Fermi National Accelerator Laboratory

ArgonCube Cryostat Technical Proposal

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Introduction

This document is a design proposal for the ArgonCube cryostat. The design of ArgonCube is modeled off the 35 Ton cryostat, which is currently operational at Fermilab. The 35T cryostat (US short tons) is a membrane cryostat that consists of a thin layer of corrugated stainless steel followed by insulation and concrete. The goal of the ArgonCube design is to minimize the radiation length of one cryostat wall. This can be accomplished by creating a "window" in one wall and replacing the concrete with a thinner material, such as G10. G10 was the primary material analyzed for this report. However, the group is currently researching other materials, including Carbon Fiber, and other window concepts to achieve the low-radiation length cryostat wall.

Contents

Membrane Cryostat Background Information

Membrane cryostats consist of a very thin layer of corrugated stainless steel (the membrane) surrounded by a structural support system and insulation. The membrane design, shown in Figure 1, allows for expansion and contraction of the stainless steel wall, which is typically a few millimeters thick. Membrane cryostats have been successfully used for transportation and storage in the liquid natural gas (LNG) industry since 1959 [1]. With advancing technology, tanker ships now have the capacity to carry up to 266,000m^3 of LNG in membrane vessels [2].

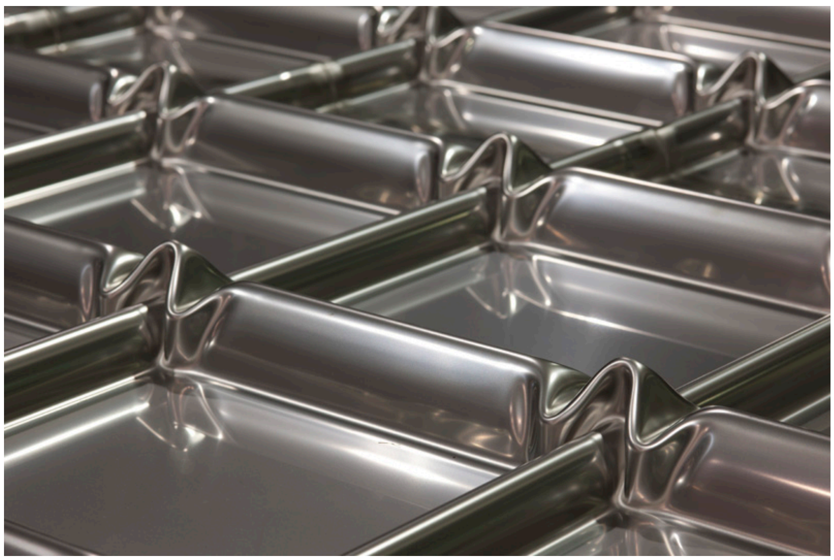

Figure 1: Section of membrane wall at Fermilab [3]

35T Experiment- Summary of Successfully Built Membrane Cryostat

Fermilab built a membrane cryostat for the 35 Ton experiment in 2013. IHI Corporation designed the membrane cryostat and oversaw the installation process at Fermilab. The 35T cryostat, with a volume of 29m^3, was built as a prototype to determine if membrane tank technology would meet the scientific and engineering requirements of the LBNF/DUNE project. Factors taken into consideration during the design and construction processes were thermal performance, feasibility for liquid argon, argon purity, and leak tightness [4]. These goals were successfully met. The heat leak through the cryostat walls, calculated by Terry Tope, was found to equal 11.5 W/m^2 [5]. The 35T cryostat has proven to be feasible for liquid argon use and has been operational since 2014. Physicists have achieved high purity levels of liquid argon, more than 1.4 millisecond electron lifetimes, by circulating the liquid argon through an external filtration system [4]. The two filters, the first containing a molecular sieve and the second containing copper pellets, remove water and oxygen impurities from the liquid argon. During the initial cryostat pressure test, a leak check was performed on the membrane and no leaks were found [4].

There are eight layers that make up the 35T vessel walls. The layers are summarized in Table 1, below. The GRE/GRU layers are estimated to be 0.5mm thick, so the radiation length for these two layers was considered negligible.

Table 1: 35 Ton Cryostat Layers

Layer	Material	Thickness (mm)
Membrane	304 Stainless Steel	2
Fireproof board	Calcium Silicate board	10
GRE/GRU	Glass reinforced epoxy/glass reinforced urethane	0.5
Insulation	High temperature polyurethane foam	190
GRE/GRU	Glass reinforced epoxy/glass reinforced urethane	0.5
Insulation	High temperature polyurethane foam	200
Moisture Barrier	Carbon Steel	1.2
Reinforced Concrete	Reinforced concrete	300

Terry Tope's pressure vessel engineering note on the 35T cryostat contains the structural calculations and testing of the concrete. Cured concrete cylinders were tested 5, 7, and 28 days after being poured. The resulting 28-day compressive strength was 35.9MPa (5,213psi), which met the 34.5MPa (5,000psi) requirements for 35T [5]. The design pressure of 35T is 20.6kPa (3psig) at -189°C (-309°F).

Design Proposal for ArgonCube Cryostat

The basis of the ArgonCube cryostat design stems from the design of the 35 Ton vessel. The proposal is to build a membrane vessel for ArgonCube with the same (or similar) cryostat walls as 35T. A critical design component of the ArgonCube cryostat is reducing the radiation length through one of the cryostat walls. The goal is to achieve a radiation length of 0.5. This minimized radiation length is only important for the cryostat wall between the liquid and gas vessels (Figure 2). Calculations determined that the radiation length through the 35T vessel is 2.9. The largest contributing factor to this high radiation length is the concrete layer. Table 2 shows the layers and corresponding radiation lengths.

Table 2: Radiation Lengths of 35 Ton Cryostat Layers

Layer	Radiation Length based on Material Composition		Density	Thickness	Calculated Radiation Length	Percentage of Total Radiation Length
	g/cm^2	*mm*	*g/cm^3*	*mm*	*unitless*	*%*
304 SS Membrane	13.904	17.6	7.9	2	0.11	3.95
Fireproof Board	23.955	399.25	0.6	10	0.03	0.87
Insulation 1st Layer	40.8	5440	0.075	190	0.03	1.21
Insulation 2nd Layer	40.8	5440	0.075	200	0.04	1.28
Carbon Steel	7.85	17.60	7.9	1.2	0.07	2.37
Concrete	28.875	115.5	2.5	300	2.60	90.31
Total Radiation Length					2.88	100.00

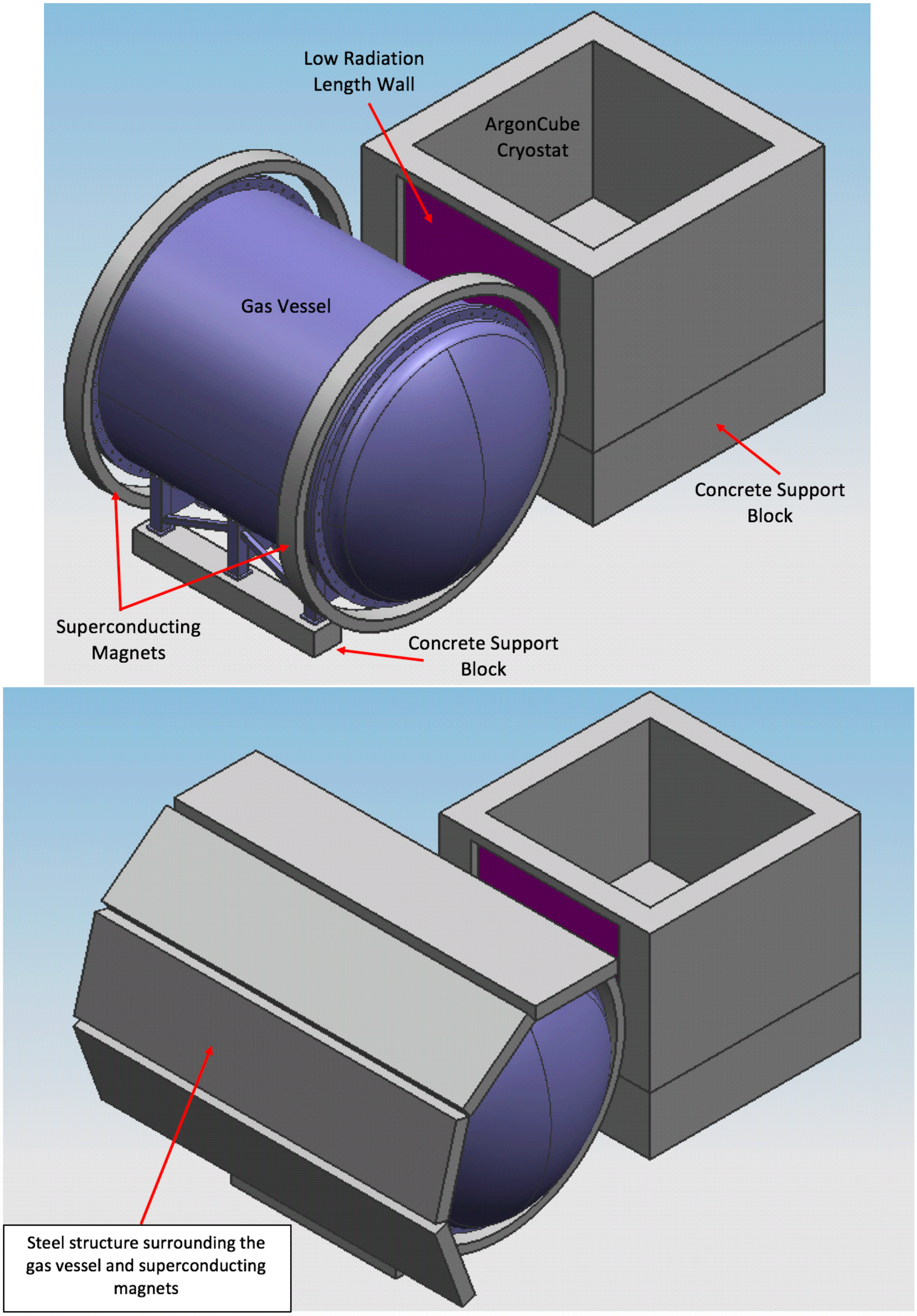

Figure 2: ArgonCube cryostat and gas vessel (top) and depiction of steel shielding around magnets (bottom)

A layer of G10 instead of concrete could be used for the ArgonCube cryostat to maintain structural requirements and minimize radiation length. The layers of the ArgonCube cryostat, including the G10 window, are shown in Figure 3. A 3.25m x 4.5m x 0.1m (10.7ft x 14.8ft x 4in) window of G10 would be fixed within the surrounding concrete wall (Figure 4). The specific method of fixing the sheet of G10 in the surrounding concrete has yet to be finalized. However, the edge conditions for the calculations remain the same regardless of what material or method is used. The area of the G10 window covers most of the dimensions of the cylindrical TPC (5m diameter, 5m-long) in the gas vessel. This ensures that a large portion of the gas TPC area would see the low radiation length. The radiation length through the eight layers of the ArgonCube cryostat wall, using G10 instead of concrete, is 0.8. Calculations for this result are shown in Appendix A. Table 3 summarizes each layer and the corresponding radiation lengths.

Table 3: Radiation Lengths of ArgonCube Cryostat Layers with G10 Sheet

Layer	**Radiation Length based on Material Composition**		**Density**	**Thickness**	**Calculated Radiation Length**	**Percentage of Total Radiation Length**
	g/cm^2	*mm*	*g/cm^3*	*mm*	*unitless*	*%*
304 SS Membrane	13.904	17.6	7.9	2	0.11	14.16
Fireproof Board	23.955	399.25	0.6	10	0.03	3.12
Insulation 1st Layer	40.8	5440	0.075	190	0.03	4.35
Insulation 2nd Layer	40.8	5440	0.075	200	0.04	4.58
Carbon Steel	7.85	17.60	7.9	1.2	0.07	8.50
G10 Sheet	32.98	194	1.7	101.6	0.52	65.28
Total Radiation Length					0.80	100.00

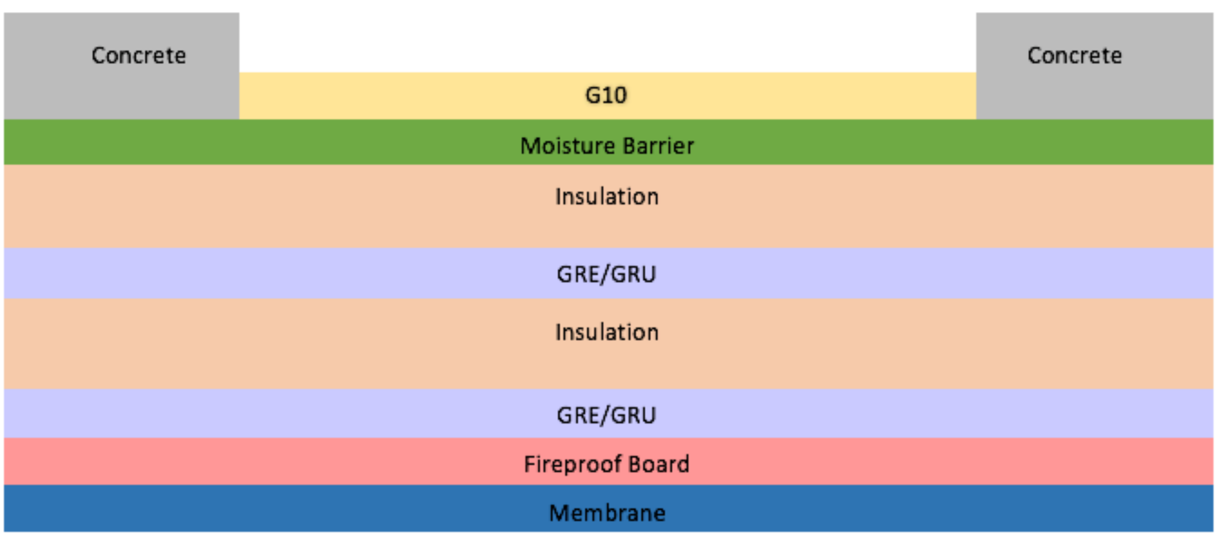

Figure 3: Layers of ArgonCube cryostat's low radiation length wall (layers not to scale)

Using 35T as a baseline again, it was assumed that the maximum design pressure in the ArgonCube cryostat would be approximately 20.6kPa (3psig). That pressure, combined with the hydrostatic pressure of 50.9kPa (7.4psig), equals a total pressure of 71.6kPa (10.4psig) applied uniformly across the G10 window. Roark and Young flat plate formulas were used to determine the maximum stress and deflection values of the G10 plate [1]. It was assumed that a uniform pressure of 71.6kPa (10.4psig) was distributed evenly across the entire plate because it was more conservative than using a hydrostatic pressure distribution. It was also assumed that all four edges of the G10 plate were fixed. A solid 0.1m x 3.25m x 4.5m sheet of G10 was used for the calculations. As a result, the G10 plate could withstand a maximum bending stress of 31.9MPa (4,629psi). The resulting maximum deflection with these conditions is equal to 11.35mm (0.4in). This deflection is less than half the thickness of the G10 plate, so the Roark and Young formulas used are valid [1]. These calculations are located in Appendix B.

