MIT Rocket Team LOX Tank

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Abstract

In order for the MIT Rocket Team to achieve its goal of launching a sub-orbital vehicle into space, it needs a low-cost liquid oxygen (LOX) tank. A shrink fit connection between the cylinder and end cap of a LOX tank would be low-cost, in that the tank could be constructed for less than \$500, and it could be machined and constructed on MIT campus. The shrink fit is a process in which the end cap is heated in an oven so that it will expand and fit over the cylinder. When the end cap cools, it shrinks onto the cylinder. This experiment assesses whether a shrink-fitted tank can hold the maximum expected operating pressure (MEOP) of 100 psi. Two shrink-fit connections are pressure tested, one with a Kapton-Teflon adhesive and the other with no adhesive. Results show that the prototype with the adhesive cannot hold the proof pressure of 150 psi, but the plain shrink-fit connection without adhesive can hold above 150 psi.

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1 Introduction

1.1 Background and Significance

The purpose of this project is to provide the Rocket Team with a low-cost liquid oxygen (LOX) tank connection technique for a sub-orbital vehicle. Tanks made for liquid oxygen are very expensive because of the work it takes to make them light and reliable. Much of the cost is a consequence of complicated cylinder-dome connection processes. To buy a fully manufactured LOX tank for the Rocket Team's purposes might cost as much as \$20K. However, the Rocket Team believes that it is possible to make an inexpensive version of a LOX-tank that would cost less than \$500. The cylinder-dome connections tested in this project will help make this low-cost tank possible.

This low-cost LOX tank connection will contribute towards the mission and vision of the MIT Rocket Team. The mission is to launch a sub-orbital rocket into space, testing a new type of rocket engine, and boldly doing what no student rocket team has done before. The rocket team needs a low-cost LOX tank to achieve this mission. The vision of the rocket team includes educational outreach to Boston students through a partnership with the Boston Museum of Science. The rocket using the LOX tank would carry a camera payload. This payload would create a virtual-reality exhibit for the Boston Museum of Science, a voyage for astronauts of all ages and backgrounds. Thus, this LOX tank experiment contributes towards the MIT Rocket Team's mission to launch a sub-orbital rocket and the vision of educational outreach.

1.2 Brief Overview of Previous Work

Based on the AIAA journals, research into the design, fabrication, and pressure testing of propellant tanks has been concentrated on large-scale and/or composite tanks for NASA and major companies such as Boeing. Very little research has been done in designing and testing small, low-cost LOX tanks for amateur and student rocket teams. Also, no research has been done on the design of a shrink-fit cylinder-dome connection. This experiment applies the design

and test processes of the larger-scale, composite tanks to a smaller-scale, low-cost, aluminum tank.

1.3 Conceptual Overview of Experiment

In this experiment, two LOX tank designs that use two different shrink-fit cylinder-dome connections were fabricated. One connection used a Kapton FN adhesive, and the other used no adhesive. The LOX tanks had an outer diameter of 6". After fabrication, the tanks underwent hydrostatic and cryogenic testing to assess whether their burst pressures would be above 100 psi, which was the predicted LOX maximum expected operating pressure (MEOP) for the MIT Rocket Team's suborbital rocket. The tank was designed with a safety factor of 2, and proof-tested with a safety factor of 1.5.

2 Hypothesis, Objective and Success Criteria

2.1 Hypothesis

A cylinder-dome shrink fit connection of a low-cost (<\$500) LOX tank for the MIT Rocket Team can withstand pressures greater than 100 psi.

2.2 Objective

Design two types of shrink-fit connection. Buy two cylinders and machine the end-caps with appropriate dimensions, so that the normal force between the end-caps and the cylinder after the attachment procedure is high enough to create the friction force required to hold the cap in its place when the tank is pressurized. Perform hydrostatic and cryogenic testing of the sealing.

2.3 Success Criteria

Discover which design has the largest burst pressure and assess whether the designs will hold at least 100 psi.

