

PSFC/RR-06-1

## **Desktop Vacuum Pressure Impregnation Experiment for ITER Insulation Testing**

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**Motivation:**

For the ITER central solenoid coil, as well as other superconducting magnets, it is important for the cables to be electrically insulated from each other. Due to the large forces in the magnets, the insulation systems must be designed so that the insulation will break benignly, if at all. The tensile strain, normal to the surface of the insulation layers, comes from flexure of the conductor jacket as well as from quenches. Under tension, the insulation is expected to break along the Kapton planes, which is considered a benign break since the insulation would still be electrically insulating. However, if the insulation breaks through the insulation exposing a path from one cable to another, arcing can occur. Investigating the consequences of cracking and de-bonding will help in the evaluation of proposed ITER insulation systems.

**Purpose:**

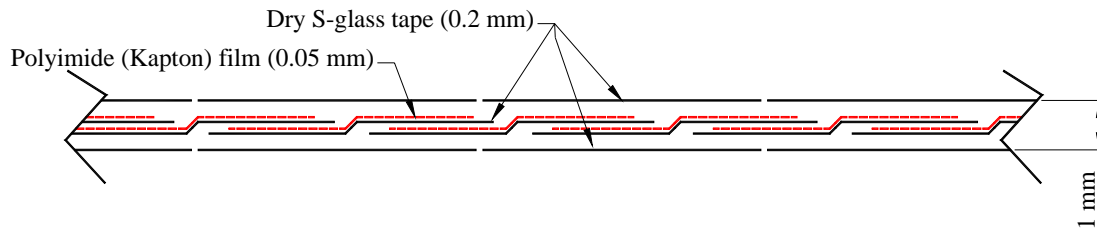
The purpose of this experiment is to develop a test method and sample to qualify through thickness tensile strains expected in the ITER CS conductor. Once the sample has been created, it will be broken in tension. After the sample is broken, the electrical barrier of the cracked insulation between the two samples will be tested.

**Executive Summary:**

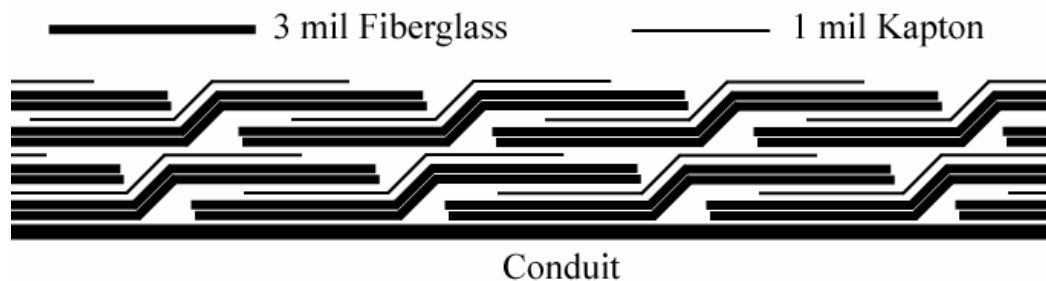
This experiment successfully developed a method to vacuum pressure impregnate an insulation sample. The sample was broken at an unexpectedly low load; however, the sample held 18 kV after breaking. Throughout the experiment several problems were encountered and modifications to the experiment have been suggested. One of the main problems encountered was how to make sure that the breaking test is a purely tensile test. If the load is applied slightly off center, or at a small angle, the desired tensile test will quickly become a tearing test. During the electrical test another problem was encountered. At a voltage of about 7 kV arcing would occur between the faces of the conduits which is only an experimental problem since these faces will not be exposed in a magnet. There are ways to block this arcing: epoxying on a G-10 blocker after the breaking test, or extending the insulation past the face of the conduit.

**Materials:**

- The conduit we used in this experiment was cut from a compacted CSMC CS2 jacket. The history of the jacket is not known, but measurements were taken to determine that the conduit bulges out on all four of the sides, (see Chen-yu's memo ITER No.: ITER-USMIT-GUNG-20050926-01).
- The jacket was grit blasted using Rich Alum Oxide 100 grit at 110 psi.
- A G-10 rod was machined to fit inside the conduit for the impregnation, so the middle will not fill with epoxy. During the impregnation the threaded part of the jacket was filled with RTV so epoxy would not get into the threads.
- Another G-10 piece was also machined to fit inside as well as being tapped to aid in the breaking test (although it was not used).
- According to the latest (Feb 2006) ITER Central Solenoid Specification document, the insulation will be a one step VPI system consisting of three layers:
  - o Inner: dry glass, one layer, minimum gaps between tape butts, no overlap.
  - o Middle: dry glass and polyimide film tape, one pass, 45% overlap
  - o Outer: dry glass: one layer, minimum gap between tape butts, no overlap

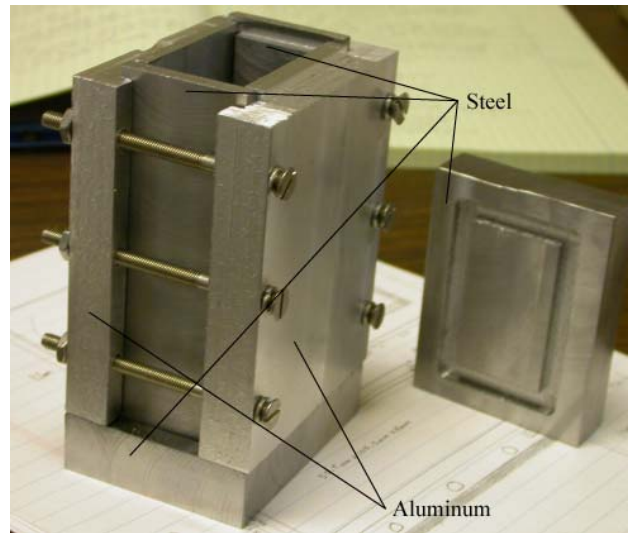


- The insulation we used in the experiment is composed of 3 mil silane treated E-glass and 1 mil Kapton tape. Instead of the desired 6 mil fiberglass, 2 layers of the 3 mil glass were used. The insulation consisted of 2 half lapped layers of 6 mil of fiberglass and 1 mil of Kapton.

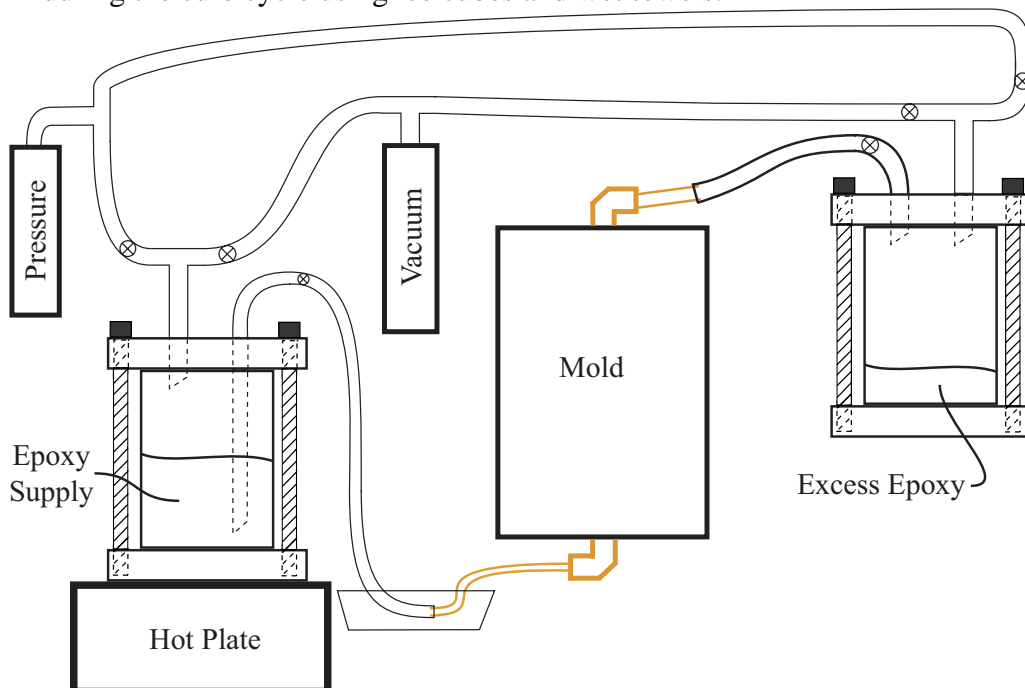


- The epoxy used in the impregnation was CTD 101-K composed of resin, hardener, and an accelerator. The manufacture date is 7/14/05 and was shipped 7/15/05 and was refrigerated upon arrival in the lab.

- The mold is part steel and part aluminum (for ease of machining). Before the run, it was also grit-blasted to help the RTV adhere to the metal and form a good seal. (The figure to the right is before the holes were tapped in the top and bottom for the epoxy to enter and exit the mold.)



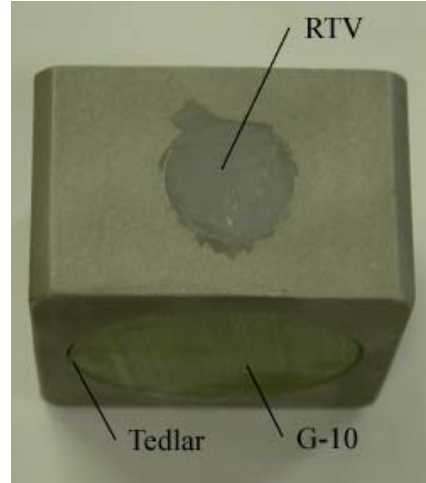
- Below is the vacuum pressure impregnation setup:  
All tubing was plastic except copper parts near the inlet and outlet, which are used to form a leak-tight seal. During the cure cycle the mold needs to be pressurized; however, the input and output tubes cannot simply be clamped shut since the change in temperature in the mold would change the pressure if it could not expand. The bottom piece of copper tubing is bent so it can sit in an ice bath (the Tygothane tubing cannot hold the pressure above ~80 C and the cure temperature is 135 C). The copper tubing on the output side is tilted up so air bubbles can escape during the impregnation; therefore, that copper tube needs to be cooled during the cure cycle using ice cubes and wet towels.



## Pre-Run Day Procedure:

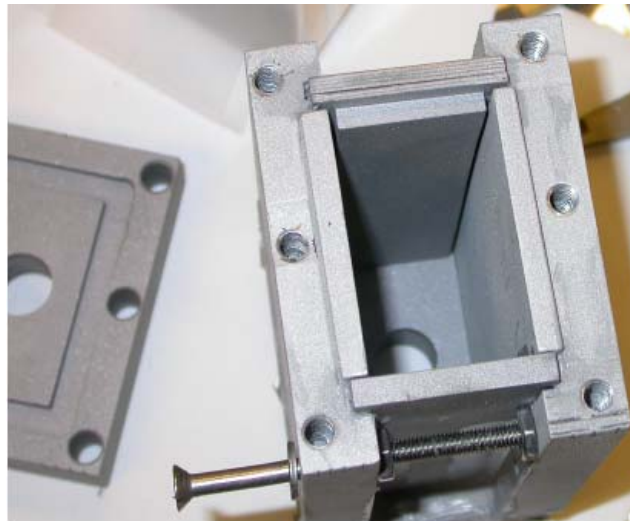
### 1. Conduit Preparation:

- a. The conduits were grit-blasted by hand using Rich Alum Oxide 100 grit at 110 psi. The conduits were then cleaned using ethanol and acetone.
- b. The G-10 fillers were wrapped in Tedlar around the curved circumference to allow for easy removal after impregnation.
- c. The G-10 fillers were inserted into the conduits and the threaded parts of the conduits were filled with RTV (let dry for 2-3 days).



### 2. Mold Assembly:

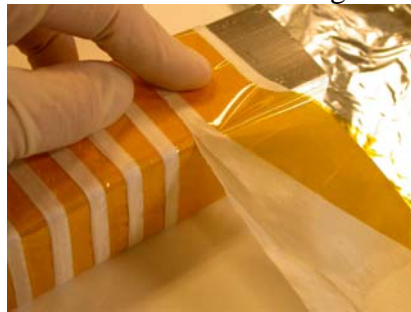
- a. The mold pieces were grit-blasted to help the RTV form a good seal.
- b. The pieces were cleaned with ethanol and acetone.
- c. A thin layer of RTV was applied to the grooves of the mold and left to dry for 24 hours.
- d. The next day another thin layer of RTV was applied on top of the dried layer. RTV was also applied to the flat parts near the grooves that would form a seal with other parts of the mold.
- e. The mold was assembled (except for the top piece).
- f. A healthy amount of RTV was spread in all corners of the mold from the outside (similar to caulking a sink) to cover all cracks.
- g. This was left to dry for 24 hours.



### 3. Insulation wrapping:

- a. It is difficult to begin a half lap on the sample itself, so two pieces that were the same dimensions were placed on either side of the two samples to be wrapped. The fiberglass and Kapton tapes were taped to one of the end pieces and the wrapping started there. Once the wrapping cleared the second sample, the Kapton glass was cut and taped to the other end piece. This process was repeated for a second lap.

