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EML4551-2

Team 513: Reusable Cryogenic Connectors

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Abstract

As an interest in missions to Mars continues to grow, NASA strives to build a space shuttle refueling station on the moon. This will work similarly to a gas station; however, the fluid being stored will be liquid oxygen rather than gasoline. The refueling station on the moon is crucial for space travel. It would allow spaceships to travel further without refueling on Earth. We designed a reusable cryogenic connector to transfer fuel from a storage tank to the spacecraft. This requires a design that will provide a tight seal to prevent any leakage so that as much fluid is transferred as possible. However, transferring liquid oxygen through the connector produces problems. Liquid oxygen boils around -300 degrees Fahrenheit and the materials in contact must withstand the temperature variations. Stainless steel and Kel-f, a thermoplastic used for sealing, are used for cryogenic and space applications. They are less affected by the extreme conditions provided by the liquid oxygen and the moon.

Most cryogenic connections require twisting motions to screw components together. This causes problems with astronauts as they use bulky gloves which make it hard to handle small objects and twisting motion. We have designed the use of three latches and hooks to engage the seal which will allow astronauts to seal the connection. The connector has two valves that will control the flow of the fluid and prevent any outside particles from entering the tubing during disconnection. A handle connects to each valve that will be used by the astronaut to control flow.

Life-cycle testing will be done using liquid nitrogen and helium gas since liquid oxygen is highly explosive. It will test the connector at very low temperatures and show the sealing capability of the connection to prevent leakage. The result of these tests is to confirm the reusable cryogenic connector can be used for multiple missions and refueling needs.

Disclaimer

The FAMU-FSU College of Engineering cannot be held responsible for any damages or injuries that result from any attempt to replicate this design.

Acknowledgement

We would like to thank our sponsor, NASA Marshall Space Flight Center, for providing this project to the university and providing resources for the success of the project. A special thank you goes out to our advisors who have been instrumental in the completion of this project: Shawn Brechbill, our technical point of contact at NASA-MSFC, Dr. Mark Vanderlaan, our advisor at FAMU-FSU College of Engineering, and finally our professor Dr. Shayne McConomy. As the Mechanical Engineering Department Office helped with purchasing our parts, we would like to give a special thank you to Neil Coker and Chrissy Karantinos. Thank you to everyone at Machine Shop, Justin and Tom, for working closely with us and making sure that we were able to produce a working prototype. Finally, thank you to the FAMU-FSU College of Engineering for providing the education and tools required to successfully complete this project.

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Notation

MEOP	Maximum Expected Operating Pressure
MLI	Multi-Layer Insulation

Chapter One: EML 4551C

1.1 Project Scope

1.1.1 Project Description

To design, build, and test a cryogenic connector interface and conduct age life testing with a focus on the seal/joint design. The environment will require correct selection of materials for the interface to allow for successful operation and maintenance. A process for the protecting the interface between uses will be developed so that the connector can support multiple missions on the moon.

1.1.2 Key Goals

Create a connector interface that could be used as a refueling/depot station for cryo-fluids (90 k range). Design a connector that will be compatible for multiple applications. Cater to strength differences by allowing a minimum operable force by a suited astronaut in the 95% female category. Conduct age cycle life testing that will result in low loss from the valve design. The connector must be ergonomic for the astronaut to operate with thick gloves.

1.1.3 Primary Market

Primary market will include research that involves the transfer of cryogenic fluids. Another primary market is the aerospace industry. Within this industry, NASA-Marshall Space Flight Center (MSFC) showed a tremendous interest in this technology.

1.1.4 Secondary Market

Our secondary market includes cryogenic storage and transportation companies. This is a growing market that will find interest in incorporating our refueling design to their existing cryogenic tanks.

1.1.5 Assumptions

For this design, it will be assumed that the system is isothermal and the connecting hoses for our joint will handle 50 PSI without blistering. Furthermore, the astronaut will have knowledge of quick release valves and locking mechanisms. The focus is on the joint design; thus, it is important to not overextend the scope of the project.

1.1.6 Stakeholders

The stakeholders for our project are NASA, astronauts, Dr. Shayne McConomy, and the FAMU-FSU College of Engineering. As our sponsor, NASA will be providing the resources and funds for this project. The primary users of this project will be astronauts. They will operate and depend on our design to complete their missions. As our project manager, Dr. McConomy is investing time and effort to ensure our success. We are representing him and our institution, the FAMU-FSU College of Engineering.

1.2 Customer Needs

1.2.1 Interpreted Need

The interpreted needs of the customer help to define and narrow the scope of the project to produce the outcome that is desired by the customer. Table 1 shows a list of questions that were directed towards the sponsor of this project in order to assign various functions/needs that are necessary for the final product.

Table 1: NASA-MSFC team statements and interpreted needs.

Question Asked:	Customer Statements	Interpreted Needs
1) What soft materials can be used for sealing/joining?	"Kel-F polymer, Teflon, and Vespel."	Materials need to be suitable for space and moon use.
2) What metals are suitable for cryogenic temperatures?	"Avoid high carbon content metals. Most stainless steels will work for this project"	The metal used needs to maintain its mechanical properties, specifically its ductility, at cryogenic temperature.
3) What resources are available for us to understand the approach that should be taken for this design?	"The aerospace fluid component designer handbook will be sent to you."	Avoid designing a new sealing system. Use accepted pre-existing valves and connectors.
4) Our focus seems to be the sealing-system; however, are we responsible for connecting hoses leading to a reservoir? If so, should one of our focuses be heat leak?	"Don't overextend the scope of the project and focus on the joint and seal of the connector"	Design will incorporate only the joint, sealing surface, and the mating and de-mating of the connector for a life cycle.

5) Will we need to provide a thermal analysis of this system?	"No"	Design will not consider thermal transfer.
6) What is the biggest issue with current sealing designs that are in use?	"Too much fluid loss through connected components"	Design a seal that will limit fluid loss through the connection.
7) What is the budget for this project?	"$5000 for materials and $4000 for traveling split amongst the four NASA-MSFC projects."	Materials need to be under $1250 for the connector and final product.
8) What level of testing do you require? 100 cycles were mentioned in the project brief but how do you define cycles.	"A cycle is the entire process of connecting and disconnecting the device"	Design will withstand the process of connecting and disconnecting with transfer of fluid for a life span that is roughly 100 cycles with little/no maintenance.
9) What is the pressure of the fluid that will pass through the connector?	"For testing purposes, the fluid will be at 50 psi or lower, but would be much higher in conditions used."	The connector design needs to withstand a pressure through it at 50 psi.

10) What would the operator of the connector be like? Suited or not?	"Design for a suited astronaut considering dexterity and strength."	Connector is operable by a suited astronaut that would have a force at minimum of 95% female category.
11) What are the dimensions that are required for this connector?	"Inner diameter greater than 1 cm and less than 3 cm."	The design will need to follow the range of 1-3 cm as the inner diameter while outer diameter can allow for use by a suited astronaut.

From these customer statements in Table 1, the team has determined specific needs for the final connector design. The main focus that the sponsor wishes to accomplish with this project is a connector design that has an emphasis on the mating/de-mating mechanism, useable by suited astronaut in the 95% female category, with a specific identification of materials that will be appropriate for the joint, sealing, and overall connector that is used in space or the harsh conditions of the moon. Taking away potential heat dissipation or thermal transfer from the connector, the seal/joint aspect of the connector will require the low fluid loss at the specified psi range of the fluid. This connector will also need to survive a life cycle test of 100 cycles with little or no maintenance that would essentially cover the potential life span that NASA-MSFC would require in years to come. The connector and testing will also be produced with a budget of roughly $1250 that would limit certain design and material selections. These needs will help determine the final connector design that will be sufficient for the end goal of the sponsor.

1.2.2 Explanation of Results

In order to determine the specific needs of this project, questions were directed towards the team at NASA-MSFC: Rachel McCauley, David Edleman, Shawn Brechbill, Kevin Higdon, Marvin Barnes. After the meeting, the agreement moving forward was to reduce the scope of the project as much as possible to allow for enough time to complete the project. The further questions expanded our understanding of the project and determined the desired needs for the connector which can be seen in the section above, 1.2.1 Interpreted Needs. Their statements were then interpreted into needs that are to be met for the project which can be found in Table 1.

1.3 Functional Decomposition

1.3.1 Explanation of Results

The functional decomposition (F.D.) consists of a flow chart, cross reference chart, as well as a hierarchal chart. The data was produced through a combined understanding of the project scope and common operation methods for connecting two pipes together.

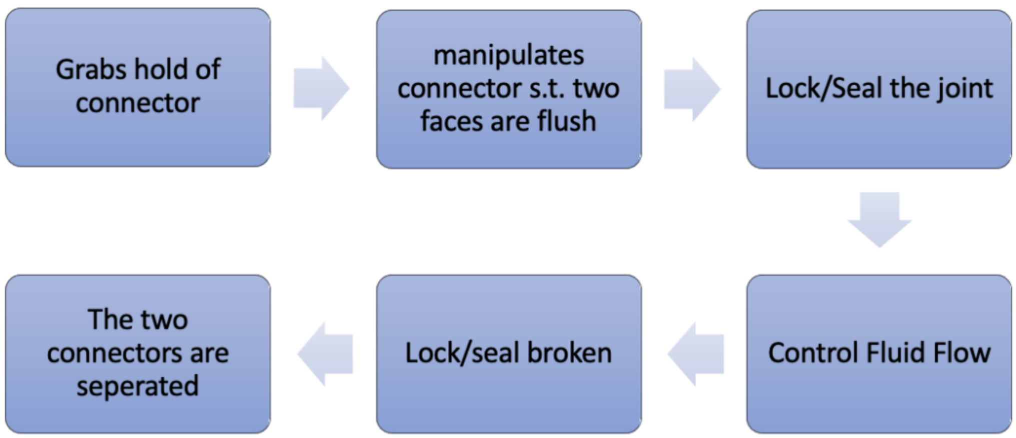


Figure 1: Functional Decomposition Flow Chart

In Figure 1, the flow chart embodies the process of operation done by both components and operators. The assumptions are that the user (astronaut) will be able to manipulate the orientation of the connector that is being linked with ground. The ground is the connector that is secure to a tank or other structure which will be attached to one of the sides of the connector system.

Functions	Systems	
	Operate	Maintain
Manipulate two connector ends together	x	
Lock the two ends together	x	
Transfer cryo-fluid across the joint	x	
Seal the space between the two ends.	x	x
Control fluid dynamics	x	
Unlock two ends	x	
Release seal between connector faces	x	x
Keep dust and dirt particles out of the system		x
Mind thermal expansion wear		x
Prevent breaking between uses	x	x

Figure 2: Cross Reference Chart

In Figure 2, the cross-reference table is used to associate systems of the connector to a verb/functions that relates to its purpose in the design. This was organized with the project scope and thought of what needs to be done by the user.

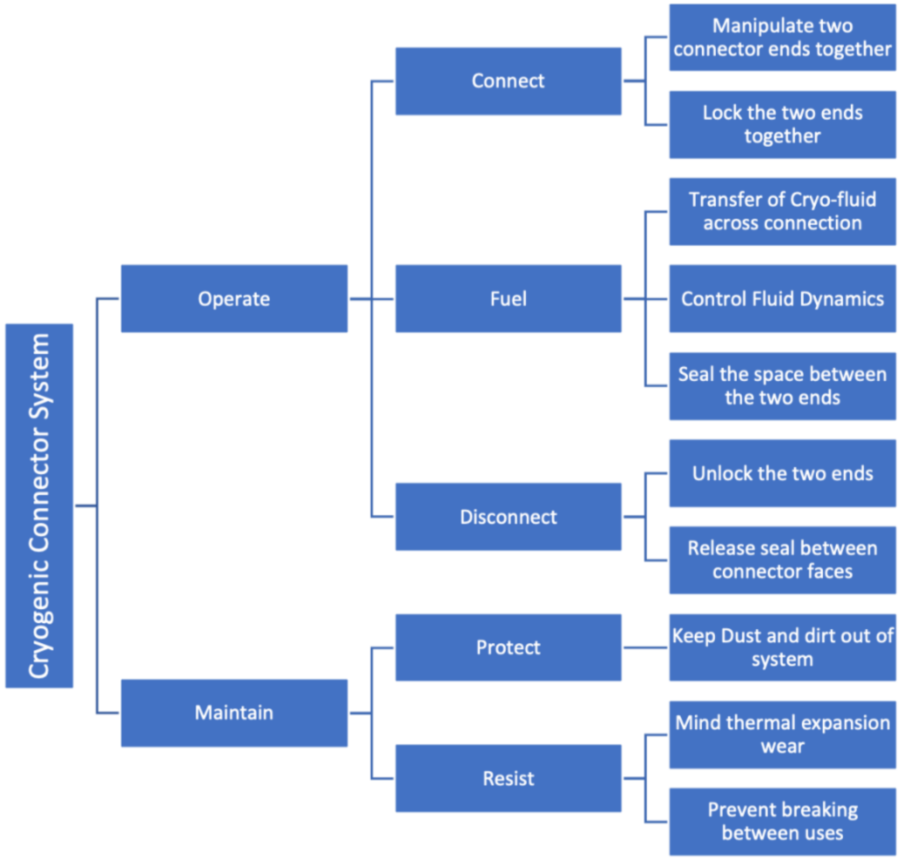


Figure 3: Hierarchal Chart

In Figure 3, the hierarchal chart is used to better understand the system and its components. The overall system is broken up into sub-systems. These sub-systems are then broken down further into the sub-systems needed by them, and so on. The main distinction for our system is between components that need to be operated by the user and components of the system that are passive and require no action, such as material strength.

