SoLID HGC Prototype Front Window Testing

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Abstract

The SoLID Heavy Gas Cherenkov detector requires a window for its vessel that is made of a material that can hold high pressures for long periods of time and can do so with minimal bulging. Windows made of aluminum and carbon fiber were tested to see which material performs better. Different inner liner materials to use with the carbon fiber window, such as Tedlar and Mylar, were tested as well. In the tests, the total deformation of each window, as well as the leak rates, were found. The aluminum window had a maximum deformation of 4.5 cm when inflated to 1340 Torr and a minimum leak rate of $(5 \pm 3) \times 10^{-5} \frac{\text{Torr}\cdot\text{L}}{\text{s}}$. This leak rate is equal to $(2 \pm 1) \times 10^{-7} \frac{\text{g}}{\text{s}}$ of C_4F_8 gas. The carbon fiber window's maximum deformation was 4.4 cm when inflated to 1340 Torr and its minimum leak rate was $(6.2 \pm 0.2) \times 10^{-3} \frac{\text{Torr}\cdot\text{L}}{\text{s}}$ which converts to $(2.0 \pm 0.1) \times 10^{-5} \frac{\text{g}}{\text{s}}$ of C_4F_8 gas. The carbon fiber window leaked when used with a Tedlar inner liner and the bolt holes ripped when used with a Mylar inner liner, causing sealing failure. The aluminum window performs better, more consistently, and is easier to construct then the carbon fiber window, and therefore is the recommended choice.

Introduction

The SoLID Heavy Gas Cherenkov detector (HGC) is designed to be filled with C_4F_8 gas at a pressure of 1.7 atm, or 22.0 psi (absolute), and must fit into the SoLID detector assembly at Jefferson Lab Hall A. Due to this requirement, the entrance window of the vessel must be made of a material that can handle the pressure with minimal expansion (no more than approximately 10 cm), while also minimizing the material traversed by the reaction particles. In a previous test [3], the window was made out of carbon fiber-epoxy and Kevlar with Mylar as a seal underneath. In the current tests, two windows were used, one made out of aerospace-grade aluminum 2024-T4 alloy and one constructed from carbon fiber-epoxy. Tedlar and Mylar sheets were used as seals under the carbon fiber each in individual tests. Furthermore, the geometry of the front window was revised from the earlier test. This report details the procedures used to test the window, and the final results.

Experimental Procedure

Front Window and Frame Geometry

The window and frame design was changed from the 2019 tests [3]. The current window frame design is made of aluminum alloy 6061-T651 that is 0.731 inches (1.86 cm) thick, 42.604 inches (108.21 cm) long and 44.426 inches (112.84 cm) wide at its widest (Fig. 1). It has a 0.257 inch (0.653 cm) clearance between the O-ring groove and the inner cutout for the window (Fig. 2). The inner thickness of the frame is curved all the way round with a radius of 0.375 inches (0.953 cm).

The aluminum window is 0.040 inches thick (1.0 mm), 42.60 inches long (108.20 cm), 44.43 inches (112.85 cm) wide at its widest. The bolt holes are 0.87 inches (2.2 cm) away from the top edge and 0.47 inches (1.2 cm) from the bottom edge. The carbon fiber window has similar dimension to the aluminum window but is 0.080 inches (2.0 mm) thick, approximately 0.070 inches (1.8 mm) thick when compressed under the frame.

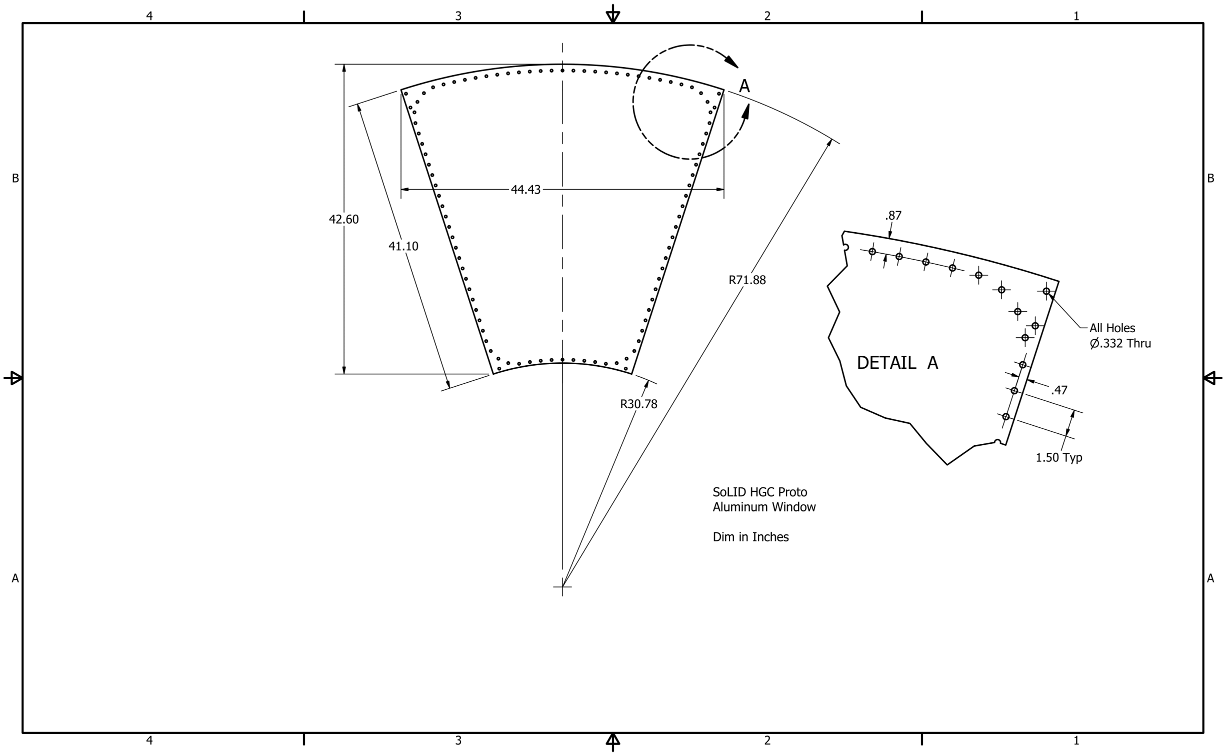


Figure 1: A technical drawing of the front window drawn by Gary Swift. All dimensions are in inches.

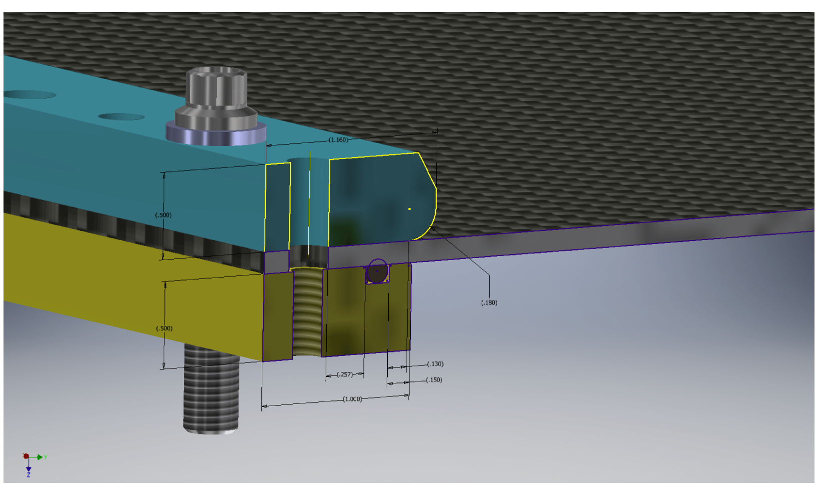


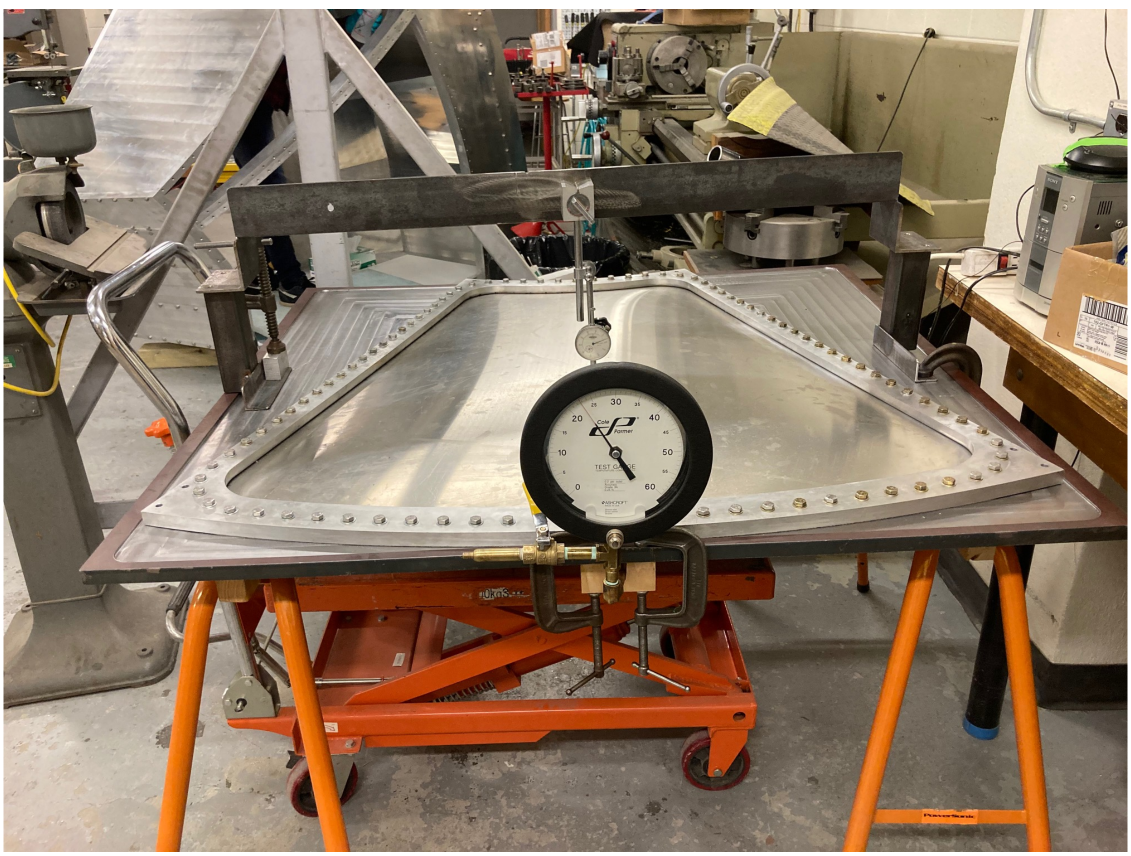
Figure 2: A 3D rendering of the window frame and the O-ring groove

Test Protocol and Setup

Whit Seay, a member of the JLab Hall A engineering staff, has specified that all HGC thin windows need to be tested to 2× operational (design) pressure for an extended period to qualify the design and material batch. An absolute C_4F_8 gas pressure of 1.7 atm implies a differential pressure of 0.7 atm (10.3 psi) across the window. The testing protocol thus requires the window to be inflated to 20.6 psi. We decided to exceed this, going to 2.5× operational, or 25.7 psi (1340 Torr) differential pressure.

