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Team 519: Retain Water Ice in Regolith at Vacuum

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# Abstract

NASA’s Marshall Space Flight Center is sponsoring Team 519 to design a process and a test fixture to cool a bed of dirt from the moon’s surface, called regolith. This test fixture should be able to work in spacelike conditions including extreme pressures and cold temperatures. NASA wants the test fixture to run drilling, excavation, and land rover experiments on the regolith. These experiments are important for space exploration because hydrogen and oxygen can be extracted from the water in the regolith. These elements can be used to make fuel for spacecrafts. The most important conditions to be designed around are cooling to cryogenic temperatures, compatibility with a high vacuum chamber, and maintaining a specified amount of water in the regolith.

The team has designed a test fixture that is eight inches deep and has a removeable lid for testing access. The fixture will be placed inside one of NASA’s testing chambers to mimic the high vacuum pressure in space. However, regolith does not transfer heat efficiently, so the process of cooling is divided into two methods. The fixture is placed inside the vacuum chamber, but the vacuum is not turned on yet. The first method of cooling is a drip system, where liquid nitrogen (LN2) drips down from a lid with holes through the regolith. As the LN2 expands to a gas, it exits the fixture at the bottom. Ideally, the nitrogen gas (GN2) spreads evenly through the regolith, transferring heat by physical contact. Once the desired temperature is reached, the drip lid is turned off and the vacuum chamber begins pumping down to the desired pressure. The second method of cooling is an LN2 sleeve around the inside of the test fixture. This cooling method transfers heat by conduction and stays on throughout the whole test.

# Disclaimer

Your sponsor may require a disclaimer on the report. Especially if it is a government sponsored project or confidential project. If a disclaimer is not required delete this section.

# Acknowledgement

These remarks thanks those that helped you complete your senior design project. Especially those who have sponsored the project, provided mentorship advice, and materials. 4

* Paragraph 1 thank sponsor!
* Paragraph 2 thank advisors.
* Paragraph 3 thank those that provided you materials and resources.
* Paragraph 4 thank anyone else who helped you.

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# Notation

|  |  |
| --- | --- |
| A17 | Steering Column Angle |
| A27 | Pan Angle |
| A40 | Back Angle |
| A42 | Hip Angle |
| AAA | American Automobile Association |
| AARP | American Association of Retired Persons |
| AHP | Accelerator Heel Point |
| ANOVA | Analysis of Variance |
| AOTA | American Occupational Therapy Association |
| ASA | American Society on Aging |
| BA | Back Angle |
| BOF | Ball of Foot |
| BOFRP | Ball of Foot Reference Point |
| CAD | Computer Aided Design |
| CDC | Centers for Disease Control and Prevention |
| CU-ICAR | Clemson University - International Center for Automotive Research |
| DDI | Driver Death per Involvement Ratio |
| DIT | Driver Involvement per Vehicle Mile Traveled |
| Difference | Difference between the calculated and measured BOFRP to H-point |
| DRR | Death Rate Ratio |
| DRS | Driving Rehabilitation Specialist |
| EMM | Estimated Marginal Means |
| FARS | Fatality Analysis Reporting System |
| FMVSS | Federal Motor Vehicle Safety Standard |
| GES | General Estimates System |
| GHS | Greenville Health System |
| H13 | Steering Wheel Thigh Clearance |
| H17 | Wheel Center to Heel Pont |
| H30 | H-point to accelerator heel point |
| HPD | H-point Design Tool |
| HPM | H-point Machine |
| HPM-II | H-point Machine II |
| HT | H-point Travel |
| HX | H-point to Accelerator Heel Point |
| HZ | H-point to Accelerator Heel Point |
| IIHS | Insurance Institute for Highway Safety |
| L6 | BFRP to Steering Wheel Center |

# Chapter One: EML 4551C

## Project Scope

* + 1. **Project Description**

The objective of this project is to develop a solution to maintain water ice in lunar regolith simulant while reaching high vacuum pressure. The design or process should integrate into the National Aeronautics and Space Administration’s (NASA) Planetary, Lunar, and Asteroid Natural Environments Testbed (PLANET) chamber, for continued use on further experiments.