- b. The wrapped pieces were then wrapped in a layer of Tedlar and then in a layer of duct tape. The duct tape is used to keep pressure on the insulation so it won't unravel, and the Tedlar is used so nothing sticks to the insulation.
- c. In order to get the samples out, a razor blade is used to cut between the end pieces and samples. Slight pressure on the ends is helpful to keep the crack small where the razor blade is cutting and will help make a cleaner cut. Once the samples were cut out, scissors were used to clean up the edges.
- d. The Tedlar and duct tape was cut off of one sample which was placed on another long piece of Tedlar with a pre-cut hole in it for the epoxy to come in through the bottom. The Tedlar and duct tape was then cut off of the other sample and it was placed on top of the first sample. The long piece of Tedlar was then wrapped around both pieces, keeping the insulation from unwinding.
- e. A second long piece of Tedlar was then used to wrap the samples in the other direction, to avoid an epoxy bond between the sample and the walls. The better the sample is wrapped with Tedlar, the easier it will be to remove it from the mold after curing the epoxy.



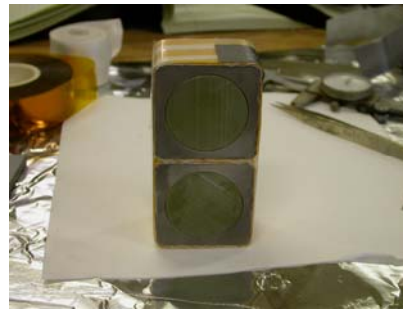
a



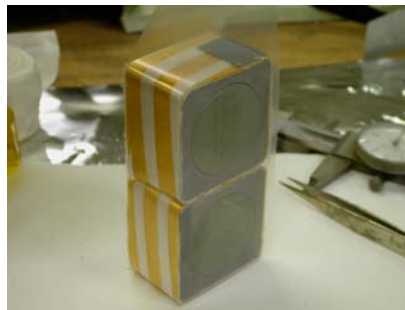
b



c



d



e



4. Sample insertion:

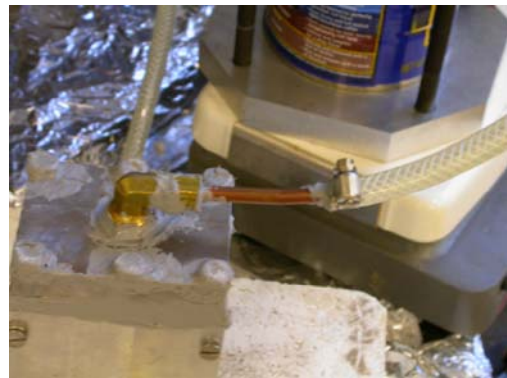
- a. The inside walls of the mold were sprayed with a Teflon spray to keep the epoxy from adhering to the mold.
- b. The samples (wrapped once in each direction with Tedlar) were inserted into the mold. They fit snugly, but if they didn't spacers would have been used to make the fit snug.
- c. A hole was cut in the top of the Tedlar for the epoxy to exit.



- d. A hole was cut in the top of the Tedlar and the hole in the top of the mold was inserted on the top, so that the vertical fit would be snug as well. (This was not sprayed with Teflon spray, but probably should have been since it is now epoxied to the top of the mold).



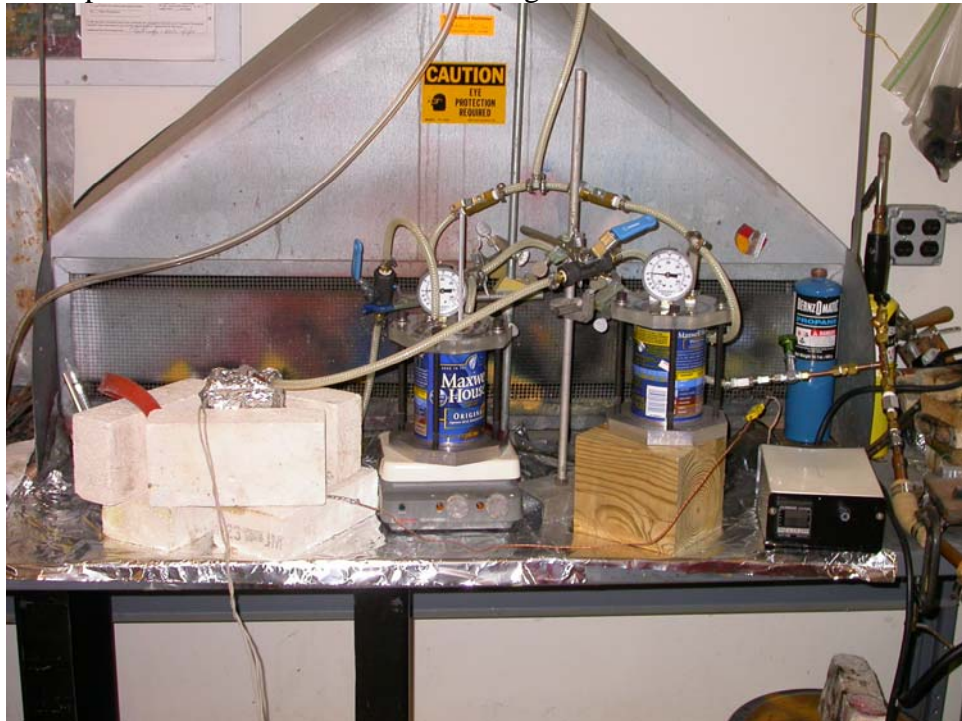
- e. A thin layer of RTV was applied to the groove in the top piece and the flat parts around that would bond to the mold.
- f. The top piece of the mold was bolted in place and the outside corners were covered in RTV to seal any cracks.
- g. The inlet and outlet pipe fittings were screwed into place and RTV was applied around the edges to seal off any cracks.
- h. This was left to dry for 3 days. (Should be left for more...maybe a week or two to make sure the RTV dries. There was still a little wet RTV when the mold was opened after the cure cycle).



## Run-Day Procedure:

### 1. Heating Tape Setup

- a. During the impregnation, the mold should be around 60 C to maintain an epoxy viscosity capable of moving through the insulation.
- b. A thermocouple was positioned on a wall of the mold to relay the temperature to the thermostatically controlled heat tape.
- c. The mold (with thermocouple on the wall) was first wrapped in a thin layer of Al foil to keep the heating tape from directly contacting the RTV.
- d. The heat tape was wound around the mold without overlapping so it wouldn't burn itself.
- e. More Al foil was wrapped around the heating tape and mold to keep as much heat in as possible.
- f. The mold was placed inside an "oven" of fire-bricks to keep as much of the heat in as possible. (A cardboard box was also mounted around the mold in case of epoxy leak during the pressure cycles or curing cycle).
- g. Once this is set up, the thermostat was turned on to 60 C so the mold would heat up and the heat would diffuse throughout the mold and insulation.



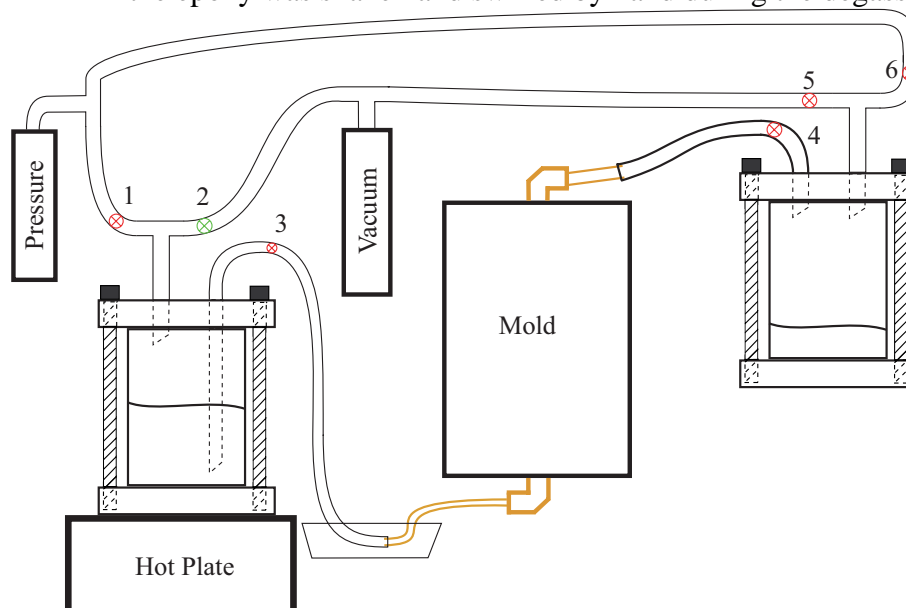


## 2. Epoxy Mixing

- a. We needed ~280 mL of epoxy for the impregnation, filling the tubes and containers and having left-over, so we mixed ~500 mL to be safe.
- b. According to the mixing ratios, this came out to be 300 g of resin (1.2 g/mL), 270 g hardener (1.2 g/mL), and 4.5 g accelerator (1 g/mL), to make 479.5 mL.
- c. The epoxy container (a very well cleaned coffee can) was placed on the scale and zeroed. The resin was poured in until the scale reached 299.7 g. The hardener was poured in until the scale reached 569.7 g (180.0 g hardener). The 4.5 g of accelerator was added with a syringe until the scale reached 574.2 g.
  - i. The resin was very thick and not easy to pour, which is why its measurement was not as exact as the others, but the 0.3 g is only 0.1% error.
- d. The epoxy was mixed using a glass stirrer first and then a magnetic stir-bar was added to continue the stirring on the hot plate. However, the tin coffee can shielded the magnetic stirrer enough that it did not spin. (Next time use a larger magnetic stirrer with a stronger magnet).

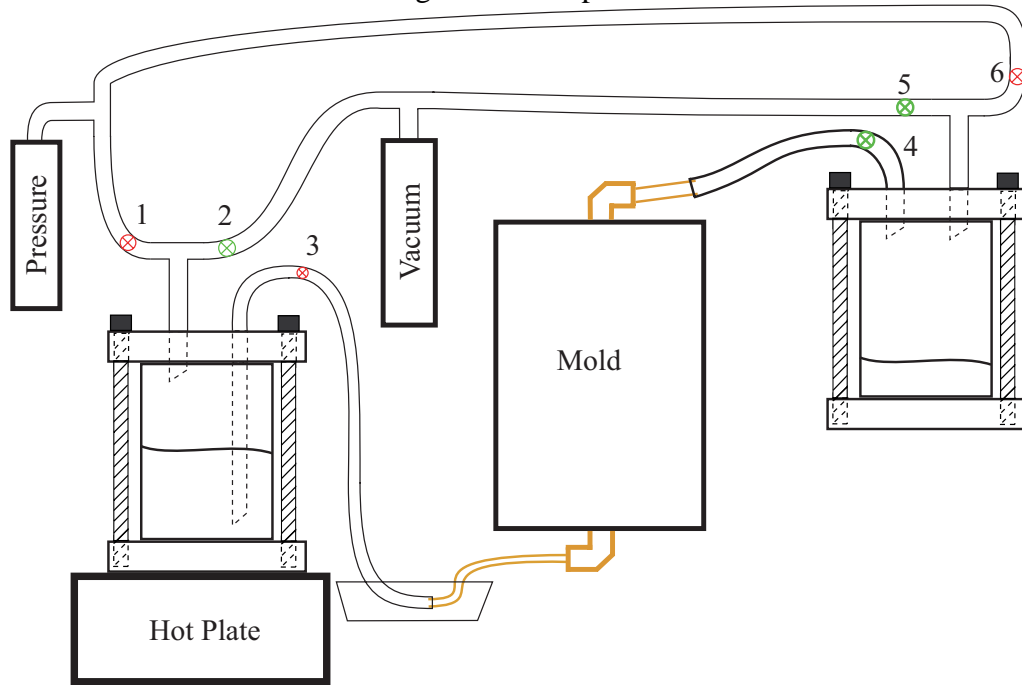
## 3. Epoxy Degassing

- a. According to CTD, the epoxy should be heated and stirred until it becomes a clear solution at 40-60 C. A standard thermometer was used to measure the epoxy temperature during this process.
  - i. The coffee can bottom sits on a rim of the can, so there was not good thermal conduction between the hotplate and can and it took 1.5 hours to heat the epoxy from room temperature to 55 C. (next time make that a better conduction path.)
- b. Valve 2 was opened and the epoxy was degassed at ~55 C and ~27 in Hg for about 50 min (CTD specs say 20-40 min or until bubbles stop evolving).
  - i. Since the stirrer was not mechanically stirring the epoxy, the can with the epoxy was shaken and swirled by hand during the degassing.