As in the earlier tests, the front window and its frame were bolted to a steel testing jig designed specially for this task. Since the window geometry is new, a new test jig was procured from Ross Machine Shop [5], machined from $\frac{3}{4}$ inch thickness steel plate that is 44 inches by 47 inches. A flat level metal frame was clamped to the steel plate and a dial gauge attached to the frame above an initially estimated high point (see Fig. 3); this frame has a $10\frac{1}{4}$ inch clearance between the bottom of the frame and the top of the steel plate. The fasteners are 316 stainless steel $\frac{5}{16}$ inch × 24 tpi × $2\frac{1}{2}$ inch long hex head machine screws, as well as some 316 stainless steel $\frac{5}{16}$ inch × 18 tpi × $1\frac{1}{2}$ inch long hex head machine screws from the small prototype box. A 0.139 inch diameter ($\frac{1}{8}$ nom.) O-ring, very lightly coated with vacuum grease, was placed in the 0.152 inch wide x 0.097 deep machined groove of the steel testing fixture to create an airtight seal. Air was pumped through a hole in the underside of the fixture using a bicycle pump fastened to a pressure gauge and valve. The deflection was measured with a dial gauge placed on the window's highest point.

Figure 3: The setup used to measure the window deflection while inflating.



Deformation test setup

Figure 4: The setup used to measure the window total deformation.

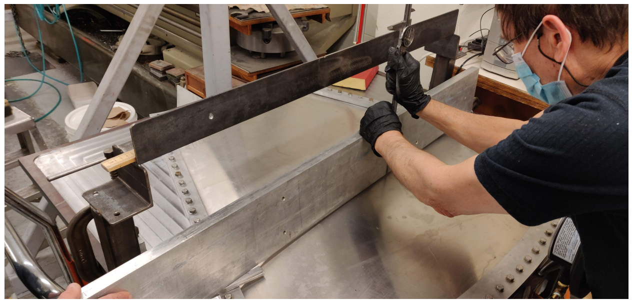
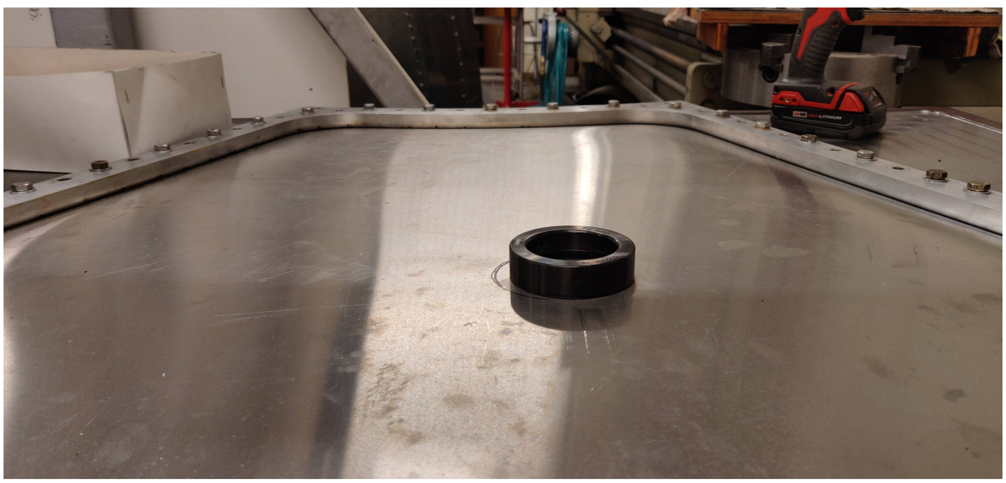


Figure 5: A level ring is used to find the highest point of the window deflection.



To test the deformation of the window while being inflated, a flat level bar was placed across the window above the highest point (see Fig. 4). The height of the deformation was found by subtracting the average height of the two points on the left and right sides of the window where the deflection is the least from the lowest measurement for the high point, and then the thickness of the aluminum window (0.04 inches) was subtracted as well. This difference is the amount the apex bulges from the steel plate. The measurements were made with a caliper. The highest point on the window was determined by placing a level ring on the window and finding the area on the window which it laid flattest using an accurate level (see Figs. 5 and 6). An example calculation using the measurements from the first test is as follows:

Left side reading: 7.275 inches
Right side reading: 7.278 inches
Highest point: 6.236 inches, 6.241 inches, 6.242 inches, 6.254 inches
Thickness of window: 0.04 inches

$$(7.275\ in + 7.278\ in)/2 = 7.277$$
$$\text{Lowest high point} = 6.236\ in$$
$$7.277\ in - 6.236\ in - 0.04\ in = 1.001\ in$$

Total deflection: 1.001 inches

Figure 6: Finding where the apex is using a level and parallel faced ring.

Leak Rate Calculation

The leak rates were calculated by creating an estimate of the volume of the window that depends on time and multiplying this by the pressure per time. The volume was approximated by a trapezoidal wedge whose cross sections are parabolas. The height of the parabolic cross sections vary over time and the highest part of the wedge is equal to the apex of the window. The measurements were converted from psi, inches and minutes to Torr, cm and seconds to make calculating the leak rate in units of $\frac{\text{Torr}\cdot\text{L}}{\text{s}}$ easier. The deflation of the window in the second test was used as an example.

The sides of the wedge were determined from the angles and side measurement of the window found in the vessel diagrams. The sides were described using linear equations. The volume will be bound by these equations.

$$\text{The trapezoid's sides make a } 18^\circ \text{ angle with the x-axis}$$
$$m = \frac{y}{x}$$
$$m = \frac{\sin 18^\circ}{\cos 18^\circ}$$
$$m = 0.325$$
$$\text{The small end of the trapezoid is 45.96 cm}$$
$$b = \frac{45.96}{2}$$
$$b = 22.98$$
$$\text{The volume is bound by:}$$
$$y = 0.325x + 22.98$$
$$y = -0.325x - 22.98$$

The bottom of the parabola, s, is found by subtracting the top equation by the bottom equation. The volume is calculated with integration.

$$s = (0.325x + 22.98) - (-0.325x - 22.98)$$
$$s = 0.650x + 45.96$$

$$V = \int_a^b A(x)dx$$

Where a = 0 and b = 108.21 cm , b is the length of the window

$$V = \int_a^b \frac{4}{3}h(0.650x + 45.96)dx$$
$$V = \frac{4}{6}h(108.21 \text{ cm})^2 + \frac{4(45.96 \text{ cm})}{3}h(108.21 \text{ cm})$$
$$V = 14438.42 \text{ cm}^2 h$$
$$h = \frac{1}{2}D(t)$$
$$V = 7219.21 \text{ cm}^2 D(t)$$

Since the deflection and the pressure change at the same time, they are multiplied together and plotted against the time. The $\frac{\text{dDP}}{\text{dt}}$ is from this graph. The leak is found by multiplying $\frac{\text{dDP}}{\text{dt}}$ by 7219.21 cm^2.

$$L = \text{leak rate}$$
$$L = -7219.21 \text{ cm}^2 (\frac{\text{dDP}}{\text{dt}})$$
$$\frac{\text{dDP}}{\text{dt}} = -0.0004808552 \ \frac{\text{Torr} \cdot \text{cm}}{\text{s}}$$
$$L = 3.471 \ \frac{\text{Torr} \cdot \text{cm}^3}{\text{s}}$$
$$\text{Converting to } \frac{\text{Torr} \cdot \text{L}}{\text{s}}$$
$$L = 0.0035 \frac{\text{Torr} \cdot \text{L}}{\text{s}}$$

Error Calculations

The error in the measurements was ±0.005 in, which converts to ±0.01 cm. The error propagation for the volume and leak rate is below.

$$l = 108.21 \pm 0.01 \text{ cm}$$
$$Area = \frac{4l^2}{6} + \frac{4(45.96)(l)}{3}$$
$$\text{Let } b = l^2 \text{ and } c = l$$
$$Area = \frac{4}{6}b + \frac{4(45.96)}{3}c$$
$$\delta_b = b\sqrt{(\frac{2\delta_l}{l})^2} = 2.16$$
$$\delta_c = c\sqrt{(\frac{\delta_l}{l})^2} = 0.01$$
$$\delta_{Area} = \sqrt{(\frac{4}{6})^2(\delta_b)^2 + (\frac{4(45.96)}{3})^2(\delta_c)^2}$$
$$\delta_{Area} = 1.47$$

The area is $7219 \pm 1\text{cm}^2$. To find the error in $\frac{\text{dDP}}{\text{dt}}$, a formula derived from the standard error in the slope is used.

$$m = \frac{\text{dDP}}{\text{dt}}$$
$$\delta_m^2 = \frac{n\delta_{DP}^2}{n\sum_{i=1}^n t^2 - (\sum_{i=1}^n t)^2}$$
$$\delta_{DP} = DP\sqrt{(\frac{\delta_D}{D})^2 + (\frac{\delta_P}{P})^2}$$
$$\delta_{DP} = 10.8 \text{ Torr} \cdot \text{cm}$$
$$\delta_m = 0.00004766 \ \frac{\text{Torr} \cdot \text{cm}}{\text{s}}$$

The rate is $-0.00048 \pm 0.00005 \frac{\text{Torr}\cdot\text{cm}}{\text{s}}$. The total error in the leak rate is:

$$\delta_L = L\sqrt{(\frac{\delta_{Area}}{Area})^2 + (\frac{\delta_m}{m})^2}$$
$$\delta_L = 0.345\frac{\text{Torr} \cdot \text{cm}^3}{\text{s}}$$

The leak rate is $3.5 \pm 0.3\frac{\text{Torr}\cdot\text{cm}^3}{\text{s}}$. When converted to $\frac{\text{Torr}\cdot\text{L}}{\text{s}}$, the leak rate becomes $0.0035 \pm 0.0003\frac{\text{Torr}\cdot\text{L}}{\text{s}}$.