3 Literature Review

3.1 Thermal-Mechanical Cyclic Test of a Composite Cryogenic Tank for Reusable Launch Vehicles ¹

Messinger and Pulley did experimental cyclic testing and a burst test on a reusable composite hydrogen tank that was 8-feet in diameter. The tank was designed for the Boeing risk reduction program working towards a Single-Stage to Orbit (SSTO) Reusable Launch Vehicle (RLV). After the cyclic testing, this group did a burst test. This burst test was similar to the burst test that was conducted in this MIT LOX tank experiment. They presented their burst pressure results in a Strain vs. Pressure graph. Also, the report states that the next step in testing composite structures would be "the fabrication and cyclic test of an even larger tank." ¹ to demonstrate a more integrated and complex system. This experiment went in the opposite direction of this suggestion. Instead of working with larger and complex tanks for companies, this project concentrated on smaller-scale and simpler tanks designs for student rocket teams.

3.2 Design and Manufacture of a Lightweight Fuel Tank Assembly²

Griffin, Ballinger, Jaekle, and Jackson pressure cycle tested, vibration tested, and burst pressure tested a hydrazine tank design for a Pressure Systems Inc. geosynchronous satellite contract. The tank was made of a titanium inner liner and a carbon fiber jacket, with an inner diameter of 35.25" and a MEOP of 300 psia. The results of the experiment were that the tank passed its qualification testing, including holding pressures greater than the required burst pressure. This

MIT experiment sought similar results to a burst pressure test, except with a different tank design with a smaller diameter.

3.3 Design and Manufacture of a Composite Overwrapped Pressurant Tank Assembly³

Tam, Griffin, and Jackson did pressure testing of a titanium-lined, composite overwrapped helium pressure vessel for Pressure Systems, Inc (PSI). This tank was designed for a minimum burst pressure of 7,200 psi with a 16.7" outer diameter. They defined their tank efficiency to be burst_pressure*volume/weight. With an efficiency of 1.57×10^6 , this tank achieved the highest efficiency of any tank ever made by PSI. This MIT LOX tank design did not have as high an efficiency as this PSI tank because the tank was made with lower-cost processes than those of PSI.

3.4 Ultralight Propellant Tank for NASA Space Technology⁴

Harris, Grande, and Higgins designed and tested a propellant tank of aluminum liner and polybenzoxazole fiber. It was designed to hold an MEOP of 2240 psig and a diameter of 6 in. This group did burst pressure tests and part of the development testing to prove that the design would work. The tank performed with a burst pressure of 6165 psig and an efficiency PV/W of 1.0×10^6 . This MIT tank had the same diameter, but had a different cylinder-dome connection and a different MEOP.

3.5 Conclusions About Literature Review

The above experiments discovered knowledge about the cyclic loading and burst pressures of large and/or expensive composite tanks. Also, none of these experiments tested a shrink-fit cylinder-dome connection. This MIT experiment tested how to make a 6 inch diameter, shrink-fit connected, low-cost aluminum LOX tank for the MIT Rocket Team. Even though this project's tank was not the cutting edge technology of composite structure, it was valuable

because the MIT Rocket Team had a limited budget and had never flown a LOX fed rocket before. Thus, it was very important that this team gained knowledge about how it could fabricate its own low-cost and lightweight LOX tank.

4 Description of Experiment

4.1 Conceptual Overview of Experiment

As stated in the HOS of this experiment, the objective was to design fabricate and test two cylinder-dome connections for a LOX-tank. The design was developed during the fall of 2004, while the fabrication and testing was done during the spring of 2005. The end-caps were machined with a band-saw, lathe and drill in the Gelb machine shop. They were then attached in the Glass Lab facilities by cooling down the cylinders in liquid nitrogen to make the OD decrease, heating up the end-caps to make them expand and then tapping them onto the cylinders. The two tanks were then tested in the Telac Lab, first hydrostatically to test if they could hold the proof pressure of 150 psi and then with cooled gas to burst pressure.

4.2 Design of Prototypes

The wall thickness was over designed to make sure the the tanks would fail at the end-cap connection. Two cylinders with outer diameters of 6 in.. lengths of 1 ft., and thickness of 0.125 in. were purchased. The dimensions of the end caps were designed using the following criteria:

- 1. Stress in the walls less than yield strength when pressurized at 200 psi.
- Friction force is large enough to hold pressure force when pressurized at 200 psi (See Figure 4.2-1)



Figure 4.2-1: Forces acting on cylinder and end-cap

To establish tank dimensions that satisfied these criteria, an Excel program was used to measure stresses and forces on the tank. This program is shown in Appendix A, and the engineering drawings of the end caps are given in Appendix B. An isometric view is shown in Figure 4.2-2.



