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SCC

Design and Analysis Report

Full Size Submersible Vehicle – Cylinder and Dome

OceanGate, Inc.

OGt1501

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REVISIONS

CHANGE	DATE	ENGINEER	PAGES AFFECTED OR REMARKS
NC	06/25/2015	BES	Initial Release
A	08/11/2015	BES	Added composite dome
B	8/18/2015	BES	Added sub scale dome and cylinder design and analysis

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ABBREVIATIONS & SYMBOLS

SCC [redacted] Composites Corporation

CFRP Carbon Fiber Reinforced Polymer

PV Pressure Vessel

FW Filament Wound

CSAI Compression Strength after Impact

FEM Finite Element Model

FEA Finite Element Analysis

ILS Interlaminar Shear Stress

IML Inner Mold Line (or surface)

Ksi 10^3 Pounds per in^2

LVID Low Velocity Impact Damage

Max Op Operating load condition at which minimum safety margin occurs

MEOP Maximum Expected Operating Pressure

MS Margin of Safety or Middle Surface

Msi 10^6 Pounds per in^2

OHT Open Hole Tension

OHC Open Hole Compression

OML Outer Mold Line (or surface)

Psi Pounds per in^2

R Ratio of membrane to bending stress concentration factors for a hole in a plate

ROA Reduction of Area

TL Tangent Line

Yld Yield

Strain

ε_{Allow} Allowable strain at ultimate load

ε_m Membrane strain = (Outer surface strain + Inner surface strain)/2

ε_b Bending Strain = (Outer surface strain - Inner surface strain)/2

ε_T Tensile Strain

ε_C Compressive Strain

Micro (10^{-6}) inch/inch

FIGURES

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1. INTRODUCTION

This report summarizes the design and analysis of a filament wound composite external pressure hull for a 6000 meter submersible vehicle for OceanGate, Inc. The hull consists of a CFRP hoop wet wound cylinder with hand laid axial prepreg, Grade 5 Titanium interface rings bonded to the CFRP cylinder. Optional Grade 5Titanium and composite dome designs are presented with supporting analysis.

The Titanium domes are designed without penetrations for a sight glass or air, power and data connections. The composite design includes an 8 inch sight glass. It is assumed that reinforcement necessary for adding these features will be welded to the Titanium dome. No penetrations will be made in the composite cylinder.

The design is based on OceanGate defined design parameters and SCC assumptions and analysis. The basic design parameters and assumptions are listed in Table 1.

Table 1. Composite Vessel Design Basis

Parameter	Optimum	Limit	Unit	Source	Comment
Net Buoyancy Including Aft and Fwd Closures	>4000	2000	lbs.	OceanGate	
Hull Composite OD Maximum	68	68	in	OceanGate	
Hull Cylinder Length	100		in	OceanGate	Spherical Domes add ~ 1 OD to OAL
Hull Composite ID Minimum	58	54	in	OceanGate	
Maximum Operational Depth	6000 19680	3000 9840	m ft.	OceanGate	
Safety Factor	2.25	1.5		OceanGate	2.25 is design goal, but <2.25 is acceptable
Cycle Life	10000	1000	Cycles	OceanGate	To maximum rated depth
Max Temperature Submerged	30	30	°C	OceanGate	
Min Temperature Submerged	-5	-5	°C	OceanGate	
Max Temperature on Surface	100	100	°C	OceanGate	Will be covered from UV exposure most circumstances
Min Temperature on Surface	-40	-40	°C	OceanGate	
Density of Sea Water	0.037	0.037	lb/in^3	SCC	Varies w/ temperature & salinity
Design Pressure	9000	9000	lb/in^2	SCC	8740 psi calculated from max depth and density
Design Collapse Pressure	20250	13500	lb/in^2	SCC	Design Pressure x SF
Maneuvering Loads	Negligible			SCC	Assumed Pressure & Temperature Only Significant Loads
Internal Coating	none			SCC	Assumed
External Coating	TBD			SCC	External Sealing of CFRP and Interface Joints is Necessary
Carbon Fiber	37-800	37-800		SCC	Mitsubishi Grafil 37 msi modulus fiber
Dome-Cylinder Alignment/Retention Method	TBD			SCC	Retention method should prevent violent slip when overcoming friction

The reliability of the composite cylinder and dome designs relies on the strength of the carbon fiber composite laminates. Most high performance composite tanks contain internally pressurized fluids or gases which place the composite shell in tension. Failure theories and design allowables for tensile applications of filament wound pressure vessels are well established, but compressive applications are much less common. The compressive failure of composite laminates is much more dependent on the local stress state, local stress gradients, manufacturing quality. Consequently, it is highly recommended that subscale testing be performed prior to fabricating a full scale pressure hull.

A 3/10 subscale hull design is presented in Appendix E. The hull scale was selected to fit within the available test chamber. The design is nearly an exact scale of the full scale design except for non-scalable ply thickness. The adhesive and rubber thicknesses were also scaled. Analysis and discussion of the effects of the non-scalable factors are presented in the Appendix.

2. MATERIALS

The materials used in fabricating the hull consist of carbon fiber and epoxy resin for the composite cylinder, titanium for the interface fittings and domes and a paste adhesive bond between the composite cylinder and interface fitting. A description of these materials is presented in the following paragraphs.

2.1 Grade 5 Titanium (6AL4V)

The domes and interface fittings are fabricated with annealed Grade 5 Titanium. The compressive stress-strain curve for annealed Grade 5 Titanium, shown in Figure 1, is used in the analysis and was calculated using the Ramberg-Osgood Equation (Ref.1, p. 5-65). The physical and mechanical properties are listed in the figure. The minimum tensile yield and ultimate strengths for Grade 5 Titanium are120ksi and 130ksi. The minimum compressive yield strength is 123 ksi. The elongation, 10%, is the average strain over a two inch length and understates the local strain at failure. The local fracture strain, ε_f, can be calculated from the reduction of area (ROA):

$$\varepsilon_f = \ln(1/(1\text{-ROA})) = \ln(1/(1\text{-.20})) = 22.3\%.$$

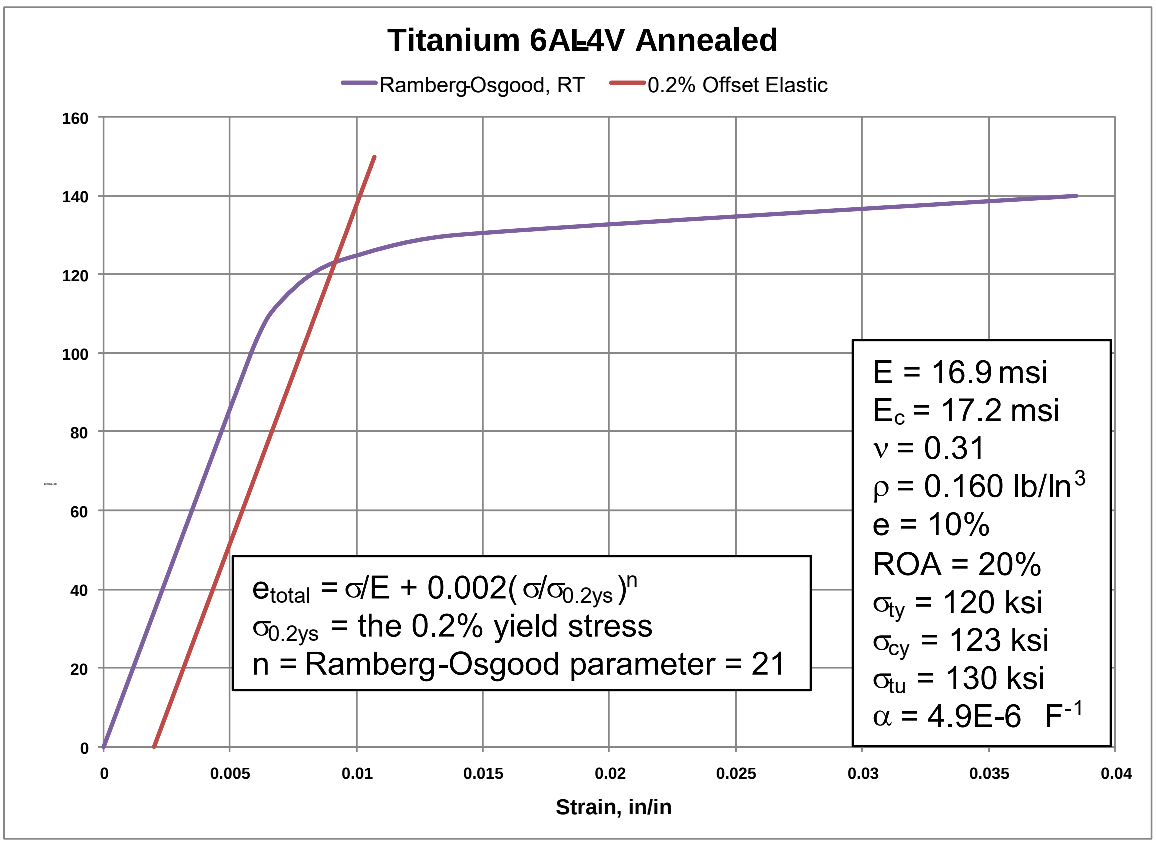


Figure 1. Annealed Type 5, 6AL4V Titanium Stress-Strain (Ref. 1).

2.2 **Fiber and Resin**

The vessel is a combination of filament wound hoop plies and axial prepreg using Mitsubishi Grafil 37-800 WD carbon fiber with 30k filaments per tow. The prepreg and filament wound hoops both use an SCC epoxy resin formulation based on Hexion Specialty Chemical's resin Epon 862, see Appendix B. The resin system selection is based on SCC's experience with this matrix combination and requirements for this project.

The B-Basis room temperature dry tensile and shear properties for 37-800 in Table 2 are used for this design based on SCC experience in past test programs. The B-Basis room temperature dry fiber tension is based on tests on test specimens fabricated and tested by [redacted] Composites.

The compression properties are of primary importance and in-plane tension does not exist for this external pressure hull design. A compressive strain database is not available and a design allowable was derived based on available data in Mil-HDBK-17 (Ref. 2). This data is for ~34 msi carbon fiber/epoxy, for eleven fiber/resin systems. The compressive stress data for these eleven unidirectional laminate types were combined into a single data base consisting of 323 total test specimens with a mean compressive strength of 214 ksi (normalized to 60% fiber volume). The data in Mil-HDBK-17 is pre-1990. Fiber tensile strength for 37-800 has increased by more than 20% over the fibers used at that time, so it was assumed that the mean unidirectional compressive strength for 37-800 is at least 1.15x214 ksi = 246 ksi (60% fiber volume). The design allowable was defined as 85% of this mean value = 209 ksi. The compressive strain allowable corresponding to this stress in a unidirectional 37-800 laminate is 9400μ.

The ultimate compressive strength is dependent on the shape and loading of a structure. A compressive failure is accompanied by local delamination and ply buckling. Plies stabilized by surrounding plies under lower stress conditions can reach a higher ultimate strain. For instance, compressive failure strains obtained in a flexure test are much higher than in a simple compression test. The Newport Composites data sheet (Ref. 7) lists an average flexural strength and modulus of 325 ksi and 20 msi for a calculated average failure strain of 14130μ. Defining the ultimate allowable for flexure as 85% of the mean as before results in an allowable strain of 12010μ. It is probably realistic to use this allowable where high strain is isolated and surrounded by lower strain material (like plies near the bonded interface fitting). This approach was used successfully by SCC for the Hawkes Ocean Technology Deep Flight Challenger hull.

The interlaminar stress in the composite cylinder is mostly compressive, but a small analytical interlaminar tensile stress exists in an isolated area near interface ring joints. The Mil-HDBK-17 data was also used to derive an interlaminar tension allowable. This value is resin dominated and the assumption was made that the resin formulation selected is at least as strong as the various resins used in Mil-HDBK-17. The Mil-HDBK-17 data does not have interlaminar tensile data, but it does have transverse in-plane tensile data. Since transverse and interlaminar tensile strength is mostly a function of the resin, it was assumed that these two strengths are the same. Data for 13 resin systems, consisting of 323 test specimens, were combined into a single data set with at mean tensile strength of 8.43 ksi and a C.V. of 11.34%. An interlaminar tensile stress allowable was conservatively defined as the mean less 3xC.V., 5.56 ksi.

These derived allowables will be confirmed by planned subscale testing.

Table 2. Allowables for Mitsubishi 37-800 Composite

Property	Mean ksi	B-Basis	A-Basis
Room Temperature, Dry			
Fiber Tensile Strength, ksi	691	**650**	622
Fiber Tensile Strain, µin/in	18700	**17600**	16800
Uni-Ply Tension, ksi	293	**276**	264
Interlaminar Shear, ksi	10.8	**10.2**	9.4
Bearing Strength, ksi	92.0	**85.0**	80.2

Note: Uni-ply properties normalized for 60% fiber volume.

Tow cross sectional area, CSA = 13.63E-4 in^2/tow, Fiber density, ρ_f = 0.65 lb/in^3.

Fiber modulus, E_f = 37 msi.

Fiber tension stress based on 100% fiber volume.

Bearing Strength for Min 40% ±45° plies, single shear & close fit fastener. B-Basis used in analysis.

2.3 Adhesive

EA9394 paste adhesive is used to secure the interface rings to the cylinder and provide a uniform contact surface for transferring axial compression between the two components. Stress-strain charts are presented in Ref. 3. The chart for EA9394 was digitized and is plotted in Figure 2. This nonlinear stress-strain curve was used in the FEM.

Table 3. Properties of Hysol Paste Adhesive EA9394

Property	@-67°F	@77°F	@180°F
Elastic Modulus, Msi		**0.615**	
Shear Modulus, dry, Msi		**0.212**	
Shear Yield Strength, ksi	3.31	**4.21**	3.00

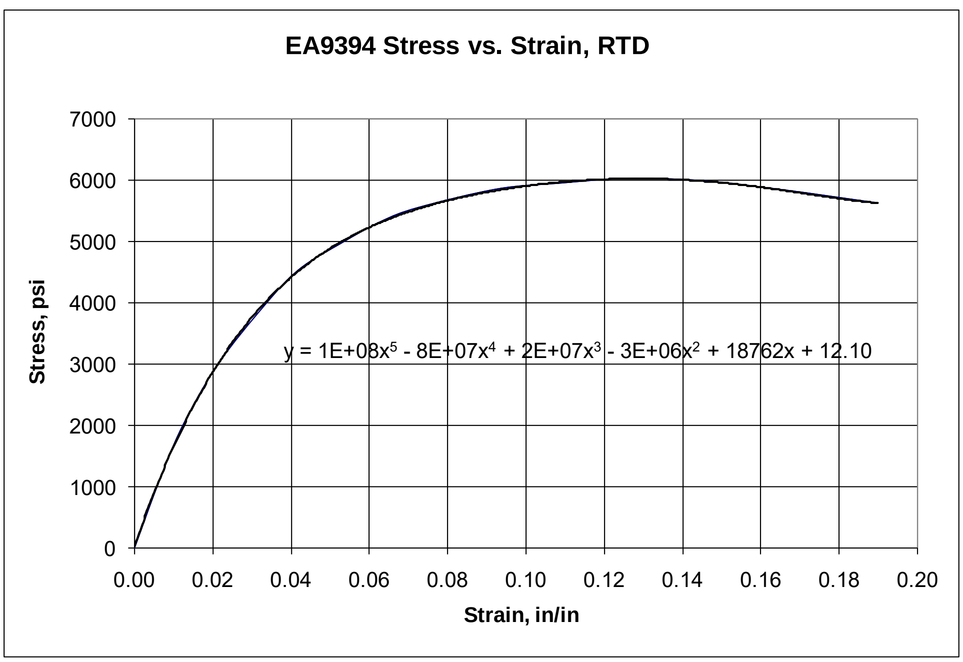


Figure 2. EA9394 Stress-Strain.

External Sealant/Impact Resistance

An external coating will be required to prevent water from being forced through the composite and through the interface ring joints. The coating will also provide some impact resistance. The coating is non-structural and is not discussed in this report.

3. HULL DESIGN AND FINITE ELEMENT MODEL

3.1 Composite Hull with Titanium Domes

After preliminary sizing using classical thick wall cylinder and sphere calculations, the FEM shown in Figure 3 was used to develop the final design configuration. Numerous iterations to the dome, cylinder layup and joint configuration were made before arriving at this final design. The details of the composite layup and cylinder-to-dome joint are shown in Figure 4.

Mitsubishi Grafil 37-800 carbon fiber was selected for the composite design. The axial and hoop plies were lumped into approximately 0.033 inch and 0.066 inch thick elements with axial and hoop ply material properties, rather than using a single combined axial/hoop orthotropic property for all cylinder elements. This approach shows the shear interaction between the two ply types, discussed in the analysis section, which would not be shown by a single orthotropic property.

The actual design will be fully interspersed with a single axial ply sandwiched between two hoop layers with appropriate number of plies and thickness. The hoop to axial ratio is 2:1. The axial ply thickness will be set by the commercial prepreg selected.

The domes and interface rings are Grade 5 Titanium (6AL4V). The composite cylinder is bonded to the interface rings with EA9394 paste adhesive, 0.03 inch thick, cured at room temperature. A single ply of axial mat is bonded between the interface ring and cylinder outer surface to resist cracking of the outer hoop ply. The domes are hemispherical. Prolate and oblate ellipsoidal domes using Grade 5 Titanium and 17-4 PH stainless steel were considered in the preliminary design trade study. Although the steel designs had competitive weights based on strength, the steel designs were thinner, and were buckling critical with buckling factor less than the design goal of 2.25. Consequently, steel was eliminated from consideration. Oblate spheroid domes are more stable than prolate spheroid domes. On the other hand, prolate domes have higher hoop stress at the cylinder joint and have lower discontinuity stresses. A sphere is a compromise between the two shapes and was chosen for the design.