1.3.2 Connection to Systems

Under the main cryogenic connector system, there are the two sub-systems called ‘Operate’ and ‘Maintain’. These two systems are the overarching systems and functionality for the connector. They each have further sub-systems that define what encompasses them. This continues to define our functions that are completed by the connector and determine a successful design and use. All the lower functions feed into the higher systems by explaining what about the use of the connector makes up operating or maintaining through missions. Through the user, the functions that encompass the higher system will be accomplished or there will be failures in the system. Therefore, the user must keep their actions under careful consideration during use. While the functions are the essence of the connector's abilities, they are grouped together to form these sub-systems of the project that by themselves also describe what is being done to the main system.

1.3.3 Smart Integration

The series of functions represent the sub-systems because they represent the physical action needed as input to the system. Without these actions the system will not properly accomplish its most basic function. These functions also incorporate different sub-systems' overall function. For instance, to accomplish our fueling needs, the system needs to seal the connector to prevent loss of fluid. This would be under the 'Operate' sub-system, but it could also apply to the sub-system 'Maintain' because one of the sub-systems there is to protect the connector from the environment. The sealing system developed has the ability to accomplish both the protect functionality and the sealing functionality for the system. Another example would be preventing the breaking of the connector. This function is under the 'Maintain' sub-system but the function itself is crucial for the operation of the whole connector. This function through whatever means would allow for multiple connections and disconnections of the system, as well as allowing fueling. While it is under the 'Maintain' sub-system, it is crucial for the 'Operate' sub-system as well. The functions described in the figures have a capacity to be incorporated into the other sub-systems and help define the connectiveness of each function to the others. It will help produce ideas that are more efficient and have parts that have more than one functionality.

1.3.4 Action and Outcome

The process that needs to take place is the astronaut will grab a hold of the connector and manipulate it such that it is flush with the grounded connector. The astronaut will then, with the help of a mechanism, lock and seal the joint between the two connector ends. The astronaut will then operate a valve to control the flow of fluid across the connector boundary. Once fluid transfer is complete, the astronaut will halt fluid flow before disconnecting the two ends of the connector.

1.3.5 Function Resolution

Essentially, the overall function of our system is the connecting of two pipes such that a seal is produced so cryo-fluids may flow through the connector joint.

1.4 Targets and Metrics

1.4.1 Critical Functions

The most important functions in the design of the device are connecting and releasing the connector ends, locking and sealing the interfaces, and transferring cryo-fluid across the joint. These functions were selected after reviewing the problem statement with our sponsor, NASA, and our advisor, Dr. Vanderlaan. Connecting and releasing the connector ends will prove to be the biggest challenge as the astronaut is fully suited and their fine motor skills will be challenged. The device should be large enough to be easily manipulated by space suit gloves, and light enough to be maneuvered by a 50^{th} percentile male and 95^{th} percentile female. Therefore, the connector diameter should be at least 2.57 cm, but cannot exceed 3 cm as requested by our sponsor, and the force required to mate, and disconnect the connectors must not exceed 48 Newtons. The lock and seal of the interfaces is arguably the most important function as the joint must have little to no loss. Excess loss will deem our design as a failure, so it is essential to not exceed the permissible leakage rate, 0.001 Standard Cubic Inches per Minute (SCIM). Transferring cryogenic fluid through the joint is the primary function that will lead to the refueling of the space shuttle. This must be done at a volumetric flow rate under 0.1 SCIM for cryogenic fluids at 90 Kelvin.

1.4.2 Secondary Functions

The secondary functions of our design are preventing dust/dirt from interfering with the connection, resist thermal expansion and contraction defects, as well as the withstanding multiple uses without failure. These functions were developed while considering the environment in which this system will operate. Therefore, any lunar dust or dirt particles will be avoided by using an ingress protection (IP) of 64. Since the connector will experience cryogenic temperatures, the connector will be subject to thermal expansion during the cooling and warming up of the connector. We must keep any expansion or contraction relative to the system equal to zero. To control fluid dynamics, the boil off rate experienced within the connector must stay below 0.0023 SCIM. This will ensure that our volumetric flow rate will not fluctuate from 0.1 SCIM. To be able to withstand multiple missions the connector must withstand a force of at least 500 Megapascals (MPa) that will prevent breakage if there was user error through pulling or misuse of the connector across missions. A low carbon metal will be preferred for the connector as these alloys hold their ductility well in cryogenic conditions. The secondary functions are separate from the primary functions since the primary functions are the design aspects that are critical for the success of this design, while the secondary functions just improve the functionality of the connector beyond the critical.

Aside from the primary and secondary functions, there are targets that must be met to ensure extra safety precautions and the needs of NASA-MSFC are reached. The connector must withstand a shear stress of 435 MPa, as a bend normal to the direction of the connection will result in a failure of the system. Meaning that a contact force of up to 435 MPa on the outside of the connector will not be able to break a piece of the connector off at any moment. The connector must be pure of any carbon content, meaning no percent of the connector can have carbon (wt% = 0). When added to alloys, carbon causes the structure of the alloy to be more brittle. This affect is especially noticeable in cryogenic applications. The alloy used in the connector must have at least 10.5 percent of its weight come from chromium, (wt% = 10.5). This will ensure the alloy will not rust. The chromium-oxide formed on the surface of the alloy will protect the connector from any rust. Although these targets extend the scope of our functions, they are necessary for the success of our design.

1.4.3 Derivation of Targets and Metrics

Each metric deemed necessary for the functions of our design requires a target value. These values were derived by a combination of our sponsor's requests and our team's calculations, which were reviewed by our advisor, Dr. Vanderlaan. The connector's diameter range was given by NASA, to ensure a user-friendly design that will accommodate an astronaut's decrease in dexterity when fully suited. Although the range given was 1-3 cm, we changed the lower limit of the range to 2.57 cm because astronauts found success working with this length during a NASA space glove tactility test. The connector must be mated using a force of less than 48 N because this is the peak force exerted by a 95th percentile female during a thumb-finger grip test. NASA requests this to ensure that the design will be operable by, if not all, a wide range of astronauts. The permissible leakage rate of 0.001 SCIM follows NASA's one percent volume fraction, as the volumetric flow rate is 0.1 SCIM. This flow rate, provided by NASA, will be met if the boil off rate within the connector stays under 0.0023 SCIM. This target was derived by finding the oxygen boil off experienced after 1 Watt of heat input, which can be generated by fluid friction. This target will avoid an unwanted two-phase flow (liquid and gas) of oxygen, as any oxygen that changes to a gaseous state cannot be used as fuel. To prevent debris from entering the connector, the connector will have intrusion and moisture protection. It will have an intrusion protection of 6, meaning it will be totally dust tight and will be fully protected in a vacuum seal. It will have a moisture protection of 4, meaning it will be protected from water splashes in all directions. This will suffice as we are not expecting the outside of the connector to encounter any water. To sustain multiple missions on the moon, our metal must withstand a load of at least 500 MPa as this is an average estimate for the ultimate tensile strength (UTS) of stainless steels. Finally, to counter thermal expansion and contraction, the connector will be made from the same material throughout. This will ensure that the material will contract or expand equally.

1.4.4 Method of Validation and Discussion of Measurement

To ensure that the design meets our targets, we will conduct testing for each function. To confirm that our connector is ergonomic for astronaut use, we will test tactility when manipulating our connector. Space gloves will be used during this test to ensure that the diameter of the connector is large enough to allow a smooth operation. To validate the diameter of the connector, vernier calipers, which have an accuracy of up to one thousandth of an inch, will be used. The force required to connect and disconnect the interfaces will be tested using a button force transducer. This is a load cell that will output the force experienced by the connector through an electrical signal. The permissible leakage and volumetric flow rate will be tested at the National High Magnetic Field Laboratory under Dr. Vanderlaan's supervision. The flow rate will be calculated using a venturi flow meter and the leakage can be calculated simultaneously by timing the test and collecting any leakage from the connector. This will give us a value in SCIM which can be compared with our permissible rate. The temperature of the cryogenic fluid will be determined using thermocouples, which generate a measurable voltage when experiencing temperature differences. Ingress protection is tested by exposing an item to an oscillating spray for a minimum of 10 minutes. Lunar dust can be simulated by putting the connector in a sandblasting simulation. This will ensure that the connector's seal meets our standard of IP64. The ultimate tensile strength of the material will be tested in Dr. Dorr Campbell's lab at the FAMU-FSU College of Engineering. A tensile test will be conducted to verify the ultimate tensile strength of the metal.

1.4.5 Target Summary

The table below shows our critical targets and the functions they belong to more clearly. It identifies the functions that are most critical to produce an acceptable design and targets the measurements that will be taken to determine the success of the design. While these targets are the critical targets for success, the other targets mentioned above are still necessary to accomplish an acceptable design that meets the requirements from our sponsor that are described as the functions defined in our functional decomposition. A catalog of all the functions and their targets and metrics described above can be found in Appendix D.

Table 2: Critical Target Summary

Function	Target	Metric
Ergonomic for astronaut use	2.57 cm – 3 cm	Diameter of connector
Accommodate 95% female finger strength	< 48 Newtons	Connection force
Lock and seal of interfaces	< 0.001 SCIM	Permissible leakage rate
Transferring cryogenic fluid	0.1 SCIM	Volumetric Flow rate
Transferring cryogenic fluid	90 K	Cryogenic fluid temperature

1.5 Concept Generation

Concept generation is an integral part to the design process that allows for design teams to produce any idea that satisfies aspects of their customer's needs and narrowing down the concepts that best meet majority of the needs and functions. Our team produced 100 concepts using various creative tools. The 100 concepts can be found in Appendix E. These concepts were then reviewed, and 8 concepts were selected and split amongst medium and high-fidelity options. The medium and high-fidelity concepts were chosen by the team through determining which concepts would be most achievable with respect to time and available technology. Also, those concepts also meet the customer needs the most from all the concepts generated.

1.5.2 Medium Fidelity Concepts

Below is a table of our medium-fidelity concepts. The concept number is referenced from the '100 Concepts' table in Appendix E. These medium fidelity concepts have ideas that are important to meeting the overall customer needs but do not fully meet or discuss all requirements.

Table 3: Medium Fidelity Concepts

Concept #	Name	Description
10	The Key	The Key is a key and slot connection. One end has an extrusion that fits into part of the other end, therefore when connection, the one end with the extrusion will slide into the other end with a slot and then twist the two ends to secure them together.
23	MLI	MLI uses multi-layer insulation for the connector. It will be made mostly of stainless steel for its compatible properties for space and cryogenics. The valve system used in the connection will be a gate valve. There would be the availability of pneumatic quick release connection that comes from an easily attachable connection that locks the two ends.
31	Fiber Glass	Fiber glass insulation will be used for insulation with overall material selection as stainless steel.

		The valve system used for this idea will be a ball valve. The concept also has a quick release connection from a pneumatic connector.
42	Non-insulate	Non-insulated, aluminum, gate valve connector This concept does not have anything to insulate any part of the connection. The material used is aluminum with a gate valve attached on either end of the connector to control fluid flow. This will also use a magnet connection at certain points that will allow for the two ends to be easily attached and also quickly released.
73	Sensor	'Sensor' utilizes a pressure sensor on the inside of the connector that detects and displays the pressure of the fluid through it. It will use a gate valve that can change the flow rate through the connector with a circular shaft for the fluid to flow through. The user will be able to adjust the flow rate depending on what they see from the sensor to keep the flow rate within the range determined for the connector.

1.5.3 High Fidelity Concepts

The table below is the high-fidelity concepts taken from the 100 Concepts. These concepts were deemed closest to meeting the requirements for the final design. A picture of their rudimentary design can be seen below the table that has various parts in the design along with the description found in Table 4.

Table 4: High Fidelity Concepts

Concept #	Name	Description
1	Bayonet Interface	The bayonet interface has a male and female end with one end sliding into the other and then locks into place using screws that pass through a flange. The bayonet design allows for fluid to transfer through the connection without flowing across a seal which could result in less fluid loss because of less pressure on seal used. The material used in this design would be stainless steel with a gate valve on the male end that controls the fluid flow.
71	Latch Sealing	Latch Sealing uses a stainless-steel circular centering ring piece with a o-ring made of viton or another material and has an outer circular ring with a latch that locks the two ends together with the centering ring and gasket between allowing for sealing. Material apart

		from o-ring would be stainless steel and consistent throughout to maintain commonality for change due to environment.
85	Lever Lock	Lever Lock has two levers that attach to the opposite side of the connection with an o-ring between them to supply a seal allowing for fluid transfer after pulling the levers towards the connection to apply pressure and lock in place. This will have ability for quick release in case of issues with fluid or functionality of the connector or piping attached.