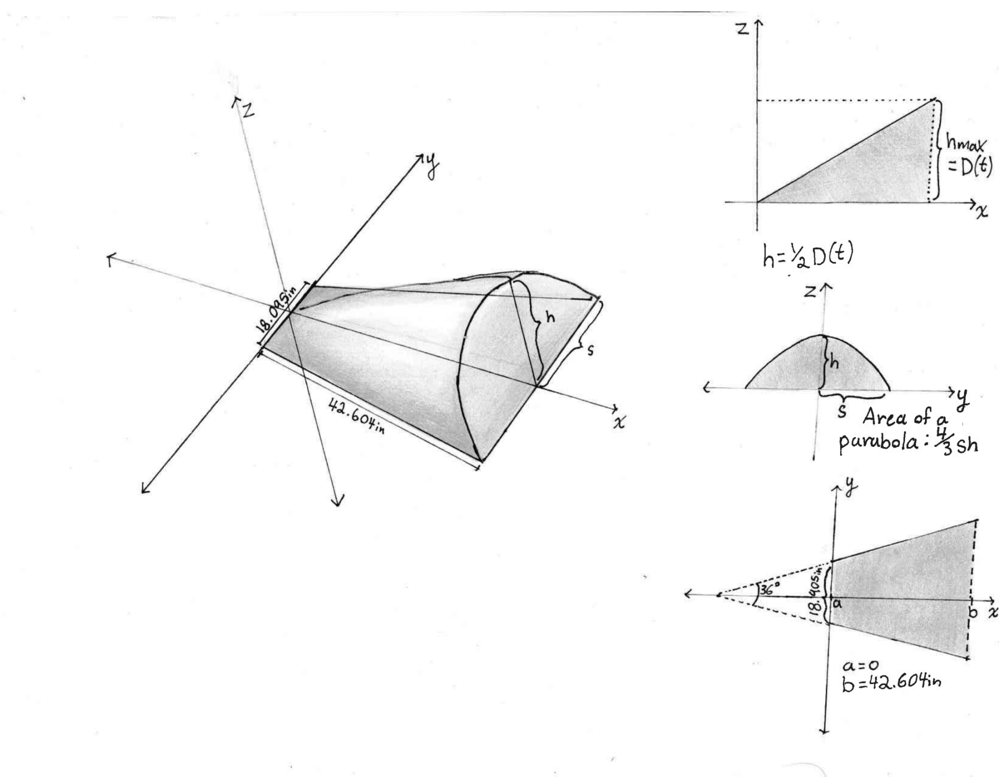


Figure 7: Model of the volume of the window. The height h varies over time. The maximum value for h is the deflection of the window at its highest point

Results: Aluminum Window 1

Summary

These tests were done on an aluminum window of 2024-T4 alloy procured from ASM Aerospace Specification Metals Inc. [1]. It is 0.040 inches thick, 42.604 inches long and 44.462 inches wide at its widest. The aluminum window did well in the initial tests. The window's deformation would decrease significantly over time, after pressure was removed. The window's deformation went from 1.375 inches to 0.522 inches when left alone for four days. An issue with the window was elongation around the bolt holes (see Fig. 15). We speculate that this happened due to uneven tightening of the bolts, as bolts were tightened by two people using two individual torque wrenches. An overview of the tests is in Table 1. The maximum deformation of the window was 1.753 inches when the window was inflated to 26 psi.

Test	Highest Deformation	Leak Rate
1	1.001 inches	N/A
2	1.753 inches	$0.0035 \pm 0.0003\ \frac{\text{Torr}\cdot\text{L}}{\text{s}}$
3	1.375 inches	N/A

Table 1: Remarks:
Test 1 - The window held pressure well. Some issues with the valve.
Test 2 - The window held pressure over long periods of time well. Some issues with the valve and bike pump.
Test 3 - The window had slight tearing around its bolt holes. It was placed on the vessel during the vessel's pressure test.

Test 1

The first pressure test of the aluminum window happened on February 8th. The window was set up in the manner described in the experimental procedure. The dial gauge was placed on the window's estimated high point. An issue occurred with this test where the valve was leaking. The results are listed in Table 2. A graph of the defection over pressure is in Fig. 8.

Table 2: Test 1. The pressure and deflection measured in imperial units (Raw Data) as well as the pressure and deflection measured in metric units (converted). The pressure has an error of ±5 Torr and the deflection has an error of ±0.003 cm.

Pressure (psi)	Deflection (inches)	Pressure (Torr)	Deflection (cm)
3.0	0.209	155	0.531
6.0	0.400	311	1.015
9.0	0.542	466	1.377
12.0	0.658	620	1.671
15.0	0.760	776	1.930
18.0	0.856	931	2.174
Dial was re-zeroed			
21.0	0.948	1086	2.408
24.0	1.041	1241	2.644
26.5	1.116	1370	2.835
Residual deformation afterward at 1 psi: 1.001 inches			

The first time the deformation of the window was measured was on February 9th. The window was deflated to 1 psi. The deformation was measured using the method outlined in the experimental procedure. The residual deformation at 1 psi was 1.001 inches.

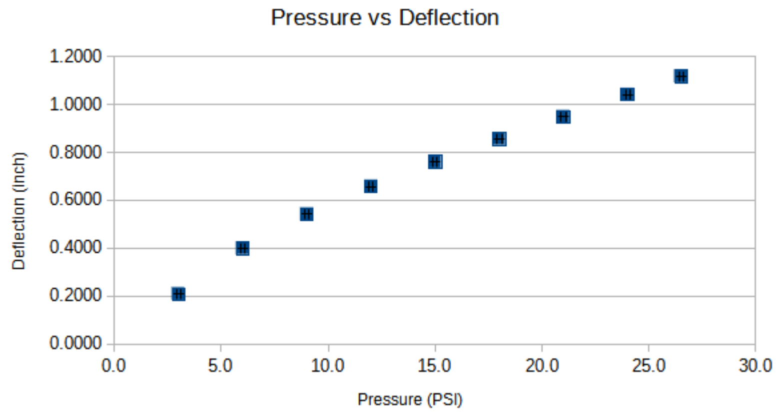


Figure 8: A graph showing the relationship between pressure and deflection for the first test in imperial units.

Test 2

The deflection was tested for a second time on February 10th. The window had 1 psi before it was inflated. Some problems that occurred with this test were that both the bike pump and the valve were leaking. The results are in Table 3. A graph of the defection over pressure is in Fig. 9.

Table 3: Test 2.1 The pressure and deflection measured in imperial units (Raw Data) as well as the pressure and deflection measured in metric units (converted). The pressure has an error of ±5 Torr and the deflection has an error of ±0.003 cm.

Pressure (psi)	Deflection (inches)	Pressure (Torr)	Deflection (cm)
1.0	0.025	52	0.064
3.1	0.385	155	0.978
5.0	0.467	259	1.186
7.1	0.530	368	1.346
9.0	0.579	466	1.471
10.7	0.615	554	1.562
10.7 (held)	0.615	554 (held)	1.562
13.0	0.658	672	1.671
15.0	0.694	776	1.764
17.0	0.726	879	1.843
19.0	0.754	983	1.914
21.1	0.783	1091	1.989
21.8	0.794	1127	2.017
22.6	0.804	1169	2.042
22.95	0.810	1187	2.056

After this test, the window was left inflated for almost one day. The window's deflection and pressure were checked periodically. The results are in Table 4. A graph of the deflection and pressure over time is in Fig. 10. The leak rate of the window was 0.0035 ± 0.0003 $\frac{\text{Torr}\cdot\text{L}}{\text{s}}$. This leak rate was affected by the leaking valve.

On February 11th at 15:24, the window was at 22.65 psi and seemed to be working well. Additional air was pumped into the window. The results are in Table 5. The temperature of the room was 72 °F and

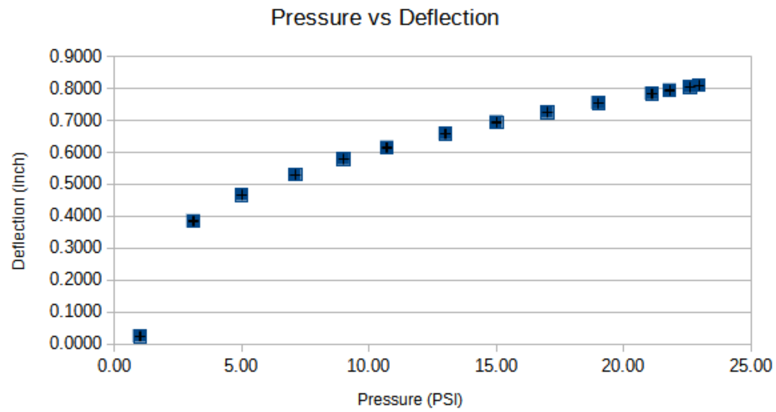


Figure 9: Test 2.1 A graph showing the relationship between pressure and deflection for the second test in imperial units.

Table 4: Test 2.2 The window's deflation from the 10th. The pressure is given in units of psi and Torr and the deflection has units of inches and cm. The pressure has an error of ±0.1 psi or ±5 Torr and the deflection has an error of ±0.001 inch or ±0.003 cm. The time is given in minutes.

Pressure (psi)	Deflection (inches)	Pressure (Torr)	Deflection (cm)	Elapsed Time (minutes)
22.95	0.810	1187	2.056	0
23.00	0.808	1189	2.052	313
22.90	0.806	1184	2.047	1075
22.65	0.805	1171	2.046	1435

the atmospheric pressure was 1039 hPa (15.07 psi) according to weather.com. The window was left inflated overnight at a pressure of 26.0, and later at 20:26 the pressure was 25.0 psi.

On February 12th, the pressure of the window in the morning at 11:30 was found to be 26.0 psi, and in the afternoon at 14:30 it was still 26.0 psi. The window was left inflated and the deformation was measured as 1.753 inches using the methods mentioned in the experimental procedure. The high point of the window was then found and marked using the method mentioned in the experimental procedure. At 16:22, the pressure was 26.0 psi and the dial gauge was zeroed on the window's highest point. The atmospheric pressure was measured with a pressure gauge to be 71.6 mmHg (955 hPa or 13.85 psi).

