HGC Window Prototyping - Full Scale Carbon Fiber Testing Series

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As part of the prototyping process for the SoLID Heavy Gas Cherenkov detector (HGC), a suitable material must be chosen to be used as the entrance window. The HGC will be filled with gas at a differential pressure of 0.9 atm, or 13.2 psi (1.9 atm absolute) and must bulge less than 10 cm in order to fit within the SoLID assembly in Hall A at Jefferson Lab. In order to be certified for use, the window must meet these conditions under 2× operating conditions, i.e. 1.8 atm, (26 psi) differential pressure. In this series of tests it will be shown that a carbon fiber and Mylar window design meets these requirements.

1 Introduction

The goal of these tests was to bring the relative pressure of the window up to 26 *psi*. This is because operating pressure of the window is to be 1.9 *atm* absolute pressure, since the ambient pressure is 1 *atm* the relative pressure is only 0.9 *atm* which is about 13 *psi*. In order for this design and material to be certified it must be tested at a safety factor of 2, thus it must be tested under 26 *psi* relative pressure [1]. Other goals include showing that the deflection of the window is less than 10 *cm*, so that it fits in the SoLID enclosure without interfering with the other detectors, and showing that the design does not leak. Importance has been placed on the window having a good seal because the gas that is intended to be used in the Heavy Gas Cherenkov (HGC) is expensive. The HGC is also intended to be used during experimental operation with consistent air pressure.

These tests are a follow up to successful small scale tests on a similarly designed window [2]. This prototype window consists of two layers, a carbon fiber shell and a sheet of Mylar. The shell provides a secure hold of the pressure and keeps the Mylar in place. The Mylar provides a good seal with the O-ring on the window frame, it also prevents air from leaking through the carbon fiber. Further description of the window fabrication is given in Section 3.

During testing the window did not fail, however, it was shown that the window was leaking. This is a success of the carbon fiber, and a failure at the Mylar and O-ring. Currently, the leaking is attributed to poor frame design, which is discussed in Section 2. The leaking was slow enough that the window could still be pumped up to the target pressure. As more pressure was applied the shell gradually expanded. Like previous tests with the carbon fiber, creaking noises were heard sporadically throughout the inflation process of the first three tests, however, they were never very loud and there was never any indication that the window was going to fail.

2 Window Frame Design

The window frame that was used during these tests was the original mock up of the design from 2015. Since its creation, several flaws have been found with the design, in the most recent design these have been addressed. The first draft of the window frame (Figures 1 and 2) was made using a poor estimate of the required clamping force. When the calculation was redone, it was found that the required clamping force was higher than expected and larger bolts were needed to hold the window in place. As such, the existing holes on the frame were drilled out to be wider than they were previously. In some areas the holes were close to the O-ring slot, causing the overlap seen in Figure 3. The quantity of bolts required to reach the new clamping force value was also higher than in the initial design. The additional bolts that were required were placed further from the O-ring slot, this is the cause of the staggered bolt pattern that can be observed in Figure 3. The current design of the HGC window frame (Figure 4) now takes into account the required clamping force, as well as proper positioning of the bolts in relation to the O-ring. This has the net result of wider holes that are placed further from the O-ring and that are spaced further apart from each other. This design conforms to the requirements for clamping force and rigidity, as such, this updated design should resolve any leaking issues that are due to the frame.

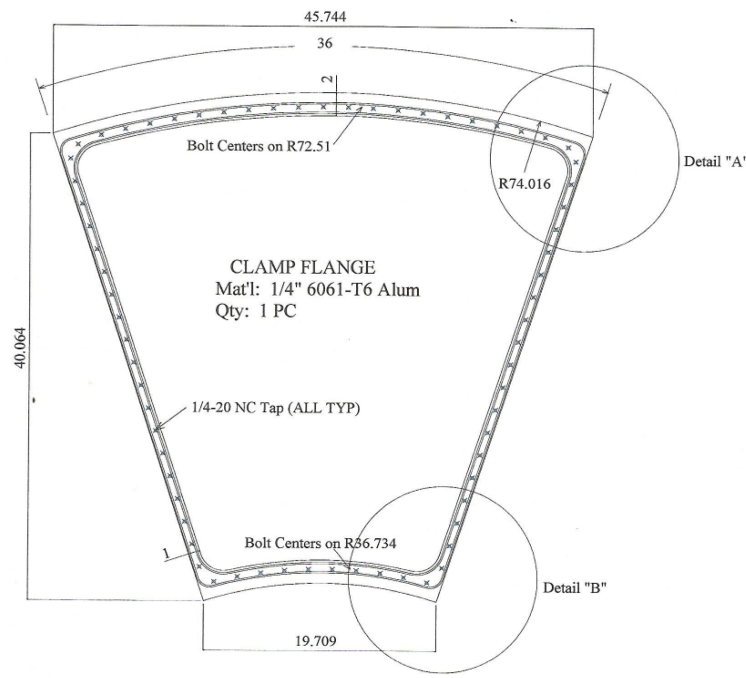


Figure 1: Original drawing of the frame, used to fabricate the design which was used in these tests. The current version that is in use now has been modified as calculations for the required clamping force were redone.

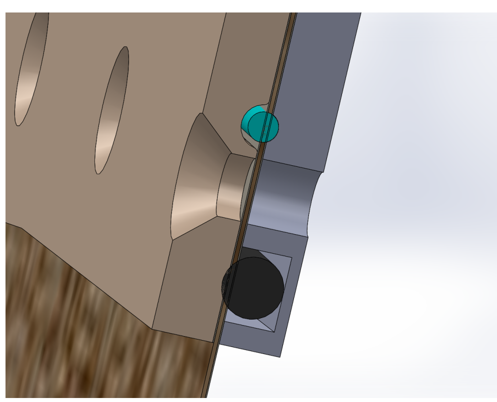


Figure 2: 3D rendering of the cross section of the original design for the HGC window frame. The black cylinder is the O-ring while the teal cylinder is where a clamping wire would have gone. This clamping wire is no longer is use and is not part of any current design.

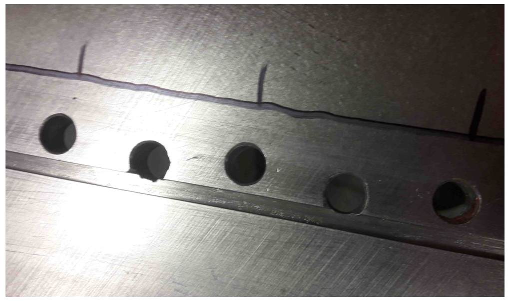


Figure 3: Holes that were drilled right into the O-ring slot on the test frame base.

