point of discussion.

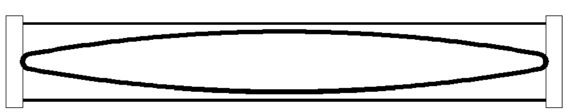

Figure 2(a): E926 Vacuum Chamber Beampipe External Support Concept

Figure 2(b): E926 Vacuum Chamber Beampipe Internal Support Concept (2 septums)

4.0 Preliminary Structural Analysis

Once the conceptual design was complete, a structural analysis was required. Due to the complex shape of the vessel and the fact that materials with anisotropic properties were being considered, a finite element analysis was deemed appropriate. The specific package used was COSMOS/M (version 2.0)[5].

4.1 Materials Candidates

A Graphite-reinforced plastic composite is being considered in this design study. Graphite fibers are available as yarn, unidirectional prepreg plies and fabric. Table 3 shows some typical high-modulus graphite fibers and their mechanical properties.

Trade Name	Density (g/cc)	Tensile Modulus (GPa)	Tensile Strength (GPa)	Yield (g/m)
Amoco P75	2.0	520.0	2.1	0.320
Amoco P120	2.2	827.0	2.37	0.317
Mitsubishi K135	2.1	612.2	3.53	0.29-0.32
Mitsubishi K137	2.2	619.1	2.74	1.41
Amoco T650/42	1.8	290.0	4.83	0.224

There are a wide variety of matrices available, including various epoxies and ester-based polymers. Cyanate ester was selected because of outgassing concerns. Epoxies typically outgas at a level four times greater than cyanate esters. Fiberite 954-3 was selected for this design study since it has been used successfully in the past in space applications and was proposed for use in the SSC GEM central tracker[6].

The initial ply configuration chosen for the analysis is a quasi-isotropic $\{[0/90/45/-45]^2\}_{sym}$ layup of 16 plies. The Mitsubishi K137 fiber was chosen following discussions with manufacturers. The K137 fiber is considerably less expensive than the P75 and P120 fibers. The primary disadvantage of the K137 fiber is that it is larger in diameter, meaning that fewer plies can be used for a given overall thickness.

4.2 Finite Element Structural Models and Results

The finite element model was created on the basis of two planes of symmetry to save computing time and hard disk space (one quarter of the actual vessel was modeled). **Figure 3** shows an isometric view of the model.