The axial and hoop ply properties used in the analysis are listed in Table 4. These properties were calculated, using the methods of Ref. 6, from the fiber and matrix constituent properties. The constituent transverse properties were intentionally adjusted to understate the ply moduli transverse to the fibers while accurately estimating the properties parallel to the fibers. The thick wall hoop strain gradient through the thickness is a function of the wall thickness and to the wall transverse modulus. A lower transverse modulus produces a higher strain gradient and a more conservative analysis. The axial and hoop fiber volumes were assumed to be 62.5% and 64.5% respectively, based on previous thick filament wound composite experience at SCC. The cylinder thickness at the joint must be 4.5 inch thick to mate with the machined interface ring. The predicted failure mode at the joint is axial compressive failure and requires that all of the designed axial plies be present. The hoop stresses are lower than those remote from the joint and the laminate thickness at the ends can be adjusted by tapering the hoop thickness at the ends. The ply thicknesses will be monitored during winding, and adjustments in the hoop thickness made as necessary. The thickness taper rate at the end should be about 30:1. The subscale vessel fabrication will define the final method used at the end of the cylinder. Since an outside surface fit is required for the interface ring additional material will be added during manufacturing that will allow machining to the required tolerance without affecting the required load carrying cylinder laminate.

Geometric and material axisymmetric nonlinear analysis was used for hull analysis. Eight node axisymmetric solid elements were used exclusively. Linear orthotropic properties were used for the composite elements and elastic-plastic properties were used were used for the titanium and adhesive properties.

Normal pressure was applied to the entire external surface. The contact between the dome and cylinder interface ring was modeled with full contact and without slip. Slip will be prevented naturally by friction and by some sort of locking feature in the design (yet to be designed).

The hull design mass summary is itemized in Table 5. The total mass is 10042 lb_m . The volume of displaced sea water is 298.1ft^3 and displaced sea water mass is 19060 lb_m. So the net buoyancy is 9018 lb, which exceeds the 4000 lb requirement.

Table 4. Hoop and Axial ply properties use in FEA.

Property	Unit	Hoop Ply	Axial Ply
v_f	%	64.5	62.5
E_a	Msi	0.945	23.29
E_n	Msi	0.945	0.931
E_θ	Msi	24.03	0.931
ν_{an}		0.3606	0.2277
$\nu_{n\theta}$		0.0088	0.3684
$\nu_{a\theta}$		0.0088	0.2277
G_{an}	Msi	0.573	0.593
$G_{n\theta}$	Msi	0.630	0.540
$G_{a\theta}$	Msi	0.630	0.593
α_a	$°F^{-1}x10^{-6}$	14.1	-0.29
α_n	$°F^{-1}x10^{-6}$	14.1	14.6
α_θ	$°F^{-1}x10^{-6}$	-0.31	14.6
ρ	lb/in^3	0.0573	0.0569

a = axial, n = normal, θ = hoop

Table 5. Pressure Hull w/ Titanium Domes Mass Summary

Component	Constituent	Mass/Component lb_m	Mass/Constituent lb_m
Grade 5 Ti End Rings, Qty = 2	Grade 5 Ti	170.6	170.6
Grade 5 Ti Domes, Qty = 2	Grade 5 Ti	4750.0	4750.0
Carbon Composite Cylinder	Axial 37-800		1196.8
Carbon Composite Cylinder	Hoop 37-800		2449.6
Carbon Composite Cylinder	Total 37-800		3646.4
Carbon Composite Cylinder	Resin		1471.4
Carbon Composite		5117.8	
EA9394 Adhesive		4.1	2.0
Total Tank		**10042**	

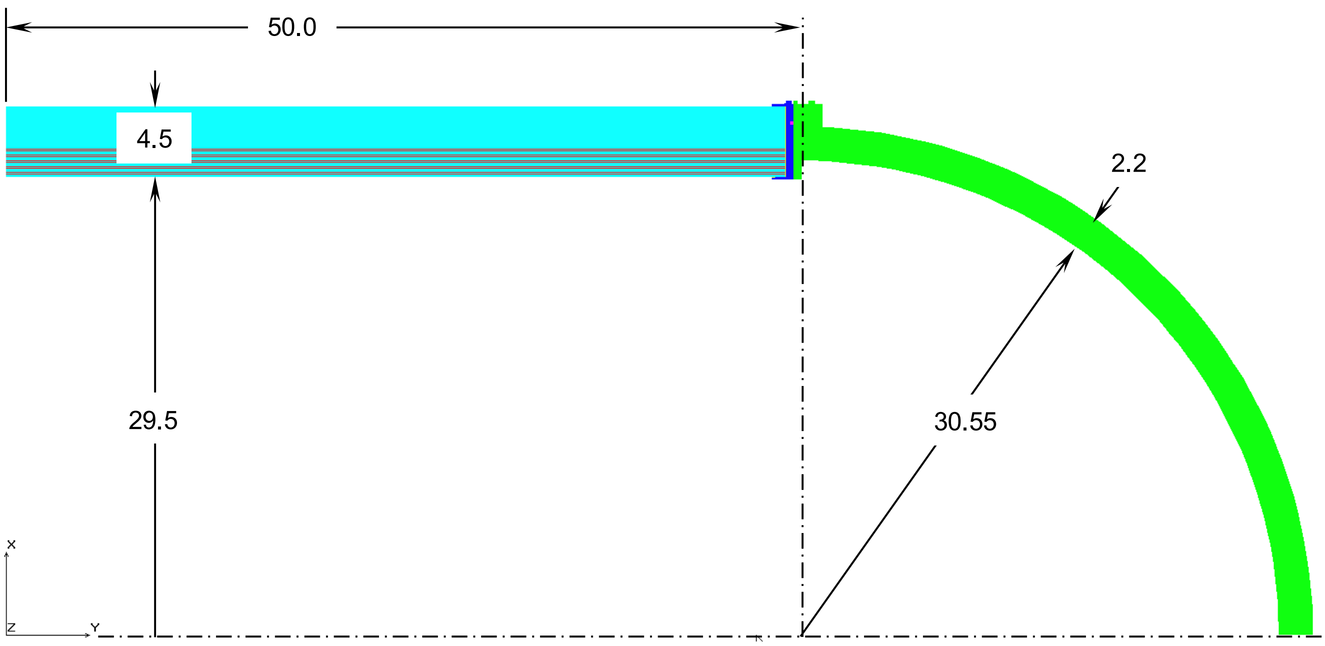


Figure 3. Hull Basic Dimensions, ½ Model w/ Titanium Dome

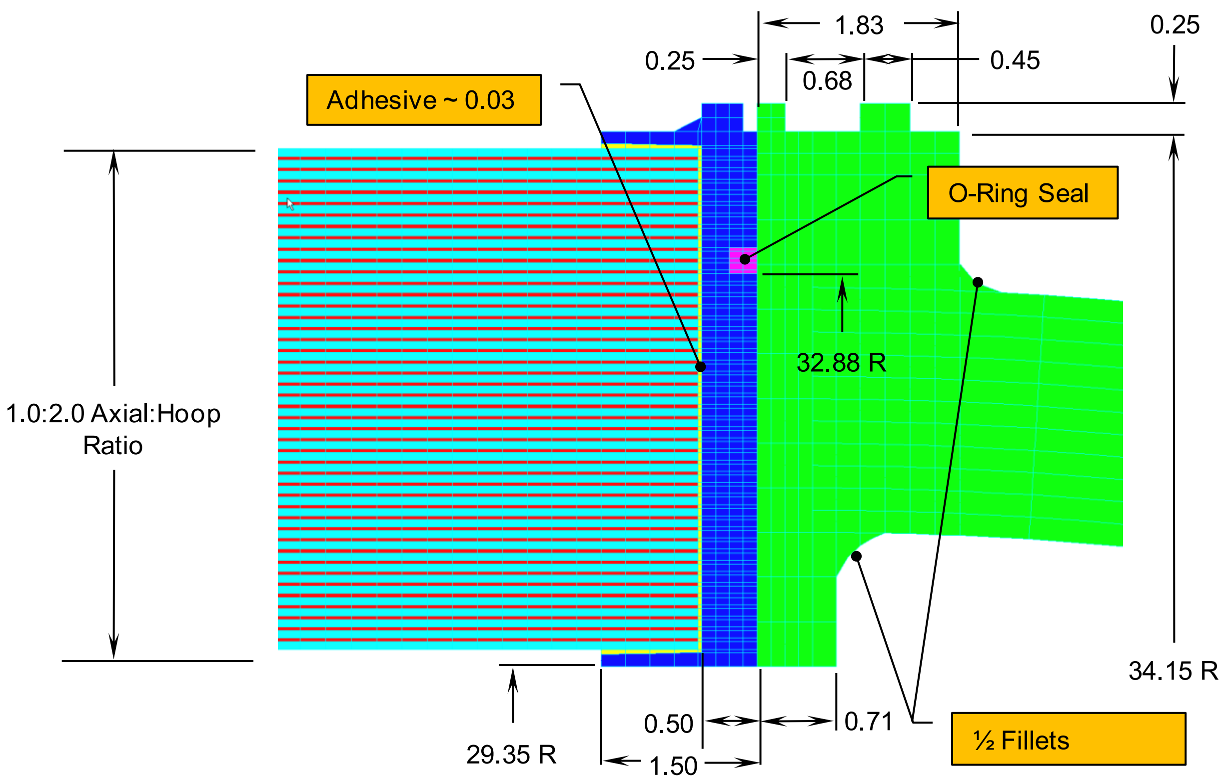


Figure 4. Cylinder-to-Titanium Dome Joint Details

3.2 **Composite Hull with Composite Domes**

The FEM used to evaluate the composite dome/cylinder assembly is shown in Figure 5. The composite cylinder design and FEM is identical to the cylinder used for the Titanium domes. The details of the composite layup and cylinder-to-dome joint are shown in Figure 6. A single ply of axial mat is bonded between the interface rings and composite outer surface on both the cylinder and dome to resist cracking of the outer hoop plies. The adhesive was replaced with HNBR rubber between the interface rings and composite inner surface to reduce the stress concentration in the inner composite layer caused by the high shear in the adhesive.

The domes are wound with a delta-axisymmetric pattern sequence (Ref. 9). This type of winding sequence produces a generally uniform wall thickness and quasi-isotropic properties on a spherical mandrel. A pattern sequence consists of a number of sequential patterns with uniformly increasing wind angles. The total required thickness is obtained by repeating the sequence as required. In this design, the pattern sequence consists of 14 unique wind patterns and the sequence is repeated seven times to obtain an approximately 4.5 inch thick laminate at the cylinder joint. The first sequence is tabulated in Table 6. The succeeding sequences are basically the same except the layer thicknesses decrease due to the larger diameter of the underlying composite. Additional tows are added to the outer sequences to increase the reduced ply thicknesses in those sequences. All seven sequences are tabulated in Appendix C. The polar opening composite is machined to mate with the sight glass with a 0.03 inch bonded HNBR rubber interface.

It is important to accurately predict the composite thicknesses, fiber angles, and material properties in order to properly model the spherical composite dome. The fiber angles within a pattern at a point in the dome are not unique and vary over a range of values. The presentation in Appendix D describes the SCC approach to this problem used in this analysis.

The same Mitsubishi Grafil 37-800 carbon fiber and resin was selected for the dome composite design as for the cylinder.

Each element in the dome has a unique material property set to approximate the continuously varying dome properties. The tank was modeled to represent the individual helical and hoop patterns. These properties were calculated using the methods of Ref. 6.

Normal pressure was applied to the entire hull external surface. Material and geometric nonlinear analysis was used. Eight node quadrilateral axisymmetric solid elements were used exclusively. The Grade 5 Titanium interface rings were modeled using elastic/plastic material properties. A 0.03 inch thick adhesive layer was modeled between the composite cylinder and dome and the interface rings. The contact between the interface rings was modeled without slip, due to the high friction that will be present.

The sight glass configuration is preliminary and will be custom designed by Rayotek Sight Windows with an 8 inch aperture and rated for a minimum of 10 ksi. Rayotek recommends 2205 Duplex Stainless Steel supplied by Rolled Alloys Inc. Properties per the Rolled Alloys Bulletin No. 1007 were used in the FEM to simulate the sight glass housing. This steel has minimum yield and ultimate strengths of 65 and 95 ksi. Elastic properties for borosilicate glass (Schott Borofloat 33) were used for the sight glass. The sight glass was assumed to be 1.5 inch thick.

The hull design mass summary is itemized in Table 7. The total mass is 10303 lb_m. The volume of displaced sea water is 305.4 ft^3 and displaced sea water mass is 19550 lb_m . So the net buoyancy is 9247 lb, which exceeds the 4000 lb requirement.

Table 6. Pattern Sequence No. 1 Pattern Table

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	3.10	59	29	9.43	0.02248	0.0450	29.545	5.7	0.00
2	2	4	17.77	1.75	3.10	57	29	9.36	0.02233	0.0893	29.634	11.7	3.11
3	1	2	23.79	1.75	3.10	55	29	9.40	0.02243	0.0449	29.679	17.8	6.24
4	1	2	29.81	1.75	3.10	52	29	9.38	0.02236	0.0447	29.724	23.8	9.37
5	1	2	35.83	1.75	3.10	48	29	9.26	0.02209	0.0442	29.768	29.8	12.51
6	1	2	41.85	1.75	3.10	45	29	9.45	0.02254	0.0451	29.813	35.8	15.66
7	1	2	47.87	1.75	3.10	40	29	9.33	0.02224	0.0445	29.858	41.8	18.82
8	1	2	53.88	1.75	3.10	35	29	9.29	0.02215	0.0443	29.902	47.9	21.99
9	1	2	59.90	1.75	3.10	30	29	9.36	0.02232	0.0446	29.947	53.9	25.17
10	1	2	65.92	1.75	3.10	24	29	9.20	0.02195	0.0439	29.990	59.9	28.36
11	1	2	71.94	1.75	3.10	19	29	9.59	0.02287	0.0457	30.036	65.9	31.55
12	1	2	77.96	1.75	3.10	12	29	9.00	0.02147	0.0429	30.079	71.9	34.76
13	1	2	83.98	1.75	3.10	6	29	8.95	0.02135	0.0427	30.122	78.0	37.97
Hoop	1	2	90.00	1.75	2.90		29	10.00	0.02385	0.0477		84.0	
Total	15	30				482				0.6695			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in^2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 59.00 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

Table 7. Pressure Hull w/ Composite Domes Mass Summary

Component	Constituent	Mass/Component lb_m	Mass/Constituent lb_m
Grade 5 Ti Dome Interface Rings, Qty = 2	Grade 5 Ti	524.6	524.6
Grade 5 Ti Cylinder Interface Rings, Qty = 2	Grade 5 Ti	464.0	464.0
Sight Glass Housing, Qty = 1	Duples SS	248.2	248.2
Sight Glass, Qty = 1	Borosilicate	6.4	6.4
Sight Glass Assy, Qty = 1		254.6	
Blank Fitting, Qty = 1		271.9	
Carbon Composite Cylinder	Axial 37-800		1196.8
Carbon Composite Cylinder	Hoop 37-800		2449.6
Carbon Composite Cylinder	Total 37-800		3646.4
Carbon Composite Cylinder	Resin		1471.4
Carbon Composite Cylinder		5117.8	
Carbon Composite Domes, Qty = 2	37-800		2437.1
Carbon Composite Domes, Qty = 2	Resin		1220.2
Carbon Composite Domes, Qty = 2		3657.3	
EA9394 Adhesive	EA9394	8.6	8.6
HNBR Rubber	HNBR	4.2	4.2
Total Tank		**10303**	