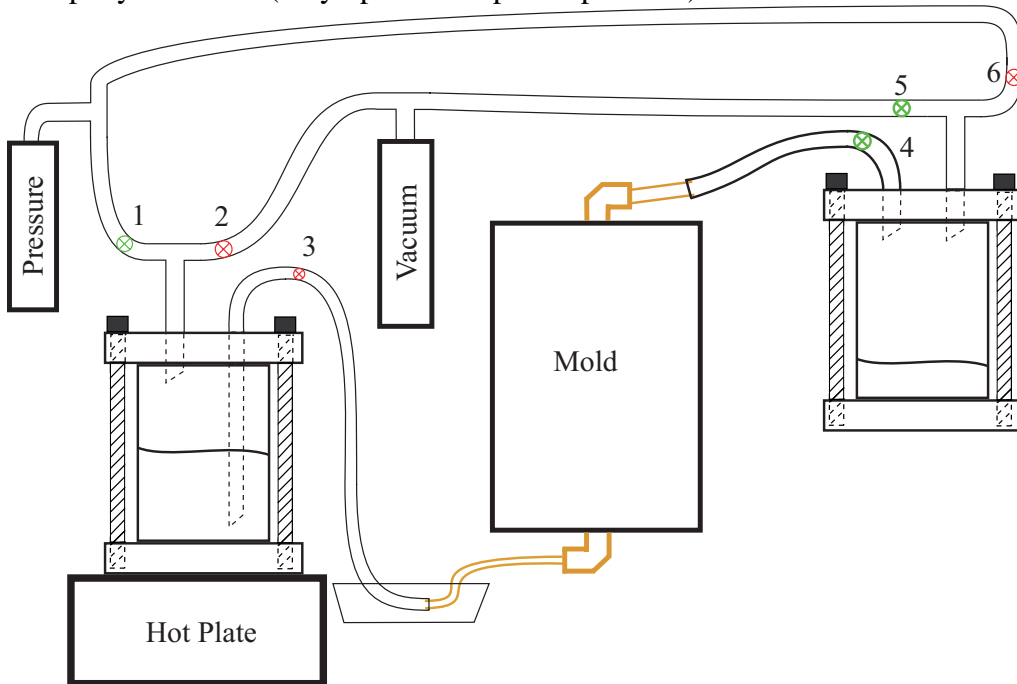


4. Impregnation

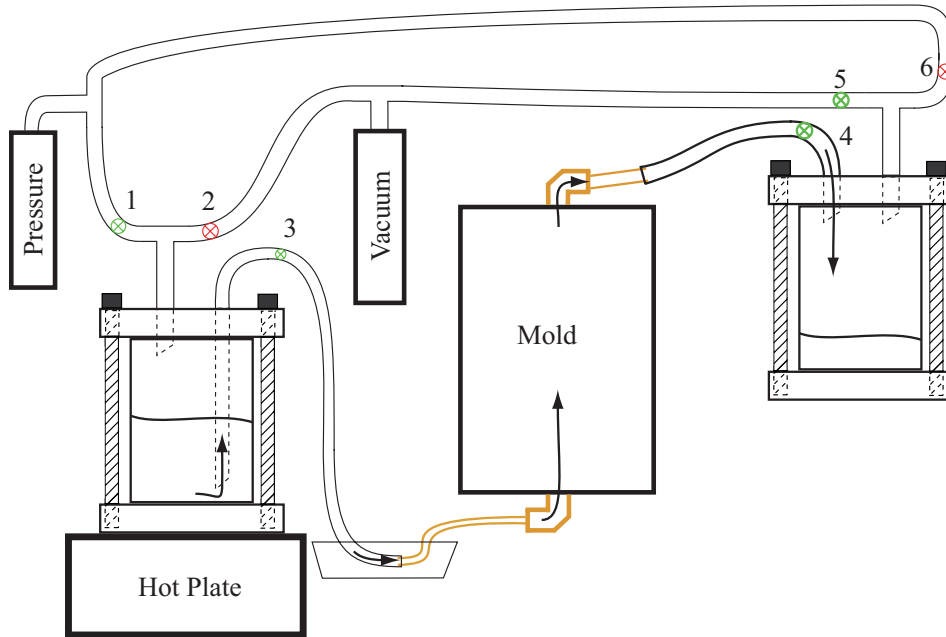
- a. For the last 10 minutes of the degassing, valves 4 and 5 were opened to get the mold and the rest of the tubing to vacuum pressure.



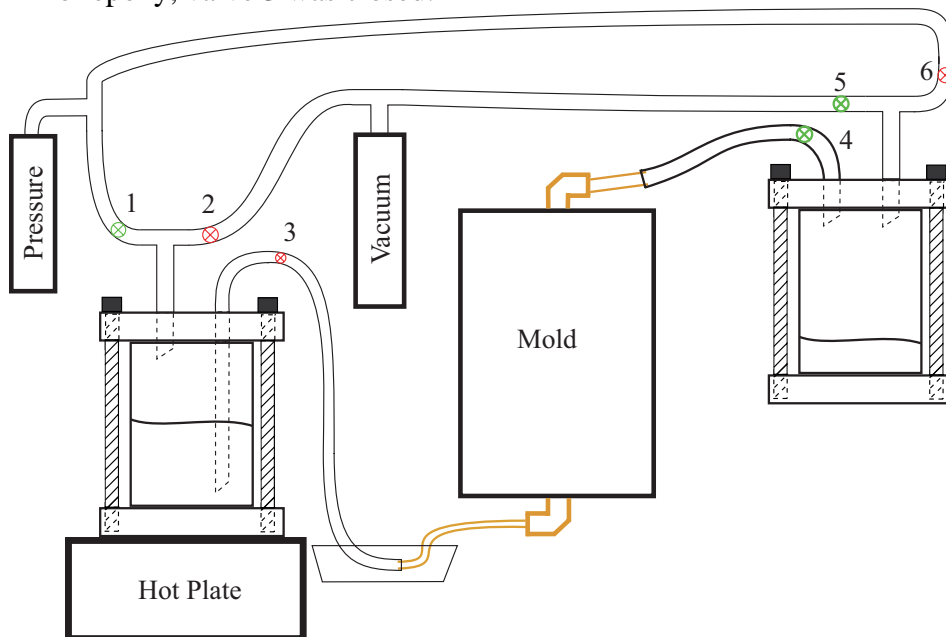
- b. Valve 2 was closed and then valve 1 was opened to allow nitrogen to fill the epoxy container (only up to atmospheric pressure).



- c. With the mold at vacuum and the primary epoxy container at atmospheric pressure, valve 3 was opened and the epoxy began to flow through the tubing and into the mold.



- d. After about a minute epoxy could be seen entering the secondary epoxy container. (Should take more time...maybe only open valve 3 a little so epoxy seeps up through mold slower).
- e. Some bubbles were seen in tubing, so the valves were left open for about 1 minute until the bubbles in the tubing became less frequent. To stop the flow of epoxy, valve 3 was closed.

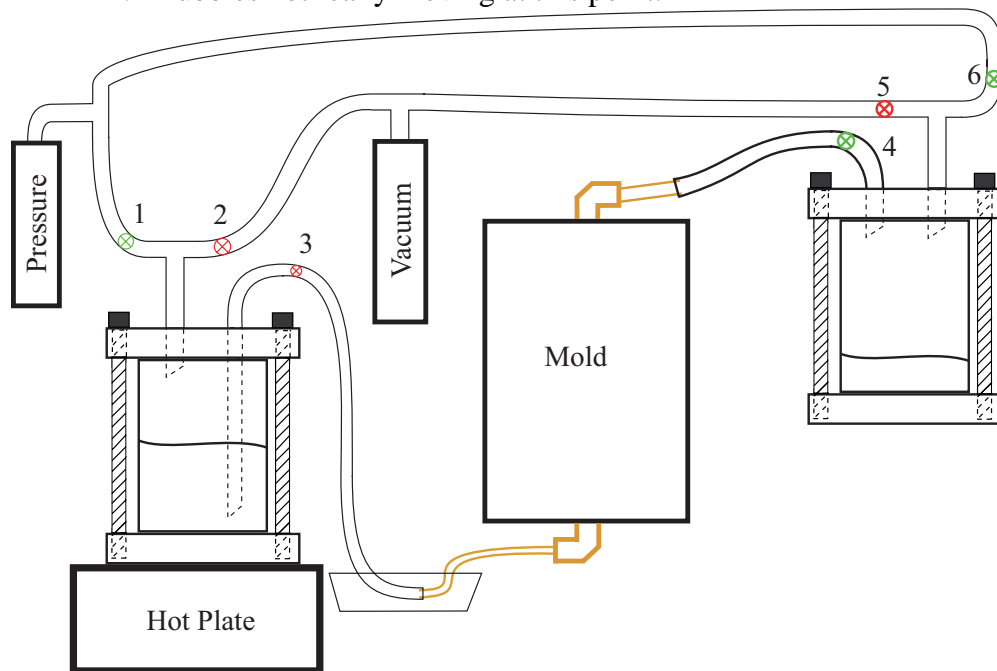


f. The vacuum pressure in the secondary container continued to pull some epoxy through for a few seconds after valve 3 was closed.

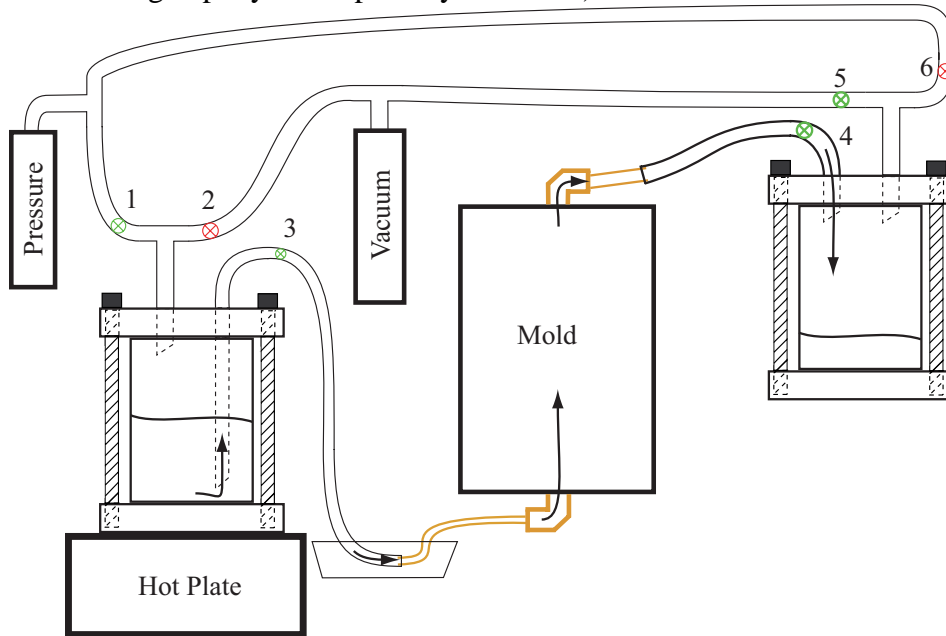
- i. The secondary epoxy container was not heated, but we saw the epoxy “boiling” in it. The can was not hot, and the epoxy was not above 60 C. Possibly the epoxy picked up bubbles while moving through the insulation, and also while entering the secondary container. (It was not a laminar flow out of the tubing...the epoxy would form bubble drops at the end of the tubing and then fall into the can. Similar to squeezing honey out of a bottle that is running out of honey. The bubbles were being pulled out through the tubing and forming bubbles before falling into the container.)



- g. When the epoxy stopped flowing into the container, bubbles continued moving up the tubing (which was at an upward angle so the bubbles would rise out away from the mold).
- h. After ~15 min with the vacuum pulling, valve 5 was closed and 6 opened with the pressure set to ~14 psi.
  - i. Bubbles not really moving at this point.



- i. After ~5 min, the valves were switched back to pull vacuum on the secondary epoxy container. (Valve 6 closed, and valve 5 opened).
- j. Valve 3 was also opened again to push more epoxy through (make sure there is enough epoxy in the primary container).

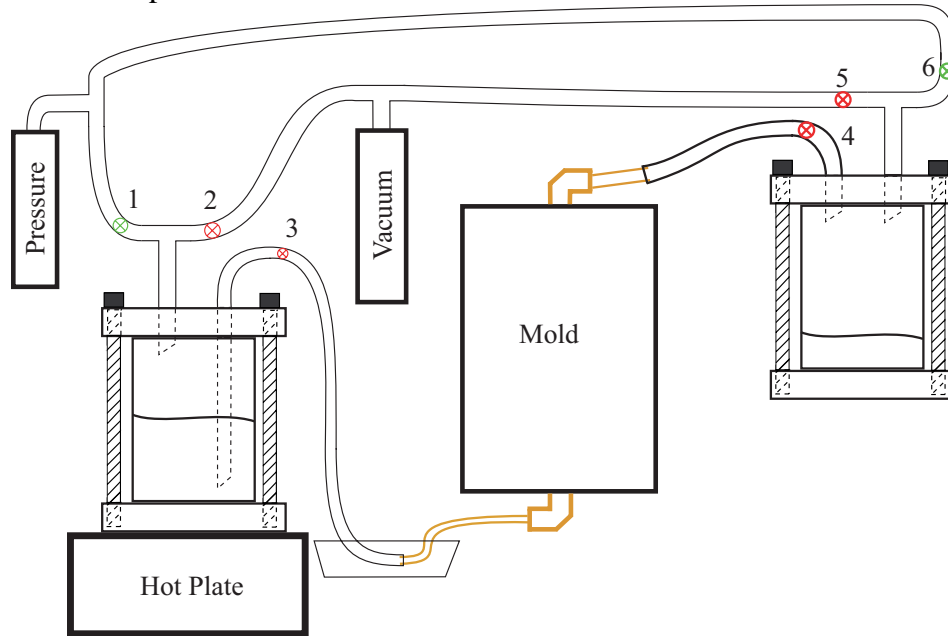


- k. Bubbles were seen leaving the mold with the epoxy flowing, but after a few seconds, there were very few bubbles leaving the mold.
- l. \*\*Steps h, i, and j can be repeated as many times as needed...until comfortable that there are no more air bubbles in the mold.
  - i. We let the epoxy flow for ~2 min, then closed valve 3 and let sit under vacuum for ~10 min.
  - ii. Then we switched back to pressure (step h) for ~5 min.
  - iii. Then switched back to vacuum (step i), allowed a little more epoxy to flow through (step j) for ~5 sec.
    1. didn't see anymore bubbles leaving
  - iv. Let sit under vacuum for ~25 min.