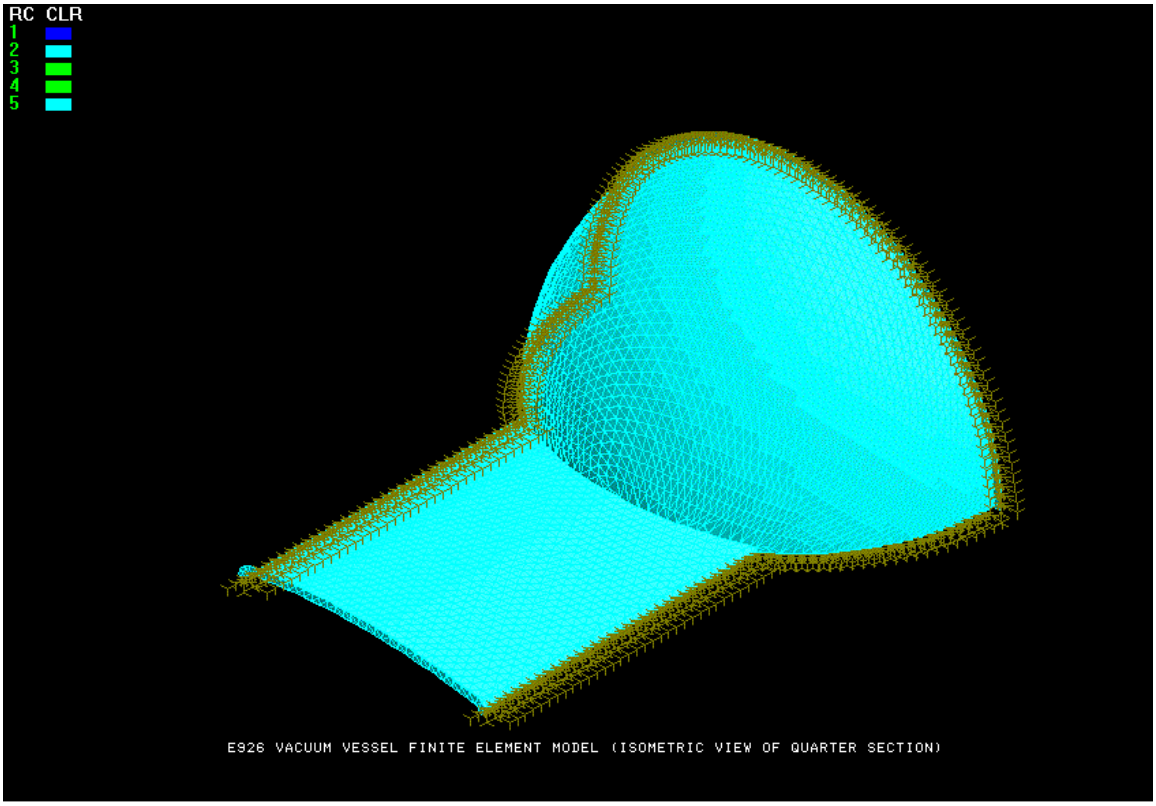

Figure 3: Finite Element Model of E926 Vacuum Vessel Quarter Section

Two constraint criteria were considered: continuous lateral support along each side of the beampipe and discrete support at several points along each side. **Figures 4** and **5** show the displacement and maximum failure index for the first constraint set. **Figures 6** and **7** show the same type of results for the latter set. An external loading of one atmosphere was applied in both analyses.

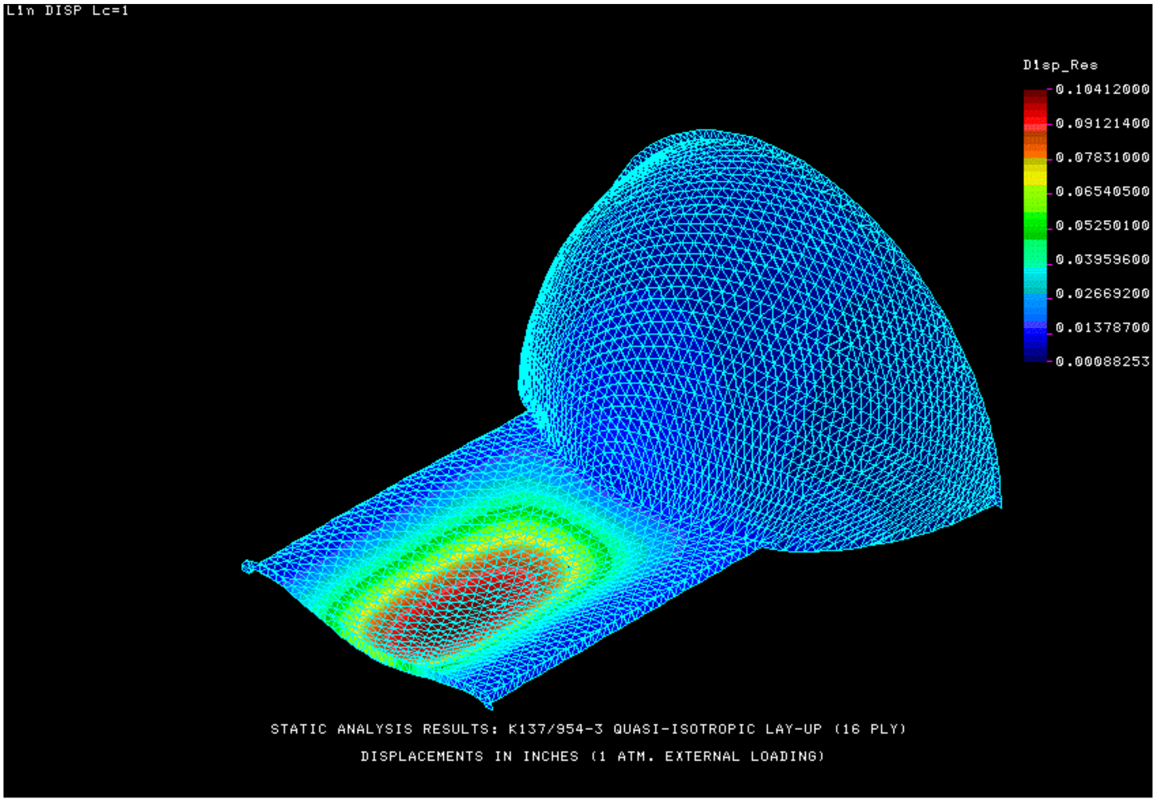

Figure 4: Maximum Deflection of 2.64 mm (Continuous Lateral Support)