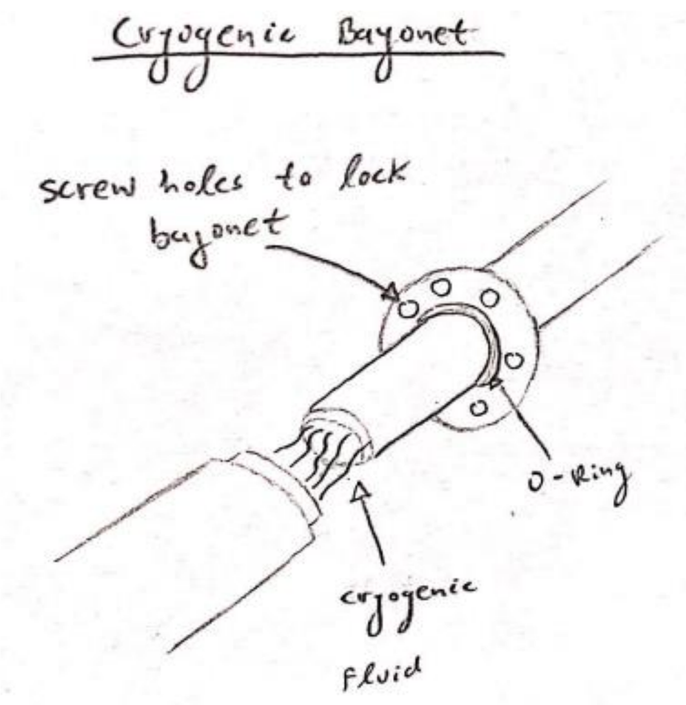


Figure 4: Concept 1 – Bayonet Interface

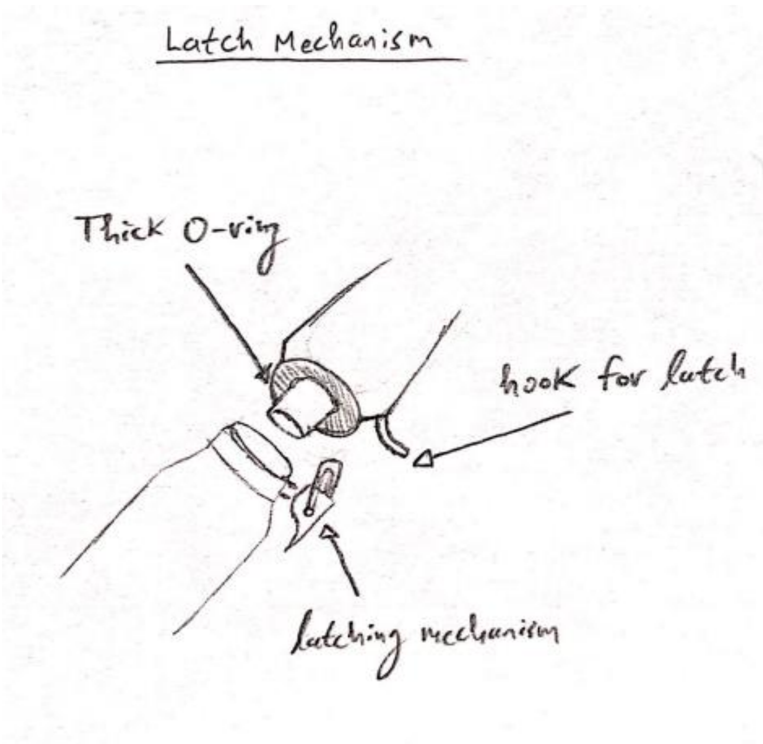


Figure 5: Concept 71 - Latch Sealing

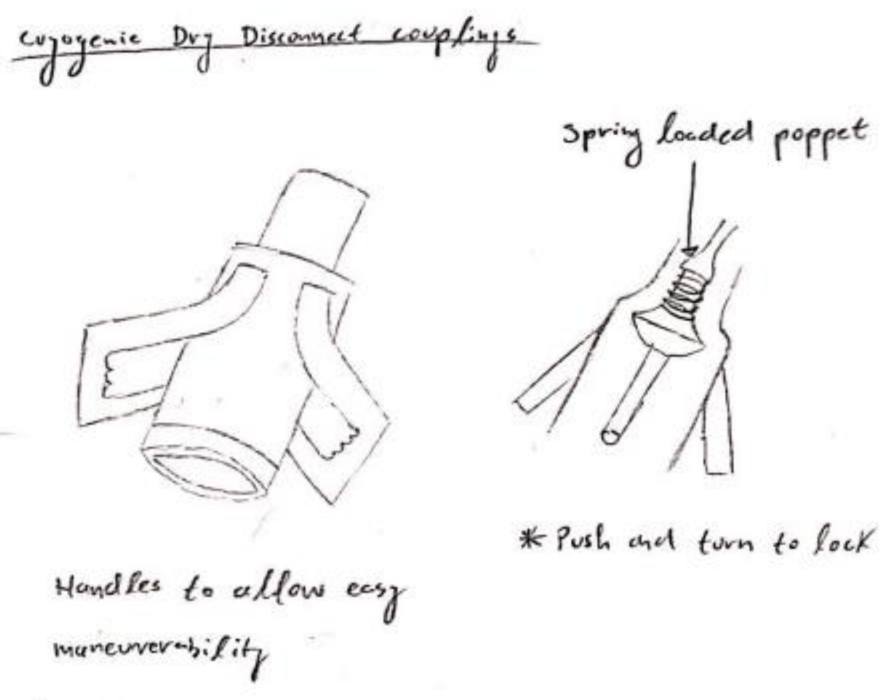


Figure 6: Concept 85 – Lever Lock

1.5.4 Concept Generation Tools

1.5.4.1 Biomimicry

Relating cryogenics to nature is quite a difficult task as the coldest temperature found in nature is about 180 K, which is twice as hot as the cryogenics we are working with. Despite this, valves can be found across nature in many forms. For example, the buckling valve found in bladderworts. These insectivore plants use a vacuum driven valve in the form of a small capsule to suck in prey. This system can be implemented to ensure that the system will not exceed 50 PSI, as installing this vacuum would create a pressure drop. An important function of our design is to prevent breaking between uses so the connector can sustain multiple missions on the moon. 100 cycles of testing could create fatigue that would affect the integrity of the connector if the metal used has weak mechanical properties. This can be prevented by mimicking the aortic valves found in vertebrate hearts. These valves are elastic and expand under high pressure. Active ventilation of the system can also be considered as this would ensure that no back flow will occur. This is how the Madagascar hissing cockroach breathes, as diffusion alone is not sufficed for oxygen to enter its respiratory system. It achieves this by contracting its pores and expanding its abdomen, and vice versa.

1.5.4.2 Morphological Chart

The functionality of our connector can be achieved in multiple ways. To explore these different ideas, we listed the three main components of the connector and generated a combination of these to achieve 50 of our concepts. The components we used to generate these ideas were form of insulation, material, and valve type.

After discussing with our sponsor, they rescinded the original assumption of an isothermal system, therefore we must now consider how to prevent heat loss. The insulations that we considered were MLI, fiberglass, bulk fill, and no insulation. No insulation will remain an option until we can completely confirm that the section of the moon corresponding to our project experiences radiation. Bulk fill insulation was broken up into two types, aero-gel bubbles, and perlite powder. These substances are small enough to be tightly packed together into empty spaces surrounding the connector to serve as insulation. MLI consists of thin layered polyester film that would be wrapped around our connector. Fiber glass insulation is hot glass spun into small fibers that reinforce plastic sheets. Each of these modes of insulation are viable for cryogenic application and will be a decisive factor in concept selection.

The materials considered for our design were stainless steel, brass, and aluminum. These were selected because they are metals with low carbon content. Brass, as an alloy of copper and zinc has good corrosion resistance and an ultimate tensile strength comparable to aluminum. Aluminum, while being the lightest of the three, has a much higher thermal conductivity, which is unfavorable as we need to keep heat out of the system. Stainless steel is the best option because it offers the highest tensile strength, lowest thermal conductivity, and retains its ductility at cryogenic temperatures, making the metal less susceptible to stress failure.

The valve types considered were ball valve, gate valve, and globe valve. Globe valves are commonly seen in faucets and water hoses. They are faster to open than gate valves, however, they can cause high pressure drops. Gate valves offer low pressure drops, however, have slow response characteristics and require high actuation forces. Ball valves offer low pressure drops, low leakage rates, and rapid actuation, however, this can lead to a hydraulic shock pressure wave that occurs when a liquid is subject to an immediate stop or direction change. Ball and gate valves are at the top of our list.

1.5.4.3 Crapshoot

To reach our goal of 100 ideas, creativity became an essential aspect of the ideation process. Three dice were used to help us generate a design that would satisfy the three parts that came from each die. A category is assigned to each die and six concepts were given for each die. The categories used were operator, function, and connection type. Our best ideas came from an effort to satisfy a monkey sealing the connector, for example, a quick release mechanism that is easily operable and requires little to no knowledge of connections. This concept was added to our medium fidelity ideas as we are striving to design an ergonomic and low maintenance connector.

1.6 Concept Selection

After generating our 100 concepts and choosing eight that we feel represent the highest and medium fidelity concepts, the team progressed into concept selection. In this section, of tables are used to identify the most important customer needs and targets, then dwindle down the concepts to the top three and rank them with respect to the top targets. The output is the alternative values that rank the top three concepts. The largest of the values is the selected concept which the tables help produce the most unbiased selection. These next few sections break down each step of the selection process that helps explain the final selection.

1.6.1 House of Quality

The House of Quality is the first step to the selection process. First, the importance of each customer need is analyzed with the binary pairwise comparison shown in Appendix F. The table provides a cross comparison of each need from row to column. When compared to one another, the need that is deemed more important is given a value of 1, while the other receives a 0. After comparing each, a sum is taken across the row and used as the weight of the customer need. This data is then used for the House of Quality.

The House of Quality was used to determine the importance of each target. The target's relevance to the customer need is recorded by assigning one of the following values: 0 for no correlation, 1 for little correlation, 3 for some correlation, and 9 for very related. The relation value is then multiplied by the weight of the customer need, which was calculated in the binary pairwise comparison. Each target's sum is called the raw score found at the row third from the bottom of the table. The raw score for each column is divided by the total raw score of every target that results in the relative weight of each target. The relative weight is then used to rank all the targets from one to nine which the order can be found at the bottom of the table. This gives the ability to identify the most important targets that continue to be used in selecting a final concept. How we wish to successfully complete the targets and the units looking for are above them. For instance, to achieve the target of Force, a test will measure the force in Newtons that it takes to secure the connector. The target is to limit this force required as much as possible and that is why there is an arrow facing down above the unit.

Table 5: House of Quality

House of Quality										
		Engineering Characteristics								
Improvement direction		-	↓	↓	↑	↓	↑	-	↓	↓
Units		cm	N	SCIM	SCIM	K	Mpa	PXX	SCIM	Dollars
Customer Needs	{w}	Diameter	Force	Leakage	Flow Rate	Fluid Temp.	Tensile Str.	Ingress	Boil Off	Price
Fluid Loss	3	1	1	9	9	1	0	9	9	3
Withstand Flow	3	3	1	9	9	3	1	9	3	3
Fit to existing pipe	6	9	0	3	1	0	0	1	0	1
Reusable	4	3	9	3	9	0	9	1	0	3
Cryogenic Temp.	1	3	0	1	1	9	0	0	9	0
Ergonomic	1	9	3	0	3	0	9	0	0	3
Below $1400	4	3	0	1	1	1	1	1	0	9
Reliable coupling	7	3	9	9	3	0	3	9	3	3
Control Flow	7	1	3	9	9	0	0	3	3	3
Raw score		130	129	215	188	25	73	152	87	117
Relative weight		0.11648746	0.1155914	0.19265233	0.16845878	0.02240143	0.06541219	0.13620072	0.07795699	0.10483871
Rank order		4	5	1	2	9	8	3	7	6

As a result of the House of Quality, 8 of the 9 targets continue as the relative weight and raw scores are closer together for the top 8 and then decreases quite drastically for the ninth target. The targets that move to the next steps are: Diameter, Force, Leakage, Flow Rate, Tensile Strength, Ingress, Boil Off, Price.

1.6.2 Pugh Charts

The next step in the process is the Pugh Charts. Pugh charts were used to compare our high and medium fidelity concepts to a current product in the market using the selected targets from the House of Quality. We used a National Piped Thread (NPT) Liquid Nitrogen connector as our datum. This was used as a benchmark for our 8 concepts to be compared to. NPT is quite common for cryogenic connections; however, the threads must be wrapped in Teflon to prevent leakage. This can be quite tedious, especially for a gloved astronaut. Therefore, our high and medium fidelity concepts strayed away from NPT and the other parts of each design were compared to the connector datum. The team's targets from the House of Quality are used as the selection criteria, which is used to compare the datum to each concept as follows. If the concept's criteria are better than the datum's, a plus (+) is assigned, if it is worse, a negative (–) is assigned, and if they are about equal, an (S) is assigned to denote that it is satisfactory. The concepts are then ranked by the number of pluses and minuses that identifies the best and worst concepts with respect to the datum and its criteria.

Table 6: Pugh Chart First Iteration

Pugh Chart										
Selection Criteria		Concept of datum	Concepts							
			The Key	MLI	Fiber Glass	Non-Insulate	Sensor	Bayonet Interface	Latch Sealing	Lever Lock
1	Diameter	Datum	S	S	S	S	S	S	S	S
2	Force		+	+	+	+	S	+	+	+
3	Leakage		-	-	-	-	S	+	+	+
4	Flow Rate		S	+	-	S	+	+	S	S
5	Tensile Str.		S	S	+	-	S	S	S	S
6	Ingress		+	S	S	-	+	S	+	-
7	Boil Off		-	-	-	-	-	+	S	S
8	Price		+	+	+	-	+	-	+	+
# of Pluses			3	3	3	1	3	4	4	3
# of Minuses			2	2	3	5	1	1	0	1
# of S's			3	3	2	2	4	3	4	4
RANK +'s			3	3	3	8	3	1	1	3
Rank -'s			3	3	2	1	5	5	8	5

The results from the table show that Non-Insulate is the worst while Latch Sealing proved to be the best out the eight concepts with respect to the datum. Latch Sealing is tied for first ranked with Bayonet Interface in terms of pluses but outranks it by having the least number of minuses. The next step is to take a new datum that is assigned as one of these concepts and compare the others that remain.

In the Pugh chart shown in Table 7, the five designs from Table 6 that follow the highest and middle of the field move on to this round where a new Pugh chart was created. These designs were: Bayonet Interface, Latch Sealing, Fiberglass, MLI, and Lever Lock. A sixth design with relatively neutral results from Table 6 was chosen as the next datum for this Pugh chart. This is done to verify that the concept selected in the end is truly the best design because it is being compared to more than one datum.