* + 1. **Key Goals**

The primary goal of this project is to adequately cool a regolith simulant bed before and during high vacuum (10^-7 torr) pump down. The regolith needs to be cooled from a high enough temperature before pumping down so that water is not condensed out of the air. The generated solution must be compatible with NASA’s PLANET chamber dimensions and plumbing/wiring configurations. Other key goals include: the regolith simulant bed operates in cryogenic temperatures, all materials used are vacuum compatible, and the bed is open for testing while inside the NASA PLANET chamber.

* + 1. **Markets**

This design’s primary market is NASA, who is acting as the project sponsor. Secondary markets include private aerospace companies developing extraction and excavation technologies. Possible companies include SpaceX, Boeing, or Blue Origin. High vacuum is typically only used for space applications, so the markets for this project are limited.

* + 1. **Assumptions**

There are multiple assumptions made for this project. The first assumption includes that the following materials will be supplied by our sponsor to the team for final testing at the NASA-MSFC facility: liquid nitrogen (LN2), regolith simulant, and a vacuum chamber. Consequently, the pipes, pumps, and instrumentation are the responsibility of the sponsor. The assumption is the LN2, vacuum, and regolith will operate under a known range of conditions and no extreme conditions will be experienced (i.e. no pressures beyond a high vacuum, no cryogenic temperatures beyond that of liquid nitrogen). The main fluid to be used for this project is deionized water. Another assumption is the users of the final design will have the instructions to regularly check and maintain the product.

* + 1. **Stakeholders**

This project will have multiple stakeholders over the course of the project. These

sponsors include NASA Marshall Space Flight Center (NASA – MSFC), the National High Magnetic Field Laboratory (MagLab), and Dr. Shayne McConomy. NASA – MSFC is the principal stakeholder as the sponsor of the project and final approver of the design. Other potential stakeholders include companies in the space industry including but not limited to: SpaceX, Lockheed Martin, and Blue Origin. These companies have business units that are pursuing aerospace research and exploration and act as potential influential stakeholders.

## Customer Needs

* + 1. **Investigation of Needs**

NASA has collaborated with the FAMU-FSU College of Engineering to generate a device and procedure to retain water ice in regolith at vacuum. NASA provided contacts with our team mentor Annette Gray, Material Test Engineer at Marshall Space Flight Center, along with our sponsor Marvin Barnes, Branch Chief at Marshall Flight Center.

On September 19th and October 5th of 2023, the team conducted interviews with Annette Gray, Marvin Barnes, Erin Hayward, Patrick Lynn, Jason Vaughn, and Todd Schneider through a Microsoft Teams meeting. The team prepared a list of questions for the mentors to answer and converse on. Their responses were recorded and put into the table below (Table 1).

The responses to these questions gave the team more insight on the problem and which characteristics to direct our efforts toward. From the responses to the given questions, interpreted needs were formed. The interpreted needs highlight the requirements needed to progress through the next stages of the project. The team’s questions focus on the environment in which the fixture and soil will be tested, the PLANET chamber, and the water that is within the regolith simulant. These questions were designed to further define our project, eliminate project creep, and create constraints for our design/process.

