Crewed Lunar Lander Door Mechanism

Final Report

Team 5
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Sponsor - Blue Origin

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Executive Summary

It has been over half a century since humans have stepped foot on the Moon, but in 2029 Blue Origin's MK2 Lunar Lander will overwrite decades of perennial challenges. We have been selected to model the lunar lander door mechanism for this mission, which will serve as a bridge between the safety of the Blue Moon Lander Module and the unknowns of the lunar surface.

We have been asked to ensure that the door mechanism is able to withstand the harsh lunar environment and the conditions during takeoff and landing. This project is intended to reflect sustainability and human centered design. Our background research on Apollo 11 and other attempts to design lunar landers have aided us in defining our design problem and developing user requirements. Our primary concerns for our product are resistance to lunar dust, durability for extreme temperatures and gravitational forces, and usability of the door mechanism.

The team has created a CAD assembly of our proposed rotational opening and latching mechanism, the hinges connecting the hatch to the frame, and the hand crank. While the model lacks fasteners and intricacy regarding the controls, these aspects are outside project scope and would be best carried out by Blue Origin Engineers according to their discretion and testing.

Our team measured the efficacy of our seal design by fabricating a 1:2 scale model of the hatch-frame interface with accurate materials representation. Using sponge tape, fiberglass sheets, and a vacuum we gauged the instantaneous leak rate of our design. We also applied heating and cooling to the titanium to simulate stress cycles that would impact material performance.

The detailed CAD model and our seal validation testing gave us valuable insight into how our design performs with respect to the key engineering specifications for this product. Our recommendations for future design improvements are based on the empirical results we collected during testing.

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1. Abstract

Human spaceflight missions to the lunar surface necessitate robust and reliable door systems on lander vehicles in order to facilitate ingress and egress of people and cargo. These doors must accommodate pressurization requirements, harsh conditions of the lunar surface and open space, withstand G-forces associated with launching and landing, operate safely throughout its lifetime, and be ergonomic for astronauts in spacesuits. Designing for a lunar landing module (LLM) presents unique challenges, as the only fully successful benchmark is NASA's Apollo program from the 1960's and 70's. The team has performed a background review, conceptualized design choices, and chosen a concept to pursue for later engineering testing and analyses.

2. Project Info, Background, and Information Sources

Human exploration to the Moon and beyond requires development of technology to address specific challenges associated with non-Earth environments. To assist in this mission, Blue Origin is developing a crewed human landing system (HLS) that will deliver astronauts and cargo from lunar orbit to the lunar surface. The door or hatch system for the astronauts to enter and exit the HLS is an important design feature that must satisfy several requirements, which will be detailed in the following sections.

2.1 Background

NASA announced its plan to return to the Moon, known as the Artemis Program, on May 23rd, 2019, for the purposes of proving technologies and capabilities to send people to Mars, establish American leadership and strategic presence, inspire a new generation, and expand the U.S. global economic impact [2]. The plan has been revised and delayed since then, but the current mission strategy can be summarized in *Table 1* below.

Table 1. Artemis missions I-V with a summary of the mission's purpose and predicted year [3].

Mission	Purpose	Predicted Year
Artemis I	Uncrewed flight test of the Space Launch System (SLS) and Orion spacecraft around the Moon.	Launched Nov. 2022
Artemis II	10 day crewed flight around the Moon.	Set for April 2026
Artemis III	30 day crewed surface landing to the lunar South Pole region.	Set for mid-2027
Artemis IV	First lunar space station, Gateway.	Set for late 2028
Artemis V	Docking with Gateway, taking Blue Origin's Blue Moon MK2 lander down to the lunar surface.	Set for 2029

Through NASA's NextSTEP-2 (Next Space Technologies for Exploration Partnerships) program, Blue Origin was awarded a contract to participate in the Artemis V mission on May 19th, 2024 [4]. For this mission, NASA's SLS (Space Launch System) will launch four astronauts to lunar orbit via the Orion spacecraft. The spacecraft will dock with Gateway, an orbiting lunar space station, and two of the astronauts will transfer to Blue Origin's Blue Moon MK2 lander for a week-long trip to the Moon's south pole [5].

The Blue Moon MK2 is the spacecraft we will be designing the door mechanism for. A concept of it is shown in *Figure 1* below. The team has confirmed with the sponsor that they may use the image as a reference to base the team's design from.

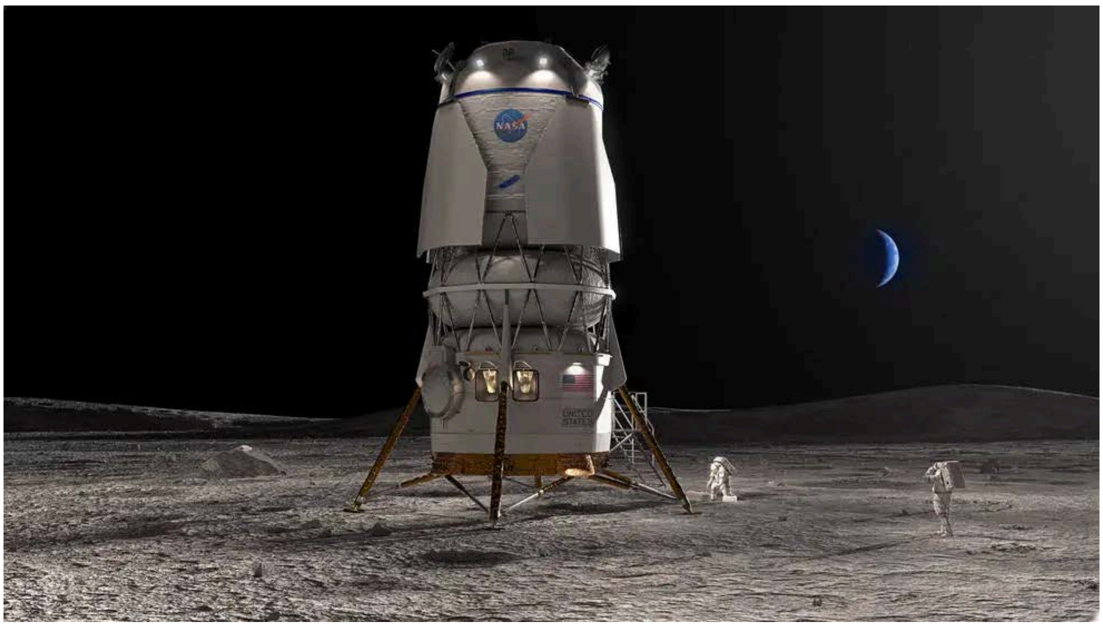

Figure 1. A concept illustration of Blue Origin's Blue Moon MK2 lander [5].

The goal the sponsor has asked us to achieve is to design the door (or hatch) and opening mechanism that will accompany Blue Origin's Blue Moon MK2 lander. This remains to be a relatively open-ended problem, since there is not a large quantity of publicly available documentation detailing this type of mechanism. However, it's important to solve in order to make the Artemis V mission possible and increase mankind's presence beyond Earth. A successful project outcome may be realized in different forms, but overall it should address the requirements set by the team in Section 5. Further, it must be in alignment with what the sponsor is seeking from the team.

2.2 Benchmarking

To date, the last time astronauts explored the lunar surface was with NASA's Apollo program. The Apollo program ran from 1962-1972 and featured eleven crewed missions. Fifteen lunar landing modules (LLMs) were developed, but only six were launched and landed on the Moon [6]. As a result, there is scarce documentation specifically related to door mechanisms designed for a LLM. This section will detail design schematics from an Apollo Operations Handbook for the Lunar Module (LM) 10 and subsequent lunar modules [7]. Further, other door latching and airlock mechanisms will be referenced and summarized.

2.2.1 Benchmarking Apollo

Apollo's LM 10 featured two hatches, an overhead hatch and a forward hatch. The position of these two hatches on the LM have been highlighted in *Figure 2* below.

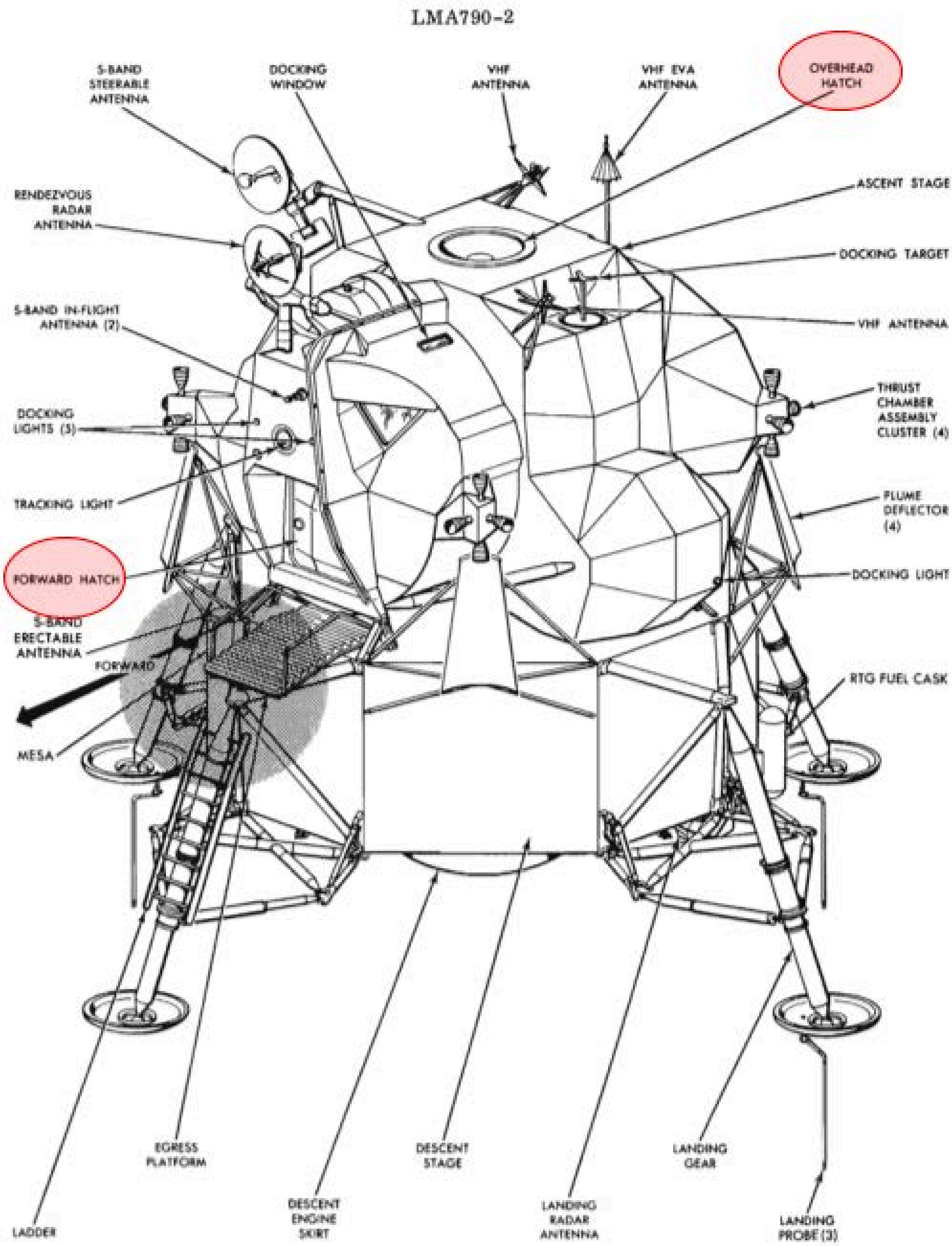

Figure 2: A diagram of the vehicle configuration for the Apollo LM 10 [7].

The overhead hatch and forward hatch operated on a dual set of quick-release hinge pins that swung the door into the cabin. A cam latch assembly holds the hatch in the closed position, and when the cabin is pressurized, the hatches are sealed against the LM structure using a preloaded elastomeric silicone compound seal. Each hatch featured a cabin relief and dump valve to depressurize the cabin before the hatch was opened. It was specified that the forward hatch was approximately 32 inches in length and width. For the overhead hatch, it was specified that the door opened 75 degrees into the cabin, and the latch to open the hatch required 35 in-lb of force to rotate. Finally, the forward hatch featured a lockpin in a plate over the latch that allows the latch to be released in case of an emergency. The diagrams given in the documentation for the front and rear hatch can be seen in *Figure 3* and *Figure 4* below [7].

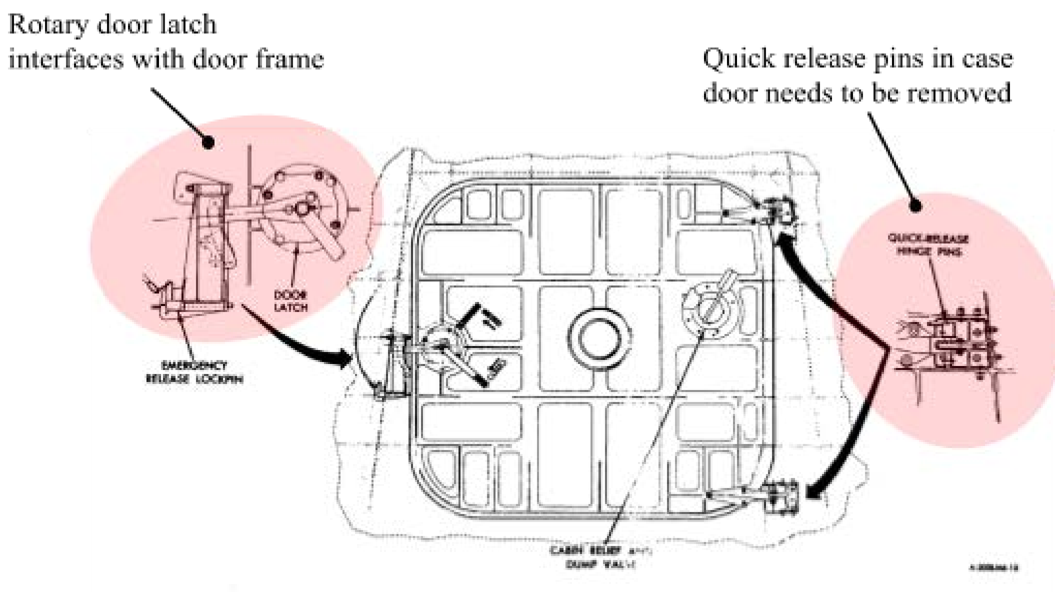

Figure 3: Diagram of the front hatch for the Apollo LM 10 and subsequent LMs [7].

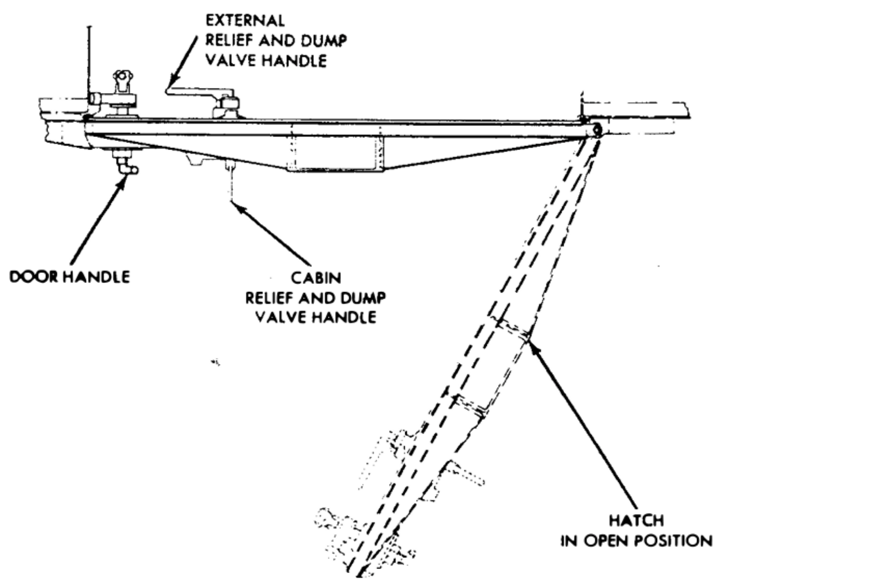

Figure 4: Diagram of the overhead hatch for the Apollo LM 10 and subsequent LMs [7].

In 2004, an article was published by NASA documenting key engineering and operational lessons learned from lunar surface exploration missions in the Apollo program [8]. The following lessons learned are the ones most applicable to this project:

- “Hatches Should Have External Latches” - The forward (or “egress”) hatch did not feature an external latch mechanism, so the hatch had to remain open during Lunar extravehicular activity (EVA).
- “Lunar Dust is a Major Problem During Surface Operations” - It was stated in the article that, potentially due to lack of weathering conditions by wind or water abrasion, lunar dust particles are much sharper and more jagged than terrestrial dust particles. More details and the challenges associated with lunar dust will be discussed in Section 6 of this report.

This is the only existing reference for a crewed lunar lander door mechanism, as there has not been a crewed mission to the Moon since the Apollo program. While it performs its intended function, there are several opportunities for improvement or changes necessary for Blue Origin’s MK2 the team has identified, along with the lessons learned points:

- **Longevity**: The LMs used on the Apollo program had various fates, but none were intended to be reusable [9]. Given the requirement for the MK2 to be reusable for at least 5 missions, the team will have to ensure the hatch and mechanism can withstand the test of time over multiple missions.
- **Door size:** The ingress/egress door used on the Apollo program was only 32 inches in width and height. For the MK2, the door will need to allow astronauts to enter and exit while walking, and potentially carrying cargo.
- **Opening mechanism:** On Apollo, both the overhead and front hatch opened by swinging into the cabin. This reduces the space available inside the cabin since the door must have sufficient clearance to open. For MK2, a door that opens out of the cabin could save interior cabin space.

2.2.2 Aerospace Door Patents

Doors and latches for airplanes and other aerospace vehicles may be a useful reference in designing doors for pressurized cabins. A patent published in 1956 describes a plug-type door mechanism. When closed, the door’s lateral width is wider than the hole it sits in, resulting in a very reliable and safe interface when pressurized. The frame or the door would have to structurally fail for an accidental depressurization to occur, as opposed to relying solely on a latch or locking mechanism. One added benefit to this design is that it swivels and slides open (using an “articulated double quadrangular linkage mechanism”) to the exterior of the cabin, allowing for more room for components on the interior side of the cabin. This door mechanism is unique in its design in that it can be safely pressurized against the cabin to provide a strong seal, while still opening to the exterior of the cabin. Diagrams of the mechanism are shown in *Figure 5* below [10].

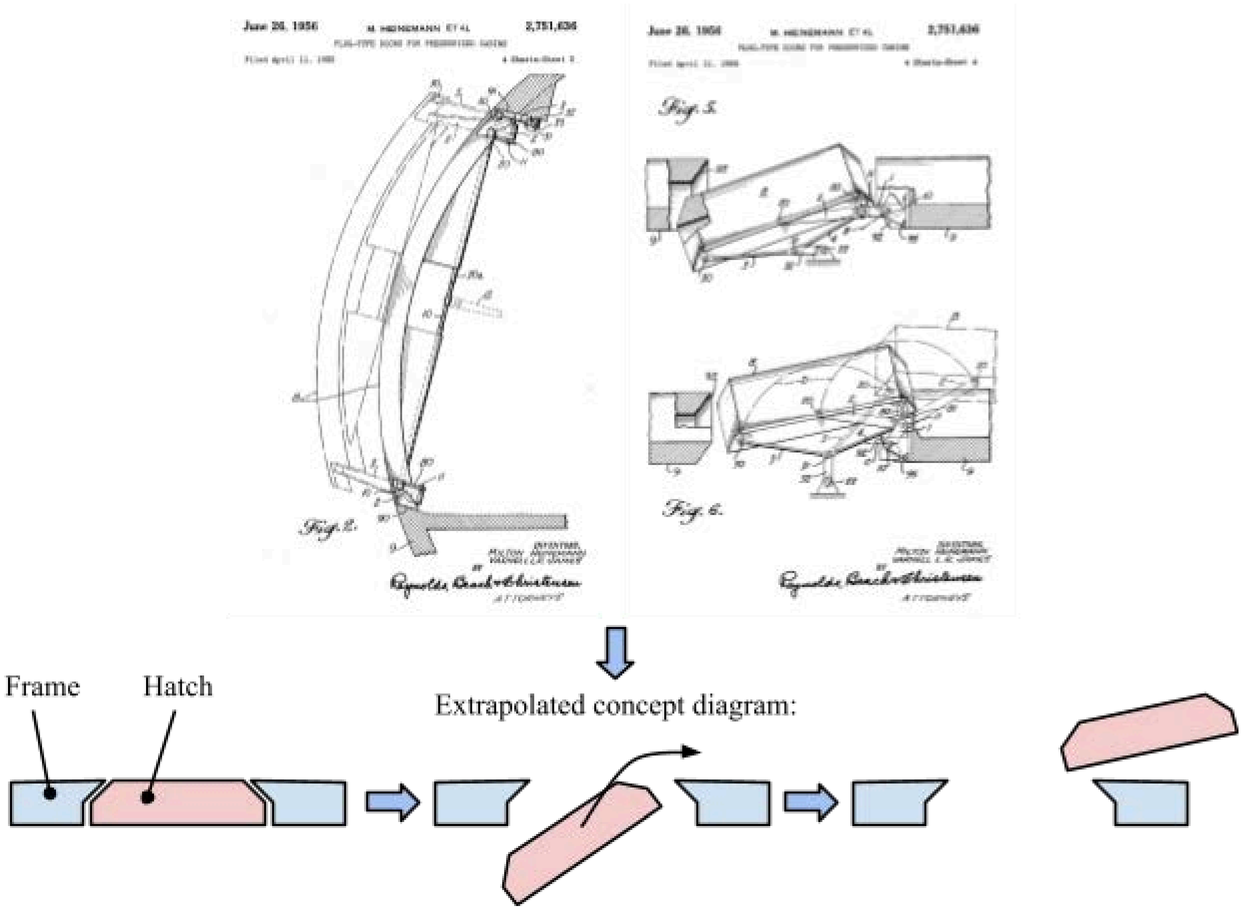

Figure 5: Diagrams of a patent design of a plug-type door for pressurized cabins [10].

Another patent published in 2022 details a bolt-type latching mechanism for a cabin door in a pressurized cabin. The mechanism, as shown in *Figure 6*, is a useful reference because it incorporates a pressure relief valve into the unlocking mechanism, and the author also claims the mechanism to be easy to use, lightweight, and take up less space than existing solutions [11].

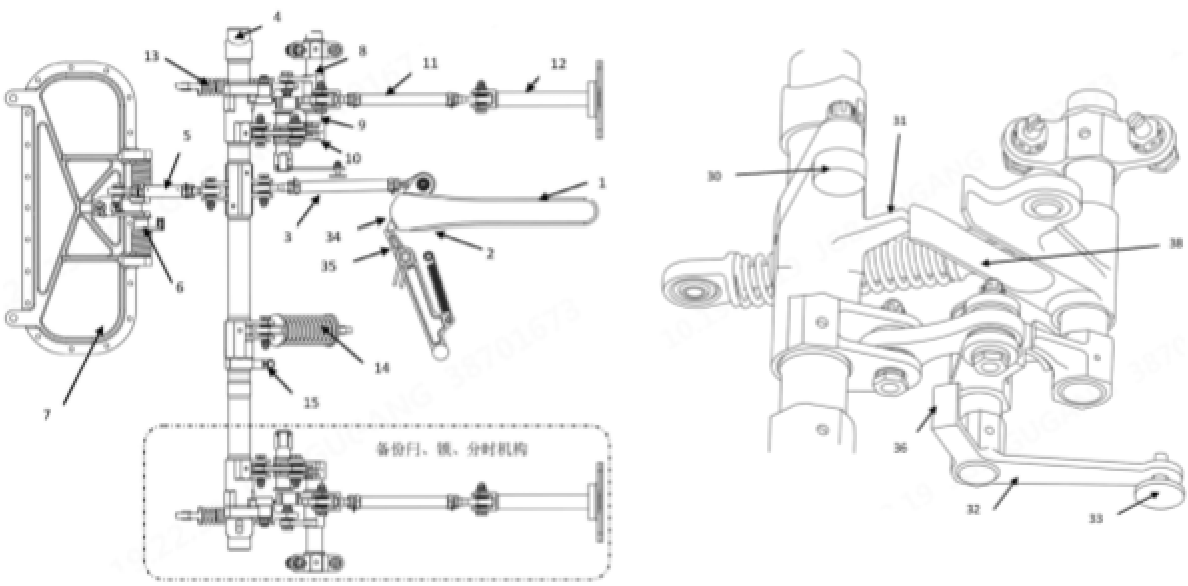

Figure 6. A patent detailing a bolt-type latch mechanism for a pressurized cabin door [11].

While the mechanism functionality within these two patents are difficult to completely understand and may not be directly applicable to a door designed for space and the lunar surface, they provide unique concepts compared to the previous Apollo benchmark that may be useful in our design. For one, the concept of a plug-type door that can still open to the exterior of the cabin may be more complicated, but ensures safety while not compromising interior space necessary for an inward-hinging door. Further, the dual functionality of incorporating the pressure relief mechanism into the door latch could make the mechanism easier to use and more convenient but could introduce new design challenges.

2.2.3 ISS Hatch Docking Benchmark

One type of solution that is comparable to our design problem is hatches used for connecting docking spacecrafts to orbiting crewed space stations, such as the International Space Station (ISS). In 2012, a video was published showing NASA engineers using a hatch on the ISS to access cargo in a SpaceX Dragon spacecraft that docked to the space station [12]. A screenshot from the video of the hatch being opened can be seen in *Figure 7*.

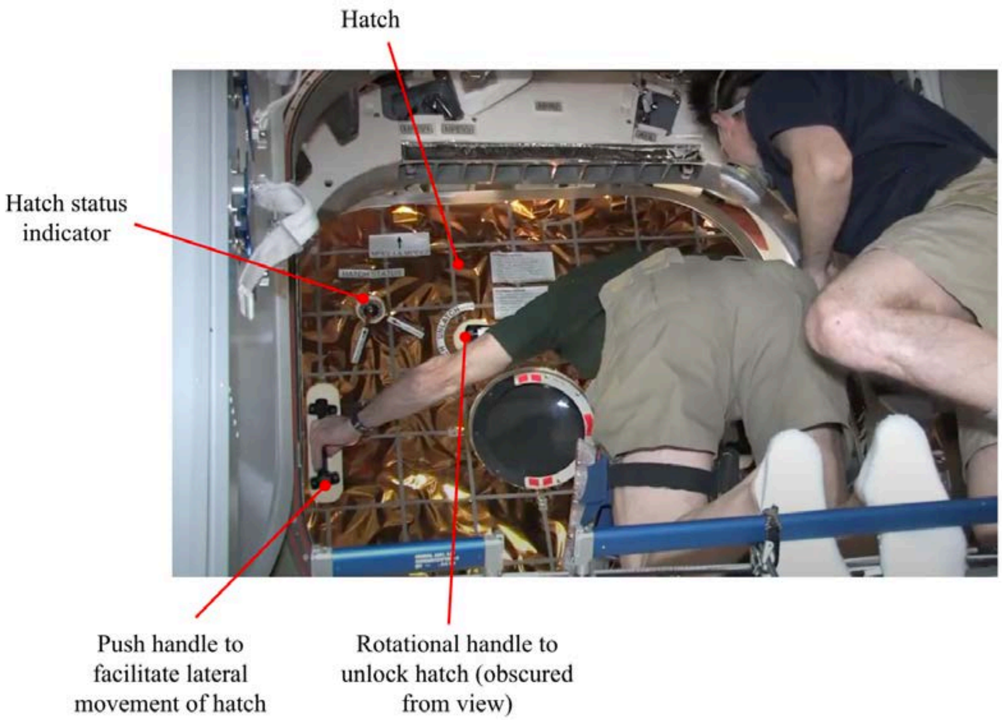

Figure 7. Screenshot from video showing door being pushed open after being unlocked [12].

While the mechanism is not shown in this video, it can be observed that the door is unlocked using a rotational crank positioned slightly offset from the center of the hatch. Further, when opening, the door follows a path more similar to a sliding door than a purely rotational door. We were unable to find details of the specific mechanism the door uses to slide, but *Figure 8* below shows the path the door travels along in the video.

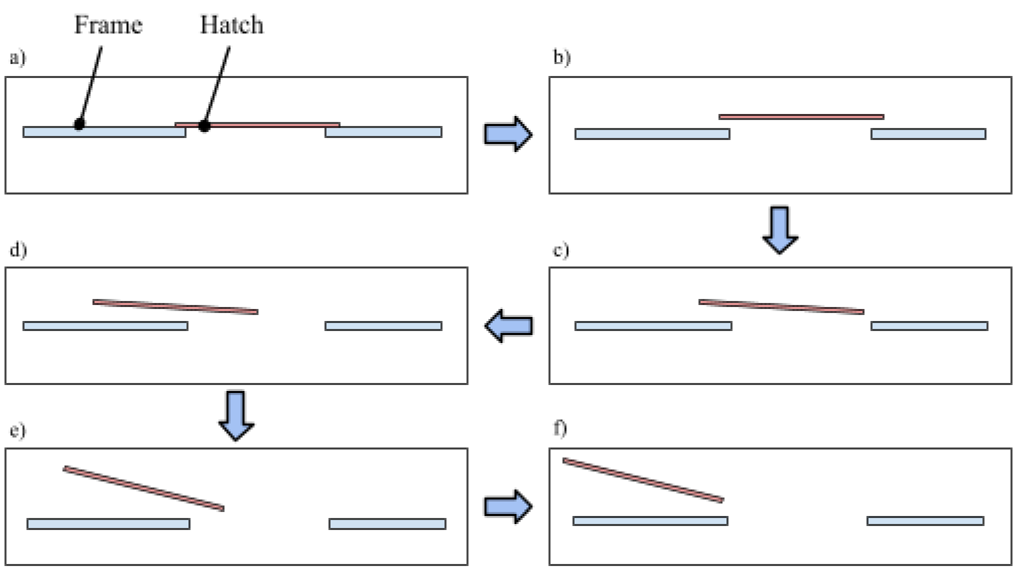

Figure 8. A diagram showing a top-down section view of the travel path for the door used on the ISS in 2012 [12].

Further, another hatch door aboard the ISS (presumably a different door than the one shown in *Figure 7*) has been featured on NASA Astronaut Jonny Kim's Instagram page. In his post, Kim shows a video of the internal mechanism of the door in motion, and how the locking mechanism is actuated via a rotational crank [13]. This video was very helpful to see how the mechanism functions. A screenshot from the post is shown below in *Figure 9*.

