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Team 512: In Space Cryogenic Propellant Storage

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Abstract

NASA strives to improve space travel technology to extend the amount of time crews can remain in space on various missions. Team 512 designed a storage tank that holds the amount of fuel required for spacecraft to return to Earth from any mission destination. It maintains the temperature and pressure of fuel by reducing heat transfer into it. This reduces fuel loss and increases storage time, resulting in longer missions. The design of a prototype is necessary for testing and validation, as well as a full-scale tank that will be recommended to NASA.

The rocket fuel we are designing for is cryogenic, meaning it is in a usable, liquid state from -238°F to -460°F. Out tank protects propellant from heat transfer to sustain temperatures lower than the fluid's boiling point. This heat transfer is from conduction through connections, convection through liquids and gases, and radiation from surroundings. If the temperature exceeds the boiling point, a fluid goes through a phase change from liquid to gas. This gas causes a rise in pressure inside the tank. It is necessary to release gas to prevent the internal pressure of the tank from exceeding its limit, causing rupture. This release reduces the amount of usable fuel in the tank.

The team designed the tank by selecting ideal geometry, scale, wall thickness, supports, and insulation type. Prototype testing determines the mass flow rate of gas leaving our tank, which should be less than the rate from existing tanks. The results are compared to heat transfer calculations to predict the performance of the recommended large-scale tank. A successful tank prototype reduces the mass flow rate and does not fail during testing. Data obtained from testing should validate all design choices for both the prototype and full-scale design.

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Nomenclature

CAD – Computer Aided Design

MLI – Multilayer Insulation

MSFC – Marshall Space Flight Center

NASA – National Aeronautics and Space Administration

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Chapter One: EML 4551C

1.1 Project Scope

1.1.1 Project Description

This project aims to design and prototype a storage container to hold cryogenic propellants in space. The design must reduce heat transfer to preserve the propellant in a cryogenic state for an extended period of time.

1.1.2 Key Goals

The main goal of this project is to create a propellant storage solution that NASA can utilize on upcoming long-term missions. To achieve this goal, the container must maintain the fuel at a specified temperature and pressure for at least two weeks. Additionally, a solution should be proposed for the storage container to reduce the amount of heat transfer and fuel loss. A successful project will be defined by the ability of the team to create a prototype and perform testing on the container to validate design choices.

1.1.3 Primary Market

The primary market for this product is NASA, specifically the MSFC and their commercial partners.

1.1.4 Secondary Market

The secondary market for this product includes other companies interested in space travel, such as SpaceX and Virgin Galactic, as well as aerospace companies that use cryogenic fuel for space flights. Once our design is in use, it is expected that other space agencies will incorporate aspects of the design into their own projects. Another secondary market is cryogenic research facilities with an interest in extending storage time, as well as cryogenic manufacturers.

1.1.5 Assumptions

A hypothetical lunar mission with a duration of two weeks is assumed. The tank is assumed to store the fluid with no disturbance, i.e., filling or draining for fuel use. We will also assume that the fuel stored in the container is liquid hydrogen, although liquid nitrogen will be used in testing due to safety requirements and current available resources. A comparison will be performed between the two cryogens. In addition to this, the tank we construct will be on a much smaller scale than one used in practice. This will not be directly scalable, since heat transfer is directly related to the surface area and volume of the tank, but we are assuming that the necessary calculations can be performed to determine the heat transfer for a tank of any size based on our design. It is assumed that the final design will be operated by individuals who are familiar with cryogenic propellant storage and trained to handle the container. Finally, we are assuming that the tank will be utilized on Earth, during liftoff, in a space environment, as well as reentry into Earth's atmosphere, therefore the tank should be able to withstand conditions in each stage.

1.1.6 Stakeholders

For this project, the stakeholders are NASA (specifically Marshall Space Flight Center), astronauts, spacecraft mechanics, cryogenic scientists, and other space companies. NASA-MSFC is the sponsor of this project and will receive the benefit of using the design on their spacecraft in the future, making them the primary stakeholder of the project.

With this project being implemented into spacecrafts in the future, more long-term space travel will be possible. This means that more astronauts will have the opportunity to man missions, making them main stakeholders in this project as well.

Spacecraft mechanics are another main stakeholder group, since they will be actively working on the ships. Creating an updated storage solution for cryogenic fuels will require the mechanics to be trained to manufacture and maintain these fuel containers.

Scientists studying cryogenics are another group of stakeholders for this project, because a successful product from this project will propel the field of cryogenics forward. Cryogenics will be put front and center of space travel and cryogenic scientists will be expected to further the technology.

Other space and air travel companies are stakeholders in this project, because a better cryogenic fuel storage solution will advance all of space and air travel. They will either incorporate some of the design aspects or improve their own designs based on the information from this project to advance cryogenic fuel storage.

1.2 Customer Needs

1.2.1 Communication

The team met with representatives from NASA-MSFC to get a better understanding of what is expected of the project. Questions were generated to gather information in an unbiased way to determine the needs that the client would like to see in the final design.

After recording the answers our team received to each question, we then determined the need statements for each topic. A need statement is what the customer expects or wants to see in the final design. These needs may be physical requirements for the project or related to the function and efficiency.

To arrive at the final need statements, we looked at the provided answers from our project sponsor and determined what the technical need was for the final design. Many of these needs gathered during the meeting were expected, however this process was helpful in organizing and accurately defining the needs of this project.

1.2.2 Questions and Answers

Table 1: Sponsor Questions and Answers

Team Question	Provided Answer	Interpreted Need
Are we expected to fabricate the storage container?	Yes, prototype a scaled model.	The prototype has the ability to scale to a larger size.
What improvements can be made to current products?	Extend the amount of time the fuel can be stored.	The container has the ability to increase time maintained at cryogenic temperature and pressure.
Are we expected to perform experiments and present data to validate our design?	Yes, prototyping and testing are the main goal NASA has for this project.	The system has the ability to be validated for scientific calculations and design choices.

How long will the container be in space?	This factor is up to the group.	The system has the capability to be used on a hypothetical mission of a determined length.
Does NASA have a previous model that the group can improve?	NASA wants to see original ideas. It would be best to start from scratch.	The system has the capability to store cryogenic propellant with different materials and systems than previous models.
What type of fuel will be stored?	Liquid hydrogen or liquid oxygen.	Cryogenic container has the ability to hold liquid hydrogen or liquid oxygen and maintain them at the appropriate temperature and pressure.
What would be considered a successful project?	Improve how the container handles outside heat sources.	The container has the ability to decrease the rate of heat transfer more significantly in comparison to current state-of-the-art.
Are we designing for Earth, Mars, or the moon?	This factor is up to the group.	The cryogenic tank has the ability to store the propellant properly for the mission that the team decides to design for.
Does our design have to mount onto the ship in a certain way?	The storage container should work with existing state-of-the-art support structures.	Container has the ability to connect with other parts of the ship for structure.

1.2.3 Interpreted Needs

Based on the answers provided by NASA, the main needs of this project are to increase the amount of time the cryogen is kept at the proper temperature and pressure and to reduce the amount of heat transfer from the peripherals to the tank itself. Accomplishing these interpreted needs from our project sponsor allow us to have a successful design.

1.3 Functional Decomposition

1.3.1 Introduction to Functional Decomposition

A functional decomposition is created to simplify complex systems into smaller components and processes. This is accomplished by developing a list of major functions that the product must accomplish. The major functions for this project can be seen in the second column of the hierarchy chart (Figure 1). These major functions can be broken down further into individual actions that must be performed by each function. For this project we include store and insulate as the major functions.

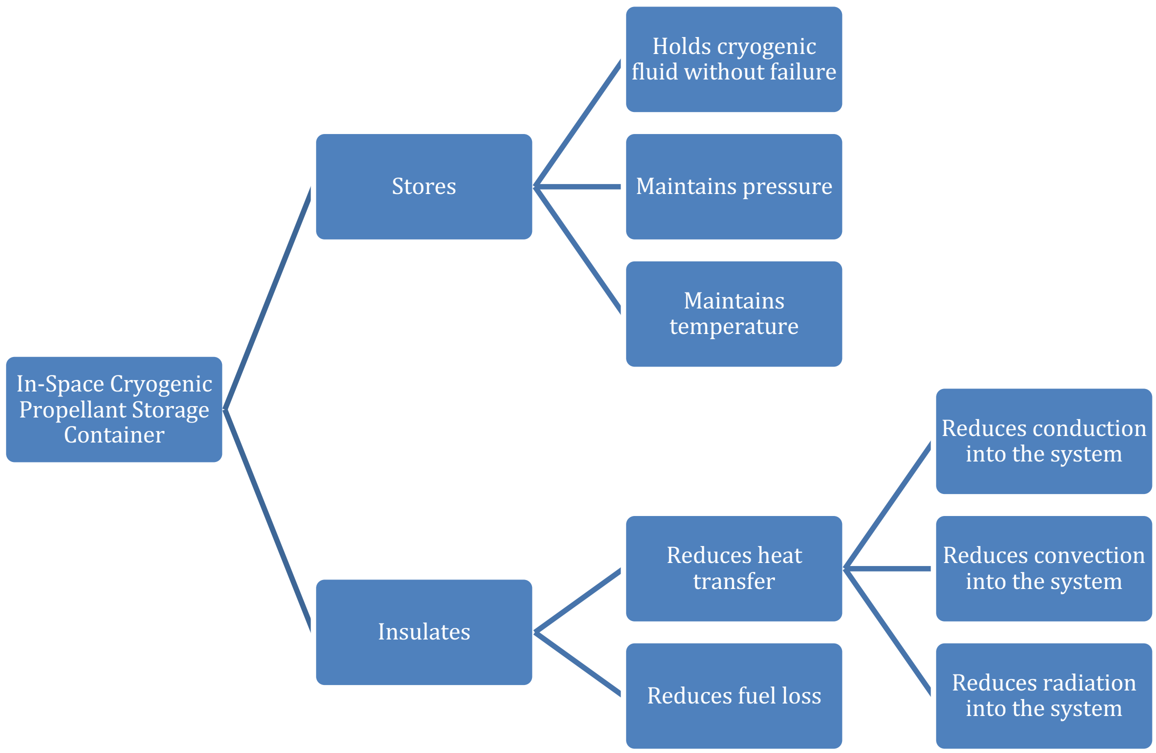

Figure 1: Hierarchy Chart

1.3.2 Major and Minor Functions

The store function is what physically holds the cryogenic fluid in the container. The tank must have the ability to hold fluids at cryogenic temperatures without fracture in a space environment, as well as on Earth, during lift-off, and during reentry into Earth's atmosphere.

Maintaining the cryogenic temperature ultimately prevents fuel loss. It must also be able to expand and contract as fluid is emptied and filled into the container, as well as regulate the pressure. Insulate controls the amount of heat transfer coming in and out of the system. Heat transfer must be reduced so that the fluid can be maintained at the appropriate temperature for a longer period of time. These functions work together to perform tasks as a system.

1.3.3 Action and Outcome

The In-Space Cryogenic Propellant Storage Container is a container designed for use by space companies to maintain cryogenic propellants in space at their respective temperatures for extended periods of time. For this to happen, the tank must have a way to control the magnitude of the temperature and pressure. To increase the amount of time that the pressure and temperature are controlled, the product must also be able to reduce the heat transfer and fuel losses through the system.

1.3.4 Cross-Reference Table

The following cross-reference table was completed by examining how each function impacts another. Some functions may only interact with one system but are still integral to the success of the project. In some cases, system integration can be performed to combine the major functions and make the system more efficient.

Table 2: Cross-Reference Table

	Stores	Insulates	
Holds cryogenic fluid without failure	x		1
Maintains pressure	x		1
Prevents fuel loss	x		1
Increases heat loss		x	1
Decreases heat absorption		x	1
Total	3	2	

Some major functions are related through their shared minor functions. The functions of maintaining pressure and reducing fuel loss are important in storing and communicating with the user. All minor functions are related because they are all required to operate successfully to consider the entire system successful.

1.4 Targets and Metrics

1.4.1 Targets Discussion

To define targets and metrics for this project, our team first had to define what aspects of the project are the most important to our project sponsor. Utilizing the customer's needs, we were able to define targets and metrics for the in-space cryogenic fuel storage tank. These targets and metrics can be found in Appendix C.

For the project to be usable by NASA, there are specific metrics that our product must meet. A target or metric is a measurable value for a function of the product. For this project, the metrics were set by looking at the needs of the customer and the most important functions of the product.

1.4.2 Critical Targets and Metrics

The most important critical functions for our design are to hold cryogenic fluid, maintain pressure, and reduce heat transfer. Our critical targets and metrics will reflect these functions as seen in the table below.

Table 3: Critical Targets

Function	Target
Hold cryogenic fuel without failure	• Withstand 6 Gs of force on takeoff • Maintain structural integrity for two weeks
Maintain pressure	• Maintain a pressure of 15 psi
Reduce heat transfer	• Fuel will boil off with a mass flow rate less than 1% per day

1.4.3 Method of Validation

The method of validation for our function of holding the cryogenic fluid can be found by testing the tank being filled with cryogenics at the proper temperature. We are testing with liquid nitrogen which in a liquid state is stored between 63 – 77 K. We must also ensure that the tank does not fail while it contains the fluid. We expect the material of the tank to expand and contract to some degree when filled and emptied due to the cryogenic being at such a low temperature. To avoid failure of the tank, we must choose a material that has the needed properties for this to occur.

We need to ensure that the tank can withstand six Gs of force that it will experience during lift off. We will determine the best material based on the conclusions of scientists performing similar tests, since we will not be able to do adequate material testing with the time and resources available to us. Finally, we need to test the tank in zero gravity conditions as well as conditions on the moon by the same methods as G forces. This is also not possible given our resources; therefore, we will validate some of our design choices with relevant calculations.

Our second critical target is maintaining the pressure, which can be tested by filling the container with cryogenic fuel and measuring the change in pressure over time with a sensor inside the tank. As heat transfer occurs, the pressure in the tank will increase and need to be released. The pressure relief valve will then be used to relieve the pressure until it reaches the desired pressure, which is 15 psi for liquid nitrogen.

Our final critical target is reducing the heat transfer into the system. Once again, the fluid will be held in the container and the weight of the fluid inside the tank will be measured. Our heat transfer target will be reached by utilizing multi-layer insulation (MLI) and a vacuum. MLI is effective at reducing radiation and convection from outside the tank.

1.4.4 Arriving at Targets and Metrics

To arrive at these targets and metrics, background research was conducted into each function. To define the target for fuel storage, we investigated the conditions and the time frame that the tank would have to be in use. Upon takeoff the ship will experience up to six Gs of force, or three times the force of Earth's gravity. This is the most G forces that we need to design for in a lunar mission, so if it can maintain integrity through takeoff, it will keep its structural integrity throughout the mission. In order to determine the amount of time the storage tank must hold cryogenic fuel we defined a hypothetical mission to design for that will last two weeks travelling to the moon and back.

Our second key function is to maintain pressure within the tank. The target for this function is to maintain an internal pressure of 15 psi for the entirety of the mission. This pressure will allow for the liquid nitrogen we are designing for to remain in a liquid state at the desired temperature.

The third key function of our project is to reduce heat transfer in the system. We arrived at this target by looking at the specific heat of liquid nitrogen and the size of the tank. Our target of less than 1% boil off per day was chosen so that there will enough remaining fuel for the duration of the hypothetical mission.

1.4.4 Targets Beyond Functions

Targets outside of the main functions of the project can be found in Appendix C. One of our targets is to make the tank useable for up to five missions. Since this tank at full scale will cost millions of dollars, it will be more efficient if the tank can be reused. This is especially true since the tanks will be used to get back to Earth, so they will return with the rocket instead of being left in space. The tank should be refillable and then placed in another ship.

The second target that is beyond the functions of the project is to alert the user if the tank leaks. 80 decibels will be used to ensure that the problem is recognized by the crew and attended to. This is critical for the mission because if the tank leaks a substantial amount there may not be enough fuel to complete the mission.

The third major target beyond the scope is to alert the user if the material properties of the tank are outside the acceptable range; mainly if the tank becomes brittle. If this occurs the system should alert the user with an 80-decibel alarm to ensure that the user is aware.

1.4.5 Discussion of Measurement

The tools needed to measure our targets include a bathroom scale to measure the weight of the fluid inside the tank, as well as the weight of the inner tank that must be supported by internal supports. When the temperature increases, the fluid will go through a phase change from liquid to gas. The gas created is fuel that is no longer usable for propulsion and causes the pressure inside the tank to increase. Once the pressure exceeds the acceptable value, the gas must be released, which is fuel that is no longer usable. The scale will allow us to know a starting weight and find the time it takes for all of the fluid to boil off, which gives us the mass flow rate of our system.

1.4.6 Summary

We will be performing tests to validate that the material we choose for the tank will operate under the various conditions that the tank will be subject to. For the conditions in space and during lift off, we will have to do calculations and simulations to test. We also need to maintain the pressure and temperature to avoid boil off and fuel loss. The weight of the fluid will be measured using a standard bathroom scale to find the time it takes all of the fluid to boil off.

1.5 Concept Generation

Concept generation is a vital part of any design process. Concept generation provides the design team with a breadth of ideas to select a final design from later. Our design team generated 100 ideas for our design problems. This list can be found in Appendix D.

1.5.1 Concept Generation Tools

Multiple methods were used in brainstorming our concepts. These include the use of a morphological chart, as seen in Appendix D, biomimicry, and brainstorming. The first 48 ideas in the list came from the morphological chart. Concepts 75-80 on the list were conceptualized through biomimicry, for example, the blubber of a whale can be examined when looking at insulation for the tank. The remaining concepts came from brainstorming, research, and speaking with our technical advisor and sponsor.

1.5.2 Medium Fidelity Concept

Five concepts from the concept generation list were selected as medium fidelity concepts. These concepts are shown below in Table 4. A medium fidelity concept is a concept that embodies many of the characteristics that the project should fulfill but is likely not the direction that the design team will pursue. Even though they may not be found in the final design, they are still helpful to show what factors are desirable in the project.

Table 4: Medium Fidelity Concepts

Concept number	Description
62	Film that would specifically block and reflect radiation that would be emitted from the sun.
2	The double shell with a vacuum in between the layers would help alleviate heat transfer from conduction and convection.
97	Supports in between the two layers could be made from a ceramic that would not have a high level of heat transfer.
4	A pill shape allows for a good surface area to volume ratio, powdered insulation will help keep the cryogenic fluids at the proper temperature.
82	Foam insulation between the two shells can help keep the cryogen cold.

1.5.3 High Fidelity Concepts

Three high fidelity concepts were chosen from the list of generated concepts. These are concepts that meet the needs of the project to a high extent. These will be utilized later in the design process during concept selection to arrive at concepts that best fit the project.

Table 5: High Fidelity Concepts

Concept Number	Description
23	Utilizing multi-layered insulation in the fuel storage will be effective at keeping temperatures at cryogenic levels.
99	Securing the tank with clips allows for the tank to be removed from the ship and reused for another mission.
95	Many thin supports between the two tank layers would allow for structural integrity and small, localized sources of heat transfer.