Table 7: Pugh Chart Second Iteration

Pugh Chart							
Selection Criteria		Datum (Sensor)	Concepts				
			Bayonet Inte	Latch Sealing	Fiber Glass	MLI	Lever Lock
1	Diameter		S	S	S	S	S
2	Force		+	+	-	S	-
3	Leakage		+	+	S	S	+
4	Flow Rate		+	+	S	S	+
5	Tensile Str.		S	S	+	+	S
6	Ingress		+	S	+	S	S
7	Boil Off		+	+	-	S	+
8	Price		S	S	+	+	+
# of Pluses			5	4	3	2	4
# of Minuses			0	0	2	0	1
# of S's			3	4	3	6	3
Rank			1	2	4	5	2

From Table 7, the concepts that compare best to the datum are the Bayonet Interface, Latch Sealing, and Lever Lock. These are the concepts that are selected to move forward to the Analytical Hierarchy Process.

1.6.3 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) cross references the targets against each other to establish the weights of our criteria. This is a similar process to the binary pairwise comparison, however, instead we are using the targets. It uses a scale of 1, 3, 5, 7, 9. They are ranked by comparing the criteria in the row to the criteria in the column. The table can be seen in Appendix G for reference. Giving a rank of 1 means that the criterion in the row is of equal importance as the criteria in the column. The rest of the scale is as follows (comparing row to column): 3 is moderately more important, 5 is strongly more important, 7 is thought to be much more important or demonstrated as more important, and 9 is demonstrated to be much more important. The inverse of the rank is taken in the cell opposite the yellow diagonal line across the table. Each cell is then divided by the sum of each column to provide the value of the target and put into the corresponding cell in the Normalized Comparison Matrix found in Table 8. The weight of each criteria is then determined by average of every cell in the row. This will then be used to find the final alternative values.

Table 8: Normalized Comparison Matrix

Normalized Criteria Comparison Matrix [NormC]									
Criteria	Diameter	Force	Leakage	Flow Rate	Tensile Str.	Ingress	Boil Off	Price	Criteria Weights {W}
Diameter	0.23	0.32	0.20	0.17	0.25	0.29	0.21	0.17	0.23
Force	0.08	0.11	0.07	0.17	0.15	0.17	0.21	0.17	0.14
Leakage	0.23	0.32	0.20	0.17	0.25	0.17	0.07	0.28	0.21
Flow Rate	0.23	0.11	0.20	0.17	0.15	0.17	0.07	0.17	0.16
Tensile Str.	0.05	0.04	0.04	0.06	0.05	0.06	0.07	0.06	0.05
Ingress	0.05	0.04	0.07	0.06	0.05	0.06	0.21	0.06	0.07
Boil Off	0.08	0.04	0.20	0.17	0.05	0.02	0.07	0.06	0.08
Price	0.08	0.04	0.04	0.06	0.05	0.06	0.07	0.06	0.06
Sum	1	1	1	1	1	1	1	1	

The results showed that the diameter has the strongest weight, followed by leakage, and decreases down to least as tensile strength. A consistency check is then done to determine whether the values given to each ranking is consistent with each other. The consistency check is shown in Appendix G. The values for Consistency Check are found by dividing the Weighted Sum Vector by the Criteria Weights found from the normalized comparison table. This is then averaged and used to find the Consistency Index that is used to find the Consistency Ratio. The most important value of those is the Consistency Ratio. To be deemed consistent throughout, the Consistency Ratio should be less than 0.1. The value found for the consistency ratio was 0.07 which is less than 0.1 and therefore means the weights found through the tables are consistent.

Table 9: Final Rating Matrix

Final rating matrix			
Selection Criteria	Bayonet Interface	Latch Sealing	Lever Lock
Diameter	0.14	0.43	0.43
Force	0.20	0.60	0.20
Leakage	0.17	0.39	0.44
Flow Rate	0.33	0.33	0.33
Fluid Temp.	0.43	0.14	0.43
Ingress	0.43	0.14	0.43
Boil Off	0.14	0.43	0.43
Price	0.60	0.20	0.20
Sum	2.45	2.66	2.89

The table above represents the final rating of each concept. This is found by doing the same AHP style tables but just comparing the three final concepts to each other with respect to one criteria at a time. It is then normalized and taking the average across the row, an importance weight factor for each concept is given for each criteria. Those are then placed in the Final Rating Matrix shown above. All the tables for this can be seen in Appendix H. A consistency check was done for each of these table and average Consistency Ratio of 0.009 which identifies the results as consistent and very little bias. From the final rating matrix table, it seems that Lever Lock would be the final selection. However, each column is then multiplied by the weight factors for the criteria found in the Normalized Comparison and it produces final values for each concept shown in Table 10.

Table 10: Alternative Values

Concept	Alternative Value
Bayonet Interface	0.25
Latch Sealing	0.38
Lever Lock	0.37

1.6.4 Final Selection

After analyzing the AHP and other tables that led to it, the final concept is the Latch Sealing, which is shown in Figure 5. It had the highest overall alternative value of 0.38 and was consistently among the highest ranked in iterations of the Pugh Charts. This design uses a latch mechanism that engages a thick O-ring to seal the two interfaces together. The material of the O-ring will be made of polychlorotrifluoroethylene, commonly known as Kel-F. This is a thermoplastic that is used commonly as a cryogenic polymer because it resists brittleness well at low temperatures. One side of the connector will have a clamp wrapped around to hold the latch and the other side of the connector will have a hook and O-ring on the shaft. This sealing mechanism will be used in combination with a single poppet quick release valve design for flow control.

1.7 Spring Project Plan

Table 11: Spring Project Plan

ID	Active	Task Mode	Name	Duration	Start	Finish	Predecessors	Outline Level
1	Yes	Manually S	Order Parts	1.2 wks?	January 5, 2022 8:00 AM	January 12, 2022 5:00 PM		1
2	Yes	Manually S	Revise Bill of Materials	2 days	January 5, 2022 8:00 AM	January 6, 2022 5:00 PM		2
3	Yes	Manually S	Create invoice	1 day	January 7, 2022 8:00 AM	January 7, 2022 5:00 PM	2	2
4	Yes	Manually S	Submit purchase order	1 day	January 10, 2022 8:00 AM	January 10, 2022 5:00 PM	3	2
5	Yes	Manually S	Adviser Meeting (Jan)	5 days?	January 24, 2022 8:00 AM	January 28, 2022 5:00 PM		1
6	Yes	Manually S	Create agenda and Timeline	1 day	January 24, 2022 8:00 AM	January 24, 2022 5:00 PM		2
7	Yes	Manually S	Email Adviser	1 day?	January 25, 2022 8:00 AM	January 25, 2022 5:00 PM	6	2
8	Yes	Manually S	Attendance	2 days	January 26, 2022 8:00 AM	January 27, 2022 5:00 PM	7	2
9	Yes	Manually S	Submit any documents	1 day?	January 28, 2022 8:00 AM	January 28, 2022 5:00 PM	8	2
10	Yes	Manually S	Assembly	3.4 wks	January 13, 2022 8:00 AM	February 4, 2022 5:00 PM	1	1
11	Yes	Manually S	Receive parts and prep for Assembly	5 days	January 20, 2022 8:00 AM	January 26, 2022 5:00 PM		2
12	Yes	Manually S	Deliver to machine shop	3 days	January 26, 2022 8:00 AM	January 28, 2022 5:00 PM		2
13	Yes	Manually S	Work with Vanderlaan to prep testing procedures	17 days	January 13, 2022 8:00 AM	February 4, 2022 5:00 PM		2
14	Yes	Manually S	Adviser Meeting (Feb)	5 days?	February 21, 2022 8:00 AM	February 25, 2022 5:00 PM		1
15	Yes	Manually S	Create Agenda and Timeline	1 day	February 21, 2022 8:00 AM	February 21, 2022 5:00 PM		2
16	Yes	Manually S	Email Adivser	1 day?	February 22, 2022 8:00 AM	February 22, 2022 5:00 PM	15	2
17	Yes	Manually S	Attendance	2 days	February 23, 2022 8:00 AM	February 24, 2022 5:00 PM	16	2
18	Yes	Manually S	Submit any documents	1 day?	February 25, 2022 8:00 AM	February 25, 2022 5:00 PM	17	2
19	Yes	Manually S	Testing	35 days?	February 7, 2022 8:00 AM	March 25, 2022 5:00 PM		1
20	Yes	Manually S	Test 1	10 days	February 7, 2022 8:00 AM	February 18, 2022 5:00 PM		2
21	Yes	Manually S	Analyze results of Test 1	2 days	February 21, 2022 8:00 AM	February 22, 2022 5:00 PM	20	2
22	Yes	Manually S	Determine design changes	3 days	February 23, 2022 8:00 AM	February 25, 2022 5:00 PM	21	2
23	Yes	Manually S	Test 2	10 days	February 28, 2022 8:00 AM	March 11, 2022 5:00 PM	22	2
24	Yes	Manually S	Analyze results of Test 2	2 days	March 14, 2022 8:00 AM	March 15, 2022 5:00 PM	23	2
25	Yes	Manually S	Determine design changes	3 days	March 16, 2022 8:00 AM	March 18, 2022 5:00 PM	24	2
26	Yes	Manually S	Repeat necessary tests	5 days	March 21, 2022 8:00 AM	March 25, 2022 5:00 PM	25	2
27	Yes	Manually S	Adviser Meeting (Mar)	5 days?	March 25, 2022 8:00 AM	March 31, 2022 5:00 PM		1
28	Yes	Manually S	Create Agenda and Timeline	1 day	March 25, 2022 8:00 AM	March 25, 2022 5:00 PM		2
29	Yes	Manually S	Email Adviser	1 day?	March 28, 2022 8:00 AM	March 28, 2022 5:00 PM	28	2
30	Yes	Manually S	Attendance	2 days	March 29, 2022 8:00 AM	March 30, 2022 5:00 PM	29	2
31	Yes	Manually S	Submit any Documents	1 day?	March 31, 2022 8:00 AM	March 31, 2022 5:00 PM	30	2
32	Yes	Manually S	Engineering Design Day (end)	5 days	March 28, 2022 8:00 AM	April 1, 2022 5:00 PM	19	1
33	Yes	Manually S	MSFC Trip	2 days	April 8, 2022 8:00 AM	April 10, 2022 5:00 PM		1
34	Yes	Manually S	Finals	5 days	April 25, 2022 8:00 AM	April 29, 2022 5:00 PM		1
35	Yes	Manually S	Graduation	1 day	May 2, 2022 8:00 AM	May 2, 2022 5:00 PM	34	1

1.8 Restated Project Definition and Scope

The restated project definition and scope consists of tracking changes to the project and editing the corresponding sections of the evidence manual. Minimal changes were made to the document; however, they are shown in red and can be seen by accessing the “track changes” through the review section on the navigation pane.

1.9 Operation Manual

Project Overview

The objective of this project is to design a connector that will transfer cryogenic fluid to refuel rocket ships on the moon. Developing this system will result in extended space travel missions that will venture further from Earth. When developing a solution, there were two key points involving this connection that determined the direction of development. These points were: the fluid being transferred with respect to how it would affect the connection and the environment's effects on the system.

The fluid was the first step to consider. The fluid, liquid oxygen, boils at a temperature of roughly 90 Kelvin. Testing was conducted with liquid nitrogen at 77 K, and therefore all components selected can withstand the temperature of liquid oxygen. Undergoing the drastic change in temperature can cause changes in properties, as well as expansion and contraction. Materials selected were chosen to limit the change in properties at that temperature and keep consistent expansion and contraction with temperature changes. To produce a successful connector, the solution withstands thermal cycling while maintaining a secure connection to limit the loss of fluid while refueling.

The environment was the next to consider. The use of this connector interface on the moon can produce varying issues. The moon may have a temperature range of 140 K – 400 K depending on whether it is shaded from direct sunlight. Considering the effects of radiation on the connector while undergoing fluid transfer is out of the scope of the project. There are still safeguards to release pressure build-up if there were to be boil off and over-pressurization of the system. Regolith on the moon would also cause system failure if it was to enter the connector and remain there during fluid transfer.

The following sections will describe all components and how to assemble the parts. It will also describe how to operate the interface along with troubleshooting possible issues. There will also be an inclusion on how to maintain protection against regolith that the connector interface can come into contact with while used on the moon.