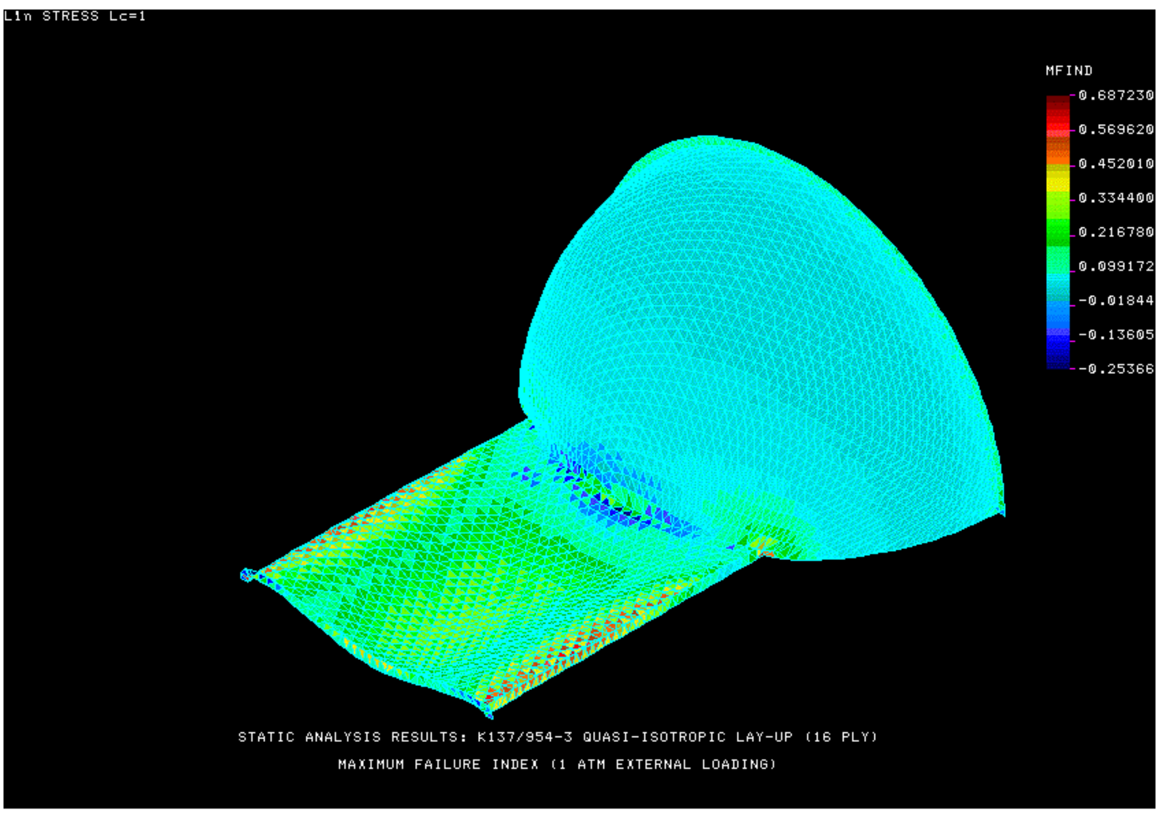

Figure 5: Maximum Failure Index of 0.69 (Continuous Lateral Support)