The window was left inflated over six days. The results are in Tables 6, 7. The pressure and deflection over time are graphed in Fig. 11. The leak rate is $(5 \pm 3) \times 10^{-5} \frac{\text{Torr}\cdot\text{L}}{\text{s}}$. There is much error in calculating this leak rate, due to the leak rate being so small. Afterwards, the window was deflated and used to test the vessel.

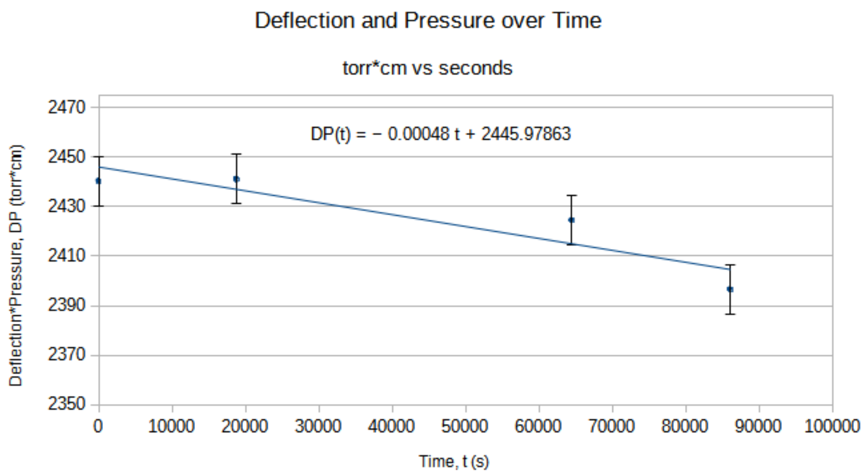


Figure 10: Test 2.2 The deflation of the aluminum window over time.

Table 5: Test 2.3 The pressure and deflection measured in imperial units (Raw Data) as well as the pressure and deflection measured in metric units (converted). The pressure has an error of ±5 Torr and the deflection has an error of ±0.003 cm.

Pressure (psi)	Deflection (inches)	Pressure (Torr)	Deflection (cm)
23.5	0.8145	1215	2.069
24.6	0.8280	1272	2.103
25.6	0.8410	1324	2.136
26.6	0.8552	1376	2.172
26.6 (held)	0.8555	1376 (held)	2.173

Table 6: Test 2.4 Table of the window's pressure over a few days. The data for the pressure and deflection were originally in imperial units, the data for atmospheric pressure were originally in hPa.

Absolute Pressure (psi)	Deflection (inches)	Atmospheric Pressure (psi)	Differential Pressure (psi)	Elapsed time (days)
26.0	0.000	13.9	12.1	0
26.1	-0.001	15.1	11.0	1.0868
26.1	-0.001	15.1	11.0	2.1069
26.5	0.000	14.8	11.7	3.1229
26.4	0.001	14.8	11.6	4.1146
26.4	0.000	14.9	11.5	5.1007
Deformation at 26.0 psi: 1.753 inches				

Table 7: Test 2.4 Table of the window's pressure over a few days. The data is converted as follows: pressure and atmospheric pressure Torr, deflection to cm and time to seconds. The error of the pressure is ±5 Torr and the error of the deflection is ±0.003 cm.

Absolute Pressure (Torr)	Deflection (cm)	Atmospheric	Differential Pressure (Torr)	Elapsed time (seconds)
1350	-0.0025	782	568	0
1350	-0.0025	782	568	93900
1350	-0.0025	779	571	182036
1370	0.000	766	604	269819
1365	0.0025	764	602	355501
1365	0.000	771	594	440700
Deformation at 1350 Torr: 4.453 cm				

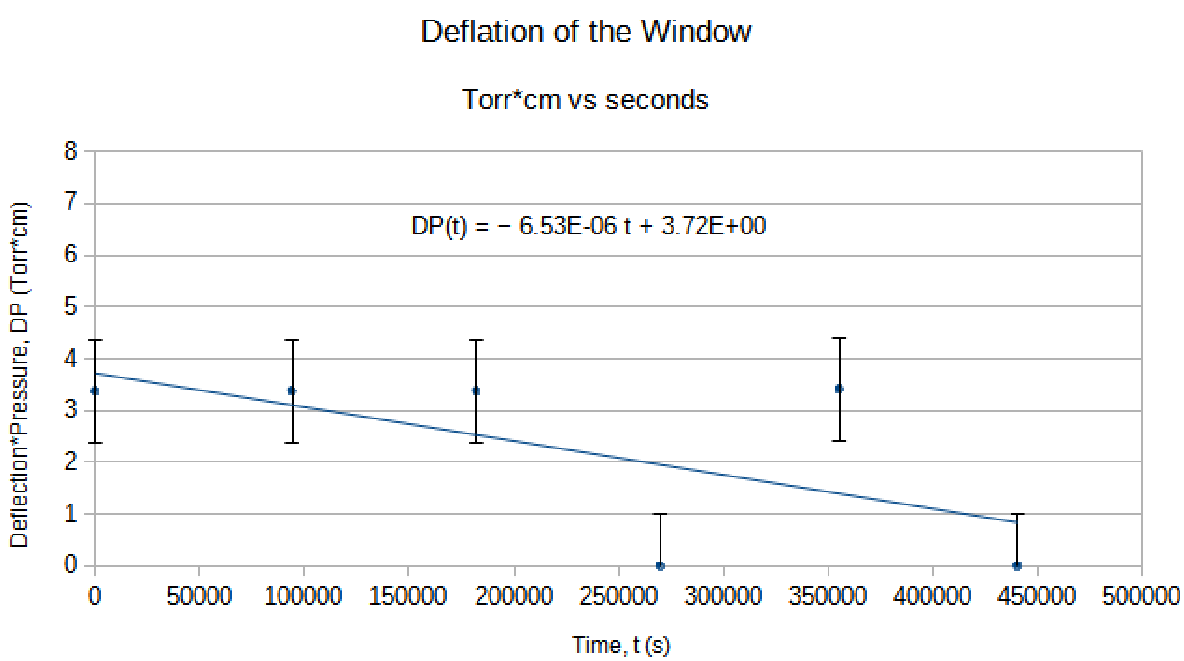


Figure 11: Test 2.4 The rate is $(-7 \pm 4) \times 10^{-6}\ \frac{\text{Torr}\cdot\text{cm}}{\text{s}}$.

Test 3

Table 8: Test 3. The pressure and deflection measured in imperial units (Raw Data), as well as the pressure and deflection measured in metric units (converted). The pressure has an error of ±5 Torr and the deflection has an error of ±0.003 cm.

Pressure (psi)	Deflection (inches)	Pressure (Torr)	Deflection (cm)
26.2	0.001	1355	0.002
0.2	0.978	11	2.483
0.0	0.977	0.0	2.482

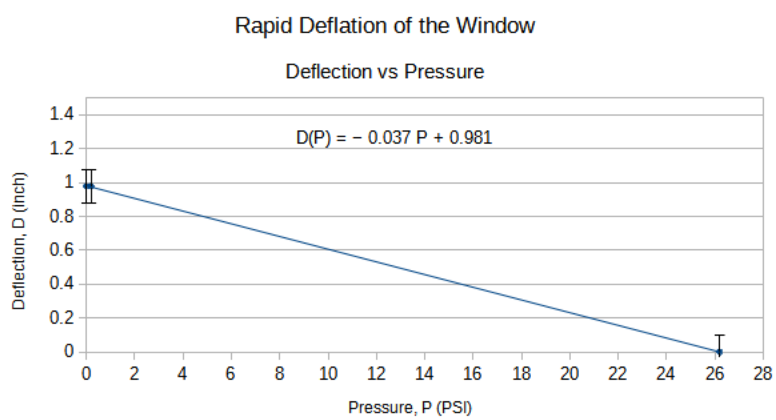


Figure 12: Test 3. The window's rapid deflation.

Figure 13: The aluminum window's bolt holes on February 18th. Stretching is observed around some bolt holes on the left.

On February 18th, the window was deflated. The deflection was measured as the window was deflating.

The deflection decreased rapidly when the window's pressure was almost gone (during the last 10 psi). The measurements can be found in Table 8. A graph of this deflation is in Fig. 12. After the window was deflated, the window was removed and its deformation was measured using a dial gauge. Some elongation around the bolt holes was noticed (see Fig. 13). Unfortunately, the dial gauge was bumped in the process of removing the window. Since the gauge was bumped, the deformation may be either 1.102 inches or 1.202 inches. The window was placed back on the steel plate and was bolted in a zigzag pattern with 100 in-lbs torque, then 110 in-lbs and finally 120 in-lbs torque.

On February 19th, while testing the vessel, the window bulged to roughly 1.375 inches while inflated to 9.0 psi. This is a rough measurement, because of the difficulty of measuring the bulge while the window was attached to the vessel. On February 23rd, the window's deformation was measured again after it had been off the vessel for a few days. The deformation was found to be 0.522 inches, a significant decrease.

The window was used in one more pressure test. On March 1st, the vessel was tested with a pressure of 15 psi. Afterwards, the window was removed and significant stretching near the bolt holes was noticed (see Fig. 14). A new window was required for further testing. A comparison of the stretched bolt holes can be found in Fig. 15.

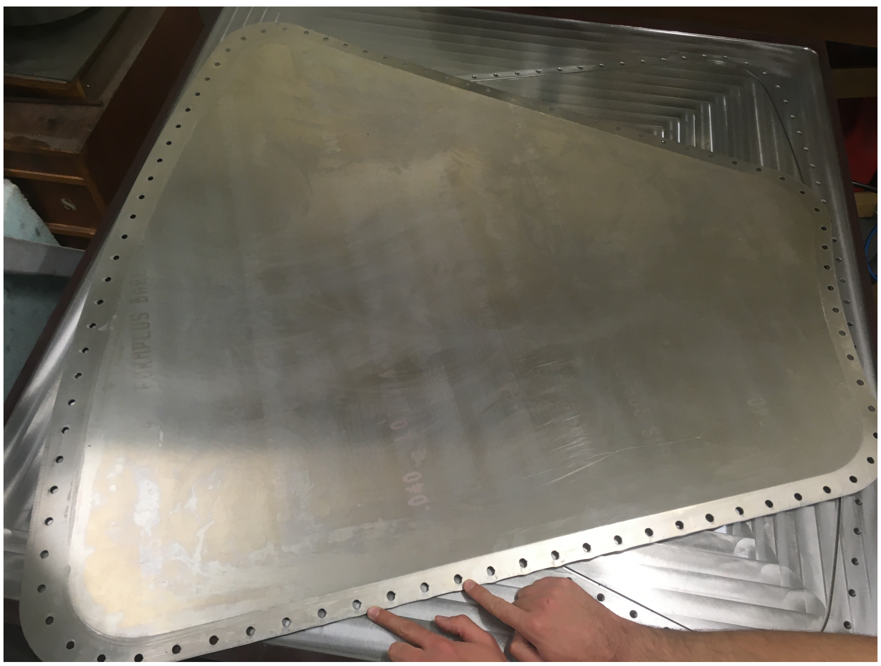


Figure 14: The aluminum window bolt holes on March 1st.