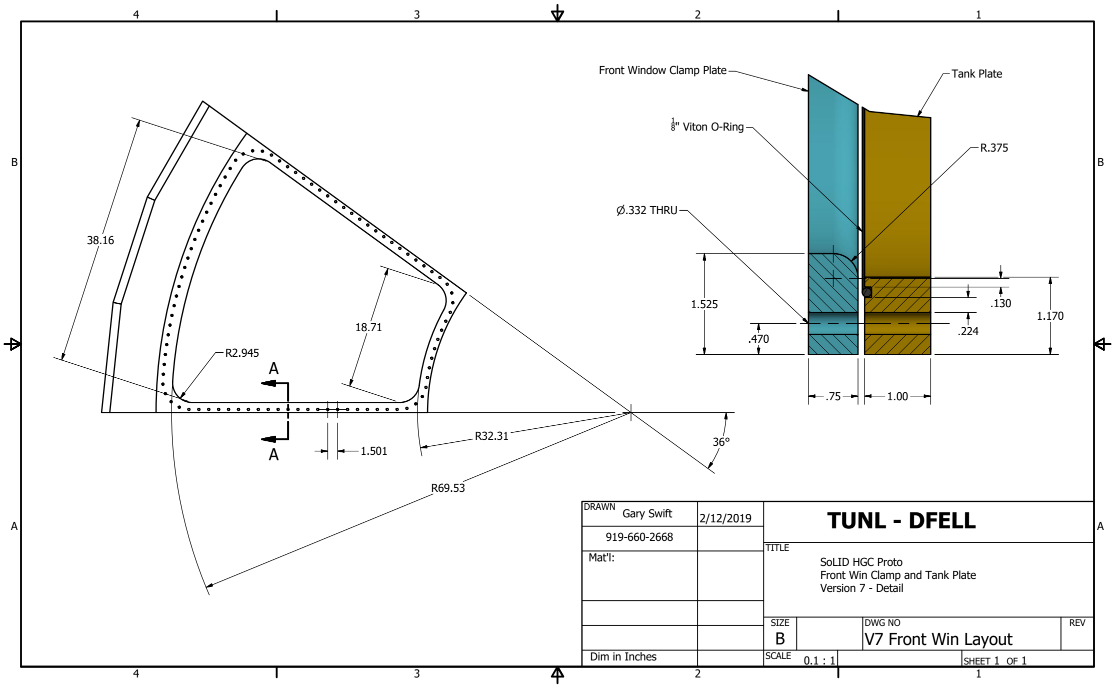


Figure 4: Current design for the HGC window frame. The spacing between the bolt holes and O-ring, and the spacing between bolt-hole and edge of frame is much more than it was in the old design (Figure 1).

3 Window Design and Fabrication

Due to the success of the previous small scale configuration [2], a series of large scale tests were undertaken. The window itself is made up of two parts, a sheet of Mylar and a strong carbon fiber shell, like the small scale version. The list of materials used in the construction of the window are listed below. For each test, the window was mounted to the test jig, which is a 1/2" thick steel plate larger than the window frame, with a hole in the bottom to allow connection to a valve and bolt holes at the appropriate positions. No vacuum grease was used as there is concern that it would interfere with the Ultra Copper gasket maker which was used.

- 2 layers of 48" × 48", .012" thick carbon fiber cloth [3], specs listed in appendix A
- Fibre Glast Epoxy resin (2000 and 2060) [4]
- 5 *mil* Thousandths of an inch thick Mylar (part number MNX5) [5]
- REXCO Partall paste # 2 [6]

- Sailcloth self adhesive Kevlar (part number MKV22PSA) [5]

The ratio of epoxy resin 2000 to 2060 was 3:1 by volume for a total amount of 2400 mL of 2000 resin to 800 mL of 2060. The working time on this epoxy is about 1 hour. The Kevlar was included in this design as a safety precaution, if the Kevlar was not there and the carbon fiber to fail then there would be a great deal of shrapnel ejected. The purpose of the Kevlar is then to stop a great deal of these shards from being ejected, and not to provide any structural support. The Mylar was simply cut to the dimensions of the window frame (Figure 1). In these tests, 3 sheets of Mylar were used, Figure 5 shows the finished product.

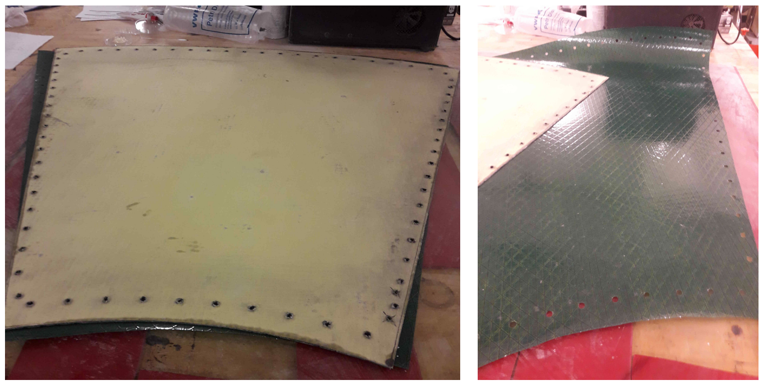


Figure 5: (left) Finished carbon fiber window, before any tests, as it would be placed in the window frame. (right) An unobstructed view of the Mylar layer, which goes underneath the carbon fiber.

Only one carbon fiber shell was used during this series of tests. This shell was initially made completely flat, using a sheet of glass as the construction surface. Glass was chosen simply because it was available in the workshop and was sufficiently flat. The glass was coated in two layers of the Partall paste [6], the second of which was then polished, before a thin film of # 1153 FibRelease [7] was applied with a cloth, this was allowed to fully dry before the first layer of carbon fiber was placed onto the surface.

After the first layer of 48 inch square carbon fiber cloth was placed onto the glass, it was saturated by brush with the epoxy mixture. The second layer of carbon fiber was then draped over and additional Epoxy was applied by brush. A brush was used for applying the epoxy, but it is thought that a squeegee would be better for this task. The Epoxy was then allowed to cure for a minimum of 24 hours before a layer of sailcloth self adhesive Kevlar material was draped over top. These final steps can be seen in Figure 6.

Figure 6: Carbon fiber shell before being cut to size. (left) Without the Kevlar layer. (right) With the Kevlar layer. The final size of the window is demonstrated on the right by the overlaid window frame.

The test frame was the same one that had been used in the previous testing (Section 2), except that another top plate was added as well as additional reinforcement plates laid on top. This made the frame three times thicker in most places, and two times thicker on the corners, than the original test frame, this can be seen clearly in Figure 7. The O-ring used was 1/8" in diameter. The basic assembly of the window goes as follows:

1. Clean the faces of the Mylar with acetone and the test jig around the O-ring slot
2. Place O-ring into position in the slot
3. Apply Ultra Copper gasket maker [8] 'glue', placement varies
4. Put Mylar, carbon fiber shell, both frames, and all braces in position, in that order
5. Hand tighten all bolts, so as to not squeeze out 'glue'
6. Let set for about an hour then torque bolts to desired value (specific to test)

This is the basic construction, however, throughout the course of testing the window was assembled, disassembled and reassembled several times in order to try do deal with observed leaking, and each time changes were made to the setup. These changes will be detailed further in the sections on those tests.