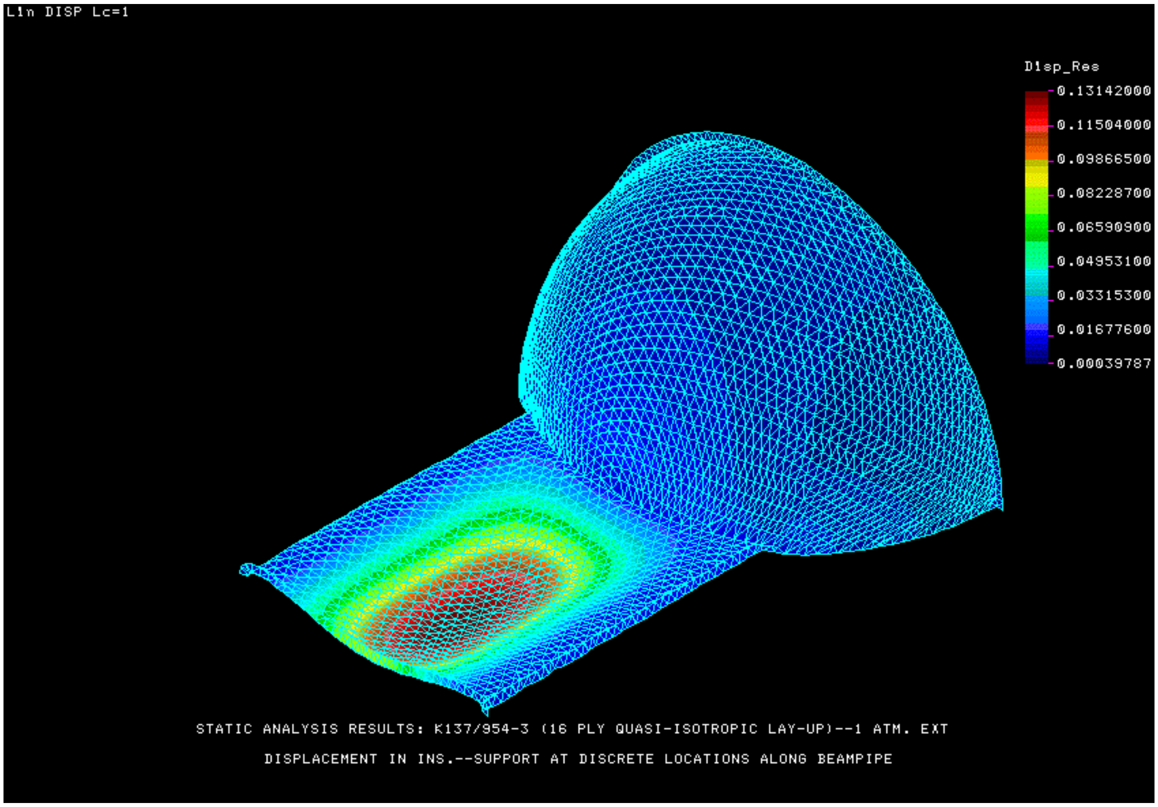

Figure 6: Maximum Deflection of 3.32 mm (Discreet Lateral Support)

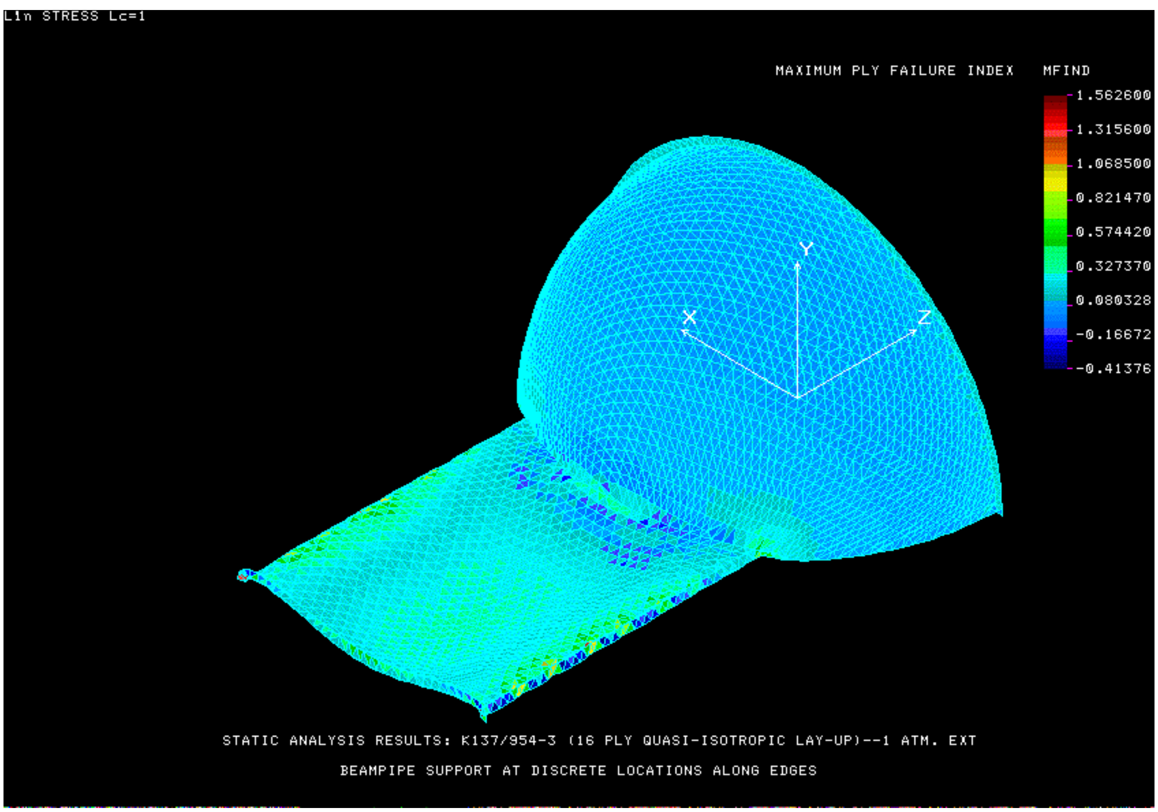

Figure 7: Maximum Failure Index of 1.56 (Discreet Lateral Support)

The failure index is a measure of the onset of ply failure in a laminate[7]. Values greater than unity are indicative of failure. **Figure 5** illustrates a best case while **figure 7** shows a worst case scenario. In fact, the lateral restraints would not be applied at desecrate points, since the vertical struts shown in figure 1 would tend to distribute the load.