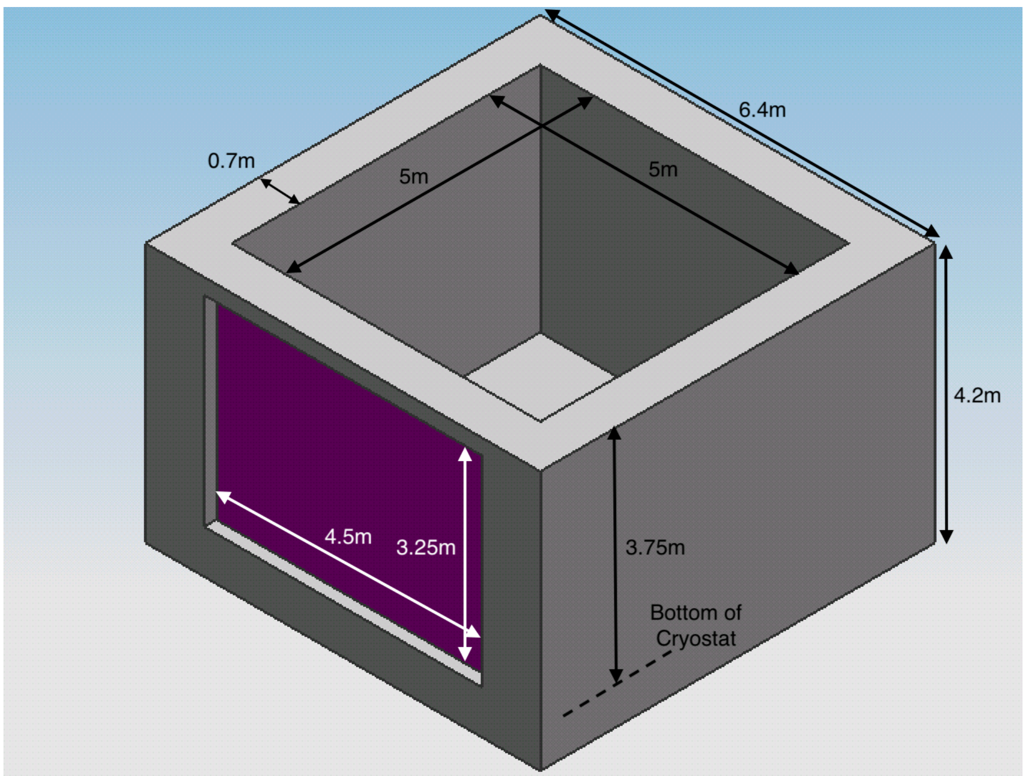

Figure 4: Dimensions of ArgonCube cryostat

G10 was chosen as one option for the material of the low radiation length wall due to its high strength and low radiation length. In addition, sheets of Aluminum and Titanium were tested in place of the G10 window. With these materials, the resulting radiation lengths were 1.16 for all layers including Aluminum and 1.96 for all layers including Titanium. Future analyses will include calculations for a Carbon Fiber window, and curved Aluminum and Titanium windows. Curved sheets can withstand higher pressures than flat plates. With resistance to higher pressure, the thickness of the material could be reduced, thus reducing the radiation length.

FEA Results of G10 Window in ArgonCube Cryostat

Ang Lee (Fermilab) completed a finite element analysis (FEA) to analyze the G10 window and insulation. A total pressure of 71.4kPa (10.35psig) was applied to the window and insulation: 50.7kPa (7.35psig) of hydrostatic pressure and 20.6kPa (3psig) of uniform pressure (Figure 5). A vertical plane of symmetry was applied to the window for ease of analysis. This is clarified in Figure 6.

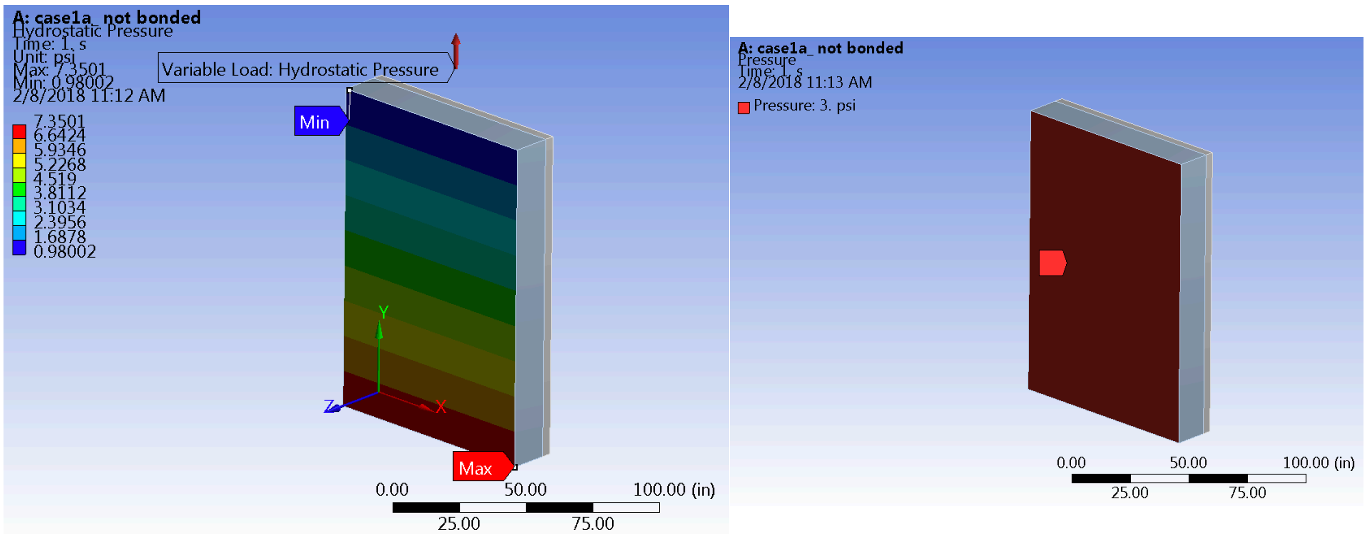

Figure 5: Pressure boundary conditions for G10 window and insulation

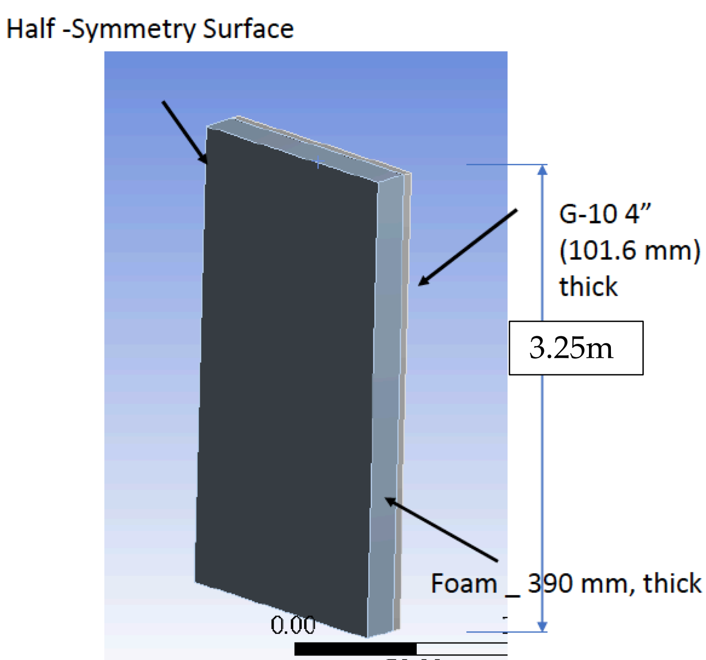

Figure 6: Dimensions of window and plane of symmetry

Four cases were analyzed with different boundary conditions:

- Case 1a:
  - Outer 4 walls of G10 are fixed
  - G10 and insulation are not bonded
- Case 1b:
  - Outer 4 walls of G10 are fixed
  - G10 and insulation are bonded
- Case 2a:
  - Outer 4 walls of G10 and insulation are fixed
  - G10 and insulation are not bonded
- Case 2b:
  - Outer 4 walls of G10 and insulation are fixed
  - G10 and insulation are bonded

The worst-case scenario is 1a. Even with these boundary conditions (outer four walls of the G10 are fixed and the G10 and insulation are not bonded), the deflection is 9mm (0.36in). This is minimal compared to the overall size of the window. Additionally, the applied stress is 20.4MPa (2,954psi). This is well below the tensile and compressive strengths of the G10: 257MPa (32,278psi) and 448MPa (65,000psi), respectively [6]. The majority of the 71.4kPa (10.35psig) pressure applied to the window is absorbed by the G10 window, but the insulation does experience some of the stress. The tensile and compressive strengths of the Rohacell insulation are 100kPa (145psi) and 400kPa (58psi), respectively [7]. These are larger than the maximum (tensile) and minimum (compressive) principal stresses on the insulation. The maximum deflection at the center of the G10 window is (0.36in) according to the FEA. Figure 8 shows the deflection and stress results.

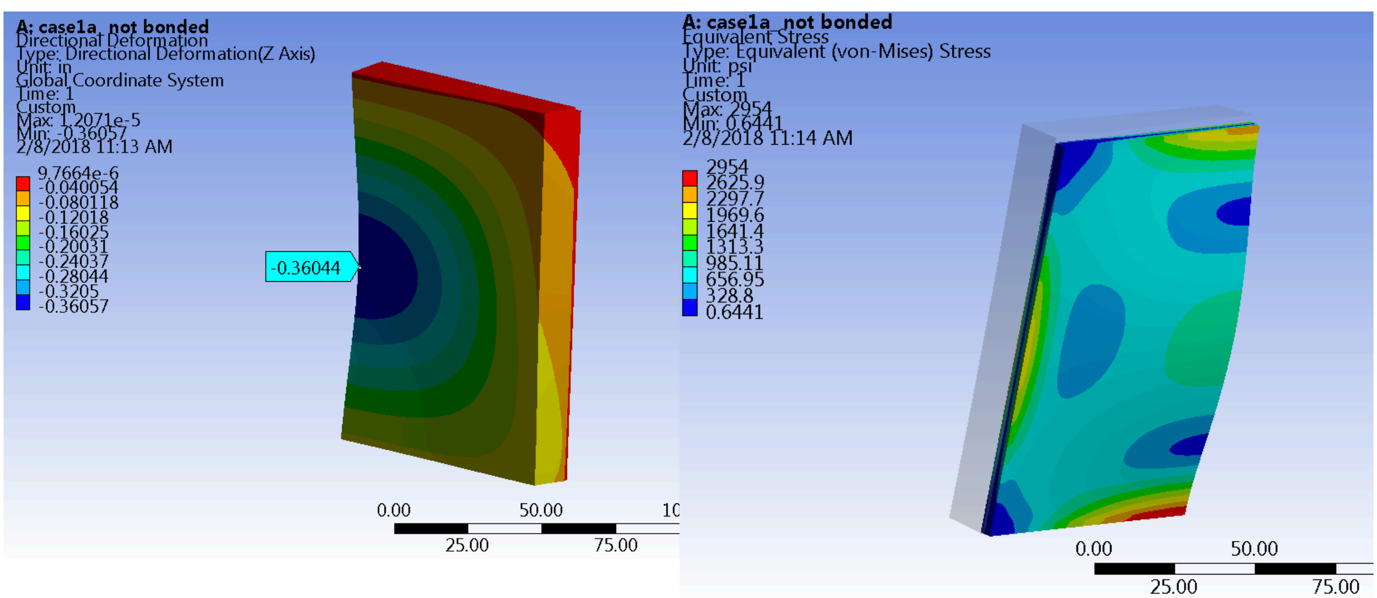

Figure 8: Equivalent stress and deflection results from FEA

Carbon Fiber Window Analysis

Another material that could be used for the thin window is carbon fiber. The carbon fiber window would consist of a 203mm-thick (8in) layer of high-density polyurethane foam insulation sandwiched between two 5mm-thick (0.19in) layers of carbon fiber. The layers of a carbon fiber window are listed below in Table 4. Figure 9 shows the layers of the cryostat wall with the carbon fiber window instead of G10. The window of carbon fiber would produce a total radiation length of 0.29.