4 Experimental Procedure

For these tests a deflection gauge was suspended over the center of the window, as this was where the most deflection occurred. A pressure gauge and valve were attached to the underside of the test jig this setup is shown in Figure 7.

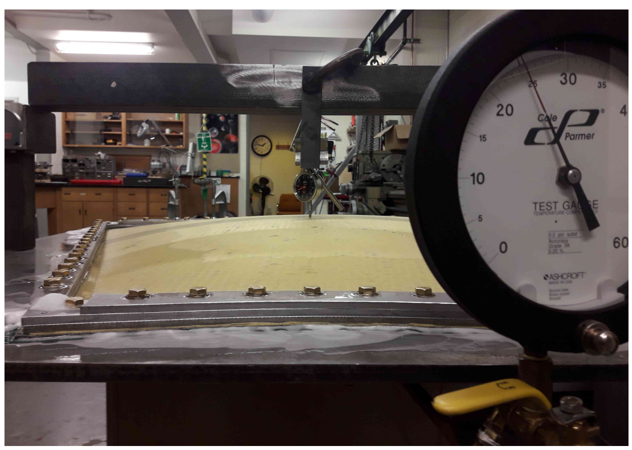


Figure 7: Experimental setup. This photo was taken during test 2, it is indicative of the other tests.

To inflate the window, air was slowly pumped in using a bicycle pump. The window was inflated in steps of 0.5 psi, the pressure and deflection were recorded at each step. Occasionally, the inflation was stopped to check for leaks. This was done by spraying soapy water onto the window, on the bolts, and around the edges. If there was a leak, bubbles would form in the water around the location of the leak. The exact instances of these leak checks, and there results, are discussed later in the test sections. In order to minimize leaking during these tests, there were occasional stops to increase the torque on the bolts. Further details on each test are given in their sections.

5 Test 1

The first test was assembled hastily as there was concern about the working time of the Ultra Copper gasket maker, and this hasty construction did not allow sufficient time to set for it to set. Also, it was later found the the application of the gasket maker was inefficient and later tests used a more efficient technique. The bolts were immediately torqued to 30 $ft-lbs$ after application of the gasket maker. This caused a great

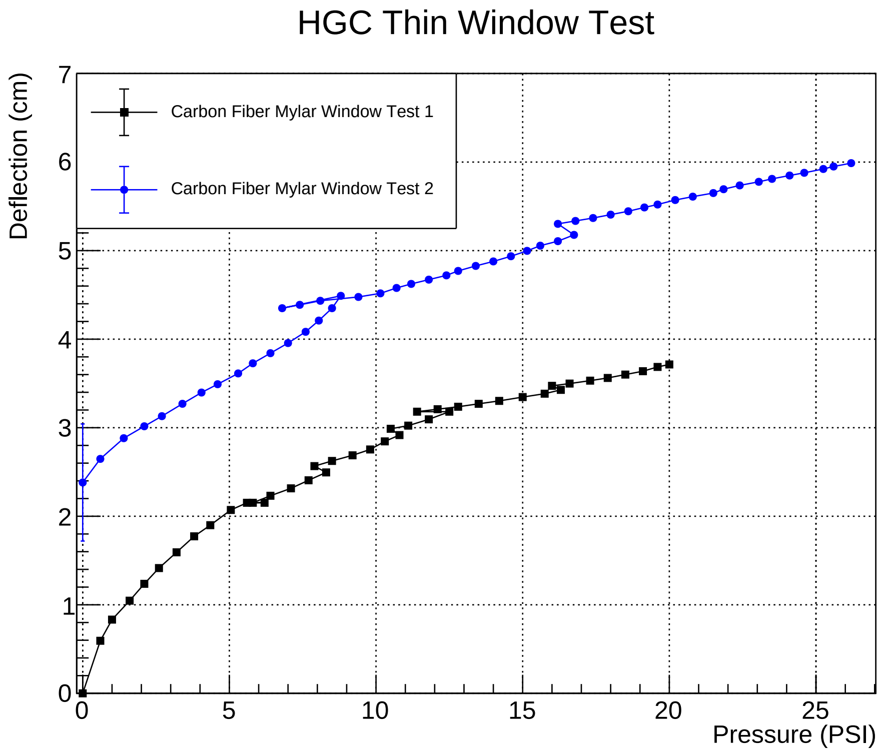


Figure 8: Pressure versus deflection of the window for the first two tests. The blue line starts above 0 because that is how much the window was deformed from the previous tests, the uncertainty from this base deflection is plotted only on the first point. The points on this plot where the pressure decreases are due to a pause in the inflation to work on the window or on the testing apparatus. This is further detailed for each test in Sections 5 and 6.

deal of it to be pushed to the inside of the window, causing it to be ineffective at providing a seal. This was not known until the window was taken apart; Figure 9 shows the window during assembly and after later disassembly. When this window leaked, it was thought that the reason was this poor placement of the gasket maker, however, further leaking from future tests with proper application ruled this out.

Figure 9: (left) The ultra copper gasket maker being applied, notice it is right on top of the O-ring. (right) After taking the window apart this is the distribution of the gasket maker. On the inside of the O-ring (i.e. not the side with the bolts) there was no gasket maker on the Mylar, suggesting that there was no contact during testing. There was however about the same amount of gasket maker on the Mylar on the outside of the O-ring as what is seen in on the test jig.

During the first test (Figure 8), the pressure was pumped up gradually until about 6.2 *psi*, at this point the deflection gauge had to be re-zeroed. At 8.3 psi, a leak test was conducted and no leaks were detected. Another leak test was carried out at 10.8 psi, and at 12.5 psi leaks were observed coming from the Mylar layer, shown in Figure 10. Following this observation, the torque on the bolts was increased to 40 $ft - lbs$ and inflation was continued. The inflation process was again paused at 16.2 psi for a further leak test, more leaks were discovered. It is notable that starting at 5 psi the occasional creaking noise could be heard from the window, this is similar to the noises that were heard during small scale testing [2]. These creaking noises continued intermittently and got somewhat louder as the pressure increased. At 20 psi, it was decided to stop inflating the window and see how quickly it deflated back to 0 relative pressure. The pressure and deflection was measured at somewhat regular intervals until the end of the day and then again in the morning, Figure 11 shows these data. Note that the first portion of the plot has an increasing deflection that then peaks and begins shrinking as the the air continues to escape. This is believed to be due to the relaxation of the carbon fiber. Also of interest, the deflection gauge rolls over every 1/10" meaning that 456/1000" looks identical to 556/1000", as such the last point was estimated to be the option that looked the most reasonable on the plot. After the test had been concluded, the window was taken apart and inspected. This post-mortem showed little to no obvious damage that would have caused the leaking. The carbon fiber was still intact, although it had been deformed into a different shape (Figure 12). The Mylar showed little in the way of stretching, although there was a cut to the Mylar at one of the bolt holes. However, the observed leaking was not around that location so it is thought that this was not the cause of the leaking (Figure 13).