1.5.4 Eliminating Concepts

In order to find medium and high-fidelity concepts, some ideas were eliminated. The first set of idea eliminations included eliminating the thin-walled ideas from the morphological chart. The team found that a thicker wall on the tank would perform better in reducing heat leak into the system. While looking at the morphological chart ideas, the team also found the pill-shaped container would perform better in maximizing the volume of storage while reducing surface area contact of the fluid to the tank compared to the cylindrical shape.

The second set of eliminations led the team to eliminate the triple-shelled idea. The third shell would cost more, weigh more, and wouldn't be necessary since the double-shell will eliminate the conduction and convection that the third shell would target.

1.6 Concept Selection

The concept selection process is the part of the design process where the generated concepts are weighed against each other to determine a final design. This design will move forward as the team's main concept for a prototype. This process is completed on Microsoft Excel where values can be quickly calculated, and tables can be created. The process and calculated values are explained in the following sections.

1.6.1 House of Quality

The House of Quality chart compares the eight customer requirements we were given with the engineering characteristics that are relevant to the project. The priority of each customer need was found using the Binary Pairwise Comparison chart that can be found in Appendix E. The engineering characteristics that we found to be the most important are volume, surface area, time, safety, durability, ease of use, and cost.

Table 6: House of Quality

House of Quality									
		Engineering Characteristics							
	Improvement Direction	↑	↓	↑	↑	↑	↑	↓	
	Units	m^3	m^2	hours				$	
Customer Needs	**Priority**	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**Total**
1	7	1	1	9	3	3	0	0	
2	1	0	0	0	0	3	9	9	
3	2	9	9	3	3	9	1	3	
4	2	3	3	9	9	9	3	1	
5	6	9	9	9	9	1	0	0	
6	4	9	3	9	9	1	0	0	
7	3	3	9	3	3	1	0	0	
8	3	0	0	0	1	3	9	3	
	Raw Score	**130**	**124**	**186**	**147**	**82**	**44**	**26**	
	Relative Weight %	**17.59**	**16.78**	**25.17**	**19.89**	**11.10**	**5.95**	**3.52**	100
	Rank Order	**3**	**4**	**1**	**2**	**5**	**6**	**7**	

Table 7: Variables from House of Quality

1 – Increase Storage Time	a – Volume
2 – Validate Design Choices	b – Surface Area
3 – Use of Hypothetical Mission	c – Time
4 – Store Cryogenic Propellant	d – Safety
5 – Maintain Temperature	e – Durability
6 – Maintain Pressure	f – Ease of Use
7 – Reduce Heat Transfer	g – Cost
8 – Connect to Existing Systems	

The customer requirements and engineering characteristics were compared to one another using the numbers 0, 1, 3, and 9. A zero means that the two are not related, a one means they are barely related, a three means they are mildly related, and a nine means they directly depend on one another. Once the columns are filled, each number is multiplied by the priority number of the customer need in the corresponding row. These numbers are then summed together to obtain a raw score for each engineering characteristic. Next, the raw scores for each engineering characteristics are added together. Each raw score is then divided by the total of the raw scores to obtain the relative weight for each column. This number is multiplied by 100 to get the value into a percentage. The sum of the relative weights should equal 100%. Based on their relative weights, the engineering characteristics can also be ranked in order of determined importance.

The results of the House of Quality indicate that the time under cryogenic temperatures is the most important engineering characteristic to this project, followed by safety and volume. Time under cryogenic temperature is the most important characteristic to this project because of the fluid's temperature increases beyond an acceptable level it will boil and will have to be released as a gas. Safety is also important to the project because if a system fails or the tank fractures it would endanger the ship and lives of any crewmember. Lastly, the volume is another important characteristic because the tank must hold enough cryogenic fuel to complete the mission.

1.6.2 Pugh Charts

The engineering characteristics along with their relative weights were then placed in the first Pugh Chart, seen below in Table 8. We gathered our medium and high-fidelity concepts that were chosen in concept selection and placed them in the table to be compared with the current state of the art cryogenic tank design.

If the design choice would perform better than the state of the art in terms of the engineering characteristic, then the box will get a “plus” sign. If it would perform worse, a “minus sign” is inserted. If it does not change, it is assigned an “S”. The number of plusses and minuses are summed for each design choice, then compared. The designs with the overall most minuses and least plusses are ruled out. In this case, Pugh Chart 1 eliminated glass bead insulation.

Table 8: Pugh Chart 1

Pugh Chart 1									
Criteria	Weight	SOTA	A	B	C	D	E	F	G
a	17.59		S	S	S	S	S	+	S
b	16.78		S	S	S	S	S	+	S
c	25.17		+	-	-	-	+	S	-
d	19.89		S	S	S	S	S	-	S
e	11.10		S	+	+	+	+	-	-
f	5.95		+	+	+	S	S	-	-
g	3.52		+	+	+	+	-	S	S
Pluses			3	3	3	2	2	2	0
Minuses			0	1	1	1	1	3	3

Table 9: Variables for Pugh Chart

A – MLI in a Vacuum, Pill Shape	E – Powder Insulation – Pill Shape
B – Foam Insulation – Pill shape	F – Spherical Shape
C – Film Insulation – Pill Shape	G – Glass Bead Insulation – Pill Shape
D – Double Shell Vacuum – Pill Shape	

The criteria variables can be found in Table 7. The designs that did not get ruled out then move on to the second Pugh chart found in Appendix E. In this chart, the designs will be compared with the design that received the average amount of plusses and minuses in the first Pugh chart, film insulation. Each box is again filled with plusses, minuses, and S's. After each box was filled, we had three designs that performed better than the others, those will to the next step in the concept selection process. These three concepts are multi-layer insulation, foam insulation, and powder insulation.

1.6.3 Hierarchy Chart

For the hierarchy chart, we took the seven engineering characteristics used in the previous charts and compared them with each other. The box is filled with a 1 if they have equal importance, a 3 if one is moderately more important than the other, a 5 if one is strongly more important than the other, a 7 if one is much more important, and a 9 if one is significantly more important than the other. When the characteristic is compared with itself, it receives a 1, which creates a diagonal of 1's in the table. Corresponding values on either side of this diagonal are the inverse of each other. Once all boxes are filled, the values in each column are summed. The labels for the rows and columns are represented by variables that can be found in Table 9.

Table 10: Analytical Hierarchy Process Chart

AHP Chart							
	a	b	c	d	e	f	g
a	1.00	3.03	1.00	1.00	1.00	3.03	9.09
b	0.33	1.00	1.00	0.33	0.33	7.00	7.14
c	1.00	1.00	1.00	1.00	1.00	7.14	9.09
d	1.00	3.00	1.00	1.00	1.00	3.03	7.14
e	1.00	3.00	1.00	1.00	1.00	9.09	9.09
f	0.33	0.14	0.14	0.33	0.11	1.00	3.03
g	0.11	0.14	0.11	0.14	0.11	0.33	1.00
Sum	**4.77**	**11.31**	**5.25**	**4.80**	**4.55**	**30.62**	**45.59**

Table 11: Variables of the Hierarchy Chart

a – Volume
b – Surface Area
c – Time
d – Safety
e – Durability
f – Ease of Use
g – Cost

In this chart, characteristics such as ease of use and cost score very highly and all other characteristics receive low sums. This data will be taken to the normalized matrix in the next step to clearly depict the meaning of the data.

1.6.4 Normalized Matrix

The hierarchy chart must then be normalized. To do this, each value in the column is divided by the sum of the values in the column. This operation is done for each value in each column and placed in a new normalized chart. When the values in each column in the normalized chart are added, they should equal 1. The variables in this table can also be found in Table 10.

Table 12: Normalization Chart

	Check Normalization							
	a	b	c	d	e	f	g	Criteria Weight
a	0.21	0.27	0.19	0.21	0.22	0.10	0.20	0.20
b	0.07	0.09	0.19	0.07	0.07	0.23	0.16	0.13
c	0.21	0.09	0.19	0.21	0.22	0.23	0.20	0.19
d	0.21	0.27	0.19	0.21	0.22	0.10	0.16	0.19
e	0.21	0.27	0.19	0.21	0.22	0.30	0.20	0.23
f	0.07	0.01	0.03	0.07	0.02	0.03	0.07	0.04
g	0.02	0.01	0.02	0.03	0.02	0.01	0.02	0.02
Sum	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	1.00

The normalized chart reveals that criteria such as volume, time, and safety are very important while cost and ease of use are secondary. This helps the design team recognize which characteristics are important to design for in this project.

The consistency check was completed to ensure that the comparisons of concepts and engineering characteristics is consistent. This was done by using the criteria from the normalized matrix, as well as the weighted sum vector. The weighted sum vector was found by matrix operation between the rows of the criteria comparison matrix by the column of criteria. The consistency vector was found by dividing the weighted sum vector by the criteria weight. After this, the average from the consistency vector was found and used to find the consistency index. Then, finding the random index value from the reference chart, the consistency ratio was found to be less than 0.1, which indicates our comparisons are consistent.

1.6.5 Final Rating Matrix

Before creating the final rating matrix, the alternative analytical hierarchy process had to be completed for each engineering characteristic for all the design concepts. For each characteristic, the concepts were compared against each other one at a time, similar to the previous process. After each column is summed, the normalized matrix for each characteristic was created by dividing each entry by the column sum. The average of each row in the normalized matrix is used as the criteria weight in the consistency check. A consistency check was completed for each engineering characteristic, ensuring the comparisons have remained consistent. The weighted sum vector and consistency vector were found using the same process as mentioned in section 1.6.4, and each characteristic was found to be compared consistently.

The criteria weights from each engineering characteristic in the alternative AHP chart were entered into the final decision matrix horizontally across, with the characteristics listed along the vertical and the design concepts along the horizontal. The final decision matrix was then transposed and using the same matrix math as the weighted sum vector, multiplying the row by the original criteria weight as found from the original AHP chart. This returned individual values for each idea, the highest value indicating the best-fit idea for the project, with each idea ranked in order of best-fit to worst-fit. The final results are listed below. The individual alternative value tables, normalized tables, and consistency tables can be found in Appendix E.

Table 13: Final Ranking with Alternative Designs

Concept	Alternative Value	Rank
MLI – Pill Shape	0.444	1
Foam Insulation – Pill Shape	0.283	2
Powder Insulation Supports	0.274	3

As shown in Table 13, multi-layer insulation (MLI) is the best candidate for us to utilize in our final design. We will be further investigating this concept as we move forward in the semester. A rough sketch of this can be seen below.

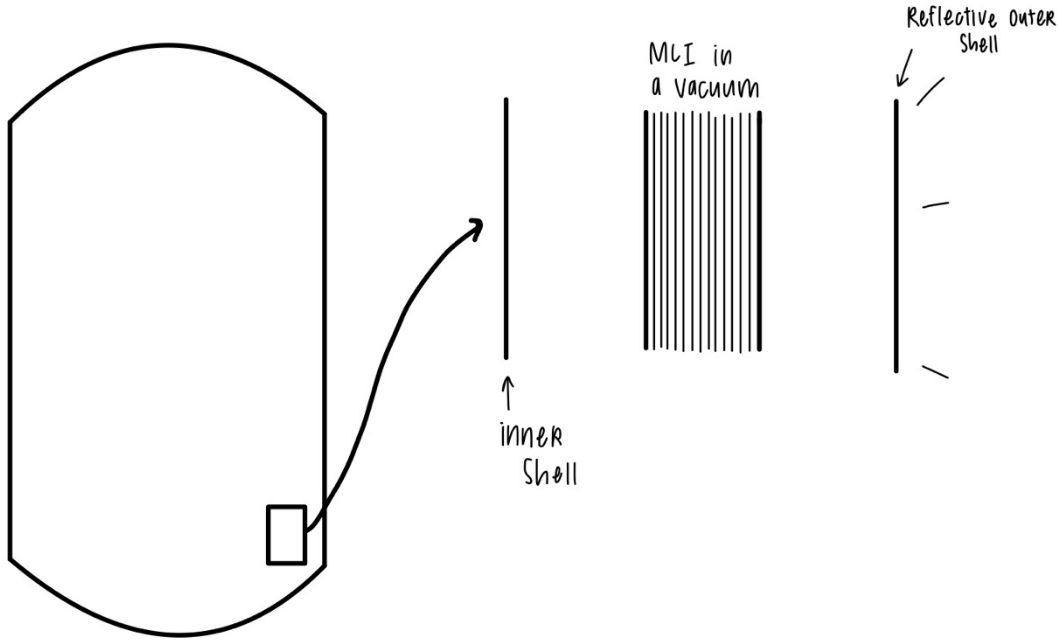

Figure 2: Final Design Concept Sketch

1.7 Spring Project Plan

This figure shows each design step that must be completed during the second semester of this course to complete the project by the deadline.

FAMU-FSU College of Engineering

Group: 512 **Project:** COE In-Space Cryogenic Propellant Storage Container **Date:** 3-De

Project Objective: Develop a solution for long term cryogenic propellant storage to maximize the length of space missions.

Project Completed By: May 01, 2022

Academic	Testing	Presentation	Graduation	#	Major Tasks	5-Jan-22	7-Jan-22	12-Jan-22	18-Jan-22	18-Feb-22	25-Feb-22	28-Feb-22	11-Mar-22	14-Mar-22	18-Mar-22	25-Mar-22	1-Apr-22	22-Apr-22	25-Apr-22	28-Apr-22	30-Apr-22	Anna	Liam	Samantha	Brandon
■				1	Semester Begins	™																			
■				2	Spring Work Breakdown Structure		™															x			
■				3	Finalize design		™																		
■				4	CAD final design		™																x		x
■				5	Update Bill of Materials		™																	x	
■				6	Update Sponsor and Advisor		™																		
	■			7	Order parts		™																x		
			■	8	Apply for graduation (opens)			™																	
			■	9	Apply for graduation (closes)				™																
	■			10	Receive parts					™															
	■			11	Assemble prototype						™											x	x	x	x
	■			12	Refine and adjust design						™											x	x	x	x
	■			13	Update final design						™														
	■			14	CAD updated design						™												x		
	■			15	Order more parts if needed						™												x		
	■			16	Finalize prototype						™														
		■		17	Update Sponsor and Advisor						™											x			
	■			18	Begin testing							™													x
■				19	Spring Break begins								™												
	■			20	Complete testing									™								x	x	x	x
■				21	Spring Break ends										™										
	■			22	Analyze data											™						x	x	x	x
	■			23	Finalize project											™									
		■		24	Engineering Design Day												™								
■				25	Last day of class													™							
■				26	Finals week begins														™						
■				27	Finals week ends															™					
			■	28	Graduation																™				
					# People working on the project: 4	1	2	3	4	5	6	7	8	9	10	11	12								

Major Tasks / Target Dates / Objectives / Costs / Summary & Forecast

Project Cost 0
Material Cost 0
Product Cost 0

Expended Budgeted

OPPM 12/3/2021 5:16 PM

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Figure 3: Spring Project Plan

Chapter Two: EML 4552C

2.1 Restated Project Charter

2.1.1 Project Description

This project aims to design and prototype a storage container to hold cryogenic propellants in space. The design must limit heat losses and transfers to preserve the propellant in a cryogenic state for an extended period of time.

2.1.2 Key Goals

The main goal of this project is to create a propellant storage solution that the National Aeronautics and Space Administration (NASA) can utilize on upcoming long-term missions. To achieve this goal, the container must maintain the fuel at a specified temperature for at least two weeks. Additionally, a solution should be proposed for the storage container to reduce the amount of thermal transfer and thermal gains.

A successful project will be defined by the ability of the team to create a prototype, perform various tests on the container, and present our findings to our project sponsors.

2.1.3 Primary Market

The primary market for this product is NASA, specifically the Marshall Space Flight Center (MSFC) and their commercial partners.

2.1.4 Secondary Market

The secondary market for this product includes other companies interested in space travel, such as SpaceX and Virgin Galactic, as well as aerospace companies that use cryogenic fuel for space flights. Once our design is in use, it is expected that other space agencies will incorporate aspects of the design into their own projects. Another secondary market is cryogenic research facilities with an interest in extending the research, as well as cryogenic manufacturers.

2.1.5 Assumptions

A hypothetical lunar mission with a duration of two weeks is assumed. The tank is assumed to store the fluid with no disturbance, i.e., filling or draining for fuel use. We will also assume that the fuel stored in the container is liquid hydrogen, although liquid nitrogen will be used in testing due to safety requirements and current available resources. A comparison will be performed between the two cryogens. In addition to this, the tank we construct will be on a much smaller scale than one used in practice. This will not be directly scalable, since heat transfer is directly related to the surface area and volume of the tank, but we are assuming that the necessary calculations can be performed to determine the heat transfer for a tank of any size based on our design. It is assumed that the final design will be operated by individuals who are familiar with cryogenic propellant storage and trained to handle the container. Finally, we are assuming that the tank will be utilized on Earth, during liftoff, and in a space environment.

2.1.6 Stakeholders

For this project, the stakeholders are NASA (specifically Marshall Space Flight Center), astronauts, spacecraft mechanics, cryogenic scientists, and other space companies. NASA-MSFC is the sponsor of this project and will receive the benefit of using the design on their spacecraft in the future, making them the primary stakeholder of the project.

With this project being implemented into spacecrafts in the future, more long-term space travel will be possible. This means that more astronauts will have the opportunity to man missions, making them main stakeholders in this project as well.

Spacecraft mechanics are another main stakeholder group, since they will be actively working on the ships. Creating an updated storage solution for cryogenic fuels will require the mechanics to be trained to manufacture and maintain these fuel containers.

Scientists studying cryogenics are another group of stakeholders for this project, because a successful product from this project will propel the field of cryogenics forward. Cryogenics will be put front and center of space travel and cryogenic scientists will be expected to further the technology.

Other space and air travel companies are stakeholders in this project, because a better cryogenic fuel storage solution will advance all of space and air travel. They will either incorporate some of the design aspects or improve their own designs based on the information from this project to advance cryogenic fuel storage.

2.2 Results

This section outlines the validation made for the design choices for the prototype for this project, as well as the relation to a recommended full-size design that will be recommended to

NASA. The following graph shows the weight of the liquid nitrogen in the inner tank in relation to time.

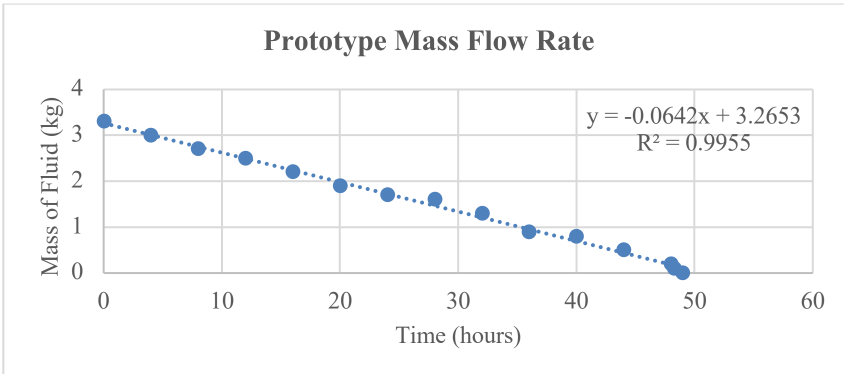

Figure 4: Prototype Mass Flow Rate

We began testing with 3.26 kg of fluid in the tank and weighed the tank with a bathroom scale every four hours until all the liquid nitrogen had been released. It took 49 hours for all the fluid to boil off, making the mass flow rate of the prototype 0.0642 kg/hr. The trend of the line is linear, meaning there is a linear relationship between mass and time. Our data is 99.55% accurate to the linear trendline, which is shown by the R^2 value on the graph.