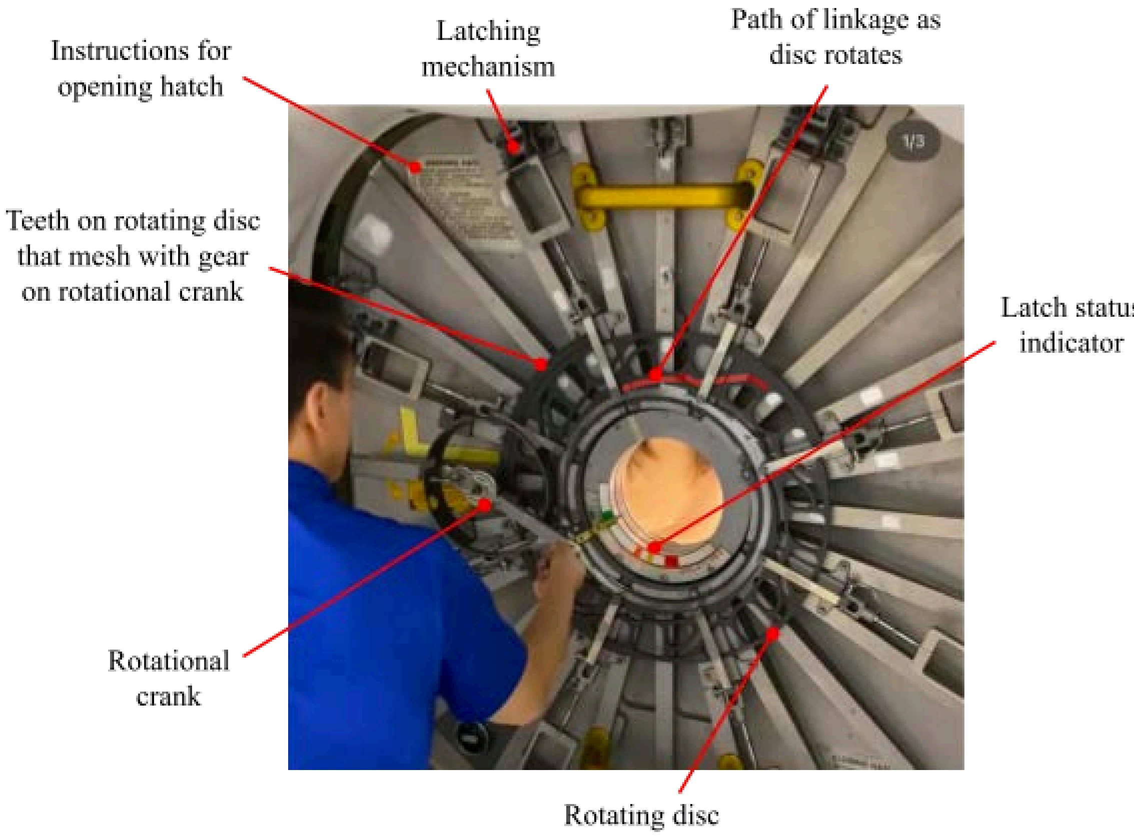

Figure 9. A screenshot from a video showing NASA astronaut Jonny Kim operating the mechanism inside a hatch on the ISS [13].

The mechanism operates by converting rotational motion from the rotational crank into linear motion in the attached linkages. While it isn't exactly clear how the door latches with the surrounding structure, we can infer that this linear motion is meant for this purpose. A more technical diagram of both sides of the mechanism can be seen in *Figure 10* and *Figure 11* below [14].

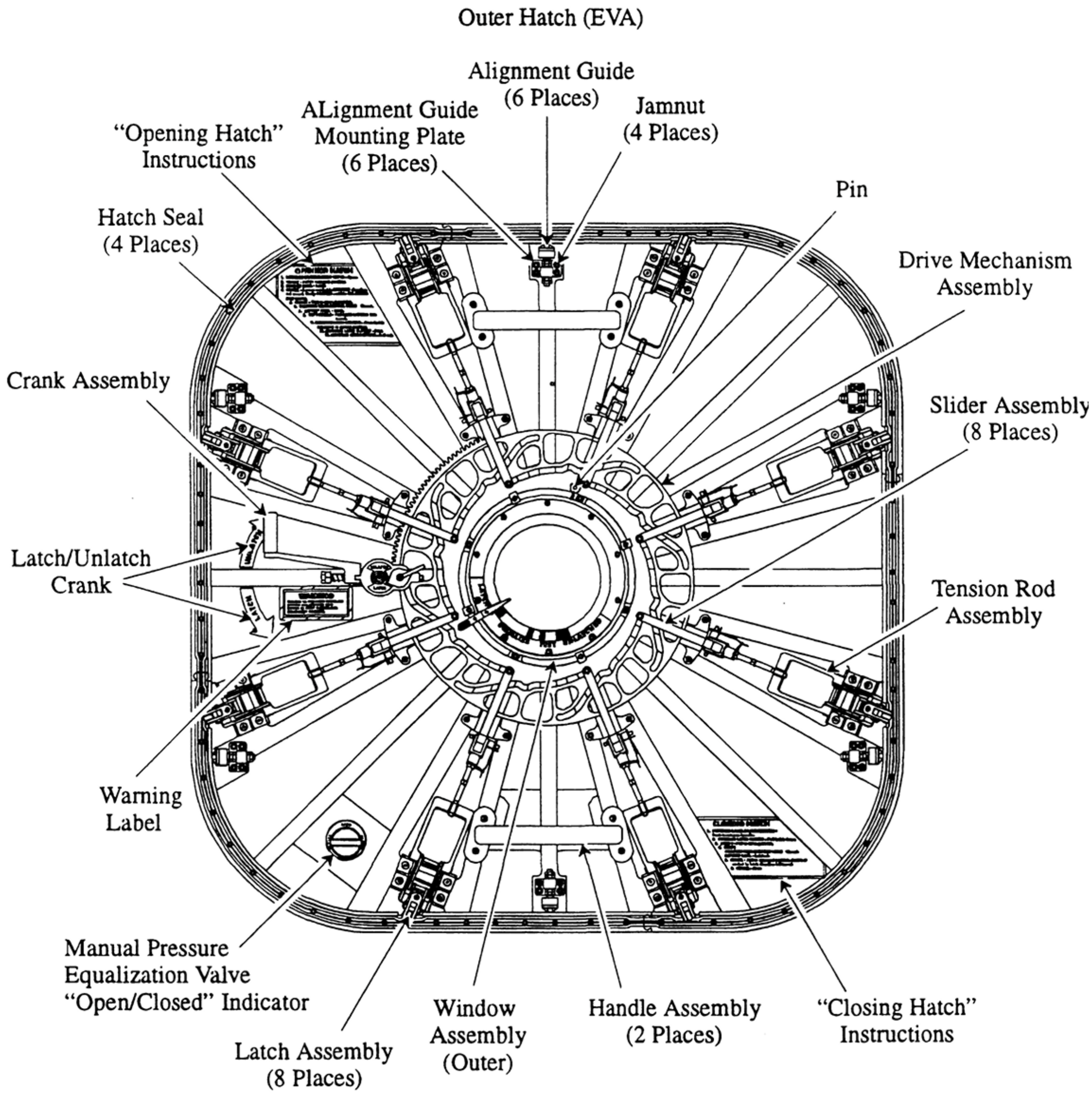

Figure 10. Outer hatch EVA technical drawing of the ISS hatch [14].

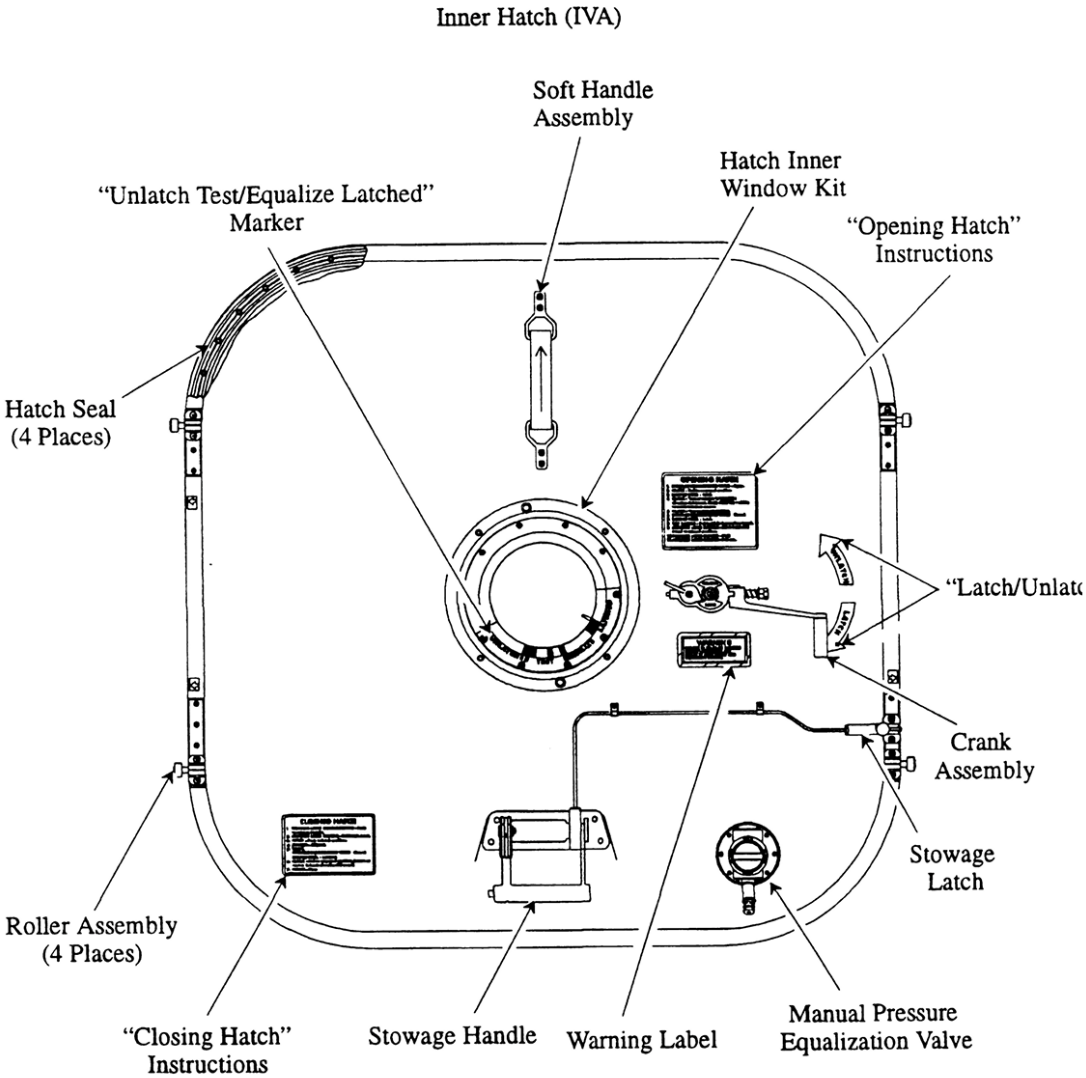

Figure 11. Inner hatch EVA technical drawing of the ISS hatch [14].

From these benchmarked examples, the team has observed the following design elements that may be good to include in our design:

- **Door status indicators**: both of these hatches feature some form of status indicator for the user to observe if the door is in the latched or unlatched position.
- **Rotational mechanisms**: by using mechanical advantage with a gear ratio, the rotational mechanism can convert a large force into a much more manageable actuation force spread over more rotations.
- **Pressure equalization valves**: the hatches shown have a manual pressure relief valve in order to allow release of pressure differences on either side of the hatch.
- **Opening/closing instructions**: instructions would be a helpful feature to add to the door in case an astronaut forgets how to open the door properly.

2.2.4 Conceptual Solutions Beyond Apollo
Since the Apollo program, many solutions have been (and are being) conceptualized for returning humans to the Moon. However, most of these solutions don't have detailed documentation on mechanical designs of the hatch and mechanism for opening, most likely due to confidentiality.

2.3 Applicable Engineering Standards
The team has found several engineering standards that are applicable to this project. These standards were used when creating and defining the requirements and specifications detailed in Section 5. The standard titled "NASA-STD-3001" supported the formation of several requirements, as it details human-related vehicle system design and operations requirements to maintain astronaut safety [15].

2.4 Information Sources
The team used several information sources available through the U of M library, online, and from the team's sponsor representative at Blue Origin, Jillian Haas. These sources included but were not limited to Scopus database, ARC (Aerospace Research Central) database, NTRS (NASA Technical Reports Server), various NASA websites, Blue Origin's website, and documentation and statements from Jillian.

3. Design Process

3.1 General Strategy
Our team has selected a problem oriented approach with a stage and activity-based design process.This decision arose from needing to assess the problems associated with previous solutions resulting in a need for a problem oriented approach. Next we needed recursion in our design process to avoid any problems that occur from 'rushing' or a lack of consideration of certain elements in the previous design stage. Additionally, we do not want to be fixed on repeating our design process so a combination of stage and activity based design process from *Figure 12* perfectly illustrates our approach in wanting best of both stage and activity based design. The diagram shown in *Figure 12* is a way to visualize an iterative design process, in which progress is made from stage 1 to stage 4, but the specific activities accomplished may be repeated in each stage.

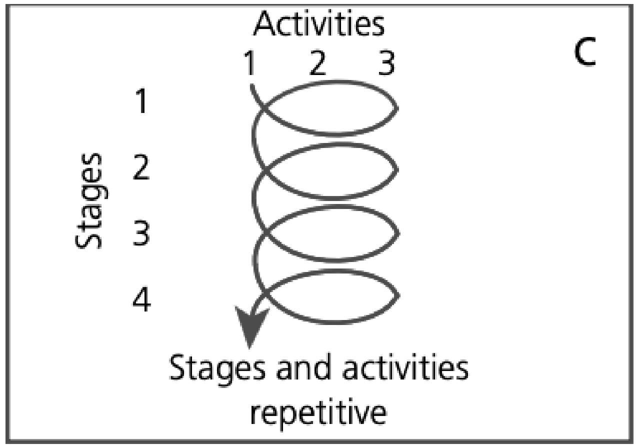

Figure 12. Illustrates how stage-based and activity-based models intersect and the order of operations [16].

The first third of the semester, or stage 1 in *Figure 12*, is dedicated to problem definition, researching literature, and assessing stakeholder needs. This is the beginning stage of our process, and we don't foresee backtracking on our requirements once they have been established. Having a thorough understanding of the problems we are addressing before we begin brainstorming or outlining solutions is critical for designing the best possible solution. If we enter the design phase with a preconceived notion of what our product will look like, it will hold us back from satisfying the user requirements most effectively.

The second third of the semester, or stage 2 in *Figure 12*, is concept generation. Concept exploration will define how we develop our prototype and thus may need to be revisited as we conduct more engineering analyses and model and/or build our prototype..

Lastly, the third part of the semester, or stage 3 & 4 in *Figure 12*, will be focused on verification. This will be our final two steps as there is a lot involved in this part of the semester. We must conduct thorough engineering analyses to verify that our solution will work with the user requirements. Additionally we plan on creating a physical prototype that will serve the same purpose of engineering analyses, to verify our design can work.

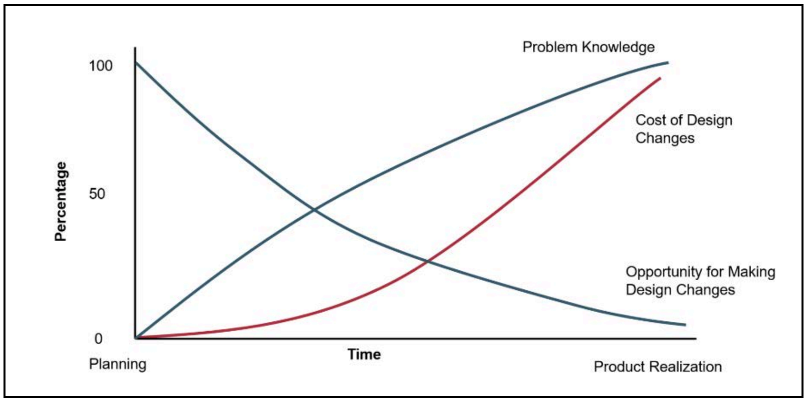

Figure 13. Proper problem definition early in the design timeline avoids expensive modification later on [17].

Next, we will move into concept exploration where we adapt activity based processes. Since we are designing for many requirements, moving in a linear path for our process is unrealistic. It is optimal if we follow a guess-and-check approach to over time satisfy all requirements, as if we are solving a system of many variables. Although we will be using this guess and check method, we are always designing with a heavy emphasis on important requirements such as those involved with lunar dust and sealing. *Figure 13* illustrates the benefits of not finalizing the design early, due to expenses of modifications towards the end of product realization.

After designing our prototype, we will begin performance analysis and list the relevant feedback for our product. If we have sufficient time we will undergo revisions to the project to verify compliance with the specifications and confirm engineering performance.

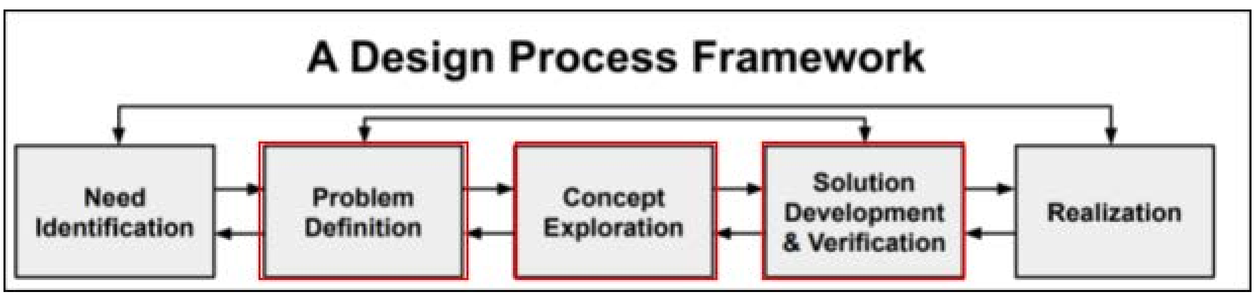

Figure 14. Conceptual outline for ME 450 project [18]. Red boxes indicate the scope of our ME450 project.

Our framework differs from the one outlined for MECHENG 450 (*Figure 14*) in that we have less stringent requirements for the Solution Development & Verification portion. We plan on providing a group of blueprints to Blue Origin with all of our designs for the project, and also would like to address expenses, social context, and iterate better versions of our design. However, we are prioritizing addressing the sponsor scope with a fully developed solution with performance testing, so providing a detailed analysis of the societal impacts is a secondary objective.

3.2 Changes

After having gone through the problem definition and concept exploration part of our design process framework, we do not expect to change our approach much. In terms of our concept exploration, we plan to go ahead with our alpha design and iterate on it. With this our stage and activity based design process indicates that we will not completely change our problem definition or concept exploration steps going forward. However, an example of us using the iterative approach to our problem definition arose after going through our concept selection. We determined that an optimal 'Alpha Design' would require redundancies or a low risk factor in case any technologies were to fail. This was mostly applicable to our concepts with a main door mechanism requiring electrical actuation.

4. Design Context

4.1 Stakeholders

In order to understand the context of this project, an analysis of the relevant stakeholders is necessary to define their potential impact on the generated concepts. *Figure 15* below shows a map of these stakeholders. They are categorized with a two letter code as follows; Resource Providers (RP), Supporters and Beneficiaries of the Status Quo (SB), Complementary Organizations and Allies (CA), Beneficiaries and Customers (BC), Opponents and Problem Makers (OP), Affected or Influential Bystanders (BC).

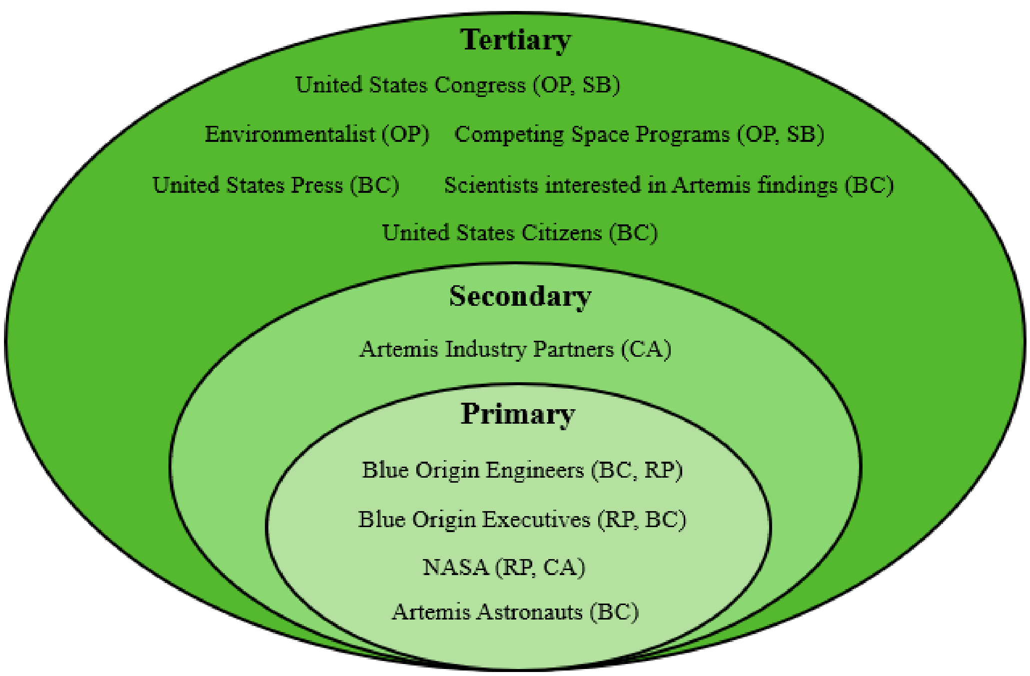

Figure 15. Stakeholder map sorted into tertiary, secondary, and primary groups.

The primary stakeholders are those whose work is directly impacted by this project. As the project sponsor, Blue Origin is the stakeholder whom we will be corresponding with the most. They have provided the project brief from which a number of our user requirements have been derived. The engineers at Blue Origin have been and will continue to be an important resource for information and general guidance. NASA, the government agency responsible for the Artemis mission series and the employer of Blue Origin for this project, is the preeminent authority on spaceborne technology. A number of the standards and codes we are adhering to in this project come from NASA. Finally, the astronauts on Artemis V will be the end user of any solution found or produced by this project. Given the distance of any true realization of a given solution these astronauts are unlikely to have any direct input in this project, however it is with them in mind that we are defining user requirements and designing solutions.

Secondary stakeholders, as defined here, are those who are a part of the problem context but will not necessarily be directly affected by any developed solutions. We have identified Artemis industry partners as a part of this group. Those being other companies contracted by NASA to design and manufacture various parts of the Artemis missions; SpaceX, Lockheed Martin, Northrop Grunman, Boeing and more. These companies have worked on similar problems to those that we will be facing in this project. As a result they are an important source of background information and can potentially serve as a source of future inspiration.

Tertiary stakeholders are groups that are outside the immediate problem context but may influence the success or failure of a developed solution. One group we have identified here is the United States Congress, them being the ones responsible for much of NASA's funding. With NASA as the employer of our sponsor, Congress's choices with regards to increasing or decreasing funding may affect how any solution we develop may or may not be implemented. Press and media's coverage of Artemis' efforts may contribute to its success or failure through influencing public perception. The general public's interest and support, as affected by the media, can in turn influence congress, as well as contribute a level of direct investment to space exploration efforts. Environmentalists may also influence the success of Artemis and as a result of this project, lobbying against space exploration efforts as a source of pollution.

The stakeholders have varying degrees of power over this project, as well as interest in seeing it succeed or fail. A map of the stakeholders mentioned here with their relative levels of power and interest is shown below in *Figure 16*.

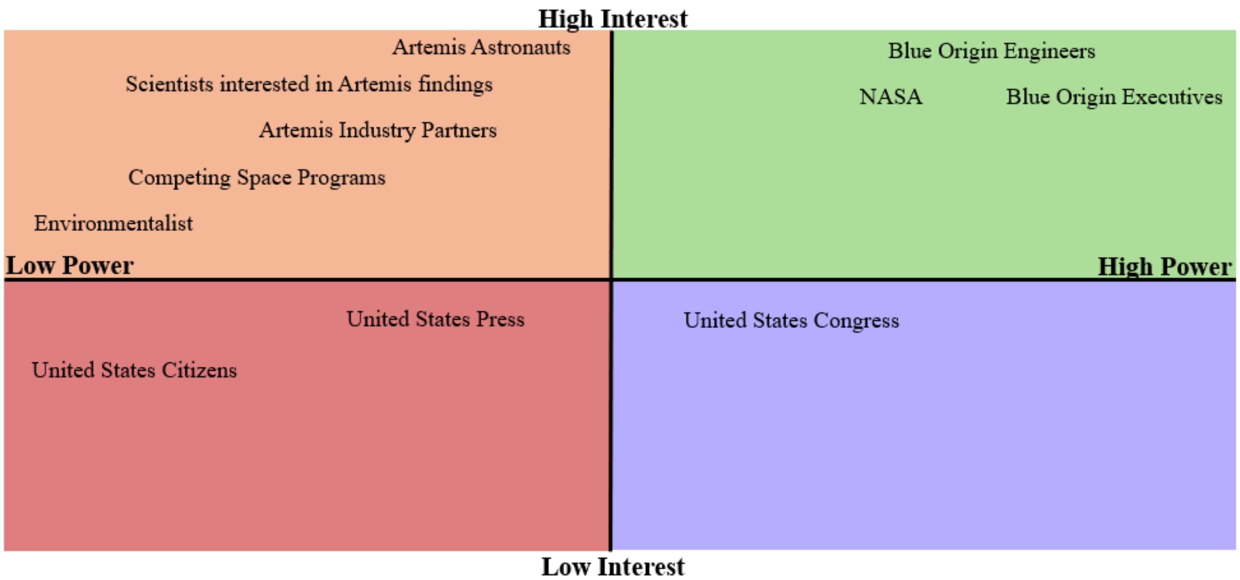

Figure 16. Map of stakeholder interest and power.

A number of these stakeholders stand to benefit from a well designed solution to the problem this project looks to address. Blue Origin will have the opportunity to incorporate any theoretical solutions into their final design for the lunar lander. If any developed solution is not to their liking they at least stand to benefit from the research we will do in an attempt to solve the problem they have posed. Ultimately, should any solution developed here be realized in a final build of the lunar module, the Artemis astronauts using said module will benefit highly from a well executed solution. Similarly, NASA and other industry partners should benefit from the successful execution of this project as a part of the larger Artemis mission series. As a part of Artemis, this project stands to benefit scientists who are interested in findings from these missions. Finally, space exploration has led to many scientific breakthroughs in the past that have benefited the average consumer in everyday life; advancements in everything from water filtration to telecommunication have resulted from humanity's efforts in space.

Some negative impacts may also be imparted on some of the mentioned stakeholders. As briefly mentioned above, in order to understand the impacts of this project it needs to be analyzed as a piece of the larger Artemis mission series. While we believe that the benefits of this project and the greater mission it is a part of outweigh the negative impacts, they still need to be considered. First and potentially foremost there are environmental impacts associated with the mineral extraction, manufacturing, and rocketry necessary for this project that must be acknowledged. Mining bauxite (the mineral form of aluminium) can create dust that can contaminate water supplies and pollute soil. Titanium mining (though less harmful than bauxite) can also lead to environmental damage. Both of these are heavily used in spaceborne construction and will likely be used in any solution we create. Carbon emissions from rocket launches are a very small percentage of the total emissions from all sources around the world, however most of the emissions from rockets happen in the upper atmosphere meaning that that carbon stays airborne for longer and has a higher environmental impact than emission that happen at earth's surface. These impacts can be felt by much of the world but are much more likely to affect people of color and/or people with low income.

While the success of this project has the potential to benefit companies in the space technology sector, it could also impact them negatively. Blue Origin's success here could lead to them out competing these other companies and starving them of contracts with NASA and other organizations interested in their services. In a similar vein, NASA's success in the Artemis missions could lead to an increase in funding from the United States Congress. This funding would potentially come from the budgets of other government agencies competing for funding.

4.2 Societal Driving Aspects

A major goal of the Artemis missions is to expand humanity's spacebound capabilities. Our project will aid this goal by easing astronaut operations in space. There are a number of societal pressures and goals associated with this goal. Colonization of other celestial bodies is often cited as a long term goal, and while this is a rather distant prospect, the Artemis missions will surely take us in that direction. Perhaps the main motivation behind colonization and the general expansion of humanity's capabilities in space is to lessen our demand on earth's resources. Additionally, as mentioned before, scientific advancements that have come from past space exploration have had a significant impact on life on earth. This alone is a major motivation in some people's support of space exploration. Perhaps more concretely, the designing of novel solutions that may occur through this project and others associated with Artemis will likely necessitate new and specialized manufacturing to realize these designs. This is worth considering as a potential source of new employment, having both societal and economic motivations. Finally, the 'why now' of the Artemis program is worth acknowledging. The expansion of competing, foreign space programs has galvanized the United States' desire to remain a leader in space. Also, a stated goal of Blue Origin, NASA, and many other space technology companies is to inspire new generations of engineers, scientists, and explorers.

Blue Origin's mission statement emphasizes their desire to make space flight more affordable so that humanity might use space as a vector for future growth and development. As such it is reasonable to say that they place a very high value on the social impacts of their ventures. Blue Origin, as a company at least partially dependent on its own profits for operation, does need to see some profit from the venture this project is a part of. However, in this case, profitability does not directly compete with functionality or social impact. As Blue Origin has been hired by NASA, it is in their best interest to develop a product that is as successful as possible in order to be contracted again in the future. As a result we are not worried about Blue Origin's priorities conflicting with ours in this project.

4.3 Intellectual Property
Intellectual property is not a major component of this project. We have not been required to sign any agreements with regards to information received from Blue Origin or about any of the intellectual property that will be created throughout this project. As such, any ideas that we develop will be owned by us and we will be free to pursue patents should we choose to.

4.4 Sustainability and Ethics
Our design requires that we lightweight our mechanism to comply with standards, presented in user requirements and specifications below, integrating the consideration of reducing waste of materials. Also, we plan on designing the use of our lightweight mechanism to be capable of multiple missions, avoiding redundant manufacturing. Lastly, the reuse or repurposing of materials will be considered later on in the design process as we choose our materials. For example, metals are easier to repurpose depending on disposal plans by the user, Blue Origin.

Additionally, the manufacturing of our mechanism design will play a role in how sustainable our design could be. Choice of materials aside, the less wasteful we can be, the overall lower amount of materials we will need. Thus, we need to consider this during our design process to ensure low waste. Lastly, through the consideration of energy consumption, we can choose the lowest energy option out of the potential manufacturing methods, both ensuring accuracy while keeping sustainability in mind.