Table 1: *Questions posed to sponsor, along with the responses and interpreted needs*

| **Customer Questions** | **Customer Statements** | **Interpreted Needs** |
| --- | --- | --- |
| Is the water already frozen? | “Water does not need to be frozen before but needs to become and stay frozen.” | The water does not have to start frozen, but at least cools to and stays in a cryogenic temperature range of -70 and -100 degrees Celsius throughout the test/run. |
| Does water have a unique mineral composition? Is it tap water? | “Deionized water” | The water used has been removed of any ions (usually mineral salts). |
| Would it be like a pressurized cryogenic Dewer, like something for liquid nitrogen or liquid helium? | “The box is not a vacuum chamber, but withstands the vacuum atmosphere, pressure, and temperature.” | The PLANET chamber controls the de-pressurization. The box functions inside the PLANET chamber. |
| Is there a preferred material? | “Any materials that withstand vacuum pressures. Aluminum preferred, not stainless steel.” | The material(s) used to create the fixture withstands the high-pressure vacuum and the extreme low temperatures in the chamber. |
| Should the fixture have any other characteristics other than providing a suitable testing environment? | “The fixture fits into the PLANET chamber. The fixture opens to do testing.” | The fixture has a way to be opened so that testing can be conducted on the regolith held inside the box. |
| What are some of the testing machineries that we should design the fixture for? | “Drilling and solar ray testing” | The fixture can have the soil extracted by drilling and withstand solar ray testing. |
| What are the ranges of temperatures and pressures the design needs to operate under? | “Temperatures are at least -70°C and a pressure of 10^-7 Torr” | The design operates in temperatures of -70°C and -100°C and pressures up to high vacuum (10^-7 Torr). |
| Is our project scope constrained to creating a testing fixture, or should we also look at other ways of maintaining water at ice? | “A fixture is not required but would be helpful. It may not need a new fixture but maybe a different process of cooling and pressurizing.” | A physical, tested prototype would be ideal but designing a different process of pumping down the chamber to properly cool the regolith without evaporation is also sufficient. |
| What are the size constraints? | “It has the ability to fit within the PLANET chamber which is 2m x 3m cylinder.” | The fixture is designed to be within those dimensions. |
| What should the lifespan of the fixture be? | “It can be tested multiple times” | The fixture is capable of being tested multiple times in a high pressure and temperature environment. |
| Are there PLANET chamber constraints? | “Just the size of the bed that is placed into the chamber.” | The fixture is made to fit within the chamber. |
| We will be testing our project with liquid nitrogen, but are there other cryogenic fluids we need to consider? | “We have only used liquid nitrogen.” | The current solution uses liquid nitrogen, but liquid hydrogen can be explored. |
| Do we need to install any measurement devices in our unit? | “The design has a way to measure temperature, pressure, and amount of moisture retained” | The fixture is equipped with thermocouples for temperature, and the correct measurement devices for pressure and moisture. |
| How much water ice should be retained in the regolith? | “4-10% water” | The goal is to retain 4-10% water ice in the regolith simulant mixture, at all times but just a design process for this might be sufficient. |

**1.2.2 Explanation of Results**

From the interpretations listed in Table 1, we have determined some of the most critical needs to be accomplished for our project. It is noted that a lot of the customer needs are integrated so the discussion often involves multiple customer needs at one time. For example, a high vacuum requires both extremely low temperature and extremely low pressure; these 2 components cannot be separated.

The most critical customer need is that water ice is retained in the regolith (or simulant) throughout the process of pumping down to a high vacuum pressure of 10^-7 torr, to simulate the atmosphere surrounding the lunar surface. Ideally, 4-10% of the regolith-water mixture is water ice. The objective of this project is to maintain that 4-10% water ice in the mixture during testing. High vacuum requires extremely cold temperatures, so the regolith is cooled to a cryogenic temperature of at least -70 degrees Celsius. However, regolith has a very low thermal conductivity, so a design process is desired to cool regolith uniformly, and without the water ice sublimating at the desired pressure.

The above critical need is related to another customer need, or rather further clarification, that the water ice does not have to already be frozen before being placed into the PLANET chamber, but it needs to become frozen and stay frozen during testing inside the PLANET chamber. If the water ice is frozen before, then there is an issue of sublimation and water being condensed out of the air and thus the water ice being vaporized once it reaches a certain pressure.