Figure 4.2-2 Isometric view of the end-cap design

4.3 Fabrication of Caps

In order to meet the requirements on friction force between the 4 end-caps and the 2 cylinders, the end-caps inner diameter (ID) had to be machined to a precision of ± 0.002 inch. A 1 foot solid aluminium cylinder with 6-inch outer diameter was cut into discs with a band-saw. Then, the disks were machined in a lathe to the desired shape of the end-caps. Two holes were drilled and threaded in two of the end-caps so that the pressurizing system could be attached during the

testing of the tanks. A precision of 0.001 inch was achieved for the ID of the end-caps in the lathe. For a detailed description of the fabrication process, see Appendix C. A picture of the machined end caps is given in Figure 4.3-1.



Figure 4.3-1 The figure shows the four end-caps and a prepared spare disc after final step in lathe

4.4 Attachment of End Caps to Cylinder

To make the shrink fit connection, the end cap was heated in a Glass Lab annealer to a high enough temperature that it could fit over the cylinder. When the cap returned to normal temperature, it shrank onto the cylinder. Figure 4.4-1 illustrates this process.



Figure 4.4-1: Shrink fit process

The attachment procedure was designed to take advantage of the thermal expansion properties of materials. By heating up a metal such as aluminum 100 °C it will expand approximately 0.2%. In our case with an end-cap ID of about 6 inch (15 cm) that result in an expansion of 0.3 mm. The cylinder OD was larger than the end-cap ID at room temperature, so to be able to fit the end-caps onto the cylinder, it was desired to get a large gap as possible between them. The melting temperature of the aluminum and the Kapton film put constraints on how much we could expand the end-cap. The temperature of the liquid nitrogen (LN) limited the shrinking of the cylinder.

Special gloves with Kevlar mittens were used when handling the extreme temperatures. Safety glasses were worn and several dry runs of the attachment procedure were performed to reduce the risk of personal injuries and to discover difficulties at a non-critical stage. Staff with experience in dealing with hot metals were consulted to make sure that use of equipment in the Glass Lab was done in an orderly manner.

The Design without Kapton Film

The tank without Kapton was put together first. We heated up the end-caps in an annealing oven to 650 °F, and the cylinder was cooled in a steel bucket down to -270 °F with liquid nitrogen (LN). They were then simultaneously taken out of the oven and the bucket. This part of the attachment required at least two persons. The end-cap was put on a heated iron plate by one person with the opening pointing upwards and one end of the cylinder was aligned to the opening by the other person. A sledgehammer was then used to tap the cylinder down into the end-cap. To protect the edges of the cylinder from the sledgehammer, a wooden plate was held in between. A large force was required to attach the two to each other.



Figure 4.4-2 The end-caps were heated in an anneal oven (left). Materials used (right)

Design with Kapton Film

The Kapton film was wrapped around the cylinder edge and held in its place by a metal coil. The end-caps where heated in the annealing oven and the cylinder was, differently from the non Kapton design, cooled in a Styrofoam chest with LN. Because of this, the LN did not boil off quickly, and the cylinder was cooled to a lower temperature than the non Kapton case. Two different approaches were used to try to prevent the Kapton from sliding down along the cylinder during attachment. With the first end-cap, only half of the film was in contact with the cylinder and the other half was above the end. During the attachment of the second end-cap, the Kapton was aligned to the edge of the cylinder. Only a slight touch with the sledgehammer was required to make the end-caps slide over the cylinder ends.

The whole tank was heated in the oven at a temperature of 670°F for about 6 minutes. This was done to melt the Teflon layer on the film so that an adhesive bond would be created in the overlapping surface.



Figure 4.4-3 The tank without Kapton (left) and the one with Kapton film between the cylinder and the end-caps (right).

4.5 Hydrostatic and Cryogenic Testing

Test Setup and Pipe Scheme

The two tanks were tested in the Telac Lab blast chamber. One of the holes in the tank was connected to pressurized gaseous nitrogen and a manual relief valve. The other hole was connected to a pressure transducer. (See Figure 4.5-1) The pressure transducer was calibrated to a specific voltage by the staff in the Telac Lab. Labview recorded the transducer output with a frequency of 2/second. Table 4.5-2 gives the test matrix for this experiment.