Addressing the last point, most energy consumption is powered through the burning of fossil fuels. This knowledge helps us understand that we will be indirectly contributing to pollutants in the atmosphere. Concurrently, any disposal method that Blue Origin decides to choose will have the potential of consuming finite resources.
If we have the ability of choosing the disposal method, we are likely to choose the method that will allow the material to be reused or repurposed. Any financial cost to Blue Origin through the recycling or reusing of the material will likely be low due to the nature of the disposal method.

This brings the question of ethics into our design. More specifically, we expect one of the challenges to face will be managing the weight of the door mechanism and the safety of those in the lunar lander. This is problematic as our lunar lander has a mass budget that will likely be exceeded given the weight of the fuel, but to add more weight through the door mechanism will likely cause issues. However, the safety of those inside the lunar lander is paramount to the success of any mission involving the lunar lander.

Furthermore, the dilemma of the complexity of the design and the feasibility of the manufacturing will likely play a role into our design concept selection. Despite not having a restriction on manufacturing methods, it would be beneficial to all parties involved in the realization of the design to minimize the complexity of the design. Despite that we would like to propose a creative design that doesn't "just get the job done."

4.5 Power Dynamics

Our design team shares very similar backgrounds, all majoring in mechanical engineering at the University of Michigan. The members in our group range from 3rd to 5th-year undergrads, and we have not had any issues with communication or representation of members within the group. Our project sponsor, Jillian Haas, graduated from U of M engineering and as such we have a common knowledge base, allowing for smoother communication. The end users of our project are the astronauts manning the Artemis V launch, and we have not been able to meet them. Their voices are heard through the sponsor's desired requirements and preferences for our design.

4.6 Inclusivity

It is critical that we adequately interview the primary stakeholders of our project, namely astronauts. Having a grip on which user features are convenient for our design is important since they are the ones who will be using our product. For example, we should provide proper ingress and egress dimensions and a simple locking mechanism. We should also aim to make sure our product is compatible with male and female astronauts alike. If the door is too heavy and requires an excessive amount of force to open, this may be unsuitable for female astronauts.

The best way to ensure inclusivity is by gaining a comprehensive understanding of our stakeholders' perspectives and needs. This comes through interviews and interactions with stakeholders from Blue Origin, NASA, and members of the Artemis V team.

5. User Requirements and Engineering Specifications

We developed our requirements and engineering specifications through multiple sources. Documents and standards from NASA have served as our primary source because they are the only organization that has been to the Moon. As such, our requirements follow closely with those of their lunar lander and are listed below in *Table 2*. Note the use of SI and imperial units. The sources we referenced used either SI or imperial units depending on the application, so we left them as stated to avoid loss of precision.

Table 2. User requirements and engineering specifications list.

User Requirements	**Engineering Specifications**
Easy operation	The hatch must be able to be opened in ≤ 60 seconds with a user-applied force on the release mechanism of ≤ 30 lbs [15]
Easy access	An astronaut and spacesuit of overall height ≥ 80 inches and overall width of ≥ 38 inches must be able to pass through

	when the door is fully opened [19]
Bi-directional ingress/egress	Hatch must be fully operable on either side by a single crew member
Operation without tools	Method of opening must occur without the use of tools
Lightweight	Hatch and mechanism mass must be ≤ 5000kg.
Reusable	The hatch and mechanism must continue to operate as expected for ≥ 5 missions
Survive launch/ reentry	The hatch and mechanism must remain intact and fully functional after being exposed to accelerations up to 50 m/s^2 when closed and locked.
Temperature tolerant	The hatch and mechanism must withstand temperatures ranging from -250 °C to 130 °C [20].
Dust tolerant	The hatch and mechanism must have dust-resistant covers
Seal under pressurization	- The hatch seals must leak no more than 10^{-2} lbm dry air/day under pressure differentials ≥ 14.7 psi [21] - A minimum of 2 seals must be used for redundancy [21]
Ergonomic	Hatch release must be fully operable when wearing an EVA suit
Safe	- The hatch and mechanism must avoid sharp edges by filleting edges to radius ≥ 3.0 mm [15], and pinch points shall be covered or otherwise out of the way of crew members [15]. - The hatch shall require two distinct and sequential operations to open [15].
Redundancy	In case of actuated mechanism failure, hatch must be manually operable
Visibility across hatch	Hatch must include a non-electronic window to view exterior of hatch prior to egress [15].
Pressure equalization across hatch	The hatch must be equipped with manual pressurization and depressurization on both sides by a single crewmember in or out of an EVA suit [15].
Pressure indication	There must be an indication of whether the lunar lander is pressurized or unpressurized on the hatch that is viewable from both sides of the hatch. [15].

Latching/ Locking status	There must be indication of the hatch's locking and latching status that is viewable from both sides of the hatch [15].

All of these requirements are important and must be followed to provide successful results. Each of these requirements has an associated specification that provides quantification or can be tested to determine if it meets the requirement.

Understanding the description of these specifications is important to ensure the desired outcome is achieved.

Easy operation. Easy operation in this context is minimal human force exertion and short wait times for the hatch to open. 60 seconds is based on NASA-STD-3001 for the hatch on the Apollo Lunar Module [15] and also applies to our design. The force requirement of 30 lbs is also derived from information in NASA-STD-3001 and references an upright, two-handed, horizontal push out. With some safety factor, we determined based on this source, that 30 lbs will be a sufficient upper force limit that accommodates all crew members' strength.

Easy access. To fulfill this requirement the hatch and mechanism need to be sized such that a crew member in a full EVA suit can fit through the door in a reasonable amount of time. Based on NASA's Volume I - Man-Systems Integration Standards [19], the upper 95th percentile of male astronauts is 75.5 inches tall and 33.4 inches wide. From this, we made our specifications for the hatch to accommodate these dimensions.

Bi-direction ingress/ egress. To prevent inaccessibility when closing the hatch, the hatch must have the capability of being unlocked/locked and opened/closed from both the interior and exterior of the lander. This operation should only require one crew member.

Operation without tools. Operation of the hatch (locking/unlocking and closing/opening) must be performed without the use of tools [15]. Crew members may need to operate the hatch quickly and the use of tools would likely impair their ability to do so. Additionally, a toolless operation reduces the risk of problems arising due to lost or broken tools.

Lightweight. To reduce the overall weight of the lander, the hatch needs to be lightweight. To stay safely within Blue Origins mass budget, the hatch must be under 5000 kg. Through information from our sponsor, we have a rough idea of the mass budget, but other components of the mission often exceed their mass budget, so we set the upper limit as stated.

Reusable. The hatch must be reusable for multiple missions. Our sponsor requested that it be designed for at least 5 missions.

Survive launch/reentry. According to NASA standards, launch accelerations are around 19.6 m/s^2 [22]. As such, the hatch must withstand accelerations up to 50 m/s^2, allowing for a margin of error.

Temperature tolerant. The hatch and mechanisms will be exposed to the Moon's temperature cycles which can range from -246 °C to 121 °C [20] depending on the region. For this reason, the hatch and mechanism need to withstand temperatures ranging from -250 °C to 130 °C.

Dust tolerant. Moon dust is highly abrasive and continues to be a major concern for mechanical components. To limit contamination of the hatch and mechanism due to dust exposure, they shall have covers that resist dust. Additional dust-resistant properties that shall be applied to our design are TBR.

Seal under pressurization. The hatch and mechanism must be able to remain sealed under pressure differentials caused by the vacuum environment on the Moon. The interior of the lander will be pressurized to no more than atmospheric pressure when on the Moon. The hatch seals must leak no more than 10^{-2} lbm dry air/day [20] when under pressure differentials $\geq$ 14.7 psi. Additionally, at least 2 seals must be used in case one fails [21].

Ergonomic. During ingress and egress, the crew members will be in EVA suits. These suits limit dexterity, making some tasks more difficult. To prevent difficulties associated with opening the hatch, the release mechanism must be operable when wearing the suit.

Safe. To avoid injury, the hatch and mechanism must avoid sharp corners by filleting edges to a radius $\geq$ 3.0 mm, and pinch points shall be covered or out of the way of crew members [15]. Additionally, to prevent the hatch from opening unintentionally, the hatch and mechanism must require two distinct operations to open [15].

Redundancy. The hatch may be equipped with electronic actuation, and such a mechanism could fail in a variety of ways including power outages, overheating, dust, etc. To prevent trapping the astronauts inside or outside of the lander, the hatch needs to be able to be opened and closed manually by an astronaut.

Visibility across hatch. Within the lunar lander, the astronauts need to have visibility to the other side of the hatch to ensure it is safe to egress. A non-electronic viewing window is required to prevent failure in case of power outages [15].

Pressure equalization across hatch. The hatch needs to have the capability of pressurizing and depressurizing the lander from both the inside and outside of the hatch by a single crewmember whether they are wearing an EVA suit or not [15].

Pressure indication. There must be an indicator to show the pressurization status of the lunar lander. The indicator must be viewable from either side of the hatch [15].

Latching/ Locking status. There must be an indicator to show if the latch is locked or unlocked and if it is latched or unlatched. The indicator must be viewable from the interior and exterior of the lander [15].

6. Concept Generation

In our concept generation we used a variety of methods to verify our understanding of the problem and break it down into its subcomponents. The first method we considered was Functional Decomposition. A simple diagram of the functional decomposition is show below in *Figure 17*:

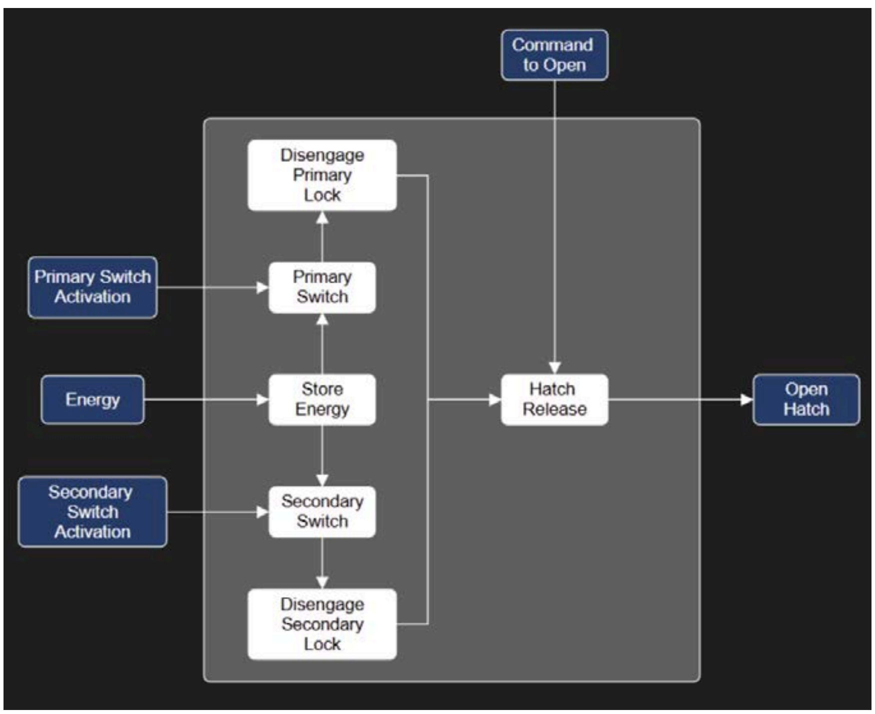

Figure 17. Functional Decomposition diagram. Energy is inputted so that the primary and secondary locks can be engaged/ disengaged. Afterward, the hatch can be released via a signal to open.

This method had some benefit in helping us understand the processes that needed to performed in order to open the hatch but did not serve us much beyond that. Another method we considered was the Subsystem Tree Diagram. We created two trees that split up two of our main subsystems which are energy and the hatch itself. These trees are shown below in *Figure 18*:

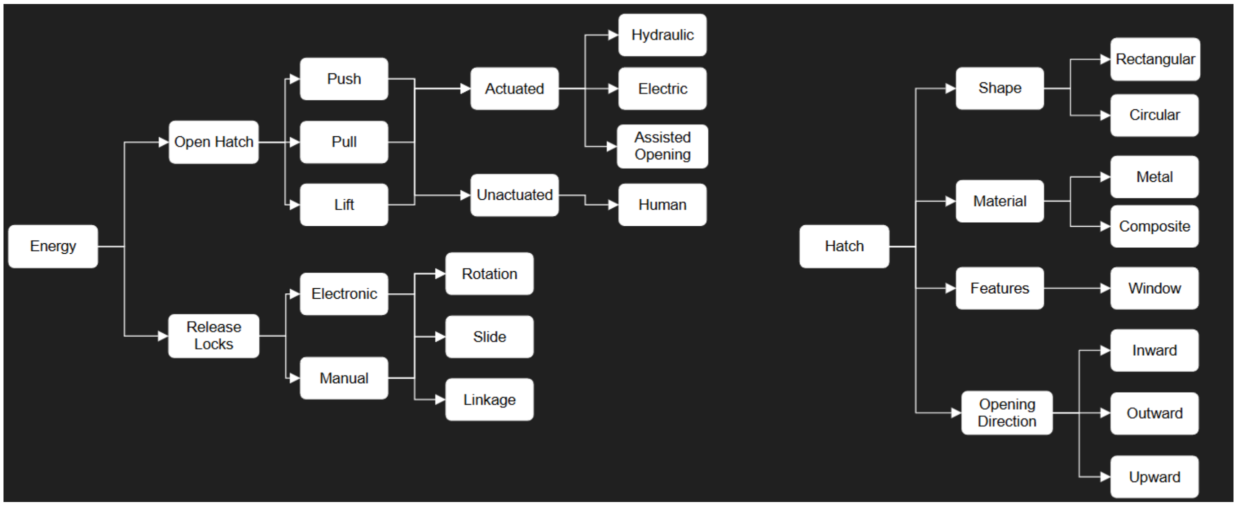

Figure 18. Subsystem Tree Diagrams. The left tree, rooting from energy, splits to release the locks and open the hatch. These operations may be actuated or unactuated. The right tree, rooting from hatch, splits into various characteristics of the hatch that support the fulfillment of the user requirements.

The tree diagrams provided some initial ideas that we could use as a basis for our drawn concepts. Considerations such as if the hatch should be actuated or unactuated, and the hatch shape, material, and opening direction were strongly considered when ideating in our future concept generation processes.

After the tree diagrams, each team member spent time using methods such as brainstorming, design heuristics, and morphological analysis to generate concept drawings. The concept drawings focused on both hatch opening mechanisms and hatch locking mechanisms. An example of some of the concepts we came up with are show below in *Figure 19*:

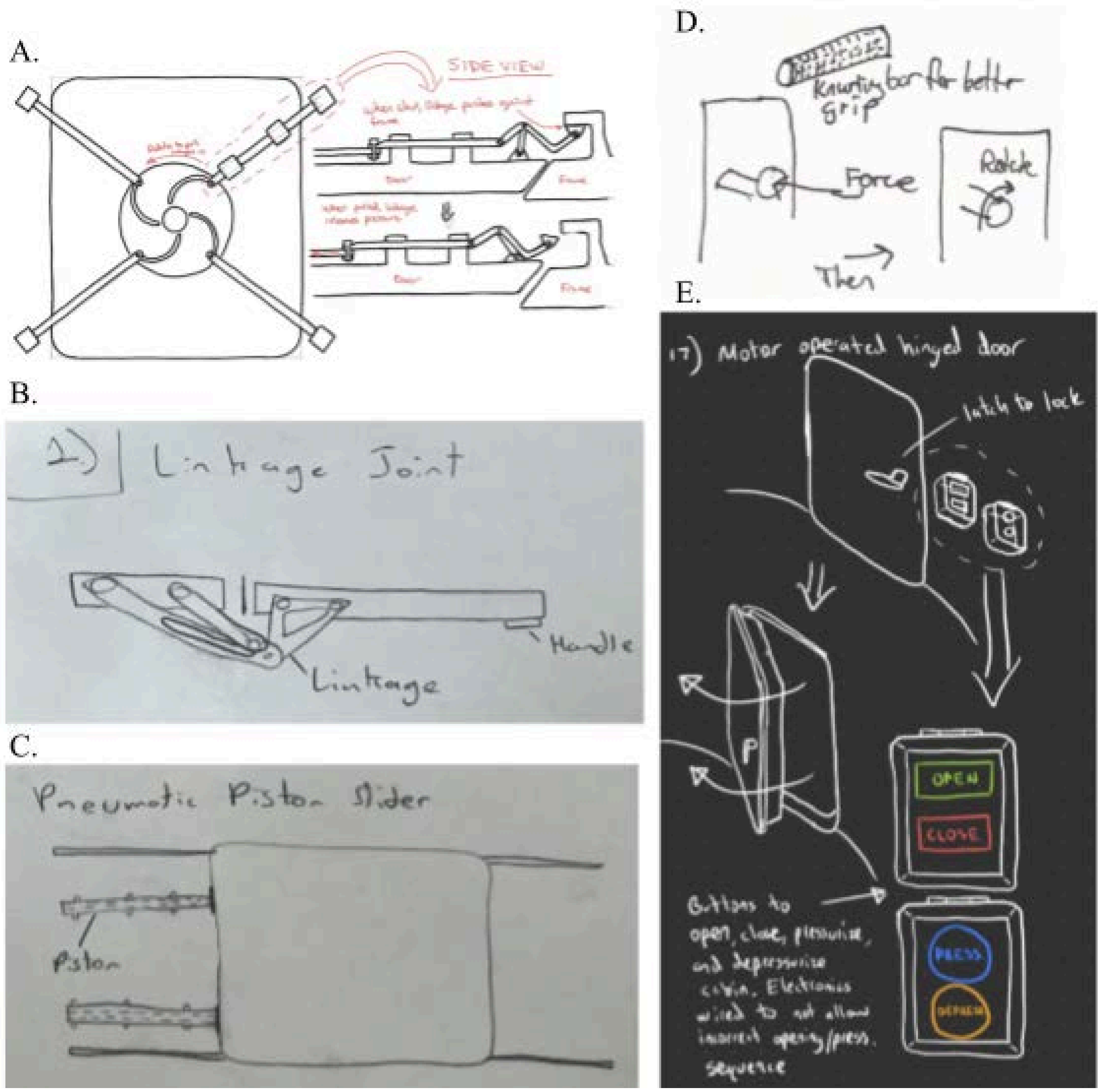

Figure 19. Five drawn concepts created through brainstorming, design heuristics, and morphological analysis.

The concepts shown in *Figure 19* above are a few of the many concepts we generated. Concept A in the figure shows a locking mechanism inspired by one used on the ISS. When the inner wheel rotates, it moves the linkage system inward or outward to put pressure on the frame of the hatch creating a seal. Concept B is a hinge mechanism to allow the hatch to rotate inward. The linkage allows the hatch to open differently than a traditional door that rotates about a pin joint. This could potentially provide more opportunities for sealing and locking. Concept C uses pneumatic pistons to actuate the hatch. This hatch design slides sideways on rails as opposed to rotating open. Concept D shows the use of a knurled grip on a rotating latch. A knurled grip could be used to provide easier operation of the hatch given that the astronauts will be in EVA suits. Lastly, concept E shows a motor actuated, inward rotating hatch that uses buttons to operate. The inward opening design allows for the pressure inside of the lunar lander to provide additional sealing force, and the buttons and motor actuation allow for the astronauts to easily operate the hatch when in EVA suits.

After generating concepts and presenting them within our team, we continued into the concept selection process to determine which ideas would best satisfy our requirements.

7. Concept Selection

After each team member generated ideas and concepts, the team developed a strategy to down-select these into ones to consider for our final full-system design concept. A diagram of this strategy is shown in *Figure 20* below.

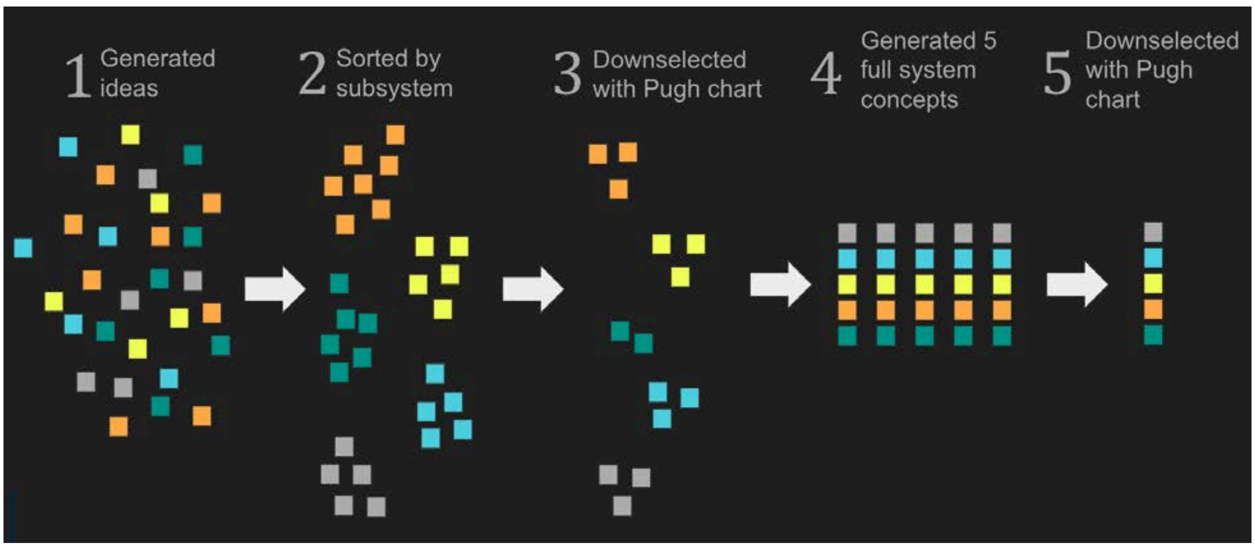

Figure 20. Concept selection strategy used by the team.

After generating ideas, each team member shared with the group their most noteworthy concepts. From here, we moved into the Stage 2 shown in *Figure 20* above, where we sorted the generated ideas into the following subsystem categories:

- Mechanism to open door (actuated/unactuated, hinge design, etc.)
- Mechanism to lock/unlock door (latching and/or locking mechanisms)
- Door shape (rectangle, square, rounded rectangle, circular, etc.)
- Direction of opening (in/out, upwards, laterally, sliding, rotating, translating, etc.)

For each of these subsystems, there were roughly 4-7 concepts to consider. For Stage 3, we down-selected concepts using a Pugh chart to determine how well each concept satisfied relevant requirements. Each concept was given a score of -1, 0, or +1 in terms of how well it satisfies the requirement in comparison to the other concepts. These scores were determined on a team-wide basis. An example of a Pugh chart used by the team will be shown in section 7.2 below.

7.1 Full-System Concepts

Using these Pugh charts, the team decreased the number of concepts to consider for each subsystem. The concepts that scored the highest from this ranking procedure were used as options when forming concepts for the entire system. We then formed 5 full-system concepts to consider for our final concept design. Each full-system concept was developed based on intuition and benchmarking of existing solutions. All concepts at this stage open inwards, since any door that opens outwards needs a latching system capable of withstanding pressurization forces from the interior cabin of the lander.

7.1.1 Concept #1: Spring Hatch

This design concept, shown in *Figure 21* below, features purely mechanical components for the latching mechanism and the opening mechanism. The latching mechanism features two separate and distinct actions to satisfy our "Safe" user requirement, in which the user pushes in the yellow handle and then is able to rotate the purple latched piece. The hatch rotates on a simple hinge system. Additionally, a spring is attached to the door that pushes the door to the closed position, in order to provide an adequate sealing force against the frame of the lander.

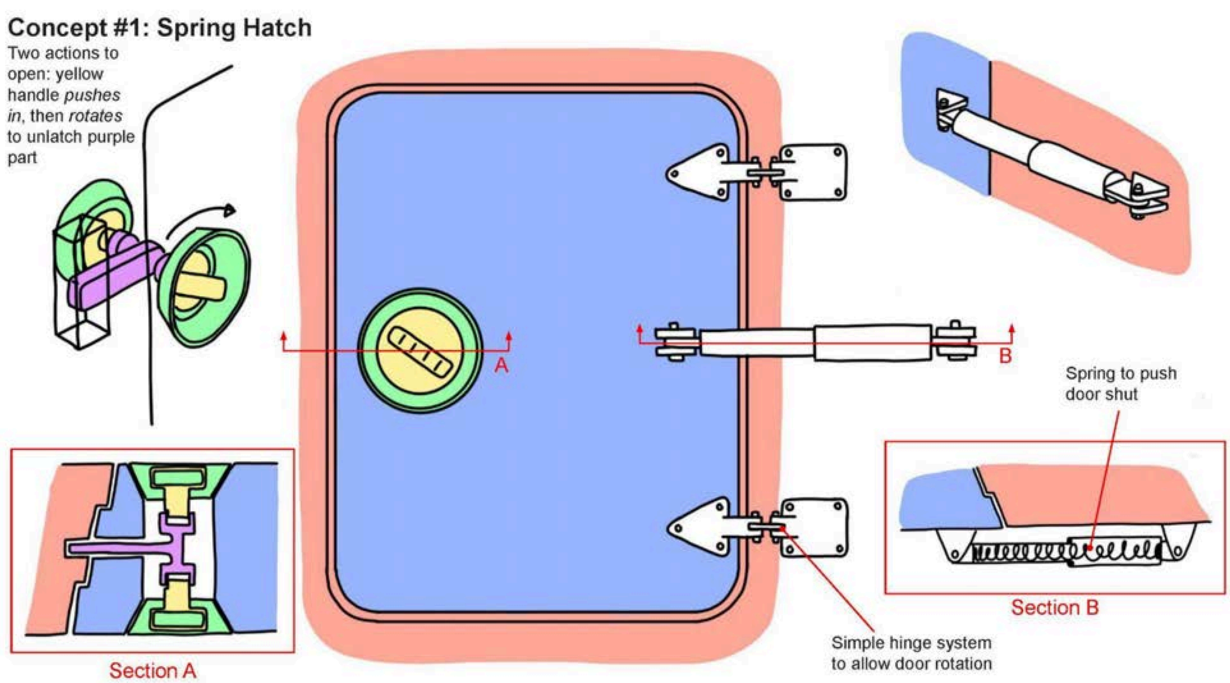

Figure 21. Concept drawing of Concept #1: Spring Hatch

One clear advantage with this concept is its mechanical operation, which removes electrical failure as a potential risk that would hinder astronauts from operating the hatch. Further, the design itself has low complexity, which results in less potential problems and easier manufacturing. Finally, the latch mechanism makes it easy to unlock or lock from either side of the hatch.

In terms of disadvantages, the spring may present some challenges with easy ingress or egress. Its purpose is to provide a sealing force against the frame of the lander, but it may make the door difficult for the astronauts to open. Further, the door has no current designed mechanism to hold in a specific position. Once released, the door will swing shut.

7.1.2 Concept #2: Electromagnetically Sealed

In contrast to Concept #1, Concept #2, shown in *Figure 22* below, is fully electronic. There are electromagnets positioned around the perimeter of the frame in which the hatch sits, which are controlled by a green “LOCK” and red “UNLOCK” button (The “UNLOCK” button is red since unlocking the door releases the seal, a more dangerous action than engaging the seal. These buttons will not function unless the cabin is first depressurized (a sensor detects pressure on the interior and exterior of the lander). Once the cabin is depressurized and the “UNLOCK” button is pressed, the access panel for the blue “OPEN” and red “CLOSE” button unlocks. These buttons control the motor to rotate the hatch between the open or closed position.

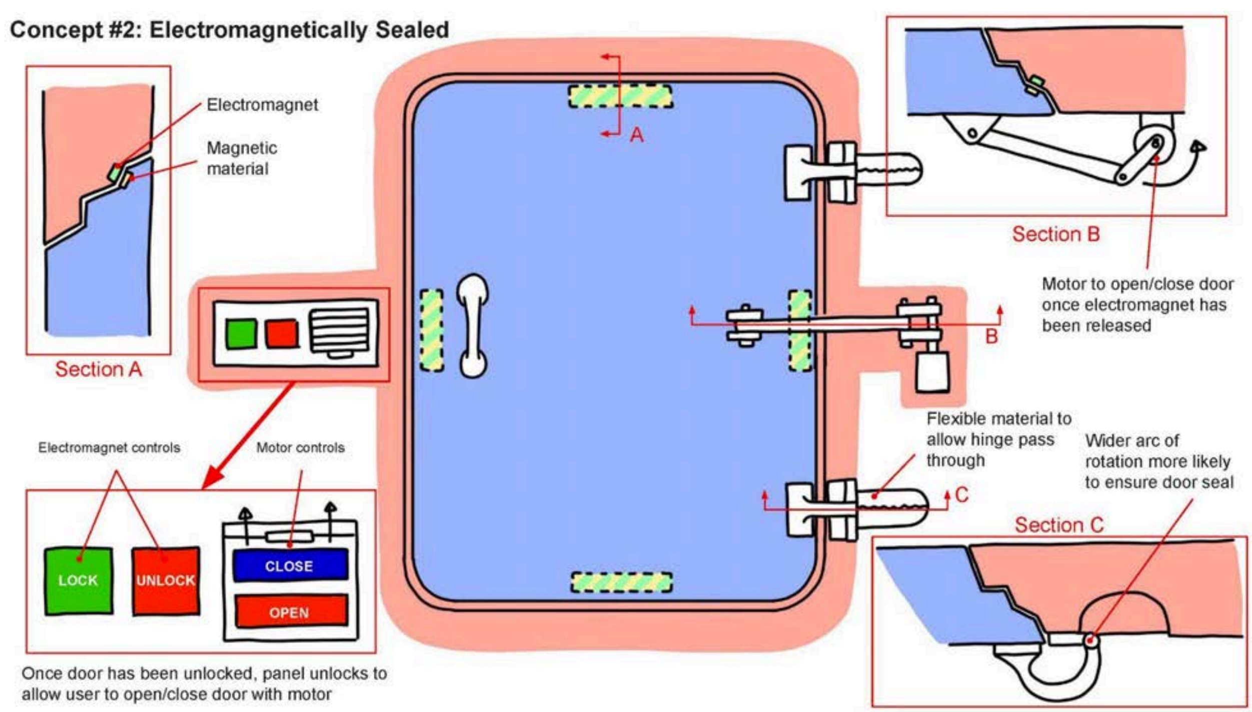

Figure 22. Concept drawing of Concept #2: Electromagnetically Sealed

The primary advantage of this hatch is it requires nearly zero effort from the user to lock/unlock and open/close, since push buttons are the means of controlling these actions. Further, since the rotational position of the hatch is controlled by a motor, the astronauts can set the desired hatch to their desired position (partially open, fully open, etc.). Finally, the electromagnets can most likely provide a strong seal to the frame of the lander.