A second critical customer need is that the system is compatible with NASA’s current PLANET chamber for pumping down to high vacuum pressure. This includes that the fixture fits within the dimensions of the PLANET chamber, and that all materials of the fixture are vacuum compatible (i.e. withstand high vacuum conditions). It is noted that our mentor recommended Aluminum 6061, but the project is not constrained to this material at this point.

Another customer need is that the temperature, pressure, and moisture are measured during the testing process. Most likely sensors will be implemented in/on the fixture, but ultimately just a design process or method to know what the temperature, pressure, and moisture levels are inside the device. Temperature will most likely be measured using thermocouples. Specific types of pressure sensors have not been discussed; this is just to ensure that the device is at the correct pressure for high vacuum within the PLANET chamber. Moisture sensors are to ensure that there is always 4-10% water ice within the regolith mixture, but at least just a way of knowing what that moisture content is. Specific moisture sensors have not been selected, but some suggestions were using a scale to measure mass or weight within the device and a way to measure humidity.

It is also desired that the device or process be designed with drilling and excavation in mind as experiments. NASA listed possible experiments as: placing a rover on the regolith to see how/if dust is thrown up when it moves, drilling capabilities to see how drilling into the moon’s surface differs from the earth, and similarity for excavation.

## Functional Decomposition

* + 1. **Introduction**

Functional decomposition is a practical problem-solving technique used to break up large systems into smaller functions. The functions are derived from the problem statement and the customer needs to simplify the systems of the project into subsystems.

* + 1. **Data Generation and Hierarchy Introduction**

In the hierarchy chart we assessed the problem and determined the simplest functions of our design. This was done through a series of brainstorming sessions. It was also important to incorporate the needs of our customer, so several meetings were conducted before the creation of the hierarchy chart. The design is broken down into three main systems: thermal, controls, and structure. These systems have their own subsystems and functions within the main system. Figure 1, the hierarchy chart, is shown below.

A diagram of a company

Description automatically generatedFigure 1: Hierarchy Chart

* + 1. **Hierarchy Chart Explanation**

The *thermal* system is responsible for cooling the regolith within our design and pumping the system down to high vacuum pressure. This system was broken up into pre and post pump down. The pre pump down section of the *thermal* system needs to keep the water in the air from condensing in the PLANET chamber and design. This would alter the regolith’s water composition, which would affect the accuracy of any experiment conducted in the chamber. Cooling the regolith is under both the pre and post pump down systems. This is because the cooling process is continuous and will take place throughout the entire process. At the end of the pump down to high vacuum the regolith needs to be kept between -70 degrees Celsius and -100 degrees Celsius, and close to 10^-7 Torr. Further experimentation will be done on the regolith sample, so maintaining this pressure and temperature is important to provide realistic testing conditions.

The *controls* system will be responsible for any motion of the design, as well as the user interface needed for data acquisition (DAQ) and display of the acquired data. The hatch or lid of the design will need to open pre and post pump down to allow for the placement of the regolith sample and further experimentation. Data will also be collected throughout any experiment conducted to measure stable properties. Water moisture, temperature, and coolant flow rate data collection will be the responsibility of the DAQ system. These values will give the user a full understanding of what is taking place inside the system during use. This data will then be displayed to the user.

The *structure* system of the design is concerned with the system’s ability to operate within NASA’s PLANET chamber, as well as withstand the conditions within the chamber. The design needs to be able to transport in and out of the chamber and fit within the chamber. The harsh conditions within the PLANET chamber will put substantial stress on the design. This includes both the cryogenic temperatures and the high vacuum pressure. The fixture should be designed to protect the electrical components and maintain structural integrity given the known temperature and pressure conditions. In the future, our stakeholders would like to utilize our setup in experiments that require materials to be invisible to microwave radiation. This feature is not in the scope of our project but would be nice to incorporate if we are able to.