Figure 8 shows the results of an elastic (linear) buckling analysis. The critical buckling load is 5.8 times the actual loading of one atmosphere.

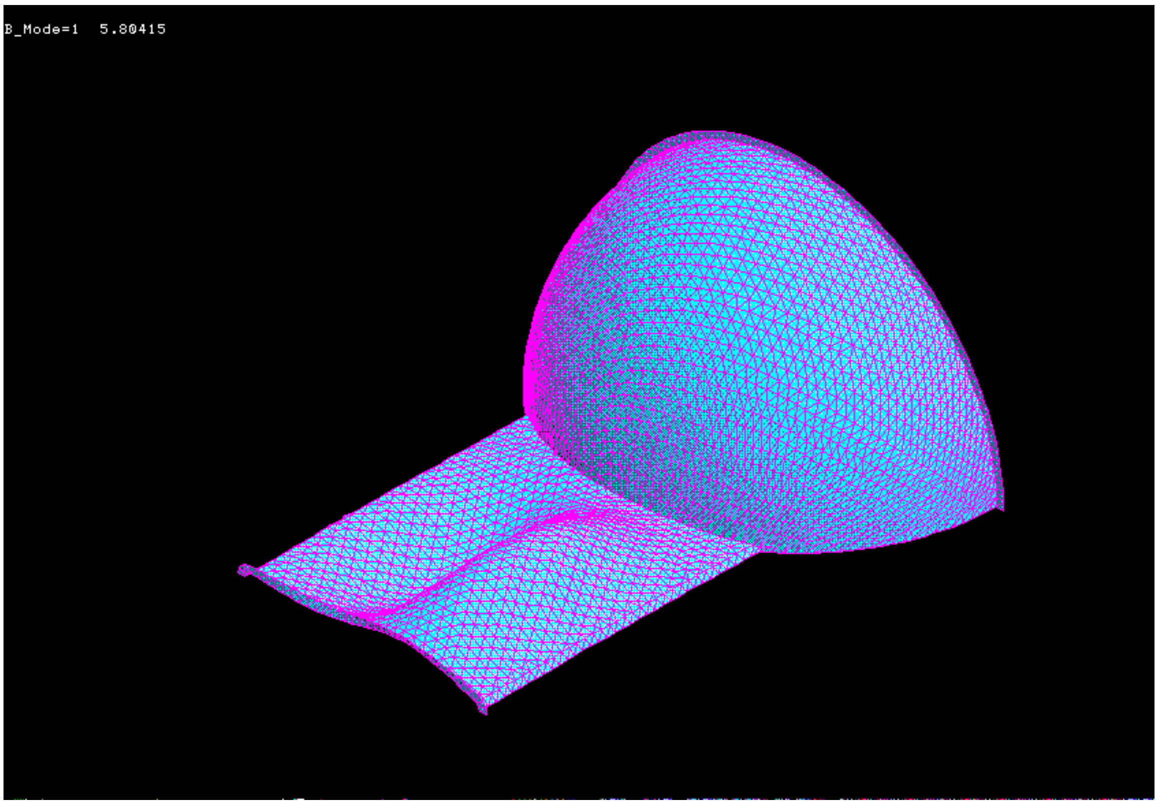

Figure 8: Linear Buckling Analysis Results

4.3 Other Design Variations

As mentioned previously, a second beampipe design was considered which involved internal supports. **Figures 9**, **10** and **11** are displacement, maximum failure index and critical loading results respectively. For simplicity, only the actual beampipe was modeled.