(a) Close up of the bolt holes on February 18th.

(b) Close up of the bolt holes on March 1st.

Figure 15: A comparison of the bolt holes from February 18th and March 1st.

Leak Rate When Filled With C_4F_8

The SoLID Heavy Gas Cherenkov detector (HGC) is designed to be filled with C_4F_8 gas, so it is necessary to calculate what the leak rate would be when filled with this gas instead of air. To make the gas loss over time more clear, the leak rate is converted from $\frac{\text{Torr}\cdot\text{L}}{\text{s}}$ to $\frac{g}{s}$. This calculation is done with the lowest leak rate for the aluminum window, $(5 \pm 3) \times^{-5} \ \frac{\text{Torr}\cdot\text{L}}{\text{s}}$, found in test 3.

The leak rate is converted from $\frac{\text{Torr}\cdot\text{L}}{\text{s}}$ to $\frac{g}{s}$ using the ideal gas law. The leak rate is first converted to $\frac{\text{Pa}\cdot\text{m}^3}{\text{s}}$. It is then divided by the ideal gas constant and the room temperature and multiplied by the molecular weight of air, which is 28.97 $\frac{g}{mol}$[6].

$$\text{Leak Rate} = 5 \times 10^{-5} \frac{\text{Torr} \cdot \text{L}}{\text{s}} = 7 \times 10^{-6} \frac{\text{Pa} \cdot \text{m}^3}{\text{s}}$$

$$\text{Leak Rate} = \text{M}\left(\frac{PV}{RT}\right)$$

$$\text{Leak Rate} = 28.97 \frac{\text{g}}{\text{mol}} \left(\frac{7 \times 10^{-6} \frac{\text{Pa}\cdot\text{m}^3}{\text{s}}}{\left(8.3145 \frac{\text{Pa}\cdot\text{m}^3}{\text{K}\cdot\text{mol}}\right)(293\text{K})} \right)$$

$$\text{Leak Rate} = 8 \times 10^{-8} \frac{\text{g}}{\text{s}}$$

After converting to $\frac{\text{g}}{\text{s}}$, the leak rate of a window filled with C_4F_8 is found by multiplying the leak rate of air by the square root of the molecular weight of C_4F_8[4] over the molecular weight of air.

$$\text{L}_{\text{C}_4\text{F}_8} = \text{L}_{\text{air}} \sqrt{\frac{\text{M}_{\text{C}_4\text{F}_8}}{\text{M}_{\text{air}}}}$$

$$\text{L}_{\text{C}_4\text{F}_8} = 8 \times 10^{-8} \sqrt{\frac{200.028}{28.97}}$$

$$\text{L}_{\text{C}_4\text{F}_8} = 2 \times 10^{-7} \frac{\text{g}}{\text{s}}$$

The lowest leak rate of an aluminum window filled with C_4F_8 is $(2 \pm 1) \times 10^{-7} \frac{\text{g}}{\text{s}}$.

Final Aluminum Window Observations

The aluminum window had a maximum bulge of 4.5 cm when inflated to 1340 Torr and a minimum leak rate of $(5 \pm 3) \times 10^{-5} \frac{\text{Torr}\cdot\text{L}}{\text{s}}$, which converts to $(2 \pm 1) \times 10^{-7} \frac{\text{g}}{\text{s}}$ of C_4F_8 gas. The window was able to hold pressure for long periods of time with minimal leaking. The aluminum had tendency for its bulge to flatten over time. The deformation went from 3.5 cm to 1.3 cm in a few days. The aluminum window appears to satisfy all of the project criteria.

Results: Carbon Fiber Epoxy Window with Liner

Summary

Several tests were done on a window made out of epoxy resin and carbon fiber. The resin used was the System 2000 epoxy resin from FibreGlast [2]. Small panels were constructed using the 2020 curing agent with a 20 minute cure time, but later the 20120 curing agent was used. One of the small panels used FibreGlast 1072-C 3K, 2×2 twill weave carbon fiber fabric. The final carbon fiber window was made with FibreGlast 1072-C 12K, 2×2 twill weave carbon fiber fabric, three layers thick. After construction, a sheet of Tedlar was cut to the window dimensions. This sheet was then placed under the window during testing to provide the pressure seal. Later, a Mylar sheet was used. The maximum deformation was 4.407 cm (1.735 inches) and the minimum leak rate was $(6.2 \pm 0.2) \times 10^{-3} \frac{\text{Torr}\cdot\text{L}}{\text{s}}$. An overview of the tests is in Table 9.

Test	Highest Deformation	Leak Rate
1 - Tedlar	4.407 cm	$0.0062 \pm 0.00002 \frac{\text{Torr}\cdot\text{L}}{\text{s}}$
2 - Mylar	N/A	N/A

Table 9: Remarks:
Test 1 - The window leaks from various locations near the window frame. Creases in the Tedlar were found at these locations.
Test 2 - The window bolt holes tore during testing. This likely happened due to it slipping.

Construction

First Small Panel Window

List of Materials Used:

- FibreGlast 1072-C 12K,2x2 twill weave carbon fiber fabric
- FibreGlast 2000 Epoxy Resin
- FibreGlast 2020 Epoxy Cure
- FibreGlast 1153 Fibrelease agent
- FibreGlast 582-C Nylon Release Peel Ply
- FibreGlast 579-C 4oz Breather and Bleeder Cloth
- FibreGlast Stretchlon 200 Bagging Film
- Vacuum Bag Sealant Tape
- Clear PVC Tubing

On March 16th, a small $16\frac{5}{8}$ inch by 20 inch carbon fiber window was constructed. To construct the window, a large glass sheet was cleaned and coated with release agent. The release agent was sprayed on an area of the glass, roughly 20 inches by 23 inches, and it was smoothed out with a brush. It was allowed to dry for over an hour. While the release agent dried, some "fisheyes" formed (see Fig. 16).

Three sheets of the carbon fiber were cut 20 inches by 23 inches, larger than the finished window, to allow for sanding and shaping. The edges were taped to prevent the fibers from unraveling. The nylon release ply, the breather and bleeder cloth, and the bagging film were cut into rectangles larger than 20 inches by 23 inches. The vacuum bag sealant tape was then stuck to the glass treated with the release agent in a 20 inches by 23 inches rectangle. The paper was left on the tape to keep it clear of dust and epoxy.

The epoxy was mixed by weight in a ratio of 100:23 of resin to cure. Roughly 500 g of epoxy was made. A layer of epoxy was brushed on the area of the glass enclosed by the vacuum sealant tape. The cut carbon

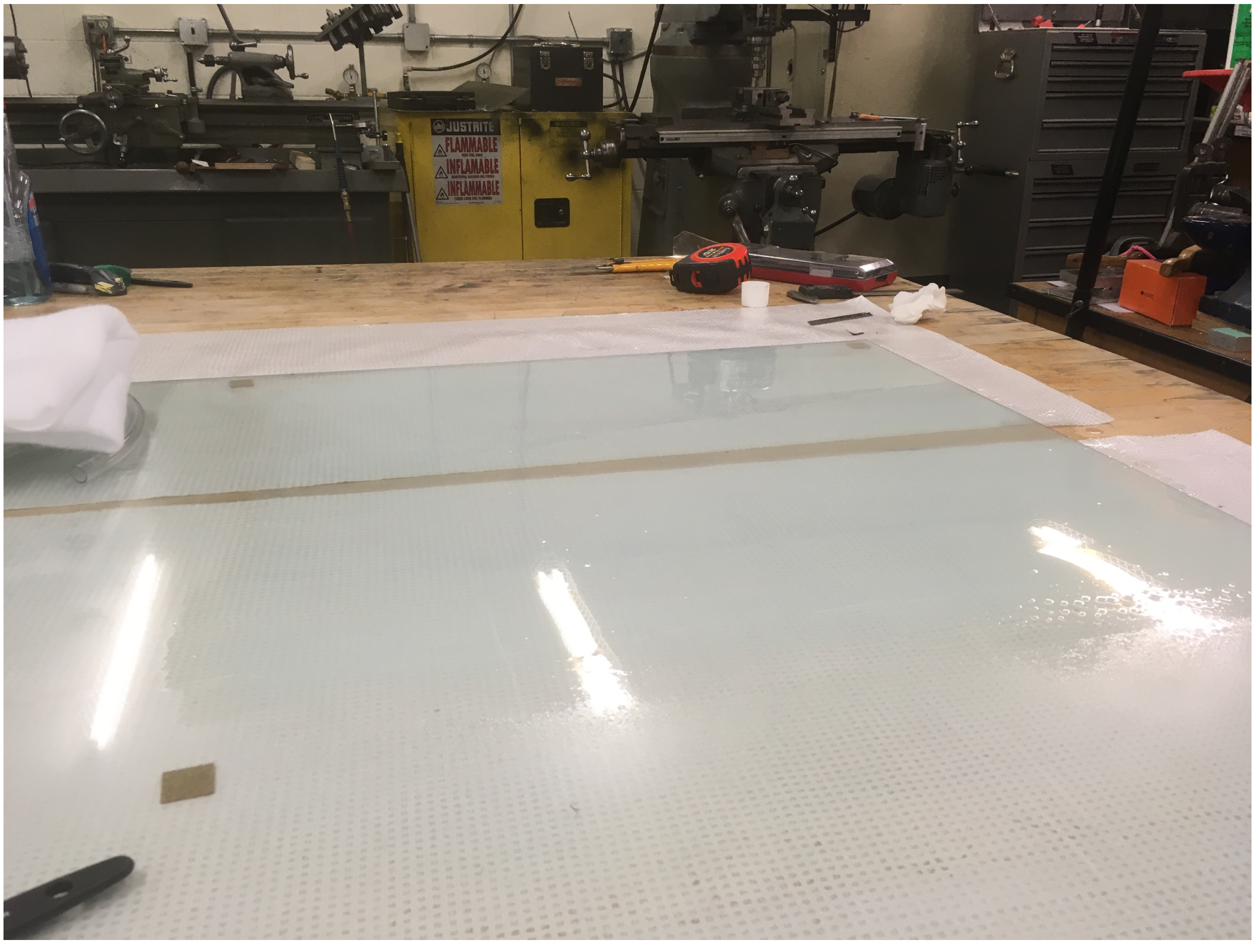


Figure 16: “Fisheyes” that formed when the release agent dried.