Figure 4.5-1 Test setup in Telac Lab

$1 a D C = 3^2 \Delta 1 C C C C A C C C C C C C C C C C C C C$	Table	4.5-2	Test	Matrix
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	Hydrostatic Test	Cryogenic Test	
Prototype #1:	Pressurize to proof	Pressurize until	
Aluminum Film	pressure of 150 psi	failure	
Prototype #2:	Pressurize until	Did not make it to	
Kapton Film	failure	this test	

Hydrostatic Proof Pressure Testing

The two tanks were filled with water almost full. This was done to reduce the amount of compressible gas in the tank. Each tank was pressurized with gaseous nitrogen slowly until it reached 150 psi or it burst. The tanks were leaking while being pressurized, so a high flow of gas was required to increase the pressure.

Cryogenic Burst Pressure Testing

Only the tank without Kapton made it to this test. In this test, the tank was connected to a cryogenic tank with LN. The pressure in the cryogenic tank was about 50 psi. Part of the

purpose of this test was to fill the tank with a liquid at cryogenic temperature and see how the tank would react under close to real conditions. However, there was never a flow of LN from the cryogenic tank. Only gas at a low temperature was flowing into the tank, cooling it slightly. The test was performed even though this unexpected problem occurred, but with a different approach than planned. After the tank was cooled, it was pressurized with gaseous nitrogen until it burst.

5 Results

5.1 Tank With Kapton

The Kapton tank was hydrostatically tested once. Figure 5.1-1 shows the test results. The tank failed at 117 psi, and then the pressure inside the tank dropped sharply. Also during the test, water droplets showed that the tank was leaking from the cylinder-dome connection.



Kapton Hydrostatic Test

Time (seconds)

Figure 5.1-1 Pressure Measurements from Kapton Hydrostatic Test

As shown in Figure 5.1-2, inspection of the tank after the test showed that the bottom end cap of the tank popped off the cylinder. The Kapton did not stay attached to either the cylinder or the cap, which means that it probably did not bond to them.



Figure 5.1-2 Post-Test Inspection

5.2 Tank Without Kapton

The tank that did not have any Kapton passed two hydrostatic tests, and burst at 176 psi during a cryogenic test. During the first hydrostatic test, the top end cap of the tank popped up about 3/16 in. at 120 psi. Figure 5.2-1 shows this. A possible reason why this occured is that the cap was misaligned.



Figure 5.2-1 Cap Popped Up From Original Position

We continued to pressurize the tank to 150 psi, and then shut off the pressure source. This tank also leaked through the cylinder-cap connection. The gradual pressure drop in Figure 5.2-2 is caused by this leaking.



No Kapton Hydrostatic Test 1

Figure 5.2-2 Pressure Measurements from No Kapton Hydrostatic Test 1

To ensure that the tank would hold 150 psi without the cap moving farther, the tank was hydrostatically tested a second time. This time, we continued to pressurize the tank to keep the pressure around 150 psi for 139 seconds. This can be seen in Figure 5.2-3.



No Kapton Hydrostatic Test 2



Then a cryongenic test was performed on the tank without Kapton. During this test, the tank failed at 176 psi, as shown by the rapid pressure drop in Figure 5.2-4. The top cap exploded off the cylinder, and landed a few feet away (see Figure 5.2-5).





Time (seconds)

Figure 5.2-4 Pressure Measurements from No Kapton Cryogenic Test



Figure 5.2-5 Detatched Top Cap

5.3 Summary of Results

Table 5.3-1 gives a concise summary of the results of this experiment. An analysis of these results will be discussed in section 7.

Table 5-1 Summary of Results					
Tank	Burst Pressure	Comments			
	(±1%)				
Kapton	117 psi	- Failed before expected			
		- Leaked			
No Kapton	176 psi	- Passed the Proof Pressure Test!			
		- Held 150 psi three times, once			
		when cooled with LN2			
		- Cap popped up 3/16 in. at 120 psi			
		- Leaked			

 Table 5-1
 Summary of Results

6 Discussion of Errors

The experiment had a \pm 1% random error in the pressure measurements due to the pressure transducer. This error was very small and had no effect on the successful assessment of the hypothesis

Labview introduced a systematic error, in that the pressures that it recorded were always 3.9 psi above the measurements of the transducer. To account for this error, we have subtracted 3.9 psi from all of the pressure results.