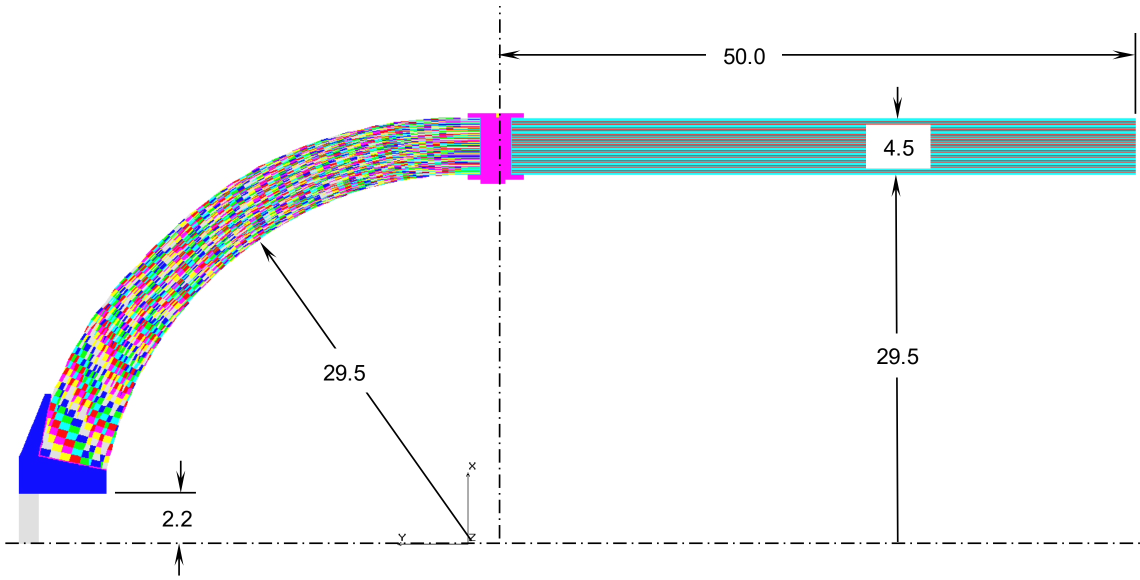


Figure 5. Hull Basic Dimensions, ½ Model w/ Composite Dome

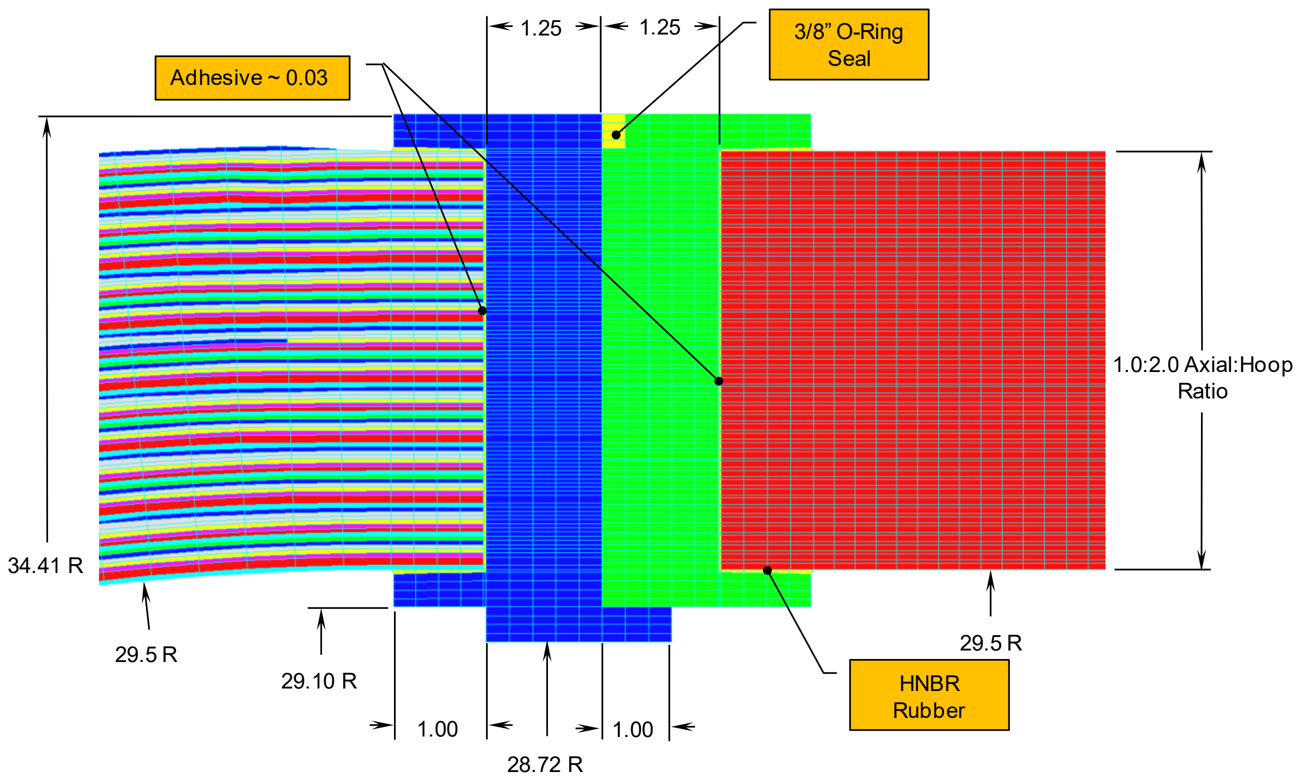


Figure 6. Cylinder-to-Composite Dome Joint Details

4. FINITE ELEMENT ANALYSIS

The FEM was evaluated for the following pressure/temperature sequence: 9000 psi (6000 meter operating pressure), @ 21° C; 9000 psi, @ -5° C (minimum temperature at 6000 meters); increase the pressure @ -5° C until plastic collapse load for the titanium dome is reached.

4.1 Hull Analysis with Titanium Domes

4.1.1 Cylinder Analysis

The strength of the composite cylinder was evaluated assuming failure occurs when either an axial or helical ply reaches the ultimate strain allowable (9400 μ). Factors of safety are calculated for axial and hoop failure at the design pressure for the critical temperature condition (21° C or -5° C) by :

FS = Allowable Strain/Maximum Ply Strain.

The maximum hoop ply strains are shown in Figure 7 for the critical temperature, 21° C. The maximum ply strain, 4289 μ, is at the mid-cylinder inside surface. The calculated factor of safety is 2.19. The maximum ply strain at -5° C is just slightly lower, 4222 μ.

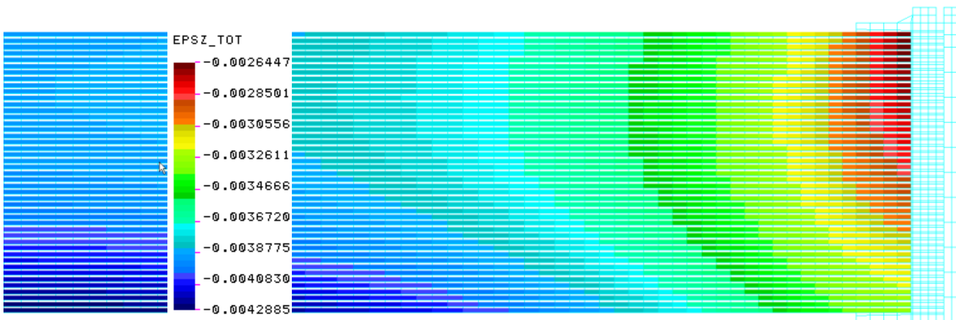


Figure 7. Hoop ply hoop strain distribution @ 9000 psi & 21° C.

The maximum axial ply strains are shown in Figure 8 for the critical temperature, -5° C. The strains are plotted for a scale between 4180 μ corresponding to a factor of safety of 2.25 and the maximum to show the local nature of the high strains. The location of the maximum strain is shown in the figure. The maximum ply strain, 4764 μ, has a calculated factor of safety is 1.97. The maximum ply strain at 21° C is just slightly lower, 4689 μ.

The max axial strain is isolated and stabilized by surrounding plies at relatively low strain and using the flexural strain allowable of 12010μ can be used to calculate a more realistic factor of safety. The factor of safety based on this allowable is 2.52.

So, the probable failure mode is hoop failure on the inner surface at the center of the cylinder at about 2.19 times the design pressure. This prediction is considered to be conservative.

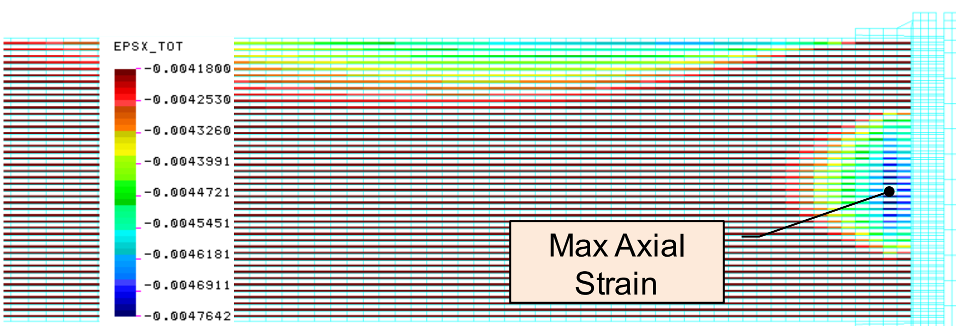


Figure 8. Axial ply axial strain distribution @ 9000 psi & -5° C.

The interlaminar tension (ILT) and interlaminar shear (ILS) distributions are shown in Figure 9 for the design pressure at 21° C. The distributions at -5° C are not significantly different. The maximums for both are at the interface joint. The maximum ILT is 1672 psi, well below the derived 5560 psi.

The ILS for the FEA is high, but is a result of consolidating the axial and hoop plies in the FEM into thicker elements. The stress is caused by the stiffer axial plies punching into the softer adhesive while the softer hoop plies are compressed to higher level. This results in a shear at the interfaces of the axial and hoop plies. By fully interspersing the axial and hoop plies, the axial load on each ply is about 5 times lower, requiring a lower shear for displacement compatibility at the interface. Also, interlaminar shear is matrix dominated and therefore has some ductility, causing even lower shear at high loads. So, neither ILS nor ILT is considered to be a potential failure mode.

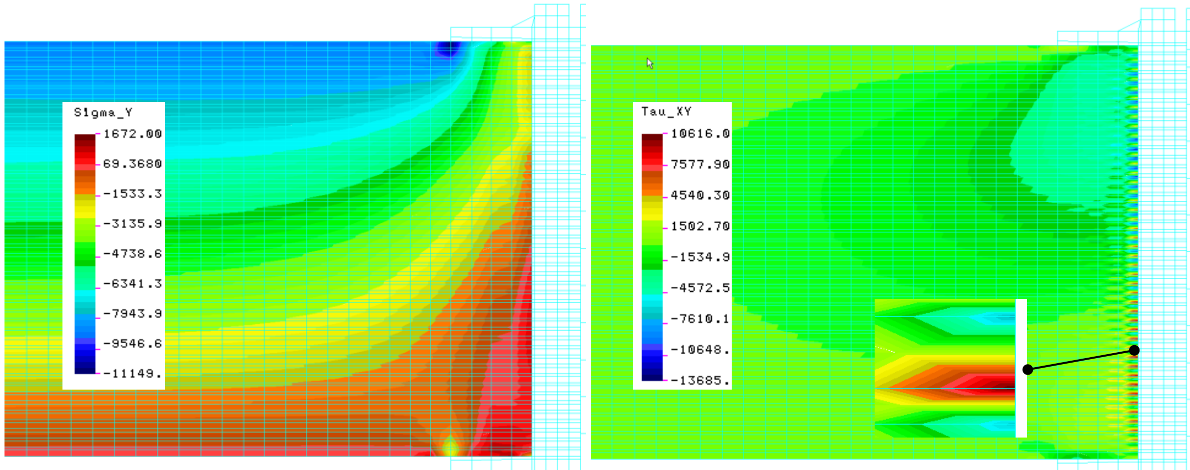


Figure 9. ILT and ILS @ design pressure and 21° C.

4.1.2 Titanium Dome Analysis

The domes were designed to meet the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3 (Ref. 8, the Code) requirements. In this case, the external pressure is the only significant load, and the Code is satisfied if the plastic collapse load is greater than 1.8 times the design pressure (see article KD-231.2 of the Code). The plastic collapse load is defined as the load at which the elastic-plastic FEA becomes unstable and fails to converge to a solution (see KD-231.3 of the Code).

The FEA was run until reaching the plastic collapse pressure at 2.03 times the design pressure (2.03x9000 psi = 18270 psi) at a temperature of -5° C, which exceeds the ASME requirement of 1.8. The results are virtually identical when run at 21° C.

The equivalent plastic strain distribution is shown in Figure 10 for a range of 0.5% to the maximum of 1.68%. The plastic strain is generally less than 0.5% except at the inner surface at the joint where the maximum is 1.68%. The strains are well below the local elongation of 22.3%, so the factor of safety based on stress is well above 2.25. The Von Mises stress distribution is plotted in Figure 11 at 1.88 times the design pressure for a stress range of 100 ksi to 123 ksi, the compressive yield stress. This shows that yielding remote from the joint has just reached the compressive yield stress on the inside surface. Since the behavior is still elastic, the axisymmetric analysis is still valid and the ASME requirement is satisfied. The plastic collapse load of 2.03 times the design pressure may be over stated by this axisymmetric analysis since non-symmetric plastic buckling could occur at a lower load, but greater than 1.88 times the design pressure.

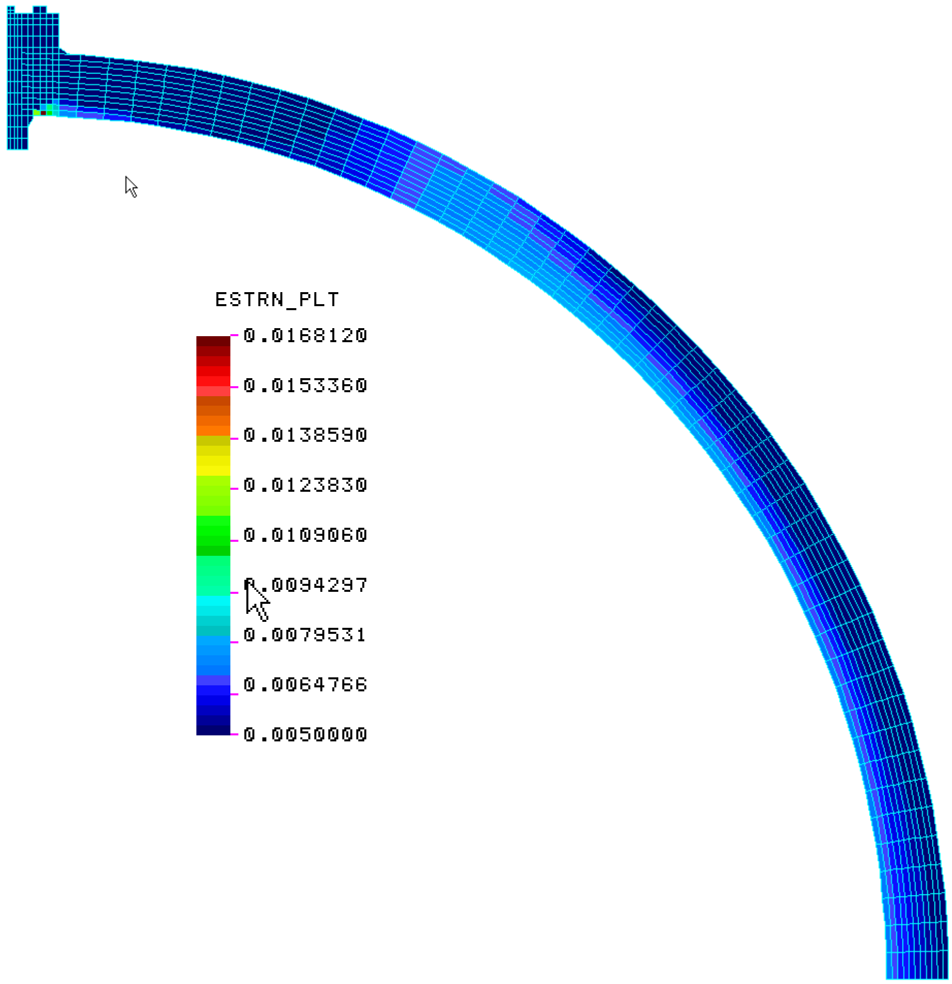


Figure 10. Equivalent plastic strain distribution @ plastic collapse pressure, 18270 psi.

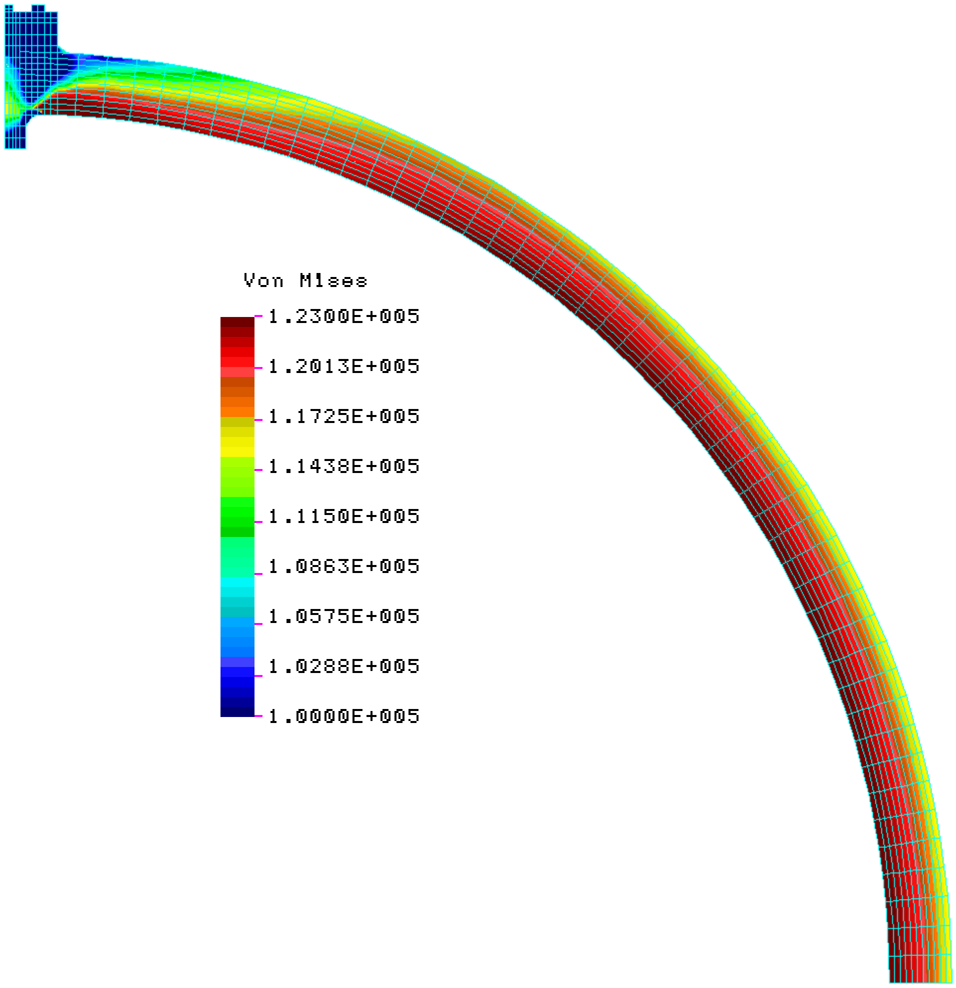


Figure 11. Von Mises stress distribution onset of general dome yielding, 1.88xdesign pressure.