Component Description

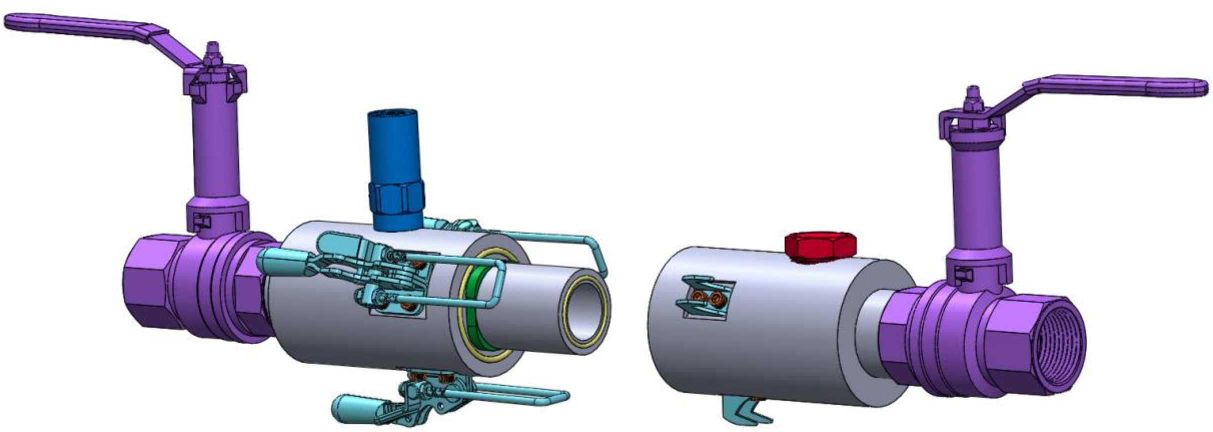


Figure 1: CAD model of the cryogenic connector assembly

The connector design is comprised of two machined parts which consist of a male and female end. The selected material for these was AISI304 stainless steel. These ends were designed to accommodate the rest of the components of the connector. The CAD drawings for both ends are in appendix I. Shown above is an angled view of the design when disconnected. This view displays the O-rings, shown in yellow, and the alignment extrusion, shown in green. The O-rings are made of Viton, which is a fluorocarbon rubber, and are the key to creating the seal of the system. The alignment extrusion was machined to help the user line up the latches in the correct orientation when interlocking the ends together. The latches and hooks that engage the O-rings' compression seal are shown in light blue. They are screwed into the body of the connector with 8-32 x 3/8" screws, shown in orange. To control the flow of the fluid passing through the connector, the handles on the purple AVCO ball valves are rotated 90 degrees. These are attached to the connector with 1" NPT fittings. These ball valves are then connected to the cryogenic storage tank extension hose on one end, and the space shuttle fueling hose on the other end. For safety measures, two pressure relief valves were implemented into the design. The blue automatic pressure relief valve cracks at 50 psi in the case that excess boil-off creates an unwanted increase to the pressure of the system. The red breather vent is removed by the user to depressurize the system and allow the remaining fluid to evaporate before disconnecting the two ends.

Integration

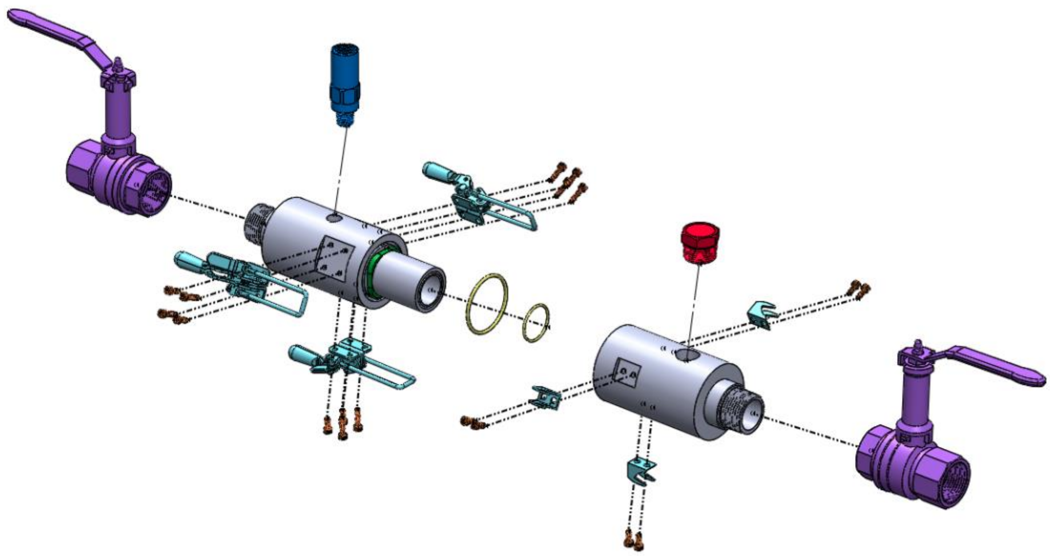


Figure 2: Exploded CAD view of cryogenic connector assembly

To assemble the connector the exploded view shown above should be followed. The dashed lines indicate the location of each component. Each end should be assembled before connecting the interfaces together. The ball valves should be threaded onto both ends and the latches and hooks should be attached with the screws. Both relief valves are threaded in as well. Next, the O-rings are placed in their corresponding grooves. To connect and seal the system, the alignment extrusion is used to help slide the parts together. Finally, the latches are hooked and locked into place.

Operation

We will define the operation of this device as a sequence of events that allows cryogenic fluid to flow through the connector. After proper completion of the assembly, the connector can simply be connected by bringing together the two ends of the connector by matching up the alignment extrusion to the other side and initiating the latches. This will seal the gap between the two faces. To attach the connector to the reservoir containing the cryogenic fuel and the rocket ship, attach the hoses to the connector at either end of the connector to the ball valve using flange to 1" NPT fitting. To operate the AVCO ball valves, there is a small slider that acts as a locking mechanism preventing the handle from rotating. Move the small slider so that it is not in its resting position and then twist the handle 90^o which will open the ball valve. At this point, the flow can be opened at the reservoir and flow to the ship. During testing, to flow cryogenic fluid through the connector we used cryogenics lab at the National Magnet Laboratory. To properly connect the ball valves on the connector to the testing equipment 1" NPT (National Piped Thread) to ½" male flange fittings are needed, shown in Figure 3. This can be used the same for the connection of the connector to piping to the reservoir and ship.

After fueling is completed, wait for the temperature of the connector to increase before starting the disconnecting process. To start the disconnecting process, make sure that the reservoir is closed off. Then close both ball valves with the same method of opening. Once ball valves are closed off, disengage the latches, and separate the two ends. Store the two ends in their respective storage locations.

When disconnected, protection is required from the environment. To prevent dirt and dust from entering the system when disconnected, attach caps onto the ends of the connector after disconnection.

Figure 3: 1" NPT (National Piped Thread) to ½" male flange fitting

Troubleshooting

A problem that could arise during use of the connector would be an increase in fluid loss through the connection point of the two sides. There are a couple solutions to this problem if it was to happen. First, one must consider the adjustability of the latch tightness. After O-rings are installed, the user can tighten the nuts on the latch ends to decrease the length of the latch itself and therefore tighten the connection. The latch can be held above the hooks to indicate to the user the placement so that they can adjust to their desired length. If the leak continues, the next option would be to replace the two O-rings used in the connection. There can be added cushions inserted into the O-ring grooves to increase the protrusion of the O-ring from the groove.

The components are also replaceable. If there were to be failures at the latch, ball valve, relief valve, hook, and O-ring, the part can be replaced with a new part. These components must be replaced following the direction for initial assembly but can be replaced as they are not permanent fixtures on the shaft.

1.10 Results

The functionality of the connector and its components were validated using four different tests. The first test was to check the required ball valve activation force. Our sponsor required the design to be operable by the 95th percentile female. Therefore, the team's target was an activation force of less than 48 Newtons, given that this is the 95th percentile females average fingertip grip strength. This target was tested by opening and closing the ball valves by pushing against a scale. This test was conducted 10 times and provided us with the average mass required to open the ball valves. To calculate the force, we then needed the acceleration required to open the ball valves. The acceleration was found by measuring the length of the handle, which was used as the radius of the imaginary circle that is created by the path of the handle. We then used one fourth of the circumference of the imaginary circle to represent the distance that the handle travels. This distance, and the average time it took for the handle to open and close the ball valves were plugged into the following kinematic equation,

$$a = \frac{(x - x_0 - V_0 * t)2}{t\hat{}2}$$

Which returned a value of

$$a = 3.19\frac{m}{s^2}$$

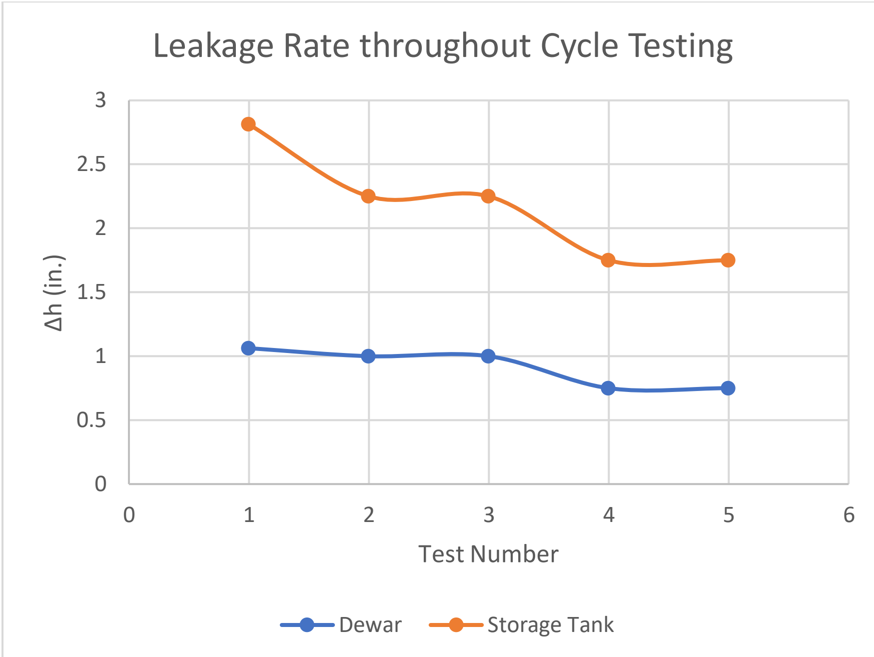
This acceleration was then multiplied by the average mass found using the scale test, which resulted in an average activation force of $14.13\ N$ and a maximum activation force of $14.3\ N$. This is well under the target value of $48\ N$, therefore, this test was deemed successful.

The following test that was conducted was the astronaut compatibility test, which ensured that the latch clearance was enough to fit an astronaut's finger. The distance between the latch and the metal under it was about 1.25 inches. We simulated an astronaut's glove with the cryogenic safety gloves used during testing. They had a thickness of about 0.05 inches. With the gloves on, a 5'11", 180-pound male with a finger thickness of 0.7" successfully opened the latch.

To verify that our connector was leak proof, we began with a helium leak test. This was a safety precaution that ensured the connection points were sealed, since for the following test we would be flowing pressurized cryogens through the prototype. The helium leak check began with establishing a baseline value. The helium leak detecting machine, the adixen asm 142, pulled a vacuum without our unit connected and returned a value of $3.2x10^{-10}\frac{Torr*l}{s}$. When our unit was added, the machine pulled a vacuum from inside of our connector and sensed any helium particles entering the system. With our unit, the machine read a value of $2.1x10^{-9}\frac{Torr*l}{s}$, meaning that our connector leaked about 10 times more than the baseline number. To determine where the leakage was occurring, helium gas was sprayed into the various connection points. Whenever a spike on the machine occurred, it was evident that there was leakage through that point. We found that the only leakage points came from the NPT threads needed to connect our design into the machines vacuum. Therefore, our connector was deemed seal tight, and because these leaking fittings would not be used for the cryogenic testing, our advisor, Dr. Vanderlaan felt more than comfortable proceeding to the next step.

The cryogenic leak testing was conducted using liquid nitrogen. A large dewar supplied the fluid at 22 psi, which flowed through our connector and was emptied into a smaller cryogenic storage tank. To calculate the leakage, the volumetric flow rate leaving the supply dewar was calculated and compared with the flow rate entering the smaller storage tank. Therefore, we would be able to calculate the amount of fluid unaccounted for, which would determine the leakage. The dewar's flow rate was calculated with a pressure gauge in terms of inches of H2O. This height difference was measured over a period of 1 minute. The height was used to calculate the volume of a cylinder, which represented the amount of volume displaced over the minute. The average of the 5 tests resulted in a volumetric flow rate of $346.70\ \frac{in^3}{min}$. The flow rate of the smaller storage tank was found by using a G10 rod as a dip stick. The extreme temperatures produced frost on the G10 rod and the distance from the tip of the rod to the edge of the frost was measured and dipped back into the tank. After one minute, this distance was measured again and the difference between the two measurements was used as the height value for the volume of a cylinder. The average of the 5 tests resulted in a volumetric flow rate of $332.72\ \frac{in^3}{min}$. After taking the difference between the two flow rates, the average calculated leakage is $13.98\frac{in^3}{min}$, which is 4.0 percent of the flow rate.

The liquid nitrogen test also determined the effect of cycle testing on the connector. A plot was created to visualize how the connector's performance changed over the 5 tests.



Both lines follow a clear trend where the change in height decreases as the cycles increase. The dewar's change in height throughout testing is not expected to change and can be due to human error as the pressure gauge's units were represented by small ticks and were difficult to read. However, the storage tank's negative slope is higher in magnitude and is most likely caused by deterioration of the O-rings over time.

1.11 Discussion

After conducting the liquid nitrogen testing, the leakage rate of the connector was a bit higher than expected. The 4.0 percent is higher than our permissible leakage rate target of 1.0 percent of the flow, however, as there were no visible leaks at the interface of the connector. Therefore, it is assumed that the unaccounted fluid is due to boil off of the liquid nitrogen. After analyzing the connector's performance during all tests, the prototype has proven to be a success. Hopefully the design will be considered to support future missions on the moon's surface.

1.12 Conclusions

Team 513's cryogenic connector is a revolutionary design that will reduce the complexity of cryogenic fluid transfer. The significance of the connector is its two key features, the latch sealing mechanism, and the 1" NPT fitting. The latches and hooks are designed with the astronaut's decreased dexterity in mind, as their bulky gloves make it difficult for them to manipulate small objects. The latches are simple and can be operated with ease. The 1" NPT connections are a universal thread that can be adapted to mate with several different fittings. This is significant because it does not limit our design to one single application. Team 513's connector has proven to be seal tight, easily operated, and can successfully transfer pressurized liquid nitrogen from one reservoir to another.