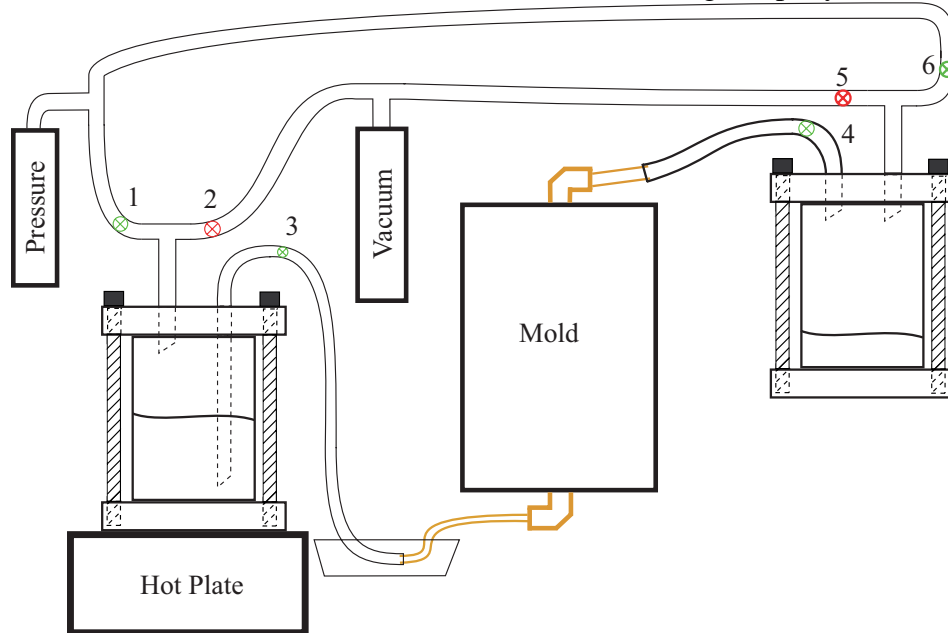


## 5. Epoxy Curing

- a. All valves were closed.
- b. Valves 1 and 6 were opened to bring the pressure in both epoxy containers up to ~10 psi.



- c. Once both epoxy containers were at 10 psi, valves 3 and 4 were opened to put that pressure on the mold.
- d. The pressure was carefully increased up to 30 psi (to make any remaining bubbles in the mold as small as possible).
  - i. Checked to make sure there was not leaking of epoxy or air.



- e. Thermostat for heat tape was increased to 135 C.
- f. Tygothane tubing is only good up to 80 C and other side of copper tubing needs to be at 135 C, so ice water is used to keep the copper/Tygothane connection at less than 80 C.
  - i. Dish with input copper tubing connection was filled with ice water.
  - ii. Ice cube and wet towels placed on copper tubing on top of mold.
    - 1. Made foil funnel system to keep water off mold.



- g. Waited for temperature of mold to increase to 135 C (took 1 hour 45 min).
- h. Held at 135 C for 1.5 hours.

#### 6. Post Cure

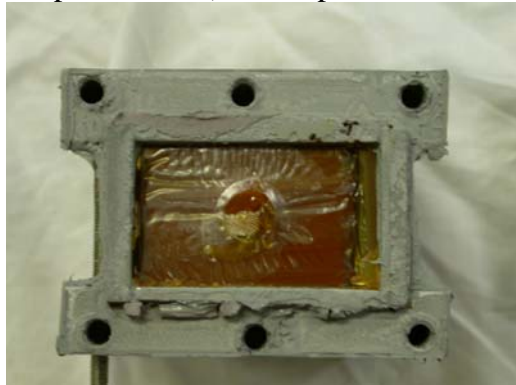
- a. After 1.5 hours at 135 C the Al foil and heat tape was removed.
- b. Vacuum pressure was applied to both ends of the mold.
- c. The Tygothane tubing was cut near the copper tubing.
  - i. Dishes were placed under the position where the cuts were made.
  - ii. The vacuum pulled all of the remaining uncured epoxy left in the Tygothane tubing back into the epoxy containers.



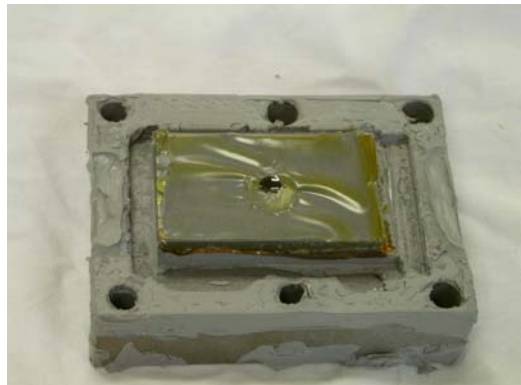
- d. The mold was left to cool down overnight.
- e. Everything with epoxy on it was cleaned with water and acetone.
  - i. Valves, tubing, thermometer, magnetic stir-bar, Plexiglas cover...

### Post Run-Day Procedure:

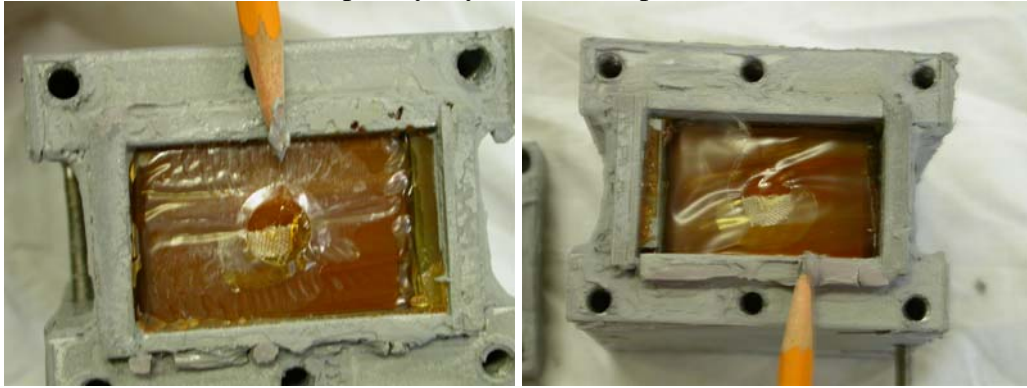
1. Visually checked to make sure that no epoxy leaks were seen.
2. Unscrewed the brass inlet and outlet elbows from the top and bottom
  - a. Took some force. The epoxy had cured from the layers of insulation, through the brass elbows, and into the copper tubing, so unscrewing these pieces broke epoxy.
3. Removed the RTV from the bolts enough to be able to use a wrench on them, and then removed all bolts.
4. The RTV is strong enough that the top and bottom cannot be pried off, so a vice had to be used. (Also epoxy filled and cured from the insulation to the threading for the top and bottom elbows, so the top and bottom pieces of the mold cannot be removed without breaking that epoxy too).
  - a. The vice was positioned on the inside of the top and bottom pieces of the mold and slowly cranked open until either the top or bottom piece could be pulled off. (Bottom piece shown below):



- b. A bolt was then inserted in the side holes and the vice was positioned between the bolt and the remaining top or bottom piece. The vice was cranked open until that piece could be pulled off as well. (Top piece with spacer shown below):



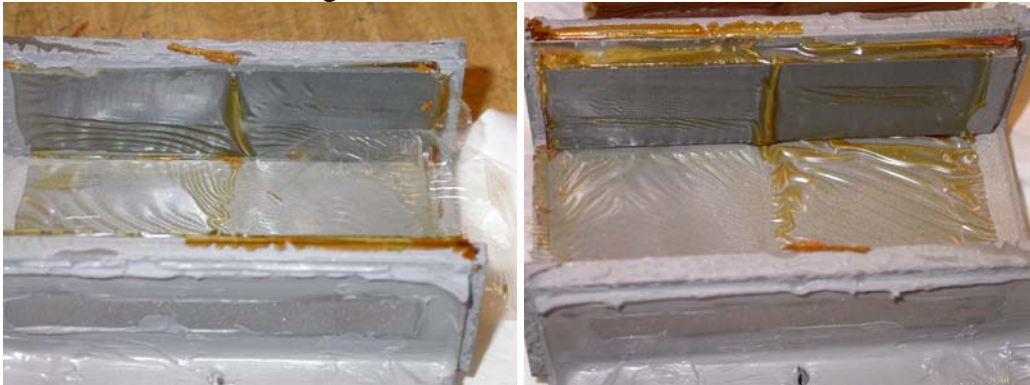
c. The RTV was not completely dry when these pieces were removed:



5. The vice was used to separate one of the sides from the mold.
- The space available between the side pieces was not enough to get the vice tips in, so 2 bolts were screwed back into each side and these were far enough apart that the vice would fit between them.

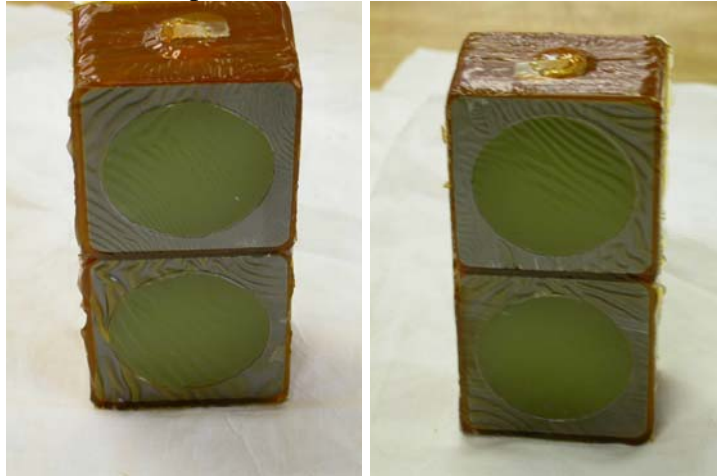


6. The Tedlar and Silicone spray did a very good job keeping the epoxy from bonding to the mold. The other side piece did not have to be separated. The samples were easily lifted out of the remaining mold without much force.





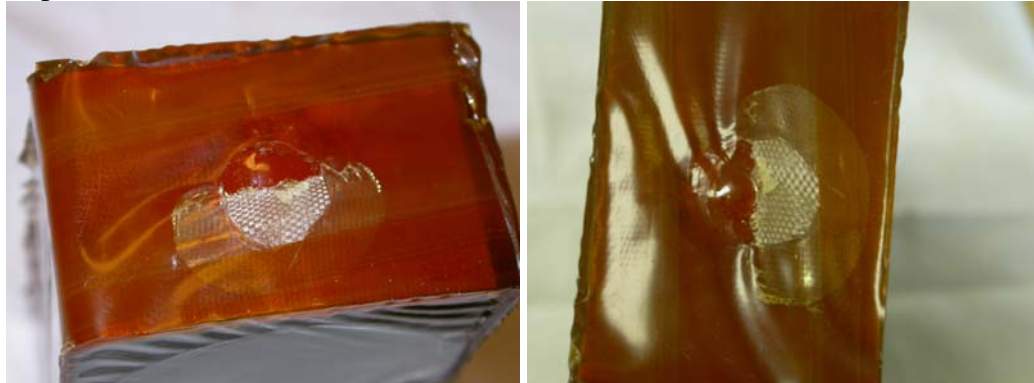
7. General pictures of the sample were taken:



8. During the removal of the sample from the mold there were a few areas where the epoxy/insulation broke.

- a. At the top and bottom, the epoxy cured in the insulation had to be broken from the epoxy cured in the entering and exiting elbows.
  - i. This was done when the top and bottom pieces were pried off.

Top:



Bottom:

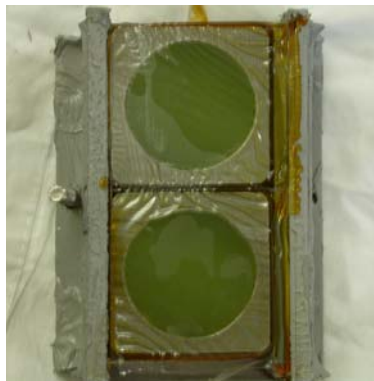


- ii. It was not clear at this time how deep these delaminations went (if they delaminated between the insulation and the jacket, or if they delaminated between layers of insulation). After dremmeling out the threaded holes, it was clear that these delaminations were between layers of insulation.





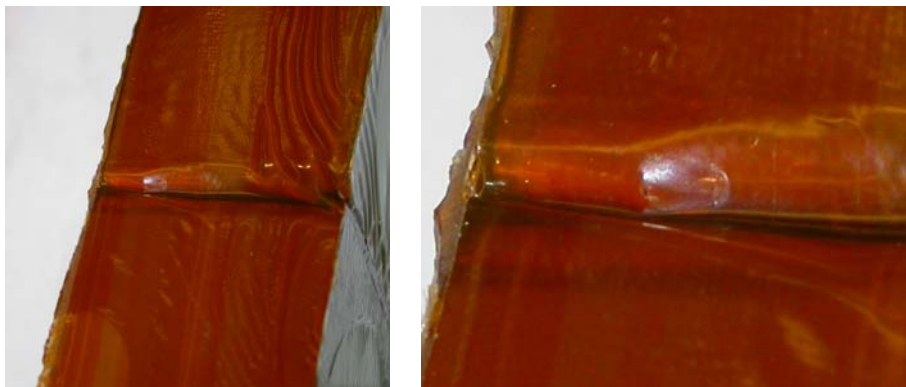
- b. There was one region on the side where the epoxy seeped between the Tedlar sheets and attached to the mold (top right of first picture). When the side was pried off using the vice, this also caused some delamination in one area of the side of the sample.