4.2 **Hull Analysis with Composite Domes**

4.2.1 **Cylinder Analysis**

The maximum hoop ply strains are shown in Figure 12 for the critical temperature, 21° C. The maximum ply strain, 4262 μ, is at the mid-cylinder inside surface. The calculated factor of safety is 2.21. The maximum ply strain at -5° C is just slightly lower, 4201 μ.

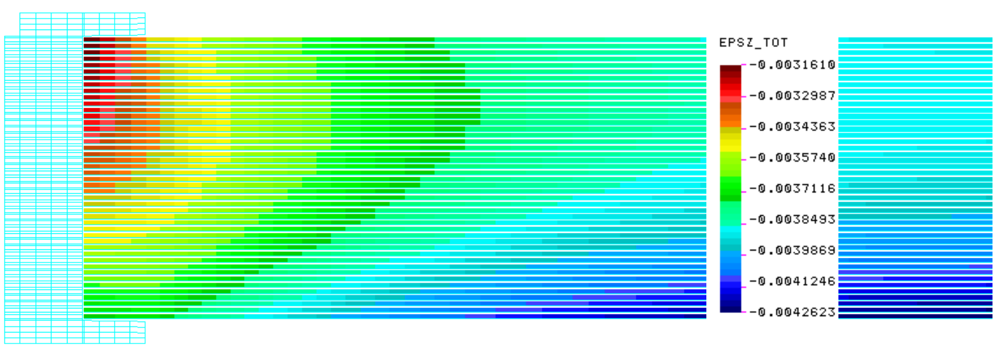


Figure 12. Hoop ply hoop strain distribution @ 9000 psi & 21° C.

The maximum axial ply strains are shown in 13 for the critical temperature, -5° C. The strains are plotted for a scale between 4180 μ corresponding to a factor of safety of 2.25 and the maximum to show the local nature of the high strains. The location of the maximum strain is shown in the figure. The maximum ply strain, 4736 μ, has a calculated factor of safety is 1.98. The maximum ply strain at 21° C is just slightly lower.

The max axial strain is isolated and stabilized by surrounding plies at relatively low strain and using the flexural strain allowable of 12010μ can be used to calculate a more realistic factor of safety. The factor of safety based on this allowable is 2.54.

So, the probable failure mode is hoop failure on the inner surface at the center of the cylinder at about 2.21 times the design pressure. This prediction is considered to be conservative.

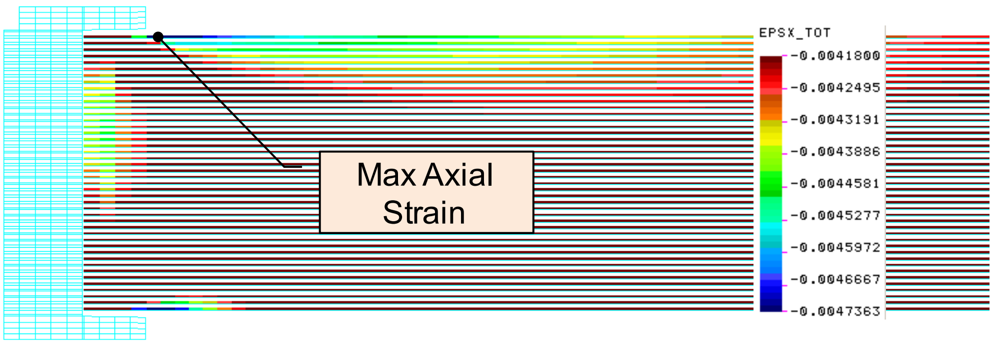


Figure 13. Axial ply axial strain distribution @ 9000 psi & -5° C.

The interlaminar tension (ILT) and interlaminar shear (ILS) distributions are shown in Figure 14 for the design pressure at 21° C. The distributions at -5° C are not significantly different. The maximums for both are at the interface joint. The maximum ILT is 1389 psi, well below the derived 5560 psi.

The ILS for the FEA is high, but is a result of consolidating the axial and hoop plies in the FEM into thicker elements. The stress is caused by the stiffer axial plies punching into the softer adhesive while the softer hoop plies are compressed to higher level. This results in a shear at the interfaces of the axial and hoop plies. By fully interspersing the axial and hoop plies, the axial load on each ply is about 5 times lower, requiring a lower shear for displacement compatibility at the interface. Also, interlaminar shear is matrix dominated and therefore has some ductility, causing even lower shear at high loads. So, neither ILS nor ILT is considered to be a potential failure mode.

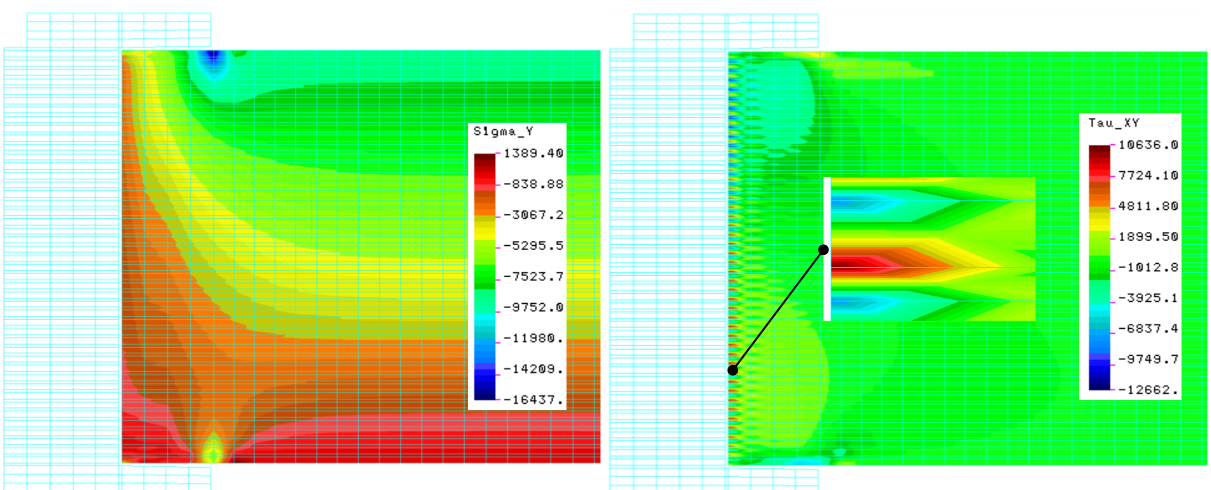


Figure 14. ILT and ILS @ design pressure and 21° C.

4.2.2 **Composite Dome Analysis**

The fiber angle at a point in the dome is not unique due to variation within the finite band width as explained in Appendix D. The differences are negligible at the cylinder joint, but become more significant as the local dome radius decreases. The highest fiber strains occur in the Pattern Sequence 1, the innermost sequence. The fiber strains for each pattern within this sequence were calculated and the maximum values are tabulated in Table 8. The strains are generally highest near the cylinder joint except for pattern No. 1, where the maximum strain occurs in the polar region. The fiber stain distributions for patterns No. 1 and 2 are shown in Figure 15 and Figure 16.

The safety factors relative to the 9400μ compressive allowable are all well above the 2.25 design goal except for pattern H1 near the pole. However, the fiber strain distribution plot in Figure 15 shows the high strain is confined to the small volume of fiber associated with the minimum angle fibers and the surrounding fibers are at a much lower strain level. In this case, the lower strain fibers can be expected to stabilize the high strain fibers and the use of the 12010μ flexural allowable is justified. The safety factor based on the flexural allowable is 2.65. So the expected failure load is 2.51 times the design pressure (22590 psi) at the dome/cylinder joint.

The strain distribution for pattern No. 2 shown in Figure 16 is typical of the remaining patterns, where the maximum strain occurs near the cylinder joint.

Table 8. Composite Dome Fiber Compressive Strain Summary

Pattern	Surface	Coordinate		Strain, μ	FS	
		r, in	z, in			
H1	Inner	7.26	28.59	-4537	2.07	2.65
H2	Inner	29.05	5.40	-3745	2.51	
H3	Inner	29.14	5.42	-3631	2.59	
H4	Inner	29.18	5.43	-3530	2.66	
H5	Inner	29.59	2.86	-3428	2.74	
H6	Inner	29.63	2.86	-3333	2.82	
H7	Inner	29.72	2.35	-3238	2.90	
H8	Inner	29.83	1.31	-3168	2.97	
H9	Inner	29.90	0.26	-3130	3.00	
H10	Inner	29.94	0.26	-3112	3.02	
H11	Inner	29.99	0.26	-3098	3.03	
H12	Inner	30.03	0.26	-3086	3.05	
H13	Inner	30.08	0.26	-3076	3.06	
H14	Inner	30.12	0.26	-3069	3.06	

Note: The factors of safety are calculated relative to the 9400μ compressive allowable, except the 2nd value for H1 is calculated realtive to the 12010μ flexural allowable.

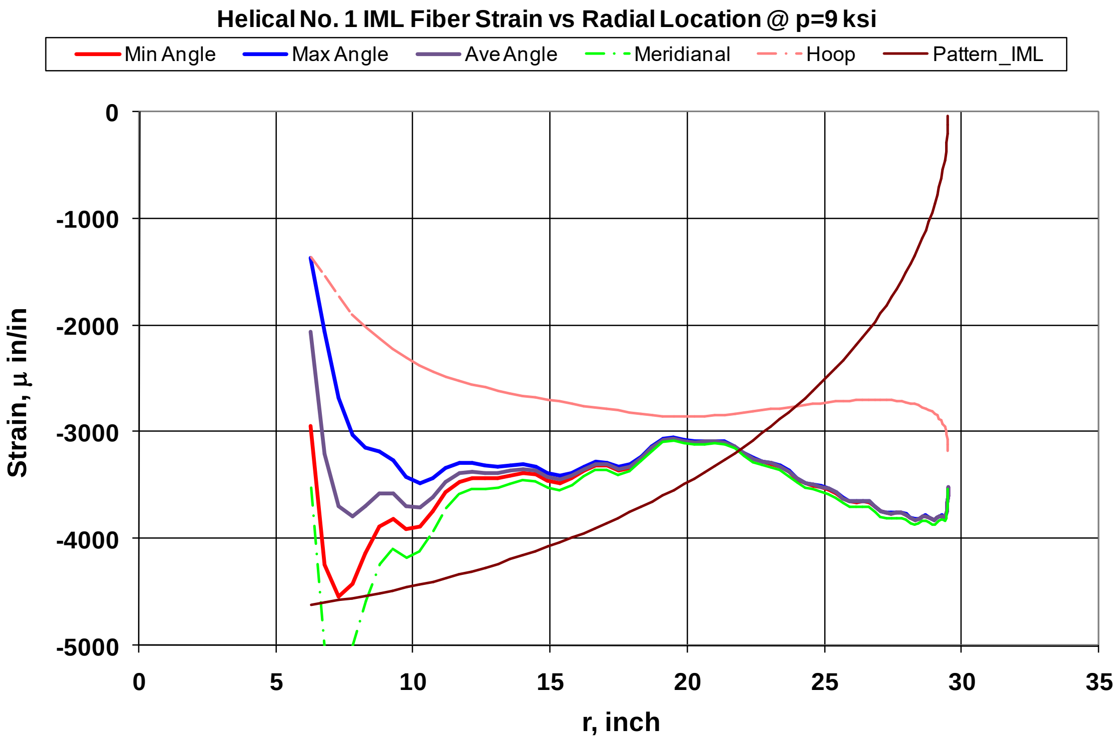


Figure 15. Pattern H1 IML Fiber Strain vs Radial Location @ 9 ksi

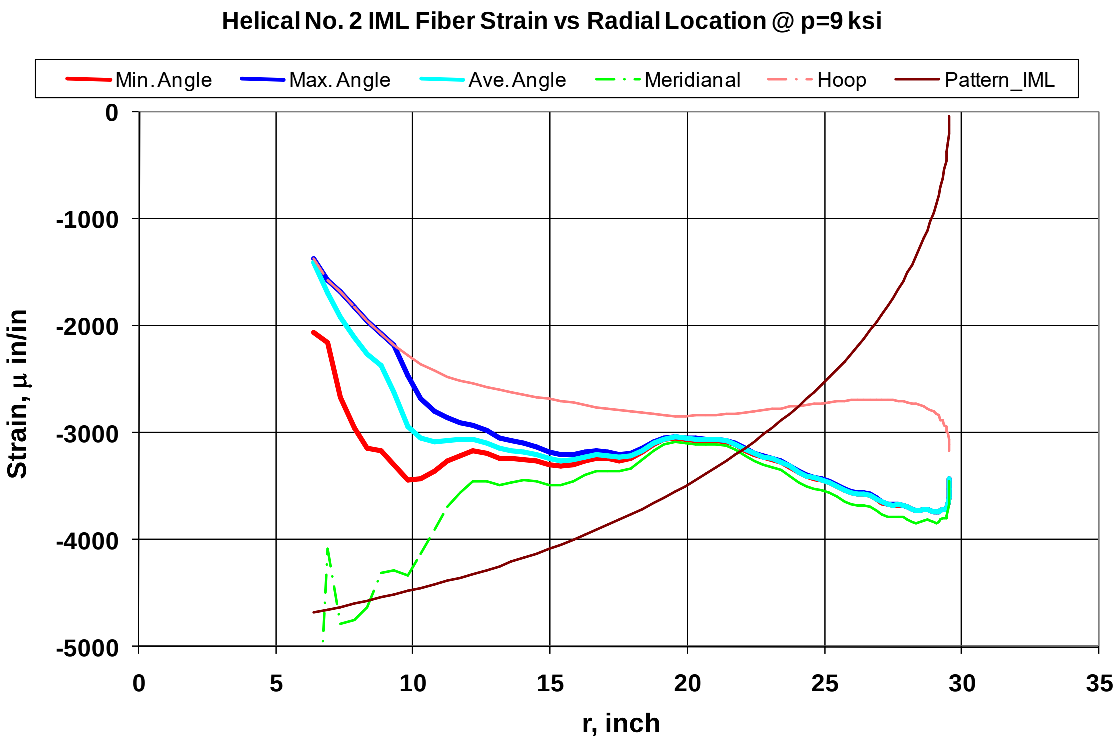


Figure 16. Pattern H2 IML Fiber Strain vs Radial Location @ 9 ksi

4.2.3 **Interface Fitting Analysis**

The Von Mises stress distributions for the interface fittings are shown in Figure 17. This stress is an indication of yielding when compared to the tensile yield strength. The stress is well below the 129 ksi yield strength of the Titanium. These stress levels are caused by the axial compressive load and so are inherent in the design and independent of the interface fitting material. Consequently, any substitute material should have a yield strength greater than 100 ksi. This requirement eliminates aluminum from consideration.

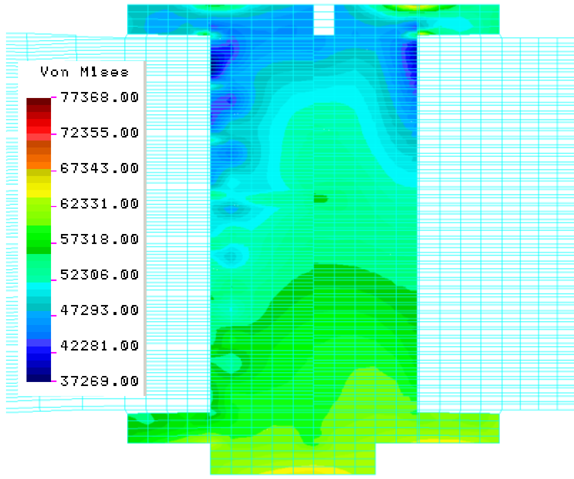


Figure 17. Interface Fitting Von Mises Stress @ 9 ksi & -5° C.

4.2.4 **Sight Glass**

The sight glass is designed and certified for a 10 ksi external design pressure. Rayotek is responsible for the design and certification. The preliminary indication is that the glass will be borosilicate and the housing will be 2205 Duplex Stainless Steel. The glass is “fused” to the housing by heat shrinking the housing on the glass to create a high interface compressive prestress. The prestress is designed such that the glass is held in place by friction and such that the stress state at all points in the glass is compressive at or below the design pressure. The sight glass design used in this analysis is preliminary in order to simulate the interface stiffness and loads for the design of the composite dome.

The results shown in Figure 18 are preliminary and show the Von Mises stress in the housing and glass at the design pressure. The figure on the left shows the configuration as designed. The second is a conservative condition with the HNBR on the bore surface removed so that all of the load is transferred to the flange. These stresses locally exceed the yield strength of the Duplex stainless steel. It is desirable to design for this condition, so the flange thickness will have to increase or a higher strength alloy will be required.