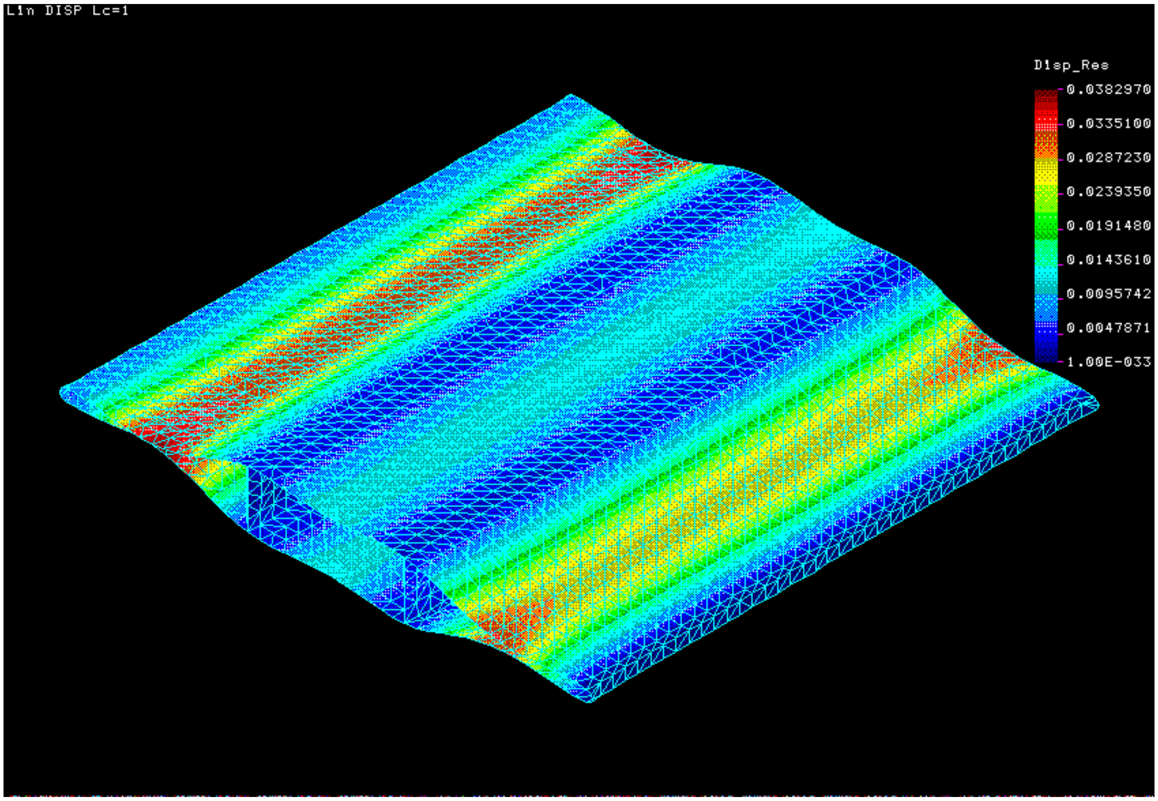

Figure 9: Beampipe with Internal Supports-Displacement (0.97 mm)