- i. Similar to the delaminations on the top and bottom of the sample, it was not clear how deep the delamination went. After smoothing down the sides with a file, it was clear that the delamination was again between the insulation layers, not between the insulation and the sample.



c. The sample was looked over for bubbles, and only one was found.



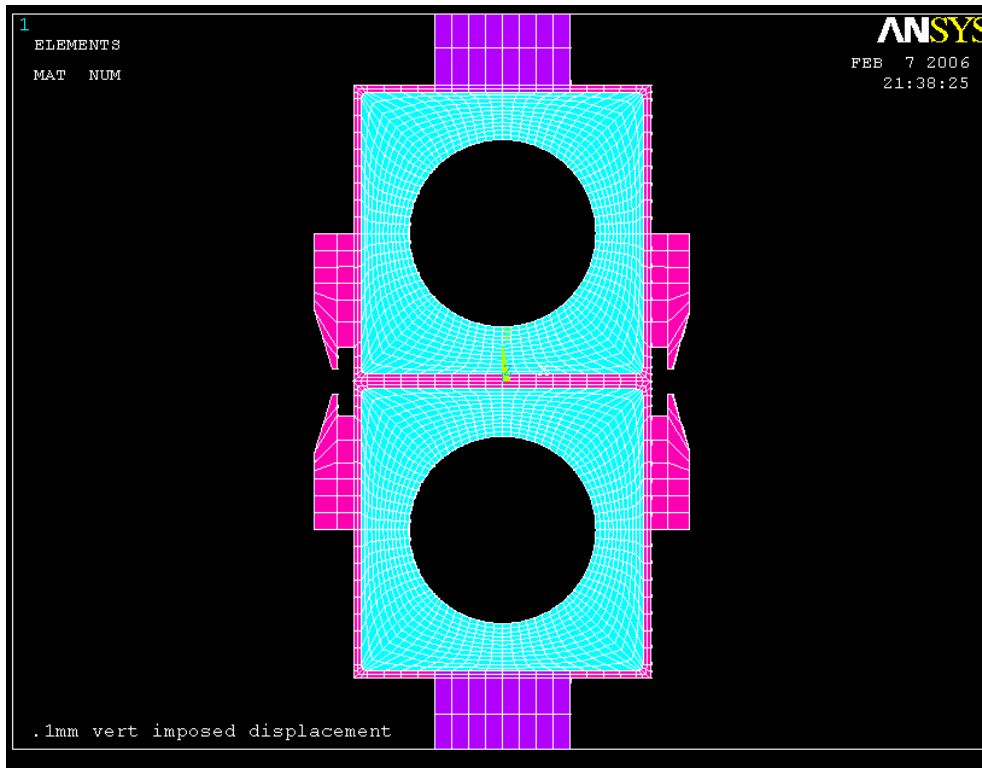
d. View of the insulation layer:



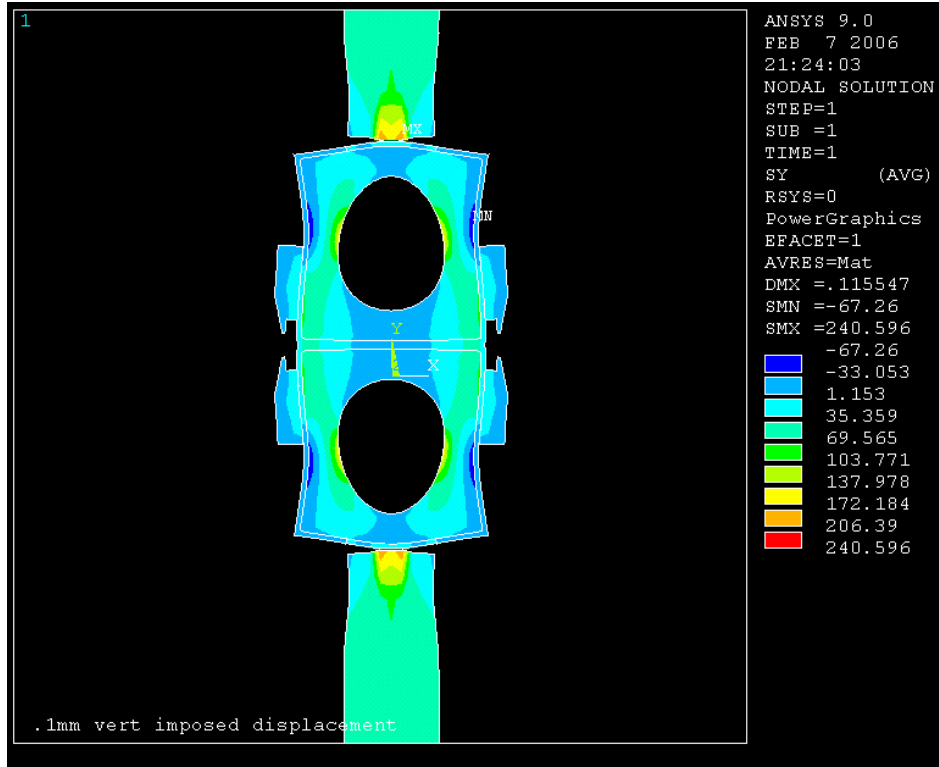
### Ansysis Analysis:

Peter Titus made an Ansys simulation to give a prediction of the expected loads needed and stresses expected for the tensile test. Since the design specification for the ITER CS coil is 55 MPA in the corners, we wanted to calculate the expected load needed to obtain these stresses, 19,368 N (4354 pounds). The expected yield strength of the epoxy is 90 MPA, so the load needed to produce that stress in the corners was also calculated, 31,693 N (7125 pounds). The vertical displacement at the clips is the expected reading from the extensometer, so an expected displacement at different loads was also noted.

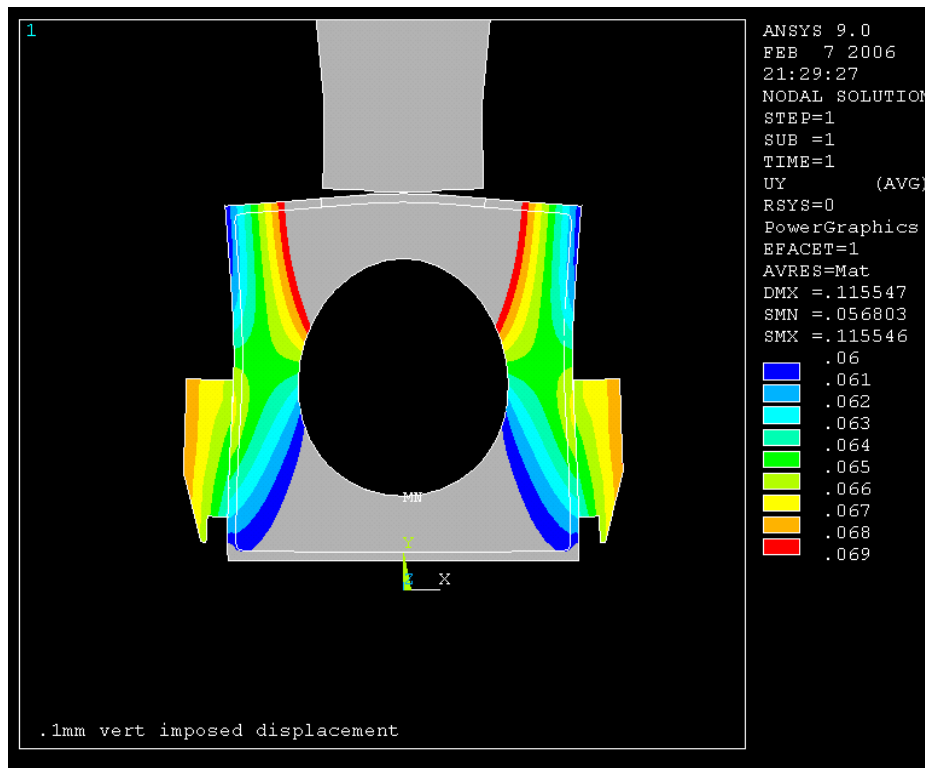
Shown below is the geometry of the sample in the Ansys program:



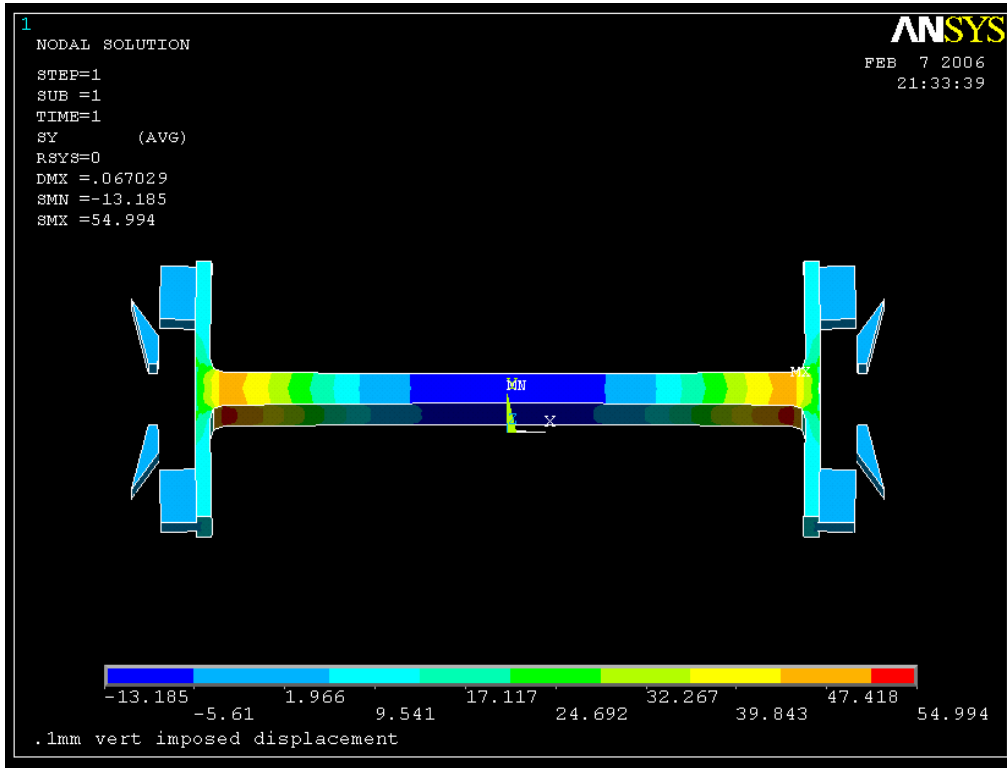
After a load of 19,368 N is applied, the expected vertical stresses (MPa) shown below:



Under this same load, the expected vertical displacement (mm) is shown below:

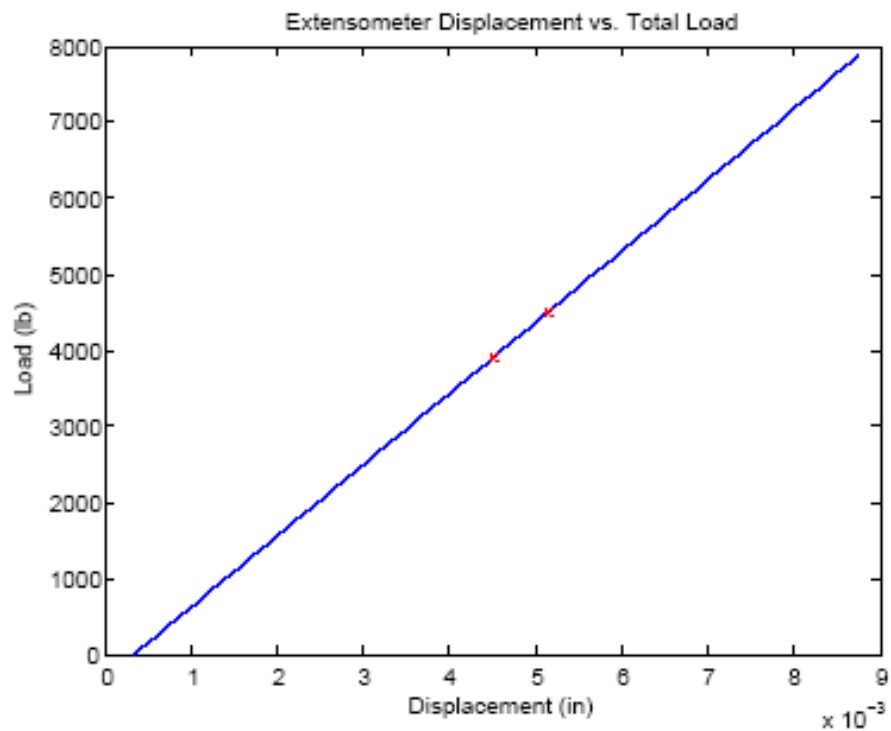
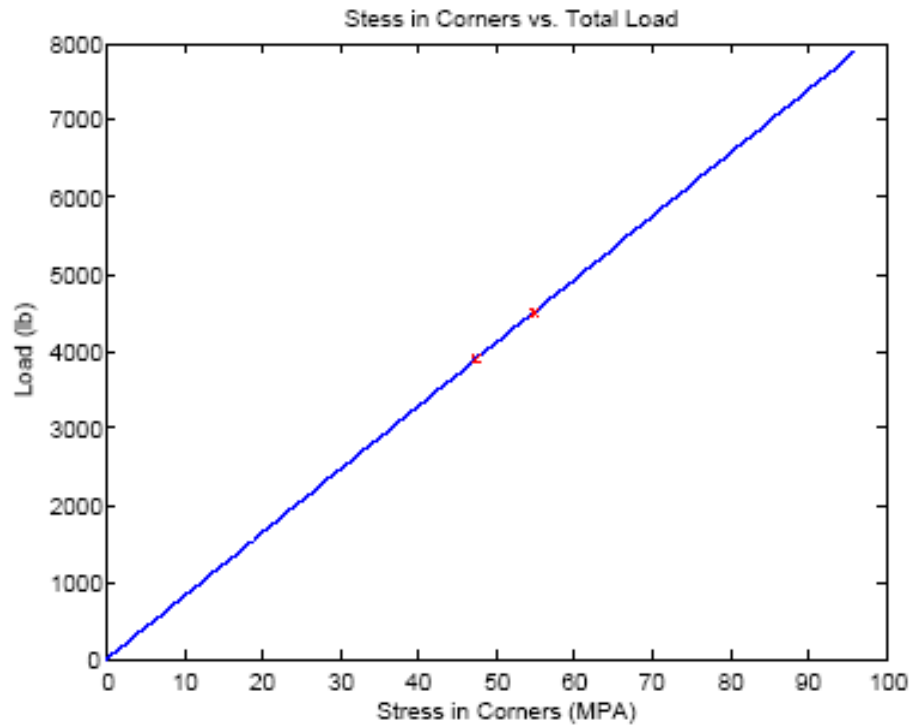


Under the same load, the expected vertical stresses (MPa) in the insulation are shown below:





Using two sets of data from two different loads, (17367 N and 20067 N), calibration curves were generated to show estimates of the expected vertical stress in the corner and displacement of the extensometer versus the applied load as shown below.