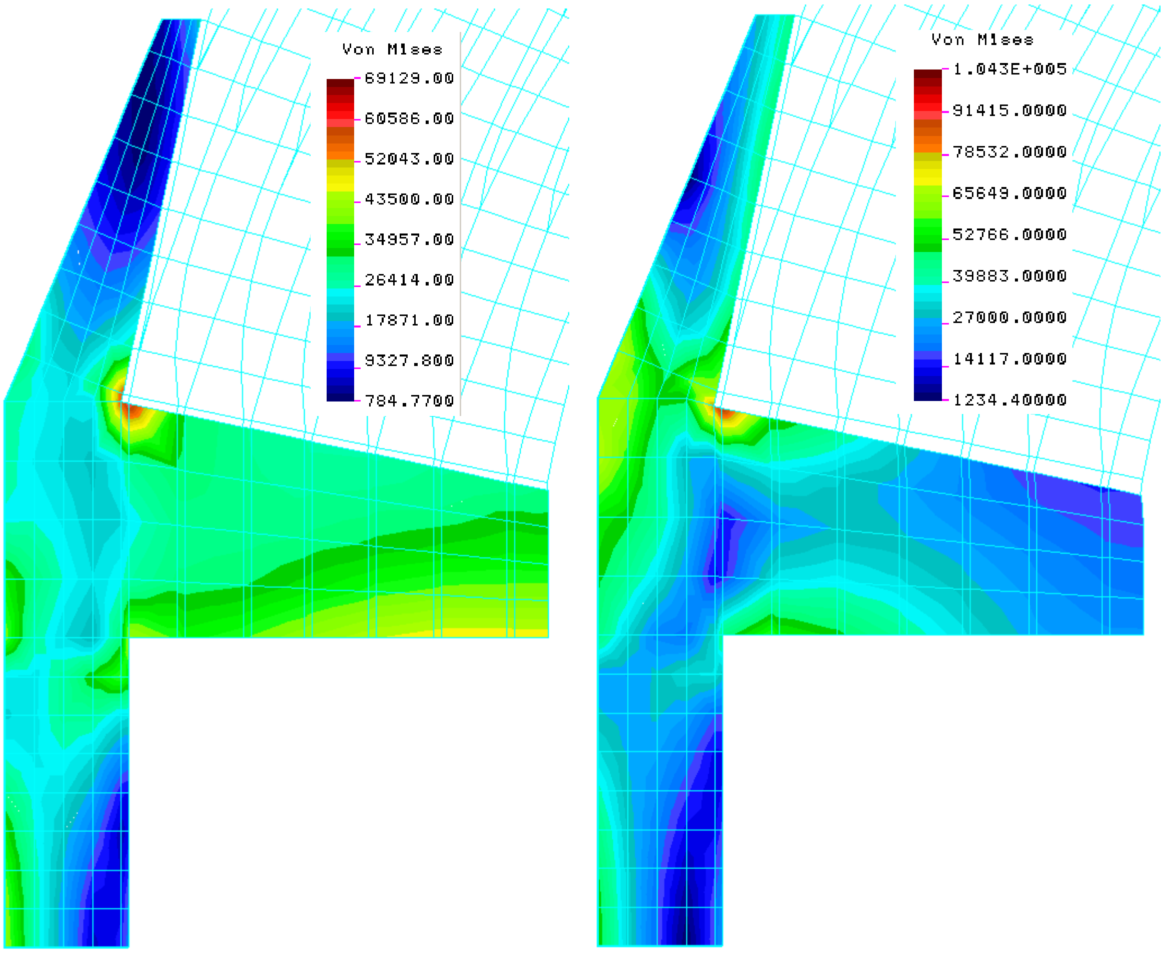


Figure 18. Sight Glass Von Mises Stress Distribution

5. Stability

Both the composite cylinder and dome and titanium dome are subjected to compressive loads and are subject to buckling failure. Semi-empirical methods in NASA SP-8007 (Ref. 4) for cylinders and NASA SP-8032 (Ref. 5) for spheres were used to evaluate the stability of the two components. SCC has a long history of successful design using these methods.

Equation 49 from SP-8007 for orthotropic shells under hydrostatic pressure was used to calculate a classical buckling pressure of 32,406 psi for the composite cylinder. The document recommends an empirical reduction factor of 0.75 be applied to account for differences between test and critical loads calculated from this equation. So, the design buckling pressure is 24,305 psi and the buckling safety factor for the cylinder is 2.70. Composite spheres are much more stable than cylinders of the same thickness and materials, so the spherical composite dome is not buckling critical.

Equation 2 from SP-8007 for isotropic spherical caps under external pressure was used to calculate the safe buckling load for the titanium domes. This equation yields a classical buckling pressure of 93410 psi. The document recommends a lower bound empirical reduction factor according to Figure 19. The intersection of the red line with the curve is the reduction factor for a safe design, which results in a safe design pressure of 16112 psi, 1.79 times the design pressure.

According to SP-8032, the discrepancy between theory and experiment is largely attributed to initial deviations from the ideal spherical shape. Since the shape of these domes will be tightly controlled, the calculated pressure is considered very conservative, and the plastic collapse load is probably the critical pressure.

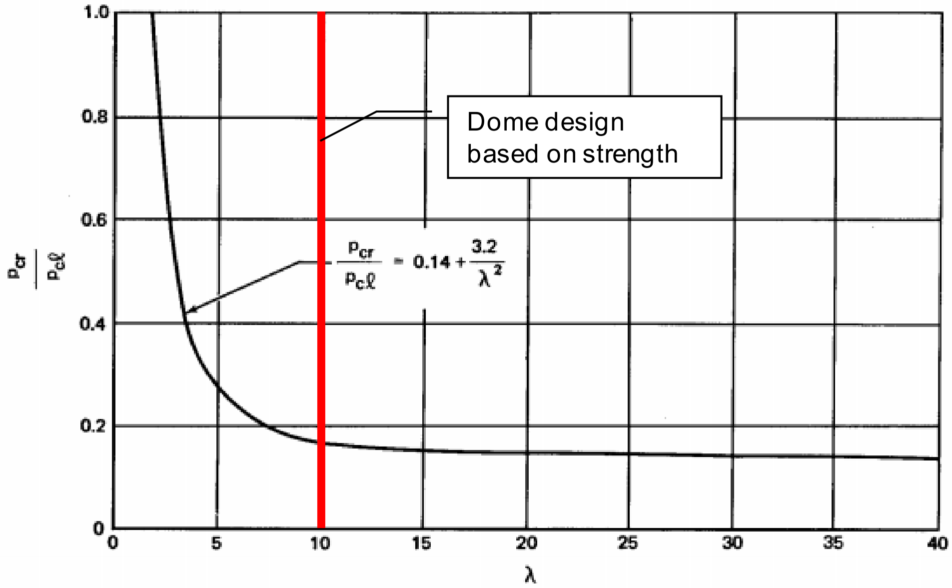


Figure 19. Recommended design buckling pressure for spherical caps (Ref. 5).

6. CONCLUSION

Based on conservative assumptions for the derivation of the ultimate compressive strain capability of the 37-800 carbon epoxy laminate, the designed composite hull has a factor of safety of 2.19 with a hoop failure at the mid cylinder location when paired with the Titanium dome and 2.21 when paired with the Composite dome. The derived allowable ultimate compressive strain needs to be confirmed by the planned sub-scale testing.

The plastic collapse load is between 1.88 and 2.03 times the design load and meets the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3 (Ref. 8) requirements. In order for the sub-scale test article to confirm the composite strength, the sub-scale dome will have to be heavier in order to reach the cylinder collapse pressure. A decision can be made after the tests whether to use the dome designed here or to scale up the heavier sub-scale dome. In any event, the full scale dome will be redesigned to accommodate a site glass and other penetrations.

Appendix A Grafil 37-800WDCarbon Fiber Certification

GRAFIL INC.

Certificate of Conformity

5900 88th Street
Sacramento, CA 95828 USA
P[redacted]
F[redacted]

Order No. **25712**
Customer No. **SPE01**

Deliver To: [redacted] Composites Corporation
4550 Pell Drive
Sacramento, CA 95838-2153
USA

Certificate of Conformity: 20840
GI Reference: 25712
Certificate Date: 01/26/2011
Fiber Type: GRAFIL 37-800WD
30,000 FILAMENTS
CONTINUOUS TOW
Size: 1.0%R
Quantity in lbs: 17,254.51

Customer Purchase Order	Item #	Specification	Salesperson	Customer Part #
P10744	378W3010R	CF-500 Rev. A	Martin Kokoshka	

Batch No.	Date of Manufacture	Quantity (lbs)	Strength (ksi)	Modulus (msi)	Yield (yd/lb)	Fiber Density (lb/in3)	Size Content (% by Mass)	Elongatior (%)
2832A	07/2010	1,948.99	786.1	36.1	310.8	0.06570	1.1	2.20
2832B	07/2010	3,423.36	776.9	36.3	312.0	0.06571	1.0	2.10
2832C	07/2010	3,116.06	777.4	37.0	313.2	0.06562	1.0	2.10
2925C	12/2010	2,331.04	765.7	37.0	308.3	0.06536	1.1	2.10
2925D	12/2010	348.44	743.7	36.8	310.5	0.06537	1.2	2.00
2925F	12/2010	3,054.52	762.8	36.8	310.5	0.06563	1.1	2.10
2925G	12/2010	3,032.10	751.5	37.1	312.8	0.06574	1.2	2.00
	Cert total:	**17,254.51**						

Shelf Life: 2 years from Date of Manufacture

Certified that the supplies/services detailed herein have been inspected and tested in accordance with the conditions and requirements of the contract or conform in all respects to the specification(s), drawings relevant thereto.

Signed: [redacted]
For and on behalf of Grafil Inc.

Print Date: 01/26/2011 Customer Original Page

Form 755.01.02.04 Version 1" Domestic Fiber form (SOCUSAB) on Lett

Appendix B Epoxy Resin

SC:3032-02

starting formulation

No. 8017

Epoxy Resin System for Pultrusion or Filament Winding

EPON™ Resin 826[1] or EPIKOTE® Resin 862[2] with LS-81K[3] Anhydride Curing Agent (MTHPA)

Introduction

EPON™ Resin 826 or EPIKOTE® Resin 862/LS-81K Curing Agent system is based on an epoxy resin cured with an anhydride. LS-81K Curing Agent is a formulated methyltetrahydrophthalic anhydride (MTHPA) containing an internal mold release additive and a cure accelerator. LS-81K is manufactured by Lindau Chemicals Inc.

This resin system's combination of low viscosity, good pot life and fast gelation characteristics during cure make it favorable for wet processing fabrication of composite parts.

- In Pultrusion processes, it processes at high line speeds with low pull loads, and it yields good surface quality. No internal release agents are needed because they are already incorporated in the curing agent.
- In Filament Winding processes, good fiber wet-out is achieved because of the resin system's low viscosity. It also has a relatively long pot life.

Neat resin casting data indicate this resin system has a unique balance of T_g, tensile and flexural strength, while providing high toughness properties.

RESOLUTION
PERFORMANCE PRODUCTS

[1] Bisphenol A epoxy resin.
[2] Bisphenol F epoxy resin.
[3] LS-81K is a specially formulated methyltetrahydrophthalic anhydride (MTHPA) manufactured by Lindau Chemicals, Inc.

EPIKOTE™ EPON™ EPIKURE™ EPI-REZ™ HELOXY™ CARDURA™ VEOVA™

Features
- Non-MDA
- Non-styrene
- Low viscosity
- Long pot life
- Good surface quality
- Retention of properties up to 105 °C (221 °F)
- Good elongation
- High toughness
- Good electrical properties

Suggested Uses
- Composite structures
- Civil engineering
- Sporting goods
- Transportation
- Electrical
- Marine

Chemical Description
- EPON Resin 826 is a bisphenol A epoxy resin
- EPIKOTE Resin 862 is a bisphenol F epoxy resin
- LS-81K is a specially formulated methyltetrahydrophthalic anhydride with an internal mold release agent

Table 1/**Typical neat resin properties of EPON™ Resin 826 or EPIKOTE' 862/LS-81K Anhydride Curing Agent**

RESIN SYSTEM		826/LS-81K	862/LS-81K
EPON™ Resin 826, pbw		100	—
EPIKOTE' Resin 862, pbw		—	100
LS-81K Anhydride Curing Agent, pbw		100	100
Viscosity @ 25 °C,[1] cP		1230	897
Time to double initial viscosity @ 25 °C,[1] hr.		8	5.5
Working life @ 25 °C, time to reach:	1,000 cP, hr.	N/A	1.0
	2,000 cP, hr.	4.6	7.0
	3,000 cP, hr.	>8.0	>9.0
Gel time[2] @ 150 °C (302 °F), sec.		80	82
@ 180 °C (356 °F), sec.		32	28
@ 200 °C (392 °F), sec.		18	18

[1] ASTM D2196 (Brookfield Viscometer – Small Sample Adapter, about 10 grams).
[2] Hot plate gel time.

Typical Properties

	EPON™ Resin 826	EPIKOTE' Resin 862
Epoxide equivalent weight,[1] (EEW)	178-186	166-177
Viscosity @ 25 °C (77 °F),[2] (cP)	6,500-9,500	2,500-4,500
Color,[3] Gardner	1 max.	2 max.
Density @ 25 °C,[4] (lb./gal.)	9.7	9.9
Specific gravity @ 25 °C, (g/cc)	1.16	1.18

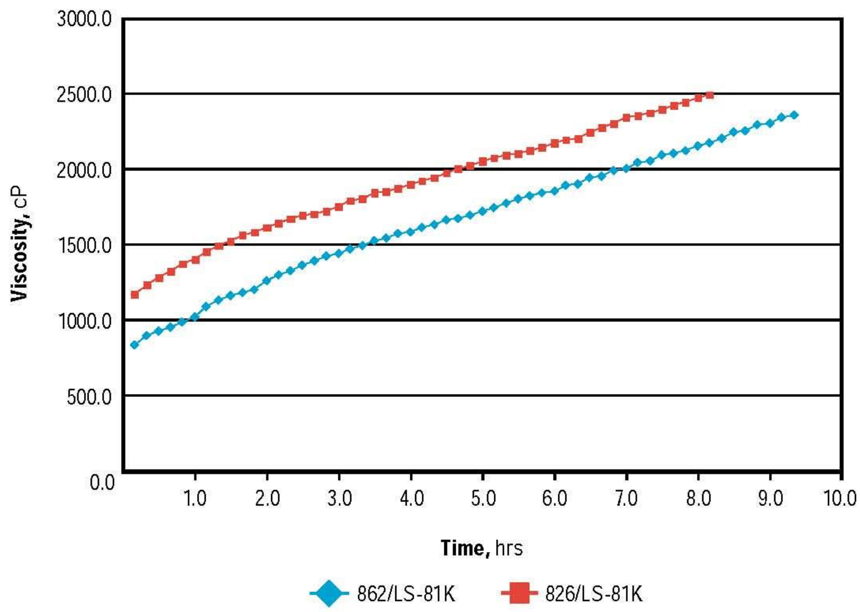
	LS-81K Anhydride Curing Agent
Anhydride equivalent weight	185-195
Viscosity @ 25 °C (77 °F),[5] (cP)	200-300
Density @ 25 °C,[4] (lb. /gal.)	9.8-10.0
Specific gravity @ 25 °C, (g/cc)	1.18-1.20

RESIN SYSTEM – EPON Resin 826 or EPIKOTE Resin 862/LS-81K Anhydride Curing Agent

	826/LS-81K	862/LS-81K
Mix ratio, (pbw)	100/100	100/100
Density @ 25 °C,[4] (lb./gal.)	9.8	9.9
Specific gravity @ 25 °C, (g/cc)	1.18	1.17
Viscosity @ 25 °C (77 °F),[5] (cP)	1230	897

[1] ASTM D1652 (Epoxy Content of Epoxy Resins – Perchloric Acid Method). Grams of resin containing one gram equivalent of epoxide.
[2] ASTM D445 (Kinematic Viscosity – Determination of the viscosity of liquids by Ubbelohde Viscometer).
[3] ASTM D1544 (Gardner Color Scale).
[4] Weight per gallon cup.
[5] ASTM D2196 (Brookfield Viscometer – Small Sample Adapter, about 10 grams).

Graph 1/**EPON™ Resin 826 or 862/LS-81K Anhydride Curing Agent viscosity @ 25 °C (77 °F) – 10 gram sample**



Graph 2/ EPON™ Resin 826 or 862/LS-81K Anhydride Curing Agent cure sweep @ 5 °C per minute

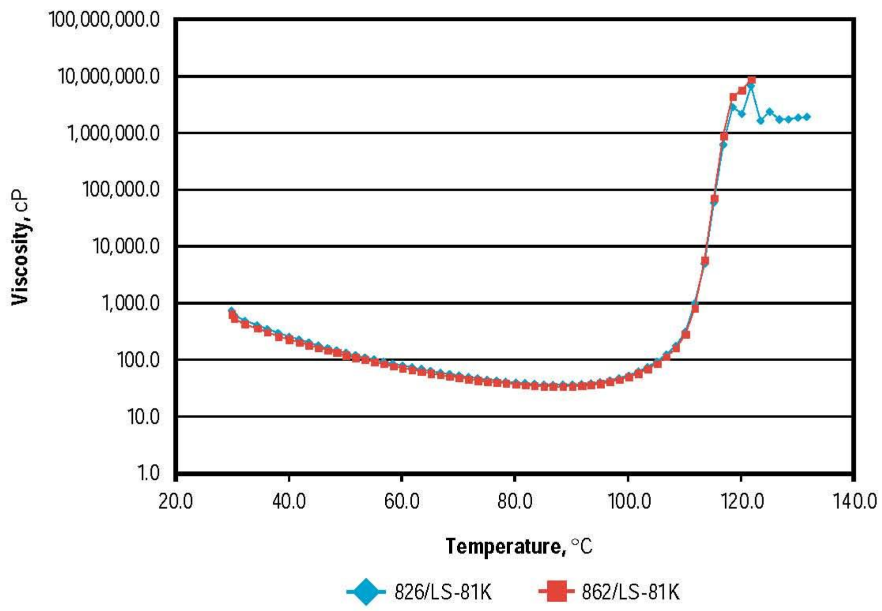


Table 2/ Typical cured neat resin system casting properties of EPON™ Resin 826 or 862/LS-81K Anhydride C.A.