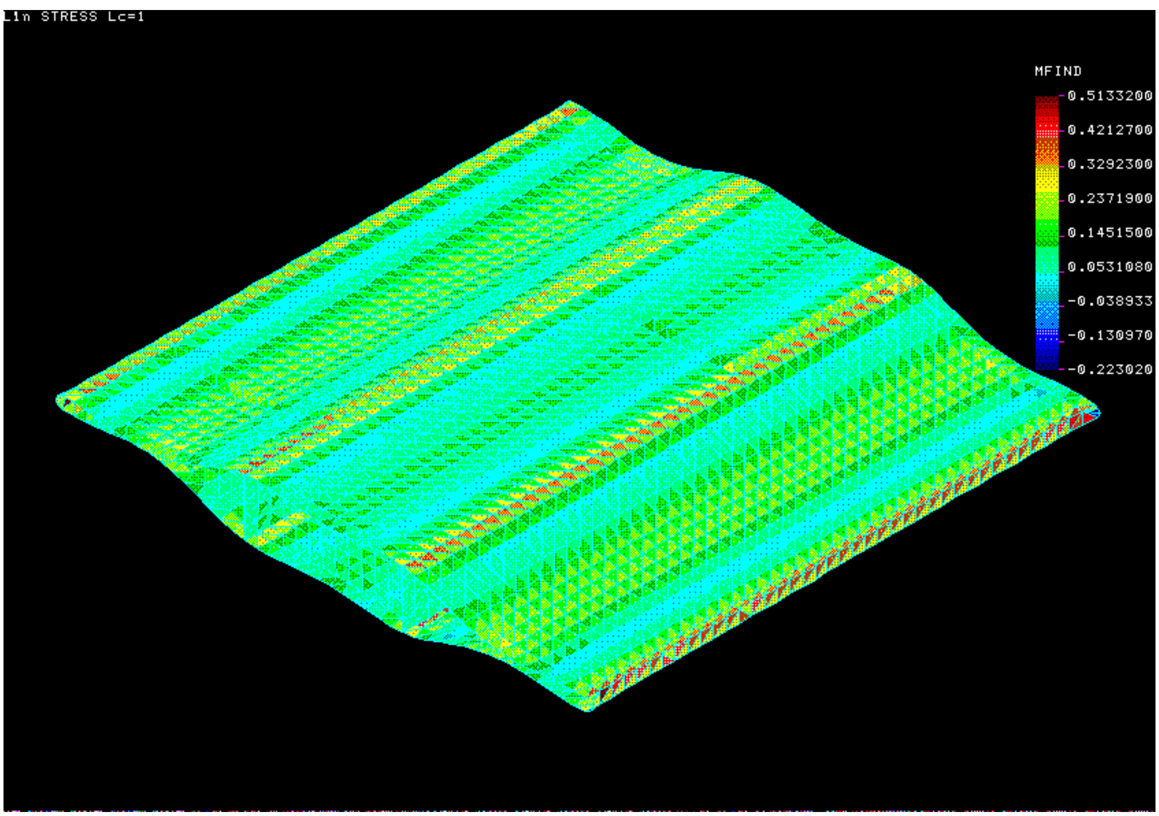

Figure 10: Beampipe with Internal Supports-Maximum Failure Index (0.51)

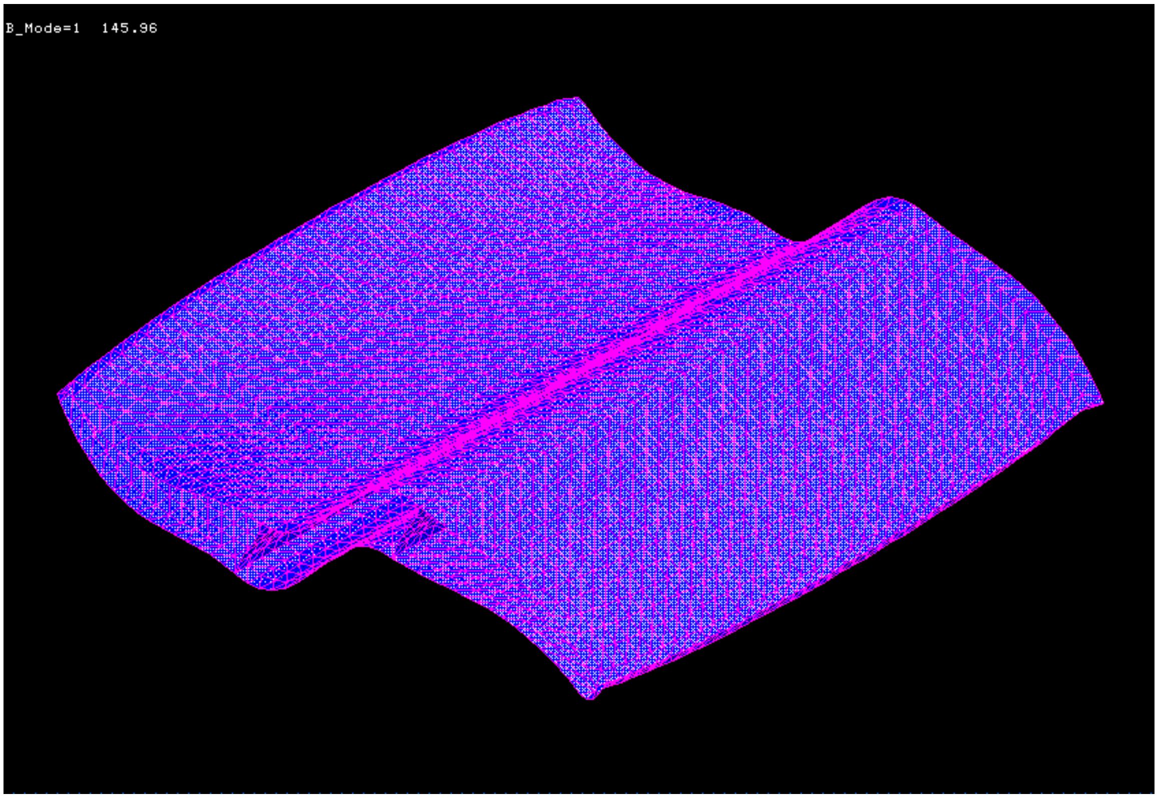

Figure 11: Beampipe with Internal Supports-Elastic Buckling (Load Factor: 146)

The biggest drawback to this approach is the extra material in the beam path. One possible solution is to provide cut-outs in the supports to reduce what is "seen" by the beam. The greatest advantage is that the need for external support is eliminated.