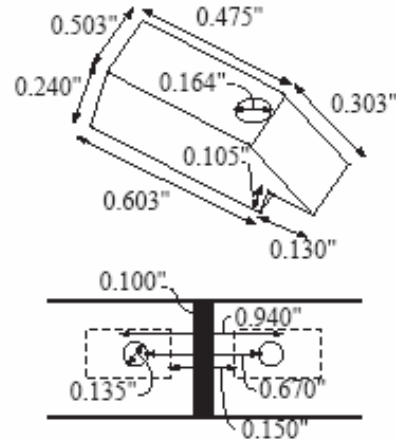


**Tensile Test:** (Thanks to Pete Stahle for his help with the tensile test).

1. G-10 mounts were made to hold the extensometer on the sample. The G-10 was mounted onto the jacket, near the insulation layer between the two samples via tapped holes and bolts (see figure below).

a. We want the loading of the sample to be displacement controlled for higher strains than the loading capacity.

i. One of the goals of this experiment is to see if the Instron we are using is capable of being displacement controlled during our tests. If it is not, when the insulation cracks, it may be ripped apart, instead of causing small fractures. In the real coil, when the insulation cracks, the displacement will be limited by the surrounding coils.



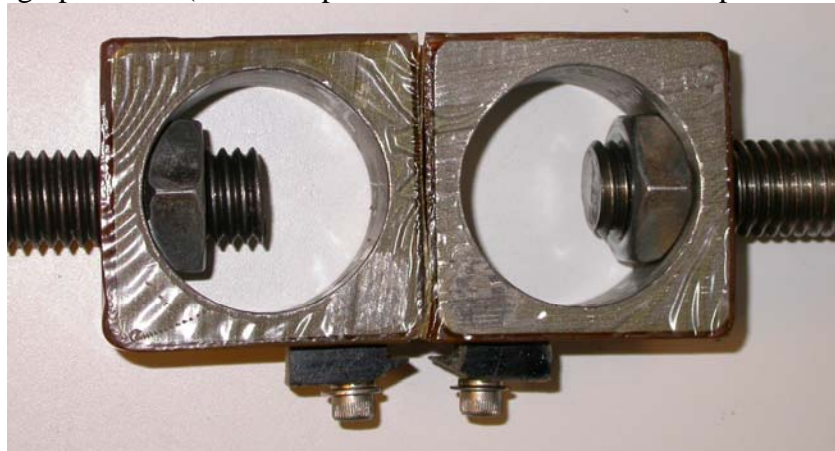
2. When we tried to screw the sample into the Instron, we discovered that the threaded holes in the sample were not perfectly aligned, which would cause an uneven load.

a. Even if the holes are perfectly aligned before the impregnation they can be misaligned when squeezed in the mold. This is still a problem that needs to be addressed before another experiment is run.

i. Some pre-aligned holes in the mold with threaded rod may hold the pieced aligned, but that introduces more problems such as:

1. New leaks for the mold.
2. The top and bottom positions are the ideal positions for epoxy entrance and exit of the mold.
3. Once the epoxy is cured, those rods will be very hard to remove since the epoxy will be in the threads.

3. Our solution was to drill out the threaded part of the sample and have two nuts machined with the curvature of the inside of the sample to hold the sample as seen in the photograph below (note: this picture was taken after the sample was broken).



4. The sample was loaded into the Instron and the calibrated extensometer was attached to the clips.
5. The plan was to load the sample with about 100 pounds of force at room temperature to see the extensometer response before cooling to liquid nitrogen.
6. When the sample was being loaded it broke at approximately 60 pounds of force.
  - a. This was only a fraction of the expected 4354 pounds.
7. The sample was removed from the Instron and examined.

One piece:



Other piece:

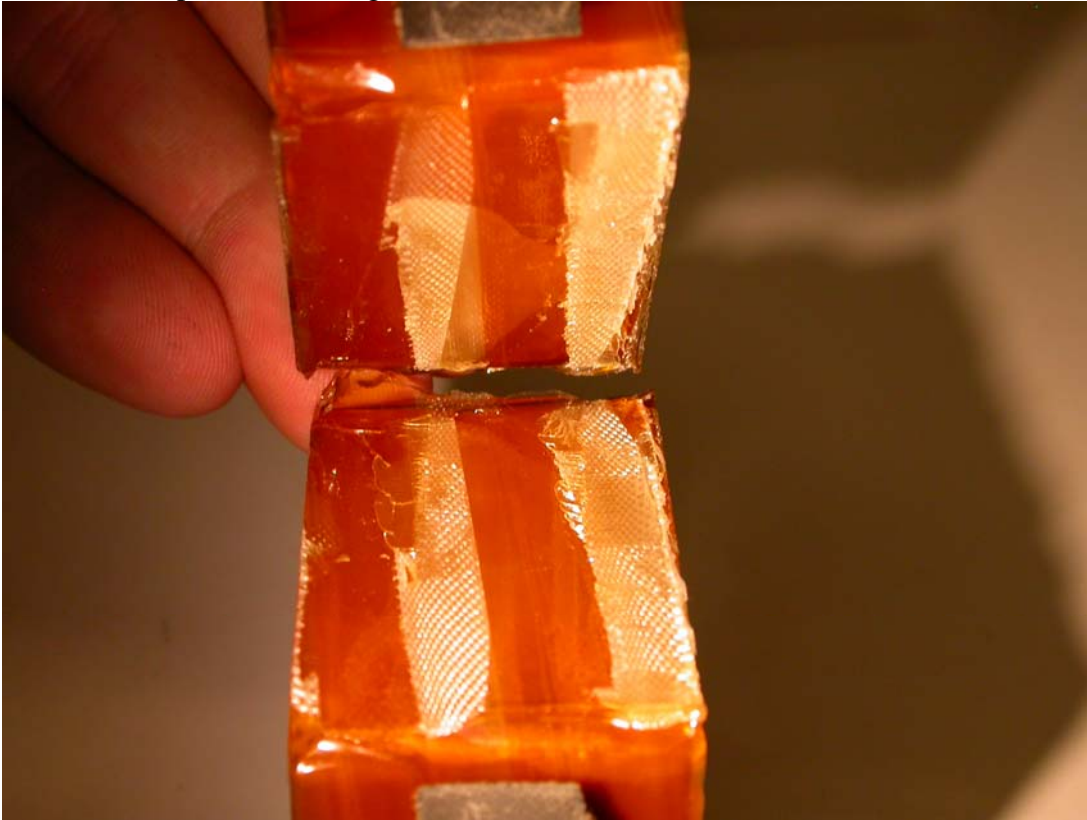


View showing delamination of fiberglass (with reflection on Kapton tape):

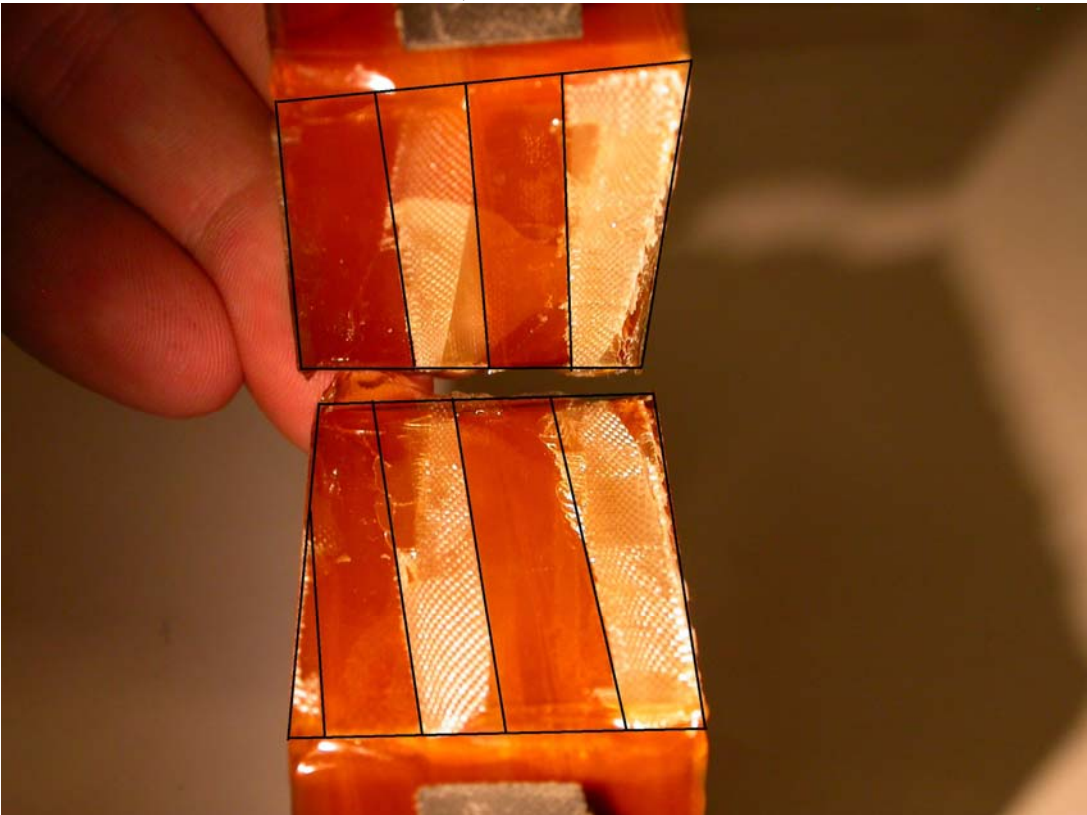




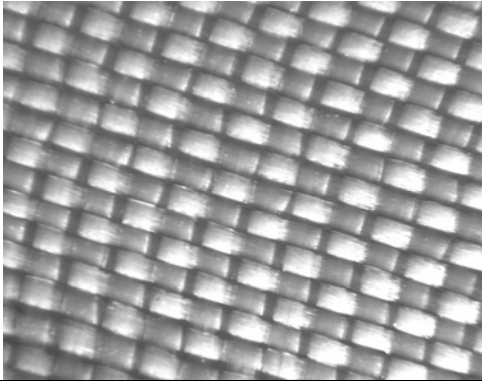
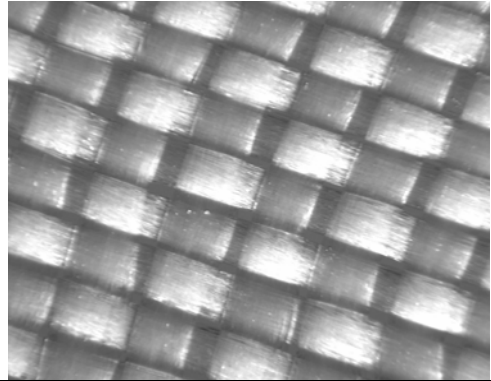
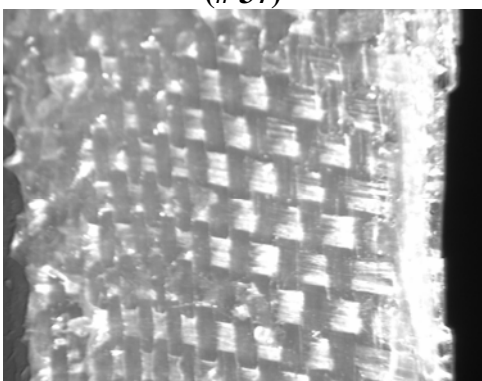
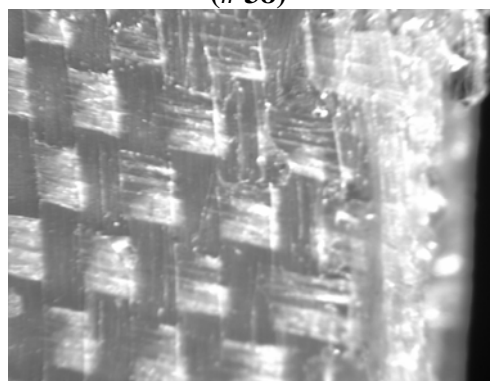
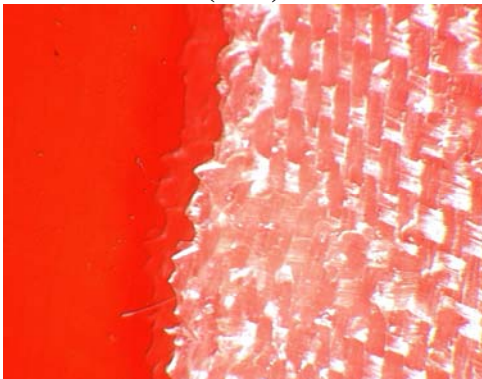
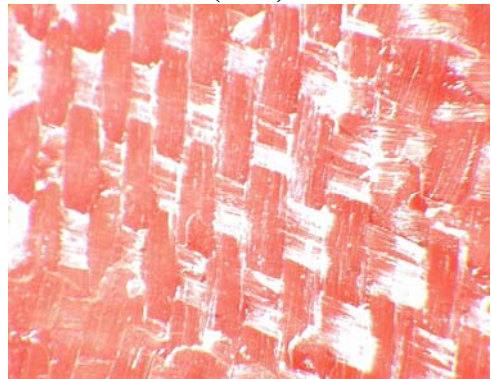
View of how pieces were aligned (cross-hatched):



Drawn in lines...when folded down, the lines cross-hatch each other.