1.13 Future Work

After concluding testing, the team developed a future development plan for the project. The first goal would be to mitigate solar radiation. This can be achieved by wrapping the connector in MLI insulation. MLI insulation provides thermal resistance to reduce the amount of heat entering the connection. This is important because the heat dissipation reduces liquid oxygen boil off. The next step in the process would be to prevent regolith contamination. Since liquid oxygen is highly combustible, it is essential to protect the fuel from contaminants. This can be tested by putting the connector through a sand or plastic blast process. The sand or plastic would replicate moon dust and give the team a reasonable idea of how well the system would protect from regolith. Once these aspects of the designs are achieved, an efficient shipping container would need to be designed. This would prove challenging because of the uneven geometries of the ball valve and latches. Two matching foam prints of the connector can be fabricated so that our design can be sandwiched by the foam to protect the metal. This process would be implemented into an assembly line for mass production.

Appendices

Appendix A: Code of Conduct

Mission Statement

The team will conduct the design project with respect and understanding for other group members with the main goal of achieving all tasks and the final design. This will be accomplished by helping each other, promoting growth, effective communication, and being open to any course of action to help accomplish the needs of the sponsor and project overall.

Team Roles

Jackson Herrod – Research/Test Engineer

Responsible for testing the system and determining the functionality and the level to which it fulfills the needs of the project. In order to do so, they will develop the way in which to test the system to produce the accurate results that are needed to understand the system and final product.

Joshua Leary – Systems Engineer

Work with materials, test and design engineers to successfully design an integrated system. Will assist other team members in various parts to complete a seamless product between members.

Juan Valencia – Fluids and Design Engineer

Responsible for finding the optimal design of the system using fluid analysis of flow control and heat transfer. The design engineer will generate CAD models and mechanical prototypes of the cryogenic connectors. This will lead to the engineering drawings needed for fabrication.

Mika Kuschnitzky – Materials/Manufacturing Engineer

Responsible for finding the optimal material selection for each step of the design. While maintaining a focus on scalability of manufacturing and overall cost reduction.

For all team members, other duties will be split amongst everyone depending on their specialties and strengths. It will also be determined on end due date and the current work that the team member is already assigned. The team will come to a consensus on the breakdown of assignments to each member.

Communication

Main form of communication will be through Basecamp to discuss important information, share progress, request information, as well as drafts of documents pertaining to the project and group work. Formal documents and communication with sponsor and advisor will be sent through email. For informal communication, text message can be used.

Meeting times and frequency with our Sponsor, NASA-MSFC, will be determined after first meeting and then amended in the Code of Conduct. This will also be the case after the first meeting with our Faculty Advisor, Dr. Vanderlaan.

Formal meetings will hopefully be in person and Microsoft Teams and Zoom will be the alternative form of communication.

Each team member should respond to internal messages within 12 hours before 7pm on any weekday and 24 hours on weekends. When responding to Faculty Advisor or Technical Point of Contact at NASA-MSFC, the team must respond within 24 hours.

Attendance Policy

The team will meet or communicate their progress twice a week on Tuesdays and Thursdays. If the need arises for the team to meet another day/time or not have a meeting, the team will discuss through Basecamp or text.

If a member is unable to attend a team or class meeting must advise this to the other team members at least 24 hours in advance for excused absence through Basecamp or text. Failure to do so will result in a strike. If a team member accumulates three strikes, there will be a disciplinary action. The strikes will be taken note on an excel that has the plan for the semester including milestones and meetings.

Dress Code

The dress code will be business casual for each class and team meeting. Advisor and sponsor meetings will be business professional. Presentations will have business professional and have a team consensus on the specific style and colors depending on the availability of each team member 48 hours before the presentation.

Outside Obligations

The team has collective availability in the morning on Mondays, Wednesdays, and Fridays until 11 am. Meetings and regrouping will be conducted after Senior Design finishes. Weekends will be reserved for relaxation unless anything is emergent and required.

Consequences/Disciplinary Actions

After a first and second strike for attendance, a team meeting will be scheduled to discuss the situation with the team. After a team member acquires a third strike, a team meeting will be scheduled to discuss why Dr. McConomy will be contacted. At this time, the team member's participation will be reduced by one point and then another for each resulting strike afterwards.

For other team issues, if they are to arise, a team meeting will always be scheduled to discuss the issue. If the issue continues, Dr. McConomy will be notified, and a meeting will be scheduled between him and the team to discuss further consequences to participation grade or course grades.

Amendments to Code of Conduct

Amendments will be made to the Code of Conduct after a meeting is called and then a majority vote will be needed to enact that amendment.

Statement of Understanding

Team Member 1 — Date: 01-14-2022

Team Member 2 — Date: 01-14-2022

Team Member 3 — Date: 01-14-2022

Team Member 4 — Date: 01-14-2022

By signing this document, all members agree to adhere to the guidelines set forth by the Code of Conduct. Failing to abide by this document will result in consequences outlined by this Code of Conduct and the course.

Appendix B: Work Breakdown Structure

Task #	Task Name	Responsibility
1	**Sponsor Meet and Greet**	
1.1	Agenda and Questions	Juan/Mika
1.2	Email	Josh
1.3	Submit Meeting Minutes	Josh
2	**Project Scope**	
2.1	Convert sponsor notes into goals and assumptions	Mika/Jackson
2.2	Assign parts to members and write	Team
2.3	Reference Rubric and Edit	Juan
2.4	Submit	Juan
3	**Work Break Down Structure**	
3.1	Determine Deliverables	Josh
3.2	Assign Order and input in excel	Josh
3.3	Assign tasks to team members	Team
3.4	Attach to Evidence Manual	Josh
3.5	Submit	Josh
4	**Adviser Meeting 1**	
4.1	Create Agenda and Timeline	Josh/Juan
4.2	Email Adviser	Juan
4.3	Attendance	Team
4.4	Submit all documents	Jackson
5	**Customer Needs**	
5.1	Summarize statements of customer	Jackson/Juan
5.2	Break down meeting minutes and input relevant information	Mika
5.3	Interpret needs	Juan
5.4	Explain how statements gathered	Jackson
5.5	Review Rubric and Edit	Josh
5.6	Submit	Josh
6	**Web Master**	
6.1	Assign Web Master and create document	Team
6.2	Submit	Mika
7	**Functional Decomposition**	
7.1	Determine Specifications	Juan/Mika
7.2	Breakdown Functions	Josh/Jackson
7.3	Create Document and Graphics	Josh/Jackson
	Explanation of results	
	Introduction	Josh
	Discussion of data	Juan
	Introduction of graphics	Jackson
	Disccussion of gathering F.D	Mika
	Function relationships	Josh
	Connection of systems	Juan
	Smart integration explained	Jackson
	Function resolution	Mika
	Action and outcome	Josh
7.4	Review with Rubric and Edit	Mika
7.5	Submit	Juan
8	**VDR1**	

8.1	Breakdown/summarize VDR Topics	Josh
8.1.1	Project Scope	
8.1.2	Customer Needs	
8.1.3	Functional Decomposition	
8.2	Create Presentation	Jackson/Juan
8.3	Review and Edit	Mika
8.4	Assign parts to members	Team
8.5	Practice with Timing	Team
8.6	Present	Team
9	**Targets**	
9.1	Determine targets and benchmarks	Jackson/Mika
9.1.1	Attach a target to each function	Josh
9.1.2	Give list of targets that go beyond functions	Juan
9.1.3	Method of validation	Jackson
9.1.4	Discussion of derivation of targets	Mika
9.1.5	Discussion of Measuring	Jackson
9.1.6	Identify/select critical targets	Josh
9.1.7	Summary and catalog into appendix and body	Josh/Juan
9.2	Review Rubric and Edit	Jackson
9.3	Submit	Jackson
10	**Concept Generation**	
10.1	Brainstorm 100 ideas	Team
10.1.1	Work through design methods	
10.1.2	Rough designs through CAD or drawing	
10.1.3	Break up fidelity of concepts	
10.1.4	Design of High Fidelity concepts	
10.2	Bring ideas onto a single document	Mika
10.3	Review and Submit	Juan
11	**Adviser Meeting 2**	
11.1	Create Agenda and Timeline	Jackson
11.2	Email Adviser	Juan
11.3	Attendance	Team
11.4	Submit all documents	Josh
12	**Concept Selection**	
12.1	Determine the methods of analysis	Team
12.2	Identify selection criteria	Team
12.3	Analyze concepts	Mika/Jackson
12.4	Create comparison charts from results	
12.4.1	AHP	Juan
12.4.2	Pugh Chart	Josh
12.4.3	Decision Matrix	Josh
12.5	Select Concept	Team
12.6	Consolidate results and explain selection	Juan
12.7	Submit necessary documents	Josh
13	**VDR2**	
13.1	Breakdown all information	Jackson
13.2	Create Presentation	Mika
13.3	Review and Edit	Josh

13.4	Assign parts to members	Team
13.5	Practice with Timing	Team
13.6	Present	Team
14	**Risk Assessment**	
14.1	Review Safety Expectations	Team
14.2	Fill out Worksheets	Team
14.3	Submit	Juan
15	**Adviser Meeting 3**	
15.1	Create Agenda and Timeline	Juan
15.2	Email Adviser	Juan
15.3	Attendance	Team
15.4	Submit all documents	Jackson
16	**Bill of Materials**	
16.1	Material list with amounts	Mika
16.2	Research Prices	Josh
16.3	Find out equipment or methods to create	Jackson
16.4	Price equipment	Jackson
16.5	Input into document and Evidence Manual	Juan
16.6	Submit	Juan
17	**VDR3 (Poster)**	
17.1	Summarize all work and future work	Josh
17.2	Creat Poster	Mika
17.3	Review rubric and edit	Jackson
17.4	Submit for Printing	Juan
18	**Spring Project Plan**	
18.1	Create Timeline w/ milestones and deliverables	Josh
18.2	Review and Agree	Team
18.3	Submit	Josh

Appendix C: Functional Decomposition

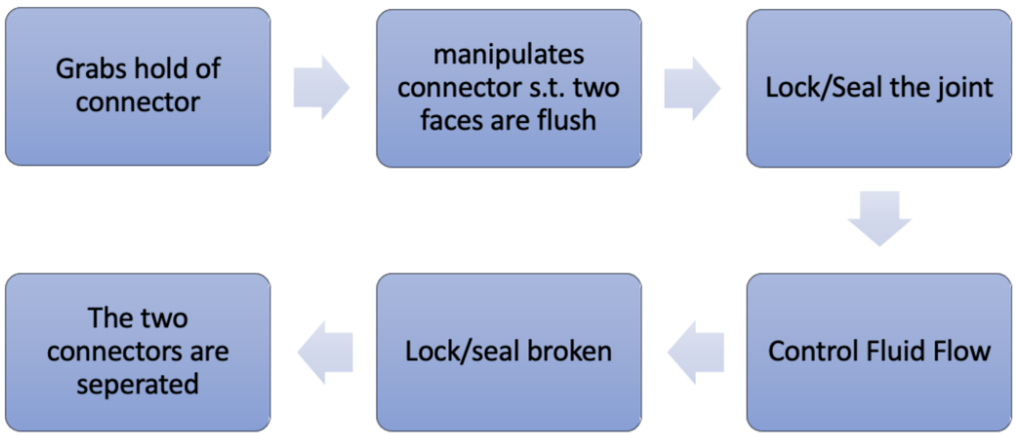


Figure 7: Functional Decomposition Flow Chart

Functions	Systems	
	Operate	Maintain
Manipulate two connector ends together	x	
Lock the two ends together	x	
Transfer cryo-fluid across the joint	x	
Seal the space between the two ends.	x	x
Control fluid dynamics	x	
Unlock two ends	x	
Release seal between connector faces	x	x
Keep dust and dirt particles out of the system		x
Mind thermal expansion wear		x
Prevent breaking between uses	x	x

Figure 8: Cross Reference Chart

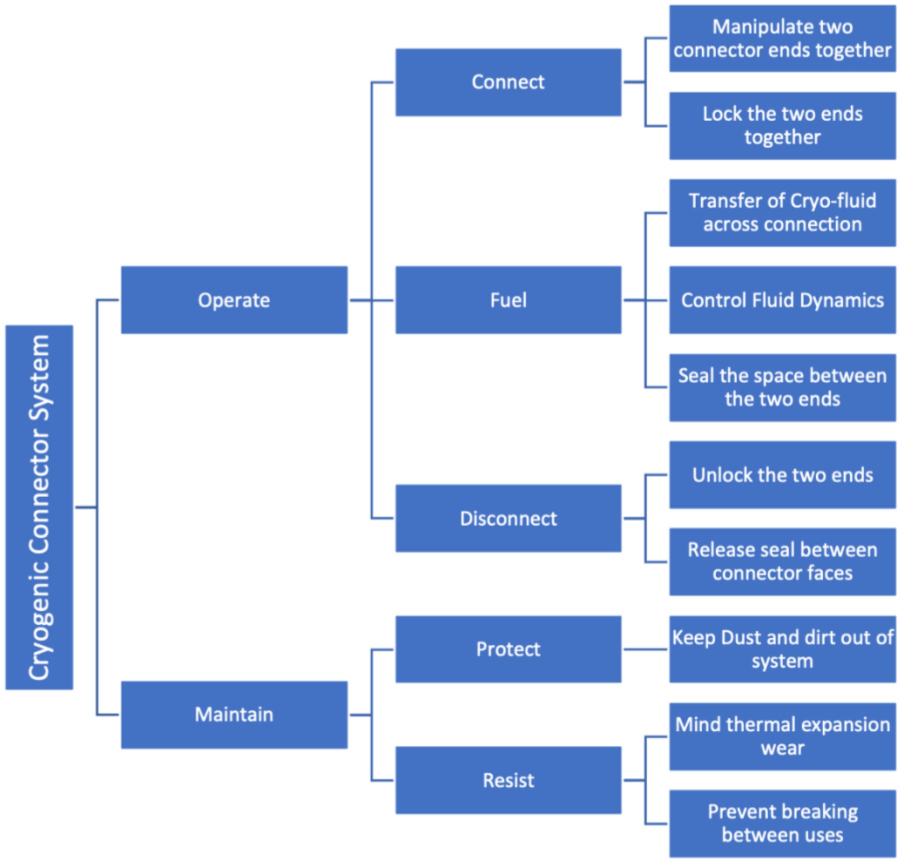


Figure 9: Hierarchal Chart

Appendix D: Target Catalog

Target Catalog

Function	Target	Metric
Manipulate two connector ends together	2.57 cm – 3 cm	Diameter of connector
Lock two ends together & Unlock	< 48 Newtons	Connection & disconnection force
Seal space between them	< 0.001 SCIM	Permissible leakage rate
Transferring cryogenic fluid	0.1 SCIM	Volumetric Flow rate
Transferring cryogenic fluid	90 K	Cryogenic fluid temperature
Protect from dust and dirt	IP64	Ingress Protection
Mind thermal expansion and contraction	0	Material expansion/ contraction difference
Prevent breaking between uses	500 MPa	Stainless steel ultimate tensile strength
Control Fluid Dynamics	0.0023 SCIM	Liquid Nitrogen boil off rate