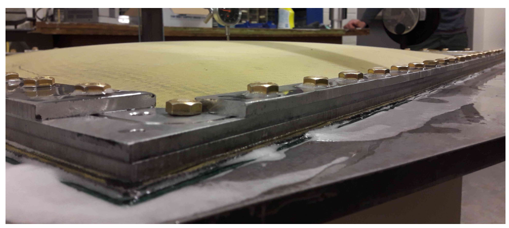


Figure 10: Leaking from around the frame in test 2, similar leaks were found around the entire window. The leaks are the locations where there is a buildup of bubbles from air escaping into the soapy water.

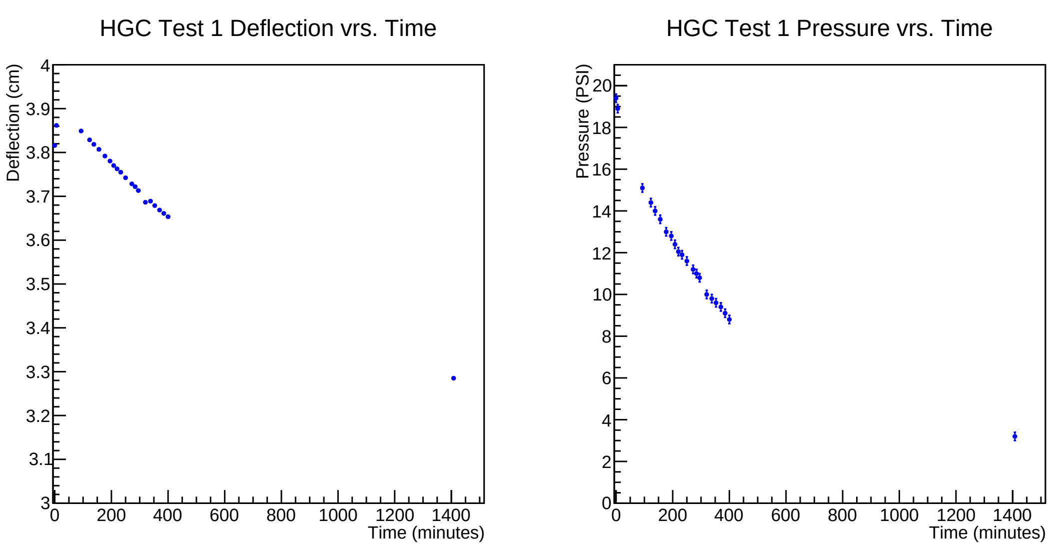


Figure 11: (left) Plot of the deflection versus time after the inflation of the first test. (Right) Pressure versus time after the inflation of the first test. Notice that the first portion of pressure dropping is accompanied by an increase in deflection as the window relaxes.

Later on, the valve and pressure gauge apparatus was used on a different piece of equipment and during that testing, the valve connecting the window test apparatus to the bike pump was found to be leaking.

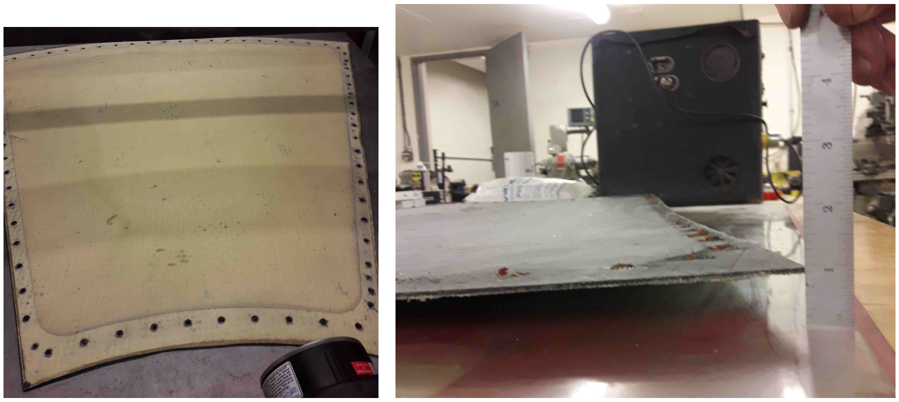


Figure 12: The carbon fiber shell after the test. The right frame shows the measurement of the deflection after the first test.

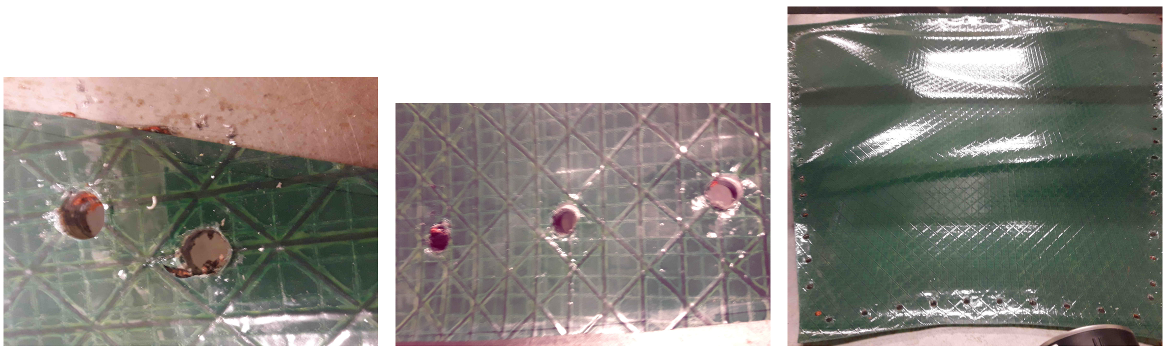


Figure 13: Mylar after Test 1. (left) the cut to the Mylar, probably caused by some stray shard of carbon fiber or aluminum. (middle) An example of the most stretched holes. (right) Overview photo of the Mylar.

Since this valve was used during the first two tests, this leak is thought to have had a significant effect. However, leaking was observed out of the sides of the window so the leak in the valve was not the only source of leakage.