2.3 Discussion

2.3.2 Prototype Design Validation

The experimental boil off time was found to be 49 hours, and the calculated time is 48.85 hours. Comparing these results gives us an error of 0.3%, which can then be applied to a full-scale design. The targets and metrics we determined are based on a full-scale design. The bathroom scale used also has a 3% error, so a total of 6% error should be applied to the recommended design. Each mode of heat transfer into the system can be seen in the table below. This allows us to see which design components contribute to the most heat transfer, allowing us to continue to edit them to reduce the total heat transfer into the system. Changes can be made to the insulation, tank geometry, and internal and external support geometry to improve the design further.

Table 14: Prototype Heat Transfer Calculations

Radiation through MLI [W]	0.21
Conduction through Fill Pipe [W]	7.33
Conduction through G-10 CR supports [W]	0.83
Total Heat Transfer Rate [W]	8.37
Mass of Fluid [kg]	3.3
Specific Heat Capacity of Liquid Nitrogen [J/kg*K]	2000
Time [hours]	48.85
Time [days]	2.04
Experimental Time [hours]	49
Calculated Time [hours]	48.85
Calculation Error [%]	0.31

2.3.3 Full-Scale Design Validation

Using the same calculation process used for the prototype, it was determined that a full-scale tank will hold liquid hydrogen at the proper conditions for 1.14 years. We accounted for heat transfer during lift-off, while in space, and during reentry, due to our assumption that the tank will be undergoing each of these conditions. It was found that the tank would lose 7.14 kg of liquid hydrogen during lift-off and 3.61 kg during reentry to Earth's atmosphere. This left a total of 128,925.5 kg of fluid to be used in space. Applying error from prototype testing, the minimum length the tank will hold the fluid in space is 1.07 years, which is much longer than the two-week goal. It has a mass flow rate of 310.24 kg/day, which is 0.24% per day. This is lower than the 1% goal, so both the prototype and full-scale designs are successful. These values do not account for external struts that would connect the storage tank to the inside of the spacecraft, which would contribute significantly to these calculations, but this was outside the scope of our project. The heat transfer into this system can be seen in the tables below at each stage of the rocket's movement. Again, these values can be used to alter the design choices to further reduce the total heat transfer.

Table 15: Full-Scale Liftoff and Reentry Calculations

	Lift-Off	**Re-Entry**
Specific Heat Capacity of Liquid Hydrogen [J/kg*K]	14,304	14,304
Total Heat Transfer Rate [W]	381,176.17	1,667,194.24
Time for Lift-off [s]	510	90
Temperature of Lift-off/Re-Entry [K]	1,922.04	2,922.04
Temperature of Fluid [K]	20	20
Change in Mass [kg]	7.14	3.61

Table 16: Full-Scale in Space Calculations

	Space
Remaining Mass [kg]	128,925.5
Specific Heat Capacity of Liquid Hydrogen [J/kg*K]	14,304
Temperature of the Moon Facing the Sun [K]	400
Temperature of Fluid [K]	20
Total Heat Transfer Rate [W]	19,517.51
Storage Time [years]	1.1385 (9973.63 hours)

2.4 Conclusions

The full-scale design that will be recommended to NASA will hold and maintain liquid hydrogen for 1.07 years accounting for error, which is much higher than the goal of two weeks. This is assuming the fuel is not being used and is only being stored in space for that period of time. The percent boil off per day for the full-scale design is 0.24%, which is less than the 1% intended target. Since both targets were met, we can consider the design successful.

2.4.1 Errors

An experimental error of 0.3% was found by comparing experimental results with calculated results. This error could be from fluctuations in the quality of the vacuum, fluctuations in surrounding conditions, and additional random and human errors. Instrumentation error was also accounted for from the pressure relief valve, which was 4%, but did not include it in the total error of our prototype, since we left the vent open throughout the duration of testing and the relief valve was never used.

2.4.2 Design Flaws

During the machining and welding process, the bottom flange warped, making it difficult to seal the outer tank to create the vacuum between the layers. Additional clamps had to be added in certain locations to create the necessary seal. If a second prototype were designed, it would be important to make thicker flanges to prevent this.

The pipe that was selected to use as the vacuum port had a diameter of 0.25 inches, which made the process of pulling the vacuum take a longer amount of time than it could have if the diameter was larger. That process took away time we could have been using to do more testing.

To make assembly and machining simpler, we added a clamp between the two tank layers to connect the fill pipe, rather than connecting the entire fill pipe in one piece. This decision was made so that we could easily disassemble and access each part of the tank if problems arose during testing. It created more problems when creating seals to pull the vacuum between the layers, since we had to create two different seals instead of the one, we had initially planned for.

Sealing the inner and outer tank took many attempts, and each time, the screws in the flange had to be removed. This caused the threads in both the flange and screws to stretch, making it too difficult to screw them in. Time was spent rethreading each flange several times, again taking time away from further testing. This could have been avoided by not threading the flange and using nuts and bolts instead of screws.

Finally, the initial design included a reflective outer layer, which was not implemented into our physical prototype. That would have reduced the heat transfer further and extended the testing time.

2.5 Future Work

The continuing stages of this project would be further refinement of the design of our full-sized tank. The team focused more on the physical prototype than the full-scale design, so there is still more research and refinement to be done on that design. One aspect to improve is the supports that fix the inner tank to the outer tank. The research and development of the optimal geometry for these supports is pivotal to the structural integrity of the tank.

Integrating screens or display options on the full-sized tank will increase ease of use and overall safety of the full-sized tank. The displays would show the current temperature and pressure readings of the cryogenic fluid in the tank, as well as the amount of fuel remaining in the tank.

Another aspect that needs to be further researched is the external connections and ports on the tank. It is necessary to have vents, pressure relief valves, a vacuum port, and fuel inlets and outlets. Since this tank is so much larger, there are significantly more safety precautions that must be taken, meaning more relief outlets are needed in case others fail. Further research should be conducted on how to integrate these into the tanks geometry as to not take away from the pill shape or increase heat transfer too drastically. Lastly, it is important to include the heat transfer through the struts connecting the tank to the inside of the spacecraft. Current state-of-the-art struts that connect tanks to spacecrafts are responsible for most of the heat transfer to the tank. The goal is to increase cryogenic fuel hold time by reducing heat transfer, so extensive work must go into developing the most efficient struts for the full-sized design.

The next stage of the project would be to incorporate a space graded bill of materials. This would be in accordance with the standards upheld by NASA on material selection.

Finally, prototypes with similar design components as the full-sized design should be built and tested. The prototypes would be tested using liquid nitrogen, hydrogen, or oxygen.

These prototypes would also be tested in different conditions such as zero gravity, liftoff, and reentry to see if they can withstand the forces they will undergo on the spacecraft. During these tests, thermal analysis would be performed on the prototype tanks to see the temperature gradients. This would show where most of the heat transfer is coming from, as well as provide information on the locations on the tanks that need improvement.

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Appendices

Appendix A: Code of Conduct

Mission Statement

The goal of this project is to develop a way to store and protect cryogenic propellant in space for an extended period of time.

Outside Obligations

All class times, outside obligations, and meetings will be put on the team Google Calendar. If obligations arise suddenly, the group will be notified as soon as possible through a text. Obligations do not need to be detailed but need to specify exactly when and for how long the obligation occurs. Each member is responsible for updating any changes as soon as possible and for checking the schedule prior to scheduling a meeting. Obligations per member are as follows:

Anna Gilliard: Work (Friday nights and Sunday mornings)

Liam McConnell: Frisbee Practice (Tuesday/Thursday 7:30 - 9:30 pm)

Samantha Myers: None at this time

Brandon Young: None at this time

Team Roles

Team roles for each group member are flexible and subject to change with updates to the document. The team roles are decided based upon which track each group member is on in their degree, as well as how active each member is in communicating. The roles are as follows:

Anna Gilliard: Fluids Engineer and Advisor Meeting Coordinator/Communicator

Liam McConnell: Test Engineer and Sponsor Meeting Coordinator/Communicator

Samantha Myers: Dynamics/Controls Engineer and Professor Communicator

Brandon Young: Materials Engineer and T.A. Communicator.

The assignment of individual tasks based on the needs of the project will be decided after each Senior Design class at a brief meeting in the College of Engineering

Communication

The general method of communication for day-to-day conversation for group members only will be through an iMessage group chat. Team members are expected to reply to messages directed at them (direct name use) within 24 hours of the original message. Gmail and Google Drive will be used for sharing documentation and more formal conversations. Microsoft Office will be used to share all working documents for the project. University emails will be used when contacting the advisor, sponsor, T.A., or professor. Team meetings will occur in person at the College of Engineering or through a Zoom link that will be shared through email. Meetings with the sponsor will be through Microsoft Teams while meetings with the advisor will be either in-person or on Zoom. The T.A. and professor will meet in-person. In the case of an emergency, a phone call is appropriate.

In a professional meeting, people will be responded to respectfully and to the best of our abilities at that moment. If we are unable to answer any questions, we will apologize for not having the pertinent information and find a way to give that person the answer as soon as possible.

If an issue arises within the group, we will do everything possible to resolve the conflict by communicating directly within the group either in person, by text, or in a Zoom meeting. If this does not work, a TA will be contacted for assistance. Our very last resort is contacting Dr. McConomy. If Dr. McConomy is contacted, we hope that he will speak to the conflicted parties directly and help them come to a solution.

The same process will be followed if anyone in the group has a question that cannot be answered by our project sponsor. We will attempt to find the answer ourselves before contacting a TA. Dr. McConomy will be contacted if assistance is still needed.

Dress Code

For presentations, the team will be in business casual attire and wearing masks. In meetings, the team will be in casual attire with masks. There is no dress code during regular class times unless specified a full day prior to class time.

Attendance Policy

If a team member has more than two absences without notifying the group, members of the group will contact them directly to check in. If the missing group member does not reply within 24 hours, an email to the T.A. will be sent with the goal of the T.A. being able to reach the missing person. If there is no response to the team after 48 hours, Dr. McConomy will be contacted with the goal of some type of solution depending on the situation (a way to contact the group member, an extra day to work on an assignment, etc.). If a team member knows they are going to miss a meeting, they should notify the group through text as soon as possible.

Statement of Understanding

This document is subject to change at any time, as long as all team members agree on the changes. Changes can be proposed in person or on other meeting platforms as long as all group members are present.

Signature Page

I agree to all terms discussed in this document and understand that any part may be changed as long as all members are in agreement.

X Anna Gilliard

X Liam McConnell

X Samantha Myers

X Brandon Young

Appendix B: Functional Decomposition Charts

Table 17: Sponsor Questions and Answers

Team Question	Provided Answer	Interpreted Need
Are we expected to fabricate the storage container?	Yes, prototype a scaled model.	The prototype has the ability to scale to a larger size.
What improvements can be made to current products?	Extend the amount of time the fuel can be stored.	The container has the ability to increase time maintained at cryogenic temperature and pressure.
Are we expected to perform experiments and present data to validate our design?	Yes, prototyping and testing are the main goal NASA has for this project.	The system has the ability to be validated for scientific calculations and design choices.
How long will the container be in space?	This factor is up to the group.	The system has the capability to be used on a hypothetical mission of a determined length.
Does NASA have a previous model that the group can improve?	NASA wants to see original ideas. It would be best to start from scratch.	The system has the capability to store cryogenic propellant with different materials and systems than previous models.
What type of fuel will be stored?	Liquid hydrogen or liquid oxygen.	Cryogenic container has the ability to hold liquid hydrogen or liquid oxygen and maintain them at the appropriate temperature and pressure.
What would be considered a successful project?	Improve how the container handles outside heat sources.	The container has the ability to decrease the rate of heat transfer more significantly in comparison to current state-of-the-art.
Are we designing for Earth, Mars, or the moon?	This factor is up to the group.	The cryogenic tank has the ability to store the propellant properly for the mission that the team decides to design for.

Does our design have to mount onto the ship in a certain way?	The storage container should work with existing state-of-the-art support structures.	Container has the ability to connect with other parts of the ship for structure.

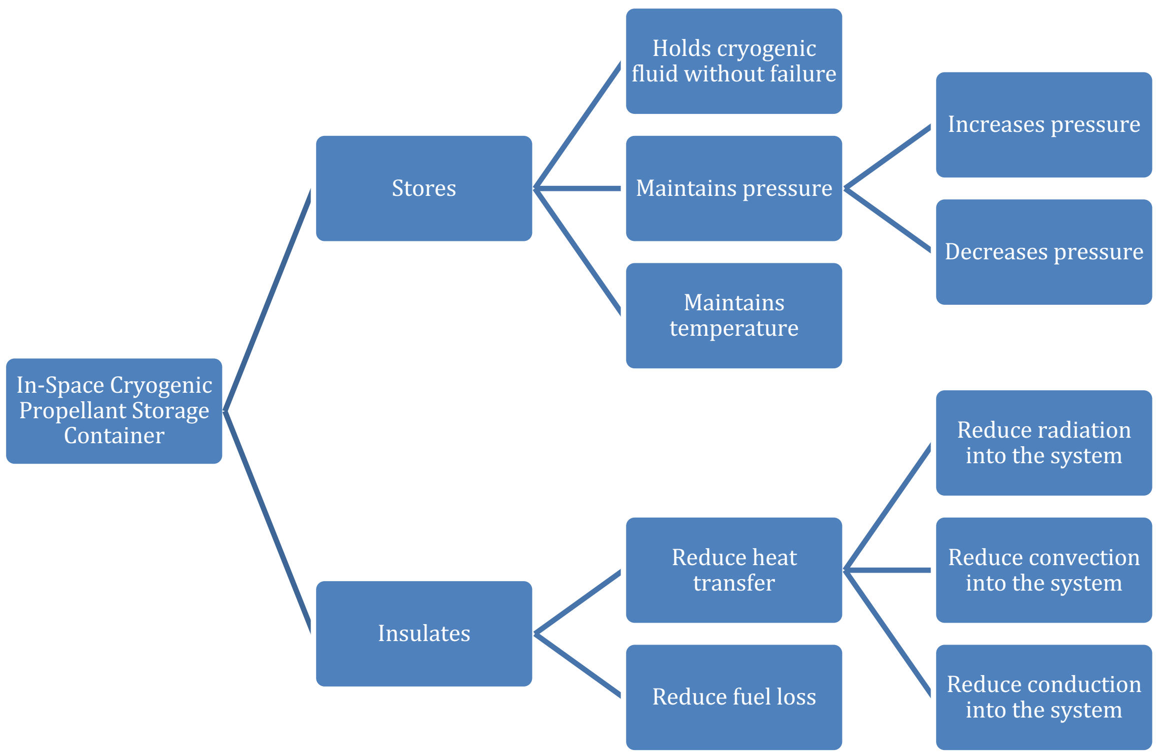

Figure 5: Hierarchy Chart

Table 18: Cross-Reference Table

	Stores	Insulates	Communicates to User	Connects	
Holds cryogenic fluid without failure	x				1
Maintains pressure	x		x		2
Prevents fuel loss	x		x		2
Increases heat loss		x			1
Decreases heat absorption		x			1
Sends information			x	x	2
Displays on container			x		1
Attaches to space craft interior				x	1
Attaches inner and outer shell				x	1
	3	2	4	3	

Appendix C: Target Catalog

Table 19: Targets and Functions

Function	Target
Holds cryogenic fluid without failure	• Withstand 6 Gs of force on takeoff • Maintain structural integrity for two weeks
Maintains pressure	• Keep pressure between 80 and 90 psi for entire mission
Reduce fuel loss	• Less than 1% per day mass boil off for the duration of the mission
Increases heat dissipated	• Dispel all but 10 kJ of energy per unit volume per day
Decreases heat transfer	• Inner tank will be subject to less than 10 kJ of energy per day
Communicate to user	• Information display synchronized to instruments to the accuracy of a second
Displays on container	• Digital presentation: at least 300 nit displays, 14-point font size or larger • Analog Presentation: Gauges or dials clear and easy to read
Attaches to space craft interior	• Attaching brackets can withstand 3 Gs of force upon takeoff • Tank is fixed on inner walls of spaceship
Attaches inner and outer shell	• Inner Struts can withstand 3 Gs of force on takeoff • Useable for up to five missions • If the storage container leaks, alerts user within 5 seconds with 80 decibels • If metal becomes too brittle alert user with 80 decibels

Appendix D: List of 100 Generated Concepts

Ideas from Morphological Chart:

1. Thick Double-shell pill with coolant between the shells
2. Thick Double-shell pill with vacuum layer between the shells
3. Thick Double-shell pill with foam insulation
4. Thick Double-shell pill with powder insulation
5. Thick Double-shell pill with fiber type insulation
6. Thick Double-shell pill with high vacuum multi-layer insulation
7. Thick Double-shell pill with multi-screen insulation
8. Thick Double-shell pill with vacuum powder insulation
9. Thick Double-shell cylinder with coolant between the shells
10. Thick Double-shell cylinder with vacuum layer between the shells
11. Thick Double-shell cylinder with foam insulation
12. Thick Double-shell cylinder with powder insulation
13. Thick Double-shell cylinder with fiber type insulation
14. Thick Double-shell cylinder with high vacuum multi-layer insulation
15. Thick Double-shell cylinder with multi-screen insulation
16. Thick Double-shell cylinder with vacuum powder insulation
17. Thin Double-shell pill with coolant between the shells
18. Thin Double-shell pill with vacuum layer between the shells
19. Thin Double-shell pill with foam insulation
20. Thin Double-shell pill with powder insulation
21. Thin Double-shell pill with fiber type insulation
22. Thin Double-shell pill with high vacuum multi-layer insulation
23. Thin Double-shell pill with multi-layer insulation
24. Thin Double-shell pill with vacuum powder insulation
25. Thin Triple- shell pill with coolant between the shells
26. Thin Triple-shell pill with vacuum layer between the shells
27. Thin Triple-shell pill with foam insulation
28. Thin Triple-shell pill with powder insulation
29. Thin Triple-shell pill with fiber type insulation
30. Thin Triple-shell pill with high vacuum multi-layer insulation
31. Thin Triple-shell pill with multi-screen insulation
32. Thin Triple-shell pill with vacuum powder insulation
33. Thin Double-shell cylinder with coolant between the shells
34. Thin Double-shell cylinder with vacuum layer between the shells

35. Thin Double-shell cylinder with foam insulation
36. Thin Double-shell cylinder with powder insulation
37. Thin Double-shell cylinder with fiber type insulation
38. Thin Double-shell cylinder with high vacuum multi-layer insulation
39. Thin Double-shell cylinder with multi-screen insulation
40. Thin Double-shell cylinder with vacuum powder insulation
41. Thin Triple- shell cylinder with coolant between the shells
42. Thin Triple-shell cylinder with vacuum layer between the shells
43. Thin Triple-shell cylinder with foam insulation
44. Thin Triple-shell cylinder with powder insulation
45. Thin Triple-shell cylinder with fiber type insulation
46. Thin Triple-shell cylinder with high vacuum multi-layer insulation
47. Thin Triple-shell cylinder with multi-screen insulation
48. Thin Triple-shell cylinder with vacuum powder insulation