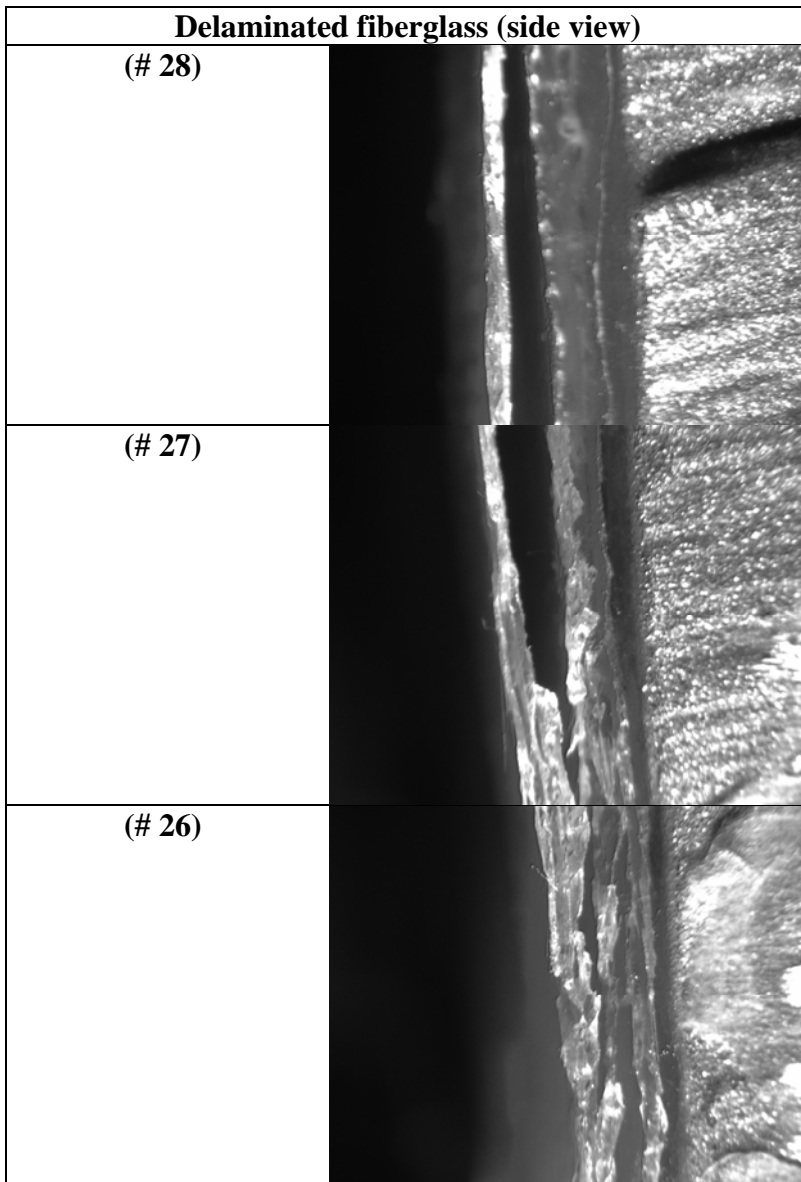


The samples were viewed under a microscope to determine if the epoxy had impregnated the fiberglass, and it was concluded that the epoxy did impregnate the fiberglass (see Appendix B for an index of where each photo number is located on the sample).

<b>Clean Fiberglass</b>	
<b>Magnified (# 41)</b>	<b>Higher Magnification (# 42)</b>
	
<b>Impregnated Fiberglass on Sample</b>	
<b>Magnified (# 37)</b>	<b>Higher Magnification (# 38)</b>
	
	

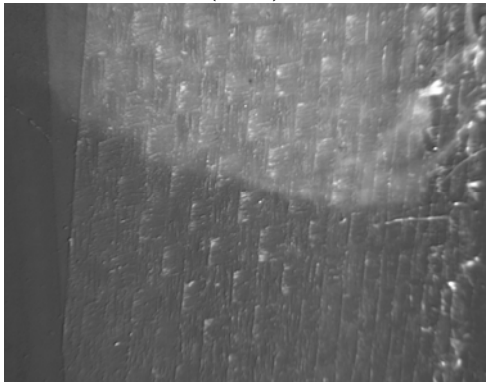
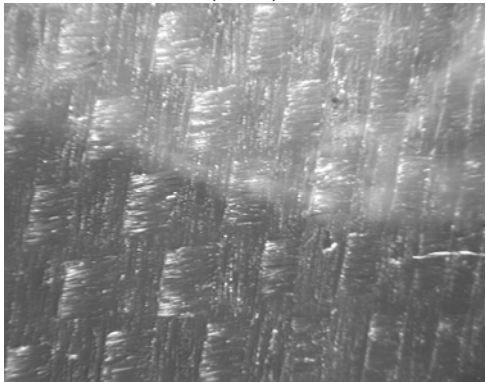
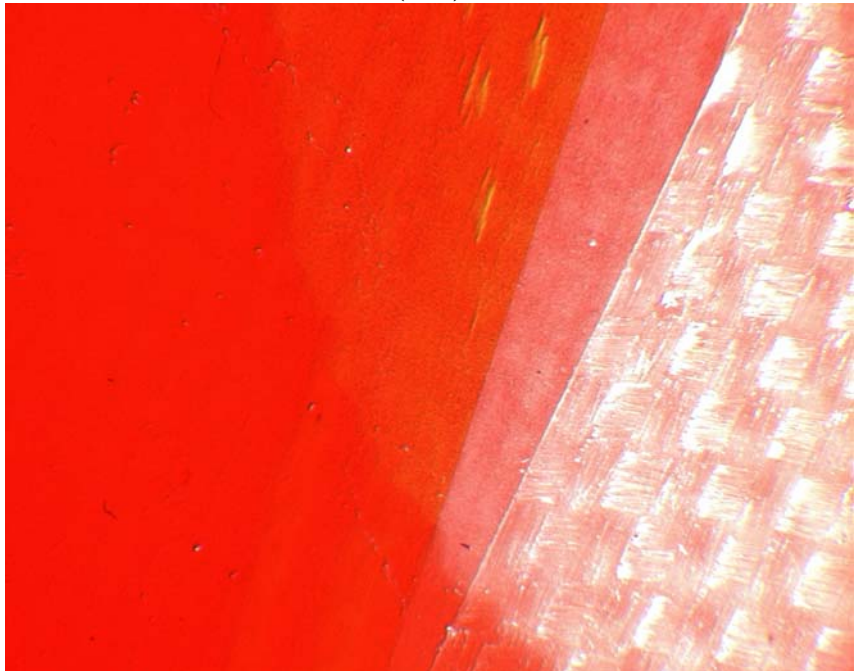


The break occurred between the two initial samples and was relatively clean. However, there was one piece of fiberglass that was originally on the bottom sample that broke and ended up epoxied to the top sample. This piece of fiberglass is seen from the side view in photos # 26 and # 27. The fiberglass delaminated from both samples, but it was still attached near the corners of the sample that it was not originally wrapped around. Other than this piece, the insulation remained wrapped around the sample it was originally wrapped around.



There was a noticeable region of delamination in the middle of one of the samples, and part of this region is shown in photos # 39 and # 40. The delamination was under the shown layer of fiberglass, most likely at the fiberglass-Kapton plane.

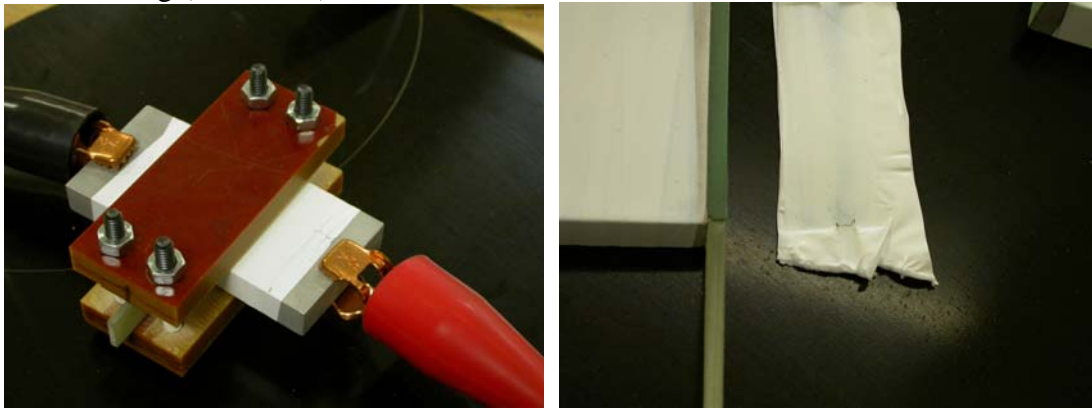
Photo # 43 shows a zoomed in view in color of the top left portion of photo # 39. This region is very interesting, since there are three distinct textures visible. The solid red-orange on the left is Kapton tape. The lighter red-orange strip near the middle is a layer of epoxy on top of the fiberglass. This is flat because the Kapton tape that was there peeled away and is still attached to the other sample (This is a good example of the breaking plane that Kapton provides). The right side of the photo is impregnated fiberglass. The interesting part is that the middle strip is very smooth, which shows that the epoxy and Kapton tape form a very good breaking plane.

<b>Region of central delamination</b>	
<b>Magnified</b>	<b>Higher Magnification</b>
(# 39)	(# 40)
	
<b>Region of delamination showing Kapton surfaces</b>	
(#43)	
	

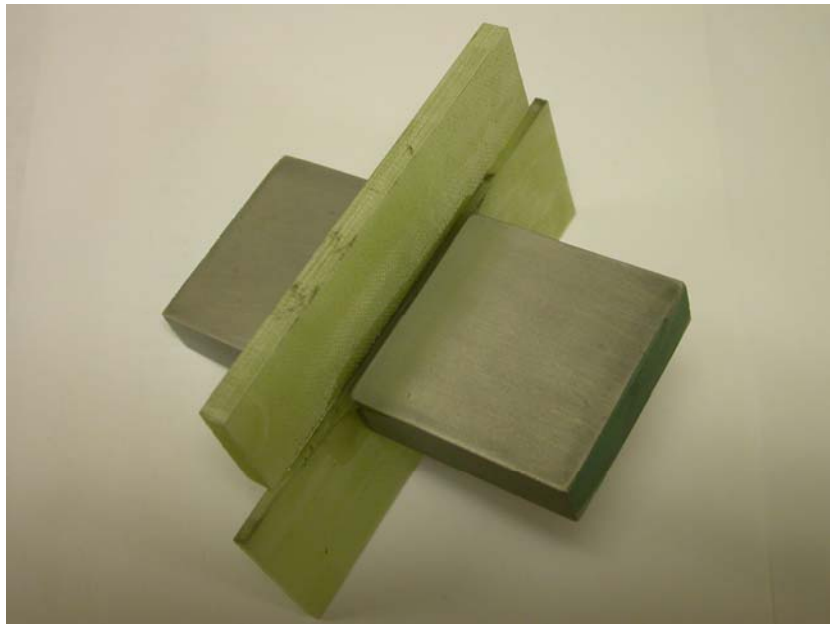
## Electrical Test:

The main problem with a normal Meggar test is that the insulation is only ~0.1 inches thick, and the air breaks down at ~7 kV and arcs over this distance. Since we want to make sure that the insulation still can insulate a 21 kV potential (the maximum voltage under anticipated upset conditions + 1 kV, from N 11 DDD 178 04-06-04 R 0.4), we need to eliminate this arcing path.