The electrical components have also been identified as a disadvantage to this design. In the event of an electrical failure, the door will not be able to seal well against the frame without the electromagnets. Further, if the motor is unable to be backdriven, the motor will have to be decoupled from the door in order to open it. Another potential disadvantage is the hinges used in this design. They stick out into the cabin and require more clearance for their swing path than a traditional hinge.

7.1.3 Concept #3: Manual Slide

This concept was inspired by the ISS door shown in section 2.2.3, in which a rotational mechanism is used to actuate links inwards and outwards. A simple drawing of this concept is shown in *Figure 23* below. The center disc, which features tracks for pins to slide through, is rotated via a crank handle. The links connected to the tracks on the disc are constrained to only move linearly towards or away from the center of the door. This controls a latching system that pushes against the frame of the lander to lock and provide a sealing force. Additionally, it is not illustrated in *Figure 23*, but the hatch will slide along a track below and above the door to move it from the closed position to the open position.

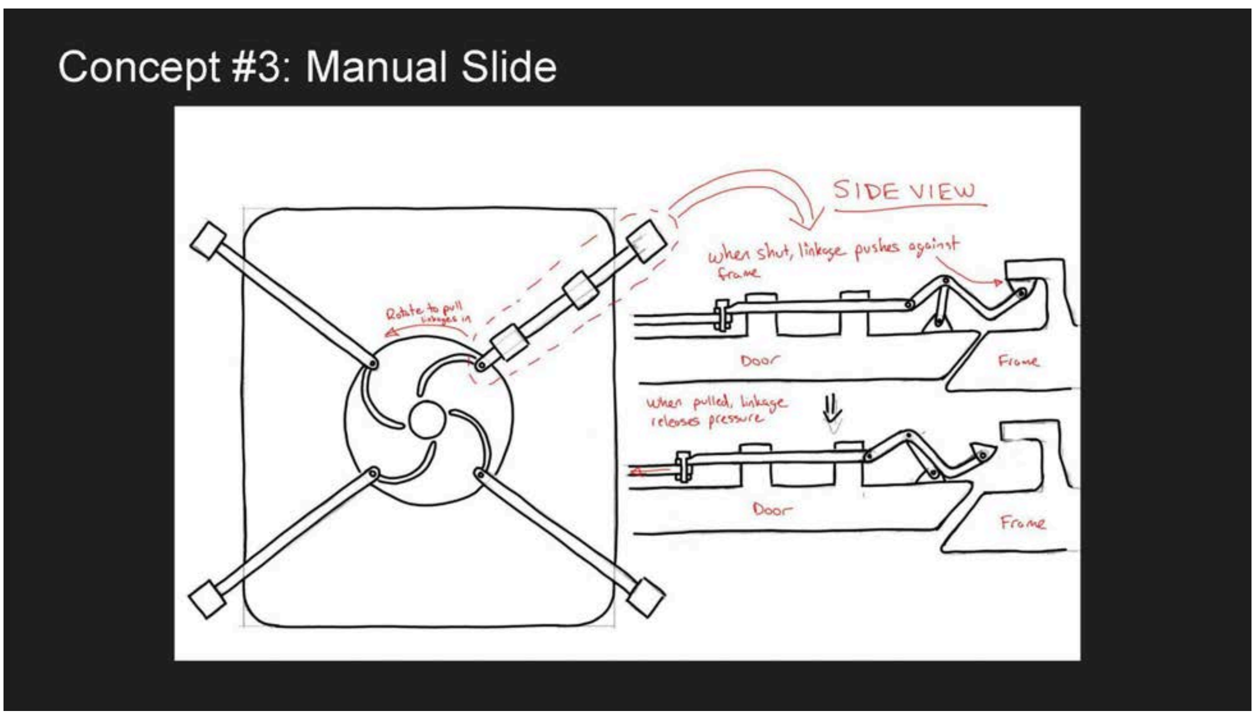

Figure 23. Concept drawing of Concept #3: Manual Slide

This mechanism is advantageous because it both pushes the door into the seal and locks the door at the same time. Additionally, this system can be sealed evenly around the hatch. Further, the rotational crank allows the design option of using mechanical advantage via a gear ratio, which would allow the user to input significant force into the links.

The main disadvantage of this design is the tracks the door will slide on to move. These may collect lunar dust very easily, and which may severely impact the functionality. Since the tracks will be constraining the door on the bottom and top of the mechanism, this could also introduce alignment issues. Additionally, the design is fairly complex and features several rotating and sliding pieces, which will have to be designed to function well in extremely low temperatures.

7.1.4 Concept #4: Electronic Hinged Circle

The fourth concept we designed is the only circular door concept we developed. It features the same rotational latching mechanism as shown in Concept #3. Further, it hinges upwards on the same hinges shown in Concept #2. To actuate the door open, a motor and cable system is used in tandem with a button control panel (not illustrated).

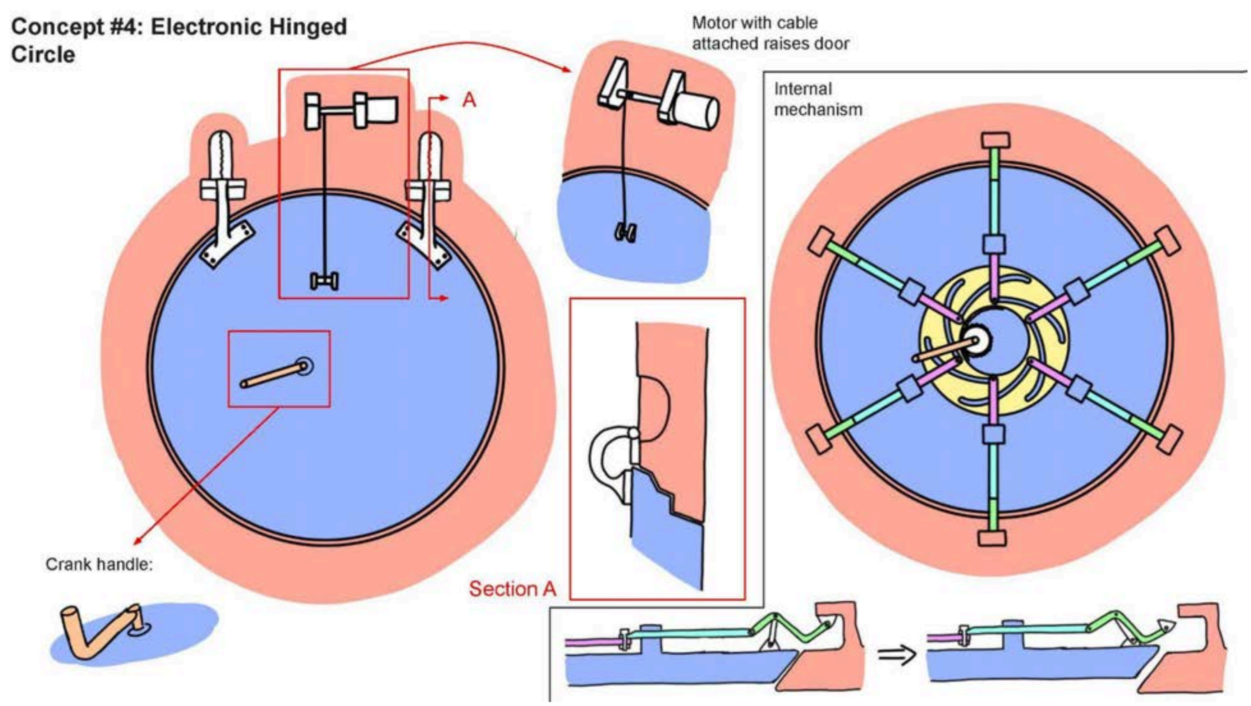

Figure 24. Concept drawing of Concept #4: Electronic Hinged Circle

As mentioned for Concept #3, the rotational mechanism provides an advantage in being able to evenly seal the hatch at multiple points, and latch the hatch shut in the same system. Further, with this hatch being circular in shape, the pressure forces are distributed more symmetrically throughout the system. Additionally, the motor actuation controlled with a button requires minimal effort from the user.

The circular shape can also be a disadvantage, because there will be some form of lip astronauts will need to step over, which may be a tripping hazard. Further, the door opening upwards has some added risks. If the door was in an open position and something failed, it could fall and injure an astronaut or damage an EVA suit or other equipment. Finally, in the event of an electrical failure, the door may be difficult to open in an upwards motion because of the force of gravity.

7.1.5 Concept #5: Electronic Slide

This concept is another hatch that is controlled electronically with motors, shown in *Figure 25* below. The door will slide on tracks similar to those described in Concept #3, but the bearings in the track will be paired with motors to control the hatch's position. Further, the hatch features several pins (labeled as "Seal Assist Columns" in the drawing) that will interface with the frame of the lander in a way that pushes the door against the seals.

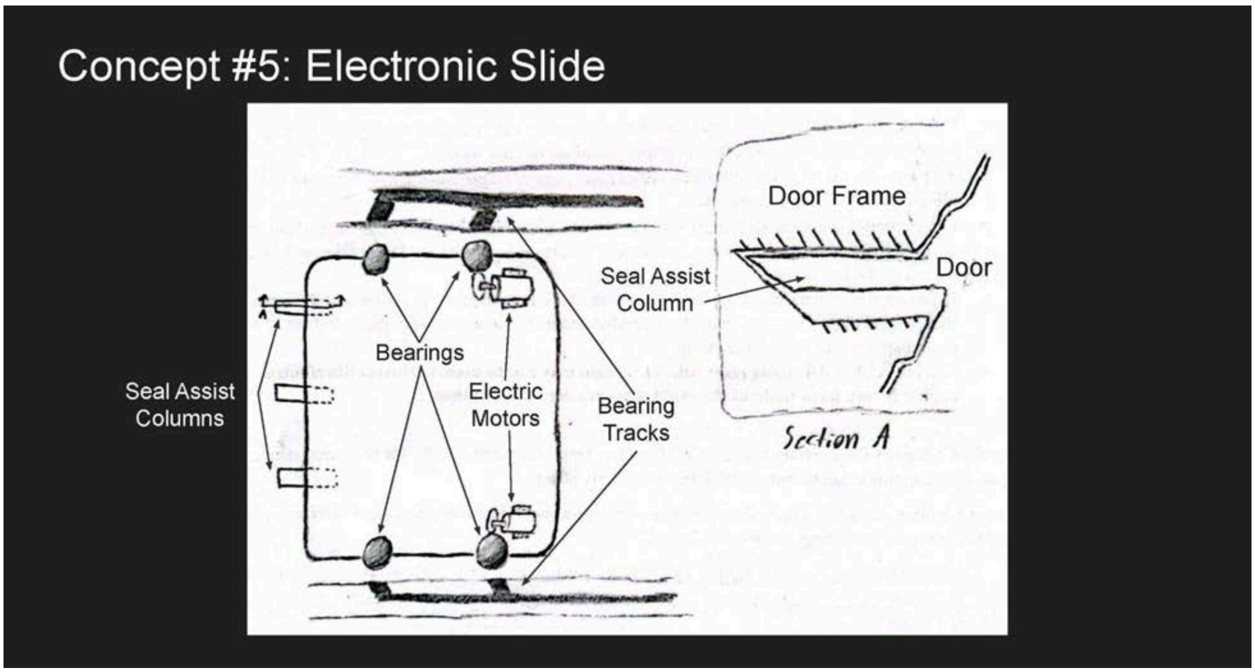

Figure 25. Concept drawing of Concept #5: Electronic Slide

This concept, as a motor-actuated concept, is advantageous because it requires minimal effort from the astronaut to open or close. Further, with this passive locking mechanism, the design is fairly simple and presents little risk in mechanical complexity.

For disadvantages, as mentioned previously with the sliding concept in Concept #3, the tracks could collect dust which may impact the functionality. Further, if an electrical failure occurred, the hatch would not be able to seal properly against the frame or be actuated from the open or close position.

7.2 Pugh Chart Ranking

After forming these concepts, we ranked each in a Pugh chart to test them against our requirements. Each concept received a score of -1, 0, or +1 for its ability to satisfy the requirement relative to the other concepts (-1 meaning unable to satisfy, 0 meaning partially satisfied or neutral, and +1 meaning the requirement is satisfied). Note that at the time this analysis was done the visibility across hatch, pressure equalization across hatch, pressure indication, and latching/locking status requirements had not been added and as such that are not included in the chart. The Pugh chart ranking is shown in *Table 3* below.

Table 3. Pugh chart ranking for five full-system concepts.

Requirements:	Concept #1 Spring Hatch	Concept #2 Electromagnetically Sealed	Concept #3 Manual Slide	Concept #4 Electronic Hinged Circle	Concept #5 Electronic Slide
Easy Operation	0	+1	-1	+1	+1
Easy Access	+1	+1	+1	-1	+1
Bi-directional Operation	+1	+1	+1	+1	+1
Operation Without Tools	+1	+1	+1	+1	+1
Lightweight	+1	-1	0	0	-1
Reusable	+1	+1	+1	+1	0
Survive Launch/Reentry	0	+1	+1	+1	+1
Temperature Tolerant	+1	0	+1	0	0
Dust Tolerant	+1	-1	0	+1	-1
Seal Under Pressurization	-1	+1	+1	+1	+1
Ergonomic	0	+1	0	+1	+1
Safe	-1	+1	0	+1	0
Risk	+1	-1	+1	-1	-1
Total	**6**	**6**	**7**	**7**	**4**

As it can be seen in the table, the Pugh chart ranking gave fairly comparable results and didn't display one concept as significantly better than the others. However, after discussing the results with the team, we decided to pursue an adapted version of Concept #4. It tied in terms of scoring with Concept #3, but by making the shape non-circular, designing the door to rotate laterally instead of vertically, and including redundant mechanisms to eliminate risk in the case of electronic failure, it would receive (at minimum) an additional two points, and therefore justify it as our concept to pursue in future design stages. This adapted concept will be discussed in more detail in the following section.

8. Selected Concept Design

The design we plan to further develop (will be referred to as the Alpha Design from here on) is a combination of a number of the subsystems that performed the best in our concept selection efforts. The mechanisms in the Alpha Design that will allow the door to open can be seen in *Figure 26*.

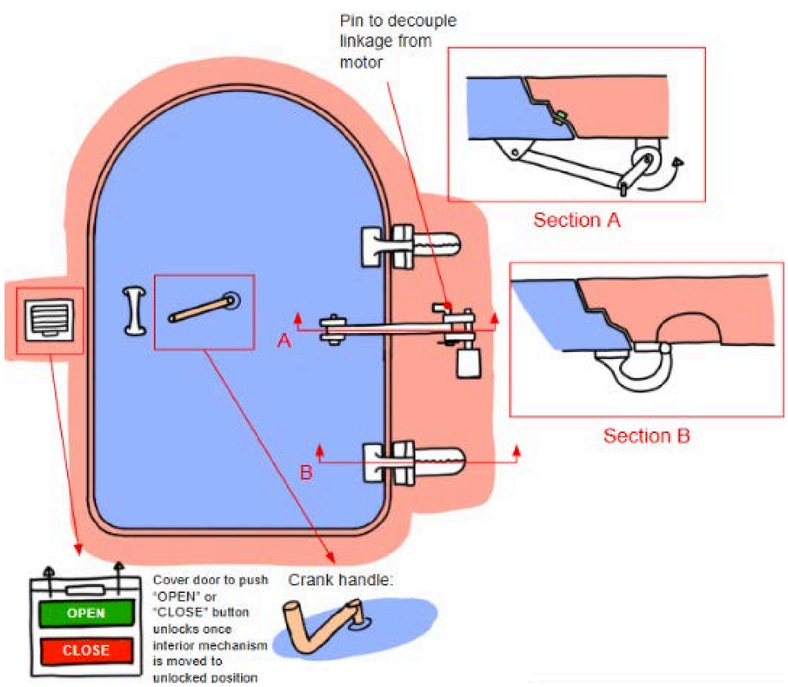

Figure 26. Mechanisms for opening the Alpha Design

The rectangle with a rounded top door shape was chosen for a number of reasons. A rectangularly shaped door is the most ergonomic shape for the astronauts in their EVA suits. The rounded corners shown here were also chosen with the EVA suits in mind to avoid places where the suit could be punctured or torn. The size of the door is not yet confirmed, but will be dictated by the EVA suits as well as any cargo the astronauts will need to move in and out of the landing module. The hinge design, shown in Section B, was selected for its shape. This should allow the doors to open in a fashion that allows the nested door and frame shape shown. The materials and size of the hinge will be determined through analysis discussed later in this report. The motor, shown in Section A, will open the door once it is unlocked. The motor to be used has not yet been determined, analysis of the weight of the door and door opening simulations will inform this decision. The door will be operated using the buttons shown. These will be covered and this cover will not open unless the door itself is unlocked. In the case of failure of the motor or an electrical issue we have included the capability to uncouple the motor and open the door manually. Finally, the crank handle to unlock the door is shown. The mechanism this crank operates is displayed in *Figure 27* below.

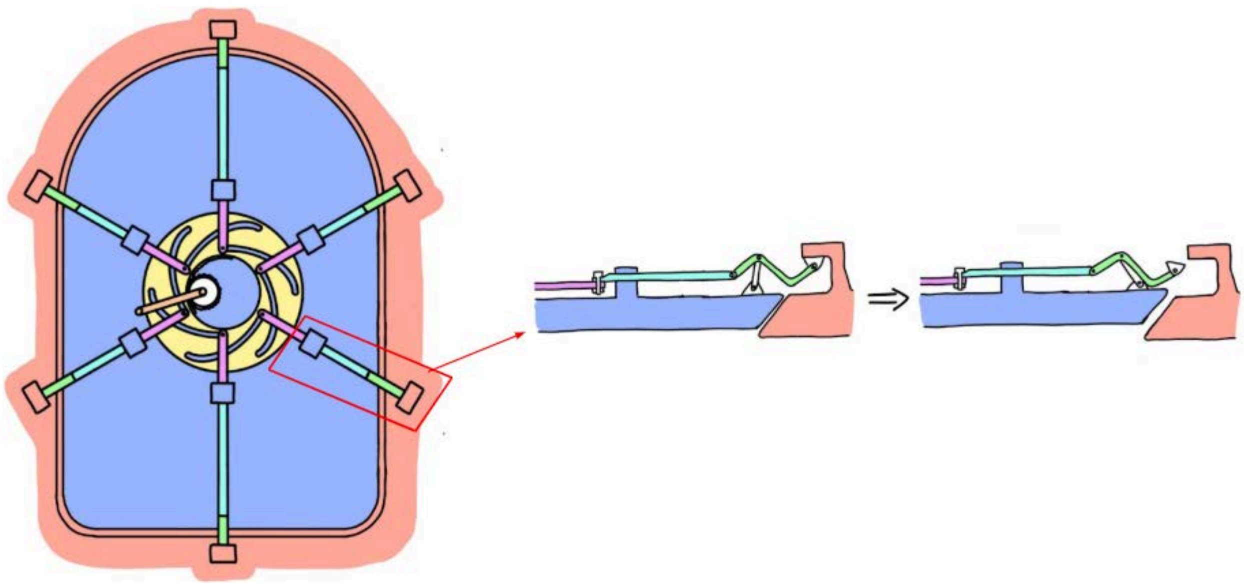

Figure 27. Interior Locking Mechanism

The crank shown in *Figure 26* operates the gear system shown here. The drive mechanism shown in yellow rotates, shifting the linkage systems (shown from another perspective on the right) from the locked to unlocked positions and vice versa. When the crank is turned to the locked position, the linkage system is extended and the sealing armature, shown in green, pushes against the designed lip incorporated into the door frame and thus presses the door against the entire door frame, locking the door and providing the initial seal in order to prepare the landing module for pressurization.

There are a number of features not explicitly included in these sketches that we intend to incorporate in the final solution. An external door latch is required per our requirements. When astronauts exit the landing module and close the door behind them, they will need to be able to close it. A complex locking and sealing mechanism will not be required as the module will not need to be pressurized when unoccupied. As such, a simple lever and latch is our plan to address this requirement at this stage. Perhaps an issue that will require some more creativity is that of decoupling the motor from outside the module with the door closed. The electronically actuated opening of the door will be operable from the outside of the module, however, should the motor experience issues, electronic or otherwise, there must be a way to decouple the motor from outside the shuttle and open the door manually. Finally, we plan to implement a status indicator for when the door is locked or unlocked.

9. Engineering Analysis

The team is conducting several different types of analyses and calculations to optimize the design with respect to our requirements and specifications. Due to complexity of the full CAD system and the timeline of the project, some of the analyses have necessitated base-level calculations and approximations, as opposed to full numerical simulations using FEA or CFD. The work completed so far, as well as planned work, will be detailed in the following sections

9.1 Linkage Latching System

The linkage latching system is the subsystem that latches against the frame of the lunar lander and pushes the hatch into the seal. This is therefore a critical subsystem, and thus future work will be done to optimize the current geometry. A "design by successive analysis" approach was used for this subsystem, since there is not a definitive mathematical technique for designing a linkage mechanism for a given situation. The design proposed in this section will be further analyzed to determine its effectiveness and then revised based on insights from this analysis.

The following criteria were kept in mind when designing the linkage system:

- The coupler end-effector that interfaces with the frame must move laterally towards and away from the center of the hatch, to allow the hatch to be moved from a closed to open position.
- The linkage system must be mounted to the hatch.
- It must generate a force normal to the hatch to provide sealing force.
- The linkage will be actuated with a linearly constrained link from the center of the hatch.
- The input arm of the linkage does not need to fully rotate.

The design drawn in *Figure 27* above served as a foundational illustration to base the design from. A rod or rail is actuated towards and away from the center of the door, which drives a linkage system to push into the frame of the lander.

The team first attempted to use the three position graphical synthesis method in Solidworks to design the linkage. This is shown in *Figure 28* below.

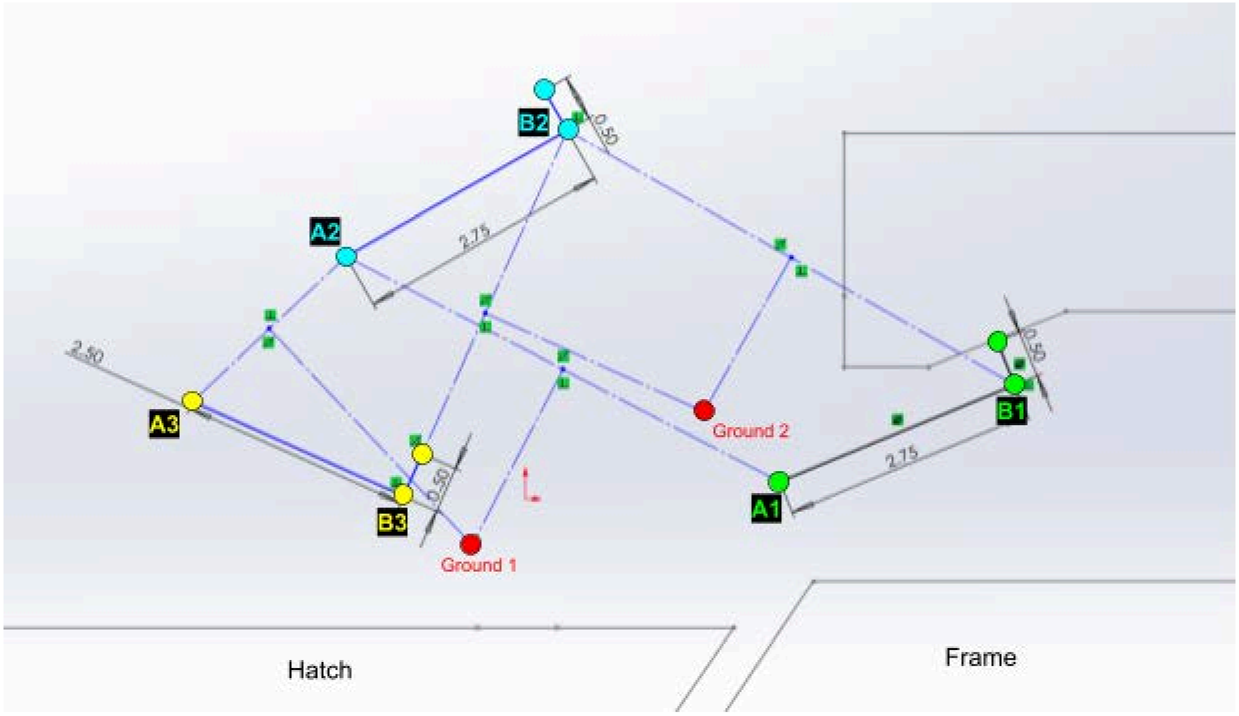

Figure 28. Linkage position graphical synthesis in Solidworks

In this method, three known positions of the coupler linkage are drawn. Each end (point A and point B) of each coupler position is connected to the corresponding positions with a line, i.e. A1 is connected to A2 and A2 is connected to A3. The perpendicular bisector is drawn from each of these lines, and then the intersection of each pair of lines is the ground point of the linkage. In the drawing, the positions of couplers A1/B1, A2/B2, and A3/B2 could be manipulated to any desired positions and angles, and then the ground pin locations would be provided.

This analysis strategy proved to be overly complicated and not very useful. The coupler positions were difficult to manipulate, and the ground pin locations were often not feasible. The team then used a "guess-and-check" technique, in which a linkage would be defined in a Solidworks sketch, and then adjusted until the desired coupler output was generated. The output of this is shown in *Figure 29* below.

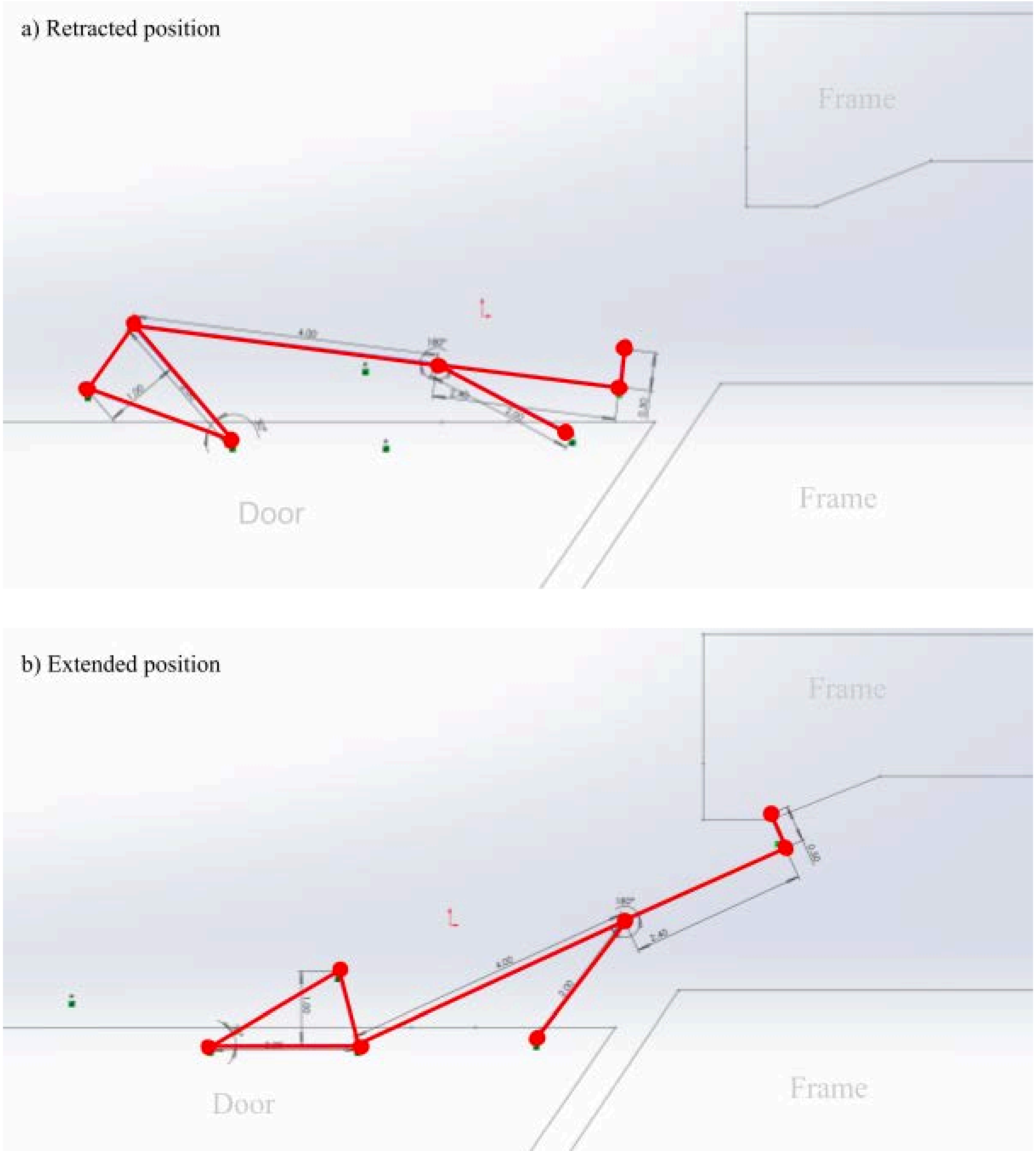

Figure 29. Extended and retracted positions of the designed linkage system

Figure 29a shows the linkage in the retracted or stowed position, and *Figure 29b* shows the linkage in the extended position when it is pushing against the frame. The triangle on the input link was added in order to make the transmission angle through the linkage's range of motion closer to 90 degrees, since that is the most optimal transmission angle.

After implementing the design into the final assembly, the team realized the path of the linkage coupler is not optimal. Ideally, the displacement at the end of the motion, when it is pushing against the frame of the lander, is in a direction perpendicular to the face of the door. However, this is not achieved with the current design.

As a result, a new linkage was designed that fit this criteria better. A diagram showing the old linkage (V1) and the new linkage (V2) in their start and end positions, as well as a trace of the coupler path through its motion, is shown below in *Figure 30*.