6 Test 2

Due to the last window failing to hold air overnight and the discovery that the gasket maker was positioned ineffectively, a new strategy was implemented. Between tests, it was noted that some of the bolt holes where drilled right through the slot for the O-ring (Figure 3), this was discussed in more detail previously in Section 2. To compensate for this flaw, some of the gasket maker was applied to the inside this slot. In order to make sure that most of the Mylar was covered, the gasket maker was applied differently. Instead of onto the O-ring, gasket maker was applied on the outside of the O-ring as well as around each bolt hole. As observed in Figure 14, the resulting application pattern resembled flower petals. It was also observed that the gasket maker did not adhere very well to the Mylar, so this time some scratches were made to the underside of the Mylar above where the bolt holes would be. The scratches were made using a medium scotch bright pad and straight edge. Care was taken to not scratch where the O-ring would go, as to not introduce a place were it might leak (Figure 15)

In addition to the different application technique, care was taken to ensure that the gasket maker had sufficient time to set before torquing the bolts. A fresh piece of Mylar was also used for this test, as some very slight stretching around the bolt holes was noted in the piece from the previous test. The same carbon

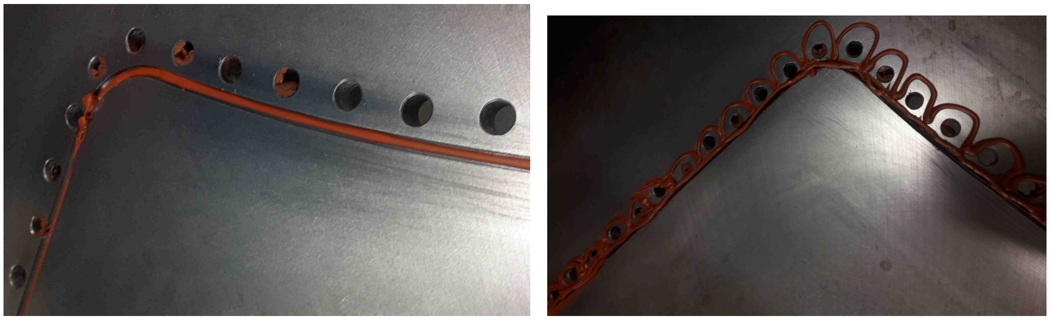


Figure 14: (left) The gasket maker in the slot before the O-ring went in. This was done to fill the bolt holes that were to close to the slot (Figure 9). (right) The final 'flower petal' pattern, taken directly before placing on the Mylar.

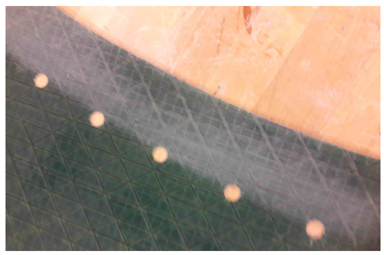


Figure 15: Scratches put into Mylar for better contact with the gasket maker.

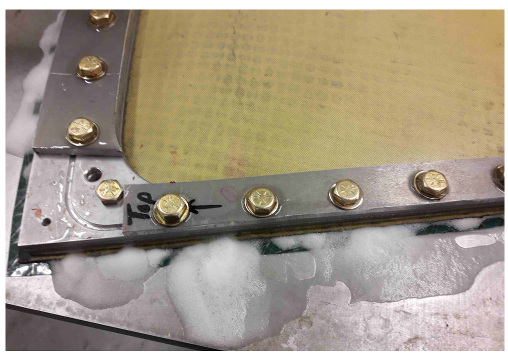


Figure 16: The location of some of the leaks observed in test 2, this is the same location as those shown in Figure 10. Leaking during the second test was much more apparent as seen by the much larger quantity of bubbles. This is believed to be caused mostly by air trapped between the Mylar and carbon fiber escaping, although some will still be from a poor seal at the O-ring.

fiber shell was used as in the previous test, when the test had concluded the shell did not relax all the way back down to flat and had gained a profile. This deflection was measured to be roughly 15/16" or 2.38 cm.

The testing procedure for this test was similar to the first one. The goal of this test was to get all the way up to the target pressure of 26 psi. After assembly, the window was slowly inflated. No creaking was noted until 20.2 psi, where only quiet creaks were heard infrequently. The inflation went steadily until 8.8 psi where it stopped to allow for a leak check, as well as time to re-zero the deflection gauge. During this time, a great deal of leaking, coming from the same places as before but much more intense, was detected (Figure 16). In an attempt to rectify this, the torque on the bolts was further increased up to a total of 60 $ft - lbs$. This process took around 10-15 minutes, which caused the large jaunt to the left seen in the blue data in Figure 8. The smaller jaunt is a short break to get more paper to record data. After reaching 26.2 psi, the inflation process stopped and the observation of the deflation began.

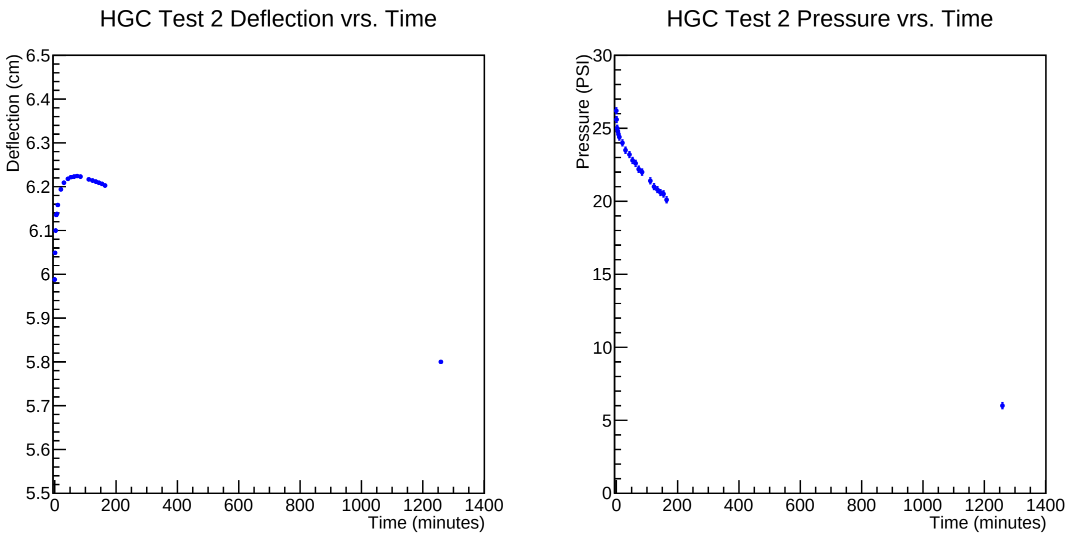


Figure 17: (left) Deflection versus time for the deflation of the second test. (right) Pressure versus time for the deflation of the second test. The last point is on its own because it was taken the morning after the test.

There were many more bubbles during this test (Figure 16) and they are believed to be from the air trapped in between the Mylar and carbon fiber layers escaping. This air was trapped there due to the carbon fiber being misshapen from the last test and the Mylar being a new flat sheet. Since there is nothing to keep air in between the carbon fiber and Mylar, it will escape through the gap between them. To remove this effect, one could simply drill a hole in the top of the carbon fiber shell, this was done in previous small scale tests where the shell was purposely formed to be not flat [2]. In those cases, the hole caused no compromise in structural integrity, so it should be applicable here, and this was tested subsequently as outline in Section 7. This trapping of air is undesirable, but not devastating and it is suspected that most of the air was pushed out by the end of the inflation.