Table 4: Radiation Lengths of ArgonCube Cryostat with Carbon Fiber

ArgonCube Cryostat- Carbon Fiber						
Layer	Radiation Length based on Material Composition		Density	Thickness	Calculated Radiation Length	Percentage of Total Radiation Length
	g/cm^2	mm	g/cm^3	mm	unitless	%
304 SS Membrane	13.904	17.6	7.9	2	0.11	39.68
Fireproof Board	23.955	399.25	0.6	10	0.03	8.75
Carbon Steel	7.85	17.60	7.9	1.2	0.07	23.81
Carbon Fiber	52.14	237	2.2	5	0.02	7.37
Insulation	40.8	5440	0.075	203.2	0.04	13.04
Carbon Fiber	52.14	237	2.2	5	0.02	7.37
Total Radiation Length					0.29	100.00

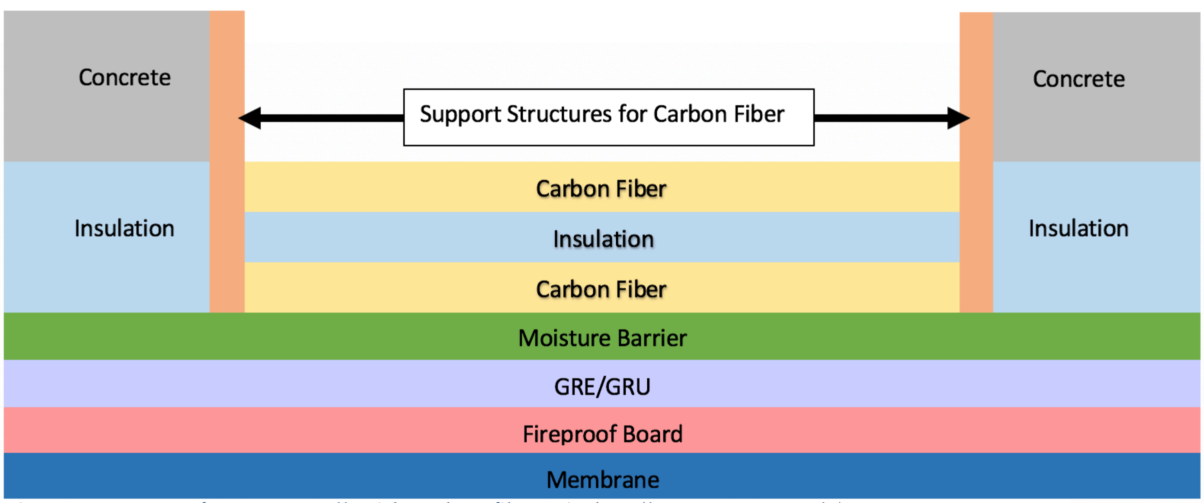

Figure 9: Layers of cryostat wall with carbon fiber window (layers not to scale)

An FEA was completed by Ang Lee for the carbon fiber window using the same input parameters as the G10 analysis. The results are listed in Figures 10-12. With 203mm (8in) of insulation between two 5mm-thick (0.19in) sheets of carbon fiber, the resulting deflection is equal to 10.16mm (0.40in). The resulting maximum principle (tensile) stress on the carbon fiber sandwich is 215.8kPa (31.3psi) and the resulting minimum principle (compressive) stress is 458.3kPa (66.48psi). These stress results are less than the tensile and compressive strengths of the insulation, which are 2.8MPa (406psi) and 1.5MPa (217psi), respectively.

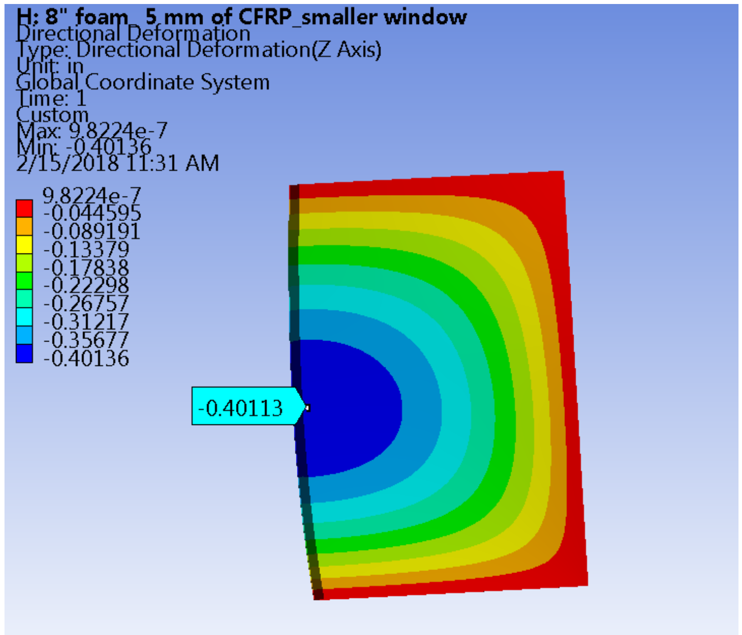

Figure 10: FEA results of carbon fiber sandwich window

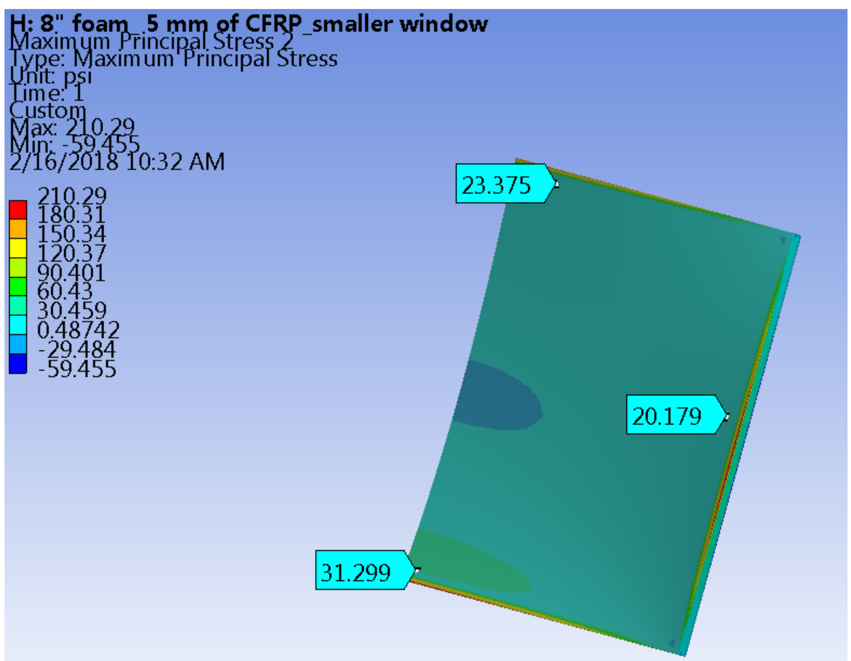

Figure 11: FEA of carbon fiber window showing maximum princle (tensile) sress

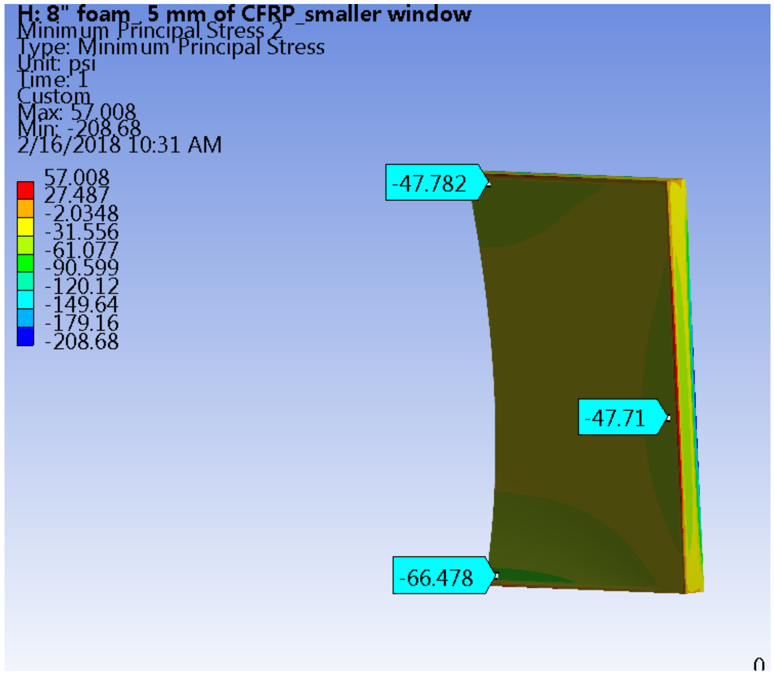

Figure 12: FEA of carbon fiber window showing minimum principle (compressive) stress

Conclusion

The proposed design for the ArgonCube cryostat provides a minimized radiation length through the cryostat wall while maintaining structural requirements for a cryostat of this size. With a 0.1m-thick G10 window in one of the cryostat walls, the total radiation length of the wall is 0.8. The wall of insulation sandwiched between carbon fiber sheets would result in a total radiation length of 0.29. The G10 and carbon fiber sandwich windows are both viable options for the ArgonCube cryostat. The basis for the ArgonCube cryostat stems from the 35T cryostat, which was successfully built at Fermilab in 2014 and has been operational since then.

References

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Appendix A- Radiation Length Calculations

Radiation Length Calculations for ArgonCube Experiment
K. Cipriano
January 2nd, 2018

This analysis calculates the radiation length through the wall of the proposed ArgonCube cryostat. The goal is to minimize the radiation length through the cryostat wall to approximately 0.5.

Cryostat Wall

The radiation length is calculated through the following materials that make up the ArgonCube vessel walls: 304 S.S. membrane, fireproof board (calcium silicate), GRE (glass reinforced epoxy)/GRU (glass reinforced urethane), insulation, GRE/GRU, insulation, carbon steel moisture barrier, and G10. For this calculation, the GRE/GRU layers are not included in the final radiation length calculation due to the 0.01mm thickness and lack of information on the radiation lengths of those materials.

Material Properties

1st Layer: 304 Stainless Steel Membrane

Density

$\rho_1 := 7.9 \frac{gm}{cm^3}$

Thickness

$t_1 := 2mm = 0.2 \cdot cm$

Radiation Length (in mm) [1]

$X_1 := 1.76cm = 17.6\, mm$

Radiation length (in g/cm^2)

$Xi_1 := \rho_1 \cdot X_1 = 13.904 \frac{gm}{cm^2}$

2nd Layer: Fireproof board (calcium silicate board- Ca2SiO4)

$\rho_2 := 0.6 \frac{gm}{cm^3}$ $\qquad t_2 := 10mm = 1 \cdot cm$

Calculations for radiation length of calcium silicate board [2]

Total number of moles in Ca2-Si-O4 (mol)

$N_O := 2mol + 4mol = 6\, mol$

Average atomic mass of Ca2-Si-O4

$$A_{avg} := \frac{(2 \cdot 20 + 1 \cdot 14 + 4 \cdot 16) gm}{N_O} = 19.667 \frac{gm}{mol}$$

Radiation length of O

$X_O := 34.46 \frac{gm}{cm^2}$

Atomic Mass of O (g/mol)

$A_O := 15.99 \frac{gm}{mol}$

Radiation length of Ca

$X_{Ca} := 16.43 \frac{gm}{cm^2}$

Atomic Mass of Ca

$A_{Ca} := 40.078 \frac{gm}{mol}$

Radiation length of Si

$X_{Si} := 22.08 \frac{gm}{cm^2}$

Atomic Mass of Si

$A_{Si} := 28.09 \frac{gm}{mol}$

Radiation length of fireproof board (in g/cm^2)

$$Xi_2 := \frac{A_{avg} \cdot N_O}{\left(\frac{20 \cdot 2gm}{X_{Ca}}\right) + \left(\frac{1gm \cdot 14}{X_{Si}}\right) + \left(\frac{4gm \cdot 16}{X_O}\right)}$$

$Xi_2 = 23.955 \cdot \frac{gm}{cm^2}$

Radiation length of fireproof board (in mm)

$$X_2 := \frac{Xi_2}{\rho_2} = 399.254 \cdot mm$$

3rd Layer: GRE (glass reinforced epoxy) and GRU (glass reinforced urethane)

$\rho_3 := 1.85 \frac{gm}{cm^3}$ **[3]**

$t_3 := 0.1mm = 0.01 \cdot cm$

Negligible radiation length

4th Layer: Foam insulation

Properties of Rohacell foam used for calculations [4]