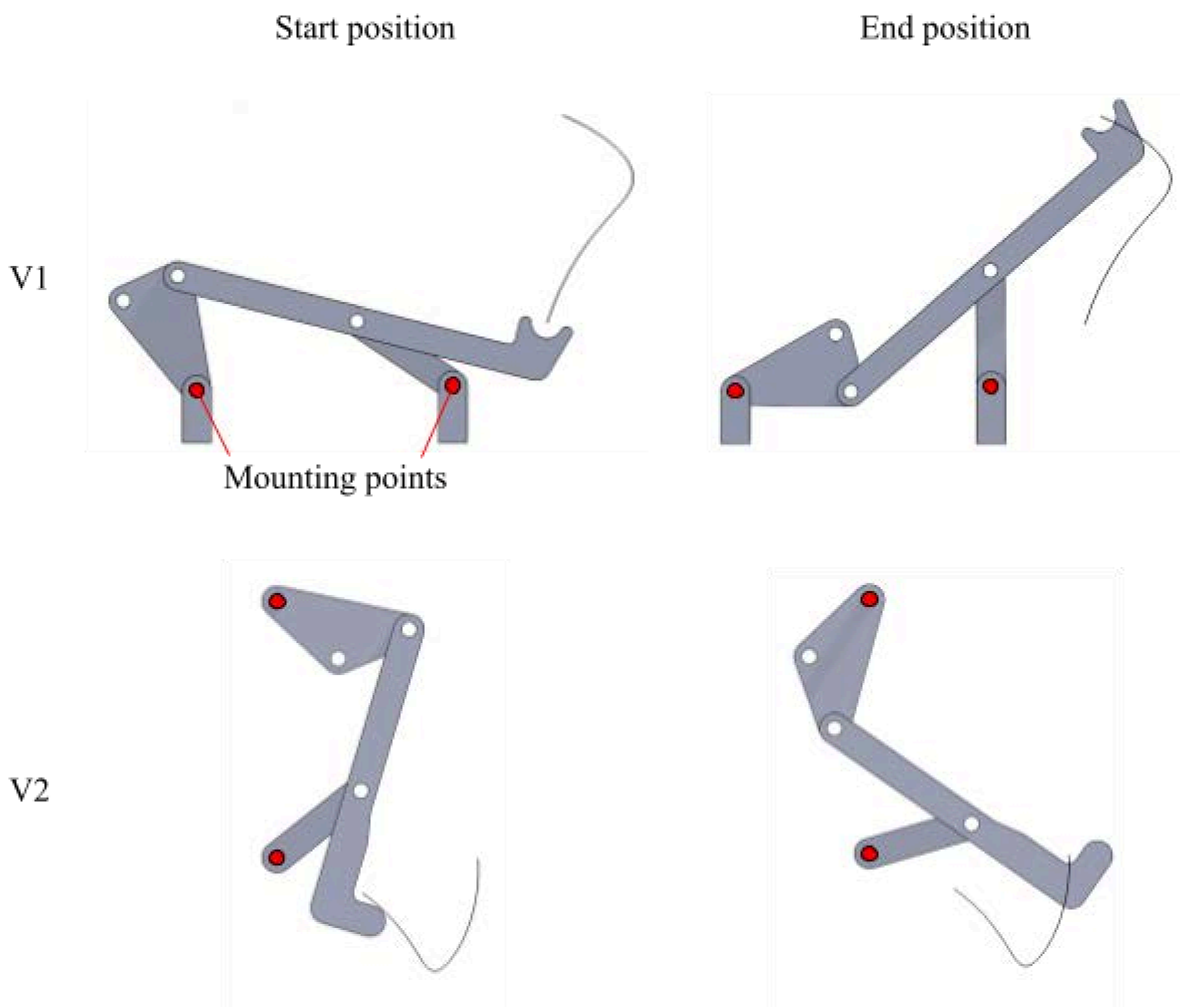

Figure 30. First (V1) and second (V2) linkage latching iterations

9.2 Rotational Mechanism Mechanical Advantage Motion Analysis

One key factor in validating the functionality of the rotational mechanism subsystem is determining how much force it can apply to seal the door before the cabin is pressurized. The team was not able to determine the specific force value that would be required to create an adequate seal, since this is dependent on the seal's geometry and material properties, but a simulation was created to determine the force output of the current arrangement. An equation was also derived to understand how different aspects of the rotational mechanism subsystem can be adjusted to decrease or increase the force output, as needed. This equation and other related calculations are shown in Appendices section 19.2.

Using the Solidworks Motion Analysis tool, the team created a simplified representation of the rotational mechanism consisting of the rotational disc, connecting rod, linkage latching system, and latching bracket. The setup is shown below in *Figure 31*.

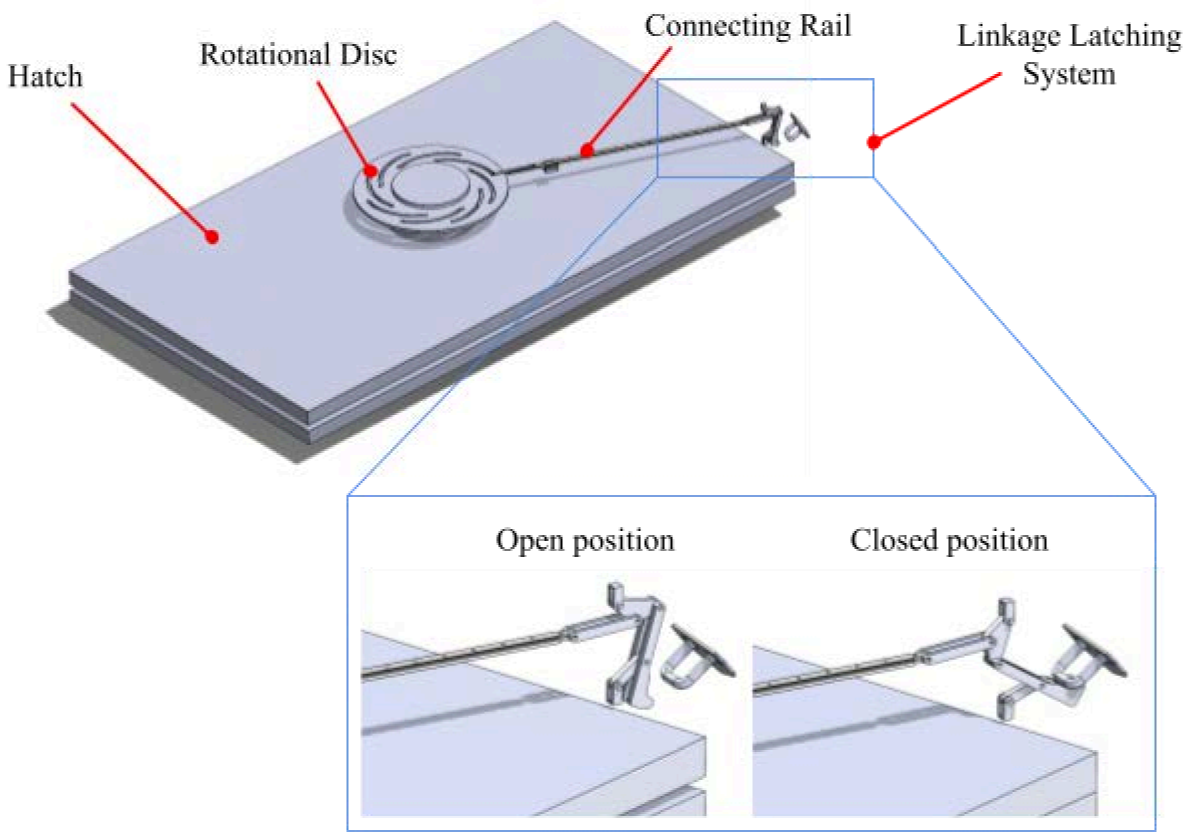

Figure 31. Setup used for the rotational mechanism motion analysis.

Using the equations derived in Appendices section 19.2, it was determined that a 15 lb-f input force applied to the input crank handle by an astronaut would produce a torque on the rotational disc of 1350 lb-in (with the dimensions shown in the CAD in section 10). This was applied to the system, and the reaction force applied to the latching bracket was measured and plotted on a graph. The results are shown in Figure 32 below.

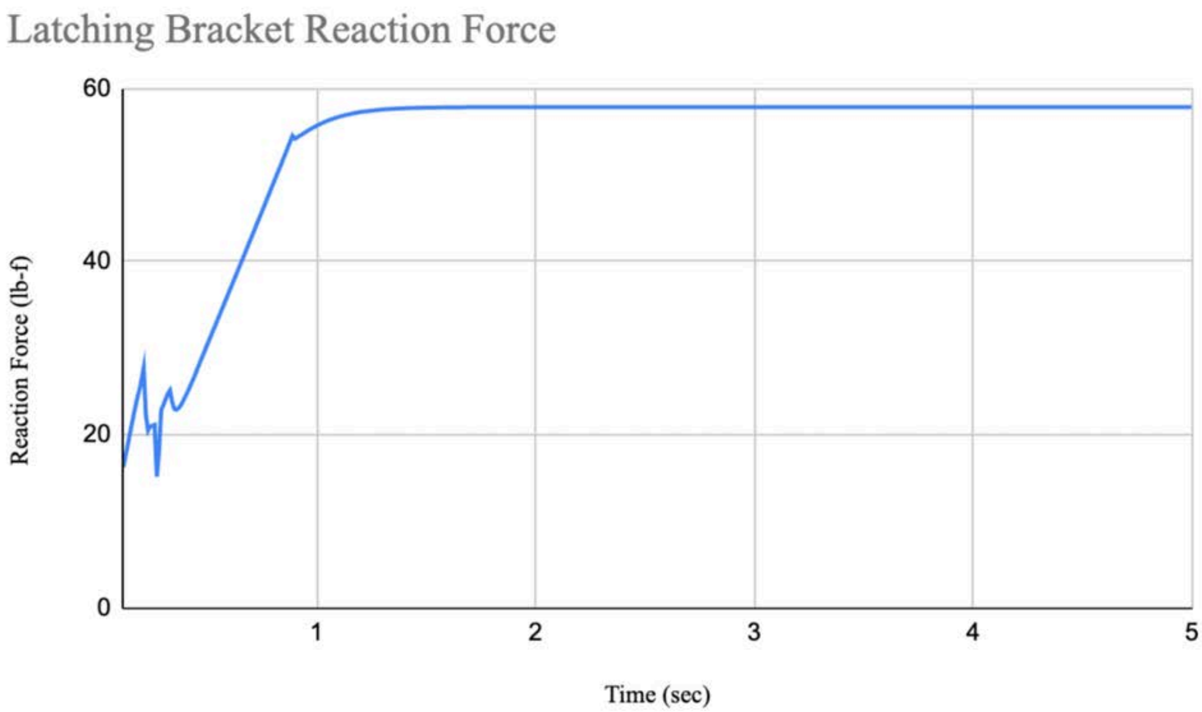

Figure 32. Plot of reaction force on the latching bracket versus time

From this plot, it can be seen that when the hatch is closed, the force applied by the mechanism is 57 lb-f. As a result, the current mechanical advantage of the mechanism is approximately 3.8:1. However, as mentioned previously, this value can be adjusted upon further development of the system. For example, the input crank handle length can be increased or the diameter of the transmission gear connecting the input crank to the rotational disc can be decreased in order to increase the mechanical advantage of the system.

9.3 Structural FEA Simulation

To verify the hatch will be thick enough to withstand the pressure difference between the interior cabin and space environment, an FEA simulation study was performed in Solidworks. The simulation was done using the following parameters:

- The hatch nominal thickness is 2 in
- The upper and lower "ring" of the lander frame will be fixed (shown in *Figure X* below). All other faces of the simulation will react to the pressure difference applied
- Pressure is applied at 14.7 psi in the normal direction on all interior surfaces
- The material of the hatch and lander frame will be a Titanium alloy (Ti-6Al-4VSolution treated and aged (SS))
    - Elastic modulus is 105 GPa

The setup of the simulation is shown in *Figure 33* below.

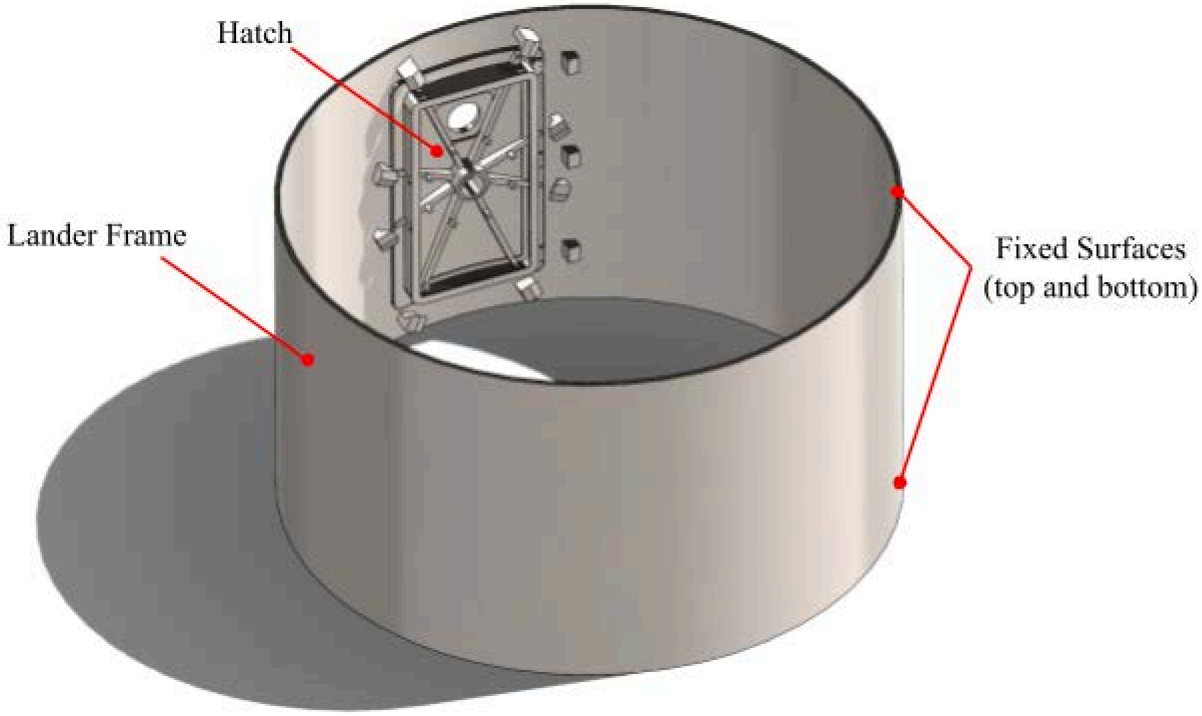

Figure 33. Setup of the FEA structural simulation to verify the hatch thickness

The results of the simulation are shown below in *Figure 34* and *Figure 35*. *Figure 34* shows the displacement results, while *Figure 35* shows the stress results, and the respective scale corresponding to the colors is also shown.

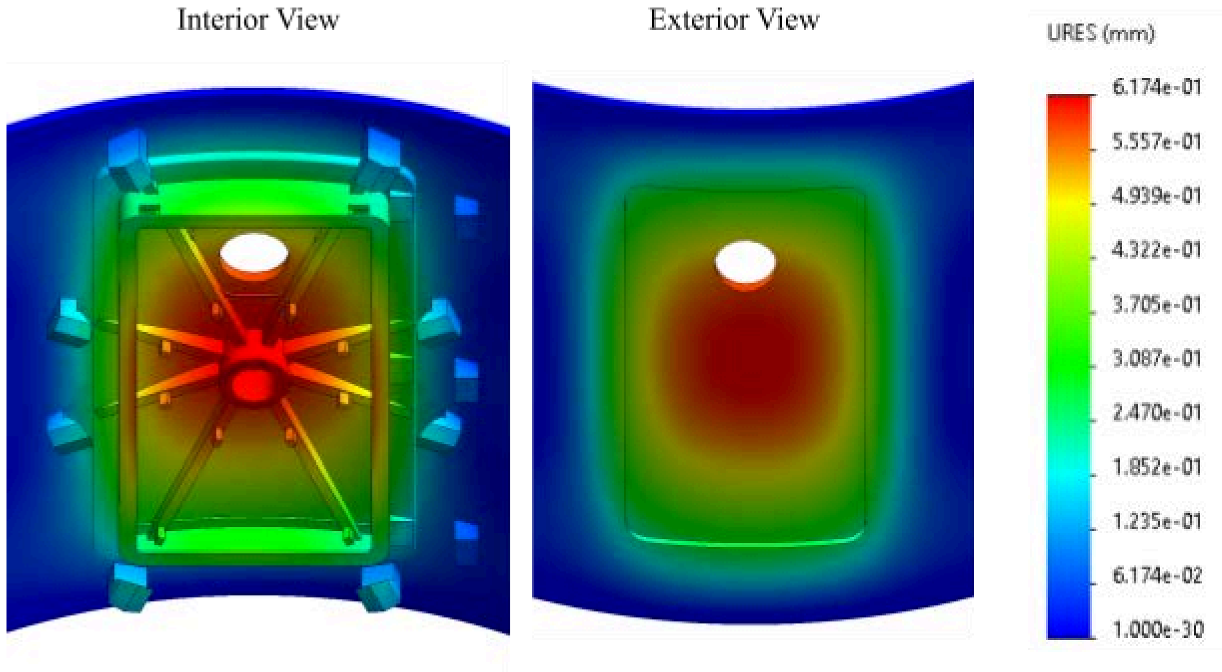

Figure 34. The resultant displacement map from an interior pressure of 14.7 psi

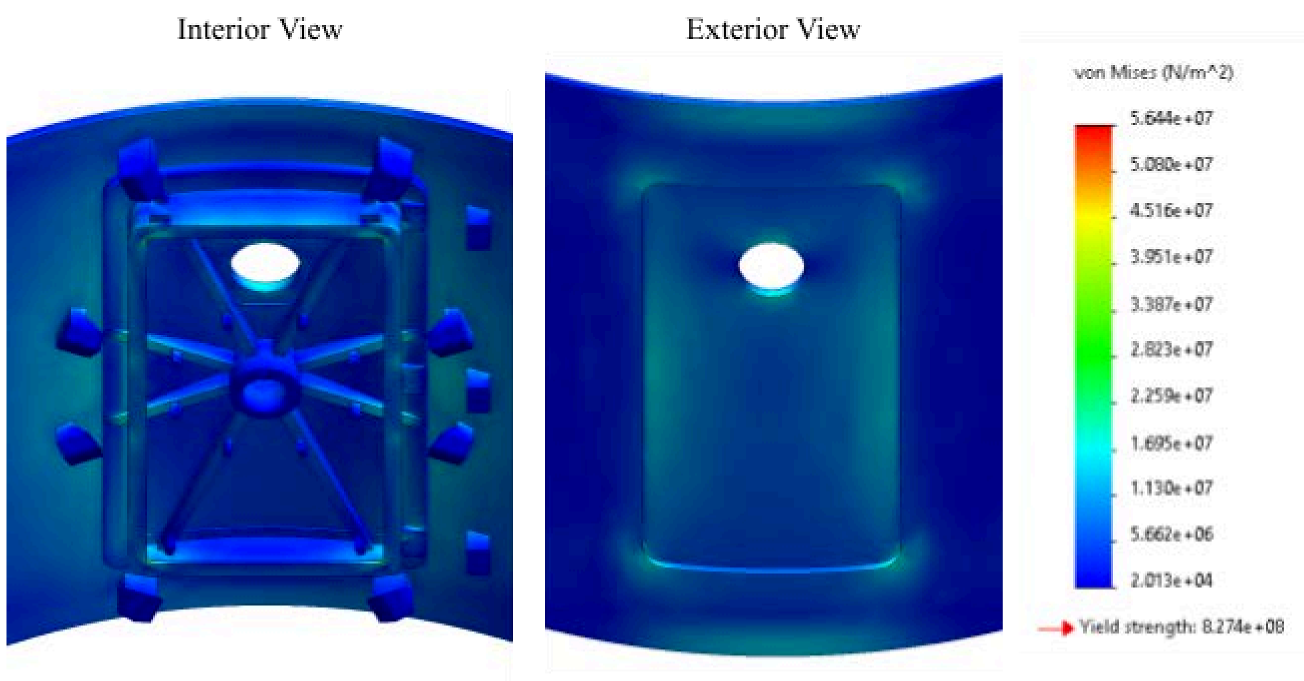

Figure 35. The resultant stress map from an interior pressure of 14.7 psi

As shown in *Figure 34*, the maximum displacement of the hatch resulting from the interior pressure is approximately 0.62 mm (0.024 in).

10. Final Design Description

For the final design of this project, the team has produced a CAD design and a build design. The CAD design is in a fairly conceptual state due to the time constraints of this project, but it presents a design that meets several of our requirements and conveys the fundamental mechanisms and features of the final design. For the build design, the team physically manufactured a scaled down section of the hatch and seal design in order to validate the design against some of our requirements. A video of the CAD design as well as the testing done with the build design can be found at this link:
https://www.youtube.com/watch?v=CAIFQ4kZLbs&t=9s or by searching "ME 450 Team 5 Crewed Lunar Lander Door Mechanism WN 2025" on YouTube.

10.1 Final CAD Design

10.1.1 Hatch

The hatch consists of three main components–the main hatch body, the mechanism housing frame, and the cover panel. These are shown in Figure 36 below:

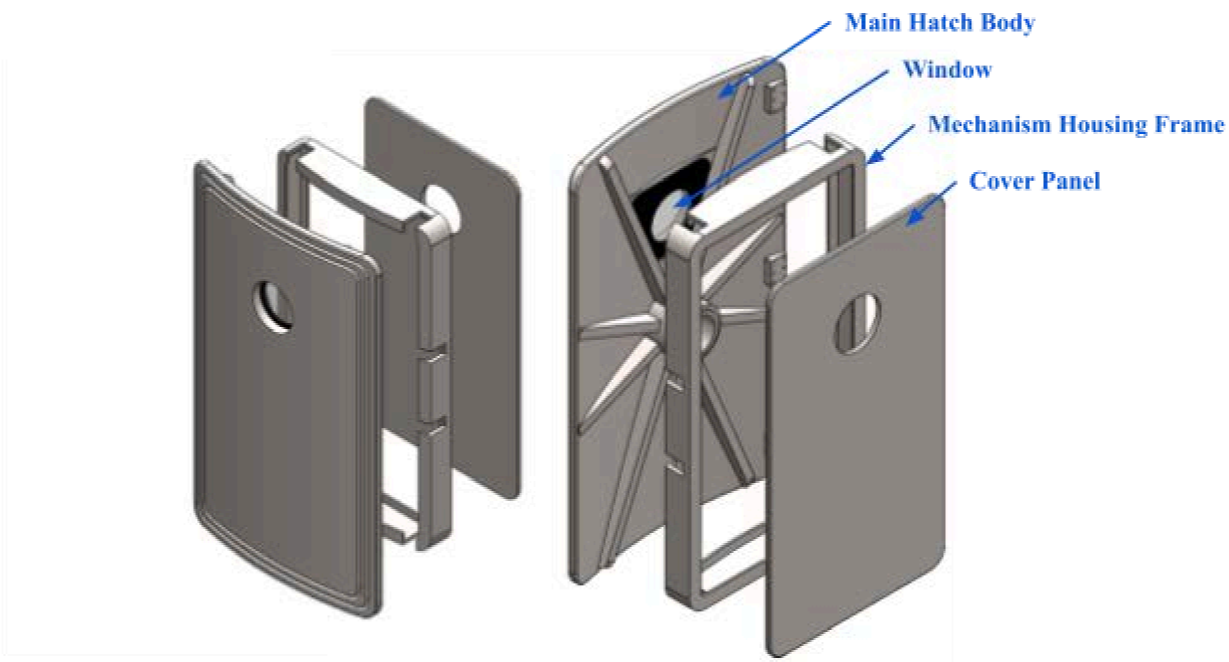

Figure 36. Exploded view of the subcomponents of the hatch.

The main hatch body is responsible for the primary seal against the lunar lander's door frame. It uses a double seal design as required by our seal under pressurization requirement. There are eight ribs that create a flat surface for the rotation mechanism, which will be discussed later, to mount to. Additionally, there is a viewing window to allow for visibility outside prior to egress. The mechanism housing frame and cover panel are design to enclose and isolate the rotational mechanism from lunar dust that would otherwise cause wear. Progressions of the design would include seals at the cutouts and existing gaps to prevent dust from entering.

10.1.2 Hinge

The current design consists of three hinges designed to allow the hatch to fully open so that egress is made easy for the astronauts. The hinge is shown in Figure 37 below:

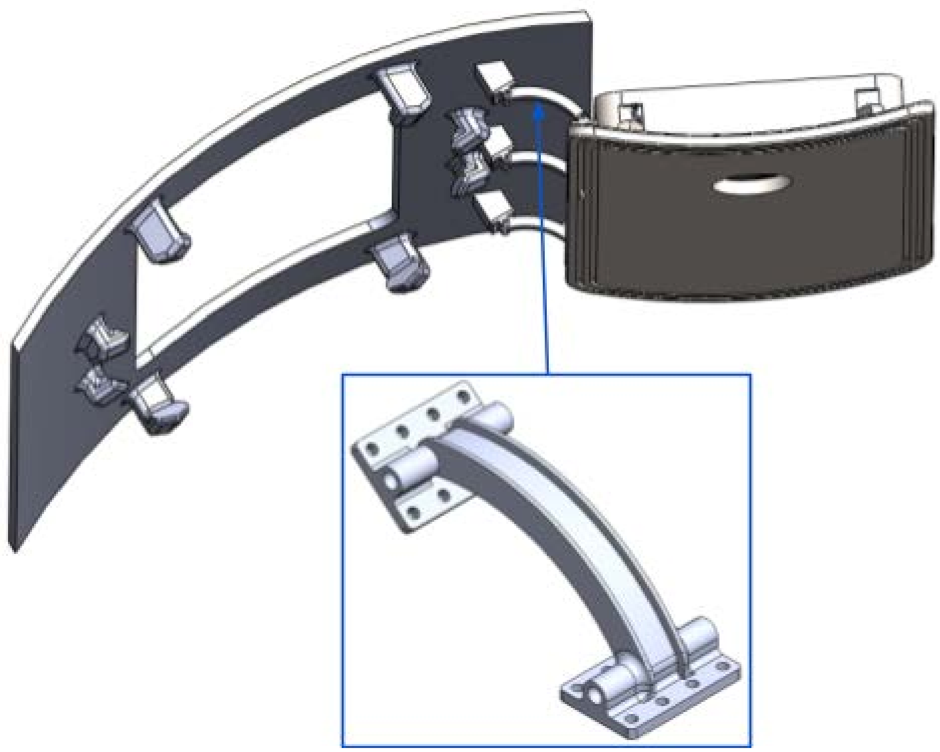

Figure 37. An enlarged image of the hinge beside the hatch in the fully open position.

10.1.3 Rotational Mechanism

The rotational mechanism inside the hatch is what is used to latch and seal the hatch against the frame of the lander. An overview of the system and its parts are shown below in Figure 38.

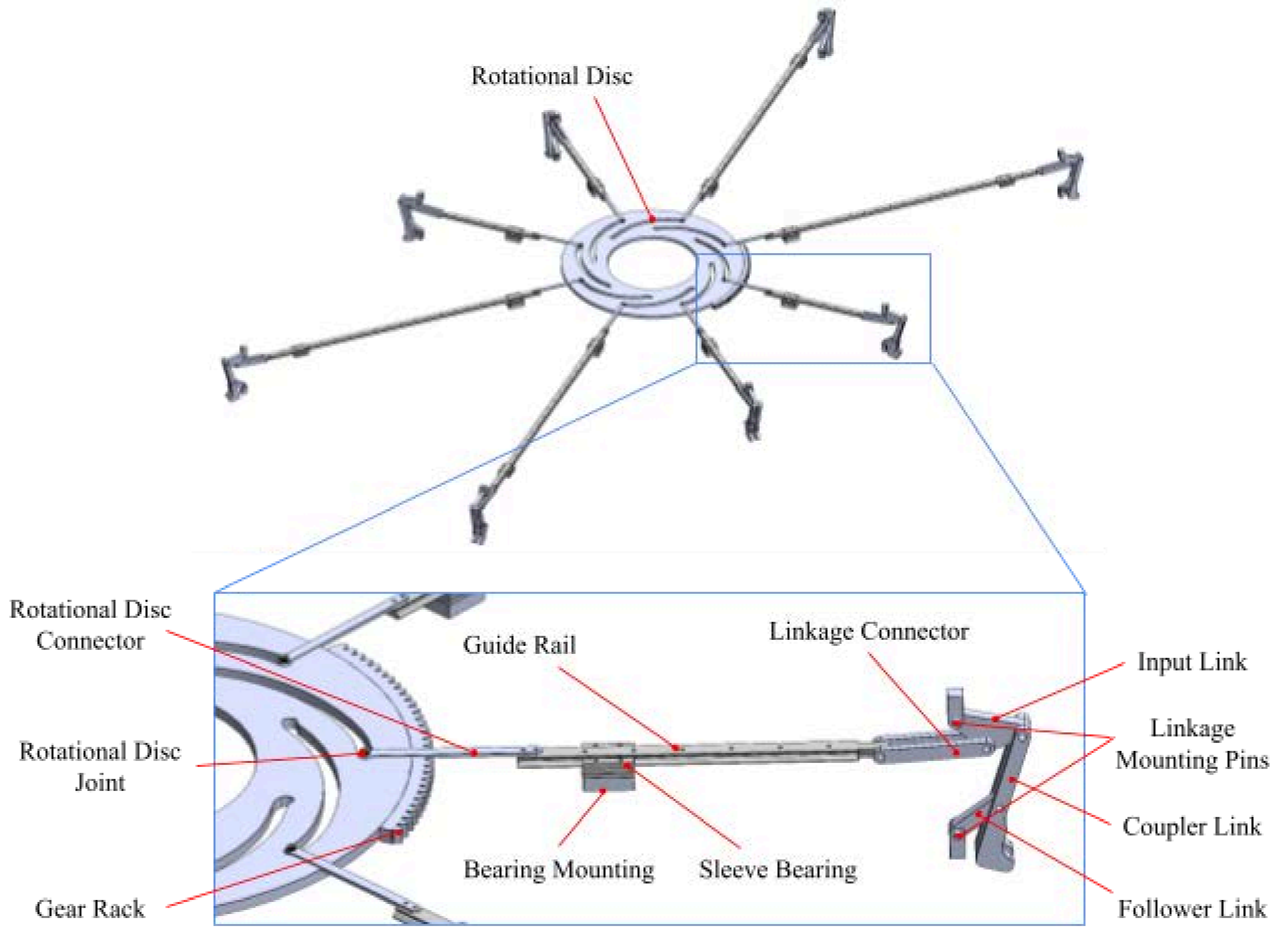

Figure 38. Overview of the rotational mechanism subsystem

For scale, the outer diameter of the rotational disc is 20 in. The system allows for one input motion to control several latches surrounding the entire hatch. As the rotational disc is rotated via the input crank handle (seen in section 10.1.4), the channels cut into the disc pull the guide rail radially inwards. This engages the linkage latching system that pushes against brackets attached to the lander frame. A diagram of this latching process is shown in *Figure 38* below.