7 Fishbone Analysis

There are a number of factors that could have caused the Kapton tank to fail below the proof pressure or caused the leaking in both tanks. To get at better overview of these factors a fishbone analysis was made. In a fishbone analysis, the most likely causes of an event are specified at one level and the factors that could have lead to those causes are specified at lower levels.

7.1 Force

The possible reasons why the Kapton tank failed below the proof pressure and the non Kapton tank failed below the design pressure of 200 psi are presented in this analysis.



Figure 7.1-1 Fishbone analysis of possible reasons why the Kapton cap did not hold the proof pressure

Friction Coefficient and Failure in Kapton Bond

During the design phase of this project, the friction coefficient was estimated to 0.4. The burst pressure is linearly depending on the friction coefficient and an error of 12 % in the estimation of this could alone have been the factor that caused the non Kapton tank to burst at 176 psi instead of 200 psi. Little knowledge about the roughness of the surface in the overlap between the end-caps and the cylinder makes this factor a likely source of error.

For the Kapton design, it is possible that the Teflon layer on the surface of the film never melted or it evaporated and did not bond. If the Teflon didn't melt, the friction coefficient should have been around 0.04 between Teflon and aluminum. ⁵ According to the excel program (See Appendix A), the burst pressure would have been 20 psi in this case. Variation in the overlap force could have made this burst pressure vary, but not as much as 600 % (which would have been required to hold 117 psi). Thus, the possibility that the Teflon made the surface slippery is therefore not a likely cause of the low burst pressure.

If the case were that the Teflon evaporated, there would have been two changes in the seal. The film would have been 0.001 inches thinner, thus making the force in the overlap lower. According to the excel model, the burst pressure would then be about 180 psi. Also, the surface between the aluminum and the leftover Kapton film would have had a different friction coefficient, causing the tank to fail below 180 psi. Thus, a possible reason why the Kapton tank failed at a lower pressure than expected was that the Teflon evaporated and the Kapton had a lower coefficient of friction than 0.04.

Variation in Cylinder OD

The cylinders used in this experiment had an average diameter 6 in., but the outer diameter variations were large (\pm 0.035 in.). This could have affected the contact surface between the endcaps and the cylinder and could have invalidated the assumption that the two surfaces where in contact with uniform pressure distribution. If the surfaces were not deformed because of this, the friction force would not have changed, but since aluminum is a soft metal, the probability is high that there was a deformation of the overlapping surface. Evidence of this was found while examining the surface of the cylinder after the tank was tested. The contact surface on the cylinder had stripes of metal scratched of in axial direction. This could have been formed during the attachment of the caps or as a result of the growing force in the overlap when the end-cap and the cylinder temperature reached equilibrium. These variations could have thus lowered the burst pressure and made it impossible for the Teflon to bond to the metal.

7.2 Leakage

During the pressurization of the tanks, they both leaked. The different ways the leaks could have occurred are discussed in this section.



Figure 7.2-1 Fishbone analysis of possible reasons for leakage

As discussed in section 6.1, the cylinder had high variations in the OD. This was very likely the reason why the tanks leaked. Areas with no contact between the end-caps and the cylinder could have vented out the high pressure in the tanks.

Also, There could have been misalignment between the end-caps and the cylinders. A small misalignment could have created channels for the nitrogen to flow through. Another way these channels could have occurred was during the quite violent attachment of the non Kapton tank with the sledge hammer, or because of wrinkles in the Kapton film and the open seam of the film for the Kapton tank. An over expanded end-cap is not a likely cause, since a high pressure inside

the tank should have tightened the sealing rather than opening it, and the end-caps had a very rigid (0.5 inch) top surface.

8 Summary and Conclusions

The hypothesis of this project states that a cylinder dome connection of low cost could withstand pressures greater than 100 psi. The results obtained during this experiment allowed for successful assessment of the hypothesis. The tank prototype without Kapton performed better than the design with Kapton. Also, because the tank without Kapton passed the proof pressure test, it can be concluded that it can reliably hold 100 psi. Fabrication of this design will be low cost (<\$500) for the MIT Rocket Team. For those who need to consider costs for facilities, lathe, band-saw, annealing oven, machine shop and lab staff, and working hours, it will not necessarily cost less than \$500.