* + 1. **Connection to Systems**

While the *thermal* system is broken down into pre and post pump down processes, the two systems directly relate to each other. If the water composition in the regolith mass is altered during the pre-pump down process, the user will not know the precise composition at the end of the pump down. This would negatively affect the vacuum and make the water composition measure inaccurate at the end of the experiment. Similarly, if the inside of the fixture is unable to reach and maintain high vacuum pressure the *thermal* system is unsuccessful. Both processes will be responsible for some level of cooling, to ensure the entire regolith mass is cooled.

The *controls* system breaks out into motion and user interface subsystems. The motion system is solely responsible for the opening of the fixture’s hatch, which limits this subsystems’ interaction with the other *controls* systems. The design’s ability to open will allow for further research on the regolith sample. While it is outside the scope of our project, this is important for the continued development of new technologies. The user interface subsystem, however, is responsible for data acquisition as well as data display. Without accurate data acquisition the display will provide inaccurate results. Without a display the user will not know how the system is operating in real time. The data being collected (water moisture, temperature, and coolant flow rate) will help the customer troubleshoot any possible problems with the system. Displaying accurate data on a constant basis is vital to the success of the design.

The devices’ *structure* must be able to hold up against the harsh conditions created by the PLANET chamber. Maintaining structural integrity and protecting electrical components from cryogenic temperatures and high vacuum pressures is of the utmost importance. Allowing flow of coolant is an important function of the design’s structure, along with invisibility to microwave radiation. This function will give the design more flexibility for future experiments. Operating within the PLANET chamber requires the design to fit within the chamber’s dimensions and be transportable in and out of the chamber. Transportation of the device is important when placing the regolith sample inside of the fixture, and for any required maintenance.

* + 1. **Cross Reference Table**

The following cross-functional relationship matrix, Table 2, displays how the functions and systems of the fixture will relate to each other. The three right columns are each of the main systems, and each of the 22 functions are listed in rows. An ‘X’ in the intersecting column of a system indicates that function will influence the corresponding system.

Table 2. *Cross-Functional Relationship Matrix* *A table with a list of different components

Description automatically generated with medium confidence*

* + 1. **Smart Integration**

Employing smart integration relationships will be greatly valuable as they optimize systems and processes, leading to increased efficiency and performance. Smart integration will reduce redundancy and save costs by incorporating functions into multiple systems. Most of the 18 functions listed above must use smart integration relationships to complete this project’s complex objective on a reasonable budget.

Many of these functions will have simple connections to multiple systems. For example, opening and closing the hatch will be connected to *controls* and *structure*, as an opening hatch will be a part of the physical structure and require controlled movement. The type of material chosen here and the placement of the hatch on the fixture will provide strength and stability in addition to being a means of accessing the inside of the fixture. Some of these functions will have the capacity for more comprehensive smart integration to strengthen multiple systems of the device in an innovative manner.

A crucial aspect stated by the customer is maintaining a consistent water composition in the regolith (4% - 10%). Haphazardly cooling the air in the PLANET chamber will lead to the unwanted consequence of water vapor condensing onto the regolith bed, increasing the water content. A clever fixture design that limits cooling exposure to the surrounding air and encloses the regolith bed from the outside air will significantly reduce the increase of water content due to water vapor condensation. Therefore, the first two functions regarding water vapor connect to both *thermal* and s*tructure* systems, as the water vapor condensing is directly affected by the cooling produced by the fixture and whether the structural design holds.

Another area with potential for smart integration is the function “Cool entire regolith mass.” The customer emphasized that the bed must be cooled to a temperature between -70 degrees Celsius and -100 degrees Celsius throughout the entire depth of regolith. Given that regolith is highly insulative, a creative approach must be devised to cool such a complex material. This can be done by making a fixture whose physical geometry further facilitates the heat transfer from the regolith to coolant, connecting both the *thermal*and *structure*systems. Conductive materials, such as aluminum, for components contacting regolith, will increase cooling. In addition, increasing the surface area of contacting components by using finned surfaces, such as finned tubes, will further increase heat transfer. Ideally, the material chosen can also be compatible with and invisible to microwave radiation, thus fulfilling that stretch goal as well.