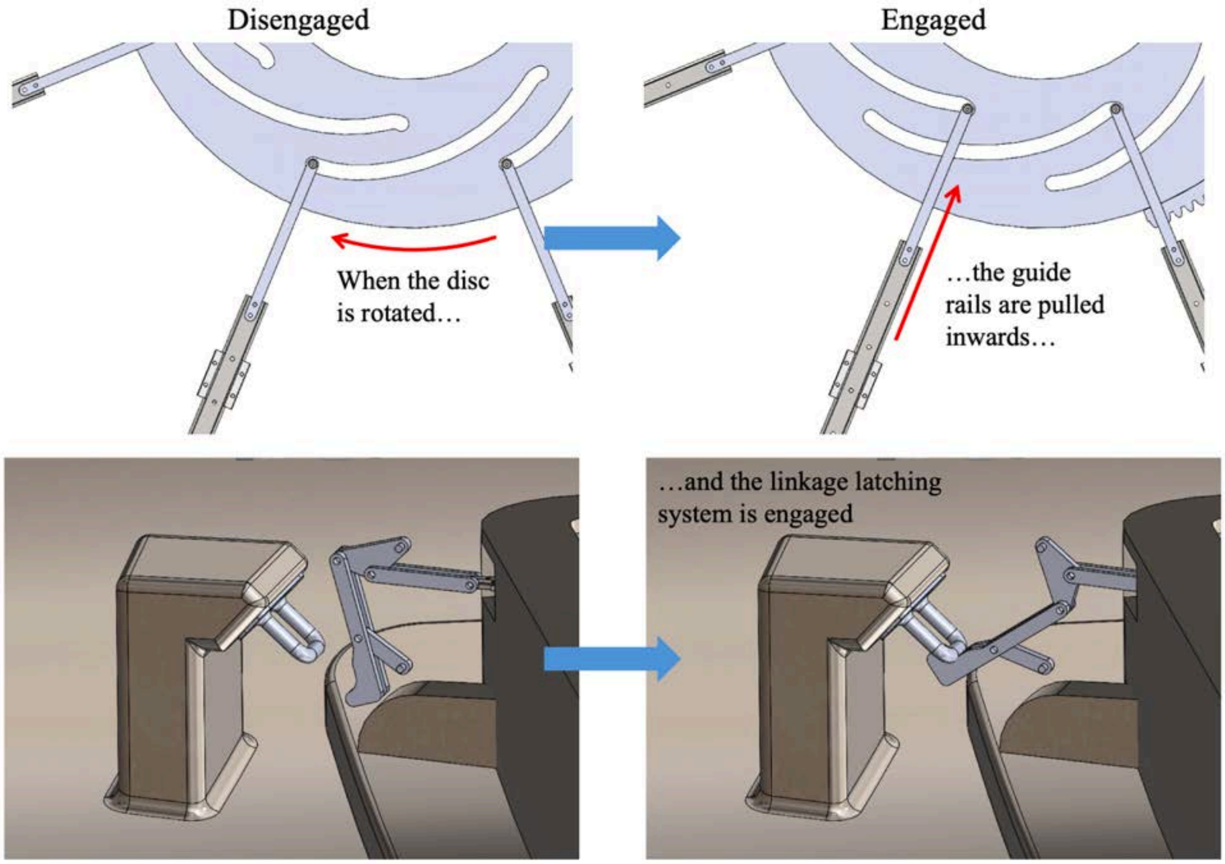

Figure 39. Rotational mechanism subassembly in disengaged and engaged states

All parts of this subassembly were designed and 3D modeled by the team, aside from the guide rail and sleeve nearing, which were sourced from McMaster Carr. The guide rail and sleeve were selected due to their high temperature tolerance (up to 149 degrees C) and simple design.

For the part labeled "Rotational Disc Joint" in *Figure 39* above, the team designed a bearing joint for this area but was unable to implement it into the CAD. A cross sectional diagram of this joint is shown in *Figure 40* below.

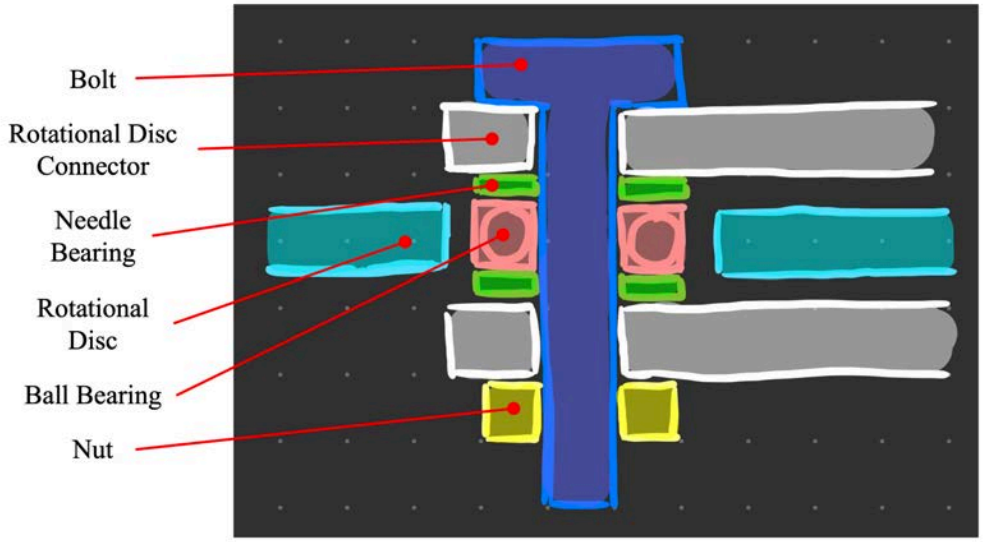

Figure 40. Cross sectional diagram of the joint between the rotational disc and rotational disc connector

This type of joint ensures rotational freedom and prevents any rotational friction between the channels in the rotational disc and the bolt that is moved within it. Further, it ensures the rotational disc connector maintains its vertical alignment while being actuated.

This specific mechanism for latching and unlatching was chosen for its ability to evenly distribute sealing pressure throughout the door before the cabin is pressurized. Further, the team believes the mechanism can function reliably through multiple uses, but physical prototyping and iterating will be necessary to validate the system completely.

10.1.4 Handle

The handle is also early in the design process, but we have developed a basic concept to demonstrate our vision for the design. The concept of the handle is shown in Figure 41 below:

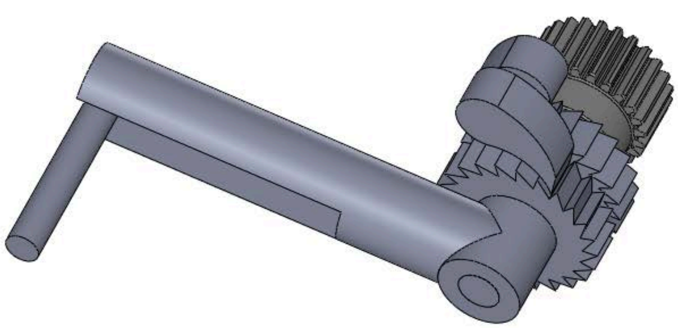

Figure 41. Early conceptual design of the handle.

The handle transmits power to the rotational mechanism through gears that can be chosen based on how much sealing force is required. It features a ratchet system to prevent being backdriven when the hatch is shut. When the hatch needs to be opened the ratchet can flip to release the rotation mechanism. Additionally, the end of the handle can rotate inward when not in use to avoid the astronauts' suits from catching on it.

10.2 Build Design

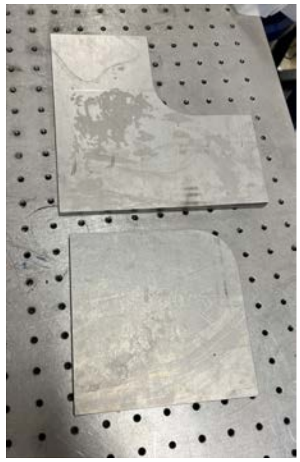

Figure 42. Preliminary door and hatch titanium cutouts

To validate our seal design, we conducted leak rate testing on a 1:2 scale model constructed from materials identical to those planned for the final build. We identified the corners of the hatch-frame interface as the most likely points of failure and prioritized these in our testing. Utilizing a 2 mm thick sheet of titanium provided by Dr. Banu, we used water jet cutting to create five identical traces for both the hatch and door (Figure 42). These layers were then welded together using scrap titanium to achieve the desired thickness and form two rigid bodies. This layered approach allowed us to approximate our intended half-inch thickness while working within material constraints. Though the correct scaled thickness would have been 1" per side, we determined that the reduced Z-dimension would have minimal impact on leak rate or sealing force, and thus accepted this tradeoff to conserve material and streamline fabrication.

Figure 43. Silicone rubber seal print segments

For the seal itself, we designed and 3D printed a silicone rubber inlay to fit into a precisely cut notch around the door's perimeter (Figure 43). However, due to limitations in the print and notch geometry, the seal did not fully extend to the edge of the cross-section, resulting in a gap. We temporarily addressed this with airtight sponge tape, but the interface between the silicone and tape created a significant leak path, limiting the accuracy of our results in this area. Additionally, positioning the seal around the tight 90-degree corner of the hatch presented further challenges. While the outer edge was accommodated, the small radius on the inner edge led to bunching of the silicone, reducing seal effectiveness. Our prototype used a fillet radius of 0.05", but testing showed that a radius above 0.20" would better accommodate the material's limitations. This adjustment is feasible given the waterjet's ±0.015" precision and is recommended for future iterations.

Figure 44. Silicone seal and titanium door interface

By constructing our prototype from titanium and silicone (Figure 44), we ensured realistic evaluation of leak performance and material behavior during vacuum phase and thermal stress cycles. While aluminum would have been a lower-cost and easier-to-machine alternative, access to titanium enabled us to closely simulate actual operating conditions and directly observe interactions at the material interface. Access to university resources, including the silicone 3D printer, waterjet, and vacuum setup, eliminated additional fabrication costs allowing us to maximize the value of our prototype within budget constraints.

This test provided valuable insight into the manufacturability of our proposed geometry and demonstrated our product's ability to handle stress cycles and leak challenges. It also highlighted the overall durability of our seal geometry when subjected to repeated use and potential degradation. The manufacturing plans and bill of materials for our build design can be found in the appendix.

11. Verification and Validation

11.1 Verification

Below in Table 4 is a brief description of the verification methods and their preliminary results for each of our user requirements and engineering specifications.

Table 4. List of User Requirements and their associated Verification Method

User Requirements	Engineering Specifications	Verification Method	Preliminary Results
Easy operation	The hatch must be able to be opened in ≤ 60 seconds with a user-applied force on the release mechanism of ≤ 30 lbs [15]	Simulink simulation of hatch opening with an applied force vector	N/A
Easy access	An astronaut and spacesuit of overall height ≥ 80 inches and overall width of ≥ 38 inches must be able to pass through when the door is fully opened [19]	Dimensional analysis of hatch	Good
Bi-directional ingress/egress	Hatch must be fully operable on either side by a single crew member	Analysis of relevant features in CAD assembly	Planned but not implemented
Operation without tools	Method of opening must occur without the use of tools	Analysis of relevant features in CAD assembly	Good
Lightweight	Hatch and mechanism mass must be ≤ 5000kg.	Mass estimation from CAD dimensions and associated materials	Good
Reusable	The hatch and mechanism must continue to operate as expected for ≥ 5 missions	Relevant mechanisms evaluated against guidelines given in NASA-STD-8729.1A [24]	Good, further analysis pending
Survive launch/ reentry	The hatch and mechanism must remain intact and fully	ANSYS simulation of CAD assembly for	N/A

	functional after being exposed to accelerations up to 50 m/s^2 when closed and locked.	predicted loads with safety factors as given by NASA-STD-5001B [25]	
Temperature tolerant	The hatch and mechanism must withstand temperatures ranging from -250 °C to 130 °C [20].	Abaqus simulation of full assembly, sub-assemblies, and parts from CAD	N/A
Dust tolerant	The hatch and mechanism must have dust-resistant covers	Analysis of relevant features in CAD assembly	Planned but not implemented
Seal under pressurization	- The hatch seals must leak no more than 10^{-2} lbm dry air/day under pressure differentials ≥ 14.7 psi [21] - A minimum of 2 seals must be used for redundancy [21]	Analysis of relevant features in CAD assembly	- See Validation - Good
Ergonomic	Hatch release must be fully operable when wearing an EVA suit	Analysis of relevant features in CAD assembly with regards to NASA-STD-3001, Vol 2 [15]	Good, further analysis pending
Safe	- The hatch and mechanism must avoid sharp edges by filleting edges to radius ≥ 3.0 mm [15], and pinch points shall be covered or otherwise out of the way of crew members [15]. - The hatch shall require two distinct and sequential operations to open [15].	Analysis of relevant features in CAD assembly	Good
Redundancy	In case of actuated mechanism failure, hatch must be manually operable	Analysis of relevant features in CAD assembly	Good
Visibility across hatch	Hatch must include a non-electronic window to view exterior of hatch prior to egress [15].	Analysis of relevant features in CAD assembly	Good

Pressure equalization across hatch	The hatch must be equipped with manual pressurization and depressurization on both sides by a single crewmember in or out of an EVA suit [15].	Analysis of relevant features in CAD assembly	Planned but not implemented
Pressure indication	There must be an indication of whether the lunar lander is pressurized or unpressurized on the hatch that is viewable from both sides of the hatch. [15].	Analysis of modeled control system and relevant features in CAD assembly	Planned but not implemented
Latching/ Locking status	There must be indication of the hatch's locking and latching status that is viewable from both sides of the hatch [15].	Analysis of modeled control system and relevant features in CAD assembly	Planned but not implemented

Each of these verification methods and their results are discussed in greater depth below. Given the limited time allotted for the realization of our solution, many of these verification methods are relatively basic. More in depth verification procedures would be doable given more time. Explored here are those verification procedures we were able to complete within the given time as well as some of those planned that are possible to complete within a reasonable time frame.

Easy Operation. We were unable to carry out the following verification plan within the time allotted. Doing so should prove relatively simple if somewhat time consuming. Simulink will be used to simulate the opening of the hatch. By using a perpendicular force vector with a varied magnitude up to that given by our specification on a simulated hatch with the mass of our designed solution we can determine whether the door may be opened within the time period given by our specification.

Easy Access. A comparison of the EVA suit to be used by the upper percentile of astronauts in terms of height and width with the designed dimensions of our hatch indicates all astronauts should have no issue utilizing the hatch.

Bi-directional Ingress/Egress. Internal latching and locking mechanism is designed and implemented with the CAD. An external latching system has been theorized but not thoroughly explored or implemented within the CAD. This mechanism will be analyzed pending its implementation.

Operation Without Tools. User operated mechanisms within the CAD assembly all function without the use of specialized tools.

Lightweight. The material make up of our design has not been finalized as of yet. However, with the dimensions from the current CAD assembly, the maximum mass of the door that is possible (supposing the entire door be made from the highest density material we plan to incorporate into the design) is around 1900 kg. Given that we expect to utilize lighter weight materials for much of the design, we can confirm that the design will be well below the maximum mass of 5000 kg.

Reusable. The hatch and its existing mechanisms have been evaluated using the guidelines for reliability and maintainability laid out in NASA standard NASA-STD-8729.1A [24]. Analysis is ongoing as the CAD is still being developed and refined, though results for existing mechanisms are good.

Survive Launch/Reentry. We were unable to carry out the following verification plan within the time allotted. Doing so should prove relatively simple if somewhat time consuming. ANSYS will be used along with a mesh created from the CAD assembly in order to simulate the maximum expected loads to be experienced by the hatch due to the acceleration associated with takeoff and landing. These simulations will take into account the safety factors for various materials as outlined in NASA-STD-5001B [25]. Resulting strains will be examined to determine any possible points of failure.

Temperature Tolerant. We were unable to carry out the following verification plan within the time allotted. Doing so should prove relatively simple if somewhat time consuming. Abaqus, along with parts and assemblies modeled in CAD, will be used to run simulations to determine the strains associated with the temperature envelope indicated by the specification. Functional analysis of the parts and various sub assemblies will also be performed under the given conditions in order to verify this specification.

Dust Tolerant. Dust covers and dust seals have been researched and some preliminary designs have been explored, though these designs have not been implemented within the CAD. These systems will be analyzed pending their implementation.

Seal Under Pressurization. CAD assembly includes two distinct and independent seals for redundancy. Validation of the leak rate will be discussed in the next section.

Ergonomic. Analysis of user operated mechanisms currently included within the CAD assembly utilized the guidelines laid out in NASA standard NASA-STD-3001, Vol 2 [15]. Analysis is ongoing as the CAD is still being developed and refined, though results for existing mechanisms are good.

Safe. All corners and possible pinch points within the CAD assembly meet the minimum specified tolerances.

Redundancy. Door mechanism is designed to be operable in the case of motor failure. Back drivable motor will be utilized.

Visibility Across Hatch. CAD design includes a window to allow view of the exterior of the hatch.

Pressure Equalization Across Hatch. Some initial research has been done into pressure equalization systems. However, as this was not a key goal of ours in this project, these systems have yet to be refined and implemented into the CAD. These systems will be analyzed pending their implementation.

Pressure Indication. A pressure indication system has been theorized but not yet implemented into the CAD. The system will be analyzed pending its implementation.

Latching/Locking Status. A latching/locking status indication system has been theorized but not yet implemented into the CAD. The system will be analyzed pending its implementation.

For any virtual simulations done it must be noted that issues arising from construction including fastening and shaping as well as any material defects could lead to discrepancies between the final solution and the simulated results. However, these simulations provide useful information with very little capital investment. Many of these requirements were verified through analysis of the CAD. This shares the same strengths and weaknesses mentioned for the simulations. While a simple analysis of the CAD has many issues in terms of reliability and the robustness of the analysis, the alternative for the majority of these requirements would rely on a small-scale or even full-scale prototype which is not possible at this stage.

11.2 Validation

The validation plans discussed below are separated into those tests that we carried out on our build model and those procedures that are outside of the scope of what we were able to do with our resources and the allotted time.

11.2.1 Build Model Testing Procedures

Leak Test. In this test we sought to validate the functionality of our designed seals in reference to the specified maximum allowable leakage rate (MALR) of 10^{-2} lbm/day under a pressure differential of 1 atmosphere. The test outlined below was designed in compliance with NASA standard NASA-STD-7012A [26]. One side of our build design for a section of the hatch including the seal interface with the door frame was subject to a vacuum. This was done using a vacuum pump with plastic sheeting and sealing tape around the edges to section off the portion of the prototype to be tested. The manometer built into the vacuum pump took readings over the course of a 15 minute test, after stabilization, in order to quantify the leakage rate. This test was repeated after thermal testing of the build model. Since we are unable to build even a small-scale complete prototype, this test is a good alternative. This test is meant to validate the seal material and design with a relatively low capital investment.

Thermal Test. This test was designed to examine the performance of various pieces of the build design under the higher temperatures within the expected temperature envelope. The build design was exposed to temperatures ranging from ambient to 140 °C. The minimum expected temperature is not achievable with the equipment and time available. For the attainable temperatures, this test was conducted in accordance with NASA standard NASA-STD-7002B [27] where the tested parts were heated using an industrial oven shown in Figure 45 below. While it is not ideal that we are not able to test over the entire expected temperature envelope this testing will still provide useful information with regards to the higher end of extreme temperatures at a low capital investment. Given more time this test could be used to test multiple parts beyond those currently included in the build design.

Figure 45. Industrial Oven used in thermal testing

11.2.2 Build Model Testing Results

The leak test was executed in the manner described above. Some difficulties were encountered in carrying out the test and interpreting the results. The majority of these issues were due to the nature of our build model. The most impactful was the end sections of the interface between the model hatch and model door frame, these areas are circled in Figure 46.

Figure 46. Problem areas with the build model

These areas introduced the majority of the leakage we measured in this test. This posed an issue in interpreting our results as these areas would not exist in a true implementation of our final design. We attempted to minimize the leakage at these locations through an abundance of sealing tape. This reduced leakage in these areas but did not eliminate it as would be the hope for the ideal test of our build model sealing solution. As such our obtained results cannot be said to be fully representative of the tested solution.

Our vacuum pump was an Orion Motor Tech Vacuum Pump as shown in Figure 47 below. We had issues with the vacuum pump not reaching the stated 5 Pa ($5*10^{-5}$ atm) ultimate vacuum. This was clear to us as when we completely block the vacuum pump, it was observed that the gauge, as seen in Figure 48, only reached to about 0.86 atm which is indicative of a larger ultimate vacuum value than 5 Pa.

Figure 47. Vacuum pump used in leak test

Figure 48. Differential pressure gauge between atmosphere and tape sealed volume.

Despite these issues with the test, we determined a leakage rate using pressure readings, from the gauge shown in figure 48, over time. As seen in Figure 49.

$$\mathrm{kg/day} = 0.00107 \cdot \frac{86400}{28.6} \approx 3.23\,\mathrm{kg/day}$$

$$\mathrm{lbm/day} = 3.23 \cdot 2.20462 \approx \boxed{7.12\,\mathrm{lbm/day}}$$

Figure 49. Leakage rate calculation

This value is much higher than the desired .01 lbm/day. While the issues with the build design mentioned above definitely contributed to leakage rate being as high as it was, we were able to observe leakage through the sealing this test was meant to evaluate. Realistically, even a leakage rate on the order of magnitude of tenths of a mass pound of air per day should not be detectable through the visual and auditory methods we used to determine the location of leaks in this test, nevermind the hundredth of a mass pound of air per day that we identified as a specification for our design. As such, we can say with a high degree of certainty that improvements to the sealing method are necessary, despite issues with the executed test.

The build model's ability to seal within the expected temperature range was also examined as described above. Our build model was heated to the maximum expected temperature our design should experience in use then allowed to cool, after which leakage tests were carried out, and the results compared to those from tests done before subjecting the model to extreme temperatures. Before the thermal stresses applied to the model the maximum temperature differential the model was able to accommodate was 0.88 atm. After heating and cooling, leakage tests revealed a maximum pressure differential in the 0.85-0.87 range. While this seems to indicate the thermal stresses negatively impacted the model's ability to seal, uncertainty associated with the testing apparatus means we cannot say this for certain.

11.2.3 Out of Scope, Low Cost, Validation Plans

While NASA has a number of rigorous testing procedures, we have formulated a number of tests that should be helpful with regards to obtaining some initial results without the significant capital investment necessary for some of the higher fidelity NASA tests.

Dust Test. This test is designed to validate the function of prototype mechanisms when a lunar dust simulant is introduced. Preparation of the lunar simulant as well as the testing procedure should be carried out in accordance with NASA standard NASA-STD-1008 [28]. Lunar simulant can be prepared by vibrationally sieving sand to obtain particle sizes <500 μm. Bake-out procedures should then be followed in order to remove any water from the simulant. Once the simulant is prepared it will be mixed into a lubricant and applied to the mechanism. The operation of the mechanism should then be examined for any excessive inhibition due to friction created by the dust. After extended operation the mechanism should be disassembled and examined for wear and abrasion. This test can be used to evaluate any proposed mechanisms at a relatively low cost.

11.2.4 Out of Scope, High Fidelity, Validation Plans

Given the rigor associated with NASA standards the vast majority of proper validation tests are out of the scope of this project and require significant capital investment. We give a brief overview of some of the most vital tests and their associated standards here. For proper pressurization validation in accordance with NASA-STD-7012A [26] a full sized prototype should be tested in a vacuum chamber as described in Method I of the standard. Additionally, Methods XI and XIV which utilize detector probes and tracer gases to pinpoint leaks should be utilized. The pressurization tests should be carried out at many points within the testing process; after all environmental tests including thermal tests, vibration tests, shock testing, acceleration testing and life cycle testing. Thermal tests with a completed prototype in accordance with NASA-STD-7002B [27] are necessary. Specifically, the entire expected temperature envelope should be tested in vacuum conditions. Dust testing in accordance with NASA-STD-1008 [28] would need to include mechanism tests as outlined above for all the relevant systems, abrasion tests for all moving parts, optical tests for the sensors and window, thermal tests for the motor, and seals and mating surfaces tests for the pressurization seals.

Structural stability, while beyond our means to validate, is a major consideration. Static loading tests, to simulate take-off and landing, of a full-sized prototype should utilize safety factors and processes given in NASA-STD-5001B [25]. Vibrational tests that simulate all acoustic, random, and sinusoidal vibrations potentially experienced by a prototype should be carried out in accordance with NASA-STD-7001B [29] and NASA-STD-7002B [27]. Finally, Pyroshock testing to simulate any potential explosions and/or impacts the system might experience structural shocks from should be done as laid out in NASA-STD-7003A [30].

12. Problem Analysis and Iteration

Selecting the right specifications for our motor depends on the performance of our design under real conditions. We will be simulating our mechanism functionality through a series of physics tests to determine the fundamental engineering requirements of our system.

12.1 Motor Torque and Force Analysis

We want our door to open in a 60 second time frame for the convenience of the user. This involves the disengagement of the linkage-piston locks and the actuated operation of the door. It is essential that our motor is properly equipped to handle this responsibility within the proper time frame.

Once we have properly established the dimensions and composition of the door, we will know the necessary horizontal applied force to rotationally accelerate the object. Using MATLAB

Simulink we can simulate the dynamic force effects on a rigid body: our hatch mechanism. This preliminary measure will ensure the smooth operability of our door under real conditions.

We also plan to validate our linkage functionality through MSC Adams modeling. Using this software we can optimize the transmission angle and mechanical advantage as we iterate through linkage ratios.

12.2 Door Seal Confirmation

The ability of our system to successfully pressurize is essential to the safety of the astronauts inside the lunar module, so we will take proper measures to test the efficacy of the seal. Part of our physical prototype testing will involve air leak testing. We will integrate a scaled down version of our design to a vessel and perform vacuumization. Using some kind of gaseous tracer inside the vacuum chamber, we will track the airflow to confirm the success of the door frame. The flow of colored gas molecules should make any unintended streamlines apparent for inspection.

In establishing the thickness for our hatch, we must ensure a proper safety factor to withstand the outward force of the cabin pressure.

Area of Door: 1.9m x 0.8m ≈ 1.60 m^2

Cabin Pressure: 14.7 psi → 0.101 MPa

$$\frac{0.101\ \text{N}}{1\ \text{mm}^2} * \frac{10^6\ \text{mm}^2}{1\ \text{m}^2} = 101\ \text{kN}$$

Figure 50. Net horizontal force approximation due to cabin pressure

Based on the data in a preliminary calculation, we will need a minimum thickness of 3 inches to avoid deformation. The projected area of the door is based on the minimum egress specification to accommodate movement of an EVA suit, and cabin pressure is equivalent to 1 atm.

Door Width: W = 0.0762m

$$0.0762\ \text{m} * 0.838\text{m} * 1.91\text{m} = 0.122\ \text{m}^3$$

Figure 51. Projected volume of door based on length, width, height specifications

With the calculated volume of the hatch we can estimate the total mass based on standard composition for an exterior lunar lander wall. This contains mostly Aluminum for lightweight durability, Titanium for structural reinforcement, and Kapkon for heat resistance. The ratio is outlined in *Figure 52* in the approximation for net maximum weight during launch.

$$\frac{1.22\ \text{m}^3}{1} * \frac{2778\ \text{kg}}{1\ \text{m}^3} * \frac{5 * 9.81\ \text{m}}{1\ \text{sec}^2} = 166.2\ \text{kN}$$

Figure 52. Calculation of net maximum weight during launch with 1G from gravity and 4G from liftoff acceleration

Considering this internal force is vital for properly designing the seal and hinges to withstand the normal applied force during the launch sequence. The free-body diagram (*Figure 31*) below shows how our components experience these different force vectors.

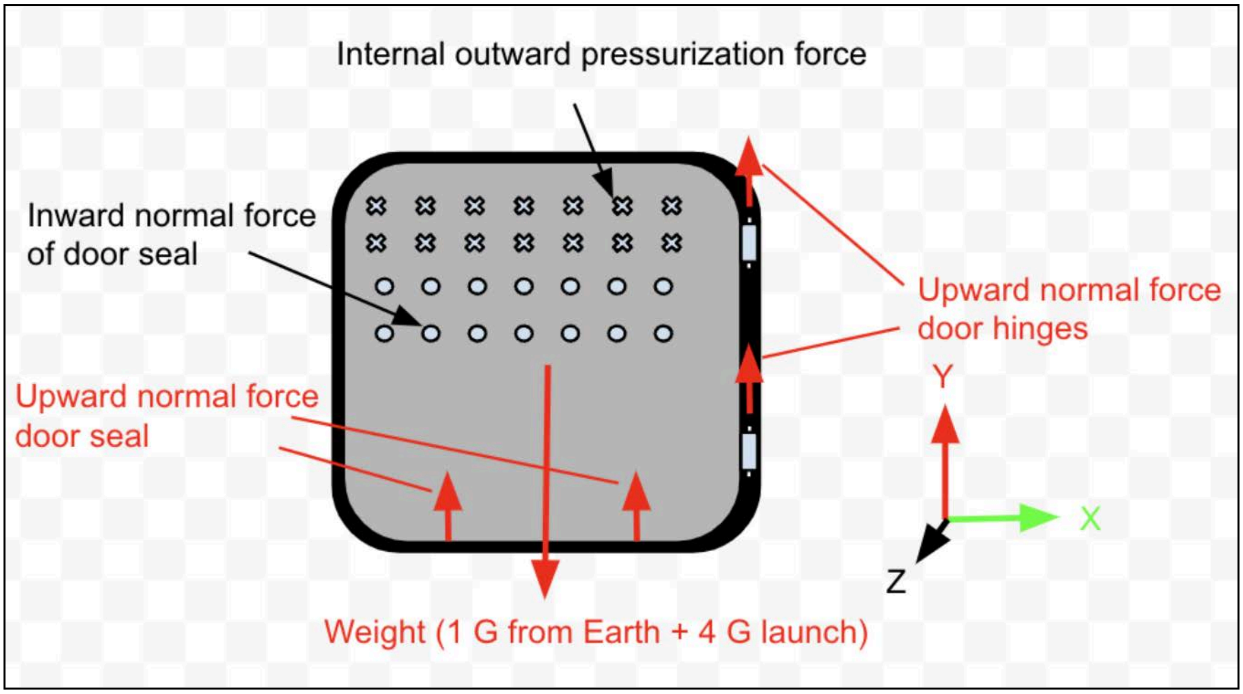

Figure 53. Free-body diagram for internal forces in hatch mechanism

12.3 Ability to Handle Dust

The physical prototype is crucial for testing the design's resistance to lunar dust exposure. The primary concern is that the linkages will be jammed by the fine particles and rendered unable to facilitate proper range of motion. The only effective method for simulating real-world complications is to analyze joint behavior under intense dust conditions. We will attempt the normal operational procedure including actuating, locking, and pressurizing with dust occupying all the moving mechanisms. Since we cannot obtain authentic lunar dust, we will use a similar combination of fine particles to create a jamming scenario so that we can address potential risk factors.