Ideas from brainstorming:

49. Wrap the outside in multiple layers of insulation
50. Keep the cryogenic fluid thermally separate from the craft in the sunlight
51. Somehow keep the tank in the shadow of the craft to reduce heat from the sun
52. A multi-storage tank network
53. Trap vaporized fuel and return it to liquid state
54. Trap vaporized fuel and utilize the vapor
55. Multi-layer aluminum insulation
56. Magnetic cooling
57. Spherical shape
58. Composite tank
59. Glass bubbles on the inside surfaces of the shells to insulate instead of powder
60. Steel or aluminum bubble shells with vacuum in each bubble on the shell surface
61. Outer film that blocks specific wavelengths
62. Very rough surface (changes emissivity)
63. Clover shape (rounds put together)
64. Cockroach shape
65. Boil off into space
66. Rectangular prism tank
67. Soft insulation shell
68. Solid insulation
69. Moving liquid

70. Liquid coolant
71. Steel
72. Nickel steel
73. Stainless steels
74. Circulate insulation
75. Bird shape
76. Teardrop shape
77. Air foil shape
78. Jellyfish shape
79. Hamburger shape
80. Pear shape
81. Foam insulation
82. Whales (blubber)
83. Asbestos insulation
84. Shiny material on outside of inner tank
85. Centipede shape
86. Cord insulation holding it from ceiling
87. Stacking insulation
88. Magnetic flotation of whole tank
89. Magnets between two layers to hold shells together
90. Flower shape
91. Wooden supports
92. Titanium supports
93. Magnets to separate tanks
94. One large support
95. Many thin supports
96. Long supports
97. Ceramic supports
98. Wireless information transfer
99. Secured to ship with clips
100. Welded to ship

Appendix E: Concept Selection Charts

Table 20: Morphological Chart

Geometry	Number of Layers	Thickness	Insulation
Cylinder	One	Thick	Coolant
Sphere	Two	Thin	Vacuum
Pill	Three		Foam
			Powder
			Fiber
			Multi-layer

Table 21: Binary Comparison Chart

Binary Comparison Chart									
	1	2	3	4	5	6	7	8	**Total**
1	-	1	1	1	1	1	1	1	7
2	0	-	1	0	0	0	0	0	1
3	0	0	-	0	0	1	1	0	2
4	0	1	1	-	0	0	0	0	2
5	0	1	1	1	-	1	1	1	6
6	0	1	0	1	0	-	1	1	4
7	0	1	0	1	0	0	-	1	3
8	0	1	1	1	0	0	0	-	3

Table 22: Variables for Binary Comparison Chart

Increase Storage Time – 1	Maintain Temperature – 5
Validate Design Choices – 2	Maintain Pressure – 6
Use on Hypothetical Mission – 3	Reduce Heat Transfer – 7
Store Cryogenic Propellant - 4	Connect to Existing Systems - 8

Table 23: Pugh Chart 2

Pugh Chart 2							
Criteria	Weight	Film Insulation - Pill Shape	MLI - Pill Shape	Foam Insulation - Pill Shape	Double-Shell Vacuum	Powder Insulation	Spherical Shape
a	17.59		S	S	S	S	+
b	16.78		S	S	S	S	+
c	25.17		+	S	-	S	S
d	19.89		S	S	S	S	-
e	11.10		+	+	S	S	-
f	5.95		S	S	+	S	-
g	3.52		S	+	S	+	S
	Pluses		2	2	1	1	2
	Minuses		0	0	1	0	3

Table 24: Variables for Pugh Chart

Volume – a	Durability – e
Surface Area – b	Ease of Use – f
Time – c	Cost - g
Safety - d	

Table 25: Consistency Check

Consistency Check		
Weighted Sum Vector	Criteria Weights	Consistency Vector
1.51	0.20	7.56
1.16	0.13	9.29
1.43	0.19	7.41
1.46	0.19	7.59
1.76	0.23	7.76
0.30	0.04	7.08
0.15	0.02	7.23

Table 26: Consistency Check cont.

Random Index Value (RI)	1.35
Average Consistency	7.70
Consistency Index (CI)	0.12
Consistency Ratio (CR)	0.09
CR < 0.1 - Consistent	

Table 27: Volume AHP Alternative Values

Volume			
	MLI - Pill Shape	Foam Insulation - Pill Shape	Powder Insulation Supports
MLI - Pill Shape	1.00	1.00	1.00
Foam - Pill Shape	1.00	1.00	1.00
Powder Insulation	1.00	1.00	1.00
Sums	3.00	3.00	3.00

Table 28: Normalized Volume AHP Alternative Values

Volume - Normalized			
	MLI - Pill Shape	Foam - Pill Shape	Powder Insulation
MLI - Pill Shape	0.33	0.33	0.33
Foam - Pill Shape	0.33	0.33	0.33
Powder Insulation	0.33	0.33	0.33

Table 29: Volume Consistency Check

Consistency Check		
Weighed Sum Vector	Criteria Weights	Consistency Vector
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00

Table 30: Volume Consistency Check cont.

Random Index Value (RI)	1.25
Average Consistency	3.00
Consistency Index (CI)	0.00
Consistency Ratio (CR)	0.00

Table 31: Surface Area AHP Alternative Values

Surface Area			
	MLI - Pill Shape	Foam Insulation - Pill Shape	Powder Insulation Supports
MLI - Pill Shape	1.00	1.00	1.00
Foam - Pill Shape	1.00	1.00	1.00
Powder Insulation	1.00	1.00	1.00
Sums	3.00	3.00	3.00

Table 32: Normalized Surface Area AHP Alternative Values

Surface Area - Normalized			
	MLI - Pill Shape	Foam - Pill Shape	Powder Insulation
MLI - Pill Shape	0.33	0.33	0.33
Foam - Pill Shape	0.33	0.33	0.33
Powder Insulation	0.33	0.33	0.33

Table 33: Surface Area Consistency Check

Consistency Check		
Weighed Sum Vector	Criteria Weights	Consistency Vector
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00

Table 34: Surface Area Consistency Check cont.

Random Index Value (RI)	1.25
Average Consistency	3.00
Consistency Index (CI)	0.00
Consistency Ratio (CR)	0.00

Table 35: Time AHP Alternative Values

Time			
	MLI - Pill Shape	Foam Insulation - Pill Shape	Powder Insulation Supports
MLI - Pill Shape	1.00	3.03	3.03
Foam - Pill Shape	0.33	1.00	1.00
Powder Insulation	0.33	1.00	1.00
Sums	1.66	5.03	5.03

Table 36: Normalized Time AHP Alternative Values

Time - Normalized			
	MLI - Pill Shape	Foam - Pill Shape	Powder Insulation
MLI - Pill Shape	0.60	0.60	0.60
Foam - Pill Shape	0.20	0.20	0.20
Powder Insulation	0.20	0.20	0.20

Table 37: Time Consistency Check

Consistency Check		
Weighed Sum Vector	Criteria Weights	Consistency Vector
1.81	0.60	3.00
0.60	0.20	3.00
0.60	0.20	3.00

Table 38: Time Consistency Check cont.

Random Index Value (RI)	1.25
Average Consistency	3.00
Consistency Index (CI)	0.00
Consistency Ratio (CR)	0.00

Table 39: Safety AHP Alternative Values

Safety			
	MLI - Pill Shape	Foam Insulation - Pill Shape	Powder Insulation Supports
MLI - Pill Shape	1.00	1.00	1.00
Foam - Pill Shape	1.00	1.00	1.00
Powder Insulation	1.00	1.00	1.00
Sums	3.00	3.00	3.00

Table 40: Normalized Safety AHP Alternative Values

Safety - Normalized			
	MLI - Pill Shape	Foam - Pill Shape	Powder Insulation
MLI - Pill Shape	0.33	0.33	0.33
Foam - Pill Shape	0.33	0.33	0.33
Powder Insulation	0.33	0.33	0.33

Table 41: Safety Consistency Check

Consistency Check		
Weighed Sum Vector	Criteria Weights	Consistency Vector
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00

Table 42: Safety Consistency Check cont.

Random Index Value (RI)	1.25
Average Consistency	3.00
Consistency Index (CI)	0.00
Consistency Ratio (CR)	0.00

Table 43: Durability AHP Alternative Values

Durability			
	MLI - Pill Shape	Foam Insulation - Pill Shape	Powder Insulation Supports
MLI - Pill Shape	1.00	3.03	3.03
Foam - Pill Shape	0.33	1.00	1.00
Powder Insulation	0.33	1.00	1.00
Sums	1.66	5.03	5.03

Table 44: Normalized Durability AHP Alternative Values

Durability - Normalized			
	MLI - Pill Shape	Foam - Pill Shape	Powder Insulation
MLI - Pill Shape	0.60	0.60	0.60
Foam - Pill Shape	0.20	0.20	0.20
Powder Insulation	0.20	0.20	0.20

Table 45: Durability Consistency Check

Consistency Check		
Weighed Sum Vector	Criteria Weights	Consistency Vector
1.81	0.60	3.00
0.60	0.20	3.00
0.60	0.20	3.00

Table 46: Durability Consistency Check cont.

Random Index Value (RI)	1.25
Average Consistency	3.00
Consistency Index (CI)	0.00
Consistency Ratio (CR)	0.00

Table 47: Ease of Use AHP Alternative Values

Ease of Use			
	MLI - Pill Shape	Foam Insulation - Pill Shape	Powder Insulation Supports
MLI - Pill Shape	1.00	1.00	1.00
Foam - Pill Shape	1.00	1.00	1.00
Powder Insulation	1.00	1.00	1.00
Sums	3.00	3.00	3.00

Table 48: Normalized Ease of Use AHP Alternative Values

Ease of Use - Normalized			
	MLI - Pill Shape	Foam - Pill Shape	Powder Insulation
MLI - Pill Shape	0.33	0.33	0.33
Foam - Pill Shape	0.33	0.33	0.33
Powder Insulation	0.33	0.33	0.33

Table 49: Ease of Use Consistency Check

Consistency Check		
Weighed Sum Vector	Criteria Weights	Consistency Vector
1.00	0.33	3.00
1.00	0.33	3.00
1.00	0.33	3.00

Table 50: Ease of Use Consistency Check cont.

Random Index Value (RI)	1.25
Average Consistency	3.00
Consistency Index (CI)	0.00
Consistency Ratio (CR)	0.00

Table 51: Cost AHP Alternative Values

Cost			
	MLI - Pill Shape	Foam Insulation - Pill Shape	Powder Insulation Supports
MLI - Pill Shape	1.00	0.33	1.00
Foam - Pill Shape	3.00	1.00	3.03
Powder Insulation	1.00	0.33	1.00
Sums	5.00	1.66	5.03

Table 52: Normalized Cost AHP Alternative Values

Cost - Normalized			
	MLI - Pill Shape	Foam - Pill Shape	Powder Insulation
MLI - Pill Shape	0.20	0.20	0.20
Foam - Pill Shape	0.60	0.60	0.60
Powder Insulation	0.20	0.20	0.20

Table 53: Consistency Check

Consistency Check		
Weighed Sum Vector	Criteria Weights	Consistency Vector
0.60	0.20	3.01
1.80	0.60	2.99
0.60	0.20	3.00

Table 54: Cost Consistency Check

Random Index Value (RI)	1.25
Average Consistency	3.00
Consistency Index (CI)	0.00
Consistency Ratio (CR)	0.00

Appendix F: Operations Manual

Overview

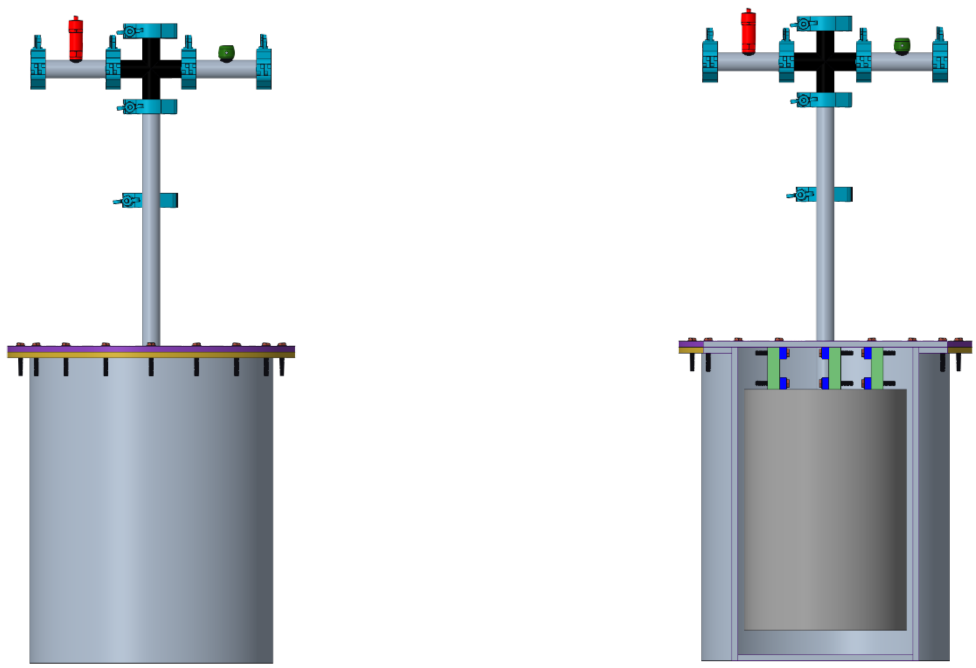

Figure 6: Prototype Front View (left) and Section View (right)

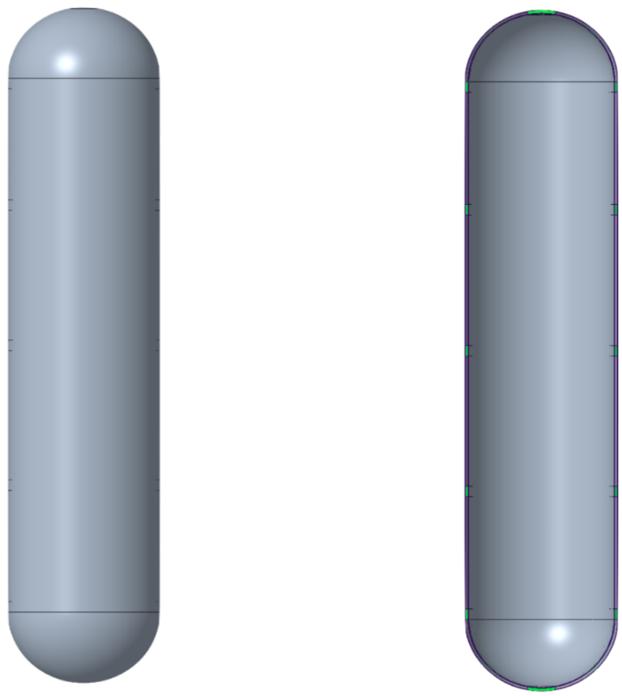

Figure 7: Large Scale Model, Front View (left), Section View (right)

Table 55: Tank Dimensions

	Prototype (in)	**Full-Scale (ft)**
Outer Tank Diameter	10.125	27.450
Outer Tank Height	13.000	130.410
Outer Tank Thickness	0.375	0.105
Inner Tank Diameter	6.625	26.240
Inner Tank Height	10.000	129.200
Inner Tank Thickness	0.438	0.105

Note the prototype dimensions are in inches and the full-scale tank dimensions are in feet.

Acronyms

CAD – Computer Aided Design

MLI – Multilayer Insulation

NASA – National Aeronautics and Space Administration

Project Description

Currently, NASA is performing research to design the most efficient cryogenic storage system to allow for longer space missions. To do this, they must design a tank that reduces heat transfer into the fluid and extends the amount of time the fluid is in a usable, liquid state. Our project aims to design and prototype a storage container to hold cryogenic propellants in space that maintains the fluid at the proper temperature and pressure by reducing heat loss into the system. We have designed a full-scale tank to be recommended for use by NASA, as well as a simplified prototype that can be tested in a lab to validate our design choices.

Project Objective

The objective of this project is to design a storage tank for cryogenic propellant that increases storage time, reduces fuel loss, and reduces heat transfer.

Key Goals

There are five main key goals to achieve for this project to be successful. They are maintaining temperature, maintaining pressure, reducing heat transfer, reducing fuel loss, and developing a prototype. Heat transfer into the tank causes the temperature of the fluid inside to rise. As the temperature exceeds the boiling point of the fluid, it will go through a phase change from a liquid to a gas. This gas causes the internal pressure of the tank to rise. To prevent the pressure from exceeding the limit of the tank, there must be a pressure relief valve. The gas that is released from the system is fuel that is no longer usable. A prototype must be developed to properly test our design and validate each design choice.

Assumptions

Three assumptions were made to narrow the scope of the project. First, we are assuming that liquid nitrogen will be used for testing, rather than liquid hydrogen or oxygen that would be used in a full-scale tank. Liquid hydrogen and oxygen are much more dangerous to test with, due to their flammability, and liquid nitrogen is readily available for use in the lab. Next, we are assuming the tank can withstand Earth, space, and lift-off conditions. The tank will be filled with fuel on Earth, loaded into the spacecraft, launched into space, undergo various temperatures and pressures based on positions in space, as well as reenter Earth's atmosphere. It should maintain structural integrity through each of these stages. Finally, we are assuming that we are designing for a lunar mission lasting two weeks, therefore the tank should maintain the fuel at the appropriate temperature and pressure for at least that amount of time.

Integration

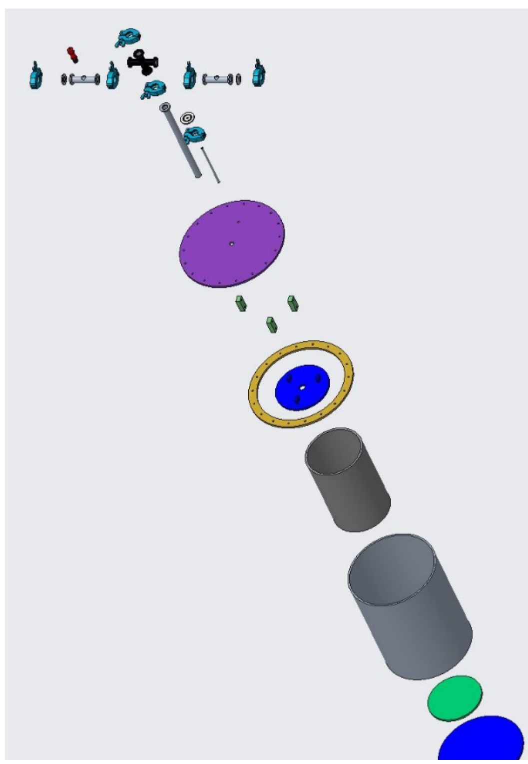

Figure 8: Full Exploded View

The outer tank is a cylinder that was cut to the correct height by the machine shop with one circular endcap welded inside the bottom end and a flange welded to the upper perimeter of the outer surface. It is its own separate part, so that the tanks can be taken apart during testing if there are any issues.