The deflation of this window proceeded very similarly to the first, the window relaxed and then began to deflate slowly. This process can be seen in the data when plotted in Figure 17. Due to the previously discussed issue with the deflection gauge, it is not possible to know what the last data point was exactly, so it was determined in the same way as with the last one.

7 Tests 3 and 4

In tests 3 and 4, the reliability and performance of the window after repeated inflation was evaluated. During operation in SoLID, the window will be inflated and deflated quite frequently. This is to minimize wastage of the gas used in the detector, as it will be emptied (i.e. fully deflated) when not in use. As such, the reliability of the window needed to be tested. This also served as a test of whether the window continues to relax and expand, or if it holds the same shape over long periods. These tests also provided an opportunity to test how a hole drilled into the carbon fiber would behave.

The setup was the same as previous tests, except for two changes: first, there was a hole drilled into the carbon fiber near the middle of the window, second, the leaky valve that was previously identified was fixed. The hole was drilled in the window through the carbon fiber without removing it from the frame, and the hole was less than 1/16" in diameter. A new way to measure the base deflection was also implemented, since the window could not placed upside down, still attached to the table. Since there was already a bar in place to hold the deflection gauge, a metal ruler was used to measure the distance from the table to the bar and the from the bar to the table (Figure 18). This allowed for an accurate measurement of the bulge off the table, and is comparable to the measurement that was made previously. This method should allow for less systematic error in the measurement of the deflection, were the old method had the potential for the

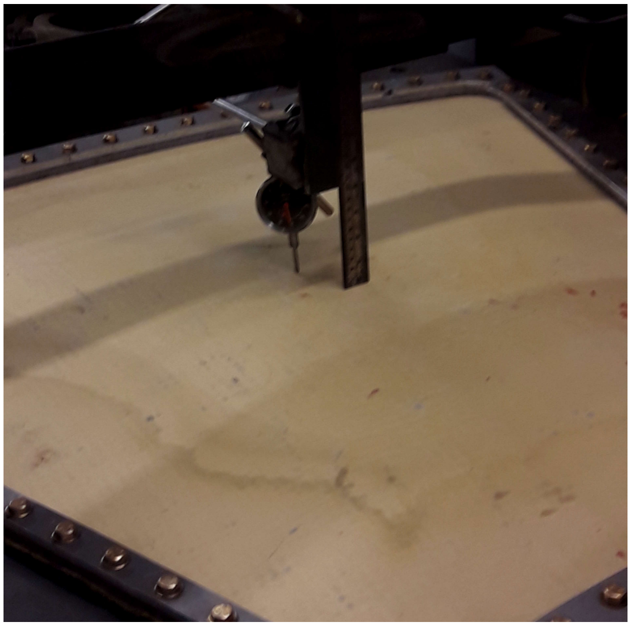


Figure 18: The new method used to measure the deflection of the window after it had been deflated. The ruler in this picture is used to measure the distance from the bar to the table and then distance from the bar to the center of the bulge, as depicted here.

window to be resting resting on the table wrong giving a measurement that may have been off by as much as ± 0.5 cm, this new method will only be affected by the position of the ruler being slightly displaced from the peak of the bulge. This displacement was minimized when the measurement was taken, and the slope of the bulge is gentle, so it should not be more than ± 0.05 cm.

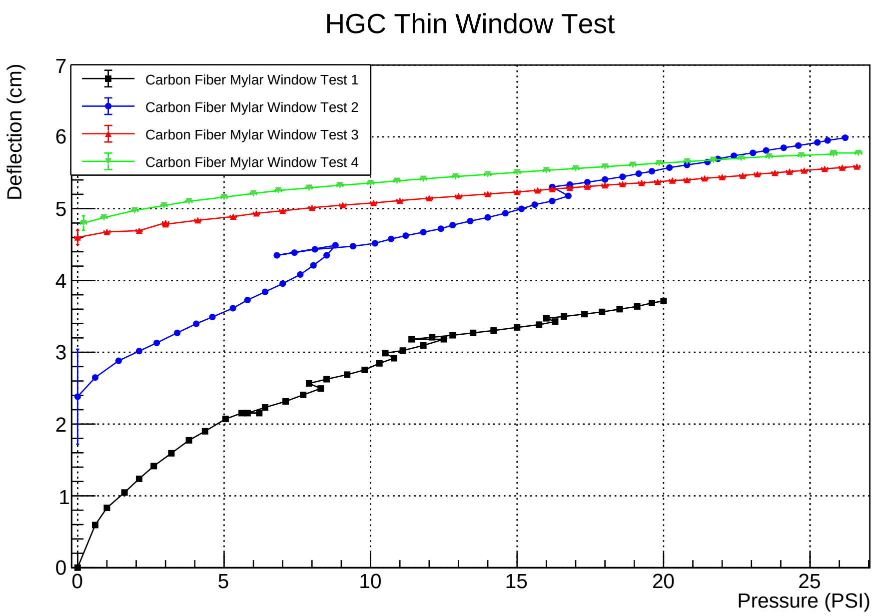


Figure 19: Pressure versus deflection of all four tests. The irregularity in test 3 at 3 psi is due to the air leaking from between the Mylar and carbon fiber layers.

Similar to the first two tests, the window was inflated with the a bicycle pump; the data for this test is plotted in Figure 19. This time, there was less interest in the leaking so during test 3 there was one stop to test for leakage. This was to check that the hole was not accidentally drilled into the Mylar as at around 3 *psi* the window started rapidly decreasing in pressure and deflection. There were a great deal of bubbles coming out of the hole in the carbon fiber. This behavior soon stopped though, it is thought that this was simply air escaping out of the gap between the carbon fiber and the Mylar. This is not seen much in the data as none were taken until it was clear that there was no hole in the Mylar. Curiously, this behavior was not seen during test 4 to any great degree, this may have been because in that test even though the air was drained there was still about 0.2 *psi* still left in the window. Thus the Mylar may have already been pushed against the carbon fiber at the start of the test. Also of note is that as the pressure increased, the bicycle pump required much more force to pump than in the first two tests. This may have been due to the valve no longer leaking, or it may have been due to the hole in the carbon fiber as there was no longer a compressible layer of air in between the Mylar and the carbon fiber.