Figure 17: The epoxy was brushed in a dabbing motion to pull the epoxy through the carbon fiber with no air bubbles.

fiber sheets were then placed on the epoxy one at a time. The epoxy was pulled through the sheet with the brush using a dabbing motion to prevent air bubbles (see Fig. 17). More epoxy was added when needed, the sheets should be fully soaked but should not have excess epoxy. There was 118 g of epoxy left over.

Figure 18: The nylon is placed over the breather and bleeder cloth.

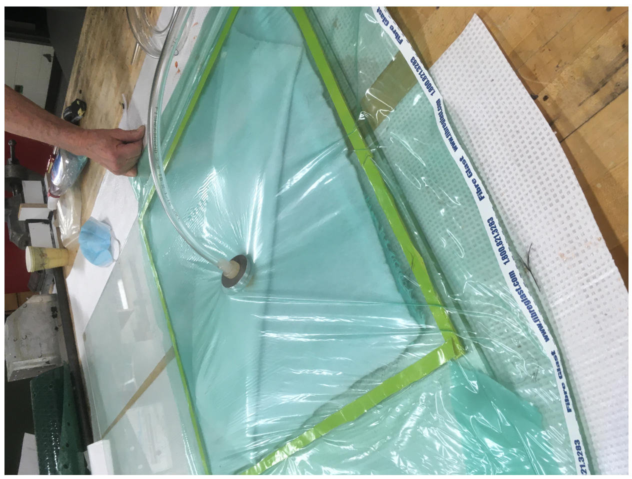


Figure 19: The vacuum being pulled on the small Carbon fiber window.

Figure 20: The final result of constructing the first small window.

After the epoxy was applied, the nylon release ply was placed on top of the carbon fiber, then the breather and bleeder cloth was placed on with extra cloth where the vacuum tubing will connect (see Fig. 18). The bagging film with the tubing attached was stuck down with the vacuum sealant tape. A vacuum was pulled overnight (see Fig. 19). The final window was unfortunately distorted from the vacuum tubing (see Fig. 20).

Second Small Panel Window

List of Materials Used:

- FibreGlast 1072-C 3K,2×2 twill weave carbon fiber fabric
- FibreGlast 2000 Epoxy Resin
- FibreGlast 2020 Epoxy Cure
- FibreGlast 1153 Fibrelease agent
- FibreGlast 582-C Nylon Release Peel Ply
- FibreGlast 579-C 4oz Breather and Bleeder Cloth
- FibreGlast Stretchlon 200 Bagging Film
- Vacuum Bag Sealant Tape
- Clear PVC Tubing

On March 20th, another small window was made using the same method as before, but with a thinner carbon fiber (see Fig. 21).

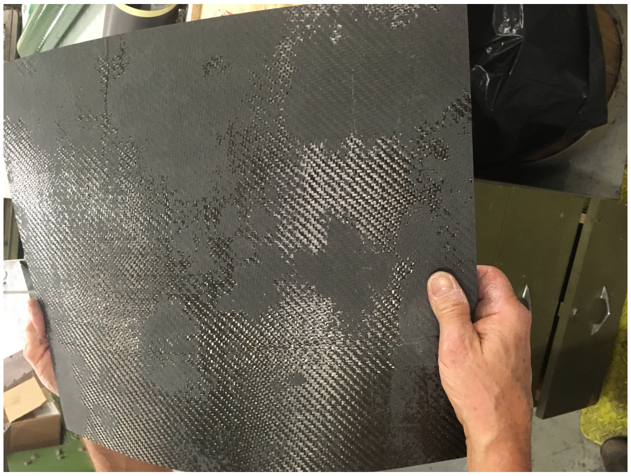


Figure 21: The final result of constructing the second small window.

Third Small Panel Window

List of Materials Used:

- FibreGlast 1072-C 12K,2×2 twill weave carbon fiber fabric
- FibreGlast 2000 Epoxy Resin
- FibreGlast 20120 Epoxy Cure
- FibreGlast 1153 Fibrelease agent

- FibreGlast 582-C Nylon Release Peel Ply
- FibreGlast 579-C 4oz Breather and Bleeder Cloth
- FibreGlast Stretchlon 200 Bagging Film
- Vacuum Bag Sealant Tape
- Clear PVC Tubing

On March 26th, a final small window was made using the same method as the first window, but the 20120 cure was used instead of the 2020 cure. Unfortunately, the epoxy was mixed with the wrong ratio. It should have been a ratio of 100:27 resin to cure, but instead was mixed to 100:23 resin to cure. The epoxy didn't cure correctly and the window remained tacky. The final result is in Fig. 22.

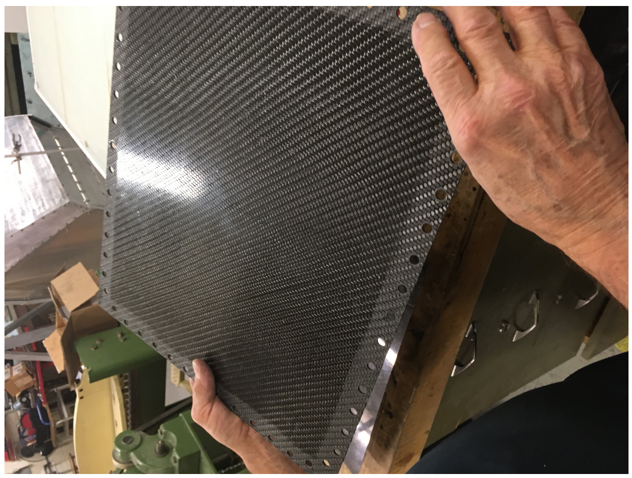


Figure 22: The final result of constructing third small window.

Full Sized Window

- FibreGlast 1072-C 12K,2×2 twill weave carbon fiber fabric
- FibreGlast 2000 Epoxy Resin
- FibreGlast 20120 Epoxy Cure
- Rexco Partall Paste # 2 paste wax mold release
- FibreGlast 582-C Nylon Release Peel Ply
- FibreGlast 579-C 4oz Breather and Bleeder Cloth
- FibreGlast Stretchlon 200 Bagging Film
- Vacuum Bag Sealant Tape
- Clear PVC Tubing

On March 27th, the full sized window was constructed in a similar method to the first window. Instead of using the Fibrelease spray, a wax mold release (see Fig. 23) was used. The wax was applied sparingly with a kimwipe and buffed onto the glass until smooth. The wax was applied to the whole glass.

Three 48 inch by 48 inch squares of the carbon fiber were cut. Straight cuts were made by pulling one of the fibers out of the weave and using the mark that it leaves as a guide. The squares were then cut to be

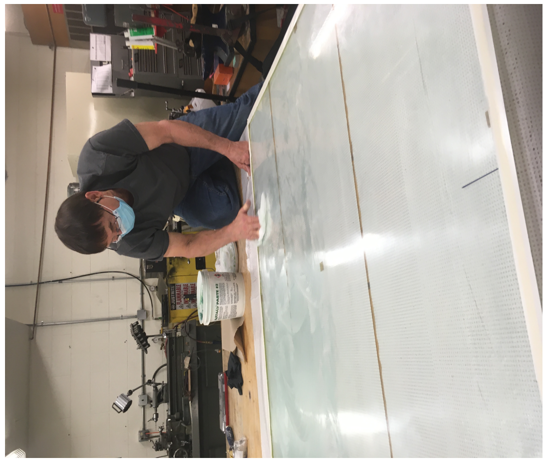


Figure 23: The wax mold release was buffed onto the glass.

Figure 24: The carbon fiber is roughly the same shape as the window.

tapered so that they roughly fit the shape of the final window; this allowed for less epoxy to be used and to position the vacuum hose correctly (see Fig. 24).

Tape was applied to the cut edges to prevent them from unravelling. The size of the carbon fiber sheets were only slightly smaller than the glass, which made the construction difficult. There was 2814 g of epoxy mixed using the ratio of 100:27 resin to cure; there was approximately 900 g left over. The epoxy was applied with a paint roller and a brush. When it was being applied, some of the wefts of the carbon fiber were shifted out of place. The vacuum nozzle was positioned to the side of the sheet to prevent the distortion (see Fig. 25). Despite the cure having a pot life of 120 minutes, it took over 9 hours to fully cure. The final result is in Fig. 26.

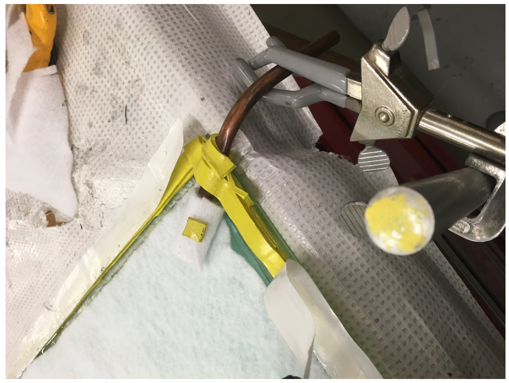


Figure 25: This vacuum setup prevents the window from becoming distorted.

Figure 26: The finished window before sanding, shaping and cutting out the bolt holes.

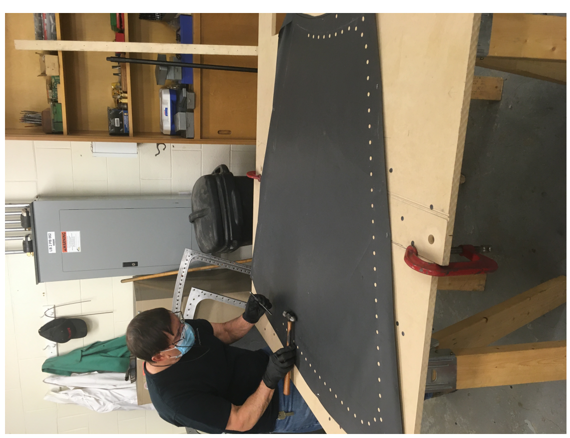


Figure 27: The Tedlar's bolt holes being punched.