Cure schedule, hrs/°C (°F)	**Step 1**	1.5/66 (151 °F)
	Step 2	1/85 (185 °F)
	Step 3	3/150 (302 °F)

Specific gravity,[1] g/cc	1.20	1.23
Moisture absorption,[2] % wt.	3.01	2.97
Tg by rheometrics (max. tan delta),[3] °C	136 (277 °F)	126 (259 °F)
Tensile[4]		
Break strength, ksi	10.7	10.7
Break elongation, %	5	5
Modulus, ksi	396	413
Flexural[5]		
Strength, ksi	17.8	17.8
Modulus, ksi	439	457
Fracture toughness Kq,[6] psi-in ^.5	1187	1234
Electrical properties		
Dielectric constant[7] **@ 1 Meg Hz & 23 °C**	3.17	3.24
Dissipation factor[7] **@ 1 Meg Hz & 23 °C**	0.018	0.016
Dielectric strength,[8] V/mil	432.3	418.8

[1] ASTM D792 (Density and Specific Gravity (Relative Density) of Plastics by Displacement).
[2] Samples immersed in 65 °C (140 °F) water for 30 days (equilibrium), sample size 0.039 in. x 0.5 in. x 2.5 in.
[3] ASTM D4065 (Dynamic Mechanical Properties of Plastics).
[4] ASTM D638 (Tensile Properties of Plastics).
[5] Per ASTM D790 (Flexural Properties of Unreinforced and Reinforced Plastics).
[6] Per ASTM E399 (Plane-Strain Fracture Toughness).
[7] ASTM D150 (AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation).
[8] ASTM D149 (Dielectric Breakdown Voltage and Dielectric Strength).

Suggested Formulations

	Pultrusion	Filament winding
EPON™ Resin 826 or EPIKOTE' Resin 862, pbw	100	100
LS-81K Anhydride Curing Agent, pbw	100	100
ASP-400P,[1] pbw	10-20	N/A

[1] ASP is a registered trademark of Engelhard Corporation.

Composite Fabrication/ Pultrusion

The properties of this low viscosity and quick cure system at elevated temperatures provide the pultruder with a processable epoxy resin system. The unique resin system characteristics translate into high line speeds, low pull forces and good surface quality. All features are advantages of fabricators who desire the higher performance properties of epoxy resins.

Mixing – A high shear mixer is recommended to insure complete dispersion of the filler. Mixing time should be kept to a minimum to avoid excess heat build-up of the resin system, as this can reduce the working life of the system.

Resin bath – The resin impregnation bath temperature should be as close to 25 °C (77 °F) as possible to maximize working life.

Process – The EPON Resin 826 or EPIKOTE Resin 862 /LS-81K Curing Agent will cure at die temperatures ranging from 170-180 °C (338-356 °F). The optimum temperatures will depend on parameters such as part thickness, line speed, and preheat temperature. The epoxy part will react to a high degree of cure during the pultrusion process. A post cure, however, may enhance the properties.

Composite Fabrication/ Filament Winding

The low viscosity and long working life of the resin system make it desirable for Filament Winding thin wall parts.

Mixing – A high shear mixer is recommended to insure complete mixing. Mixing time should be kept to a minimum to avoid excess heat build-up of the resin system, as this can reduce the working life of the system.

Resin bath – The resin impregnation bath temperature should be as close to 25 °C (77 °F) as possible to maximize working life. However, elevated temperatures may be required to obtain the appropriate viscosity for fiber wet-out.

Process – The 826 or 862/LS-81K system will cure at mandrel/oven temperatures of 80-150 °C within 1-3 hours. The optimum temperatures will depend on parameters such as part thickness.

Packaging, Storage and Shipping

EPON Resin 826 or EPIKOTE Resin 862 is supplied in 55-gallon, DOT 17E, lined steel drums and in bulk and is classified as non-hazardous by DOT regulations (Code of Fed. Reg. Title 49). With time under certain storage conditions, EPON Resin 826 or EPIKOTE Resin 862 may develop crystals. Recommendations regarding storage conditions and reconstitution procedures may be obtained by visiting our web site at www.resins.com.

Suggested Formulations

	Pultrusion	Filament winding
EPON™ Resin 826 or EPIKOTE' Resin 862, pbw	100	100
LS-81K Anhydride Curing Agent, pbw	100	100
ASP-400P,[1] pbw	10-20	N/A

[1] ASP is a registered trademark of Engelhard Corporation.

Composite Fabrication/ Pultrusion

The properties of this low viscosity and quick cure system at elevated temperatures provide the pultruder with a processable epoxy resin system. The unique resin system characteristics translate into high line speeds, low pull forces and good surface quality. All features are advantages of fabricators who desire the higher performance properties of epoxy resins.

Mixing – A high shear mixer is recommended to insure complete dispersion of the filler. Mixing time should be kept to a minimum to avoid excess heat build-up of the resin system, as this can reduce the working life of the system.

Resin bath – The resin impregnation bath temperature should be as close to 25 °C (77 °F) as possible to maximize working life.

Process – The EPON Resin 826 or EPIKOTE Resin 862 /LS-81K Curing Agent will cure at die temperatures ranging from 170-180 °C (338-356 °F). The optimum temperatures will depend on parameters such as part thickness, line speed, and preheat temperature. The epoxy part will react to a high degree of cure during the pultrusion process. A post cure, however, may enhance the properties.

Composite Fabrication/ Filament Winding

The low viscosity and long working life of the resin system make it desirable for Filament Winding thin wall parts.

Mixing – A high shear mixer is recommended to insure complete mixing. Mixing time should be kept to a minimum to avoid excess heat build-up of the resin system, as this can reduce the working life of the system.

Resin bath – The resin impregnation bath temperature should be as close to 25 °C (77 °F) as possible to maximize working life. However, elevated temperatures may be required to obtain the appropriate viscosity for fiber wet-out.

Process – The 826 or 862/LS-81K system will cure at mandrel/oven temperatures of 80-150 °C within 1-3 hours. The optimum temperatures will depend on parameters such as part thickness.

Packaging, Storage and Shipping

EPON Resin 826 or EPIKOTE Resin 862 is supplied in 55-gallon, DOT 17E, lined steel drums and in bulk and is classified as non-hazardous by DOT regulations (Code of Fed. Reg. Title 49). With time under certain storage conditions, EPON Resin 826 or EPIKOTE Resin 862 may develop crystals. Recommendations regarding storage conditions and reconstitution procedures may be obtained by visiting our web site at www.resins.com.

Appendix C Pattern Sequence Tables

The following tables specify the winding details of the seven pattern sequences required to develop the 4.5 inch composite thickness at the dome/cylinder joint. The theoretical thickness is greater than the required 4.5 inch. Note: the pattern angles are the same between sequences except the tows per band changes between sequences 3 and 4 and sequences 5 and 6. The OML will be machined to mate with the interface ring within the required tolerances. If the as wound thickness is less than 4.5 inch, additional hoop windings shall be used to develop additional thickness.

Table 9. Pattern Sequence No. 1

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	3.10	59	29	9.43	0.02248	0.0450	29.545	5.7	0.00
2	2	4	17.77	1.75	3.10	57	29	9.36	0.02233	0.0893	29.634	11.7	3.11
3	1	2	23.79	1.75	3.10	55	29	9.40	0.02243	0.0449	29.679	17.8	6.24
4	1	2	29.81	1.75	3.10	52	29	9.38	0.02236	0.0447	29.724	23.8	9.37
5	1	2	35.83	1.75	3.10	48	29	9.26	0.02209	0.0442	29.768	29.8	12.51
6	1	2	41.85	1.75	3.10	45	29	9.45	0.02254	0.0451	29.813	35.8	15.66
7	1	2	47.87	1.75	3.10	40	29	9.33	0.02224	0.0445	29.858	41.8	18.82
8	1	2	53.88	1.75	3.10	35	29	9.29	0.02215	0.0443	29.902	47.9	21.99
9	1	2	59.90	1.75	3.10	30	29	9.36	0.02232	0.0446	29.947	53.9	25.17
10	1	2	65.92	1.75	3.10	24	29	9.20	0.02195	0.0439	29.990	59.9	28.36
11	1	2	71.94	1.75	3.10	19	29	9.59	0.02287	0.0457	30.036	65.9	31.55
12	1	2	77.96	1.75	3.10	12	29	9.00	0.02147	0.0429	30.079	71.9	34.76
13	1	2	83.98	1.75	3.10	6	29	8.95	0.02135	0.0427	30.122	78.0	37.97
Hoop	1	2	90.00	1.75	2.90		29	10.00	0.02385	0.0477		84.0	
Total	15	30				482				0.6695			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in^2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 59.00 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

Table 10. Pattern Sequence No. 2

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	3.17	59	29	9.22	0.02198	0.0440	30.214	5.7	0.00
2	2	4	17.77	1.75	3.17	57	29	9.16	0.02184	0.0873	30.301	11.7	3.18
3	1	2	23.79	1.75	3.17	55	29	9.20	0.02193	0.0439	30.345	17.8	6.38
4	1	2	29.81	1.75	3.17	52	29	9.17	0.02186	0.0437	30.389	23.8	9.58
5	1	2	35.83	1.75	3.17	48	29	9.06	0.02160	0.0432	30.432	29.8	12.79
6	1	2	41.85	1.75	3.17	45	29	9.24	0.02204	0.0441	30.476	35.8	16.01
7	1	2	47.87	1.75	3.17	40	29	9.12	0.02175	0.0435	30.520	41.8	19.24
8	1	2	53.88	1.75	3.17	35	29	9.08	0.02166	0.0433	30.563	47.9	22.48
9	1	2	59.90	1.75	3.17	30	29	9.15	0.02182	0.0436	30.607	53.9	25.72
10	1	2	65.92	1.75	3.17	24	29	9.00	0.02146	0.0429	30.650	59.9	28.98
11	1	2	71.94	1.75	3.17	19	29	9.38	0.02236	0.0447	30.694	65.9	32.25
12	1	2	77.96	1.75	3.17	12	29	8.80	0.02099	0.0420	30.736	71.9	35.52
13	1	2	83.98	1.75	3.17	6	29	8.75	0.02087	0.0417	30.778	78.0	38.80
Hoop	1	2	90.00	1.75	2.90		29	10.00	0.02385	0.0477		84.0	
Total	15	30				482				0.6557			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in^2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 60.34 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

Table 11. Pattern Sequence No. 3

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	3.24	59	29	9.02	0.02152	0.0430	30.869	5.7	0.00
2	2	4	17.77	1.75	3.24	57	29	8.96	0.02137	0.0855	30.954	11.7	3.25
3	1	2	23.79	1.75	3.24	55	29	9.00	0.02146	0.0429	30.997	17.8	6.51
4	1	2	29.81	1.75	3.24	52	29	8.97	0.02140	0.0428	31.040	23.8	9.78
5	1	2	35.83	1.75	3.24	48	29	8.86	0.02114	0.0423	31.082	29.8	13.06
6	1	2	41.85	1.75	3.24	45	29	9.04	0.02157	0.0431	31.125	35.8	16.35
7	1	2	47.87	1.75	3.24	40	29	8.93	0.02129	0.0426	31.168	41.8	19.65
8	1	2	53.88	1.75	3.24	35	29	8.89	0.02120	0.0424	31.210	47.9	22.95
9	1	2	59.90	1.75	3.24	30	29	8.96	0.02136	0.0427	31.253	53.9	26.27
10	1	2	65.92	1.75	3.24	24	29	8.81	0.02100	0.0420	31.295	59.9	29.59
11	1	2	71.94	1.75	3.24	19	29	9.18	0.02189	0.0438	31.339	65.9	32.92
12	1	2	77.96	1.75	3.24	12	29	8.61	0.02054	0.0411	31.380	71.9	36.26
13	1	2	83.98	1.75	3.24	6	29	8.57	0.02043	0.0409	31.421	78.0	39.61
Hoop	1	2	90.00	1.75	2.90		29	10.00	0.02385	0.0477		84.0	
Total	15	30				482				0.6428			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in^2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 61.65 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

Table 12. Pattern Sequence No. 4

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	3.31	59	30	9.14	0.02180	0.0436	31.513	5.7	0.00
2	2	4	17.77	1.75	3.31	57	30	9.08	0.02166	0.0866	31.599	11.7	3.32
3	1	2	23.79	1.75	3.31	55	30	9.12	0.02175	0.0435	31.643	17.8	6.65
4	1	2	29.81	1.75	3.31	52	30	9.09	0.02168	0.0434	31.686	23.8	9.99
5	1	2	35.83	1.75	3.31	48	30	8.98	0.02142	0.0428	31.729	29.8	13.33
6	1	2	41.85	1.75	3.31	45	30	9.17	0.02186	0.0437	31.773	35.8	16.69
7	1	2	47.87	1.75	3.31	40	30	9.05	0.02157	0.0431	31.816	41.8	20.05
8	1	2	53.88	1.75	3.31	35	30	9.01	0.02148	0.0430	31.859	47.9	23.43
9	1	2	59.90	1.75	3.31	30	30	9.08	0.02165	0.0433	31.902	53.9	26.81
10	1	2	65.92	1.75	3.31	24	30	8.93	0.02128	0.0426	31.945	59.9	30.20
11	1	2	71.94	1.75	3.31	19	30	9.30	0.02218	0.0444	31.989	65.9	33.61
12	1	2	77.96	1.75	3.31	12	30	8.73	0.02082	0.0416	32.031	71.9	37.02
13	1	2	83.98	1.75	3.31	6	30	8.68	0.02070	0.0414	32.072	78.0	40.43
Hoop	1	2	90.00	1.75	2.90		30	10.00	0.02385	0.0477		84.0	
Total	15	30				482				0.6507			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in^2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 62.94 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

Table 13. Pattern Sequence No. 5

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	3.37	59	30	8.96	0.02136	0.0427	32.163	5.7	0.00
2	2	4	17.77	1.75	3.37	57	30	8.90	0.02122	0.0849	32.248	11.7	3.39
3	1	2	23.79	1.75	3.37	55	30	8.93	0.02131	0.0426	32.290	17.8	6.78
4	1	2	29.81	1.75	3.37	52	30	8.91	0.02124	0.0425	32.333	23.8	10.19
5	1	2	35.83	1.75	3.37	48	30	8.80	0.02099	0.0420	32.375	29.8	13.60
6	1	2	41.85	1.75	3.37	45	30	8.98	0.02141	0.0428	32.418	35.8	17.03
7	1	2	47.87	1.75	3.37	40	30	8.86	0.02113	0.0423	32.460	41.8	20.46
8	1	2	53.88	1.75	3.37	35	30	8.83	0.02105	0.0421	32.502	47.9	23.90
9	1	2	59.90	1.75	3.37	30	30	8.89	0.02121	0.0424	32.544	53.9	27.35
10	1	2	65.92	1.75	3.37	24	30	8.74	0.02085	0.0417	32.586	59.9	30.81
11	1	2	71.94	1.75	3.37	19	30	9.11	0.02173	0.0435	32.630	65.9	34.28
12	1	2	77.96	1.75	3.37	12	30	8.55	0.02039	0.0408	32.670	71.9	37.75
13	1	2	83.98	1.75	3.37	6	30	8.51	0.02028	0.0406	32.711	78.0	41.24
Hoop	1	2	90.00	1.75	2.90		30	10.00	0.02385	0.0477		84.0	
Total	15	30				482				0.6385			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in^2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 64.24 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

Table 14. Pattern Sequence No. 6

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	3.44	59	32	9.37	0.02234	0.0447	32.804	5.7	0.00
2	2	4	17.77	1.75	3.44	57	32	9.31	0.02219	0.0888	32.893	11.7	3.46
3	1	2	23.79	1.75	3.44	55	32	9.34	0.02228	0.0446	32.937	17.8	6.92
4	1	2	29.81	1.75	3.44	52	32	9.32	0.02222	0.0444	32.982	23.8	10.39
5	1	2	35.83	1.75	3.44	48	32	9.20	0.02195	0.0439	33.026	29.8	13.88
6	1	2	41.85	1.75	3.44	45	32	9.39	0.02239	0.0448	33.070	35.8	17.37
7	1	2	47.87	1.75	3.44	40	32	9.27	0.02210	0.0442	33.115	41.8	20.87
8	1	2	53.88	1.75	3.44	35	32	9.23	0.02201	0.0440	33.159	47.9	24.38
9	1	2	59.90	1.75	3.44	30	32	9.30	0.02218	0.0444	33.203	53.9	27.91
10	1	2	65.92	1.75	3.44	24	32	9.15	0.02181	0.0436	33.247	59.9	31.43
11	1	2	71.94	1.75	3.44	19	32	9.53	0.02272	0.0454	33.292	65.9	34.98
12	1	2	77.96	1.75	3.44	12	32	8.94	0.02133	0.0427	33.335	71.9	38.52
13	1	2	83.98	1.75	3.44	6	32	8.90	0.02121	0.0424	33.377	78.0	42.08
Hoop	1	2	90.00	1.75	3.20		32	10.00	0.02385	0.0477		84.0	
Total	15	30				482				0.6656			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in^2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 65.52 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