12.4 Thermal Expansion

Our system needs to maintain operability through the lunar temperature range of -250°C to 130°C. We anticipate thermal expansion of the alloys in our linkages and rotational lock, so we need to confirm that these conditions will not compromise the integrity of the mechanism. This means maintaining a full range of motion and motor linkage function. We plan to use FEA to evaluate the system behavior at these extreme temperatures so that we create the right tolerances in our joints.

12.5 Seal Design

Manufacturing an effective seal design is critical to the success of the mission and preventing catastrophic consequences. Our goal is a leakage rate of 10^{-2} lbm/day of leakage at >14.7 PSI. The benchmark for leak testing for the command modules of the Apollo mission was < 4.8 lbm/day of leakage during on the ground testing. For comparison, the requirement for the Orion program was 0.33 lbm per day for the entire vessel, largely dependent on the construction techniques such as welding, riveting, and sealing tolerances [31]. Our target is more ambitious than this one, however it is attainable with the application of the right technology. Since we are only testing this value for the lander hatch, ours is significantly lower.

We require two seals for our hatch so that in the event of a breach in the perimeter, a second layer will prevent loss of oxygen. Initially we wanted to use a silicone seal since it is lightweight, can withstand extreme heat, and is unlikely to deform under pressurization. This material is commonly used in airlocks and doors for docking modules, however it is less suitable for a lunar landing application. Our research indicates that Silicone will turn brittle at the lower threshold of lunar temperatures (-200 °C) and also that it will degrade with UV exposure. Instead, C or E seals made from stainless steel coated with silver compresses with a door seal to protect the hatch perimeter.

For a second layer, a PTFE-coated fiberglass is effective for shielding from dust on the outer layer. This class of materials is known for temperature and abrasion resistance, and since it has a nonstick surface dust will not be a concern. An inner layer incorporating a labyrinth seal or knife edge seal will enable us to hit our ambitious locking goals.

13. Discussion

As it stands, the team is satisfied with the progress that was made this semester. However, the time frame we were required to operate within severely accelerated the typical timeline for a problem of this magnitude. As a result, there are several areas that could have been approached differently or need further work in order to reach the most optimal solution to the problem.

13.1 Problem Definition

The problem statement given to the team by the sponsor was very open ended. Many areas were explored and researched by the team to properly scope and define the problem, but some aspects were certainly missed.

Firstly, the ergonomic aspect of the problem statement did not receive much attention. With more research, it may have been possible to identify ideal hand and arm positioning for an astronaut standing up to determine the placement of the handle. The effect of lower gravity also may have an impact on being able to open the hatch. Since we only have experience with opening things in Earth's gravity, it was difficult to understand the effect of reaction forces associated with moving heavy objects, such as the hatch. With more time to research and collect data with different prototypes, the team could have made several different types of opening mechanisms and collected data on which were preferred by astronauts, and if any features were necessary to prevent the astronauts from moving while opening the hatch.

Another area the team could have benefited from researching more is general design of components used in space. During the design stage, the team did keep in mind the requirements for designing against the harsh conditions associated with space, but doing more research on existing designs and mechanisms would have proved very useful, especially when specifying tolerances and designing moving or rotating parts, like the hinges or rotational mechanism.

Finally, it would have been very helpful to the team if we could have received more information on the design and specifications of Blue Origin's MK2 lander. The team did the best we could operating without an NDA agreement by using concept images and getting some details from our sponsor, but if an NDA were possible it would have greatly enhanced our understanding of the space the hatch design will be operating in and how it will fit into the full assembly of the lander.

13.2 Design and Design Process Critique

13.2.1 CAD

Our CAD model of our lunar lander door mechanism has been a large component of our design project. This task involved the team to focus on the subsystems separately. When piecing the subsystems together we faced some problems with the locking mechanism and hinge as well as the rotational mechanism. Although most of the door mechanisms fit well together we had some issues fully implementing the locking mechanism to the hatch frame. As such our locking mechanism is not completely functional. Lastly, our rotational mechanism had some issues with its linkage system not clamping properly. This required some linkage synthesis and iteration to ensure no interference with the door hatch and frame.

Although we were successful in fixing the hinge design and rotational mechanism to some extent, we were not successful in fixing the interface between the rotational mechanism and gear transmission with crank handle. In retrospect, this interface could have been achievable with more time and communication between members when creating subsystems as we had limited time and communication due to busy individual team member schedules.

Overall, the team focused too specifically on designing and optimizing some systems within the proposed solution. Some of our requirements are simply features on the hatch that we did not have time to implement or think about where they would go. Perhaps an better approach would have been to produce a higher fidelity CAD model that contained all the features to meet the team's requirements, and then work on developing and optimizing the functionality of the subsystems

13.2.1 Build Design

We were fortunate enough to leak test our build design before the design expo. However, the data collected from the build design testing gave us inconclusive results which leads us to the critique. Our testing involved sealing a volume off with tape where the vacuum could function next to the seal pressed between the plates that represented the door hatch and the lunar lander frame. This sealing did not seem to be consistent in performance over our testing. We placed and removed it several times in hopes to increase the model fidelity. To some extent this worked but we could still detect leakage through variable opening throughout the sealing tape and plate interfaces.

In addition, we had some issues with our actual seal used in between plates during leak testing. The 3D printed silicone seals were not available to print in curved geometries only in a linear path. This introduced issues when placing it around the seal groove that was waterjetted in the hatch plate. We believe this also contributed to the low fidelity of our build design leak test that we performed.

Finally, one of the more insidious defects of our tests was the actual vacuum pump. Under ideal conditions a vacuum pump should read about 1 atmospheric pressure differential between a closed off space and the environment. However, we were only able to achieve about 0.87 atm pressure differential when fully blocking the vacuum pump tube.

Looking back on our mistakes, we could have improved the fidelity of our model by purchasing a dedicated vacuum pump as well as accurate pressure sensors from our budget. Next, we could have also created a different section of our hatch to better align with our manufacturing constraints from the 3D printed silicone with a more linear seal groove. Lastly, the issues of the sealing tape could be fixed by using a dedicated vacuum chamber or a different build design that fully encapsulates a volume to better represent our final design.

13.3 Risks

Some challenges we encountered in our design process was the scale of our door. This brought about some multiple challenges in itself. We could not validate a 1-1 model of our final design through this limitation. This is apparent in our build design for our leak test as we were could only do a 2-1 model of a corner of the hatch with the materials we had on hand. The leak test along with other considerations for dust and temperature could be detrimental if not tested for correctly. As such there is risk to the end-user that we couldn't get a 1-1 model validation test. However, we attempted to minimize these adverse effects through engineering analyses and general considerations. Some of these considerations include: pressure forces acting the door when designing our rotational mechanism; crank handle input and output torques to the rotational mechanism for easy operation and access; hatch covers to mitigate dust effects on our moving mechanisms.

14. Reflection

After the conclusion of our project we have revisited the design context under which our project has fallen under. This is a direct reflection of our design context section from earlier in our design report which corresponds to our initial thoughts on the matter.

14.1 Environmental Context

14.1.1 Public Health, Safety and Welfare

Throughout the semester we have been considering the safety of all those who will be directly impacted by our design which in general will be the astronauts that will use our design on the Artemis V mission. However, we continue to believe that public health and welfare are not an immediate cause for consideration as our project is targeted to niche users and the context around the use of it, is limited to the objective use of our door mechanism during missions.

14.1.2 Global Context

Furthermore, we had not considered how our design may be a benefit to global markets through cooperation between countries but they could benefit in designing standard methods of door mechanisms in lunar exploration. This could include using our design as a basis of designing lunar lander door mechanisms.

14.1.3 Social Impact

Our outlook on the social impact of our design continues to be the same. Assuming Blue Origin continues with the manufacturing of our design we continue to expect that this could create new manufacturing methods as well as inspiring people to become aerospace professionals as well as expanding spacecraft capabilities.

14.1.4 Economic Impact

However, we no longer believe that the manufacturing of a single door for one mission will lead to new employment opportunities. But this door design could add to the expenditure given the critical components required to specially design for this critical application such as the hinges and rotational mechanism.

14.1.5 Societal Impact Tools
Some tools we used to identify the impacts and global context were stakeholder maps. One was used to identify and describe the stakeholders. The other stakeholder maps were used to determine the relative interest and power held by these stakeholders. These stakeholder maps were not modified from our initial considerations.

14.2 Team Dynamics
We had a variety of backgrounds on our team. Some of the team was better working with the hands-off part of our project. Such activities included research or computer modelling. On the other hand we had some who preferred more hands-on work such as our validation testing or concept sketching.

Our sponsor's expertise and direct knowledge on the Artemis V project complimented our research phase immensely. After the initial design report we had many questions clarified. Some stylistic differences we encountered included the design being open-ended. This brought about some problems as we found it difficult to decide what to spend most of our time on but reconsideration of our requirements helped us narrow down our validation and verification tests.

14.3 Inclusion and Equity
The power dynamics that exist between our team and the sponsor remain the same as our background has not changed. Moreover, our perspective on the project definitely changed as we researched more on our own. Although we didn't have direct contact with our end user, we took into consideration user centric design that NASA standards provided which may have some effect on how we designed compared to what the end user might want or need.

Our approach to ensuring that diverse viewpoints from stakeholders and team members were incorporated into our project work involved discussion, direct questions and advice from our professor, Miki Banu, and our project sponsor , Jillian Haas. We made certain each team member had an input by quick voting before any major decisions were made.

14.4 Ethics
One of our original dilemmas was to balance ease of manufacturing and innovation. By allowing a mix of complex subsystems and simpler subsystems we were able to have the best of both. Were our product to enter the marketplace we believe that an ethical issue could be equity in the accessibility of the manufacturing processes or materials given that not all countries have access to the same technology that NASA and Blue Origin have.

Our personal ethics are identical to the professional ethics upheld by the University of Michigan and we followed them very closely throughout our design process. The variation between these ethics standards and those from future employers is highly variable as some may have varying priorities.

15. Recommendations

From the experiences the team has had in thinking about and developing a solution to this problem, here are some:

- **Door size and position**: Based on our calculations, benchmarking, and analyses the hatch should be rectangular in shape (with filleted corners) and open inwards. This shape reduces stress concentrations while still giving necessary space for safe astronaut ingress and egress. Further, an inward opening door reduces the need for a complex and robust latching system, since interior pressurization assists in this process.
- **Sealing tests:** When conducting sealing tests for verification, it is best to design the test using a continuous seal, rather than trying to test only a section of the door (as we did). Only testing a section opens up the possibility for leakage through areas not relevant to the seal.
- **Designing for lunar dust tolerance:** While we did not have time to fully incorporate this into the CAD, this issue remains a high concern and should be addressed with any lunar lander. For our solution, our plan was to implement a flexible material the linkage latches could pass through, in order to keep dust out of the rotational hatch. Further, this same material should be used in the frame where the latching brackets are located, to keep dust out of these spaces as well.
- **Redundancy:** One design principle that we noticed in existing mechanisms used in space applications, and that we tried to embody in our solution, is redundancy. This requires careful planning and risk analysis, and then designing ways to embody it. While our solution currently only has a few examples of this developed, we recommend all aspects of a solution have redundant features for safety of the astronauts and reliability of the hatch.

16. Conclusions

The sponsor of this project, Blue Origin, asked our team to create a door mechanism for their crewed lunar lander, Blue Moon MK2, set to partake in NASA's Artemis V mission in 2029. The team benchmarked the Apollo program lunar modules as the only previous crewed missions to the Moon's surface, as well as other door hatches and mechanisms used for pressurized cabins. From this, the team identified the following as *potential* changes or areas of improvement for the hatch design used on the MK2: 1) latches placed on both sides of the hatch, 2) better dust mitigation strategies, 3) increased consideration for longevity, 4) increased size of the door, and 5) alternative door opening strategy.

The team generated 17 unique user requirements to guide the design of our hatch, which were derived from conversations with our sponsor and background research. From these user requirements, quantifiable specifications were formed to allow the team to verify and validate the created design at the end of the semester.

To generate concepts and ideas, the team used functional decomposition diagrams and various idea generation techniques. The concepts underwent rounds of down-selection using Pugh matrices and a final sketched concept was selected to move forward with.

With a low-fidelity concept selected, the team produced two embodiments of the solution: a CAD assembly built in Solidworks and a physical build design. The CAD assembly remains unfinished, but the key areas the team focused on developing are the hatch body and frame, the rotational latching mechanism, the hinges for the hatch and the handle to open the hatch. The build design consisted of a scaled down section of the designed hatch and frame, which was manufactured using titanium sheets and 3D printed silicone.

For the CAD model, analyses were performed to work towards verifying our design and proper functionality. The linkage latching system was iterated upon and improved several times using a SolidWorks analysis tool in order to achieve the most optimal positioning and latching system. Additionally, an FEA model was conducted to verify the structural capability of the designed hatch.

Furthermore, the build design helped the team assess the seal leak performance under a vacuum as well as its ability to withstand high temperatures. The tests were designed to emulate those shown in NASA standards. Based on our tests, we assess that it will have to undergo future changes regarding tolerance and geometry to mitigate air loss. We are satisfied with the model performance under stress cycles, and believe that our validation has confirmed that Titanium and silicone rubber are both excellent candidates for door composition. Not only does the model minimize underperformance effects due to extreme temperature changes, but also exhibits great sustainability and reliability for multiple mission cycles.

In terms of future work and recommendations, we would like to see implementation of the automatic control panel for ingress and egress as well as bidirectional manual and automatic access. This would further solidify our design’s efficacy in addressing relevant engineering goals and Artemis V mission objectives.

17. Acknowledgements

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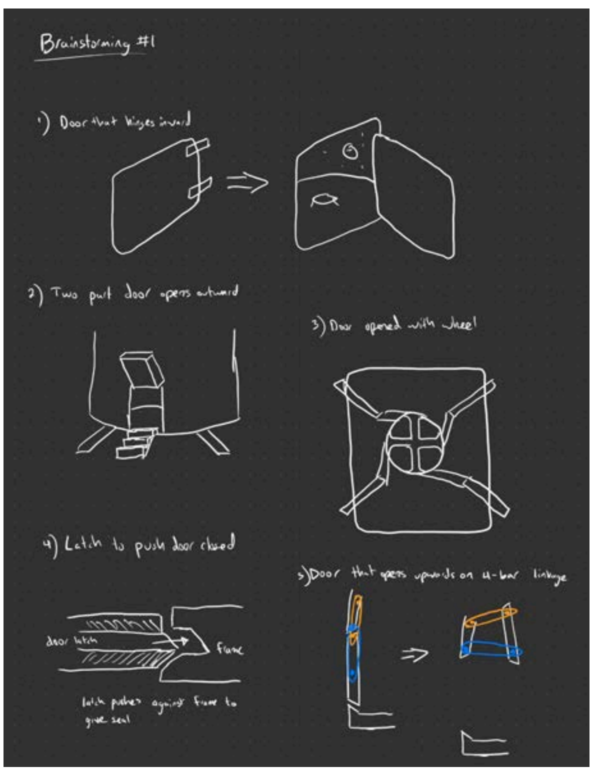
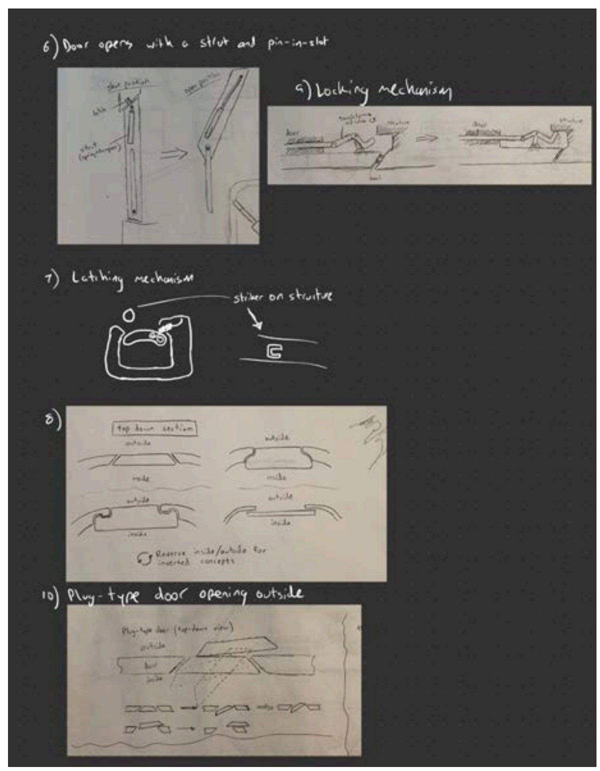
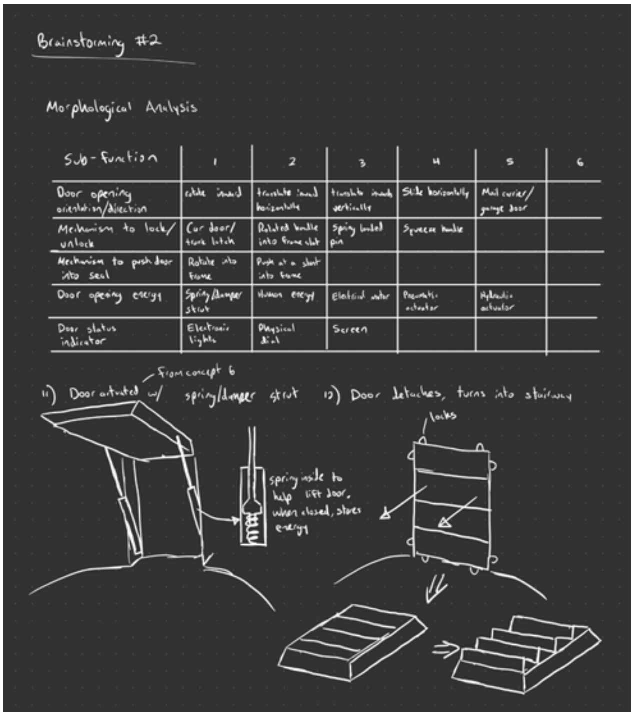
19. Appendices

19.1 Preliminary Design Concepts

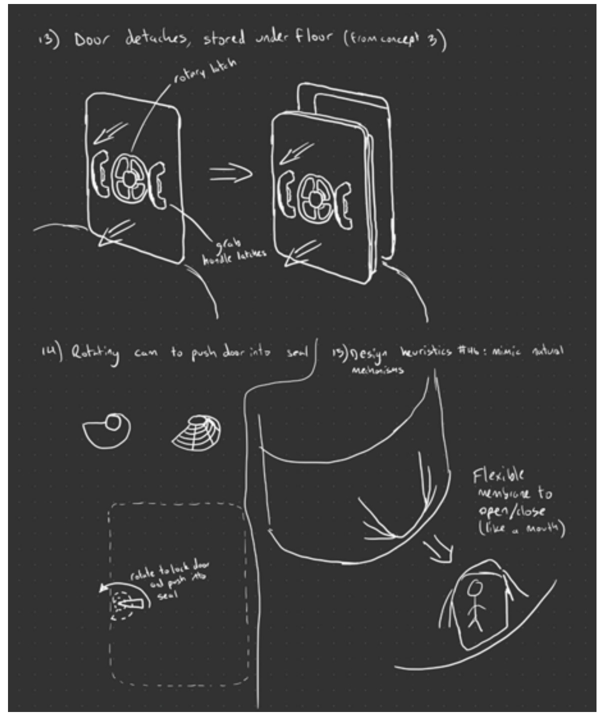
Initial brainstorming sketches and concepts are placed in this section.

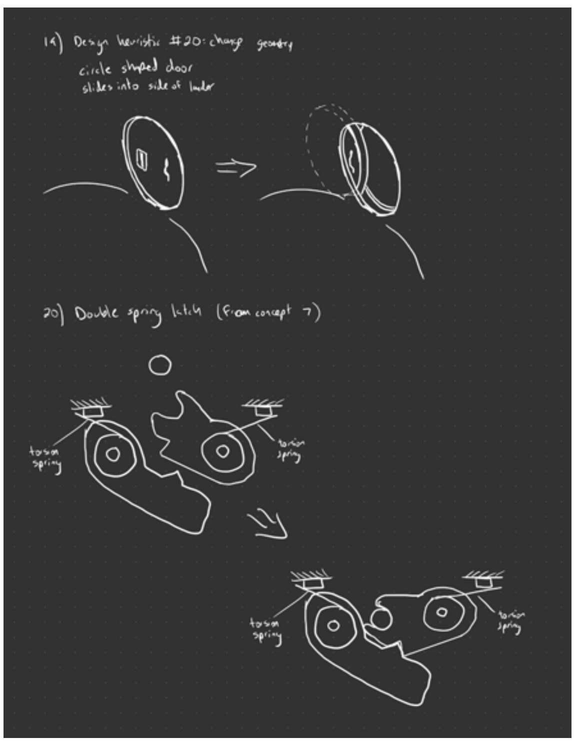


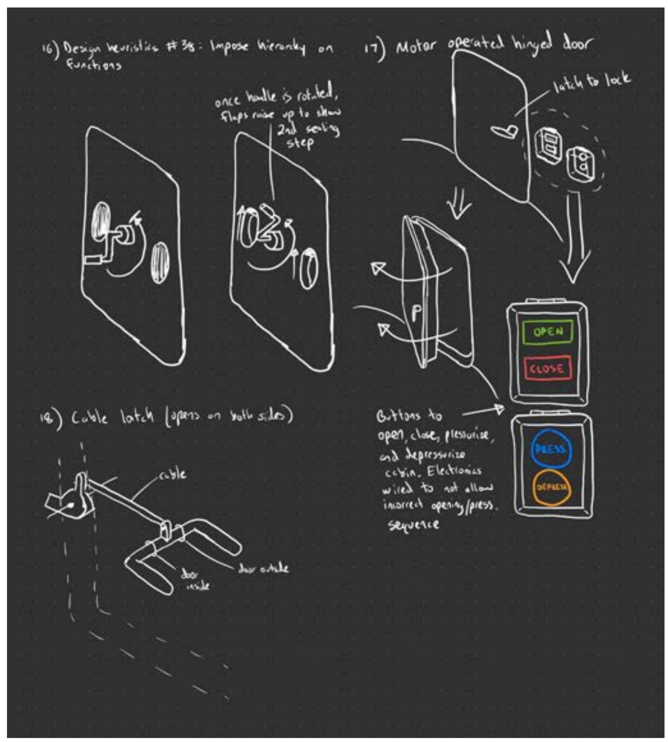


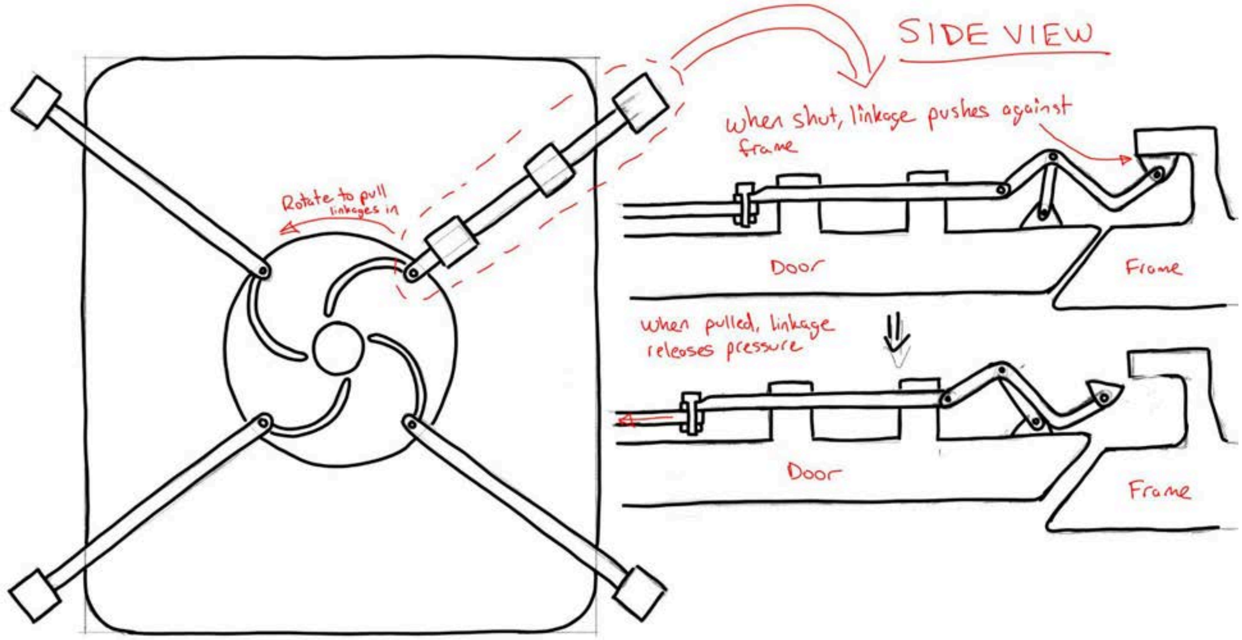


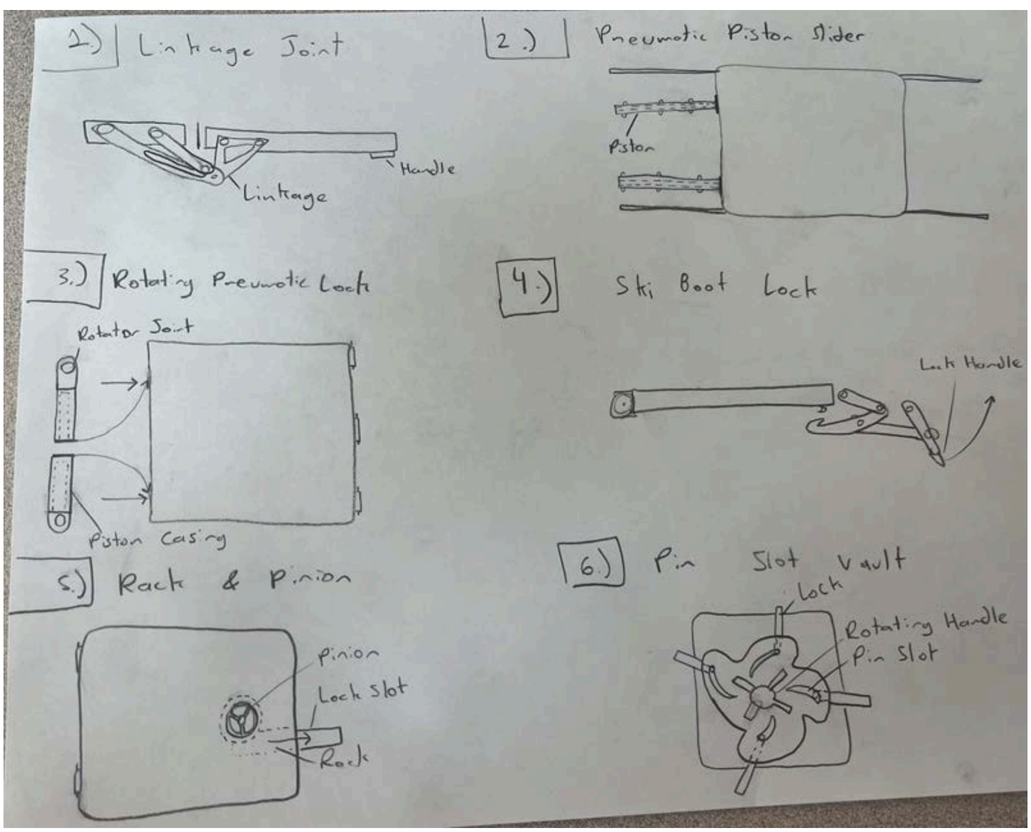
Sub-Function	1	2	3	4	5	6
Door opening orientation/direction	rotate inward	translate inward horizontally	translate inward vertically	Slide horizontally	Mail carrier/garage door	
Mechanism to lock/unlock	Car door/trunk latch	Rotated handle into frame slot	Spring loaded pin	Squeeze handle		
Mechanism to push door into seal	Rotate into frame	Push at a slant into frame				
Door opening energy	Spring/Damper strut	Human energy	Electrical motor	Pneumatic actuator	Hydraulic actuator	
Door status indicator	Electronic lights	Physical dial	Screen			








SIDE VIEW
when shut, linkage pushes against frame
Rotate to pull linkages in
Door
Frame
when pulled, linkage releases pressure
Door
Frame


1.) Linkage Joint
Linkage
Handle
2.) Pneumatic Piston Slider
Piston
3.) Rotating Pneumatic Lock
Rotator Joint
Piston Casing
4.) Ski Boot Lock
Lock Handle
5.) Rack & Pinion
Pinion
Lock Slot
Rack
6.) Pin Slot Vault
Lock
Rotating Handle
Pin Slot

7.) Piston Driven Door Lock:

When the lander is in the air, the volume behind the piston is pressurized, driving the door shut. On exit, a button is pressed releasing air into space vacuum, and upon reentry door seal is pressurized once more to lock.

8.) Switch Lock

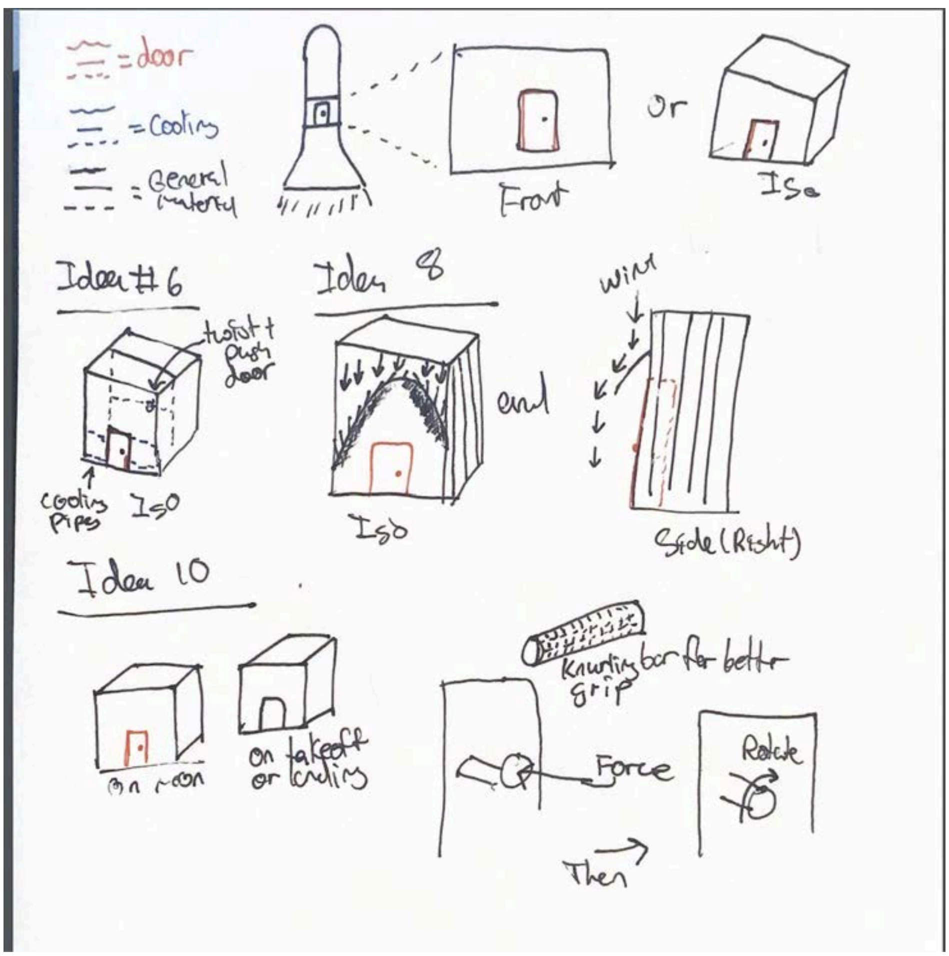
A spring driven locking cylinder/slide. Lock is activated via button push. The lock is reset via a slider.