$\rho_4 := 0.075 \frac{gm}{cm^3}$

$t_4 := 190mm = 19 \cdot cm$

$Xi_4 := 40.8 \frac{gm}{cm^2}$

$X_4 := \frac{Xi_4}{\rho_4} = 5440 \cdot mm$

5th Layer: GRE (glass reinforced epoxy) and GRU (glass reinforced urethane)

$\rho_5 := 1.85 \frac{gm}{cm^3}$

$t_5 := 0.1mm = 0.01 \cdot cm$

Negligible radiation length

6th Layer: Foam insulation

$\rho_6 := 0.075 \frac{gm}{cm^3}$

$t_6 := 200mm = 20 \cdot cm$

$Xi_6 := 40.8 \frac{gm}{cm^2}$

$X_6 := \frac{Xi_6}{\rho_6} = 5440 \cdot mm$

7th Layer: Carbon streel moisture barrier

Assume radiation length is equal to that of stainless steel, no data was found on the radiation length of carbon steel

$\rho_7 := 7.85 \frac{gm}{cm^3}$

$t_7 := 1.2mm = 0.12 \cdot cm$

$X_7 := 17.6mm$

$Xi_7 := \rho_7 \cdot X_7 = 13.816 \cdot \frac{gm}{cm^2}$

8th Layer: G10 fiber reinforced composite [5]

$\rho_8 := 1.70 \frac{gm}{cm^3}$

$t_8 := 101.6mm = 10.16 \cdot cm$ **4 inches thick**

$X_8 := 19.4cm = 194 \cdot mm$

$Xi_8 := \rho_8 \cdot X_8 = 32.98 \cdot \frac{gm}{cm^2}$

Alternate 8th Layer: Aluminum Alloy 2219 [6]

$\rho_{8a} := 2.84 \frac{gm}{cm^3}$

$t_{8a} := 69.8mm = 6.98 \cdot cm$ **2.75 inches thick**

$X_{8a} := 7.906cm = 79.06 \cdot mm$

$Xi_{8a} := \rho_{8a} \cdot X_{8a} = 22.453 \cdot \frac{gm}{cm^2}$

Total thickness

$t_{total} := t_1 + t_2 + t_3 + t_4 + t_5 + t_6 + t_7 + t_8 = 0.505\,m$

Total Radiation Length Across All Layers (G10) [4]

$$Radiation\_Length_{total} := \left(\frac{t_1}{X_1}\right) + \left(\frac{t_2}{X_2}\right) + \left(\frac{t_4}{X_4}\right) + \left(\frac{t_6}{X_6}\right) + \left(\frac{t_7}{X_7}\right) + \left(\frac{t_8}{X_8}\right)$$

$Radiation\_Length_{total} = 0.802$

Total Radiation Length as a Percentage

$Radiation\_Length_{percent} := Radiation\_Length_{total} = 80.227\cdot\%$

Alternate Total Radiation Length Across All Layers (Aluminum Alloy)

$$Radiation\_Length_{total2} := \left(\frac{t_1}{X_1}\right) + \left(\frac{t_2}{X_2}\right) + \left(\frac{t_4}{X_4}\right) + \left(\frac{t_6}{X_6}\right) + \left(\frac{t_7}{X_7}\right) + \left(\frac{t_{8a}}{X_{8a}}\right)$$

$Radiation\_Length_{total2} = 1.161$

Alternate Total Radiation Length as a Percentage

$Radiation\_Length_{percent2} := Radiation\_Length_{total2} = 116.143\cdot\%$

Alternate 8th Layer: Titanium [7]

$\rho_{8b} := 4.54\,\frac{gm}{cm^3}$

$t_{8b} := 60mm = 6\cdot cm$ **2.4 inches thick**

$X_{8b} := 3.560cm = 35.6\cdot mm$

$Xi_{8b} := \rho_{8b}\cdot X_{8b} = 16.162\cdot\frac{gm}{cm^2}$

Alternate Total Radiation Length Across All Layers (Titanium)

$$Radiation\_Length_{total3} := \left(\frac{t_1}{X_1}\right) + \left(\frac{t_2}{X_2}\right) + \left(\frac{t_4}{X_4}\right) + \left(\frac{t_6}{X_6}\right) + \left(\frac{t_7}{X_7}\right) + \left(\frac{t_{8b}}{X_{8b}}\right)$$

$Radiation\_Length_{total3} = 1.964$

Alternate Total Radiation Length as a Percentage

$Radiation\_Length_{percent3} := Radiation\_Length_{total3} = 196.395\cdot\%$

References

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Radiation Length Calculations for ArgonCube Experiment
K. Cipriano
January 12th, 2018

This analysis calculates the radiation length through the wall of the proposed ArgonCube cryostat. The goal is to minimize the radiation length through the cryostat wall to approximately 0.5.

Cryostat Wall
The radiation length is calculated through the following materials that make up the ArgonCube vessel walls: 304 S.S. membrane, fireproof board (calcium silicate), GRE (glass reinforced epoxy)/GRU (glass reinforced urethane), carbon steel moisture barrier, carbon fiber, Rohacell 71A insulation, and carbon fiber. For this calculation, the GRE/GRU layers are not included in the final radiation length calculation due to the 0.01mm thickness and lack of information on the radiation lengths of those materials.

Material Properties

1st Layer: 304 Stainless Steel Membrane

Density

$\rho_1 := 7.9 \frac{gm}{cm^3}$

Thickness

$t_1 := 2mm = 0.2 \cdot cm$

Radiation Length (in mm) [1]

$X_1 := 1.76cm = 17.6mm$

Radiation length (in g/cm^2)

$Xi_1 := \rho_1 \cdot X_1 = 13.904 \frac{gm}{cm^2}$

2nd Layer: Fireproof board (calcium silicate board- Ca2SiO4)

$\rho_2 := 0.6 \frac{gm}{cm^3}$ $t_2 := 10mm = 1 \cdot cm$

Calculations for radiation length of calcium silicate board [2]

Total number of moles in Ca2-Si-O4 (mol)

$N_O := 2mol + 4mol = 6mol$

Average atomic mass of Ca2-Si-O4

$$A_{avg} := \frac{(2 \cdot 20 + 1 \cdot 14 + 4 \cdot 16)gm}{N_O} = 19.667 \frac{gm}{mol}$$

Radiation length of O

$X_O := 34.46 \frac{gm}{cm^2}$

Atomic Mass of O (g/mol)

$A_O := 15.99 \frac{gm}{mol}$

Radiation length of Ca

$X_{Ca} := 16.43 \frac{gm}{cm^2}$

Atomic Mass of Ca

$A_{Ca} := 40.078 \frac{gm}{mol}$

Radiation length of Si

$X_{Si} := 22.08 \frac{gm}{cm^2}$

Atomic Mass of Si

$A_{Si} := 28.09 \frac{gm}{mol}$

Radiation length of fireproof board (in g/cm^2)

$$Xi_2 := \frac{A_{avg} \cdot N_O}{\left(\frac{20 \cdot 2gm}{X_{Ca}}\right) + \left(\frac{1gm \cdot 14}{X_{Si}}\right) + \left(\frac{4gm \cdot 16}{X_O}\right)}$$

$Xi_2 = 23.955 \cdot \frac{gm}{cm^2}$

Radiation length of fireproof board (in mm)

$$X_2 := \frac{Xi_2}{\rho_2} = 399.254 \cdot mm$$

3rd Layer: GRE (glass reinforced epoxy) and GRU (glass reinforced urethane)

$\rho_3 := 1.85\,\frac{gm}{cm^3}$ **[3]**

$t_3 := 0.1mm = 0.01\cdot cm$

Negligible radiation length

4th Layer: Carbon Steel moisture barrier
Assume radiation length is equal to that of stainless steel, no data was found on the radiation length of carbon steel

$\rho_4 := 7.85\,\frac{gm}{cm^3}$

$t_4 := 1.2mm = 0.12\cdot cm$

$X_4 := 17.6mm$

$Xi_4 := \rho_4\cdot X_4 = 13.816\cdot\frac{gm}{cm^2}$

5th Layer: Carbon Fiber [4] [5]
Mitsubishi Dialead K13C2U

$\rho_5 := 2.2\,\frac{gm}{cm^3}$

$t_5 := 5mm = 0.5\cdot cm$

$X_5 := 23.7cm = 237\cdot mm$

$Xi_5 := \rho_5\cdot X_5 = 52.14\cdot\frac{gm}{cm^2}$

6th Layer: Foam insulation

Properties of Rohacell 71A foam used for calculations [4]

$\rho_6 := 0.075\,\frac{gm}{cm^3}$

$t_6 := 203.2mm = 20.32\cdot cm$ **8 inches**

$Xi_6 := 40.8\,\frac{gm}{cm^2}$

$X_6 := \frac{Xi_6}{\rho_6} = 5440\cdot mm$

7th Layer: Carbon Fiber [4] [5]
Mitsubishi Dialead K13C2U

$\rho_7 := 2.2\,\frac{gm}{cm^3}$

$t_7 := 5mm = 0.5\cdot cm$

$X_7 := 23.7cm = 237\cdot mm$

$Xi_7 := \rho_7\cdot X_7 = 52.14\cdot\frac{gm}{cm^2}$

Total Radiation Length Across All Layers

$$Radiation\_Length_{total} := \left(\frac{t_1}{X_1}\right) + \left(\frac{t_2}{X_2}\right) + \left(\frac{t_4}{X_4}\right) + \left(\frac{t_5}{X_5}\right) + \left(\frac{t_6}{X_6}\right) + \left(\frac{t_7}{X_7}\right)$$

$Radiation\_Length_{total} = 0.286$

Alternate Total Radiation Length as a Percentage

$Radiation\_Length_{percent} := Radiation\_Length_{total} = 28.641 \cdot \%$

References

[1] http://www-physics.lbl.gov/~gilg/PixelUpgradeMechanicsCooling/Material/Radiation%20Lengths%20Last.doc

[2] https://cds.cern.ch/record/1279627/files/PH-EP-Tech-Note-2010-013.pdf

[3] http://www.shipham-valves.com/en/materials/glass-reinforced-epoxy-resin-composite-gre

[4] http://www-physics.lbl.gov/~gilg/PixelUpgradeMechanicsCooling/Material/Radiationlength.pdf

[5] http://mccfc.com/pitch-fiber/

Appendix B- Window Strength Calculations

Density of G10 [3]

$$\rho_{G10} := 1.8\frac{gm}{cm^3}$$

Compressive strength (crosswise) [2]

$$\sigma_t := 35000psi$$

Heigh of liquid argon in cryostat

$$h_{LAr} := 5.5m$$

Area of G10 window

$$A_{G10} := 25m^2$$

Height of G10 window

$$h_{wall} := 5m$$

Density of liquid argon at 89K and 3psig

$$\rho_{argon} := 1384.9\frac{kg}{m^3}$$

Design pressure inside cryostat

$$P_{design} := 3psi$$

Hydrostatic pressure at bottom of cryostat

$$P := \rho_{argon} \cdot g \cdot h_{wall} = 9.8 \cdot psi$$

Total pressure

$$P_{total} := P + P_{design} = 12.8 \cdot psi$$

Roark and Young
Table 11.4: Formulas for flat plates with straight boundaries and constant thickness

Assume: Rectangular plate, all edges fixed, uniform over entire plate (The pressure applied uniformly over the entire plate is more conservative than hydrostatic pressure)

Pressure
$q := P_{total} = 12.8 \cdot psi$

Height
$b := h_{wall} = 5\,m$

Wall thickness of G10
$t := 101.6mm$ (4 inches thick)

Ratio of width (5m) to height (5m) of G10 window
$Ratio := \frac{5}{5} = 1$

Constants from Roark Table 11.4
$\beta_1 := .3078$

$\beta_2 := 0.1386$

Maximum bending stress (at center of long edge)

$$\sigma_{max} := \frac{-\beta_1 \cdot q \cdot b^2}{t^2}$$

$\sigma_{max} = -9578.3 \cdot psi$

Maximum bending stress (at center)

$$\sigma_{max2} := \frac{\beta_2 \cdot q \cdot b^2}{t^2}$$

$\sigma_{max2} = 4313 \cdot psi$

Constant from Roark Table 11.4
$\alpha := 0.0138$

Modulus of Elasticity of G10 [2]
$E := 2.2 \cdot 10^6 psi$

Maximum deflection (assumptions from above still apply)

$$y_{max} := \frac{\alpha \cdot q \cdot b^4}{E \cdot t^3}$$

$y_{max} = 48.0312 \cdot mm$

This deflection result (48mm) is less than half the thickness of the G10 sheet (101.6mm). Thus, the calculations are valid under Chapter 11 of Roark and Young.

"The formulas of this section are based on the following assumptions:
(1) The plate is flat, of uniform thickness, and of homogeneous isotropic material;
(2) the thickness is not more than about one quarter of the least transverse dimension, and the maximum deflection is not more than about one-half the thickness;
(3) all forces- loads and reactions- are normal to the plane of the plate;
(4) the plate is nowhere stressed beyond the elastic limit." [1]

References

[1] W. Young, R. Budynas and R. Roark, Roark's formulas for stress and strain. New York [u.a.]: McGraw-Hill, 2011.