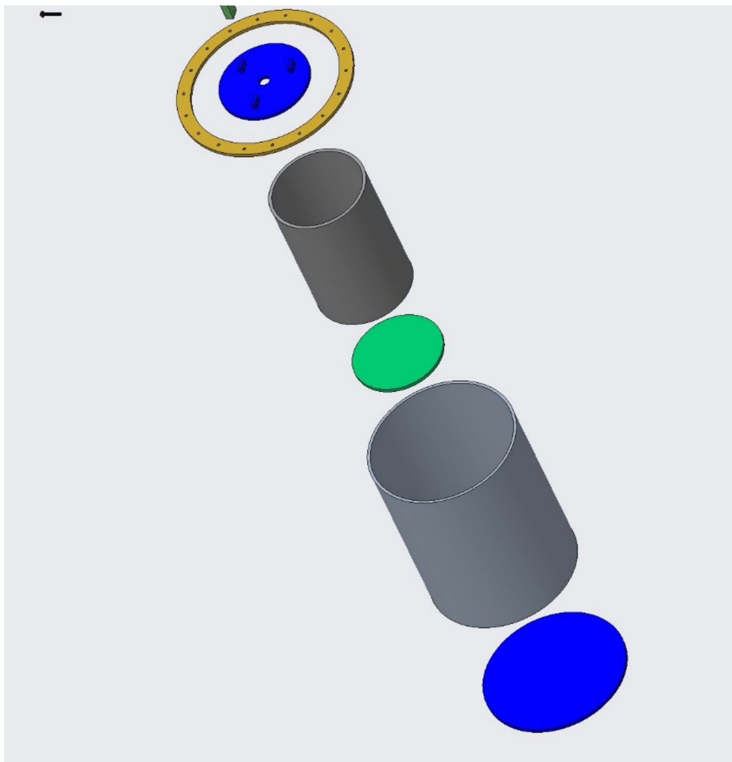

Figure 9: Exploded View, Zoomed in on Tank Assembly

The inner tank was also cut to the correct height by the machine shop with circular endcaps welded inside the top and bottom edges. The top endcap has a hole that the fill pipe is welded to. There is a flange that will serve as the top of the outer tank that will have a hole in the middle that the fill pipe goes through. Each endcap for the tanks and both flanges were waterjet from a 2’x2’ plate of Stainless Steel 304 by the machine shop, as well as the metal plates that are used to secure the G10 supports to the tank. Bolt holes were also cut during this process and threaded.

When sealing the tank, liquid flange sealant is spread between the top and bottom flange before they are bolted together. It is important to note how long the sealant takes to dry to ensure we are pulling the most effective vacuum between the tanks as possible.

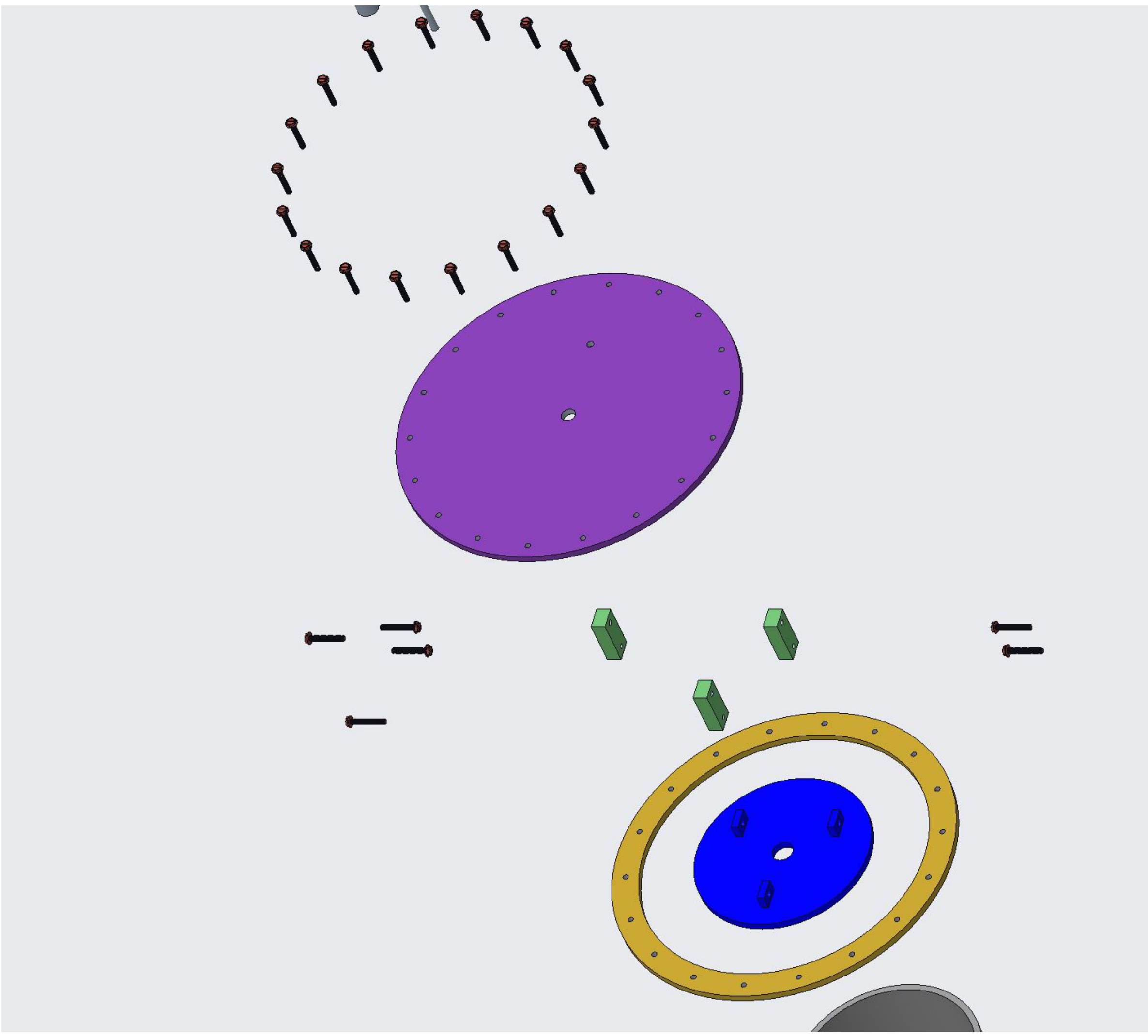

Figure 10: Exploded View, Zoomed in on G10 Assembly and Lid Assembly

Three of those metal plates were welded to the inside of the top flange, and three were welded to the top of the inner tank. The G10 was cut and is secured with bolts to the metal plates. The vacuum port is welded to the outer surface of the top flange corresponding to a hole that was cut in the flange. The final thing done by the machine shop was cutting holes in the two side pipes and threading them for our pressure release valve and vent.

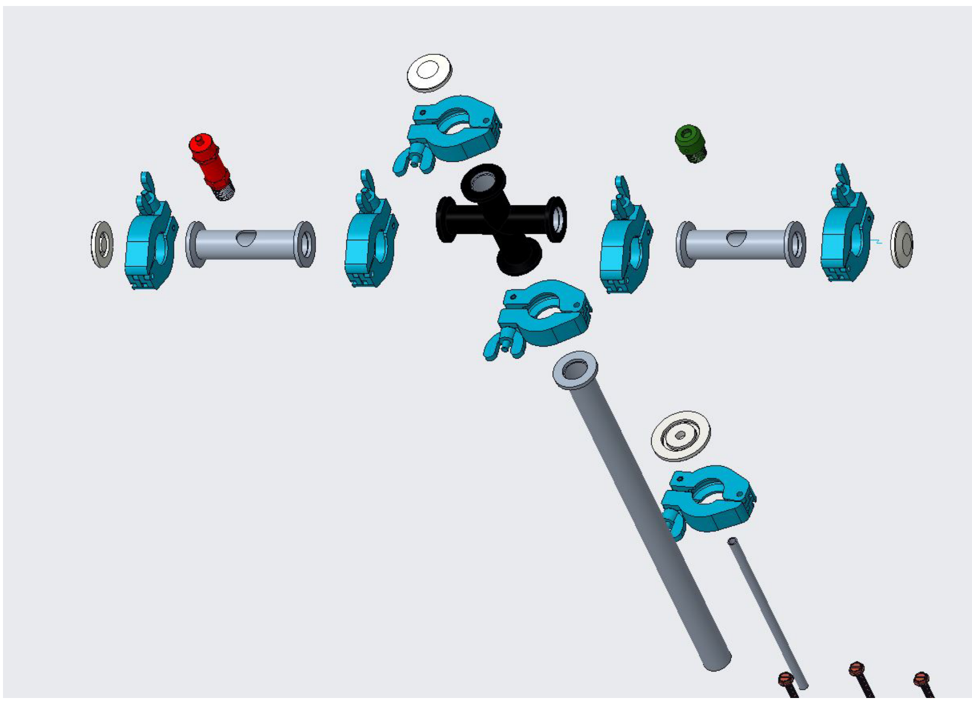

Figure 11: Exploded View, Zoomed in on Upper Pipe Assembly

The top piping portion of the tank was assembled by hand. The fill pipe coming out from the inner tank is connected to a cross-valve using a clamp and O-ring. Three more clamps and O-rings are connected to each of the other ends of the cross-valve. The top end will be sealed off with an endcap that will also be connected on with a clamp and O-ring. That endcap will only be removed while filling the tank. The left and right clamps and O-rings will connect the short pipes with threaded holes. The opposite ends of both short pipes will also have endcaps clamped on that will only be removed during the filling of the tank. The pressure release valve and vent are screwed into the threaded holes in the short pipes. Finally, a clamp will attach a vacuum port fitting to the vacuum port.

Operation

Before filling the tank with cryogen, the system should be pressurized to ensure the pressure relief valve is operating correctly and will release gas from the tank at the appropriate pressure. The error for the relief valve should be found and results should be recorded accordingly. The final mass flow rate exiting the system should account for this error. Also, before filling the tank, proof is necessary that the vacuum is effective in reducing the heat transfer due to convection through the space between the inner and outer tank walls. We did this using a thermal camera to take pictures of the system with the vacuum on and off. The active vacuum pump should be connected to the vacuum port using a clamp. The empty tank should also be weighed using a kitchen scale, so that we know the weight without fluid.

All three endcaps for the cross-valve on the top of the tank should be removed by unscrewing the clamps on each end and removing the caps. A fill line connected to the liquid nitrogen storage tank in the lab will be inserted into the top hole of the cross-valve and pushed in until the end of the line reaches the bottom of the inner tank. The fill line is also connected to a pump that can now be used to fill the tank with the cryogen. Safety precautions must be taken and are stated in our risk assessment. As the tank is filled, there will be some gas vented off. When the tank is full, the fill-line should be removed, and endcaps should be clamped back on.

Once the system is sealed, it should be weighed again, so that the tank of the full system is known. The tank should be weighed every 8 hours until the tank is empty. The time and weight should be recorded each time. This is when the tank weighs the same as the original weight taken with the tank empty. The time it takes for the tank to release all of the gas can be used to find the mass flow rate. That can be compared to values found through calculations for the system to validate our testing.

Troubleshooting

If an issue is detected with the tank while there is fluid in the system, the fluid must first be drained or allowed to boil off and vent out using the ventilation valve on the top of the tank. This must be done before any checks can be completed. Conduct a visual test on the system after it is empty to identify any obvious integrity flaws. To check for small gaps or leaks in the system, the tank should be filled with air and submerged under water and checked for air bubbles as well as filled with water to ensure that there are no gaps in the welds.

Appendix G- Engineering Drawings

These are the drawings presented to the machine shop.