Using smart integration, relationships will be immensely beneficial to this project, however, certain functions will have a greater opportunity for innovation than others. Functions regarding data collection and display will likely remain more elemental. Devices like thermocouples will be installed on the fixture and be simply connected to a DAQ system. A system like LabView, or similar programs, could be used to both retrieve data and display the measurements in a live setting to combine the data acquisition and user interface. Functions for the fixture’s physical structure and withstanding the extreme conditions will require innovation and an opportunity for smart integration such as, unique material selection and crafty structural design. Finally, functions related to the cooling method of the regolith will reap the most benefit from smart integration. Incorporating cooling process into each system and all aspects of the design will increase the efficiency & effectiveness of the fixture.

* + 1. **Action and Outcome**

The main physical action of this project is for a material, regolith, of concentration *C* to be cooled uniformly throughout over the amount of time *t* to run necessary testing. The customer needs either a device or a design process that fits within and is compatible with their pre-existing PLANET vacuum chamber. This is important to the development of the Human Landing System (HLS) for landing astronauts on the moon’s surface as part of NASA’s Artemis program. The material consists of a rocky, lunar composition mixed with deionized water ice. The water ice portion of this mixture is desired to be 4-10% of the total concentration. At time *t* = 0, the device with regolith enters the PLANET chamber. Once the device is inside the chamber, the de-pressurization process begins. The vacuum pumps down to a high vacuum pressure *P* in the range of 10^-7 torr. The phase diagram of water shows that this pressure can only occur at a specific, cryogenic temperature *T*. Cryogenic temperatures range from -150 degrees Celsius to absolute value or -273 degrees Celsius. The target temperature for this project is -70 to -100 degrees Celsius. As time *t* increases, the device needs to start at room temperature and atmospheric pressure, and then decrease to and maintain pressure *P* and temperature *T*.

Another equally important physical action is that the regolith is uniform throughout. So, the temperature *T*, pressure *P*, and moisture content *C* are the same at every *x, y*, and *z* location of the regolith. Regolith is a very good inductor with essentially zero thermal conductivity. The thermal conductivity has a range of about 1 square inch, meaning that the heat transfer only extends to 1 inch in every direction. Thus, the method of cooling selected will have to be able to reach every square inch of regolith.

A final physical action is that the device needs to open while inside the PLANET chamber for different tests and experiments to be performed on the regolith. This would require some translating or sliding type of motion to open a door on the device. Because the device will be inside a vacuum chamber, this motion will have to be remotely controlled.

* + 1. **Function Resolution**

Our project has three main systems. For the thermal system, the smallest components would be to ensure that the water inside the fixture does not condense, to maintain a specific regolith to water composition, to cool the entirety of the regolith to between -70 and -100 degrees Celsius, and to maintain high vacuum pressure within the fixture. In the structure system, our fixture must be transported in and out of the chamber, and the fixture should be made to the dimensions of the chamber so that it will properly fit inside. The fixture should be able to withstand cryogenic temperatures and high vacuum, using materials that are invisible to microwaves for future testing. In the control system, we will have to open and close the hatch doors for testing to be done while at vacuum pressure and atmospheric pressure. It must also be able to collect water moisture, pressure, temperature, hatch position, and coolant flow rate data. Along with collecting these data values, it should also display these values on a display screen.

## Target Summary

During functional decomposition, we broke our project into three major systems: *Thermal*, *Controls*, and *Structure*. The systems were then further broken down into 18 functions. Each function has been given a metric by which the function will be measured, a unit of measurement, and a target to validate the function’s performance. Three additional targets and metrics were also created to account for specific customer needs that were not sufficiently addressed by the functions. These targets will need to be met to achieve a successful design.