[2] https://www.professionalplastics.com/professionalplastics/PhenolicG-10FR4DataSheets.pdf

[3] http://www.matweb.com/search/datasheet_print.aspx?matguid=8337b2d050d44da1b8a9a5e61b0d5f85

Appendix C- Technical Paper on 35T Cryostat

First Scientific Application of the Membrane Cryostat Technology

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Abstract. We report on the design, fabrication, performance and commissioning of the first membrane cryostat to be used for scientific application. The Long Baseline Neutrino Experiment (LBNE) has designed and fabricated a membrane cryostat prototype in collaboration with IHI Corporation (IHI). Original goals of the prototype are: to demonstrate the membrane cryostat technology in terms of thermal performance, feasibility for liquid argon, and leak tightness; to demonstrate that we can remove all the impurities from the vessel and achieve the purity requirements in a membrane cryostat without evacuation and using only a controlled gaseous argon purge; to demonstrate that we can achieve and maintain the purity requirements of the liquid argon during filling, purification, and maintenance mode using mole sieve and copper filters from the Liquid Argon Purity Demonstrator (LAPD) R&D project. The purity requirements of a large liquid argon detector such as LBNE are contaminants below 200 parts per trillion oxygen equivalent. This paper gives the requirements, design, construction, and performance of the LBNE membrane cryostat prototype, with experience and results important to the development of the LBNE detector.

INTRODUCTION

The Long Baseline Neutrino Experiment (LBNE) project envisions using membrane tank technology for a large liquid argon detector referred to as the Far Detector (FD) with the start of the construction in the time frame of 2020. Membrane tank technology is significantly more cost effective than flat plate vessel construction for a cryogenic tank of this volume (~7,000 m^3) [1]. The LBNE cryostat in its current configuration is 28.56 m long, 15.63 m wide and 15.98 m high (inner dimensions). It will be instrumented with Time Projection Chambers (TPCs) and filled with liquid argon.

In order for the TPCs to operate properly and drift electrons with a lifetime greater than 1.4 ms, the LBNE-FD requires extreme purity of the liquid argon inside the tank, at the level of 200 parts per trillion (ppt) of oxygen equivalent contamination. The empirical correlation between electron lifetime and parts of oxygen equivalent contamination is outlined in equation 1 [2]. Cryogenic vessels for particle physics research are typically pumped down to remove impurities prior to filling. However, it is highly impractical to pump down a tank of the size of the LBNE-FD. An R&D project called Liquid Argon Purity Demonstrator (LAPD) proved that a slow gaseous argon purge can remove impurities down to parts per million from a large cylindrical vessel without evacuation. With a liquid argon filtration system composed by a mole sieve and copper filters, it reached over 5.0 ms electron lifetime [2], far exceeding the level of purity for the liquid argon required by the LBNE-FD.

$$Lifetime[ms] = \frac{3 \cdot 10^{-13}[ms \cdot parts\ of\ Oxygen]}{Contaminant[parts\ of\ Oxygen]} \qquad (1)$$

We have built a small prototype (~29 m^3) to demonstrate the possibility of fabricating a membrane cryostat that meets the requirements for a low background particle physics detector: thermal performance, feasibility for liquid argon, argon purity, and leak tightness. We also wanted to check the feasibility of construction interfaces and methods, including the business aspects of negotiating a contract with a large membrane cryostat supplier. The membrane cryostat manufacturer is required to have a safe, reliable design with a proven track record. History shows that membrane cryostats are the technology of choice for Liquefied Natural Gas (LNG) transportation and storage, with hundreds of ship tankers and storage tanks built and being built all over the world with sizes up to 250,000 m^3 (Fig. 1 [3]), much larger than the LBNE-FD. It is a commercially available technology and has been in service for several decades without a single recorded incident. This prototype, known as the LBNE 35 ton prototype, was competitively procured for the design, purchase of materials and supervision during the installation. IHI Corporation (IHI) won the bid.

DESCRIPTION

The LBNE 35 ton prototype is the first and only membrane cryostat built for scientific purposes, and the first and only membrane cryostat built in the United States. While membrane cryostat technology is widely used for LNG, this prototype will also be the first liquid argon. The temperatures of liquid argon and LNG are very similar, with the latter less than 30 K warmer than the former, but the densities are quite different: LNG is about one third less dense. LNG ship tankers and storage tanks are more than four times taller than LBNE-FD (and more than twenty times taller than this prototype), making the two applications very similar. The hydrostatic pressure at the bottom of the tank is almost identical.

A membrane cryostat is made of several parts (Fig. 2): the corrugated membrane that contains the liquid and gaseous Argon, the passive insulation that reduces the heat leak, and the reinforced concrete structure that is the structural part to which the pressure is transferred. A secondary barrier system embedded in the insulation protects it from potential spills of liquid argon, and a vapor barrier over the concrete protects the insulation from the moisture of the concrete (Fig. 3a) [4, 5]. A roof made by two plates, A and B, completes the cryostat. Plate A is a flat plate with insulation and membrane underneath. Plate B is a flat plate containing all the penetrations and services.

The membrane cryostat has been designed by IHI and constructed by Fermilab personnel under IHI supervision. The concrete structure has been designed by an independent contractor following Fermilab and IHI specifications and constructed by a civil construction company. The mechanics of the top plate have been designed by Fermilab in consultation with IHI and fabricated by Fermilab personnel.

The LBNE 35 ton prototype shares a liquid Argon filtration system with the LAPD project.

The basic idea was to simulate as many features as possible of the future LBNE-FD. We chose a square tank with 5% ullage and a volume comparable to LAPD. The cryostat is 4.0 meters long, 2.7 meters wide, and 2.7 meters high (inner dimensions). The design parameters outlined in Table 1 are the same as those for LBNE-FD with the exception of the insulation thickness, the type of vapor barrier, and the duration of the project. For example, due to building constraints, it was neither practical nor necessary to build this tank with 0.8 meter of insulation, so we chose 0.4 meter, which corresponds to double the thickness of a standard insulation panel. The size of LBNE-FD will make the use of a metallic vapor barrier very time consuming and expensive, so we chose to use epoxy or resin. The anticipated duration of LBNE-FD is 20 years, not 10 years as is the case for this project.

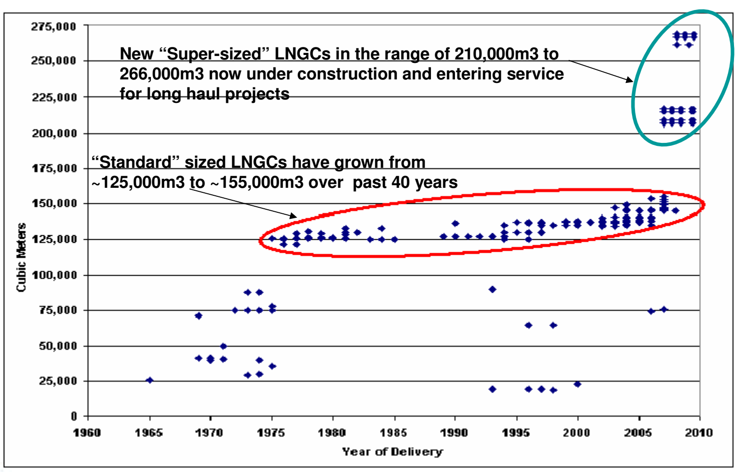

FIGURE 1. Capacity of LNG tanks in the past 50 years. Reprinted from Peter G. Noble, *A short history of LNG shipping 1959-2009*, Texas Section, SNAME, 2009.

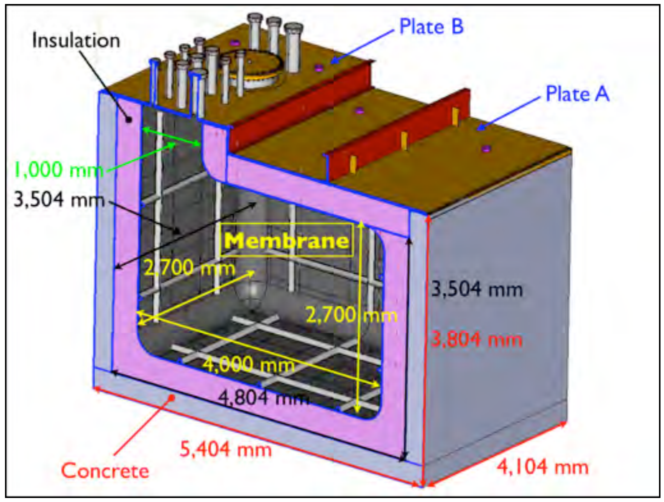

FIGURE 2. Membrane cryostat 3D drawing.

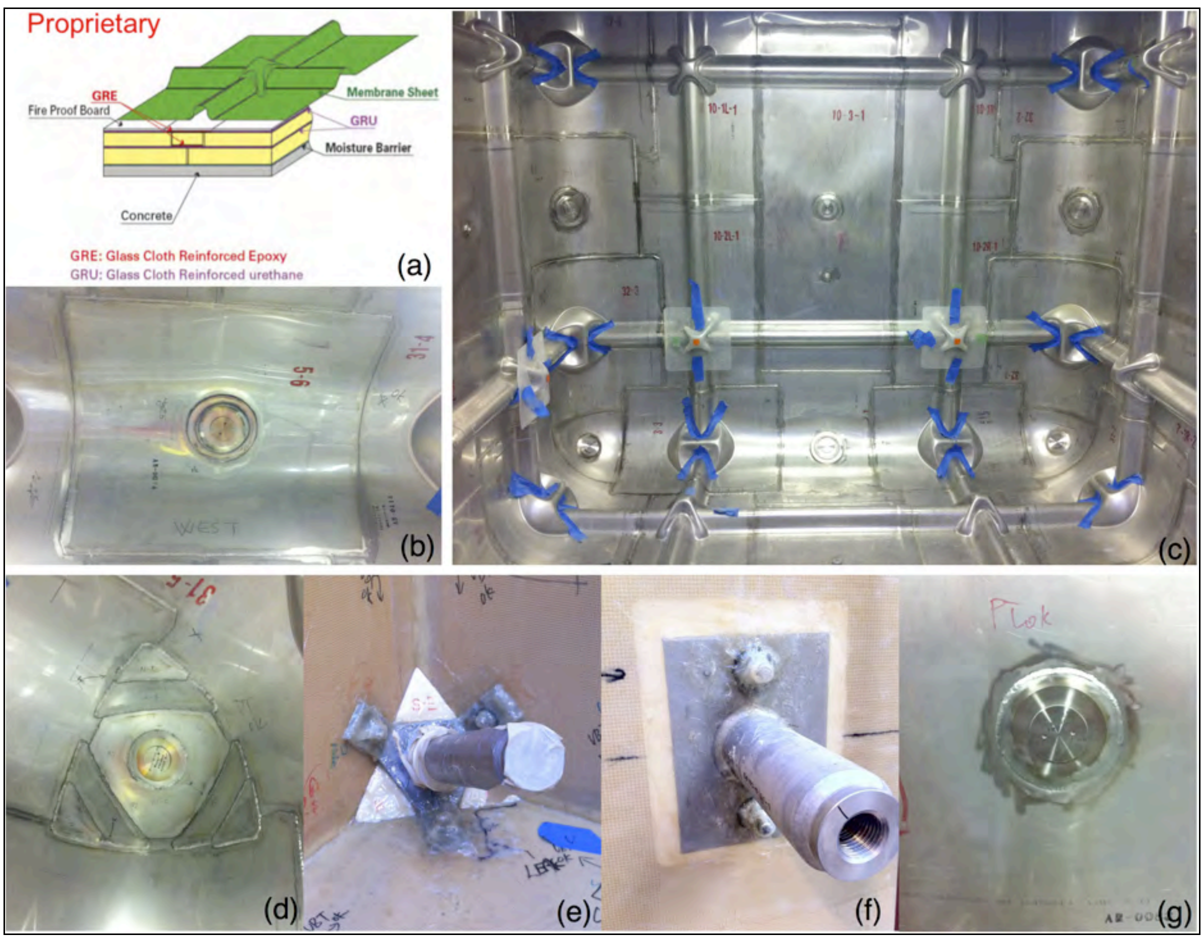

FIGURE 3. Membrane cryostat construction photos: (a) Membrane cryostat section, reprinted from IHI Corporation [5]; (b) Membrane panel in angle with screw; (c) Inside of the tank after completion; (d) Membrane panel in corner with screw; (e) Three-way anchor; (f) One-way anchor, and (g) Flat membrane panel with screw.

TABLE 1. Design parameters for the LBNE 35 ton prototype.