Suggestions for Future Research

The next step in testing shrink-fit tanks will be to make a flight-weight prototype with thinner walls. Here are some possible improvements to the design in this experiment. A seal weld along the lower edge of the caps would stop the leakage. Also, a cylinder with less variations in outer diameter could be found. Or, the cylinder diameter could be decreased so that it can be fitted on a lathe and machined to have a more accurate outer diameter. These dimensions with less variation would decrease leakage and make the predicted burst pressure more accurate. To improve the attachment process, a press could be used to make the alignment of the cap and cylinder easier. Making sure that the cylinder reaches the desired low temperature would ensure that the cylinder and cap go together more smoothly, as well. In order for the Kapton-Teflon to be used as an adhesive in LOX tanks, more research will have to be done on how to make it bond.

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10 Acknowledgements

This project has been very interdisciplinary, including fluid mechanics, structures, thermal properties of materials, chemistry (finding compatible materials for LOX) and understanding of constraints in space mission planning. This has enabled us to interact with other departments than the Aeronautics and Astronautics department. This has been a quite useful experience and we have many people to thank for the success of this project.

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Appendix A: Excel Analysis Program

Table A-1 shows the output of our analysis program for one of the caps that does not bond Kapton. The calculated forces correspond to those in Figure 4.2-1, and the dimensions correspond to those in Figure A-2.

Category	Property	Value	Equation Used
	E: Young's Modulus (MPa)	69000	
Material Properties of	a: Coeff. Thermal Expans	2.36E-05	
Aluminum 6061	Yield Strength (MPa)	320	
	Coefficient of Friction	0.4	
	MEOP (psi)	100	
Pressure Inside Tank	Safety Factor	2	
	Test Pressure (psi)	200	MEOP * Safety Factor
	Test Pressure (MPa)	1.37896	
	h (in.)	1	
	ORcap (in)	3.1165	
	ORcyl (in)	3	
	IRcap (in)	2.9915	
Dimensions of Tank	IRcyl (in)	2.875	
5.1-1)	tcyl (in)	0.125	
	tcap (in)	0.125	
	tkapton (in)	0	
	Cap Height (in)	2	
	Cylinder Length (in.)	12	
Change in Cap Radius and	Min. Delta R (in)	0.0085	tkapton + ORcyl - IRcap
Change in Temperature	Min. Delta T (Celsius)	120.3976	Delta R / (a * IRcap)
needed for shrink fit	Min. Delta T (Fahrenheit)	248.7157	
	Strain Distributed Between		
Strains and Stresses seen	Cap and Cylinder	0.001421	1/2 * Delta R / IRcap
by Cap and Cylinder	Shrink Stress (MPa)	98.02775	E*Strain
	Pressure Stress (MPa)	15.85804	1/2* Test Pressure * IRcyl / tcap
	Total Stress (MPa)	113.8858	Shrink Stress + Pressure Stress
Forces on Tank	Normal Force (N)	57706.73	Total Stress * 2 * pi * tcap * h
(Corresponding to Figure	Friction Force (N)	23082.69	Coefficient of Friction * Normal
4.1 - 2)	Pressure Force (N)	23090.03	Test Pressure * pi * IRcyl^2

 Table A-1
 Tank Dimensions, Properties, and Stresses

Note that these final dimensions satisfy the design criteria, with the total stress less than the yield strength, and the friction force greater than the pressure force.



Figure A-2 Dimension Symbols for Tank



Appendix B: End Cap Engineering Drawings







Appendix C: Fabrication of End Caps

Cutting the Solid Cylinder

The solid cylinder (SC) had to be cut in to 5 discs (4 original plus 1 spare) with the band-saw in the machine shop. A final thickness of 1.5 inch was desired for the end-caps, so the discs where cut to a thickness of 1.75 inch to cover for the band thickness of 1/16 inch. The band was lubricated by applying wax from a wax stick onto the band. It had to be applied before the band passed through the SC, since it could cause the band to slip if applied after the cutting. This was done every minute of the sawing with an increase in frequency when passing the thick regions of the SC. When cutting a thick SC the saw could start tugging. This happened a few times and could be resolved by relieving some of the pressure from the weight of the saw. The edges of the discs where pretty sharp and were therefore blunted with a file and some sandpaper to reduce the risk of personal injuries during the rest of the fabrication. Each disc required 28 minutes of sawing (6.5 inch SC) and 2 minutes of blunting.



Figure C-1 Five 1.75 inch thick discs were cut from a 1 foot long solid cylinder wit ha band-saw (left). The discs had sharp edges and where blunted with a file and sandpaper (right).