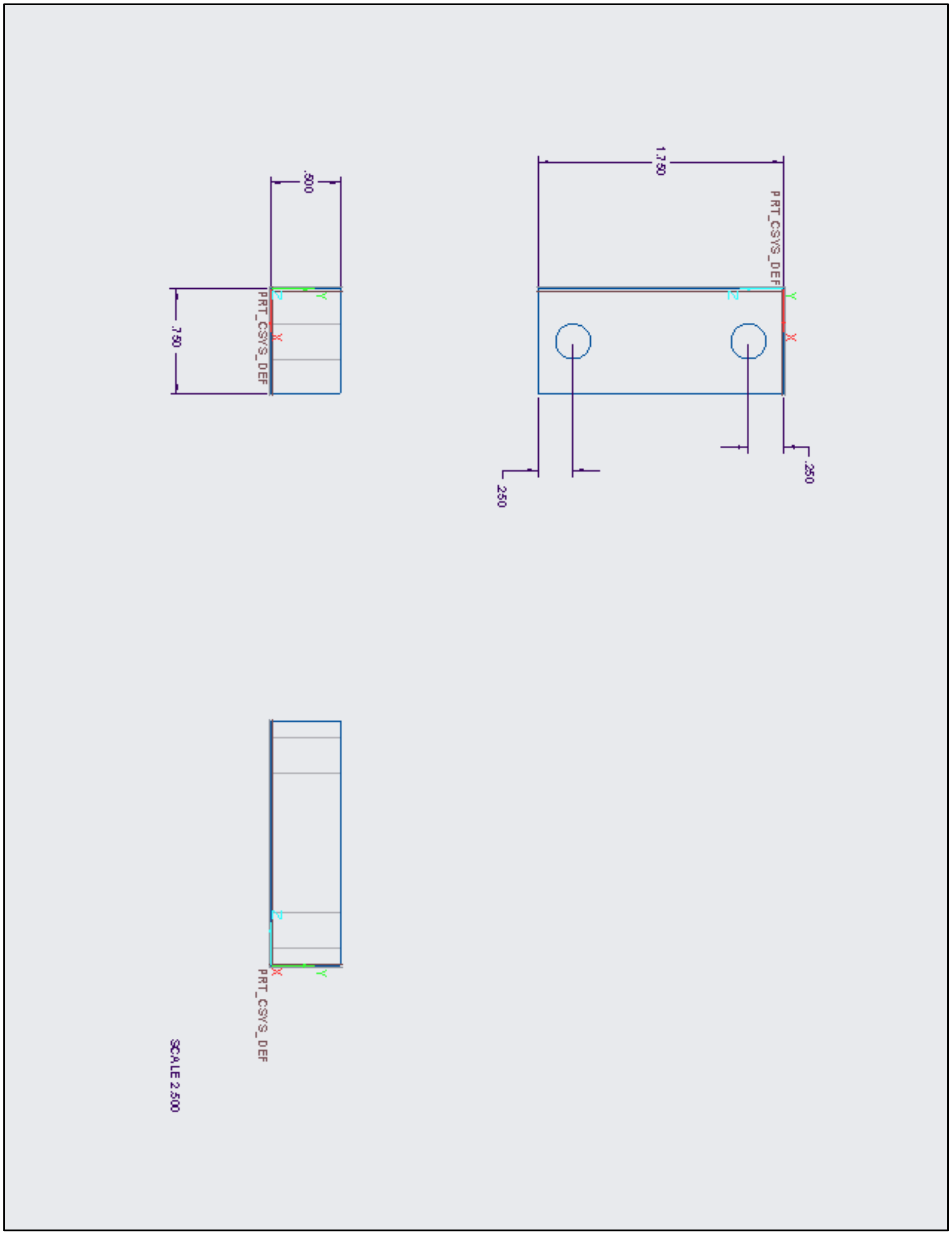

Figure 12: G10 Support Dimensions

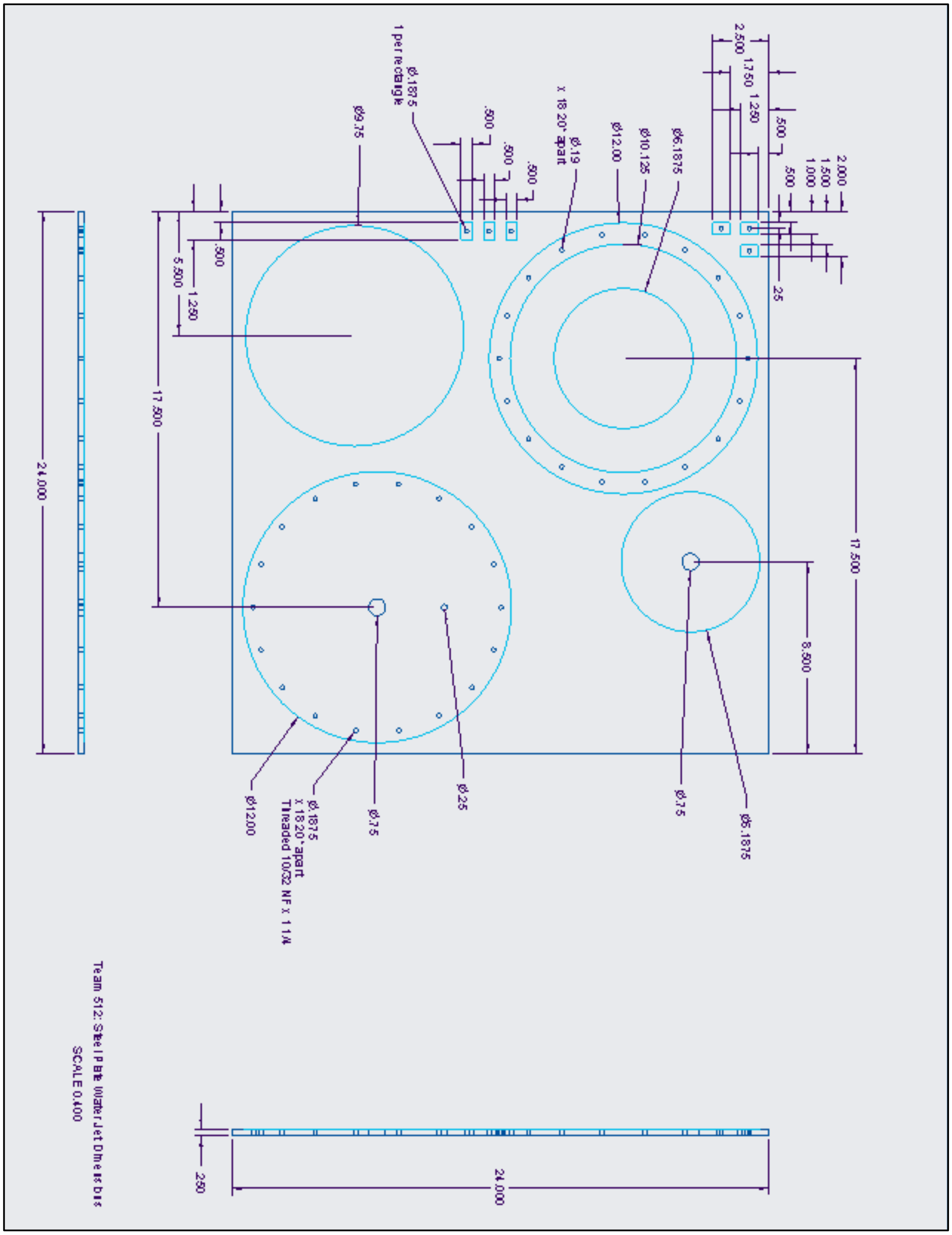

Figure 13: Steel Plate Dimensions

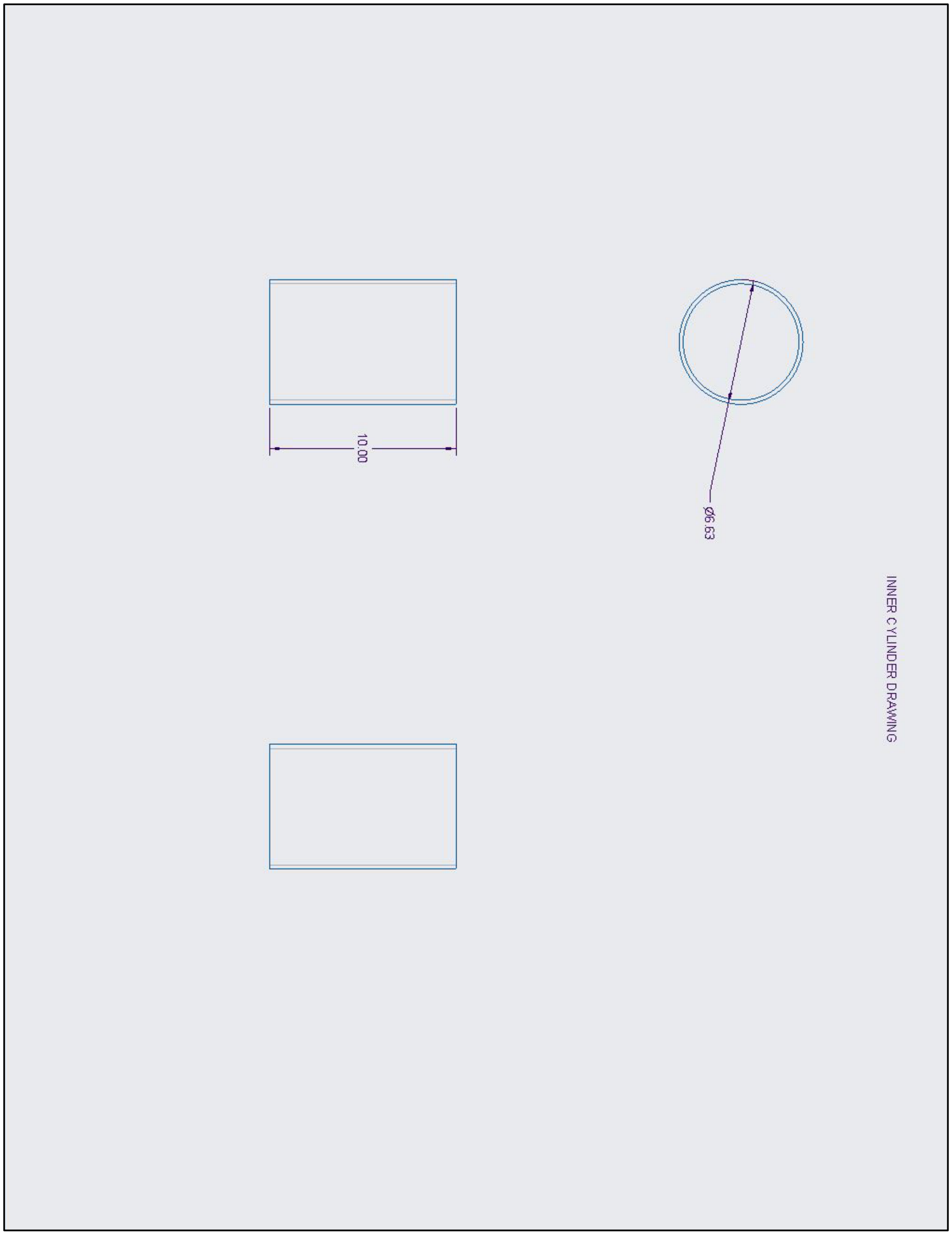

Figure 14: Inner Tank Dimensions

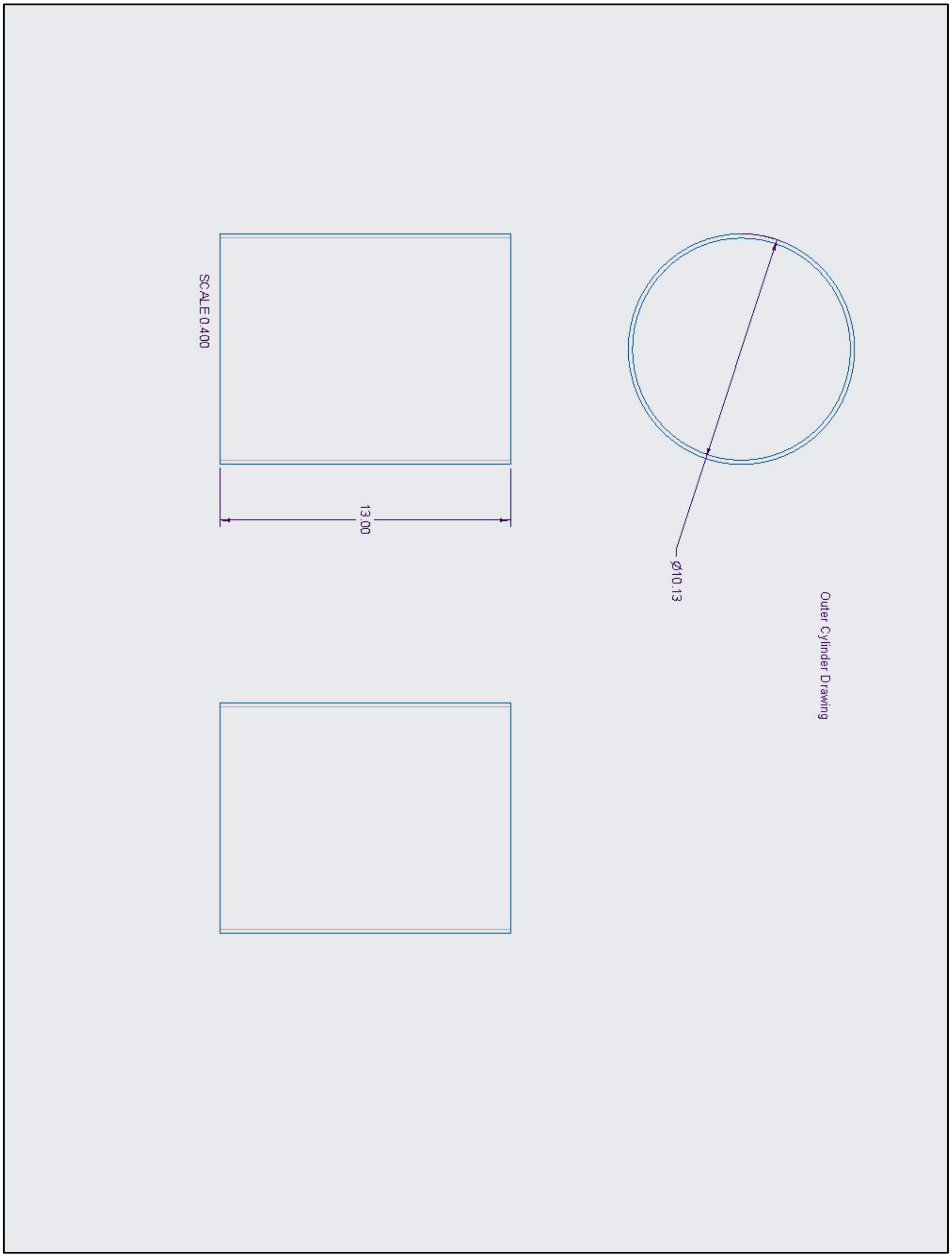

Figure 15: Outer Cylinder Dimensions

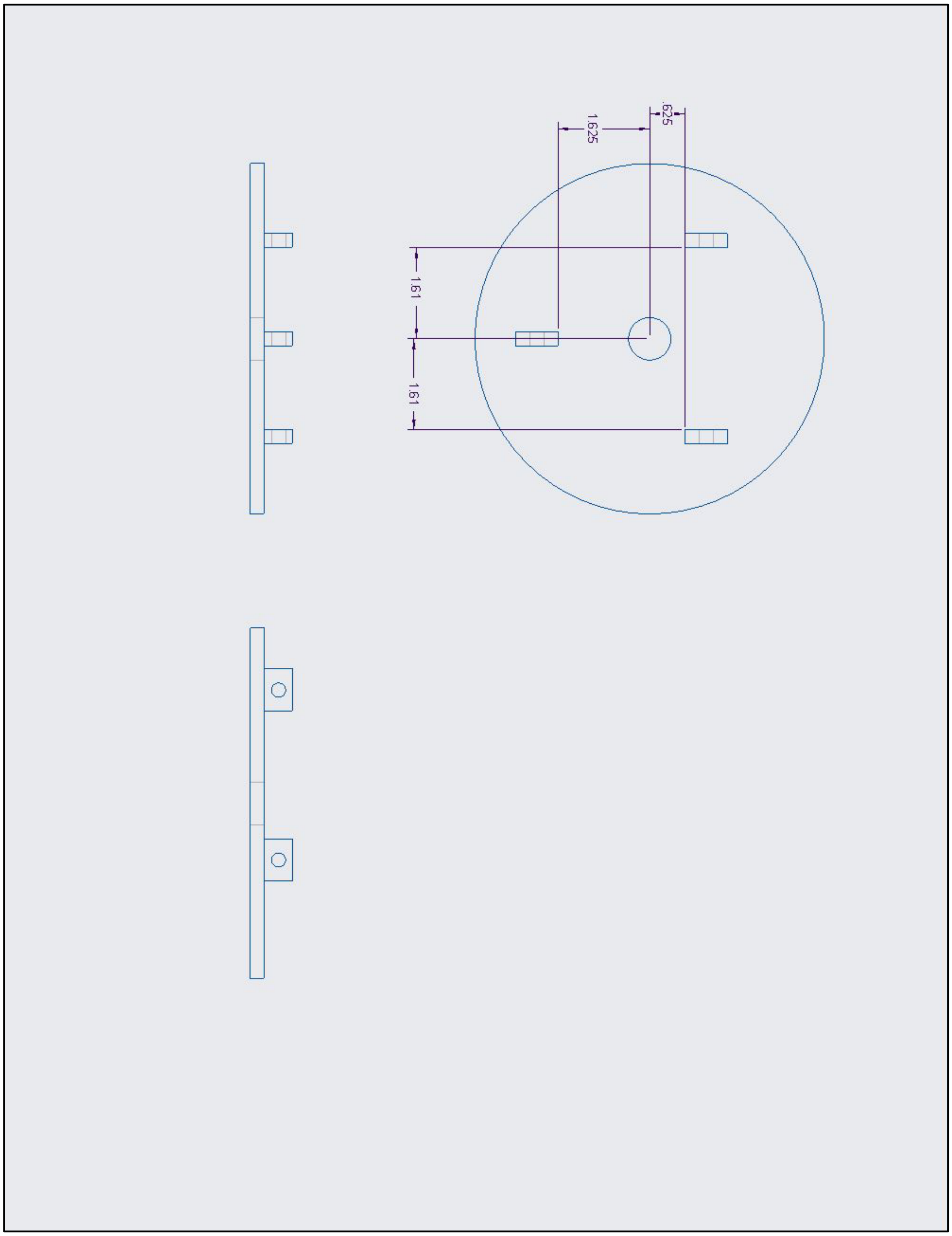

Figure 16: Inner Lid Upper Dimensions

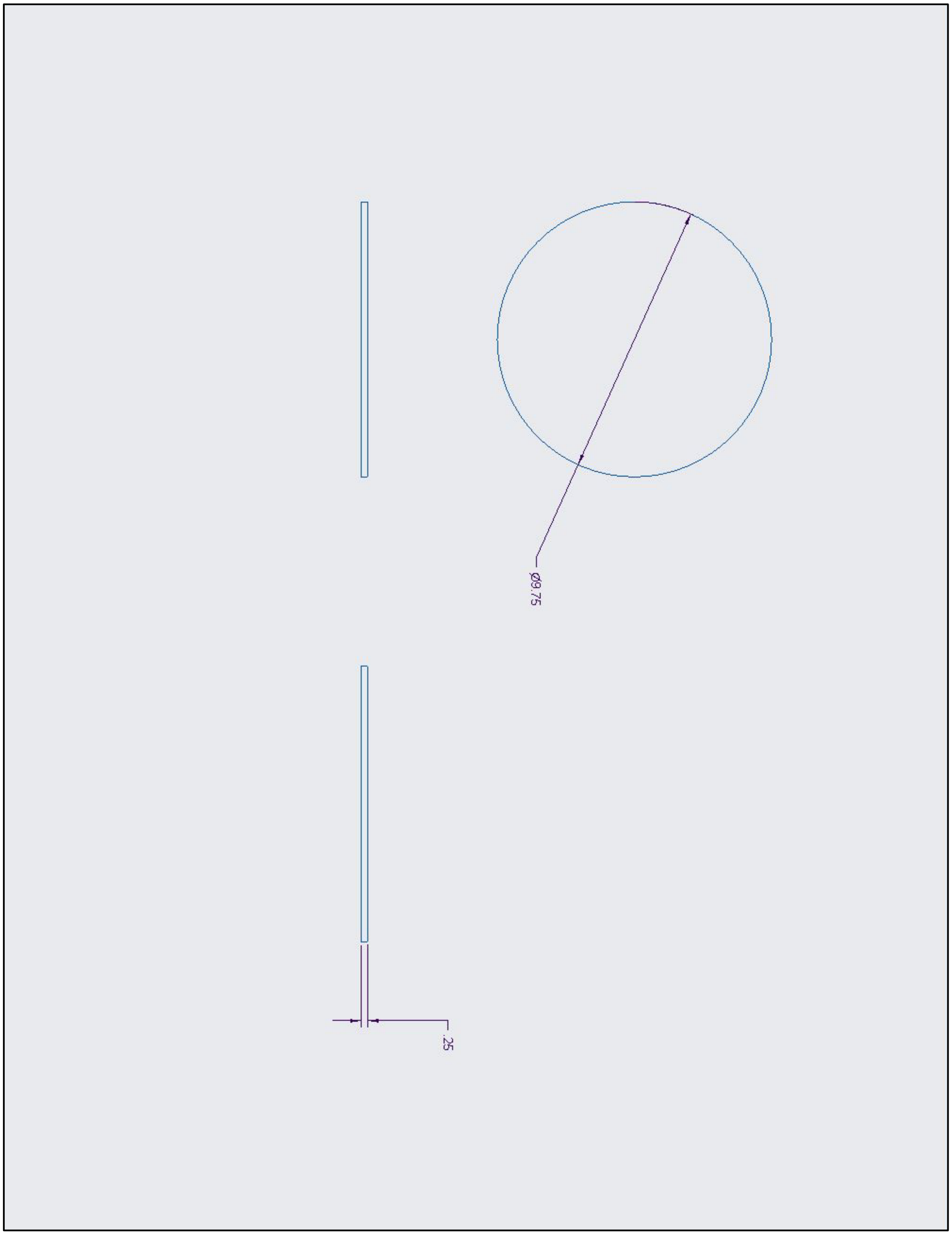

Figure 17: Outer Bottom Tank

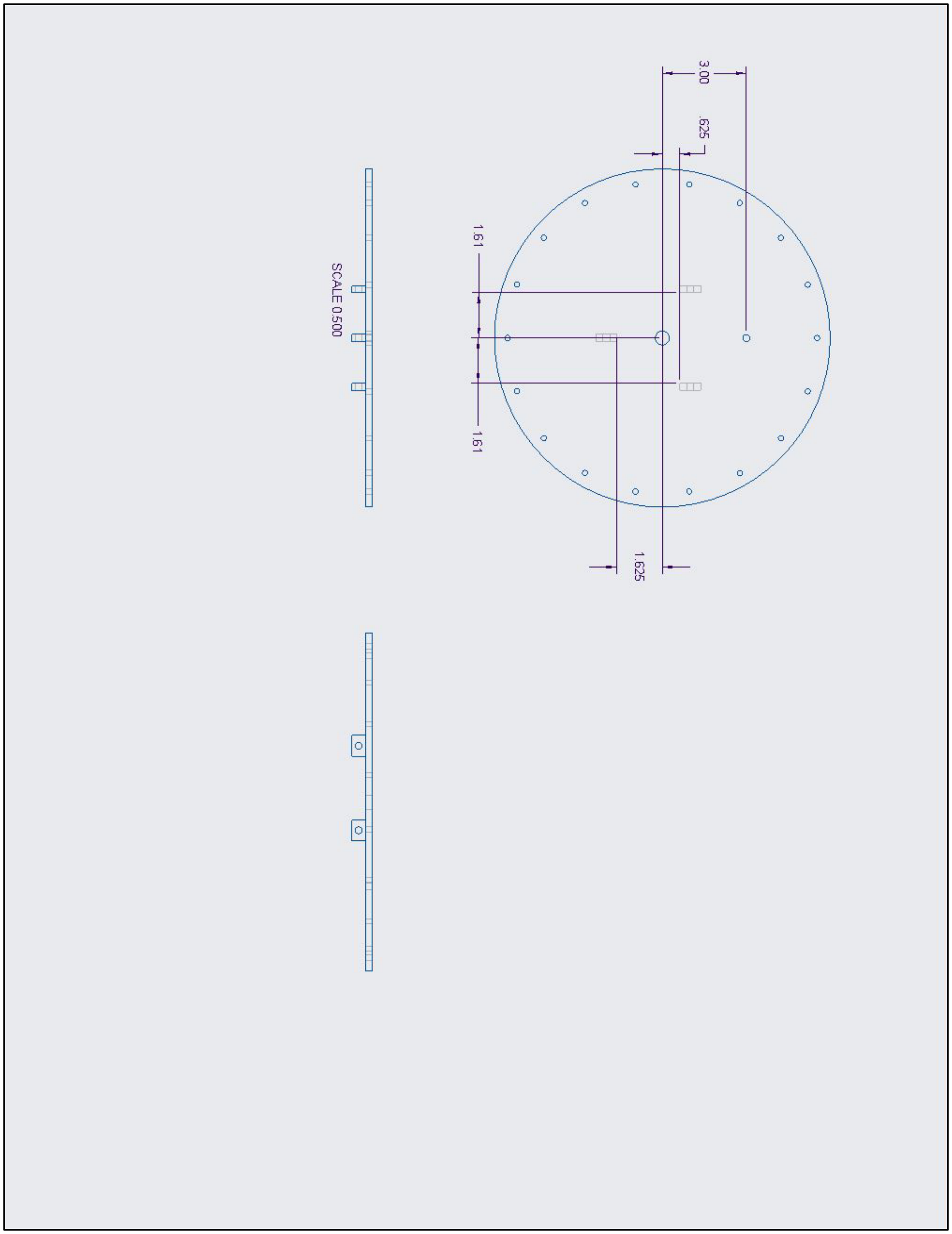

Figure 18: Top Flange Dimensions

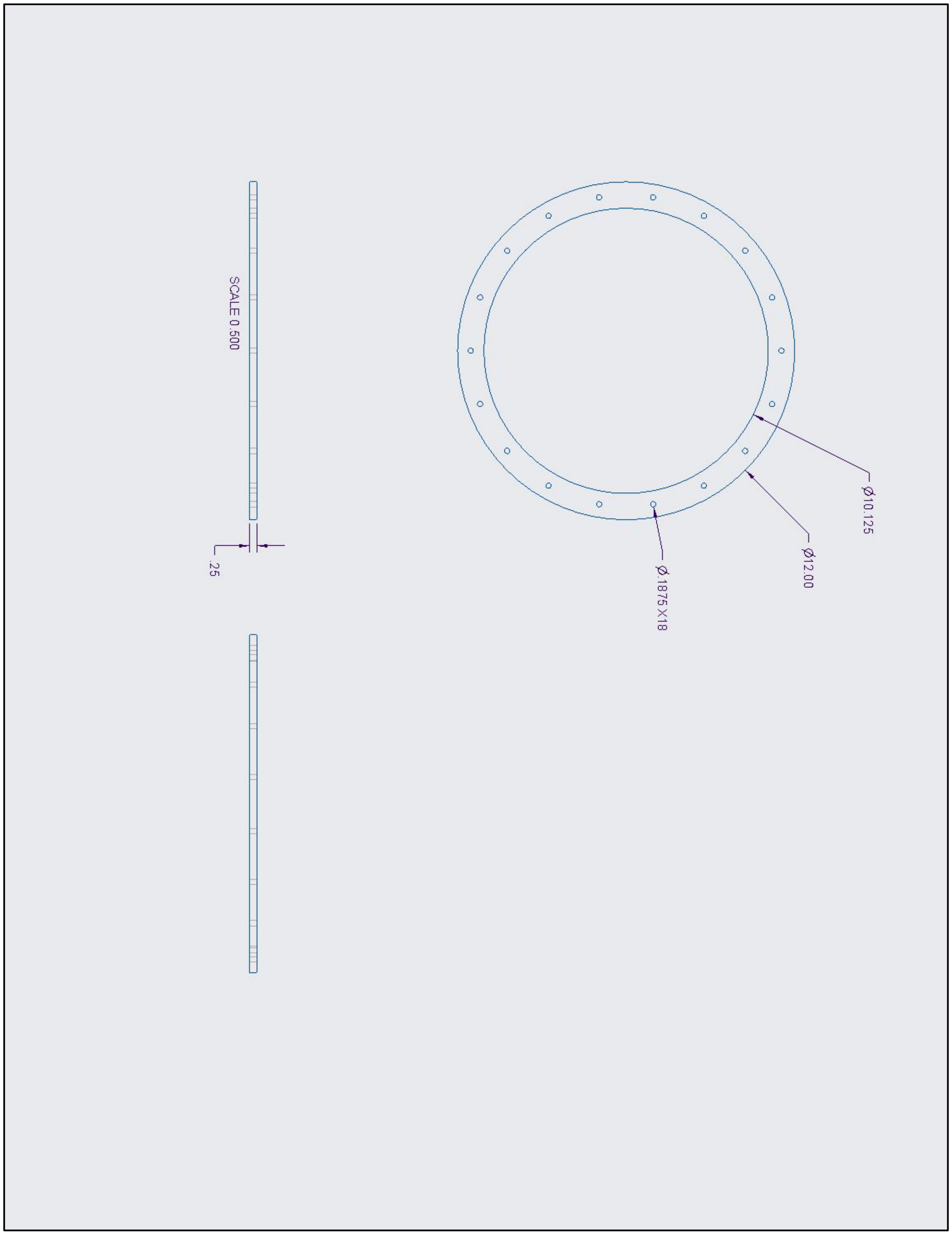

Figure 19: Bottom Flange Dimensions

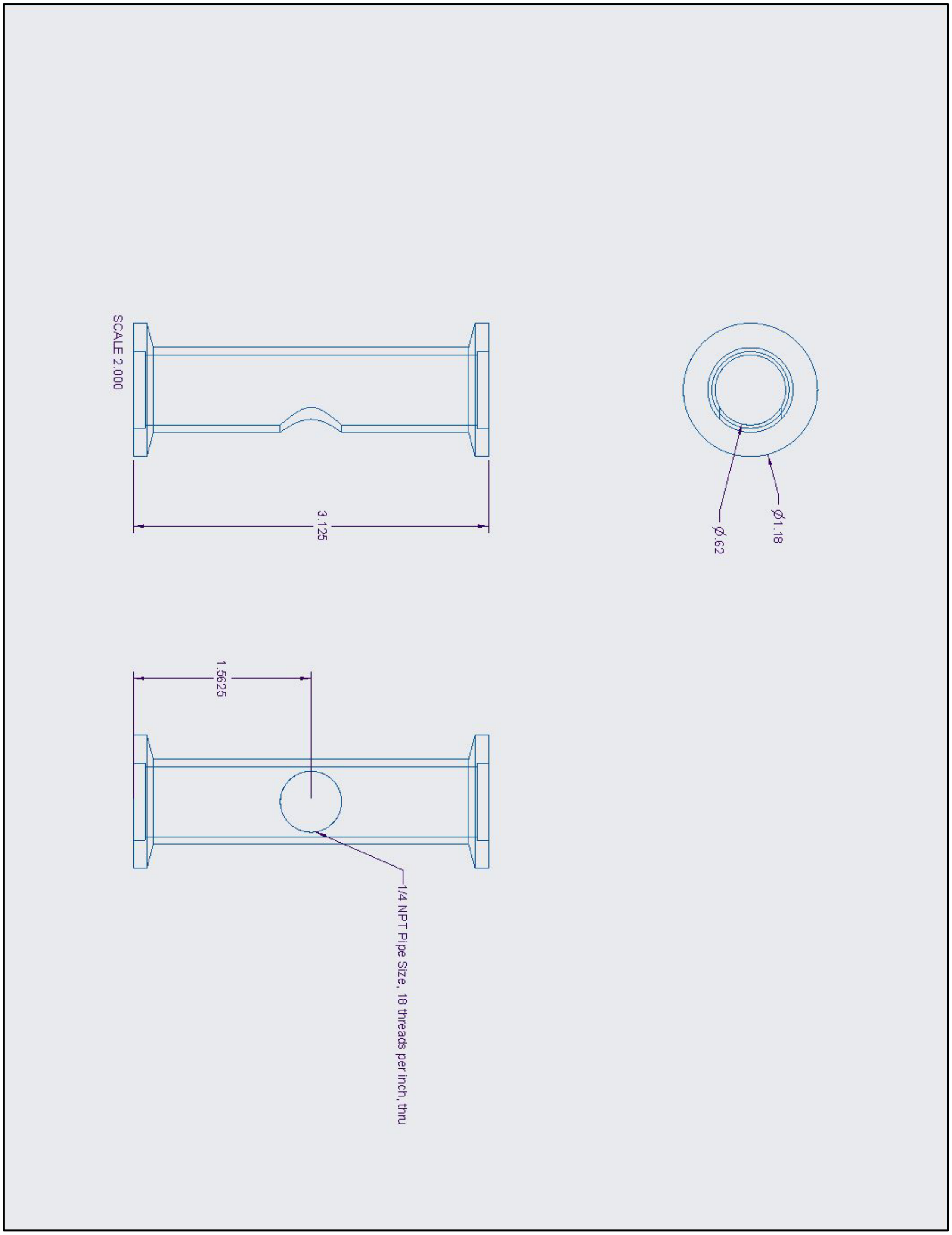

Figure 20: Connecting Pipe Dimensions

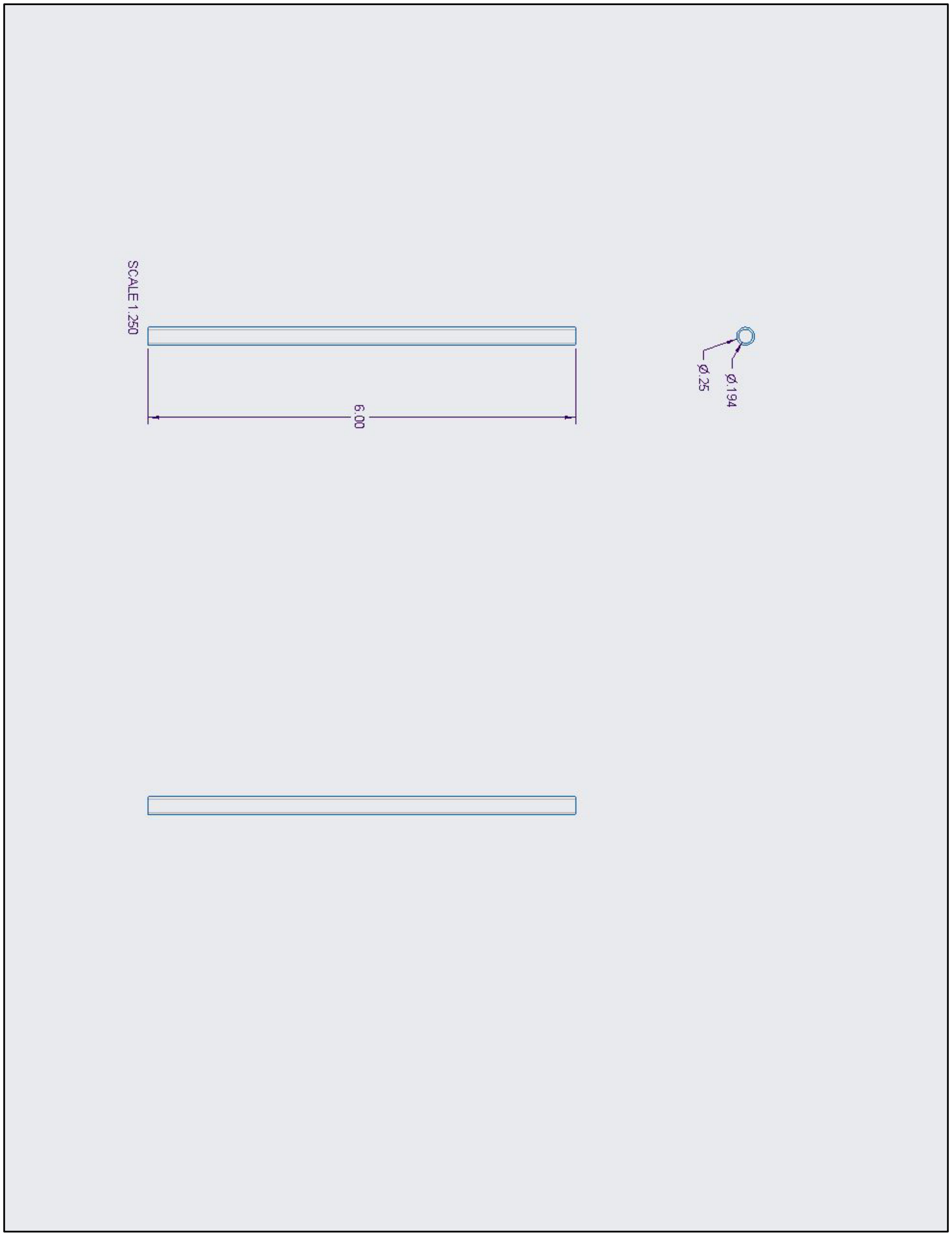

Figure 21: Vacuum Port Dimensions

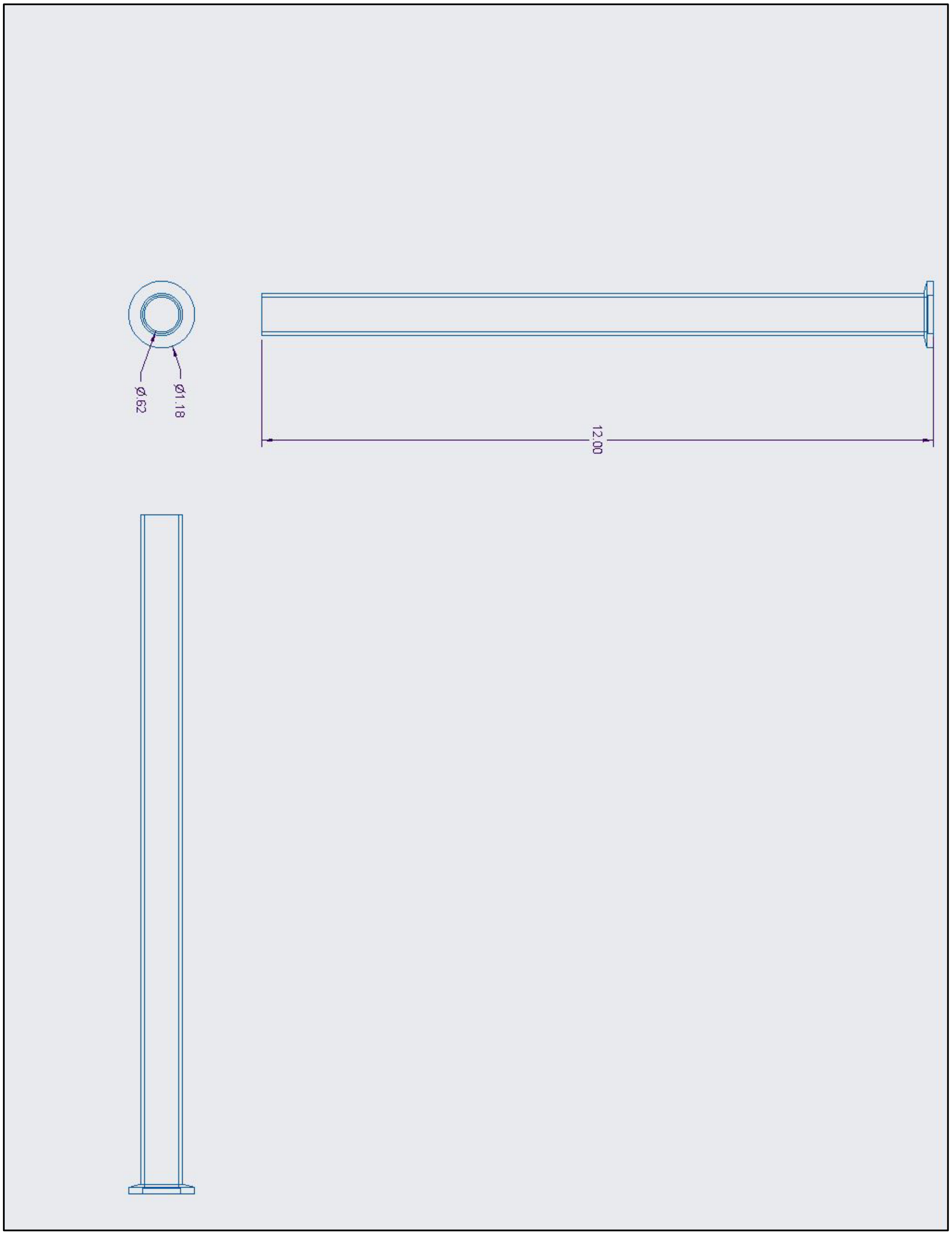

Figure 22: Fill Pipe Dimensions

Appendix H- Heat Transfer Calculations

Prototype Calculations

Table 56: Prototype Calculations without Insulation

Radiation to Inner Tank	3.06587 [W]
Conduction through Steel Walls	91.472 [W]
Conduction through G-10 Plate Supports	0.8302 [W]
Conduction through Fill Pipe	7.3345 [W]
Total Rate of Heat Transfer	102.703 [W]
Mass of Fluid	3.3 [kg]
Specific Heat Capacity of Liquid Nitrogen	2000 [J/kg*K]
Total Time Duration	3.9807 [hours] / 0.1659 [days]

Table 57: Prototype Calculations with MLI and Vacuum

Radiation through Reflective MLI	0.2049 [W]
Conduction through G-10 Plate Supports	0.8302 [W]
Conduction through Fill Pipe	7.3344 [W]
Total Rate of Heat Transfer	8.3696 [W]
Mass of Fluid	3.3 [kg]
Specific Heat Capacity of Liquid Nitrogen	2000 [J/kg*K]
Total Time Duration	48.847 [hours] (2.035 days)

Full-Scale Calculations

Table 58: Full-Scale Calculations for Lift-Off Conditions

Specific Heat Capacity of Liquid Hydrogen	14304 [J/kg*K]
Total Rate of Heat Transfer	381176.17 [W]
Time for Lift-Off	510 [s]
Temperature of Lift-Off	1922.04 [K]
Temperature of Liquid Hydrogen	20 [K]
Change in Mass	7.1453 [kg]
Total Mass without Lift-off Boil-off	128929.1 [kg]

Table 59: Full-Scale Calculations for Re-Entry Conditions

Specific Heat Capacity of Liquid Hydrogen	14304 [J/kg*K]
Total Rate of Heat Transfer	1667194.244 [W]
Time for Re-Entry	90 [s]
Temperature of Re-Entry	2922.04 [K]
Temperature of Liquid Hydrogen	20 [K]
Change in Mass	3.6147 [kg]
Total Mass without Re-Entry Boil-off	128932.7 [kg]

Table 60: Full-Scale Calculations for Space Storage