Appendix E: 100 Concept Generation

Table 12: 100 Concepts

Concept 1	Cryogenic Bayonet connection
Concept 2	Npt threaded connection
Concept 3	Viton O-rings to seal between the two ends of the connection
Concept 4	Teflon coated NPT threading
Concept 5	Vacuum jacket for heat resistance
Concept 6	Fiber glass coating for heat resistance
Concept 7	Quick release connector
Concept 8	Safety, pressure relief valve
Concept 9	Magnetic seal connection
Concept 10	Key and slot connection
Concept 11	Kel-F polymer seal
Concept 12	Vacuum jacket, stainless steel, gate valve connector
Concept 13	Vacuum jacket, stainless steel, ball valve connector
Concept 14	Vacuum jacket, stainless steel, globe valve connector
Concept 15	Vacuum jacket, aluminum, gate valve connector
Concept 16	Vacuum jacket, aluminum, ball valve connector
Concept 17	Vacuum jacket, aluminum, globe valve connector
Concept 18	Vacuum jacket, brass, gate valve connector
Concept 19	Vacuum jacket, brass, ball valve connector
Concept 20	Vacuum jacket, brass, globe valve connector
Concept 21	Multilayer insulation, stainless steel, gate valve connector

Concept 22	Multilayer insulation, stainless steel, ball valve connector
Concept 23	Multilayer insulation, stainless steel, globe valve connector
Concept 24	Multilayer insulation, aluminum, gate valve connector
Concept 25	Multilayer insulation, aluminum, ball valve connector
Concept 26	Multilayer insulation, aluminum, globe valve connector
Concept 27	Multilayer insulation, brass, gate valve connector
Concept 28	Multilayer insulation, brass, ball valve connector
Concept 29	Multilayer insulation, brass, globe valve connector
Concept 30	Fiber glass insulation, stainless steel, gate valve connector
Concept 31	Fiber glass insulation, stainless steel, ball valve connector
Concept 32	Fiber glass insulation, stainless steel, globe valve connector
Concept 33	Fiber glass insulation, aluminum, gate valve connector
Concept 34	Fiber glass insulation, aluminum, ball valve connector
Concept 35	Fiber glass insulation, aluminum, globe valve connector
Concept 36	Fiber glass insulation, brass, gate valve connector
Concept 37	Fiber glass insulation, brass, ball valve connector
Concept 38	Fiber glass insulation, brass, globe valve connector
Concept 39	Non-insulated, stainless steel, gate valve connector
Concept 40	Non-insulated, stainless steel, ball valve connector
Concept 41	Non-insulated, stainless steel, globe valve connector
Concept 42	Non-insulated, aluminum, gate valve connector
Concept 43	Non-insulated, aluminum, ball valve connector

Concept 44	Non-insulated, aluminum, globe valve connector
Concept 45	Non-insulated, brass, gate valve connector
Concept 46	Non-insulated, brass, ball valve connector
Concept 47	Non-insulated, brass, globe valve connector
Concept 48	Aero-gel bead bulk fill insulation, stainless steel, gate valve connector
Concept 49	Aero-gel bead bulk fill insulation, stainless steel, ball valve connector
Concept 50	Aero-gel bead bulk fill insulation, stainless steel, globe valve connector
Concept 51	Aero-gel bead bulk fill insulation, aluminum, gate valve connector
Concept 52	Aero-gel bead bulk fill insulation, aluminum, ball valve connector
Concept 53	Aero-gel bead bulk fill insulation, aluminum, globe valve connector
Concept 54	Aero-gel bead bulk fill insulation, brass, gate valve connector
Concept 55	Aero-gel bead bulk fill insulation, brass, ball valve connector
Concept 56	Aero-gel bead bulk fill insulation, brass, globe valve connector
Concept 57	Pearlite powder bulk fill insulation, stainless steel, gate valve connector
Concept 58	Pearlite powder bulk fill insulation, stainless steel, ball valve connector
Concept 59	Pearlite powder bulk fill insulation, stainless steel, globe valve connector

Concept 60	Pearlite powder bulk fill insulation, aluminum, gate valve connector
Concept 61	Pearlite powder bulk fill insulation, aluminum, ball valve connector
Concept 62	Pearlite powder bulk fill insulation, aluminum, globe valve connector
Concept 63	Pearlite powder bulk fill insulation, brass, gate valve connector
Concept 64	Pearlite powder bulk fill insulation, brass, ball valve connector
Concept 65	Pearlite powder bulk fill insulation, brass, globe valve connector
Concept 66	Buckling valve, vacuum suction of cryogenic fluids
Concept 67	Elastic connector to allow expansion under high pressures
Concept 68	Active ventilation to prevent backflow of cryogenic fluid
Concept 69	Switchable 90 degree angle female end for if needed
Concept 70	Biomimic humming bird's beak which transfers fluid from flower
Concept 71	Outer clamps to maintain seal
Concept 72	Flair fitting
Concept 73	Pressure sensor to detect fluid flow
Concept 74	Red LED on outer to signal when fluid flow occurs
Concept 75	Green LED to signal ability to disconnect
Concept 76	On board screen to show flow rate to user
Concept 77	Light source on either end to illuminate connection area
Concept 78	Glass panel to observe fluid flow
Concept 79	Bluetooth camera inside connector to observe from shuttle
Concept 80	Honeycomb tubing to twist into connection

Concept 81	Carbon fiber cover as protection
Concept 82	Brass coupling to seal system
Concept 83	Choke valve as safety measure
Concept 84	Installable outer ends to fit for any type of tubing
Concept 85	Outer levers to pull and lock connection
Concept 86	Force sensor on connection to observe stress levels
Concept 87	Attached spring on female end to create equal opposite forces with locking mechanism
Concept 88	Attachable rod for even greater torque output when twisting to seal
Concept 89	Relief valve gas collector to recycle escaped fuel
Concept 90	Turbine system from gas collector to generate electricity
Concept 91	Generated electricity stored in battery for lights on connector ends
Concept 92	Internal DC motor and gear system to tighten clamps
Concept 93	Adjustable tube end mold to form on any type of cryo tubing
Concept 94	Solar panel sides as potential energy collector for connection lights
Concept 95	Interchangeable out wall flaps to install proper protection for specific mission
Concept 96	Extruded hook on either end to attach to suit during transportation
Concept 97	Stainless steel shaft bearings coated with nickel reinforced PTFE for smooth closing of seal valves
Concept 98	A mesh wrap that has leakage protection that encapsulates a shaft and then a metal clamp locks it in place on the shaft with the fluid

	moving through the shaft and then through the end with the mesh. The mesh will be sealed on the inside but allow for variability of shape for variable shafts.
Concept 99	Expanded graphite ring on o rings to make fire safe
Concept 100	Adjustable torque outputs on connection seal to adjust for temperature fluctuation from fuel.

Appendix F: Binary Pairwise Comparison Chart

Binary Pairwise Comparison										
Customer Needs	Fluid Loss	Withstand Flow	Fit to existing pipe	Reusable	Cryogenic Temp.	Ergonomic	Below $1400	Reliable coupling	Control Flow	Total
Fluid Loss	-	0	0	0	1	1	0	0	1	3
Withstand Flow	1	-	0	0	0	1	1	0	0	3
Fit to existing pipe	1	1	-	1	1	1	1	0	0	6
Reusable	1	1	0	-	1	1	0	0	0	4
Cryogenic Temp.	0	1	0	0	-	0	0	0	0	1
Ergonomic	0	0	0	0	1	-	0	0	0	1
Below $1400	1	0	0	1	1	1	-	0	0	4
Reliable coupling	1	1	1	1	1	1	1	-	0	7
Control Flow	0	1	1	1	1	1	1	1	-	7

Appendix G: Analytical Hierarchy Process Charts

Development of Candidate set of critera weights {W}								
Criteria Comparison Matrix [C]								
Criteria	Diameter	Force	Leakage	Flow Rate	Tensile Str.	Ingress	Boil Off	Price
Diameter	1	3.00	1.00	1.00	5.00	5.00	3.00	3.00
Force	0.33	1	0.33	1.00	3.00	3.00	3.00	3.00
Leakage	1.00	3.00	1	1.00	5.00	3.00	1.00	5.00
Flow Rate	1.00	1.00	1.00	1	3.00	3.00	1.00	3.00
Tensile Str.	0.20	0.33	0.20	0.33	1	1.00	1.00	1.00
Ingress	0.20	0.33	0.33	0.33	1.00	1	3.00	1.00
Boil Off	0.33	0.33	1.00	1.00	1.00	0.33	1	1.00
Price	0.33	0.33	0.20	0.33	1.00	1.00	1.00	1
SUM	4.40	9.33	5.07	6.00	20.00	17.33	14.00	18.00

Consistency Check		
Weighted Sum Vector	Criteria Weights	Consistency Check
2.05	0.23	8.97
1.23	0.14	8.81
1.85	0.21	8.79
1.36	0.16	8.62
0.45	0.05	8.76
0.65	0.07	8.91
0.71	0.08	8.40
0.48	0.06	8.71

Average Cons. (λ)	8.75
Criteria	8
Consistency Index	0.10681627
Random Index Val.	1.4
Cons. Ratio (CR)	0.07629734

Consistency Ratio Table

Appendix H: Comparison Matrices for Final Design Matrix

Diameter			
Comparison [C]			
	Bayonet Interface	Latch Sealing	Lever Lock
Bayonet Interface	1.00	0.33	0.33
Latch Sealing	3.00	1.00	1.00
Lever Lock	3.00	1.00	1.00
sum	7.00	2.33	2.33

				Design
Norm Comparison [C]				Alt. Priorities
	Bayonet Interface	Latch Sealing	Lever Lock	{Pi}
Bayonet Interface	0.14	0.14	0.14	0.14
Latch Sealing	0.43	0.43	0.43	0.43
Lever Lock	0.43	0.43	0.43	0.43
sum	1	1	1	1

Force			
Comparison [C]			
	Bayonet Interface	Latch Sealing	Lever Lock
Bayonet Interface	1.00	0.33	1.00
Latch Sealing	3.00	1.00	3.00
Lever Lock	1.00	0.33	1.00
sum	5.00	1.67	5.00

				Design
Norm Comparison [C]				Alt. Priorities
	Bayonet Interface	Latch Sealing	Lever Lock	{Pi}
Bayonet Interface	0.20	0.20	0.20	0.20
Latch Sealing	0.60	0.60	0.60	0.60
Lever Lock	0.20	0.20	0.20	0.20
sum	1.00	1.00	1.00	1.00

Leakage			
Comparison [C]			
	Bayonet Interface	Latch Sealing	Lever Lock
Bayonet Interface	1	0.5	0.33333333
Latch Sealing	2	1	1
Lever Lock	3	1	1
sum	6	2.5	2.33333333

				Design
Norm Comparison [C]				Alt. Priorities
	Bayonet Interface	Latch Sealing	Lever Lock	{Pi}
Bayonet Interface	0.17	0.20	0.14	0.17
Latch Sealing	0.33	0.40	0.43	0.39
Lever Lock	0.50	0.40	0.43	0.44
sum	1.00	1.00	1.00	1.00

Flow Rate			
Comparison [C]			
	Bayonet Interface	Latch Sealing	Lever Lock
Bayonet Interface	1.00	1.00	1.00
Latch Sealing	1.00	1.00	1.00
Lever Lock	1.00	1.00	1.00
sum	3.00	3.00	3.00

				Design
Norm Comparison [C]				Alt. Priorities
	Bayonet Interface	Latch Sealing	Lever Lock	{Pi}
Bayonet Interface	0.33	0.33	0.33	0.33
Latch Sealing	0.33	0.33	0.33	0.33
Lever Lock	0.33	0.33	0.33	0.33
sum	1.00	1.00	1.00	1.00

Tensile Str.			
Comparison [C]			
	Bayonet Interface	Latch Sealing	Lever Lock
Bayonet Interface	1.00	3.00	1.00
Latch Sealing	0.33	1.00	0.33
Lever Lock	1.00	3.00	1.00
sum	2.33	7.00	2.33

				Design
Norm Comparison [C]				Alt. Priorities
	Bayonet Interface	Latch Sealing	Lever Lock	{Pi}
Bayonet Interface	0.43	0.43	0.43	0.43
Latch Sealing	0.14	0.14	0.14	0.14
Lever Lock	0.43	0.43	0.43	0.43
sum	1.00	1.00	1.00	1.00