Design Parameter	Value
Cryostat volume	29.16 m^3
Liquid argon total mass	38,600 kg
Inner dimensions of the cryostat	4.0 m (L) x 2.7 m (W) x 2.7 m (H)
Depth of liquid argon	2.565 m (5% ullage)
Insulation	0.4 m Polyurethane foam
Primary membrane	2.0 mm thick SS 304 corrugated stainless steel
Secondary barrier system	0.1 mm thick fiberglass
Vapor barrier	1.2 mm thick carbon steel
Reinforced outer concrete layer	0.3 m thick
Liquid argon temperature	89 K +/- 1 K
Operating gas pressure	70 mBar (~1psig)
Vacuum	No vacuum
Design pressure	207 mBar (~3psig)
Leak tightness	1E-06 mBar*l/sec
Heat leak	< 13 W/m^2
Duration	10 years
Thermal cycles	50 complete cycles (cool down and total warm up)
Design codes	Fermilab ES&H Applicable parts of JGA RP-107-02 ACI 318

Concrete

A reinforced concrete outer shell ensures the structural resistance to the liquid argon load, gas pressure and external loads, such as the weight of the top plate and of all the instruments and services connected to it. These loads are transferred through the insulation from the membrane to the concrete structure. The bottom slab has been equipped with heaters and temperature controllers to maintain the concrete temperature within acceptable limits. The sidewalls and the bottom have been poured in place and are 0.3 meter thick reinforced with rebar. On the inside there is a vapor barrier made by 1.2 mm thick carbon steel sheets welded to angles embedded in the concrete. The angles on the sides and the bottom are steel, and the angles at the top of the sides are stainless steel to guarantee the required leak tightness, the cleanliness and the cryogenic service (Fig. 4a). Stainless steel cover plates (9.5 mm thick) have been welded to the angles over the sides of the concrete structure. The vapor barrier has been leak checked with a helium mass spectrometer in sniffer mode and any leak repaired. Helium has been injected in the region between the concrete and the metal sheets through temporary holes. Prior to helium leak checking, the vapor barrier was tested with vacuum boxes: snoop solution is poured over the weld seam and partial vacuum is pulled inside a box placed over the region of interest; if bubbles come out of the welding seam, there is a leak. Any identified leak was repaired (Fig. 4b).

Several stainless steel rods pass through the vapor barrier and are anchored to the concrete. They hold the insulation and the membrane anchors and are welded to carbon steel sheets.

Insulation

The insulation thickness is driven by the required heat leak. We have chosen a heat leak lower than 15 W/m^2: that value can be achieved with 0.4 m of standard polyurethane foam insulation. In reality, there are two layers of insulation: a layer outside (0.2 m thick) and a layer inside (0.19 m thick). The actual calculated heat flux value is 11.5 W/m^2, without the contribution of plate B, which includes the penetrations. The standard insulation panels are 1 meter wide, 2 meters long and are joined together with liquid polyurethane foam that cures and hardens forming a single continuous layer.

A secondary barrier system is embedded over the outer layer of insulation: it covers the bottom and sides up to the liquid level height inside the tank in order to contain the liquid argon in case of a primary membrane failure. A sub-secondary barrier system is embedded over the inner layer of insulation, with the same layout and purpose.

Secondary and sub-secondary barrier systems are made by Glass Reinforced Urethane (GRU) and are bridged together with Glass Reinforced Epoxy (GRE) to form two continuous layers.

The insulation panels are bolted to the concrete through stainless steel rods and nuts that are also covered with liquid insulation and GRE.

A 10.0 mm thick calcium silicate fireproof board glued over the sub-secondary barrier system protects the insulation from the high heat generated during the welding (Fig. 4c and Fig. 4d).

Secondary and sub-secondary barrier systems have been tested with vacuum boxes: snoop solution is poured over the joint seam (between two adjacent panels or around a rod) and partial vacuum is pulled inside a box placed over the region of interest; if bubbles come out of the seam, there is a leak. Any identified leak has been repaired.

The insulation is normally purged with gaseous argon to ensure that, in case of a leak in the membrane, air will not enter the system. A distribution system is located between the insulation and the membrane, under the corrugations. It has two inlets, two outlets, and radial holes in the pipes.

FIGURE 4. Photos during construction: (a) Concrete structure before starting the installation of the vapor barrier; (b) Test of the vapor barrier with vacuum box; (c) Installation of the inner layer of insulation; (d) Top view during the installation of the second layer of insulation; (e) Installation of the membrane; (f) Top view of the completed membrane cryostat; (g) Ammonia leak check of the membrane cryostat; (h) Partial group photo after the completion of the installation, and (i) Ammonia leak check of the membrane cryostat.

Membrane

The membrane panels are 2.0 mm thick 304 corrugated stainless steel. They are fixed to the concrete with screws specifically designed to engage membrane anchors. Longitudinal and latitudinal corrugations absorb the thermal contraction and expansions of the metal with temperature.

The flat member panels were pre-welded at the vendor's site in five wall size sections for the sides and floor (Fig. 4e). They were then "TIG" welded with double passes to membrane panels for corners and angles.

The membrane anchors are bolted to membrane anchor rods over the outer layer of insulation (Fig. 3e). The inner layer of insulation has matching holes to accept the anchors and they are then filled with liquid insulation. The membrane is then screwed into the membrane anchors (Fig. 3b, Fig. 3d, Fig. 3g). Three types of membrane anchors were used: one-way (Fig. 3f) for flat membrane panels; two-way, for angle panels; and three-way for corner panels (Fig. 3e). The screws going into the two-way and three-way anchors need a backing washer to adapt to the uneven surface of the membrane panel. The head of the screws were also welded to the membrane panels.

Roof

Two flat plates constitute the roof of the LBNE 35 ton prototype: plate A and plate B. Plate A is a 19.0 mm thick carbon steel plate reinforced with two C-channels and equipped with insulation and the membrane. It was assembled upside down, and then flipped and lowered on top of the cryostat. The insulation and membrane were installed following the same process as for the sides and bottom with the anchor rods for the insulation welded to the top plate. Six anchors are welded to the plate; they pass through the insulation and terminate with a welded connection to the membrane. TPCs will be hung from the anchors during a second phase of the project. Plate B is a 25.4 mm thick 304 stainless steel plate with no insulation and membrane. It sits on a higher portion of the cryostat (0.3 m taller than the rest) and contains all the penetrations and services that are connected to the tank, which include liquid and gaseous argon inlets and outlets, a pressure relief valve, temperature and purity monitors, condenser, and a manhole to access the tank after completion. Radiation shields reduce the heat leak underneath plate B. Plates A and B are welded to the cover plates that sit on top of the concrete. Plate B is removable by design to allow the insertion of TPCs into the cryostat and attach them under plate A later in the project.

Membrane leak check

At the end of the installation, the membrane was tested with dye penetrant (for superficial cracks) and with a colorimetric leak check (for actual leaks); both ASTM standard Non Destructive Testing (NDT) methods. The colorimetric leak check has a measured sensitivity of 1E-06 mBar*l/sec. A mixture of ammonia and nitrogen was injected in the insulation region in closed loop, through special holes drilled in the membrane panels that were welded after the completion of the test. The return path was the gaseous argon purge piping, and a pump continuously circulated the gas mixture. A paint developer that changes color from yellow to blue if in contact with Ammonia in concentration greater than 3%, is sprayed over the weld seams inside the tank to detect potential leaks and their location. We periodically measured and recorded the concentration of ammonia behind every wall (sides, roof and floor). Two control holes painted with the developer were also connected to the wall with the lowest concentration of ammonia. The paint turned blue in the 10 micron hole and remained yellow in the 5 micron hole, as expected. No leak was recorded and the membrane cryostat was approved for pressure testing (at 259 mBarg or 125% of design pressure), which was successfully performed.

CRYOGENIC SYSTEM

The LBNE 35 ton prototype cryogenic system is composed of several parts: a liquid argon purification system, a gaseous argon filtration system, an argon condenser with liquid nitrogen cooling system, and a liquid and gaseous argon supply system (Fig. 5).

We will reuse the existing LAPD cryogenic system to purify the liquid argon, composed of mole sieves and copper bed filters, to remove water and oxygen respectively. While the LAPD tank and the LBNE 35 ton prototype vessel cannot operate at the same time, it will be possible to transfer the liquid from one to the other. We will also reuse the liquid and gaseous argon supply system, and the gaseous argon filtration system [2].

The membrane cryostat will have its own condenser to re-condense the boil off argon from the tank. It will be a duplicate of LAPD, but located on top of the membrane cryostat. Since it has been demonstrated that all the impurities are in the ullage at the top of the tank [2, 4, 6], the re-condensed liquid will then go to the purification system before entering the tank.

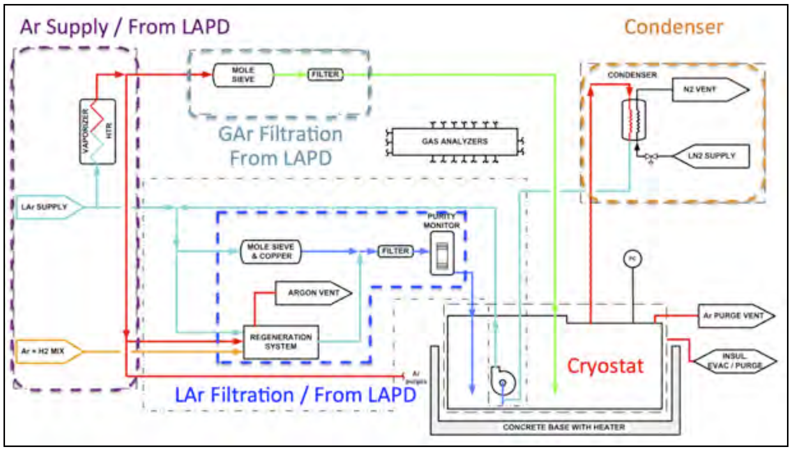

FIGURE 5. Process flow diagram for the LBNE 35 ton prototype cryogenic system

The main difference between LAPD and the LBNE 35 ton cryogenic system is the use of liquid argon submerged pumps located inside the membrane cryostat and hung from plate B. They are a commercial product, typically used in LNG applications.

The piping to connect the membrane cryostat to the existing filters is being fabricated. Once the construction is completed, the cryostat will be slowly purged with gaseous argon to reduce the impurities (we are mostly concerned with oxygen and water) to parts per millions. Then the liquid filling and circulation begins and will reduce the impurities to the required parts per trillions of oxygen equivalent contamination, or more than 1.4 ms electron lifetime.

CURRENT STATUS

The LBNE 35 ton prototype membrane cryostat has been constructed and successfully pressure tested. The cryogenic system that connects the tank to the LAPD purification system is being fabricated with a target completion in the summer of 2013, the commissioning and testing program will then begin. The LBNE 35 ton prototype is the test facility for the LBNE project, and the only prototype that will be built before the actual detector. There is an extensive test program that comprises two phases. Phase 1 main goal is to demonstrate the purity of the liquid argon, while Phase 2 is to build a prototype of the detector.

More specifically, the goals of Phase 1 are:

- To demonstrate the membrane cryostat technology, in terms of thermal performance, feasibility for liquid argon, leak tightness.
- To demonstrate that we can achieve and maintain the purity requirements in a membrane cryostat without evacuation, less than 200 ppt oxygen equivalent contamination, or more than 1.4 ms electron lifetime
- To identify design needs and changes to LBNE-FD.

Also, the goals of Phase 2 are:

- To insert TPCs inside the tank and take data, such as purity and electronic noise.
- To insert cables and test possible contamination to the purity of the liquid argon.

We have already accomplished the first goal of checking the feasibility of construction interfaces and methods, and the business aspects of negotiating a contract with a large membrane cryostat supplier.

FUTURE ACTIVITIES

The LBNE 35 ton prototype is the first and only membrane cryostat built for scientific purposes as well as the only membrane cryostat built in the United States. High energy physics and low background experiments are building larger and larger detectors and are potentially interested in this technology: membrane cryostat technology is cost effective when the linear dimension is equal to or exceeds 10 meters. There are no scheduled activities after the completion of Phase 2, scheduled for completion by the end of 2014. We have envisioned a Phase 3 where the prototype is available to scientists and researchers other than LBNE.