Table 15. Pattern Sequence No. 7

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	3.51	59	32	9.18	0.02190	0.0438	33.460	5.7	0.00
2	2	4	17.77	1.75	3.51	57	32	9.12	0.02175	0.0870	33.547	11.7	3.52
3	1	2	23.79	1.75	3.51	55	32	9.16	0.02185	0.0437	33.590	17.8	7.06
4	1	2	29.81	1.75	3.51	52	32	9.13	0.02178	0.0436	33.634	23.8	10.60
5	1	2	35.83	1.75	3.51	48	32	9.02	0.02152	0.0430	33.677	29.8	14.15
6	1	2	41.85	1.75	3.51	45	32	9.21	0.02195	0.0439	33.721	35.8	17.71
7	1	2	47.87	1.75	3.51	40	32	9.09	0.02167	0.0433	33.764	41.8	21.28
8	1	2	53.88	1.75	3.51	35	32	9.05	0.02158	0.0432	33.807	47.9	24.86
9	1	2	59.90	1.75	3.51	30	32	9.12	0.02174	0.0435	33.851	53.9	28.45
10	1	2	65.92	1.75	3.51	24	32	8.97	0.02138	0.0428	33.894	59.9	32.05
11	1	2	71.94	1.75	3.51	19	32	9.34	0.02228	0.0446	33.938	65.9	35.65
12	1	2	77.96	1.75	3.51	12	32	8.77	0.02091	0.0418	33.980	71.9	39.27
13	1	2	83.98	1.75	3.51	6	32	8.72	0.02080	0.0416	34.022	78.0	42.89
Hoop	1	2	90.00	1.75	3.20		32	10.00	0.02385	0.0477	34.069	84.0	46.5
Total	15	30				482				0.6534			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in^2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 66.83 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

Appendix D Pattern Properties

Prediction of thicknesses and fiber angles becomes more difficult near the polar opening. As illustrated in Figure A.1, at a radius, r, the fiber angle relative to a meridional line varies from one edge of the band to the other. When the radius is less than one band width from the polar opening, the fiber angle at the outside of the band, α_2 in the figure, is 90° while the fiber angle at the inside of the band, α_1 in the figure, is significantly less than 90°. For geodesic domes, the fiber angles at the inside and outside of the band are accurately predicted by equations similar to the geodesic angle equations:

$$\alpha_1(r) = \sin^{-1}\left[\left(\frac{r_{e_1}}{r}\right)\left(1 + k_{\alpha_1}\left(r - r_{e_1}\right)\right)\right], \qquad \alpha_2(r) = \sin^{-1}\left[\left(\frac{r_{e_2}}{r}\right)\left(1 + k_{\alpha_2}\left(r - r_{e_2}\right)\right)\right] \qquad \text{(D.1)}$$

where $k_{\alpha_1} = \dfrac{\left(\bar{r}\sin\bar{\alpha} - r_{e_1}\right)}{r_{e_1}\left(\bar{r} - r_{e_1}\right)}$ and $k_{\alpha_2} = \dfrac{\left(\bar{r}\sin\bar{\alpha} - r_{e_2}\right)}{r_{e_2}\left(\bar{r} - r_{e_2}\right)}$

The radii, r_{e_1} and r_{e_2}, are the edge-of-band radii tangent to the polar opening.

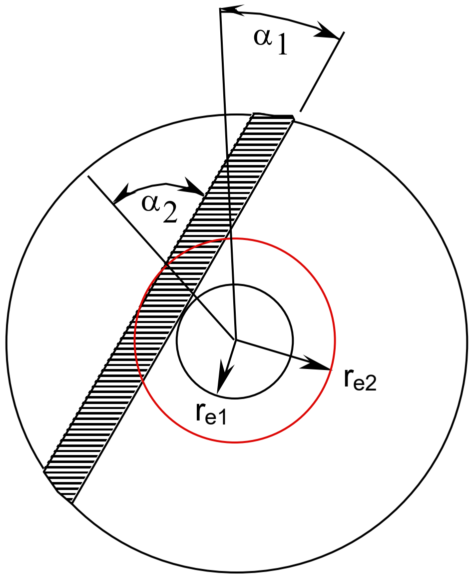


Figure D.1 Variation in Wind Angle within the Fiber Band

The thicknesses in the dome are accurately predicted by the equation for positions on the dome more than two bandwidths from the polar opening:

$$t_\varepsilon(r) = \frac{k_{ref}}{r\cos\alpha(r)}, \qquad \text{(D.2)}$$

Where $k_{ref} = t_{\bar{\alpha}}\bar{r}\cos\bar{\alpha}$ and $t_{\bar{\alpha}}$ is the thickness at the tangent line.

This equation is inaccurate and the following equation is used for positions inside two bandwidths:

$$t_\varepsilon(r) = \frac{k_{ref}}{r}\int_{-\frac{1}{2}}^{\xi}\frac{d\xi}{\cos(\alpha(r,\xi))}; \qquad -\frac{1}{2} \le \xi \le \frac{1}{2} \quad , \qquad \text{(D.3)}$$

where $$\alpha(r,\xi) = \sin^{-1}\left[\left(\frac{r_e(\xi)}{r}\right)\left(1 + k_\alpha(\xi)\left(r - r_e(\xi)\right)\right)\right],\ k_\alpha(\xi) = \frac{\left(\bar{r}\sin\bar{\alpha} - r_e(\xi)\right)}{r_e(\xi)\left(\bar{r} - r_e(\xi)\right)} \quad ,$$

and ξ is the normalized location within the band relative to the center.

The polar opening composite thickness calculated from the above equations is shown by the green line in Figure A.2. There is a characteristic cusp in the contour located one bandwidth from the boss opening. The fiber path would have a negative curvature to actually wind this contour which is impossible. The band will bridge fibers will tend to slip towards the boss for large buildups such as this in the area inside the cusp. Also, the area outside of the cusp will either bridge or be resin rich due to low compaction pressure. The assumed "practical" contour shown in Figure A.2 is estimated based on experience and was used for the analysis. The volume of material is approximately the same for both thickness representations and the material properties were assumed to be the same for both configurations.

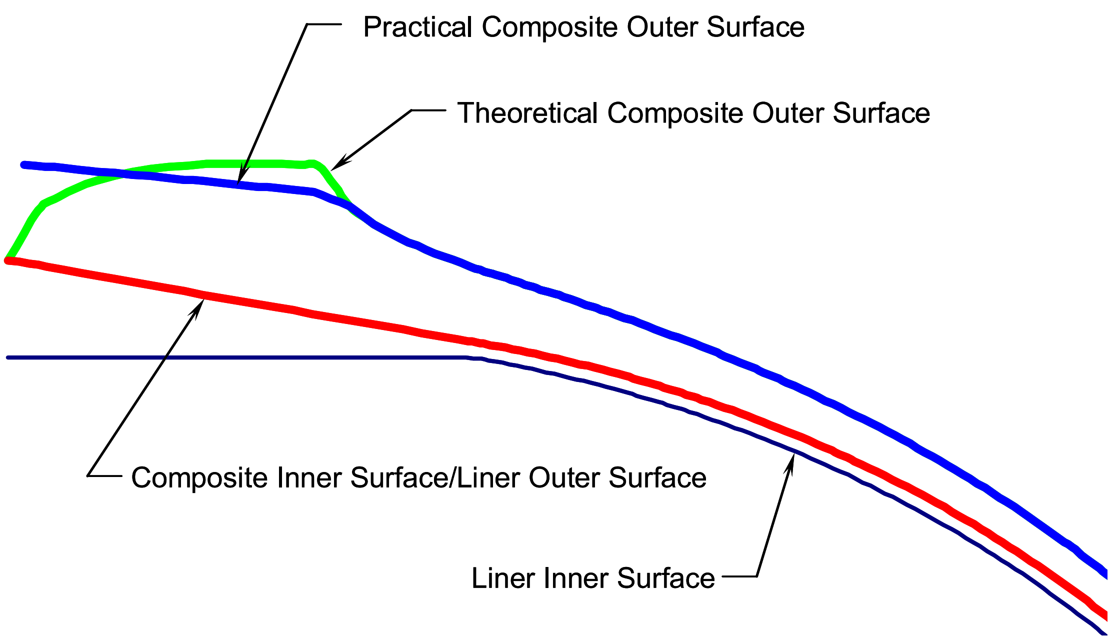


Figure D.2 Theoretical Composite Contour and Assumed Composite Contour

Material properties were calculated for unique cross ply angles of the filament wound composite using an SCC computer program based on the methods of Reference 6. As explained above, in a point in the dome, the fiber angle varies from the inner edge of the band to the outer edge of the band. Consequently, the material properties must represent a range of angles at a point. It can be shown that the material compliance matrix coefficients at a point in the dome are given by:

$$\bar{E}_{ij} = \frac{1}{\alpha_2 - \alpha_1}\int_{\alpha_1}^{\alpha_2} E_{ij}(\alpha)d\alpha \quad . \qquad \text{(D.4)}$$

A numerical integration of this equation using Simpson's rule was used to calculate the local material properties throughout the dome.

Appendix E Subscale Hull Design and Analysis

A 3/10 subscale hull design and analysis is presented in this appendix. The scale was selected (0.294) for a 20 inch composite cylinder OD. The design is shown in Figure 21~~Figures 20 and 21~~ and the composite dome laminate is defined by Table 16 and Table 17.

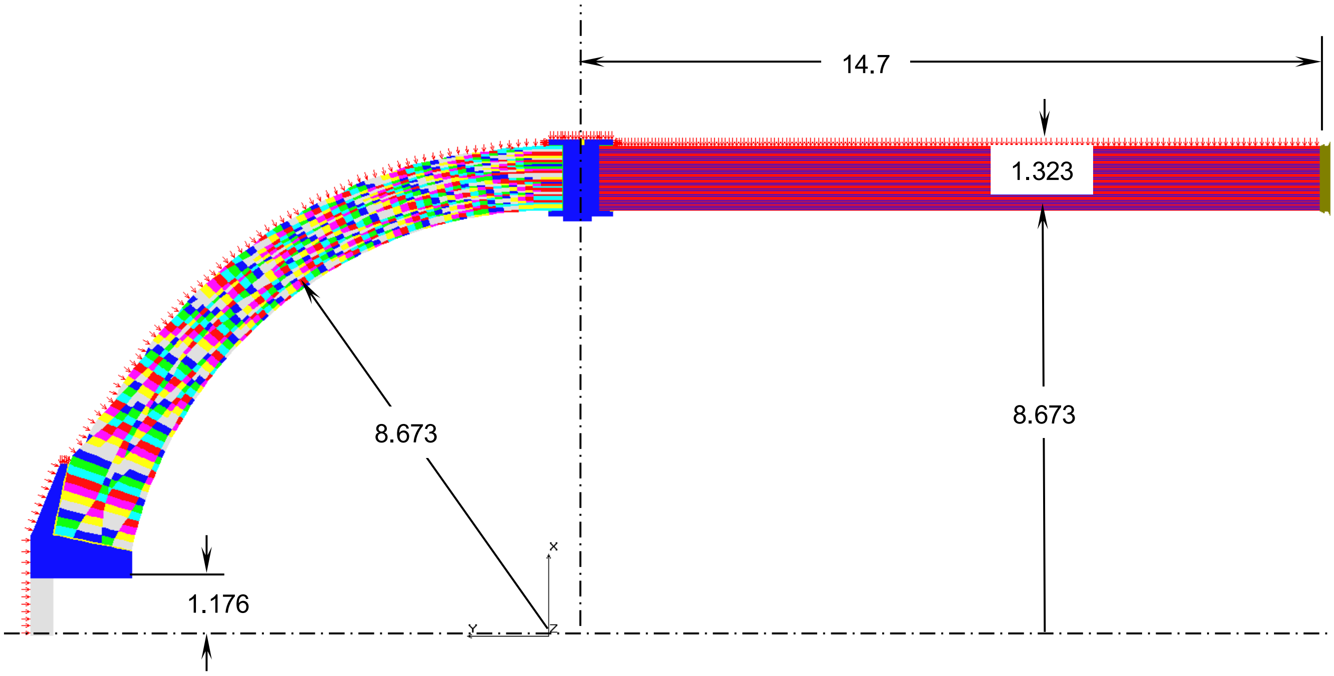


Figure 20. Subscale Hull Basic Dimensions, ½ Model w/ Composite Dome

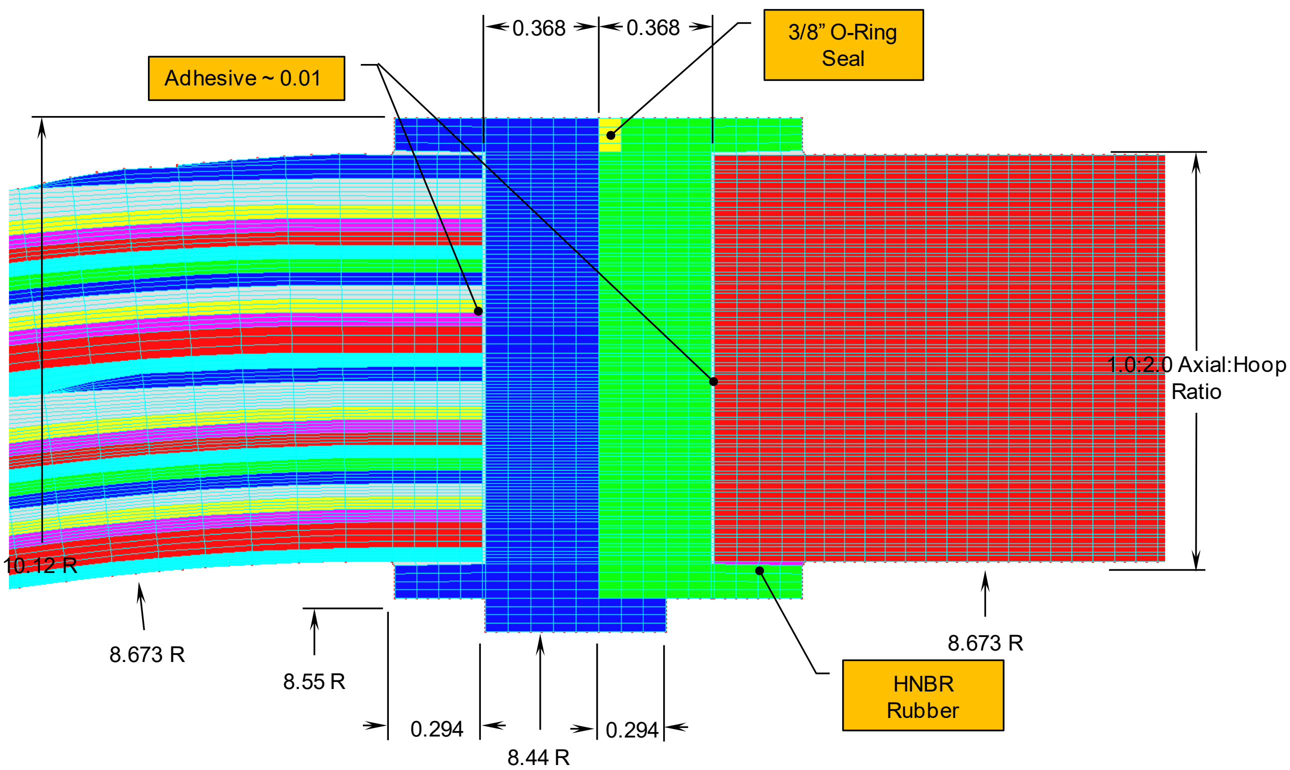


Figure 21. Subscale Cylinder-to-Composite Dome Details

Table 16. Pattern No. 1 Pattern Table

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	0.91	59	8	8.84	0.02109	0.0422	8.717	5.7	0.00
2	2	4	17.77	1.75	0.91	57	8	8.79	0.02095	0.0838	8.801	11.7	0.92
3	1	2	23.79	1.75	0.91	55	8	8.82	0.02104	0.0421	8.843	17.8	1.86
4	1	2	29.81	1.75	0.91	52	8	8.80	0.02097	0.0419	8.885	23.8	2.80
5	1	2	35.83	1.75	0.91	48	8	8.69	0.02072	0.0414	8.926	29.8	3.75
6	1	2	41.85	1.75	0.91	45	8	8.87	0.02114	0.0423	8.969	35.8	4.71
7	1	2	47.87	1.75	0.91	40	8	8.75	0.02087	0.0417	9.010	41.8	5.68
8	1	2	53.88	1.75	0.91	35	8	8.72	0.02078	0.0416	9.052	47.9	6.66
9	1	2	59.90	1.75	0.91	30	8	8.78	0.02094	0.0419	9.094	53.9	7.64
10	1	2	65.92	1.75	0.91	24	8	8.63	0.02059	0.0412	9.135	59.9	8.64
11	1	2	71.94	1.75	0.91	19	8	9.00	0.02145	0.0429	9.178	65.9	9.64
12	1	2	77.96	1.75	0.91	12	8	8.44	0.02014	0.0403	9.218	71.9	10.65
13	1	2	83.98	1.75	0.91	6	8	8.40	0.02003	0.0401	9.258	78.0	11.67
Hoop	1	2	90.00	1.75	0.80		8	10.00	0.02385	0.0477	9.306	84.0	12.7
Total	15	30				482				0.6310			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 17.35 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