Test 1

On April 12th, a sheet of black Tedlar was cut slightly larger than the window frame. This is the same frame that was used on the aluminium window. The frame was placed over the Tedlar, the bolt holes were marked with a transfer punch, and frame was traced onto the Tedlar. The frame was removed and holes were punched out of the Tedlar with a $\frac{3}{8}$ in punch (see Fig. 27). While punching the bolt holes, hearing protection was used, as the noise from hammering the punch was very loud. The carbon window was set up in a similar way to the aluminum window, but the Tedlar sheet was placed underneath the carbon fiber window. The next day, a 1-2-3 gauge block was placed underneath the dial gauge. The window was then inflated as indicated in Table 10. The total deformation was 1.735 inches when inflated to 26.0 psi and was measured using the methods in the experimental procedure.

Table 10: The pressure and deflection measured in imperial units (Raw Data) as well as the pressure and deflection measured in metric units (converted). The pressure has an error of ±5 Torr and the deflection has an error of ±0.003 cm.

Pressure (psi)	Deflection (inches)	Pressure (Torr)	Deflection (cm)
5.2	0.623	269	1.582
6.2	0.860	321	2.184
8.0	0.908	414	2.306
Dial was re-zeroed, gauge block removed			
9.8	0.186	507	0.472
12.0	0.295	621	0.749
14.0	0.380	724	0.965
15.8	0.445	817	1.130
19.5	0.565	1008	1.435
23.0	0.661	1189	1.679
24.5	0.729	1267	1.852
25.2	0.765	1303	1.943
26.0	0.781	1345	1.984
25.8 (stopped pumping)	0.885	1334 (stopped pumping)	2.248
Deformation at 26.0 psi: 1.735 inches			

Table 11: The pressure and deflection of the carbon fiber window, recorded between April 14th to April 17th, while occasionally being pumped. The pressure is given in units of psi and Torr and the deflection has units of inches and cm. The pressure has an error of ±0.1 psi or ±5 Torr and the deflection has an error of ±0.001 inch or ±0.003 cm. The time is given in days.

Pressure (psi)	Deflection (inches)	Pressure (Torr)	Deflection (cm)	Time (days)
25.2	0.650	1303	1.651	0
23.2	0.649	1200	1.648	0.5472
26.0 (pumped)	0.910	1345 (pumped)	2.311	0.55
24.3	0.092	1257	0.234	0.8444
23.9	0.094	1236	0.239	1.0486
26.0 (pumped)	0.102	1345 (pumped)	0.259	1.0507
22.2	0.091	1148	0.231	2.009
19.6	0.073	1014	0.185	2.9646
17.6	0.059	910	0.150	3.941

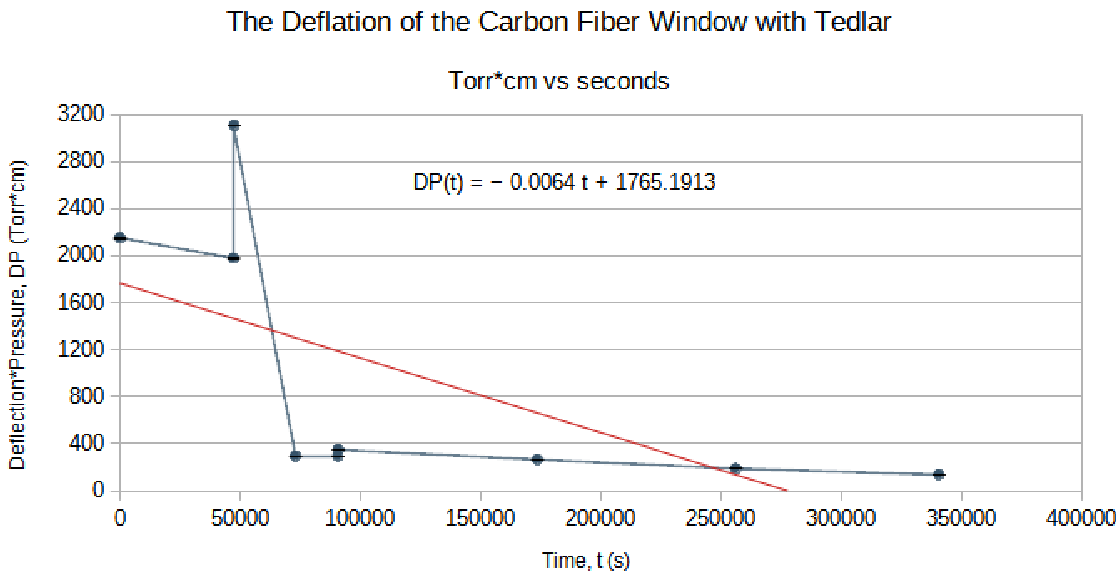


Figure 28: The deflection and pressure over time. It is clear from this graph that the window had a leak.

There were loud crackling and popping sounds heard during the first 10 psi of inflation. The crackling became less frequent as the window inflated. A loud pop was heard when inflating between 12.0 psi and 14.0 psi. The window's colour became lighter by the frame as the window inflated, indicating a reduction of the carbon fiber thickness there. The window was left over a few days, it was occasionally inflated to 26.0 psi. The results are in Table 11. Graphs of the deflection and pressure over time are in Figs. 28, 29.

The leak rate for the carbon fiber window is about $0.0062 \pm 0.0002\ \frac{\mathrm{Torr \cdot L}}{\mathrm{s}}$. This leak rate was calculated using the change in deflection and pressure from the last time it was pumped during the test. However, since the window was pumped up multiple times, this number doesn't describe the window's full behaviour. It was clear that there was a leak from some part of the setup. There were attempts to fix leaks in the plumbing underneath the steel plate. The window was pumped up to 26.0 psi and left overnight. On April 18th, at 11:50 the pressure dropped down to 23.9 psi, which showed the leaks were still there.

To find the source of the leak, a hydrogen gas mixture test was done on the window. On April 19th, the window was deflated and filled with a mixture of 98.013% dry air and 1.987% hydrogen, the same mixture used for the vessel tests, to 26.0 psi. The bulge of the window was 1.565 inches. A natural gas sniffer was run along the window frame and test apparatus. Leaks were found in-between the 10th and 11th bolt holes on both the left and the right sides. There was also a leak by the window frame along the center line by the wide end. Some Tedlar was poking out of the window frame (see Fig. 30). The window was deflated and the setup was disassembled. There were scratches (see Fig. 31) and creases (see Fig. 32) in the Tedlar near where the leaks were. Tedlar appears to not be a good material for this project because of its stiffness and tendency to crease and scratch.

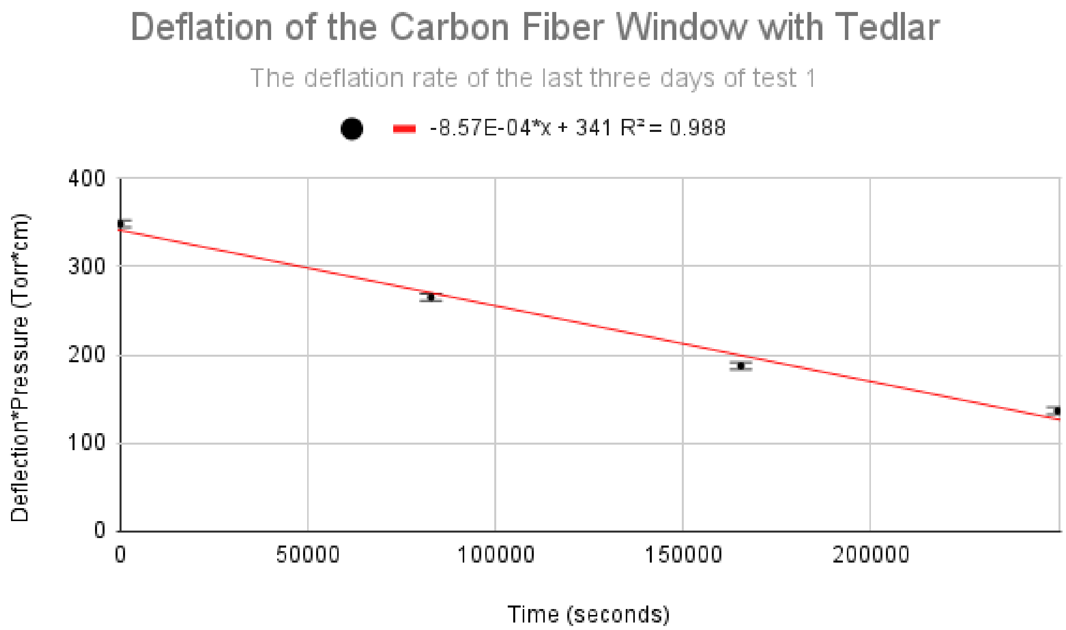


Figure 29: The deflection and pressure from the last time the window was pumped to 26 psi. This rate was used to calculate the leak rate of the carbon fiber window.

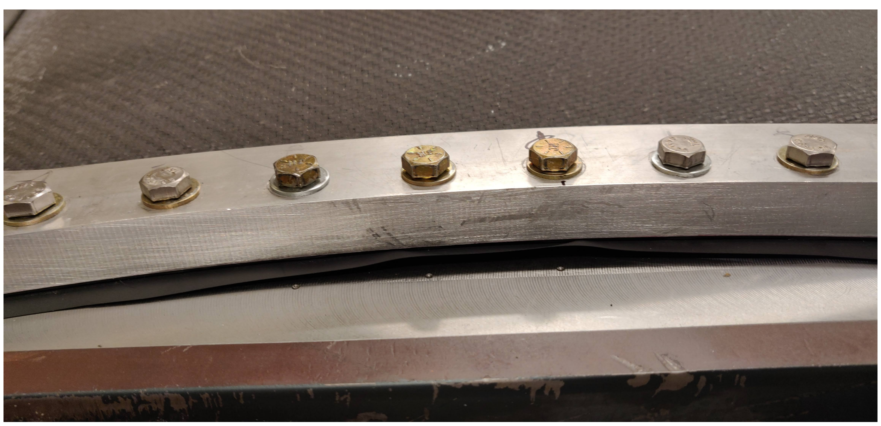


Figure 30: The Tedlar peaked out of the frame while being inflated.

Figure 31: The Tedlar scratched by the leaks.