ACKNOWLEDGMENTS

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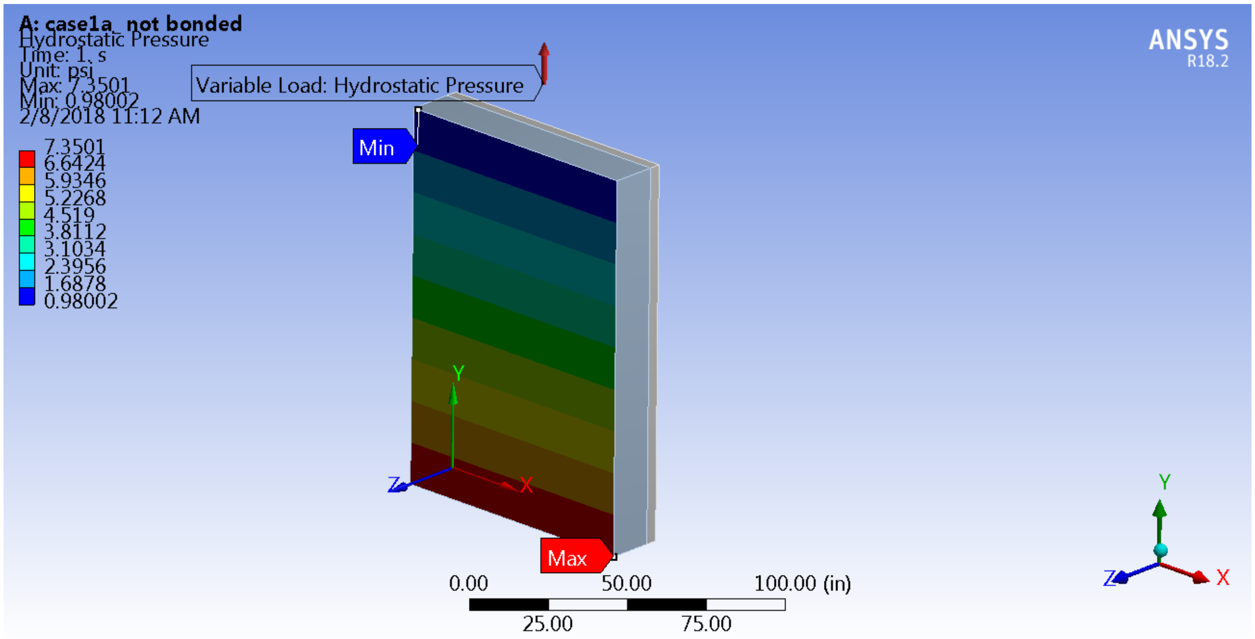
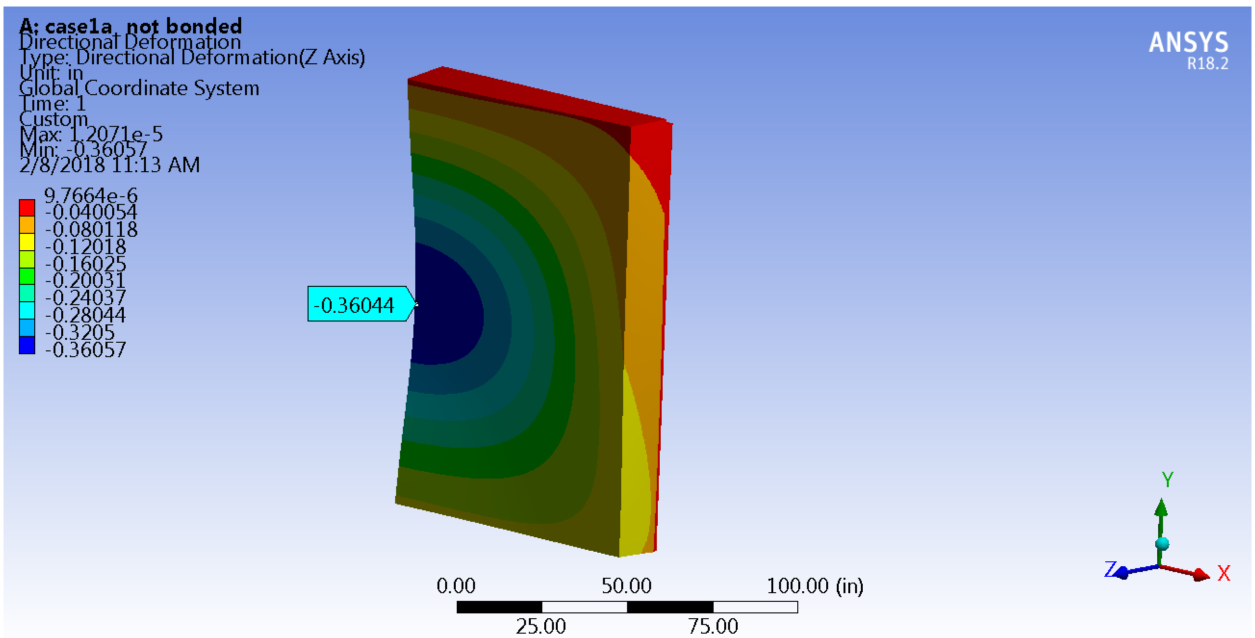
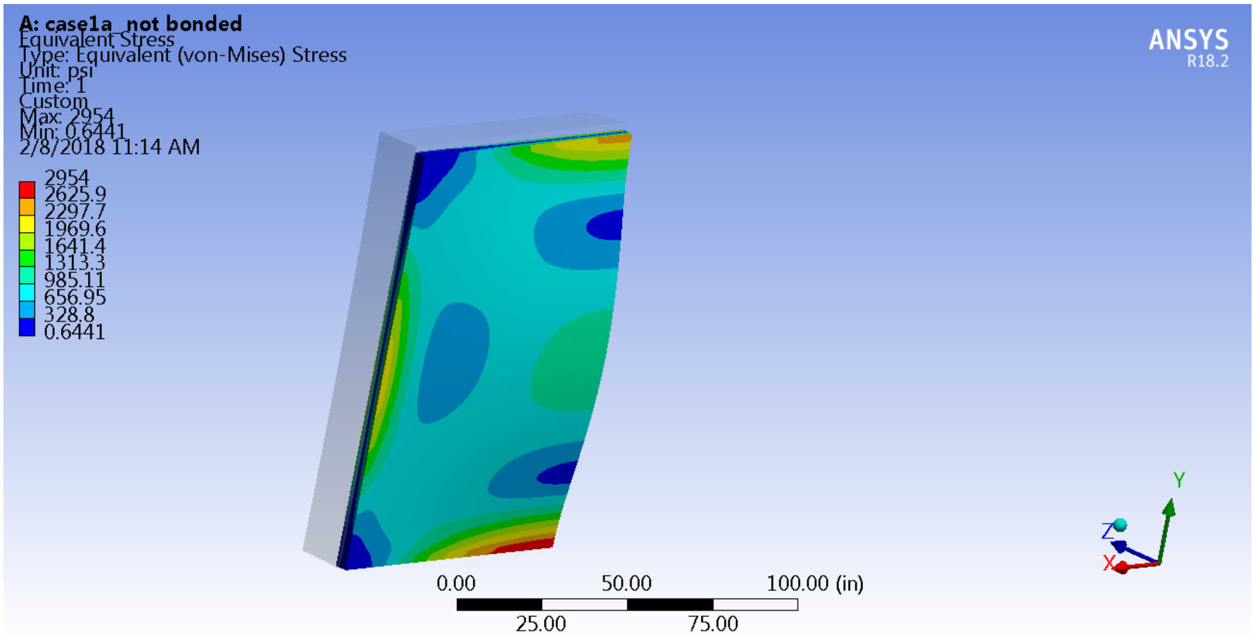
6. Brian J. Rebel (private communication), 2012.

Appendix D- FEA Results of G10 Window and Carbon Fiber Window

G10 FEA Results by Ang Lee



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1641.4
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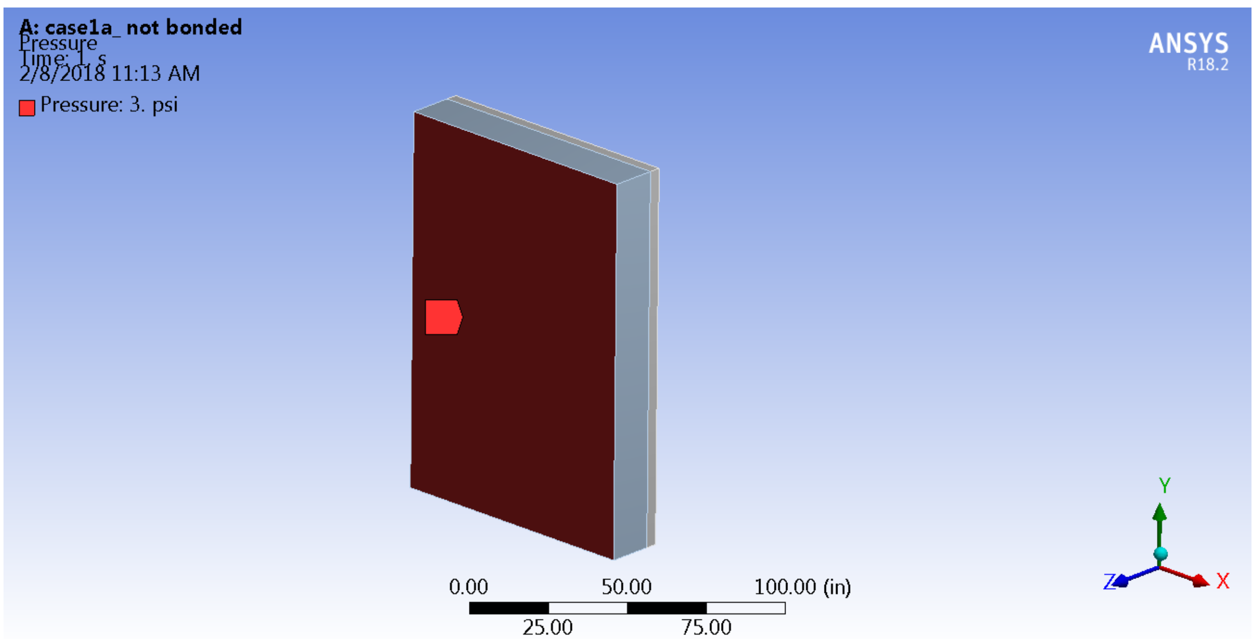
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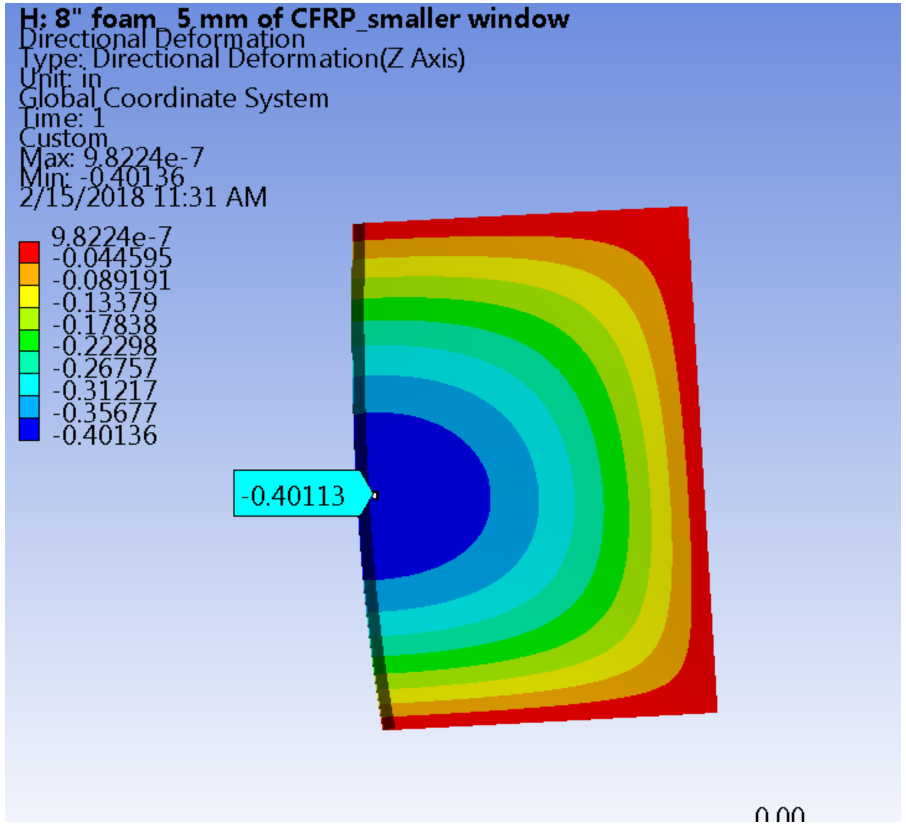
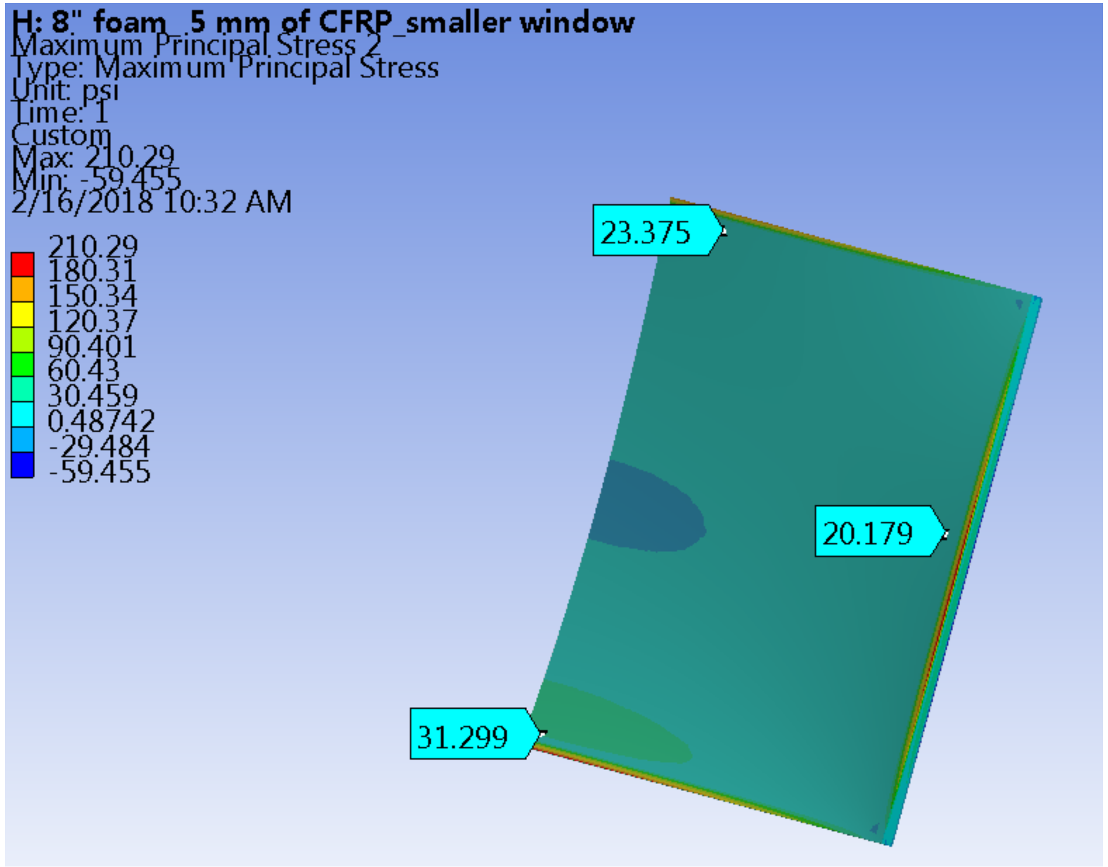
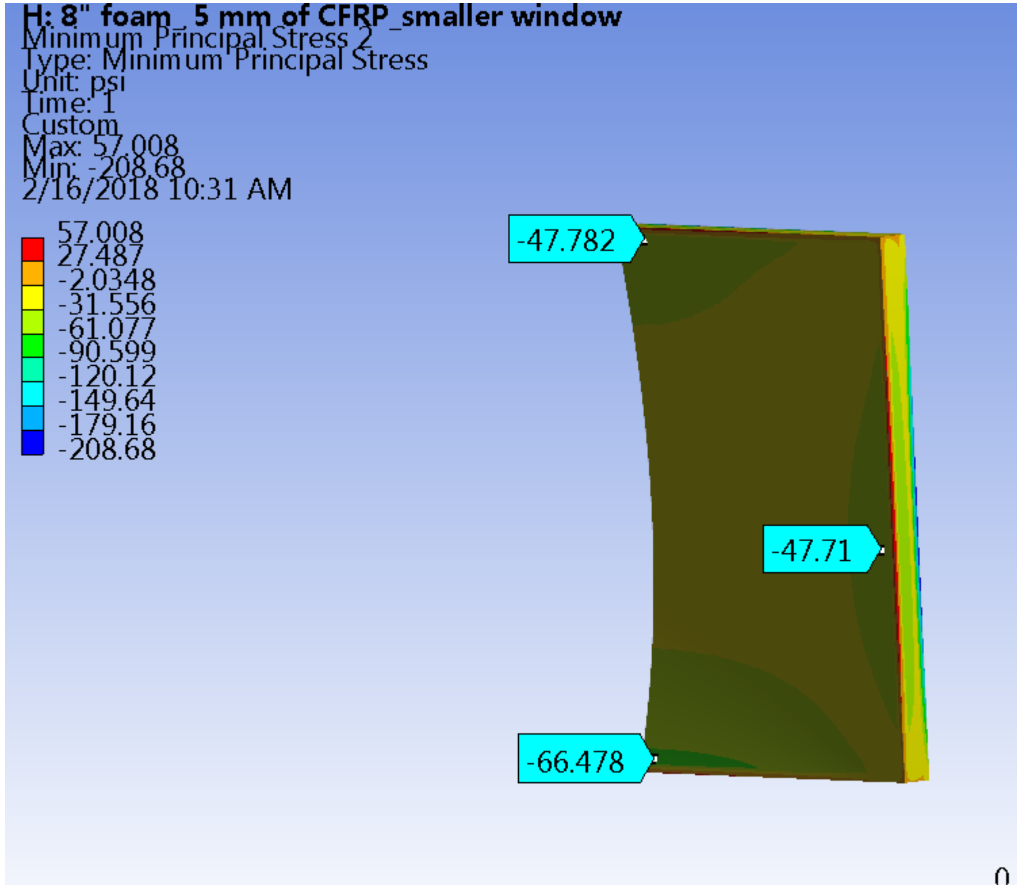