4.4 Structural Optimization

A 16-layer quasi-isotropic lay-up of Mitsubishi K137/954-3 plies results in an overall thickness of 1.47 cm (5.9% of a radiation length) with greater thicknesses locally (mounting points, flanges, etc.). In a previous design iteration, a 24 ply quasi-isotropic lay-up of Amoco P75/954-3 was considered with an overall thickness of 1.1 cm (4.4% of a radiation length). The P75 is five times as costly as the K137 fiber[8]. However, it is possible to optimize the ply orientation, thereby reducing the total number plies.

5.0 Outgassing Concerns

One of the chief disadvantages of using a fiber reinforced plastic material is the problem of outgassing. The vacuum will be continuously maintained (pumped), but FRP composites do absorb moisture and some porosity could occur in the vessel walls during manufacturing.

There are many possible solutions to this problem, including the application of a thin metallic layer to the vessel's interior by hand-spraying, vacuum deposition and using a method similar to the one used by CERN for the beampipe project discussed earlier. In the case of the E926 vacuum vessel, gores would be cut from 0.1 mm aluminum foil and would be applied to a mandrel. The vessel would then be filament wound onto the mandrel and the structure would then be cured.

Application of aluminum foil to composites is not a new idea. Grumman Aircraft, under contract to the U.S. Navy, conducted a series of tests where aluminum foil coatings were applied to composite materials at the time of cure (co-curing) and following cure[9]. Following a 90 day exposure at 60 C and

98% relative humidity, the bare composite had absorbed 1.3% moisture by weight. The co-cured samples absorbed 0.42% while the post-cured samples absorbed 0.61%.

This report's author conducted a simple test where foil was pressure-bonded with Shell Epon epoxy to a graphite-epoxy panel. Following cure for 2.5 hours in 80 C, a vacuum was drawn on the foil side. Slight bubbling was observed where voids had occurred. However, there was no breakthrough and no leak detected to the level of the available equipment (10^{-8} Torr). Proper vacuum-bagging would have eliminated the void problem.

6.0 Manufacturing

There are many types of manufacturing technologies available for composite fabrication, including vacuum bagging, resin transfer molding, pultrusion, filament winding and hand lay-up processes. Filament winding and/or hand lay-up on a mandrel are the preferred methods.

Several manufacturers were contacted and two responded with quotations. The highest quote was $500k and was not firm. The other manufacturer quoted $315k (delivery of 16-20 weeks ARO) in writing with the following conditions: 1) Mitsubishi K137 fiber would be used; 2) the upstream and downstream beampipes would be identical to save on tooling (two different mandrels in lieu of three); 3) the vessel parting flanges would be moved up and downstream from those illustrated in **figure 1**.

7.0 Recommendations

Based on the work performed thus far, there are several areas that require further work:

1) Detailed designs of flanges and mounting points;

2) Further study of optimal ply orientation to reduce wall thickness;

3) Further study and decision with regard to internal versus external beampipe support;

4) Design and fabrication of a small (1 cubic meter) composite vacuum chamber to test internal coating and vessel manufacturing techniques.

References

1) Patent Discosure E72-307, McDonnell Douglas Corporation. 6 October, 1972

2) Engelman, G. (et al). "Vacuum Chambers in Composite Material." Journal of Vacuum Science and Technology, A5(4), July/August 1987, pp. 2337-2341.

3) Streckert, H. (et al). NIF Support: Conceptual Design of a Low Activation Chamber and Components. General Atomics Report GA-C22067. June, 1995

4) Web site for Composite Solutions

5) COSMOS/M Finite Element Analysis System, Release 2.0. Structural Research and Analysis Corporation, 1998.

6) SSC GEM Technical Design Report, pp. 6.25-6.31. SSC Report GEM-TN-93-262, 30 April, 1993.

7) Tsai, Stephen W. and H. Thomas Hahn. Introduction to Composite Materials. Technomic Publishing Co., 1980. Pp. 280-287.

8) Telephone Conversation with Doug Olson of Advanced Composites, 20 July, 1998.

9) Staebler, Christian J. (et al). Metallic Coatings for Graphite/Epoxy Composites. Final Report (Contract N00019-77-C-0250), May, 1979. P. 4-19.