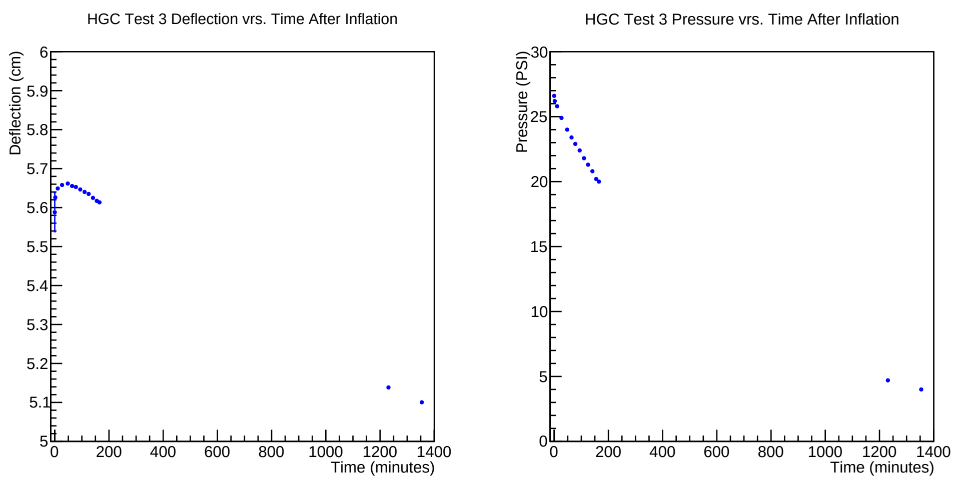


Figure 20: Data taken as the HGC deflated in test 3. (left) Deflection versus time after inflation. (right) Pressure versus time after inflation

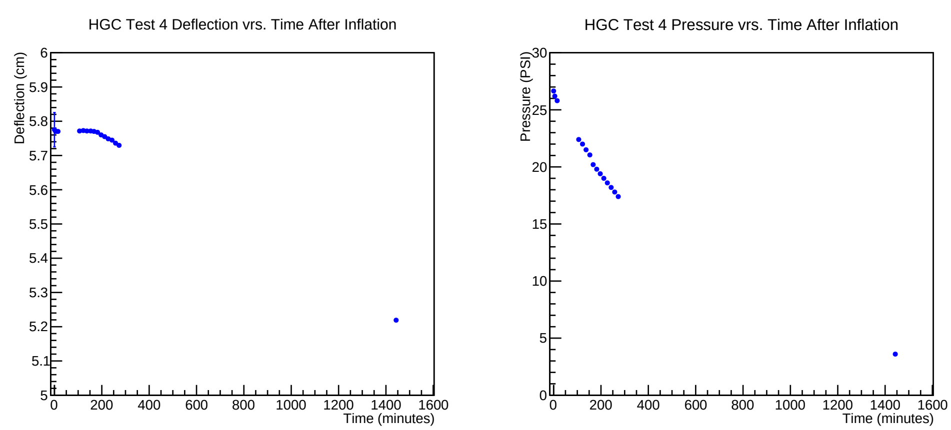


Figure 21: Data taken as the HGC deflated in test 4. (left) Deflection versus time after inflation. (right) Pressure versus time after inflation

Figure 19 also shows the data from these tests, it is clear that the window is bulging slightly with each inflation. In test 2, the deflection was within systematic uncertainties of both these tests, and test 3 deflected less than test 4. This implies that after test 2, the carbon fiber came back and was similar to when it was inflated before, just bulged slightly further. It appears that repeated working of the window does weaken the carbon fiber slightly. Also, this configuration still leaked and the data from the leaking itself is also plotted, these can be seen in Figures 20 and 21. What is interesting is that in test 4, unlike the previous tests, there seems to be little to no relaxation. The curve flattens out at about 5.76 cm. There must be some relaxation as the window is still deflating during that time, but the two effects are canceling each other out. This suggests that the window is reaching a completely worked state.

8 Durability Testing

The previous tests showed that the window was beginning to reach a fully worked state, however, since the HGC is to be used many times its reliability is an important factor. In order to test this, the window was inflated several more times. The goal of this repeated inflation was simply to determine the behavior of the window as it is worked repeatedly. After being inflated three more times, the window seemed to be in a steady state. Tests 5 and 6 did not involve a leak check, however, one was conducted for test 7. During test 7, at 10 psi there was little to no noticeable leakage through the sides of the frame, but there was some air coming out through the hole in the top of the carbon fiber. In fact, while the test was being conducted, the pressure in the window stayed steady at 10 psi. Another leak check was conducted at 20 psi, this revealed leaks, shown in Figure 22. These leaks are in a similar location to those found in the first test. The leakage found during this test is a lot less then those found during tests 1 and 2, this is probably due to the improved technique for applying gasket maker as well as the hole in the carbon fiber.

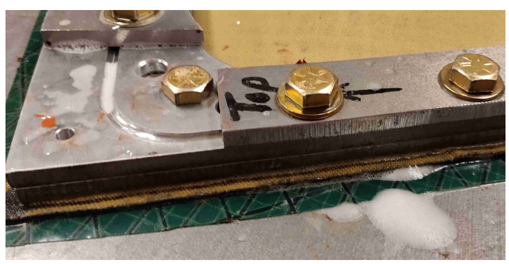


Figure 22: Leakage found in test 7. This is the same location as in Figures 10 and 16

A post-mortem was conducted after this test. This post-mortem applies to tests 2 through 7 since all these tests were done without disassembling the window. This post-mortem showed two things: first, that the technique that was used to apply the gasket maker was effective, and second, that there are no signs of damage that could have caused the leaks. Figure 23 shows the Mylar without the carbon fiber shell, as well as the test jig without the Mylar. After inspection, the bolt holes on the Mylar had been stretched similar to the stretching observed after the first test, and there were stretch marks on the Mylar in the window area. Looking at the distribution of gasket maker, it is clear that the applied gasket maker covered outside of the O-ring, and thoroughly covered the area around the bolt holes, giving good contact with the Mylar.

The window was assembled again using the same techniques as the previous assembly, detailed in Section 6. The same piece of carbon fiber was used for this test, The Mylar however was replaced with a new piece. Of note, the bolts that were used here are the same as the ones used on the previous assembly and some of them broke before they could be tightened to the 60 $ft - lbs$ that was required (Figure 24). This is likely due to the fact that they had been worked once, and that the bolts themselves are only rated to go up to 60 $ft - lbs$ when new. The bolts that broke were replaced with new ones.

After reassembly, the eighth and final test was done and the data can be seen in Figure 25. The inflation went smoothly until 10 psi where a leak test was conducted, this test showed that the valve that was being used was once again leaking, but other than that no leaks were detected. Then another leak test was done at 20 psi, this one showed some small leakage around edge of the window like in other tests. The test concluded at 26 psi, deflection data started to be taken but it was decided that the valve was leaking too fast for deflation data to be meaningful, so this was not taken.

Figure 23: (Left) test jig before removing Mylar, stretch mark is visible. Multiple stretch marks were found along all sides but no failure was found. (Right) Test jig after removing Mylar. The distribution of gasket maker is much better than in the previous test.

Figure 24: Example of bolts that broke during reassembly. These bolts were all replaced with new ones in the test assembly.