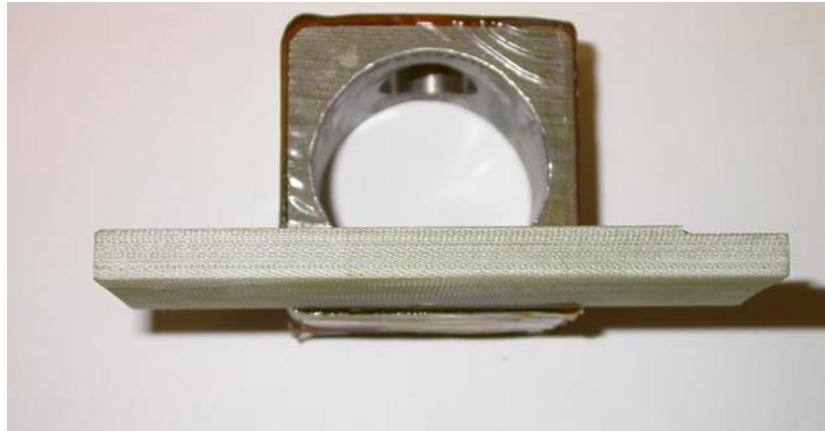
Using a model of the sample, several attempts were made to try to eliminate this arcing path, such as taping the corners of the sample with electrical and/or Kapton tape, clamping down Teflon and/or rubber to try to block the arc path. These methods did help to increase the voltage before an arc occurred, but only up to a maximum of ~10 kV before arcing (see below).



The only method that was able to hold a voltage of 21 kV (it held up to over 25kV without arcing) was to epoxy a piece of G-10 to one of the samples. This way, the path required for an arc from face-to-face of the samples was increased to over an inch (see below).



1. In order to simulate the experiment above, once the piece was cracked; it was removed from the Instron. A G-10 piece was epoxied on the faces of the samples, one on each side. This will simulate the above setup, which will prevent an arc from face-to-face of the sample.



2. Once these G-10 pieces were epoxied on, the sample was Meggar tested
  - a. At around 18 kV, there was a visible arc around the side of the G-10 blocker.
    - i. At the present time, this is an acceptable result. The insulation can hold off a voltage of at least 18 kV after cracking.
  - b. In order to bring the voltage up to 21 kV, some of the epoxy used to epoxy on the G-10 can be applied to the exposed jacket metal on the back-side of the G-10. This will extend the distance needed to arc, and should prove that the insulation is good up past 21 kV.

## Conclusions and Suggestions:

Overall this experiment was a success, in that a desktop system to successfully impregnate insulation was developed. Although the experiment did not run perfectly, I believe that this experiment has provided enough insight to design an experiment that will work much better.

### 1. Mold design

The overall concept of the mold design was a success; however, several improvements could help the experiment run smoother.

- a. In order to have the tapped holes aligned perfectly for the tensile test, there are a few options:
  - i. Don't tap the holes in the jacket. Leave a through hole and use nuts that have been radiused to match the shape inside.
  - ii. Similar to the first suggestion, but instead of a nut, tap a cylindrical plug that fits into the jacket.
  - iii. Tap holes that are perfectly aligned in the top and bottom of the mold and have a rod through the taped holes in the mold and through the tapped holes in the sample during the impregnation. (This is much more difficult than it sounds, since the two tapped holes in the mold can only be tightened so much, and this will set the distance between the two samples in the middle, where the test is).
- b. In order to avoid the need to epoxy G-10 electrical blocks onto the sample after it is broken, make the mold wider and extend the insulation wrapping about a cm on both sides.
  - i. To do this, include two pieces 1cm wide on either side of the actual sample during the wrapping (in order to wrap the samples I had pieces here anyway).
  - ii. Make sure that these pieces are wrapped in Tedlar, so they can be easily removed after the impregnation and curing of the epoxy.
  - iii. Insert the samples (with the extra 1 cm pieces on either side) into the mold and impregnate.
  - iv. Once cured, these pieces can be removed and there will be a 1 cm overhang of insulation to block the leakage current/arcs.
- c. Grit blasting all pieces of the mold before sealing with RTV seemed to allow the RTV to get a better seal for the vacuum and pressure it needs to hold.
- d. Make sure that the mold is designed so that it can be easily opened after the curing.
  - i. My mold had ridges that could be caught by a vice and pried open. Also holes for bolts in the hard-to-grip areas helped.
  - ii. Also be sure to wrap the sample in Tedlar to separate it from the mold. The more Tedlar used the easier the removal will be.

### 2. Impregnation

- a. The epoxy is supposed to be stirred during the heating and degassing stage; however, I used tin cans to hold the epoxy. I wanted to use magnetic stirrers

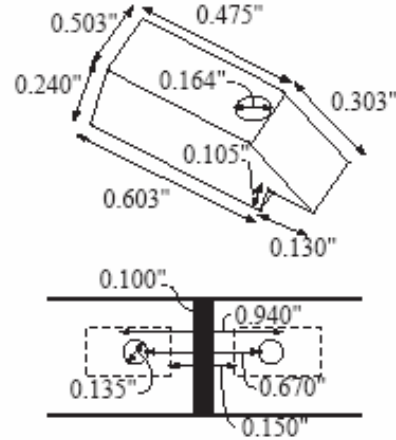
with the hotplate to automatically stir the epoxy, but the magnetic field was blocked by the tin can.

- i. Try to use a container that will not shield the magnetic field so a mechanical stirrer can be used instead of shaking and swirling the epoxy by hand to mix it.
  - b. The tin can holding the epoxy had a rim on it, the thermal conduction between the hot plate and the can was not ideal.
    - i. Try to use a container to heat the epoxy that has a flat bottom so the heat transfer will have a larger area.
  - c. When the epoxy was fed through the mold, it took about a minute for it to begin to come out the top of the mold.
    - i. The slower the better. Ideally the epoxy should rise through the insulation through capillary action, so the epoxy ideally would be fed at a rate to provide a constant supply for the capillary action to fill the fiberglass.
      1. Be careful that it is not too slow, if the epoxy in the feed line between the heated container and the heated mold is not heated. The epoxy needs to stay at ~55 C to have the right viscosity to get into the fiberglass.
3. Tensile test
- a. The hole alignment is critical. If the holes are misaligned even a little, the tensile test can quickly become a tearing test.
  - b. Do all tensile tests displacement controlled
    - i. If tensile tests are run load controlled, there is a chance that the sample will break before you expect it to, and then the testing is pretty much over.
  - c. The more extensometers the better.
    - i. At least 2 extensometers should be used. That way one can tell if the tensile test has changed into a tearing test.
4. Electrical test
- a. If the suggested mold design is used and there is a 1 cm overhang of insulation, there should not be any arcing at the voltages desired for the test.
    - i. If not, epoxy on the G-10 blockers and cover the jacket metal at least 1 cm up past the testing region. (Either cover it with more epoxy or another sheet of G-10).



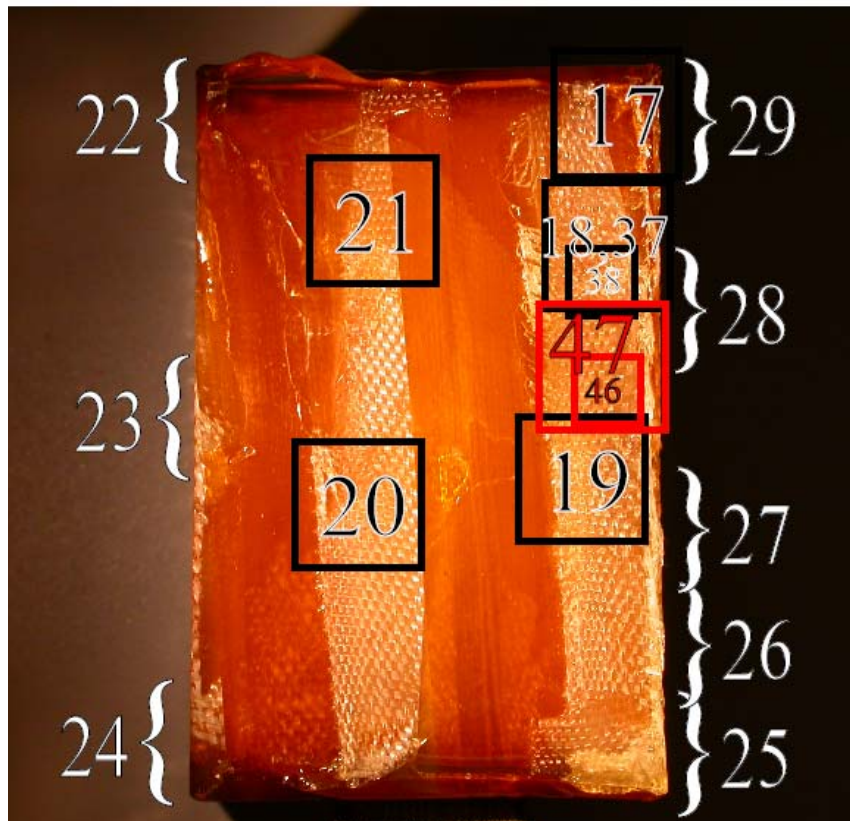
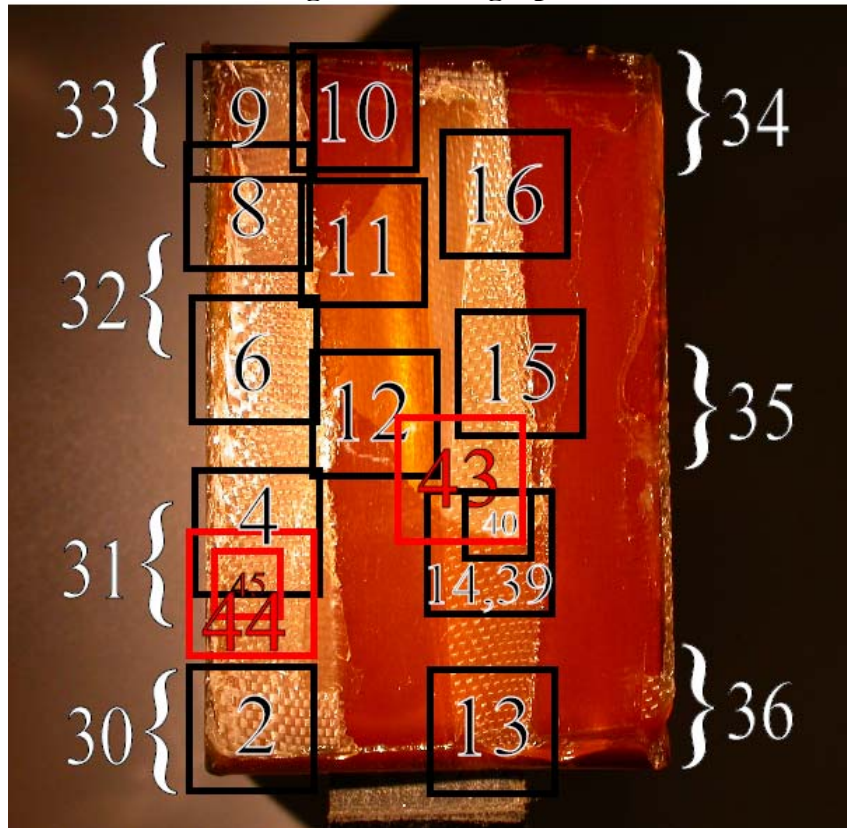
## Appendix A: Proposed Tensile Test Procedure:

1. G-10 mounts were made to hold the extensometer on the sample. The G-10 was mounted onto the jacket, near the insulation layer between the two samples (see figure below).
  - a. We want the loading of the sample to be displacement controlled for higher strains than the loading capacity.
    - i. One of the goals of this experiment is to see if the Instron we are using is capable of being displacement controlled during our tests. If it is not, when the insulation cracks, it may be ripped apart, instead of causing small fractures. In the real coil, when the insulation cracks, the displacement will be limited by the surrounding coils.
2. With the extensometers mounted on the sample, the sample will be screwed into the Instron.
3. The sample will be lowered into liquid nitrogen for the testing (ideally the tests would be conducted in liquid helium, but for this benchmark test liquid nitrogen will be used).
4. Once the sample is in place, the load will slowly be increased up to 11,111 N, which will put a pressure of 30 MPA on the corners of the sample.
  - b. During this time we will be watching the stress displacement curve to make sure that the sample is not de-bonding.
    - i. We will see a decrease in load versus displacement if this is happening.
5. Hopefully the stress-displacement curve will show that the sample is not de-bonding, and we will be able to increase the load up to 19,368 N, which will put a pressure of 55 MPA on the corners of the sample (this is the design spec for the ITER CS Coil).
  - c. Hopefully the stress-displacement curve will show that the sample is still not de-bonding. If this is the case, the displacement at this load will be recorded.
6. If de-bonding has not occurred, the load will slowly be increased until the stress-displacement curve shows de-bonding. (The design strength for the epoxy is ~90 MPA, which would be the pressure in the corners of the sample from a load of 31,693 N).
7. Once the sample has been loaded until it begins to de-bond, the load will be decreased.
8. The sample will then be cycled for an hour (~108,000 cycles) under displacement control. The displacement that will be used depends on when the sample began to de-bond.
  - d. Ideally if the sample makes it up to 55 MPA in the corners, the displacement at this load will be chosen.



- e. If the sample begins to de-bond before this stress is reached, a different displacement will be chosen.
9. After the cycling, the sample will be removed and an electrical test will be performed.

**Appendix B: Location of the Magnified Photographs**



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R.J. Greenhalgh, et al, *Strength of epoxy-resin-based insulation systems in transverse tension and shear using two novel test pieces*, International Journal of Adhesion & Adhesives 23 (2003) 485-494.

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Discussions with Matthew Hooker and Michael Stewart from Composite Technology Development.