Remaining Mass	128925.5 [kg]
Specific Heat Capacity of Liquid Hydrogen	14304 [J/kg*K]
Temperature of the Moon Facing the Sun	400 [K]
Temperature of Liquid Hydrogen	20 [K]
Total Storage Time	9973.63 [hours]
Total Storage Time	1.1385 [years]

Appendix I – Ordered Part List

This table has each pre-made part that was ordered for the project.

Table 61: Ordered Parts List

Vendor	Model Number	Item Description	Item Name	Quantity
McMaster-Carr	4518K711	Quick Clamp High-Vacuum Fitting Wing Nut Clamp for 1/2" and 3/4" Tube	Clamp	7
McMaster-Carr	4518K621	Ring for 3/4" Tube OD Quick-Clamp High-Vacuum Fitting	O-ring	7
McMaster-Carr	4518K571	Cap for 3/4" Stainless Steel Tube OD Quick-Clamp High-Vacuum Fitting	Endcap	3
McMaster-Carr	8602T31	Self-Draining Breather Vent 316 Stainless Steel, 1/4 NPT Male	Vent	1
McMaster-Carr	90316A841	Flanged Hex Head Screws w/ Slotted Drive 18-8 Stainless Steel, 10-32 Thread Size, 1-1/4" Long, Pack of 25	Screw	1
McMaster-Carr	89495K775	304/304L Stainless Steel Tube 0.028" Thick, 1/4" OD, 0.194" ID	Vacuum Port	1
McMaster-Carr	9137K11	Fast-Acting Pressure-Relief Valves for Cryogenic Liquids ¼ NPT Male, 30 psi	Pressure Relief Valve	1
McMaster-Carr	4518K241	Quick-Clamp High-Vacuum Fitting Cross Connector for 3/4" Tube OD	Cross-Valve	1
McMaster-Carr	4518K872	Quick-Clamp High-Vacuum Fitting for Stainless Steel Tubing, Connector for 3/4" Tube OD, 12-1/2" Long	Fill Tube	1
McMaster-Carr	4518K871	Quick-Clamp High-Vacuum Fitting for Stainless Steel Tubing, Connector for 3/4" Tube OD, 3-1/8" Long	Short Pipe	2
McMaster-Carr	4934A14	Thread Sealant Tape High-Density, 3M PTFE 48	Sealant Tape	1

		0.003" Thick, 1/2" Wide, 7 Yard Long		
McMaster-Carr	44745K23	Flexible Rubber Foam Pipe Insulation Tube Slit, 1/2" Thick Wall, 3/4" ID, 6 Feet Long	Solid Foam Pipe	1
McMaster-Carr	4507N57	Ultra-Low Temperature Garolite G-10 CR Sheets, 12"x12", ½" Thick	G10	1
Loctite	483630	592 Thread Sealant and Vacuum Equipment Gasket Maker with PTFE	Liquid Sealant	1

Appendix J- Risk Assessment

FAMU-FSU College of Engineering
Project Hazard Assessment Policy and Procedures

INTRODUCTION

University laboratories are not without safety hazards. Those circumstances or conditions that might go wrong must be predicted and reasonable control methods must be determined to prevent incident and injury. The FAMU-FSU College of Engineering is committed to achieving and maintaining safety in all levels of work activities.