Ingress			
Comparison [C]			
	Bayonet Interface	Latch Sealing	Lever Lock
Bayonet Interface	1.00	3.00	1.00
Latch Sealing	0.33	1.00	0.33
Lever Lock	1.00	3.00	1.00
sum	2.33	7.00	2.33

				Design
Norm Comparison [C]				Alt. Priorities
	Bayonet Interface	Latch Sealing	Lever Lock	{Pi}
Bayonet Interface	0.43	0.43	0.43	0.43
Latch Sealing	0.14	0.14	0.14	0.14
Lever Lock	0.43	0.43	0.43	0.43
sum	1	1	1	1

Boil Off			
Comparison [C]			
	Bayonet Interface	Latch Sealing	Lever Lock
Bayonet Interface	1.00	0.33	0.33
Latch Sealing	3.00	1.00	1.00
Lever Lock	3.00	1.00	1.00
sum	7.00	2.33	2.33

				Design
Norm Comparison [C]				Alt. Priorities
	Bayonet Interface	Latch Sealing	Lever Lock	{Pi}
Bayonet Interface	0.14	0.14	0.14	0.14
Latch Sealing	0.43	0.43	0.43	0.43
Lever Lock	0.43	0.43	0.43	0.43
sum	1	1	1	1

Price			
Comparison [C]			
	Bayonet Interface	Latch Sealing	Lever Lock
Bayonet Interface	1.00	3.00	3.00
Latch Sealing	0.33	1.00	1.00
Lever Lock	0.33	1.00	1.00
sum	1.67	5.00	5.00

				Design
Norm Comparison [C]				Alt. Priorities
	Bayonet Interface	Latch Sealing	Lever Lock	{Pi}
Bayonet Interface	0.60	0.60	0.60	0.60
Latch Sealing	0.20	0.20	0.20	0.20
Lever Lock	0.20	0.20	0.20	0.20
sum	1	1	1	1

Appendix I: CAD Drawings

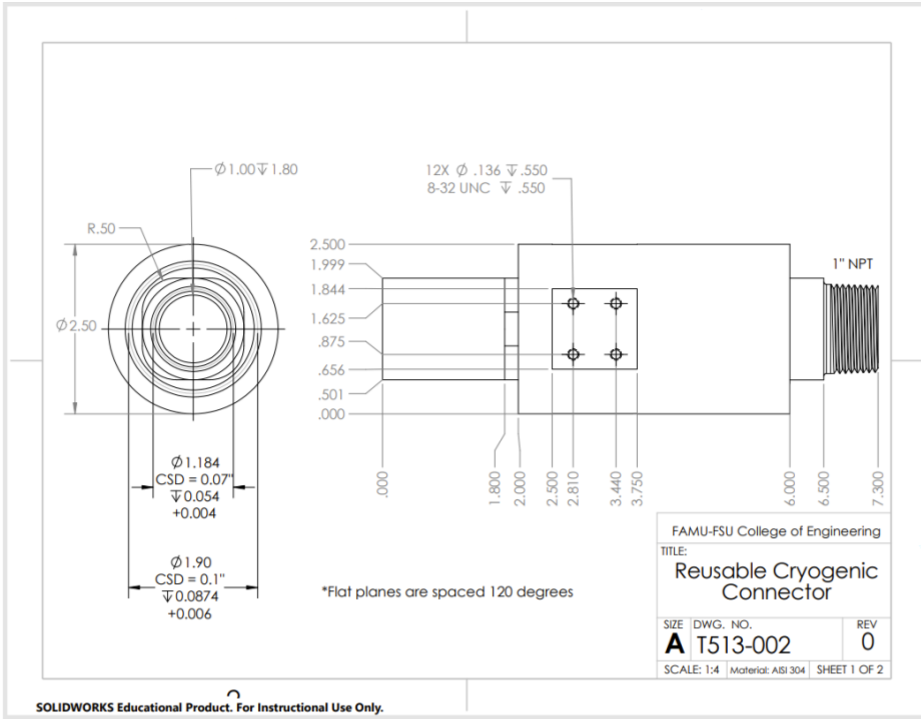


Figure 4: Cryogenic connector male end CAD drawing

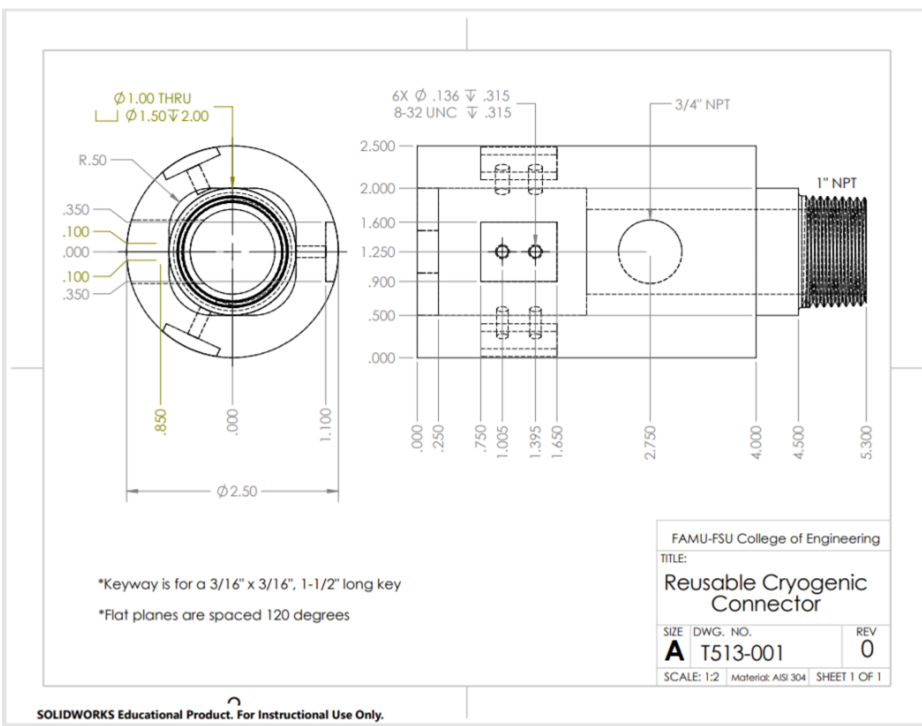


Figure 5: Cryogenic connector female end CAD drawing, page 1

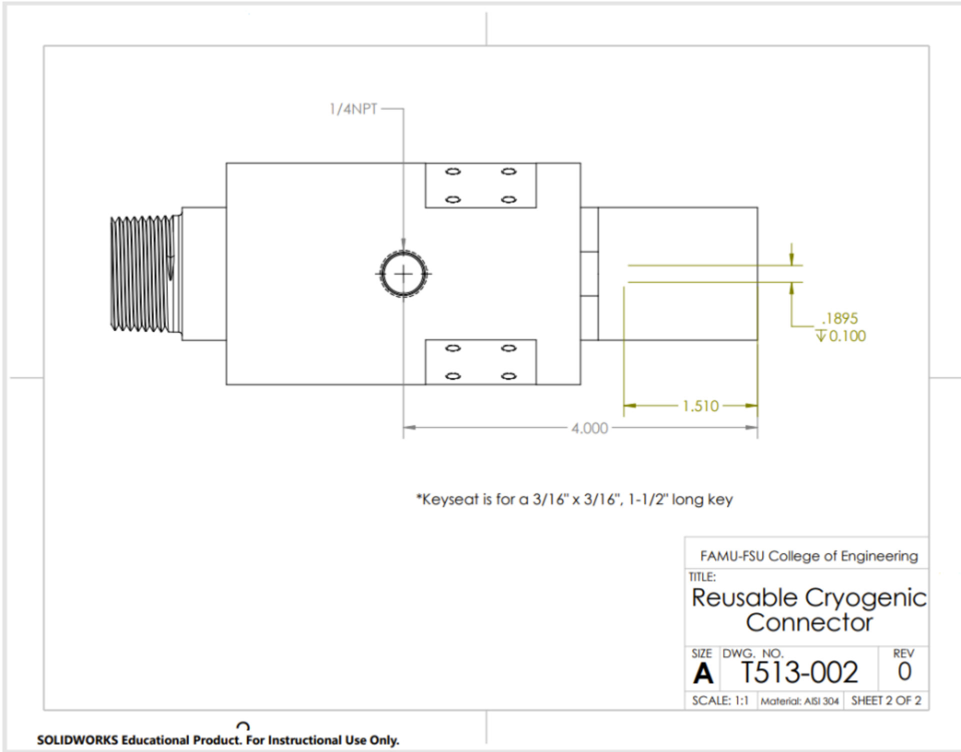


Figure 6: Cryogenic connector female end CAD drawing, page 2

Appendix J: Equations

Pressure Validation

- $Thick\ Walled\ Cylinder{:}\ t \geq 0.1r$
- $t = 0.5\ inches$
- $r = 0.75\ inches$
- $0.1 * 0.75\ inches = 0.075$
- $t = 0.5$
- $0.5 \geq 0.075$

Radial and Tangential Stress of Thick-Walled Cylinders

- p_i=50 psi
- p_o=0 psi
- r_o=0.75 in
- r_i=0.5 in
- $\boldsymbol{\sigma}\text{t} = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} + \frac{r_i^2 r_o^2 (p_i - p_o)}{r^2 (r_o^2 - r_i^2)}$
- $\boldsymbol{\sigma}\text{t} = \frac{(50\ psi)(0.5\ in)2-(0\ psi)(0.75\ in)2}{(0.75\ in)2-(0.50\ in)2} + \frac{(0.5\ in)2\ (0.75\ in)2(50\ psi - 0\ psi)}{(0.50\ in)2((0.75\ in)2-(0.50\ in)2)}$
- $\boldsymbol{\sigma}\text{t} = 130\ \text{psi}$
- $\boldsymbol{\sigma}\text{r} = \frac{p_i r_i^2 - p_o r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 r_o^2 (p_i - p_o)}{r^2 (r_o^2 - r_i^2)}$
- $\boldsymbol{\sigma}\text{r} = \frac{(50\ psi)(0.5\ in)2-(0\ psi)(0.75\ in)2}{(0.75\ in)2-(0.50\ in)2} - \frac{(0.5\ in)2\ (0.75\ in)2(50\ psi - 0\ psi)}{(0.50\ in)2((0.75\ in)2-(0.50\ in)2)}$
- $\boldsymbol{\sigma}\text{r} = 50\ \text{psi}$
- $Yield\ Strength\ of\ AISI304\ @\ 77\ K$
- $\boldsymbol{\sigma} y = 39{,}000\ psi$
- $\boldsymbol{\sigma}\text{t} = 130\ psi \leq 39{,}000\ psi$
- $\boldsymbol{\sigma}\text{r} = 50\ psi \leq 39{,}000\ psi$
- $Factor\ of\ Safety = \frac{Maximum\ Stress}{Design\ Stress}$
- $Factor\ of\ Safety = \frac{39{,}000\ psi}{130\ psi}$
- $Factor\ of\ Safety = 300$

Ball Valve Activation Force

Acceleration

- $a = \frac{(x - x_0 - V_0 * t)2}{t\hat{}2}$
- $a = \frac{\left((\frac{1}{4} * 2\pi r.) - x_0 - V_0\right)2}{(t)\hat{}2}$
- $a = \frac{\left(\frac{1}{4} * 2\pi * 8\ in - 0 - 0\right)2}{(0.4\ s)\hat{}2}$
- $a = 125.6\ \frac{in}{s^2} = 3.19 \frac{m}{s^2}$

Average Activation Force

- $F = ma$
- $m = 4429.9\ g$
- $a = 3.19 \frac{m}{s^2}$
- $F = (4.4299\ kg) * (3.19\ \frac{m}{s^2})$
- $F = 14.13\ \frac{kg * m}{s^2}$
- $1\ N = 1 \frac{kg * m}{s^2}$
- $F = 14.13\ N$

Maximum Activation Force

- $F = ma$
- $m = 4484\ g$
- $a = 3.19 \frac{m}{s^2}$

- $F = (4.484\ kg) * (3.19\ \frac{m}{s^2})$
- $F = 14.3\ \frac{kg*m}{s^2}$
- $1\ N = 1\frac{kg*m}{s^2}$
- $F = 14.3\ N$

<u>Flow Rate</u>

- $Diameter\ of\ Dewar: 22\ in$
- $Diameter\ of$ Storage Tank: 14 in
- $volume\ of\ a\ cylinder = \pi r^2 h$
- $v_D = \pi(11.00in)^2(0.9125in)$
- $v_D = 346.70\ in^3$
- $\dot{v_D} = 346.70\frac{in^3}{min}$
- $v_{st} = \pi(7in)^2(2.1625in)$
- $v_{st} = 332.72\ in^3$
- $\dot{v_{st}} = 332.72\frac{in^3}{min}$
- $leakage = 346.70\ \frac{in^3}{min} - 332.72\frac{in^3}{min} = 13.98\frac{in^3}{min}$
- $leakage = \frac{13.98\frac{in^3}{min}}{346.70\frac{in^3}{min}} = 0.040 * 100 = 4.0\%\ of\ flow$

<u>O-Ring Compression</u>

Large O-Ring

- $CSD = 0.103in$

- $g = 0.085in$
- $squeeze = \frac{CSD - g}{CSD}$
- $squeeze = \frac{0.103in. - 0.085in}{0.103in}$
- $squeeze = 0.175 * 100 = 17.5\%$

Small O-Ring

- $CSD = 0.070in$
- $g = 0.052in$
- $squeeze = \frac{CSD - g}{CSD}$
- $squeeze = \frac{0.070in. - 0.052in}{0.070in}$
- $squeeze = 0.256 * 100 = 25.7\%$

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