Deflection under 3 psi + hydrostatic pressure (for a smaller window)

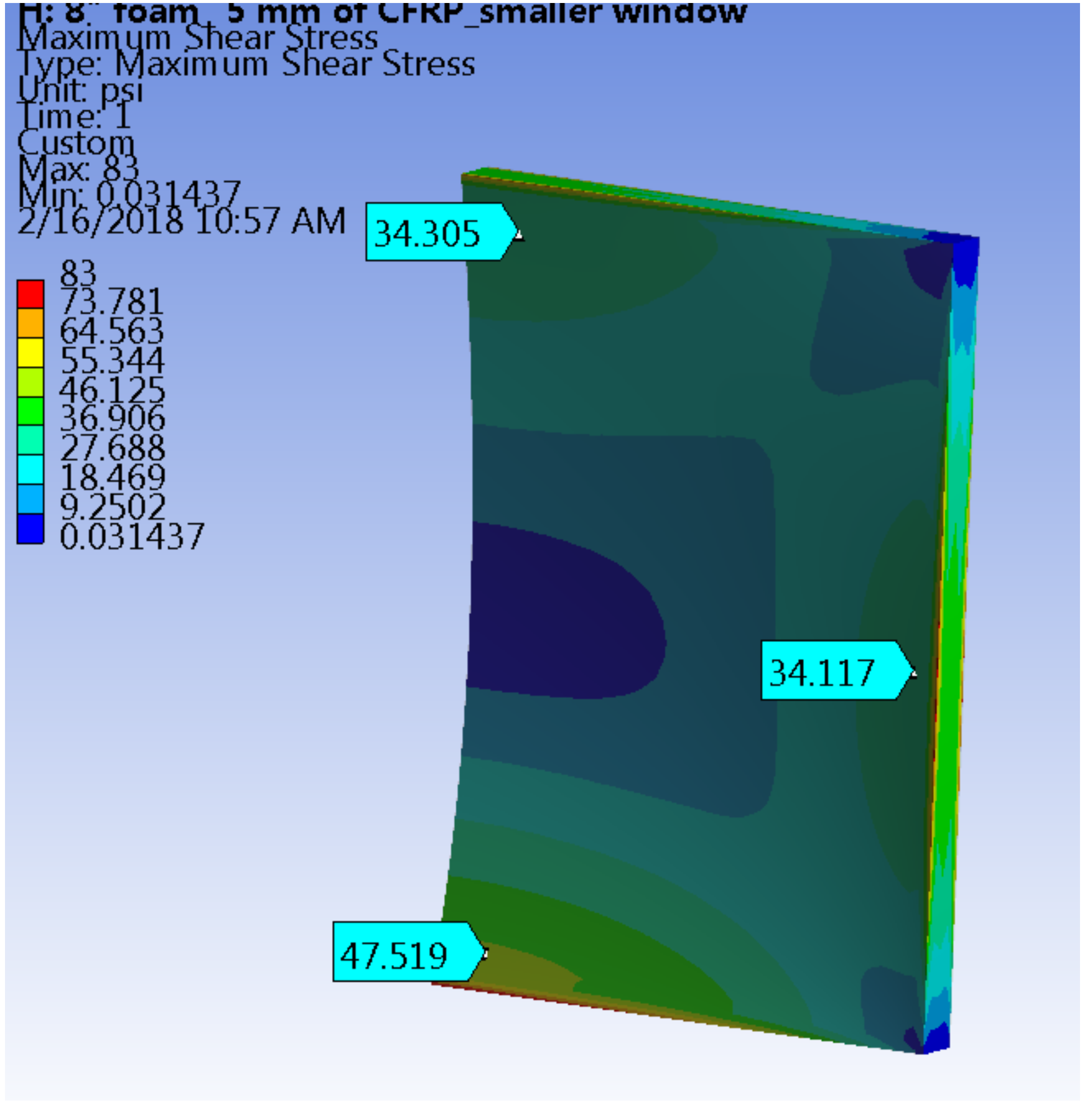
Core thickness Foam 71A	2 mm CFRP/each face	5 mm CFRP/each face
4”	1.12”	0.92”
6”	0.65”	0.56”
8”	0.45”	0.40”



Maximum principle stress of the foam (psi) < ~ 32 psi

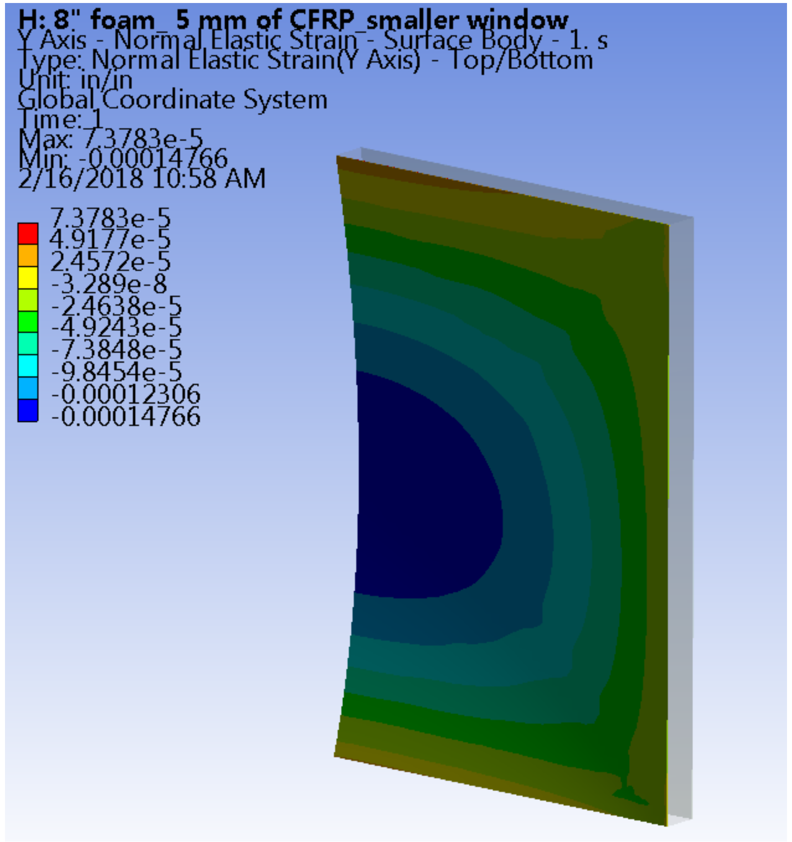


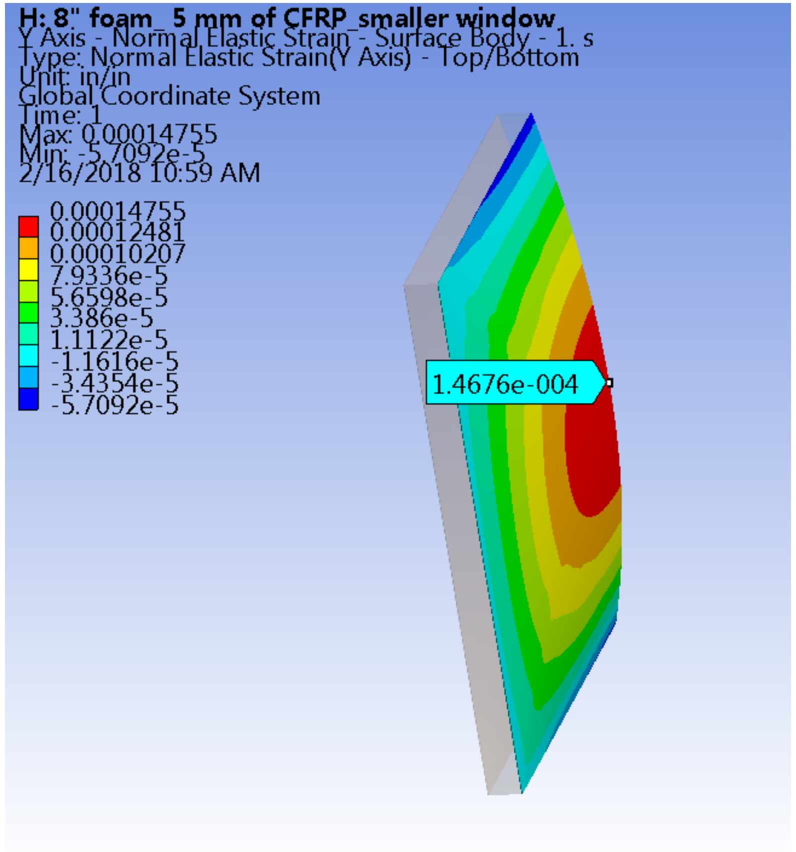
Minimum principle stress of the foam (psi) <~70 psi



The stress of the foam is acceptable for ROHACELL71 A with 8” thickness.

Maximum shear stress of the foam < ~50 psi





1) CFRP Skin strength evaluation is done based on Strain approach for the fiber due to its composite nature. The maximum strain of the -0.0147% in the inner skin. and +0.0147% in outer skin. K13C2U tensile strength is 3800 (MPa) or 0.4%. **SF=0.4/0.0147=27**_ Very Safe.
2) CFRP compressive strength will be dictated by the resin, which is assumed to be epoxy. The typical compressive strength of the epoxy will be > 80 Mpa or 11.6 ksi with a modulus of ~0.5e6 psi. Therefore, the compressive stress for the resin will be 0.000147*0.5e6=74 psi very small << 11.6 ksi.
3) https://www.900gpa.com/en/search?p=fiber&v=list&q=%2210%22&u=metric&page=8&d=pDvBnzW2vzDNc5EzK