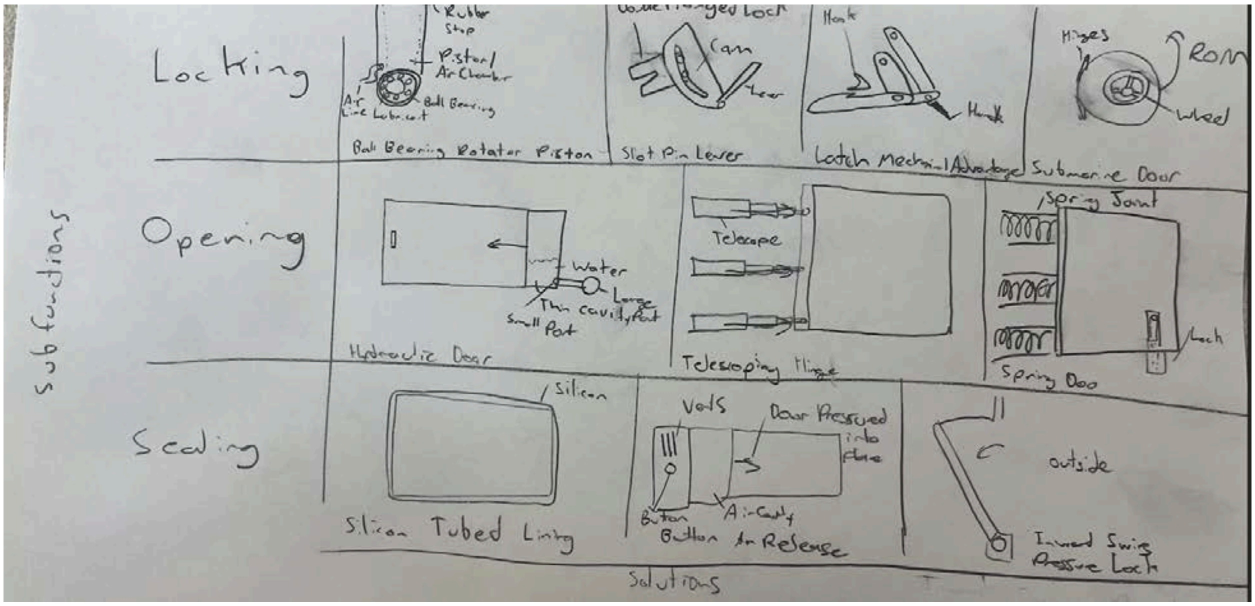
9.) Screw Door

Circular Door is mounted in threaded corridor. Rotational motion creates seal.

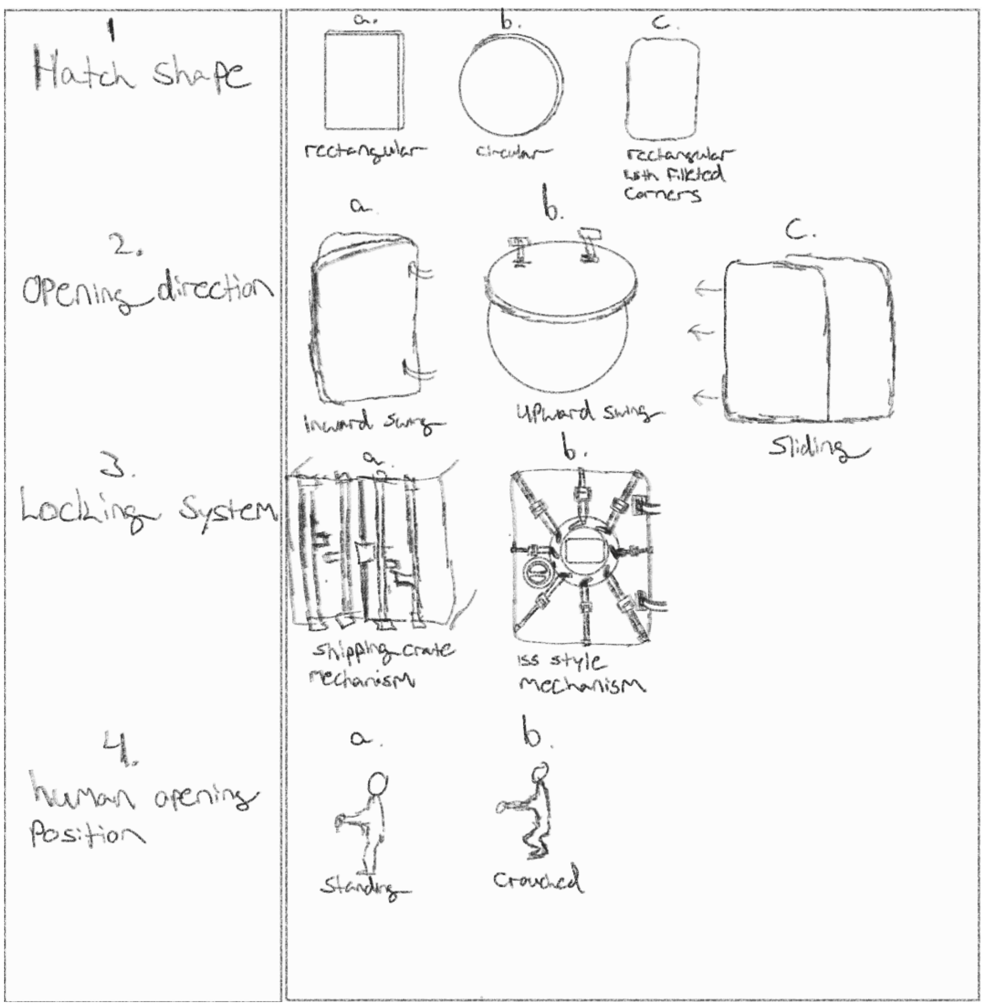
10.) Simple Door

Basic hinge design uses sliding bolt lock.





Locking
Opening
Sealing
Sub functions
Solutions
Ball Bearing Rotator Piston
Slot Pin Lever
Latch Mechanical Advantage
Submarine Door
Hydraulic Door
Telescoping Hinge
Spring Door
Silicon Tubed Lining
Button Air Release
Inward Swing Pressure Lock



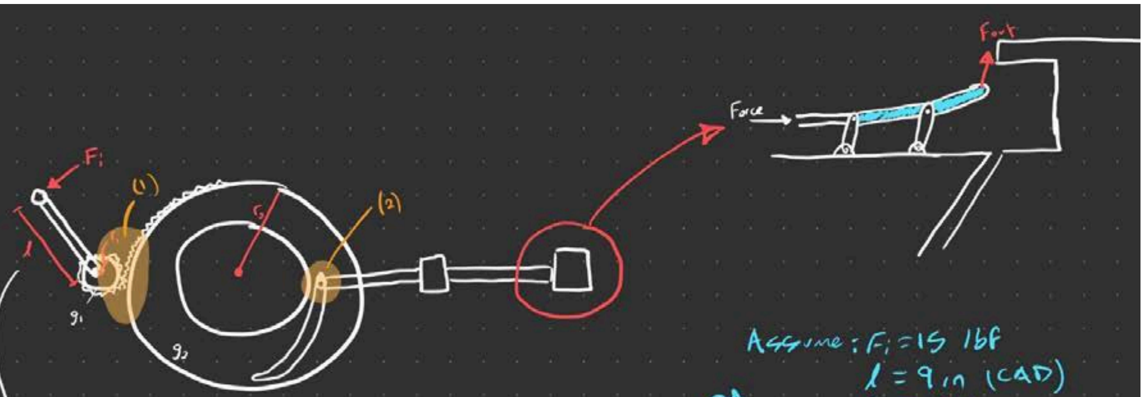
1 Hatch shape
a. rectangular
b. circular
c. rectangular with filleted corners
2. Opening direction
a. inward swing
b. upward swing
c. sliding
3. Locking system
a. shipping crate mechanism
b. iss style mechanism
4. human opening position
a. standing
b. crouched

Example of a subsystem morphological matrix used to ideate and brainstorm new concepts and combinations of subsystems.

Subsystem	1	2	3	4
Withstand High Temperatures	Use temperature withstanding materials	Use a simple layer of temp withstanding material on the exposed area	Have a cooling system	Don't expose it to high temperatures
Easy Operation	Wireless actuated	Simple door handle	Push and rotate	Operable with hands or feet
Safe	Smooth edges	Status indicator	Fail safes	
Ergonomic	Knurling	Designed with finger grooves		

19.2 Rotational Mechanism Mechanical Advantage Calculations

The following figure shows how we analysed the mechanical advantage for our rotational mechanism design.



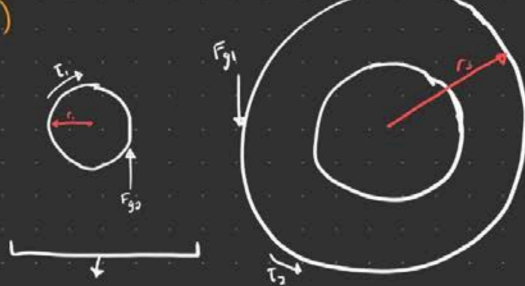
Assume: $F_i = 15\ \text{lbf}$
$l = 9\ \text{in}$ (CAD)
$r_2 = 10\ \text{in}$
$r_1 = 1\ \text{in}$

$$\tau_2 = \frac{F_i l r_2}{r_1} = \frac{15\,\text{lbf}(9\,\text{in})(10\,\text{in})}{1\,\text{in}}$$

$$\tau_2 = 1350\ \text{lbf-in}$$

$$\tau_1 = F_i l$$

(1)



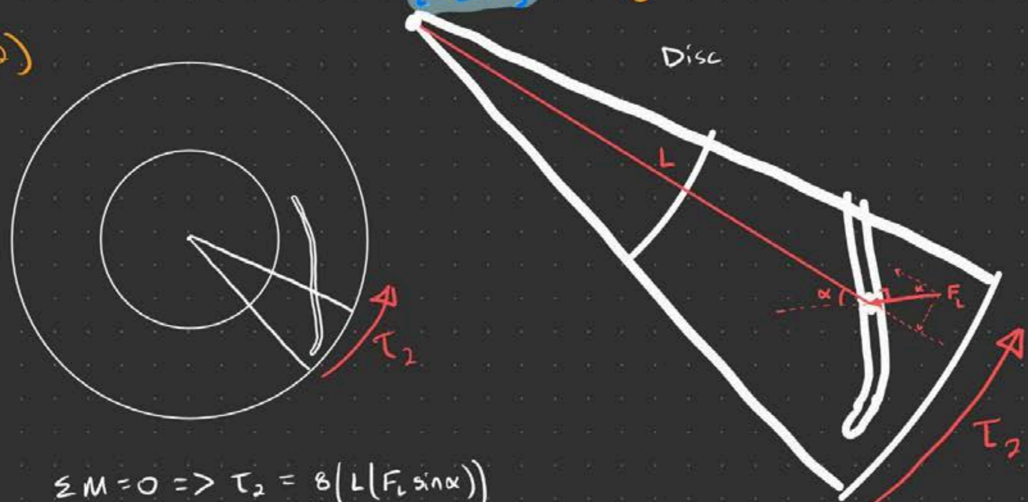
$$F_{g2} r_1 = \tau_1$$

$$F_{g2} = \frac{\tau_1}{r_1}$$

$$F_{g2} = F_{g1}$$

$$\tau_2 = F_{g1} r_2 = \frac{\tau_1}{r_1} r_2 = \frac{F_i l r_2}{r_1}$$ [Eqn 1]

(2)



$$\Sigma M = 0 \Rightarrow \tau_2 = 8\left(L\left(F_L \sin\alpha\right)\right)$$

$$\Downarrow$$

$$F_L = \frac{\tau_2}{8L\sin\alpha}$$ [Eqn. 2]

To ensure we have all materials and parts necessary for our build design, we have created a bill of materials shown in Table A1. This bill of materials is comprehensive as we do not require anything else to ensure that the validation tests are performed. Another important note is that all the costs will be covered by the Additive Manufacturing Lab at UofM so our budget for this is not a problem. These costs come from several internet sources that sell the given materials[32][33][34].

Table A1. Bill of materials for build design.

Subsystem	**Material**	**Part**	**Quantity**	**Dimension (mm)**	**Manufacturer**	**Cost**
Hatch	Titanium Sheet (Ti6Al4V)	Front Panel	1	254x254x3	Laser cut by Team	$115(sqft)
Hatch	Silicone Ring (Silicone 40A)	Seal	2	25x25x800	Additive Manufacturing Lab at UofM	$349(1L)
					Total	TBD

Also, we have included a manufacturing plan for our build design in Tables A2.

Table A2. Seal mock-up manufacturing plan

Step	Process	Details
1	Edge cut	Waterjet cut the perimeter of the hatch along with the surrounding frame out of 2mm thick Titanium sheets. Should have 5x pieces for each trace.
2	Cut Seal Path	Take the top sheet of the door and use a waterjet to cut the pathways of the inner and outer seal into the metal.
3	Assemble Bodies	Line up the 5 sections for each respective piece so that the perimeters are flush. Melt scrap titanium and use it to weld the edges together sufficiently, with at least 6 points of contacts.
4	Print Seal	Use a 3D printer to create 6 subsections that constitute the inner and outer seal. Allow 1 hour for printing and cooling of rubber.
5	Attach Seal	Press the silicone seal into the designated slot and apply pressure to set in place.

To create this build design we used a waterjet to cut down a titanium piece with the following dimensions in Figure A1. Manufacturing plans for the validation testing hatch corner are seen in Figures A2 and A3 where we waterjetted five of each piece.

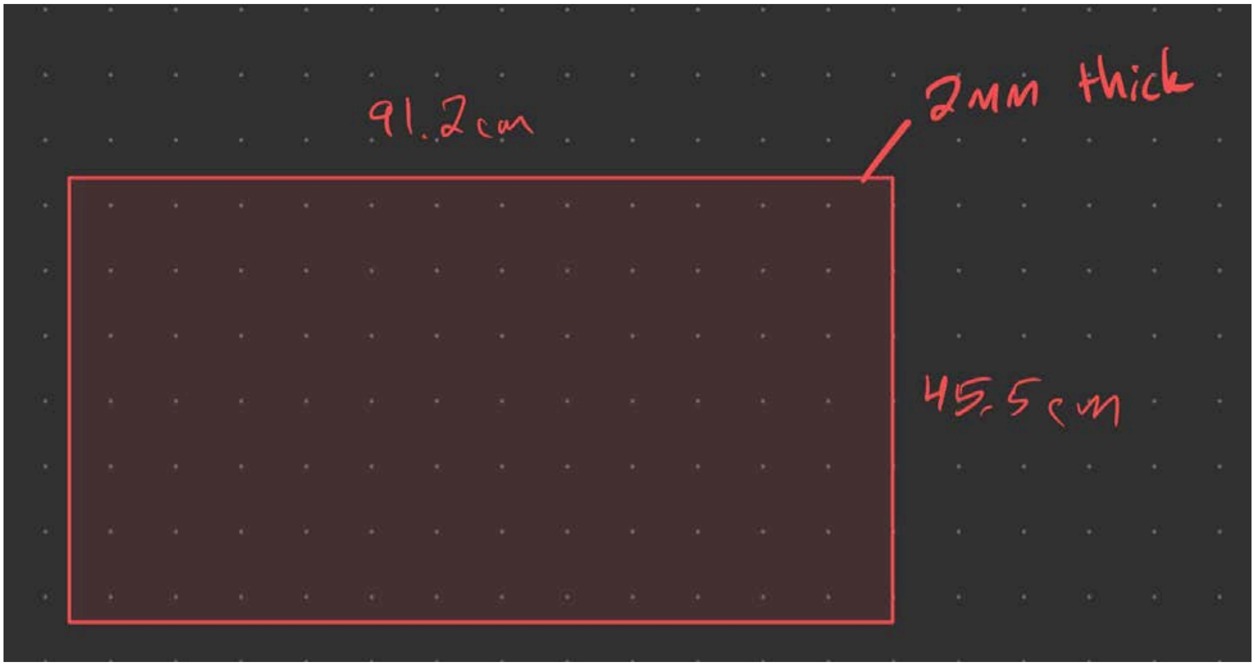


Figure A1. Representative titanium plate, and dimensions, that was provided by Professor Miki Banu.

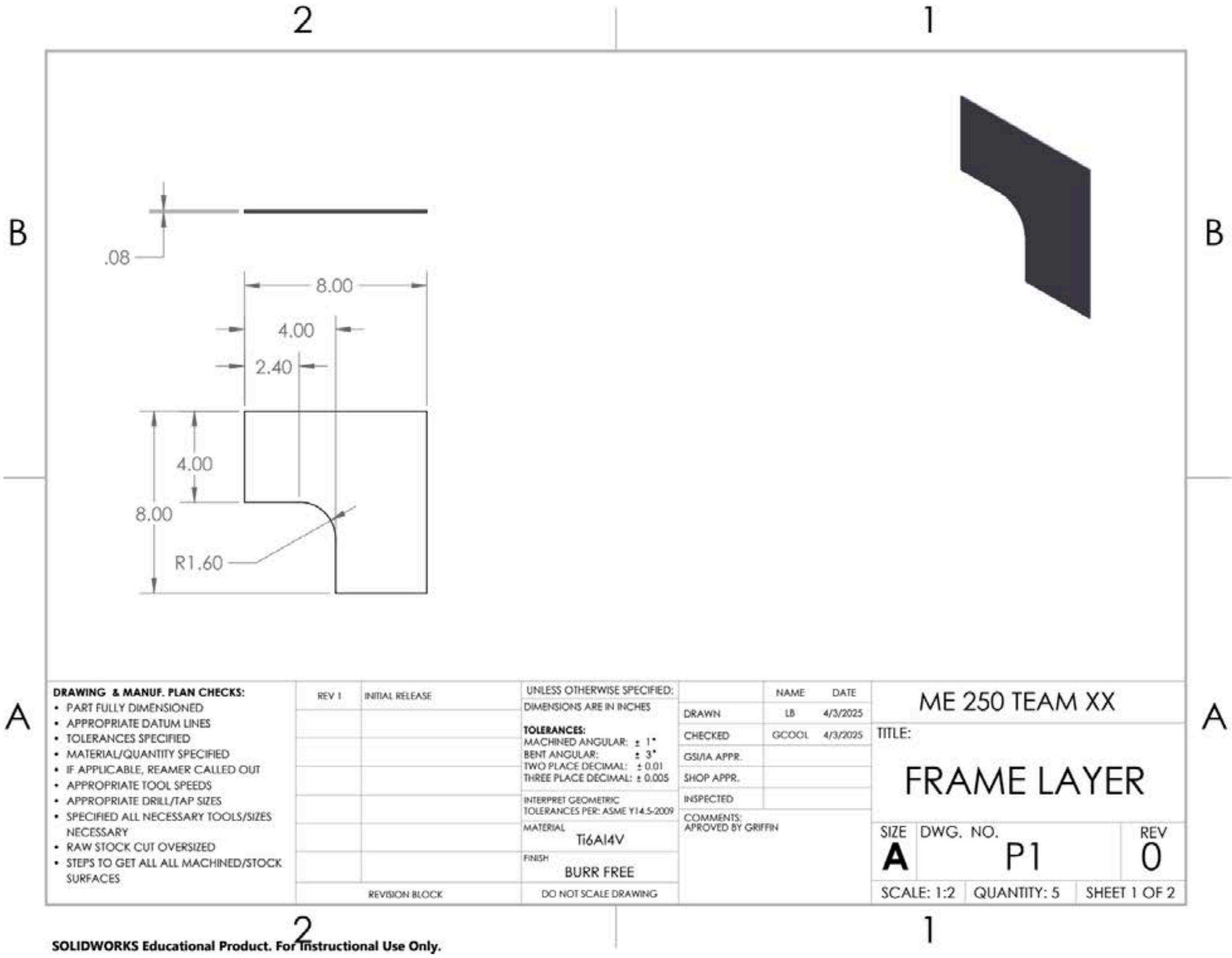


Figure A2. Manufacturing plan for the hatch frame corner.

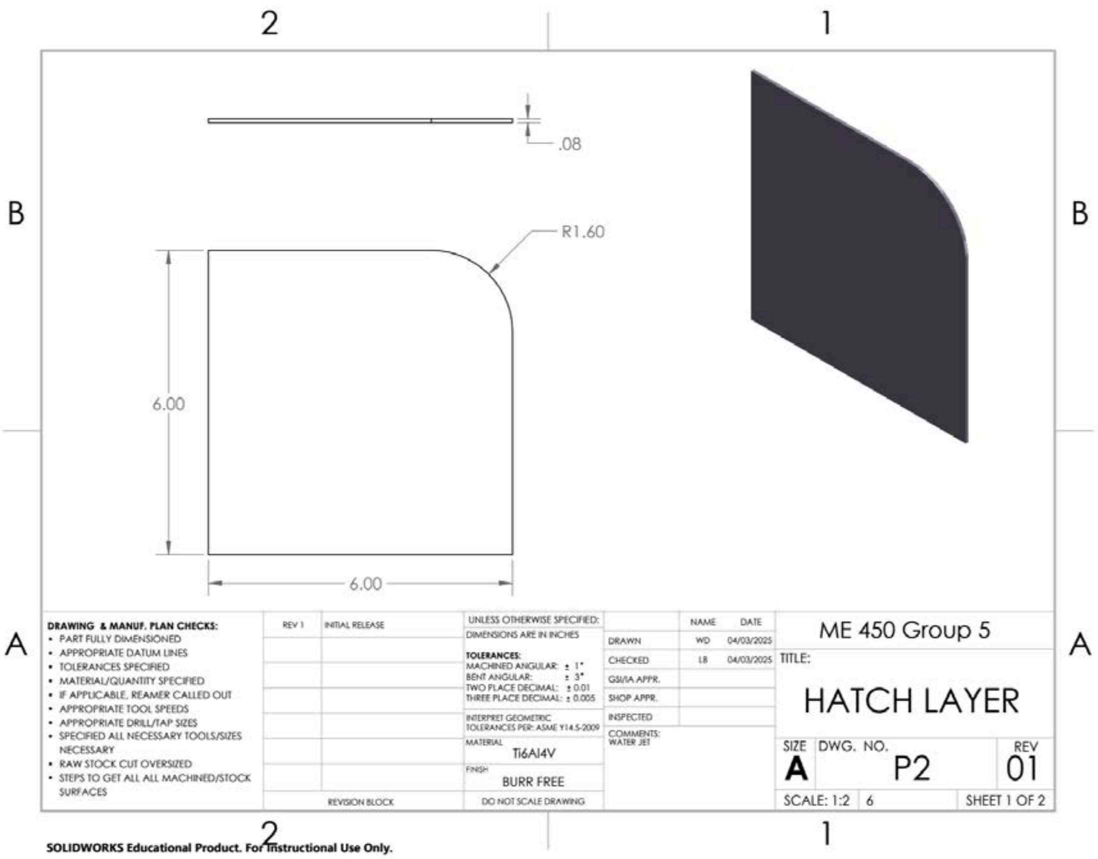


Figure A3. Manufacturing plan for the hatch corner.

To complete our build design we required our seals which were 3D printed in the exact shape of a groove as in Figure A4. This groove was created by water jetting 1 plate of the hatch layer with the dimensions also in Figure A4.

Our build design was assembled following the steps shown in Table A2 and illustrated in Figure A5 and A6.

Table A2. Leak test validation plan.

Step #	Description
1	Weld similar layers together resulting in two similar thickness plates. Place seal into groove of the hatch plate.
2	Place tape around the vacuum tube and inside the corner of build design ensuring proper sealing around test volume.
3	Attach clamps around the build design to simulate pressure and locking forces.
4	Turn on vacuum pump and record pressure differential between atmosphere and inside test volume of build design.
5	Disassemble testing tape and seal, then place into oven to 150°C. Afterwards

	repeat step 4 and compare pressure results.

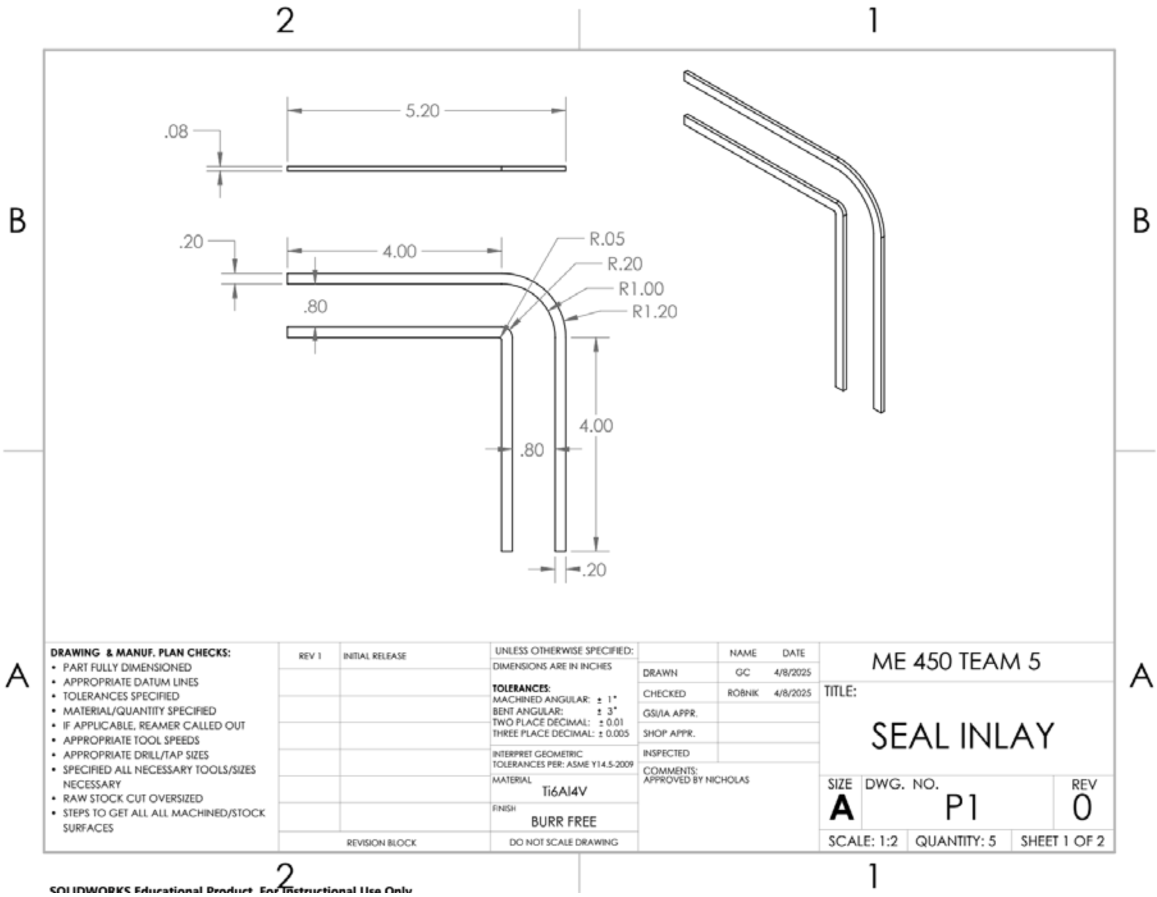


Figure A4. Manufacturing plan for the hatch frame groove and seal inlay.

Figure A5. Leak test validation setup. Figure shows vacuum tube clamps and sealing tape.

Figure A6. Seal inlay in hatch groove.

20. Bio

Griffin Coolidge
I am from Fanwood, New Jersey and I have been interested in engineering my entire life. Growing up I was always interested in how electronics and gearboxes fit together, and Mech E was a clear cut path for me coming into college. I would like to work in the automotive or aerospace industry in the future and specialize in design manufacturing. I have a pet Labradoodle named Tucker that is 8 years old, and in my free time I enjoy golfing, playing instruments, and watching movies.

Luis Barcenas
I'm from Southwest Michigan in a small town called Hartford. My interest in mechanical engineering comes from wanting to understand how vehicles, buildings etc. work and are built. Outside of school I watch comedy bits or Sopranos, run in good weather and discover new music artists with over 2000 liked songs on Spotify since 2014. In the future I would like to work in the aerospace or residential/industrial controls, and although I've been in the Midwest most of my life, I would like to move somewhere with better weather.

Weston Dietsch
Growing up in Omaha, Nebraska, I knew I had an interest in mechanical engineering from a young age. As a chronic fiddler I have always enjoyed learning about and developing mechanical systems as well as diagnosing and solving problems. After graduation I intend to work in manufacturing and process development. When I am not working or studying I enjoy getting outdoors as much as possible. I love hiking, camping, backpacking, and skiing. I have also recently been refining my sourdough bread recipe.

Brendan Hessling

I am from Livonia, Michigan, and I have always had an interest in how things work. This led to me taking things apart to do simple repairs, or just to see what was happening on the inside. Eventually, I gained more knowledge and experience from college and work which allowed me to start working on engineering projects at home. After graduating, I plan to work in either manufacturing or controls depending on what jobs are available. I spend most of my free time working out or running. I started with a marathon, then progressed into ultramarathons leading me to a 100-mile trail ultra. Also, I like to work on different projects at home that include robotics, 3D printing, programming, etc.

Nick Robinson

I grew up in Dewitt, MI, a suburban community just north of Lansing. As a kid, I was always interested in creating something, whether it be building Lego sets, drawing, making card towers, or even cooking as I got older. Coming to University of Michigan was a no-brainer, and after a brief stint pursuing a career in soccer, I started becoming more and more interested in my engineering studies. I've paired my major with a minor in Art and Design, as I'm very interested in product design and understanding the subjectivity behind what makes a design beautiful. After graduating, I'd like to pursue a career that can allow me to continue to meld art with engineering. In my free time, I enjoy working out, reading a good book, playing guitar, and getting outside as much as possible.