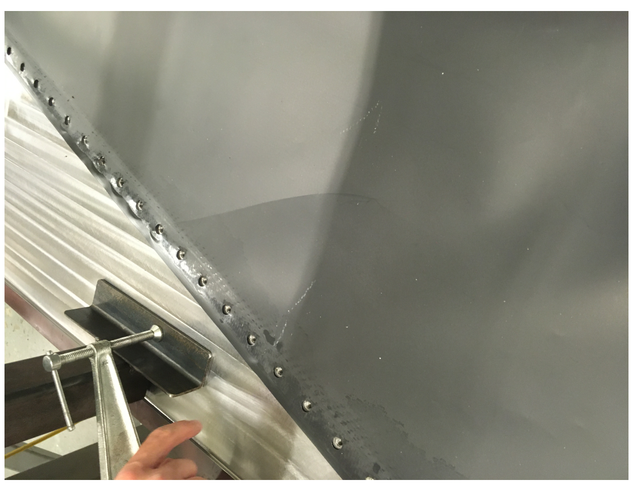


Figure 32: Creases in the Tedlar were also found near leaks.

Test 2

On April 20th, a sheet of Mylar was cut out using a similar method as the Tedlar sheet. However, the bolt holes were cut to an oblong shape this time, to allow the material to move during inflation (see Fig. 33). The bolts were tightened down while the window was slightly inflated. All the bolts were tightened to 120 in-lbs and the window was inflated to 26.0 psi. The window begin to creak and the right side became larger than the left (see Fig. 34). A loud crack was heard and the pressure quickly dropped. The window was leaking on the right side. Torn carbon fiber could be seen poking outside the window frame (see Fig. 35). The window was deflated and removed from the frame. The window had a lot of tearing and stretching by the bolt holes (see Figs. 36, 37 and 38). The window may have slipped in the frame due to the glossy texture of the Mylar. Note that this problem was not experienced in previous tests with Mylar inner liner [3].

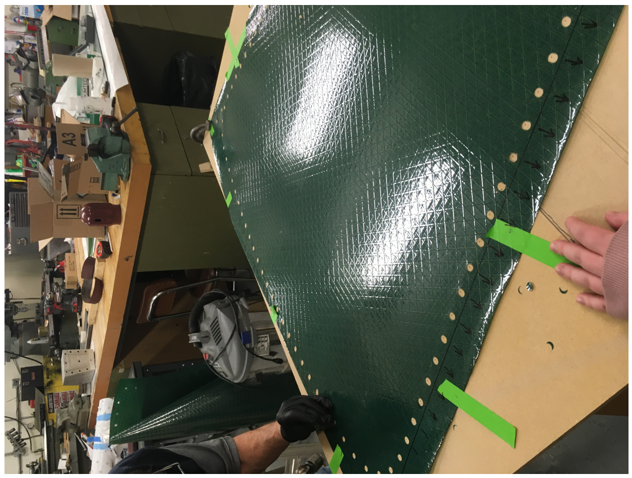


Figure 33: The Mylar was cut with oblong holes.

Figure 34: The carbon fiber window bulging more on the right side.

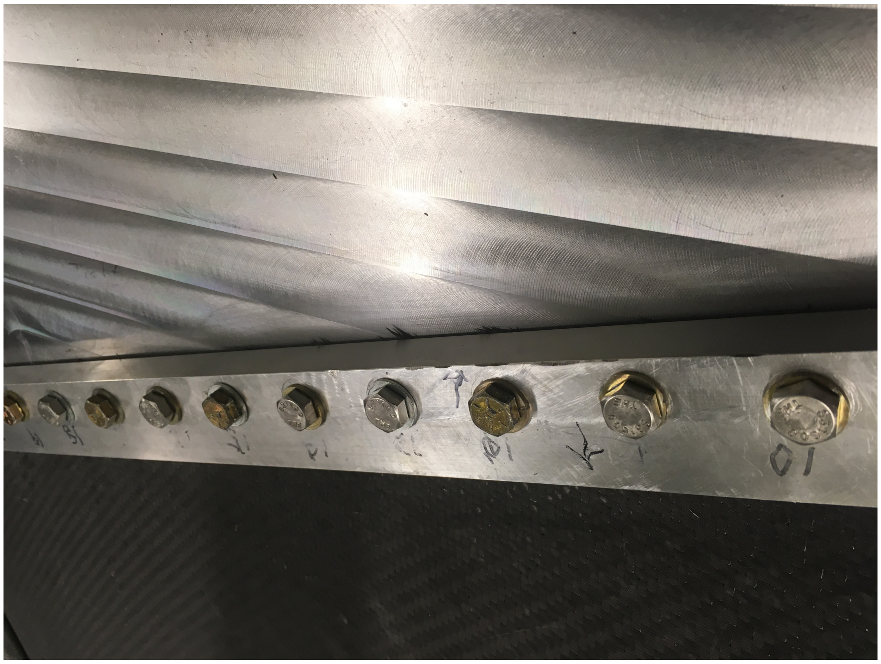


Figure 35: Stress on the window forcing out some shards of the caron fiber window beyond the frame.

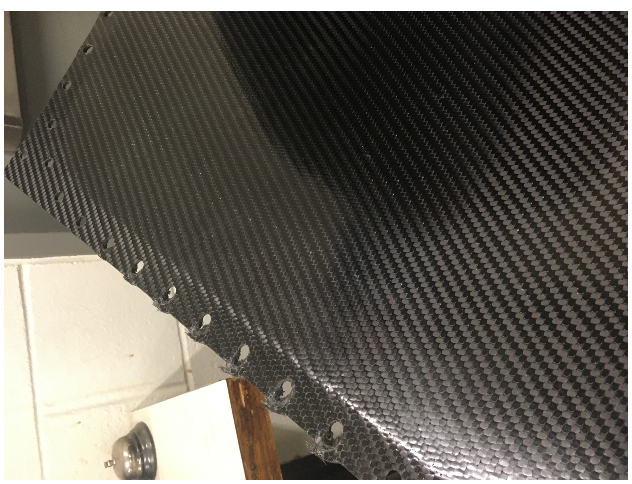


Figure 36: Torn and stretched bolt holes on the carbon fiber window.

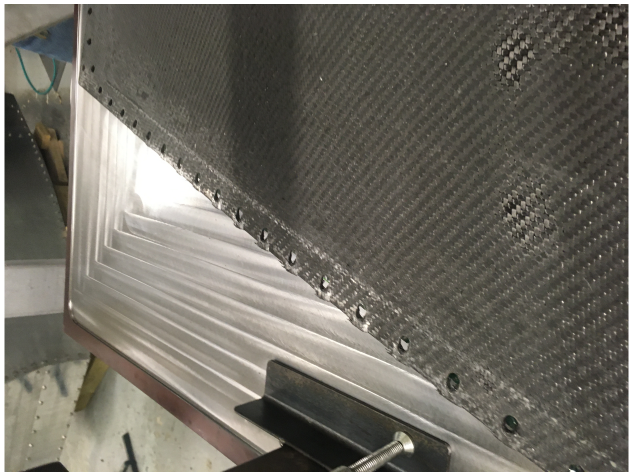


Figure 37: The left side of the stressed window.

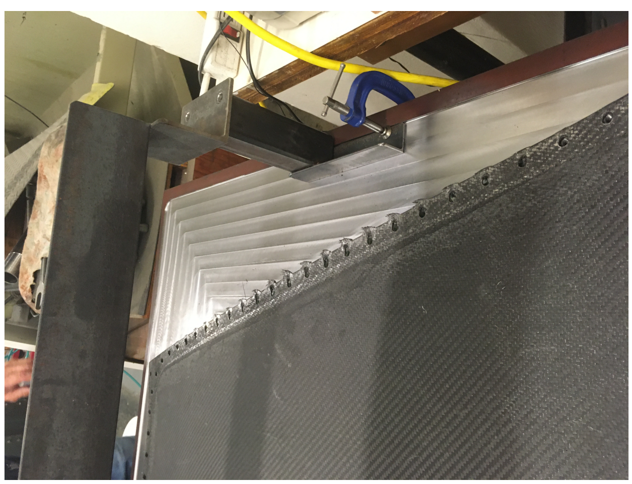


Figure 38: The right side of the stressed window.

Final Observations

The carbon fiber window's maximum deformation was at 4.4 cm and its leak rate was $(6.2 \pm 0.2) \times 10^{-3} \frac{\text{Torr}\cdot\text{L}}{\text{s}}$, which converts to $(2.0 \pm 0.1) \times 10^{-5} \frac{\text{g}}{\text{s}}$ of C_4F_8 gas. The carbon fiber window was unable to hold pressure for long periods of time. The construction of the window was lengthy and challenging. The window had to cure for a much longer amount of time than the manufacturer stated. Some other challenges were placing the vacuum so that the window doesn't become distorted, and making sure the wefts of the carbon fiber don't shift or unravel. These challenges, in comparison to the experience in our previous report [3], indicate a lack of reproducibility in manufacture and performance in the carbon fiber epoxy shell, which is a major concern. Furthermore, both the Tedlar and Mylar inner liners performed poorly. Tedlar is too stiff and tends to crease, while Mylar is too slippery to hold the window in place on its own. The carbon fiber epoxy window is not recommended for this project, due to lack of reproducibility and long learning curve in assembly.

Conclusions

The objective of these tests was to find a material that can handle 20.6 psi of pressure without bulging more than 10 cm for the the SoLID Heavy Gas Cherenkov detector (HGC) entrance window. A window made of an aluminum window of aerospace-grade 2024-T4 alloy and a carbon fiber-epoxy window were tested, as well as different materials to place under the carbon fiber window.

- The aluminum window had a maximum deformation of 4.5 cm and a minimum leak rate of $(5 \pm 3) \times 10^{-5} \frac{\text{Torr}\cdot\text{L}}{\text{s}}$, which converts to $(2 \pm 1) \times 10^{-7} \frac{\text{g}}{\text{s}}$ of C_4F_8 gas.
- The carbon fiber window's maximum deformation was at 4.4 cm and its leak rate was $(6.2 \pm 0.2) \times 10^{-3} \frac{\text{Torr}\cdot\text{L}}{\text{s}}$, which converts to $(2.0 \pm 0.1) \times 10^{-5} \frac{\text{g}}{\text{s}}$ of C_4F_8 gas. The carbon fiber window leaked when used with Tedlar inner liner, and the bolt holes tore when used with the Mylar liner.
- Overall, the aluminum window is a better choice due to its lower leak rate, reliability and easy construction. However, the aluminum window needs a second long-term leak test, due to the possible problem identified with the gauge in the test reported here. Longer term, the issue identified with the elongation of the aluminum window bolt holes needs to be rectified via further improvements to the frame design.

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