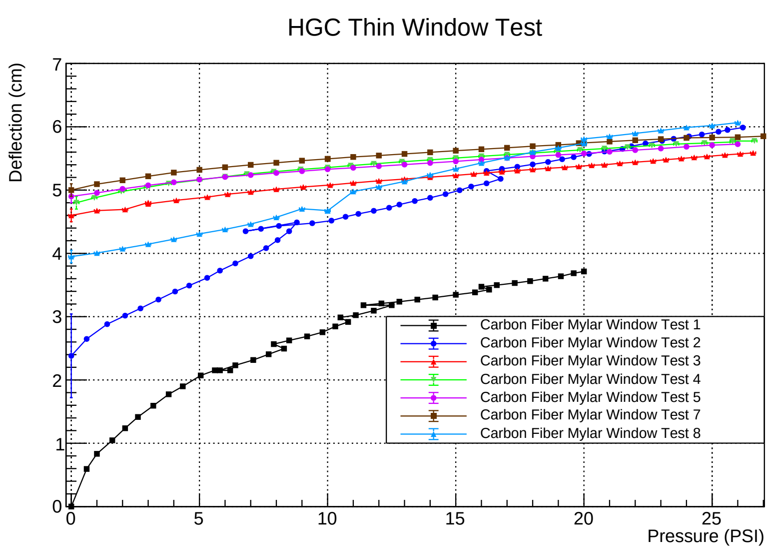


Figure 25: Plot of pressure versus deflection for tests up to date. Test 6 was omitted because its data fell directly on top of Test 7

The data from this test (Figure 25) shows that the window had relaxed while it was out of the window frame. This may have been simply because it was no longer in the frame or, it may be due to storing the window upside down. This inflation reached the same deflection, within systematic error, as the second test and it also is in the same region as the other tests. This shows that there is no significant drop in the performance of the window if it is taken apart and reused.

9 Conclusion

This window design meets safety specifications [1], that is, the window withstood repeated inflation to the test pressure of 1.8 *atm* or 26 *psi*, which is double the operating pressure, as well as disassembly and reassembly. It performed well on another design goal, as the maximum allowed deflection of the window is 10 *cm* and this window only deflected to a maximum of 6.2 ± 0.2 *cm* under the test pressure. Also, although this window leaked, in the small scale tests of this design the window held pressure for a long period of time, exceeding one year. The fact that this window leaked is attributed to the faulty valve and on a poor frame design. A new frame design has already been made, however, it had not been manufactured at the time of this testing, so the old design had to be used.

References

[1] Whit Seay. Jefferson Lab. Personal Communication, 3/11/2019

[2] Samip Basnet, Rory Evans, Ryan Ambrose, Derek Gervais, Garth Huber, Geremy Lague, Wenliang Li, Dilli Paudyal, Lorenz Weber, Ahmed Zafar. 2018/02/26. *HGC Window Prototyping - Carbonfiber Testing Series*. `https://solid.jlab.org/cgi-bin/private/ShowDocument?docid=172`, accessed 2019/08/16.

[3] Fibre Glast Developments Corporation. *3K, 2 x 2 Twill Weave Carbon Fiber Product Page*. 2010. `https://www.fibreglast.com/product/3K_2_x_2_Twill_Weave_Carbon_Fiber_Fabric_01069/carbon-fiber-fabric-classic-styles` accessed 2019/08/20

[4] MatWeb. *Fibre Glast 2000 / 2060 System 2000 Epoxy Data Sheet*. 2019. `http://www.matweb.com/search/datasheet.aspx?matguid=b0c9e07adcbb4dacbe78ec7b9e4a4985&ckck=1`, accessed 2019/07/26.

[5] Challenge Sailcloth. *Challenge Sailcloth Catalog*. 2010. `http://www.sacloma.com/CatalogoChallenge.PDF` accessed 2019/08/02

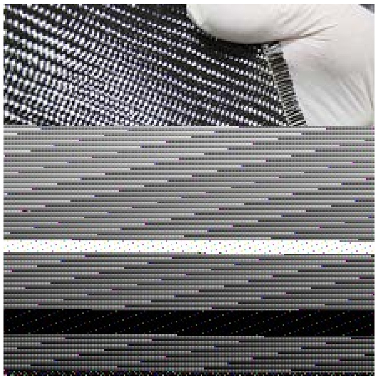
[6] Fibre Glast Developments Corporation. *Parting Wax Product Page*. 2010. `https://www.fibreglast.com/product/Parting_wax_1016/Mold_Releases` accessed 2019/08/20.

[7] Fibre Glast Developments Corporation. *FibRelease Product Page*. 2010. `https://www.fibreglast.com/product/FibRelease_01153_A/Mold_Releases`, accessed 2019/08/20.

[8] Permatex. *Permatex Ultra Copper RTV Silicone Gasket Technical Data Sheet*. November 2018. `https://441py33rout1ptjxn2lupv31-wpengine.netdna-ssl.com/wp-content/uploads/tech_docs/tds/81878.pdf`, accessed 2019/07/26.

A Appendix

Fibre Glast Developments Corporation 800.214.8572 www.fibreglast.com **Product Data Sheet**



3K, 2 x 2 Twill Weave Carbon Fiber

Part # - 1069, 2069

5.7 oz/sq yd, 50-60" Wide, .012" Thick, 3K, 2x2 Twill Weave.
This 2x2 twill weave fabric offers the cosmetic appearance so desirable on modern composite parts. But don't just use it for looks, this fabric is highly formable and slightly stronger than the plain weave.

Specific Product Properties	
Type	3K Carbon Multifilament Continuous Tow
Twist	Untwisted
Weave Pattern	2 x 2 Twill
Tensile Strength	610 - 635 KSI
Tensile Modulus	33.6 - 34.9 MSI
Elongation	1.75% - 1.95%
Warp ends/inch	12 – 14, 3K
Fill ends/inch	12 – 14, 3K
Weight	5.7 – 5.9 oz/yd^2
Width	50" (49.75 – 50.25 in) 60" (59.95 – 60.25 in)

DESCRIPTION

Graphite fibers contain up to 95% carbon and yield the highest tensile strength in the FRP industry. These fibers woven together form graphite fabric. These fabrics offer higher strength and stiffness-to-weight ratios than any other commonly available reinforcements. While there are hundreds of types to choose from, we have selected three styles of standard modulus carbon fiber which are suitable for use in racing, aircraft, competition marine, and light industrial applications. To maximize the fiber properties we recommend using only epoxy or vinyl ester resin, although polyesters will bond to the fabrics. This 2x2 twill weave fabric offers the cosmetic appearance so desirable on modern composite parts. But don't just use it for looks, this fabric is highly formable and slightly stronger than the plain.

Resin Compatibility:

1069 & 2069, Carbon Fiber Fabric, is compatible with Polyester, Vinyl Ester, and Epoxy Resins.

General Properties for Carbon Fiber Fabrics:

- Lightweight
- High Modulus
- Fire Resistant
- Dimensionally Stable
- Fatigue Resistant

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