Table 17. Pattern No. 2 Pattern Table

Pattern	No. Layers	No. Plies	Wind Angle, °	Bulk Factor	Band Width, in.	No. Circuits per Layer	No. Tows per Band	No. Tows per in.	Ply Thickness @ Equator, in.	Total Thickness @ Equator, in.	r_{OML}, inch @ Equator	Pull-Back Angle, °	Pull-Back, inch
1	1	2	11.75	1.75	0.91	59	8	8.84	0.02109	0.0422	8.717	5.7	0.00
2	2	4	17.77	1.75	0.91	57	8	8.79	0.02095	0.0838	8.801	11.7	0.92
3	1	2	23.79	1.75	0.91	55	8	8.82	0.02104	0.0421	8.843	17.8	1.86
4	1	2	29.81	1.75	0.91	52	8	8.80	0.02097	0.0419	8.885	23.8	2.80
5	1	2	35.83	1.75	0.91	48	8	8.69	0.02072	0.0414	8.926	29.8	3.75
6	1	2	41.85	1.75	0.91	45	8	8.87	0.02114	0.0423	8.969	35.8	4.71
7	1	2	47.87	1.75	0.91	40	8	8.75	0.02087	0.0417	9.010	41.8	5.68
8	1	2	53.88	1.75	0.91	35	8	8.72	0.02078	0.0416	9.052	47.9	6.66
9	1	2	59.90	1.75	0.91	30	8	8.78	0.02094	0.0419	9.094	53.9	7.64
10	1	2	65.92	1.75	0.91	24	8	8.63	0.02059	0.0412	9.135	59.9	8.64
11	1	2	71.94	1.75	0.91	19	8	9.00	0.02145	0.0429	9.178	65.9	9.64
12	1	2	77.96	1.75	0.91	12	8	8.44	0.02014	0.0403	9.218	71.9	10.65
13	1	2	83.98	1.75	0.91	6	8	8.40	0.02003	0.0401	9.258	78.0	11.67
Hoop	1	2	90.00	1.75	0.80		8	10.00	0.02385	0.0477	9.306	84.0	12.7
Total	15	30				482				0.6310			

* Fiber 37-800WD 30k
* 37-800WD Area/Tov 1.36E-03 in2
* 37-800WD Fiber Strength = 600 ksi, Tension
* Number Patterns = 14
* Inside Diameter for analysis = 17.35 in.
* NO. CIRCUITS PER LAYER ARE MINIMUM, MAY BE EXCEEDED.
* Pull-Back Angle = spherical coordinate of the inner band edge
* Pull-Back = Outer layer surface distance from boss

The composite cylinder length and thickness were obtained by factoring the full scale quantities by the scale factor (0.294). The ply thicknesses are not scalable and are basically the same for the full and sub scale cylinder and dome. The HNBR thickness between the sight glass and the polar composite is scaled

(0.10 full scale and 0.03 for the subscale). The cylinder joint adhesive thickness between the composite and interface fittings is also scaled (0.03 inch full scale and 0.01 subscale). The adhesive was replaced with HNBR rubber between the interface rings and composite inner surface to reduce the stress concentration in the inner composite layer caused by the high shear in the adhesive. The interface fittings and the sight glass are scaled by the scale factor.

The full scale cylinder is fully interspersed and the use of the same thickness plies in the subscale hull has negligible affect on the stiffness distribution through the cylinder wall.

The full scale dome is composed of seven wind pattern sequences of fourteen patterns each, ranging from a low angle pattern to a hoop pattern. The subscale pattern sequences are the same, but only two sequences are required for the subscale dome thickness. This results in a much different stiffness distribution through the thickness. The inner patterns within a sequence have higher axial stiffness relative to the outer patterns. Consequently, the subscale dome has high axial stiffness concentrated at the inner surface and the middle surface. The full scale dome has high axial stiffness at 1/7 thickness intervals through the thickness. These stiffness differences result in different stress/strain distributions in the dome and cylinder and at the dome pole between the two designs. The differences are discussed in the analysis summary below

The maximum hoop ply strains are shown in Figure 12~~Figure 22~~ for the critical temperature, 21° C. The maximum ply strain, 4188 μ, is at the mid-cylinder inside surface as it was for the full scale cylinder and is 2% lower. The calculated factor of safety is 2.24. The maximum ply strain at -5° C is virtually the same.

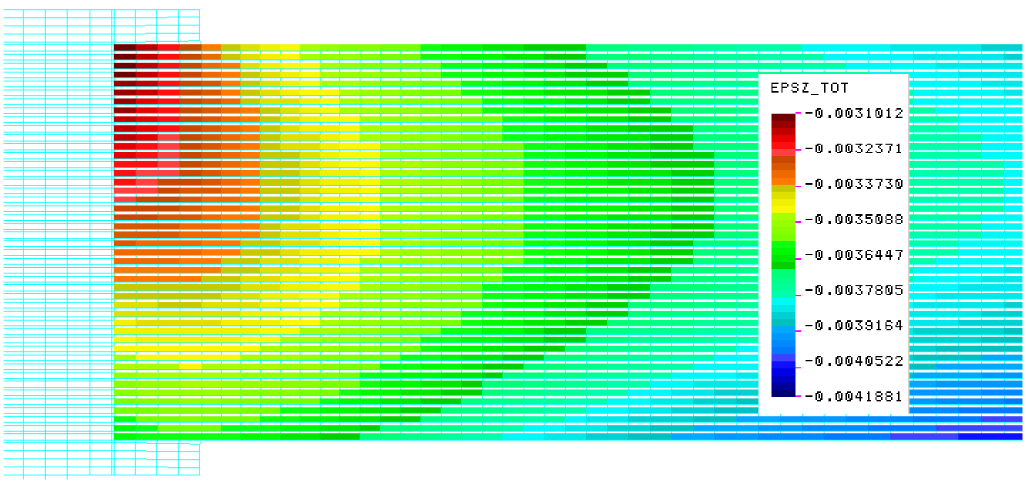


Figure 22. Hoop ply hoop strain distribution @ 9000 psi & 21° C.

The maximum axial ply strains are shown in Figure 13~~Figure 23~~ for the critical temperature, -5° C. The strains are plotted for a scale between 4180 μ corresponding to a factor of safety of 2.25 and the maximum to show the local nature of the high strains. The location of the maximum strain is shown in the figure at the inner surface. The maximum ply strain, 5185 μ, has a calculated factor of safety of 1.81. The maximum axial strain for the full scale cylinder was located at the outer surface and was 9% lower.

The max axial strain is isolated and stabilized by surrounding plies at relatively low strain and using the flexural strain allowable of 12010μ can be used to calculate a more realistic factor of safety. The factor of safety based on this allowable is 2.32.

So, the probable failure mode is hoop failure on the inner surface at the center of the cylinder at about 2.24 times the design pressure. This prediction is considered to be conservative.

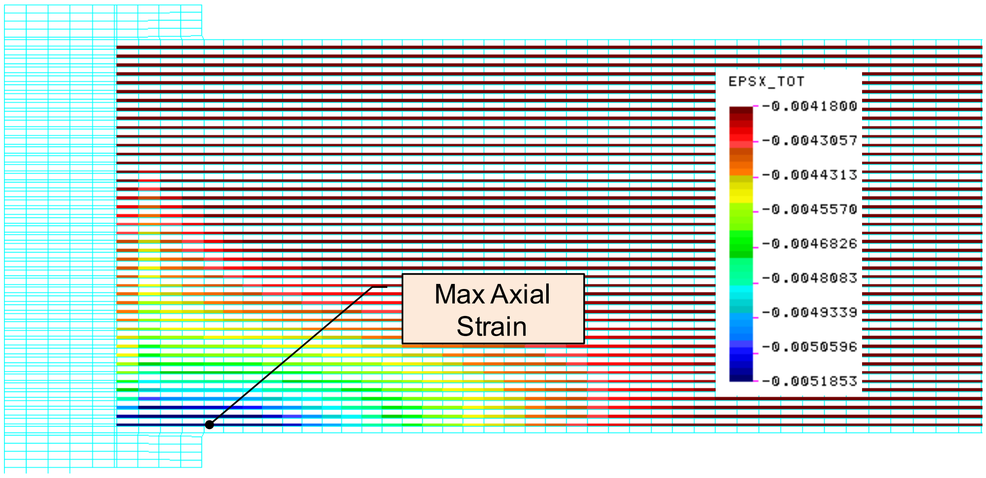


Figure 23. Axial ply axial strain distribution @ 9000 psi & -5° C.

The highest dome fiber strains occur in the Pattern Sequence 1, the innermost sequence. The fiber strains for each pattern within this sequence were calculated and the maximum values are tabulated in Table 8~~Table 18~~. The strains are generally highest near the cylinder joint except for pattern No. 1, where the maximum strain occurs in the polar region. The fiber stain distributions for patterns No. 1 and 2 are shown in Figure 15~~Figure 24~~ and Figure 16~~Figure 25~~.

The safety factors relative to the 9400µ compressive allowable are all well above the 2.25 design goal including pattern H1 near the pole. This differs from the full scale dome where the strain was 23% higher. The large difference can be attributed to the large difference in stiffness distribution of the two pattern sequence subscale and the seven pattern sequence full scale. The fiber strain distribution plot in Figure 15~~Figure 2~~ shows the high strain is confined to the small volume of fiber associated with the minimum angle fibers and the surrounding fibers are at a much lower strain level. In this case, the lower strain fibers can be expected to stabilize the high strain fibers and the use of the 12010µ flexural allowable is justified. The safety factor based on the flexural allowable is 3.27. So the expected failure load is 2.62 times the design pressure (25380 psi) at the dome/cylinder joint.

The strain distribution for pattern No. 2 shown in Figure 16~~Figure 25~~ is typical of the remaining patterns, where the maximum strain occurs near the cylinder joint.

The Von Mises stress distributions for the interface fittings are shown in Figure 26. This stress is an indication of yielding when compared to the tensile yield strength. The stress is well below the 129 ksi yield strength of the Titanium.

Table 18. Composite Dome Fiber Compressive Strain Summary

Pattern	Surface	Coordinate		Strain, μ	FS	
		r, in	z, in			
H1	Inner	2.14	8.41	-3676	2.56	3.27
H2	Inner	8.57	1.59	-3582	2.62	
H3	Inner	8.65	1.61	-3451	2.72	
H4	Inner	8.70	1.62	-3368	2.79	
H5	Inner	8.84	0.85	-3291	2.86	
H6	Inner	8.89	0.86	-3230	2.91	
H7	Inner	8.94	0.71	-3311	2.84	
H8	Inner	9.00	0.39	-3365	2.79	
H9	Inner	9.05	0.08	-3381	2.78	
H10	Inner	9.09	0.08	-3372	2.79	
H11	Inner	9.13	0.08	-3353	2.80	
H12	Inner	9.18	0.08	-3338	2.82	
H13	Inner	9.22	0.08	-3334	2.82	
H14	Inner	9.26	0.08	-3329	2.82	

Note: The factors of safety are calculated relative to the 9400μ compressive allowable, except the 2nd value for H1 is calculated realtive to the 12010μ flexural allowable.

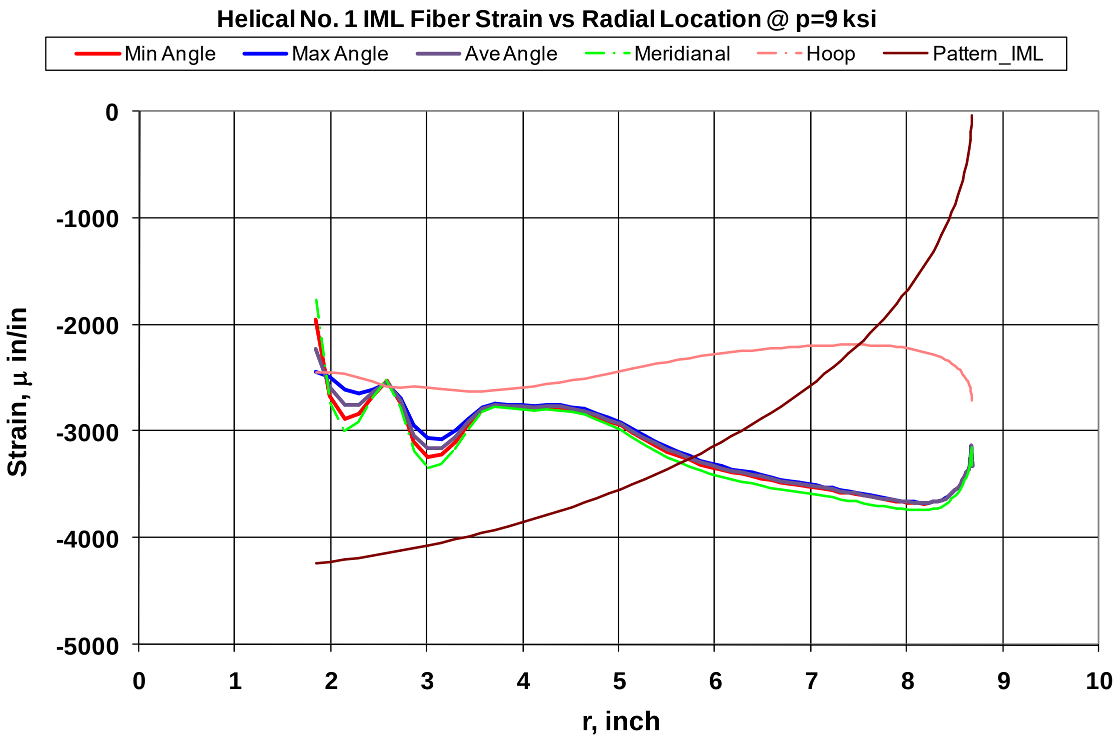


Figure 24. Pattern H1 IML Fiber Strain vs Radial Location @ 9 ksi

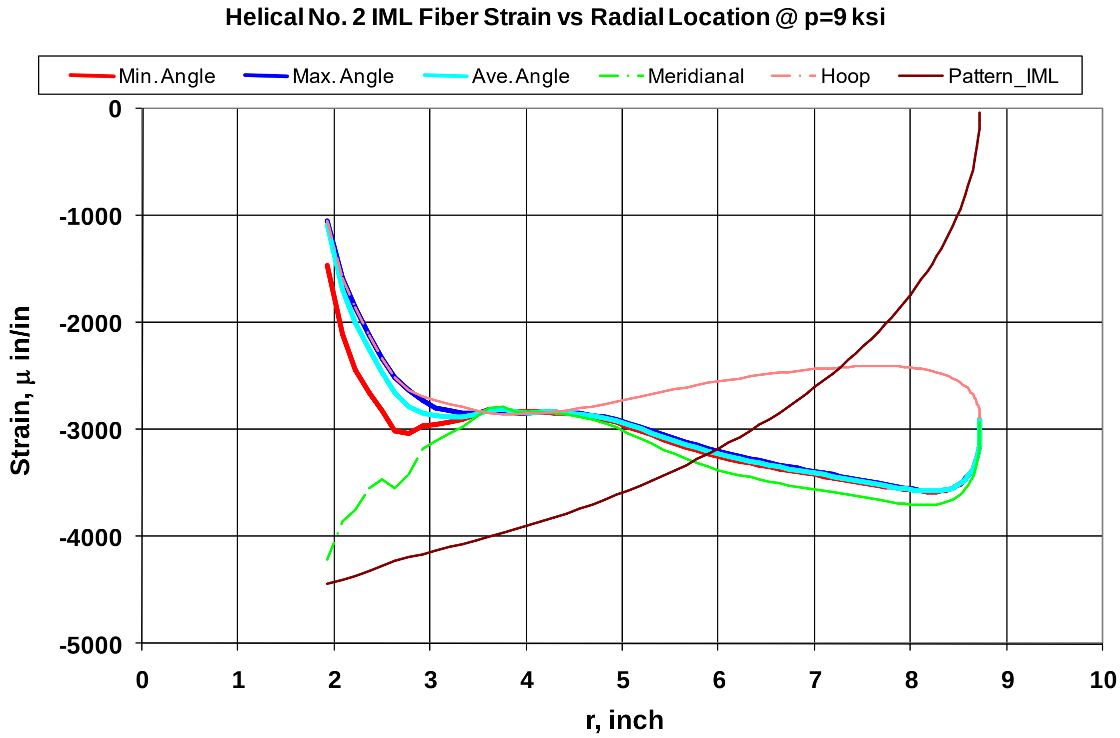


Figure 25. Pattern H2 IML Fiber Strain vs Radial Location @ 9 ksi

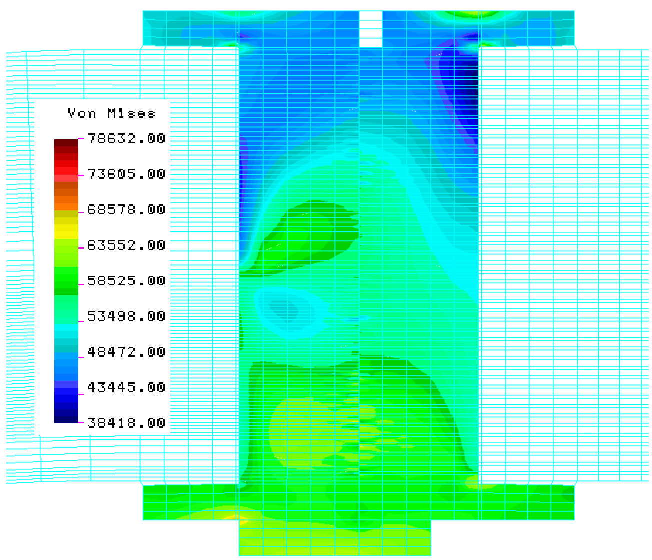


Figure 26. Interface Fitting Von Mises Stress @ 9 ksi & -5° C.