PROJECT HAZARD ASSESSMENT POLICY

Principal investigator (PI)/instructor are responsible and accountable for safety in the research and teaching laboratory. Prior to starting an experiment, laboratory workers must conduct a project hazard assessment (PHA) to identify health, environmental and property hazards, and the proper control methods to eliminate, reduce or control those hazards. PI/instructor must review, approve, and sign the written PHA and provide the identified hazard control measures. PI/instructor continually monitor projects to ensure proper controls and safety measures are available, implemented, and followed. PI/instructor are required to reevaluate a project anytime there is a change in scope or scale of a project and at least annually after the initial review.

PROJECT HAZARD ASSESSMENT PROCEDURES

It is FAMU-FSU College of Engineering policy to implement followings:
Laboratory workers (i.e., graduate students, undergraduate students, postdoctoral, volunteers, etc.) performing research in FAMU-FSU College of Engineering are required to conduct PHA prior to commencement of an experiment or any project change to identify existing or potential hazards and to determine proper measures to control those hazards.
PI/instructor must review, approve, and sign the written PHA.
PI/instructor must ensure all the control methods identified in PHA are available and implemented in the laboratory.
In the event laboratory personnel are not following the safety precautions, PI/instructor must take firm actions (e.g., stop the work, set a meeting to discuss potential hazards and consequences, ask personnel to review the safety rules, etc.) to clarify the safety expectations.
PI/instructor must document all the incidents/accidents happened in the laboratory along with the PHA document to ensure that PHA is reviewed/modified to prevent reoccurrence. In the event of PHA modification a revision number should be given to the PHA, so project members know the latest PHA revision they should follow.

PI/instructor must ensure that those findings in PHA are communicated with other students working in the same laboratory (affected users).
PI/instructor must ensure that approved methods and precautions are being followed by:
Performing periodic laboratory visits to prevent the development of unsafe practice.
Quick reviewing of the safety rules and precautions in the laboratory members meetings.
Assigning a safety representative to assist in implementing the expectations.
A copy of this PHA must be kept in a binder inside the laboratory or PI/instructor's office (if experiment steps are confidential).

Project Hazard Assessment Worksheet				
PI/instructor: Dr. Wei Guo	Phone #: (850) 644-3980	Dept.: Mechanical Engineering	Start Date:	Revision number: 1
Project: In-Space Cryogenic Propellant Storage Container		Location(s): FAMU-FSU College of Engineering Machine Shop, Mag Lab Cryogenic Lab		
Team member(s): Anna Gilliard, Liam McConnell, Samantha Myers, Brandon Young		Phone #: (229) 328-7856 (952) 239-6426 (813) 494-7997 (321) 331-6159	Email: ajg18s@my.fsu.edu lkm18c@my.fsu.edu snm16f@my.fsu.edu brandon3.young@famu.edu	

Experiment Steps	**Location**	**Person assigned**	**Identify hazards or potential failure points**	**Control method**	**PPE**	**List proper method of hazardous waste disposal, if any.**	**Residual Risk**	**Specific rules based on the residual risk**
Construct tank	FAMU-FSU College of Engineering	Liam & Machine shop	Welding, power tools.	Request experts to perform the test (machine shop). Ventilation for	Cryogenic gloves, safety goggles, closed-toed shoes, long pants,	Dispose of excess materials according to machine shop standards.	HAZARD:3 CONSEQ: Moderate Residual: Medium	After approval by PI, a copy must be sent to the Safety Committee.

				fumes, fire safe workplace, have a first aid kit on hand (OSHA).	long sleeves.			A written Project Hazard Control is required and must be approved by the PI before proceeding. A copy must be sent to the safety committee. A second worker must be in place before work can proceed (buddy system). Limit the number of authorized workers in the hazard area.
Transport tank to Mag Lab	Mag Lab	Brandon	Weight of the tank, lifting	Use a cart or dolly for tank	Closed-toed shoes.		HAZARD:1 CONSEQ: Minor	Safety controls are planned by both

			heavy objects.	transportation. Do not twist and lift, do not hold for extended periods of time, do not lift the tank higher than necessary (OSHA).			Residual: Low	the worker and supervisor. Proceed with supervisor authorization.
Create vacuum between layers	Mag Lab	Samantha & Dr. Guo	Vacuum aspirator machine	Use expert assistance in operating the machine. Mag Lab Safety training course taken.	Long pants and sleeves, closed-toed shoes, eye protection, cryogenic gloves		HAZARD:5 CONSEQ: Moderate Residual: Med High	After approval by the PI, the Safety Committee and/or EHS must review and approve the completed PHA. A written Project Hazard Control is required and must be approved by the PI and the

								Safety Committ ee before proceedi ng. Two qualified workers must be in place before work can proceed. Limit the number of authorize d workers in the hazard area.
Fill tank with fluid	Mag Lab	Anna & Dr. Guo	Fluid leaks, frost bite or cold burns	Ventilati on hood will be used.	Long pants and sleeves, eye protectio	If any liquid nitrogen spills, it evaporat es in a	HAZAR D:3 CONSE Q: Moderat e	After approval by PI, a copy must be sent to

				If exposure to skin, remove clothing NOT frozen to the skin. Place the body part in a warm water bath (not above 40 degrees C), seek medical attention immediately. (OSHA) Mag Lab Safety training course taken.	n, cryogenic gloves, closed-toed shoes	well-ventilated area.	Residual: Medium	the Safety Committee. A written Project Hazard Control is required and must be approved by the PI before proceeding. A copy must be sent to the safety committee. A second worker must be in place before work can proceed (buddy system). Limit the number of authorized workers in the hazard area.

Seal tank	Mag Lab	Liam & Dr. Guo	Pressure build-up	Pressure relief valve will be used. Do not store in a sealed, air-tight container above the liquid boiling point (OSHA). Mag Lab Safety training course taken.	Eye protection, cryogenic gloves, closed-toed shoes, pants, and long sleeves.		HAZARD:3 CONSEQ: Moderate Residual: Medium	After approval by PI, a copy must be sent to the Safety Committee. A written Project Hazard Control is required and must be approved by the PI before proceeding. A copy must be sent to the safety committee. A second worker must be in place before work can proceed (buddy system). Limit the number of authorized

								workers in the hazard area.
Collect measurements and data	Mag Lab	Anna, Samantha, Liam, Brandon	Pressure build-up, gas boil off.	Pressure relief valve will be used. Do not store in a sealed, air-tight container above the liquid boiling point (OSHA).	Eye protection, cryogenic gloves, closed-toed shoes, pants, and long sleeves.		HAZARD:1 CONSEQ: Negligible Residual: Low	Safety controls are planned by both the worker and supervisor. Proceed with supervisor authorization.
Empty tank and dispose of nitrogen gas	Mag Lab	Brandon & Dr. Guo	Frostbite, weight of the tank.	Ventilation hood will be utilized. If exposure to skin, remove clothing NOT	Closed-toed shoes, long pants and sleeves, cryogenic gloves, eye	Place in a well-ventilated area and allow to evaporate.	HAZARD:3 CONSEQ: Moderate Residual: Medium	After approval by PI, a copy must be sent to the Safety Committee.

				frozen to the skin. Place the body part in a warm water bath (not above 40 degrees C), seek medical attention immediately (OSHA). Mag Lab Safety training course taken.	protection.			A written Project Hazard Control is required and must be approved by the PI before proceeding. A copy must be sent to the safety committee. A second worker must be in place before work can proceed (buddy system). Limit the number of authorized workers in the hazard area.

Principal investigator(s)/ instructor PHA: I have reviewed and approved the PHA worksheet.

Name	**Signature**	**Date**	**Name**	**Signature**	**Date**
Dr. Wei Guo		03/11/2022			

Team members: I certify that I have reviewed the PHA worksheet, am aware of the hazards, and will ensure the control measures are followed.

Name	Signature	Date	Name	Signature	Date
Anna Gilliard		03/11/2022	Samantha Myers		03/11/2022
Liam McConnell		03/11/2022	Brandon Young		03/11/2022

DEFINITIONS:

Hazard: Any situation, object, or behavior that exists, or that can potentially cause ill health, injury, loss, or property damage e.g., electricity, chemicals, biohazard materials, sharp objects, noise, wet floor, etc. OSHA defines hazards as "*any source of potential damage, harm or adverse health effects on something or someone".* A list of hazard types and examples are provided in appendix A.

Hazard control: Hazard control refers to workplace measures to eliminate/minimize adverse health effects, injury, loss, and property damage. Hazard control practices are often categorized into following three groups (priority as listed):

Engineering control: physical modifications to a process, equipment, or installation of a barrier into a system to minimize worker exposure to a hazard. Examples are ventilation (fume hood, biological safety cabinet), containment (glove box, sealed containers, barriers), substitution/elimination (consider less hazardous alternative materials), process controls (safety valves, gauges, temperature sensor, regulators, alarms, monitors, electrical grounding, and bonding), etc.

Administrative control: changes in work procedures to reduce exposure and mitigate hazards. Examples are reducing scale of process (micro-scale experiments), reducing time of personal exposure to process, providing training on proper techniques, writing safety policies, supervision, requesting experts to perform the task, etc.

Personal protective equipment (PPE): equipment worn to minimize exposure to hazards. Examples are gloves, safety glasses, goggles, steel toe shoes, earplugs or muffs, hard hats, respirators, vests, full body suits, laboratory coats, etc.

Team member(s): Everyone who works on the project (i.e., graduates, undergraduates, postdocs, etc.). The primary contact must be listed first and provide phone number and email for contact.

Safety representative: Each laboratory is encouraged to have a safety representative, preferably a graduate student, to facilitate the implementation of the safety expectations in the laboratory. Duties include (but are not limited to):

Act as a point of contact between the laboratory members and the college safety committee members.

Ensure laboratory members are following the safety rules.

Conduct periodic safety inspection of the laboratory.

Schedule laboratory clean up dates with the laboratory members.
Request for hazardous waste pick up.
Residual risk: Residual Risk Assessment Matrix are used to determine project's risk level. The hazard assessment matrix (table 1) and the residual risk assessment matrix (table2) are used to identify the residual risk category.
The instructions to use hazard assessment matrix (table 1) are listed below:
Define the workers familiarity level to perform the task and the complexity of the task.
Find the value associated with familiarity/complexity (1 – 5) and enter value next to: HAZARD on the PHA worksheet.

Table 1. Hazard assessment matrix.

		Complexity		
		Simple	Moderate	Difficult
Familiarity Level	Very Familiar	1	2	3
	Somewhat Familiar	2	3	4
	Unfamiliar	3	4	5

The instructions to use residual risk assessment matrix (table 2) are listed below:
Identify the row associated with the familiarity/complexity value (1 – 5).
Identify the consequences and enter value next to: CONSEQ on the PHA worksheet. Consequences are determined by defining what would happen in a worst-case scenario if controls fail.
Negligible: minor injury resulting in basic first aid treatment that can be provided on site.
Minor: minor injury resulting in advanced first aid treatment administered by a physician.
Moderate: injuries that require treatment above first aid but do not require hospitalization.
Significant: severe injuries requiring hospitalization.
Severe: death or permanent disability.
Find the residual risk value associated with assessed hazard/consequences: Low –Low Med – Med– Med High – High.
Enter value next to: RESIDUAL on the PHA worksheet.

Table 2. Residual risk assessment matrix.

Assessed Hazard Level	**Consequences**				
	Negligible	Minor	Moderate	Significant	Severe
5	Low Med	Medium	Med High	High	High
4	Low	Low Med	Medium	Med High	High
3	Low	Low Med	Medium	Med High	Med High
2	Low	Low Med	Low Med	Medium	Medium
1	Low	Low	Low Med	Low Med	Medium

Specific rules for each category of the residual risk:
Low:
Safety controls are planned by both the worker and supervisor.
Proceed with supervisor authorization.

Low Med:
Safety controls are planned by both the worker and supervisor.
A second worker must be in place before work can proceed (buddy system).
Proceed with supervisor authorization.
Med:
After approval by the PI, a copy must be sent to the Safety Committee.
A written Project Hazard Control is required and must be approved by the PI before proceeding. A copy must be sent to the Safety Committee.
A second worker must be in place before work can proceed (buddy system).
Limit the number of authorized workers in the hazard area.
Med High:
After approval by the PI, the Safety Committee and/or EHS must review and approve the completed PHA.
A written Project Hazard Control is required and must be approved by the PI and the Safety Committee before proceeding.
Two qualified workers must be in place before work can proceed.
Limit the number of authorized workers in the hazard area.
High:
The activity will not be performed. The activity must be redesigned to fall in a lower hazard category.

Hazard types and examples

Types of Hazards	**Example**
Physical hazards	Wet floors, loose electrical cables objects protruding in walkways or doorways
Ergonomic hazards	Lifting heavy objects Stretching the body Twisting the body Poor desk seating
Psychological hazards	Heights, loud sounds, tunnels, bright lights
Environmental hazards	Room temperature, ventilation contaminated air, photocopiers, some office plants acids
Hazardous substances	Alkalis solvents
Biological hazards	Hepatitis B, new strain influenza
Radiation hazards	Electric welding flashes Sunburn

Chemical hazards	Effects on central nervous system, lungs, digestive system, circulatory system, skin, reproductive system. Short term (acute) effects such as burns, rashes, irritation, feeling unwell, coma and death. Long term (chronic) effects such as mutagenic (affects cell structure), carcinogenic (cancer), teratogenic (reproductive effect), dermatitis of the skin, and occupational asthma and lung damage.
Noise	High levels of industrial noise will cause irritation in the short term, and industrial deafness in the long term.
Temperature	Personal comfort is best between temperatures of 16°C and 30°C, better between 21°C and 26°C. Working outside these temperature ranges: may lead to becoming chilled, even hypothermia (deep body cooling) in the colder temperatures, and may lead to dehydration, cramps, heat exhaustion, and hyperthermia (heat stroke) in the warmer temperatures.
Being struck by	This hazard could be a projectile, moving object or material. The health effect could be lacerations, bruising, breaks, eye injuries, and possibly death.
Crushed by	A typical example of this hazard is tractor rollover. Death is usually the result
Entangled by	Becoming entangled in machinery. Effects could be crushing, lacerations, bruising, breaks amputation and death.
High energy sources	Explosions, high pressure gases, liquids and dusts, fires, electricity, and sources such as lasers can all have serious effects on the body, even death.
Vibration	Vibration can affect the human body in the hand arm with `white-finger' or Raynaud's Syndrome, and the whole body with motion sickness, giddiness, damage to bones and audits, blood pressure and nervous system problems.
Slips, trips, and falls	A very common workplace hazard from tripping on floors, falling off structures or downstairs, and slipping on spills.
Radiation	Radiation can have serious health effects. Skin cancer, other cancers, sterility, birth deformities, blood changes, skin burns, and eye damage are examples.
Physical	Excessive effort, poor posture and repetition can all lead to muscular pain, tendon damage and deterioration to bones and related structures
Psychological	Stress, anxiety, tiredness, poor concentration, headaches, back pain, and heart disease can be the health effects
Biological	More common in the health, food, and agricultural industries. Effects such as infectious disease, rashes, and allergic response.

Project Hazard Control- For Projects with Medium and Higher Risks

Name of Project: In-Space Cryogenic Propellant Storage		**Date of submission: 11/19/2021**
Team member	**Phone number**	**e-mail**

Anna Gilliard	**(229) 328-7856**	**ajg18s@my.fsu.edu**
Liam McConnell	**(952) 239-6426**	**lkm18c@my.fsu.edu**
Samantha Myers	**(813) 494-7997**	**snm16f@my.fsu.edu**
Brandon Young	**(321) 331-6159**	**brandon3.young@famu.edu**
Faculty mentor	**Phone number**	**E-mail**
Dr. Wei Guo	**(850) 644-3980**	**wguo@magnet.fsu.edu**

Rewrite the project steps to include all safety measures taken for each step or combination of steps. Be specific (don't just state "be careful").

Construct tank: Wear cryogenic gloves, safety goggles, closed-toed shoes, long pants, and long sleeves to prevent injury from welding and the use of power tools. Allow the machine shop to do most of the construction. Dispose of excess materials based on the standards of the machine shop.
Transport tank to Mag Lab: Wear closed-toed shoes and use a cart or dolly to roll the tank to the Mag Lab to reduce the risk of physical strain or injury from dropping the container.
Create a vacuum between layers: Wear long pants, long sleeves, closed-toed shoes, eye protection and cryogenic gloves.
Fill tank with fluid: Wear long pants and long sleeves, eye protection, cryogenic gloves, and closed-toed shoes to protect from leaks and frostbite injury. If any liquid nitrogen spills, it must evaporate in a well-ventilated area.
Seal tank: Wear long pants and sleeves, eye protection, and closed-toed shoes. Ensure that the pressure relief valve is operational so that the pressure in the tank does not exceed the maximum allowable in the tank and explode.
Collect measurements and data: Adhere to lab requirements for observing the tank. Ensure that pressure relief valve is operational and there is proper ventilation for the boil off.
Empty tank and dispose of nitrogen gas: Wear closed-toed shoes, long pants, and sleeves. Place the tank in a well-ventilated area and allow gas to evaporate.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

In the case of any injury, the first step taken will be to call 911.
If any problems in the lab occur, including tank rupture or fluid leaking, we will contact the lab supervisor and our department representative.
The injured person/people should be removed from the space and placed in a safe location.
The appropriate emergency response representatives should be called.
The emergency contact of the injured party should be notified.
If injury is due to faults in the lab, ensure that the source of risk is eliminated.
Ensure that emergency responders have all details about the situation.

List emergency response contact information:

Call 911 for injuries, fires, or other emergency situations
Call your department representative to report a facility concern

Name	Phone number	Faculty or other COE emergency contact	Phone number
Kermit Gilliard	**(229) 377-8455**	**Shayne McConomy**	**(850) 410-6624**
Chris Que	**(954) 478-7255**		

Charles Young	**(321) 278-4233**		
Alex Myers	**(813) 484-1953**		
Safety review signatures			
Team member	Date	Faculty mentor	Date
Anna Gilliard	**11/19/2021**		
Liam McConnell	**11/19/2021**		
Samantha Myers	**11/19/2021**		
Brandon Young	**11/19/2021**		

Report all accidents and near misses to the faculty mentor.