Machining the End-Caps in the Lathe

A lathe was used to machine the discs to the shape of the end-caps. This was done in three major steps:

- 1. Machine the outside to desired OD and the thickness to 1.5 inch.
- 2. Drill a 1 inch hole in the centre of the discs.
- 3. Take out the inside of the end-caps

A lot of aluminum had to be taken off the discs, so it had to be done layer by layer. The tool was oiled between cutting each layer, to prevent overheating and to make machining smooth. The maximum thickness of each layer depends on the material, rotating speed, the tool and type of cutting (radial or axial) and was therefore discussed with the machine-shop staff before each step in the lathe. Safetyglasses and some kind of protection against smoke coming from the heated oil and aluminum should be worn during the machining steps in the lathe.

Machining The Outside

The discs were place in the lathe and the coordinates were set in the computer. Thin layers where cut of the discs until a thickness of 1.5 inch was obtained. Large and long pieces of spiral-shaped aluminum was spinning around during this step, so extra caution was taken and surfaces near the spinning discs where cleaned.



Figure C-2 The outside of a disc was machined down to the outer shape of an end-cap during the first step in the lathe.

About half of the OD could be removed before flipping the discs in the mount. The depth of the mount was larger than the axial length of the adjusted OD. This caused some concern about alignment of the discs axis with the lathes axis of rotation. To solve this problem, three steel pieces of accurate similar dimensions were used in between the bottom of the mount and the flat surface of the discs. This step took about 45 min to 1 hour per disc.



Figure C-3 A disc with half of the OD removed. Pieces of metal were put in (centre of red ellips) between the discs and the bottom of the lathe mount to align disc-axis with lathe axis of rotation.

Drilling a Hole in the Centre

Before taking out the inside, a hole was drilled in the centre of the discs. This was also done in the lathe, using a different tool than when layers were cut off. The deepest part of the hole drilled in this step had the shape of a cone, and had to be adjusted to a cylinder shape.



Figure C-4 A one inch deep hole was drilled in each of the end-caps using the lathe. A red line painted on the drill marked where to stop.

Taking Out The Inside

The inside was taken out by starting with the tool in the centre of the discs. Thin layers where taken of in radial direction with a depth of 0.85 inch. This was done until the ID was 0.1 inch away from the design ID. To reach the full depth of 1 inch, the last 0.15 inch were taken off in axial direction. To get the desired precision of the ID, thinner and thinner layers were taken off in radial direction until 0.002 inch away from desired ID. The final adjustment was done by slowly moving the tool back and forward, stopping the lathe to measure the ID with a caliper, and continuing to move the tool until a

precision of ± 0.001 inch was obtained. This step and the drilling of a hole took approximately 1 hour per end-cap plus 2 hours of lathe set-up.

After this step, two holes were drilled in two of the end-caps. The holes were then tapered with threads to match ¹/₄ inch pipe-fittings. This step took about 1 hour for two end-caps. The result of the fabrication process were four end-caps and one spare disc prepared in a way that it could easily be machined to desired shape within 2 hours. In total, each end-cap took 3.5 hours effective time to fabricate.

Appendix D: Design Selection Matrix

Type of Connection between Cylinder and End Cap	Weight	Cryo Temperatures and LOX	Expense	Reliability	Ease of Manufacturing
Welding	Medium to light; Only will require extra material if we have to increase tank thickness to handle welding	Good; Traditional connection for LOX tanks	Somewhat high; must hire company that is certified to weld pressure vessels	Will have low leakage; if welded well, will be very reliable; If tank is not thick enough to support weld, will not be reliable	Must find a welding company that will weld the end caps to the cylinder and weld fittings onto end caps
Heat Shrink	Very light	Not sure, would have to test it to make sure that the dome would not shrink slower than the cylinder at cryo temp	Very low cost	Amount of leakage depends on precision of machining	Would make the connections ourselves
Flanged	Medium to high weight, has to include bolts	Good; Traditional connection for LOX tanks	Somewhat high; must hire company to weld flanges	Will have minor leaking; Best for preventing catastrophic failure	Must find company that will weld flange onto tank
Rolled Joint (Double Seaming)	Very light weight	Sealant used with connection would react dangerously with LOX; Could possibly do connection without sealant	high, unless company offers to give discount	Little to no leakage	Must find company that will do double seaming