* + 1. **Derivation of Targets**

The critical targets, shown in Table 3, were given by our sponsor. These targets were the most important to our customer so there will be an increased emphasis on meeting them. Our team also determined that out of all the project’s targets, the three critical ones were most essential to the success of our project. If they are not met, our customer will not be satisfied, and our design will not solve their main problems. Targets not explicitly given were derived to satisfy the needs of our customer and carry out all our designs required functions. Background research was conducted when necessary to create realistic targets for various functions. All the targets are listed below in Table 3 for reference.

Table 3: *Target Summary Table*

|  | Targets Table |  |
| --- | --- | --- |
| The water composition in the regolith is maintained between 4-10% | The temperature of the entire regolith mass is cooled to and maintained between 173.15 K and 203.15 K | The pressure within the fixture is maintained at a high vacuum range of 1.33e-4 to 1.33e-5 Pa |
| A water composition between 0 and 20% can be collected and displayed | A pressure between 1.33e-5 and 1.01e-5 Pa can be collected and displayed | A coolant flow rate of around 100 m^3/s can be collected and displayed |
| A temperature between 93.15 and 313 K can be collected and displayed | The fixture uses material that is not affected by electromagnetic waves between 0.3 and 300 GHz | The fixture fits within the PLANET chamber volume of 4 ft x 8 ft x 1ft |
| The fixture can withstand at least 80 test cycles at 173.15 K and 1.33e-4 Pa | The fixture can be transported into the PLANET chamber with an ease of 6 out of 10 scale | The fixture allows a coolant flow rate of 500 gal/hr |
| Any hatch door can open from a position of 0 degrees to at least 90 degrees |

* + 1. **Critical Targets**

The critical targets, found below in Table 4, were determined to be those which were most critical to the success of the project.

Table 4. *Critical Targets and Metrics*

|  |  |  |
| --- | --- | --- |
| Critical Function | Metric | Target |
| Maintain regolith water composition | Water composition (%) | Water composition should stay between 4-10 %. |
| Maintain high vacuum pressure within the fixture | Pressure (Pascal) | Pressure should get down to (1.33e-4 – 1.33e-5) |
| Cool entire regolith mass | Temperature (Kelvin) | Temperature should get down between 173.15 K and 203.15 K |
| Needs to fit within the PLANET chamber | Volume (ft^3) | The fixture needs to fit within a 4ft x 8ft x 1ft volume |

The first critical target is to maintain the regolith-water composition. The amount of water in the regolith-water mixture needs to be between 4 and 10%, or else there would be too much moisture in the chamber. This could cause water to be condensed out of the air or introduce problems when pumping down to vacuum pressure. The second critical target is to maintain a high vacuum pressure within the PLANET chamber. The pressure on moon is at vacuum and thus the testing environment needs to be a vacuum. This requires a high vacuum pressure range of 10^-6 to 10^-7 torr or 1.33e-4 to 1.33e-5 Pa. A pressure of 10^-5 torr or 1.33e-3 Pa would be acceptable for initial design test results, but a fully successful project would be within the range listed above. The third critical target is to cool the entire regolith mass. A high vacuum pressure is not attainable unless the temperature is dropped down to a cryogenic range. It was requested that our fixture can cool the regolith down to a temperature between -70 and -100 degrees Celsius or 173.15 K and 203.15 K. However, the fixture also needs to maintain this temperature throughout testing, and the entire regolith mass needs to be this temperature, not just certain locations. The final critical target is that the fixture needs to fit within the PLANET chamber. The PLANET chamber itself has a 2m x 3m cylindrical shape, but the bed for our fixture is 4 ft x 8 ft 1 ft, thus our fixture needs to fit within these dimensions to complete any testing.

* + 1. **Discussion of Measurement and Method of Validation**

To validate the critical targets, different methods will be used for each. The first critical target, water composition, will be measured with a soil moisture probe. The probe will be in the regolith bed throughout testing to ensure the water composition is within the 4-10% range. To measure and validate the second critical target, a k-type thermocouple will be used inside the PLANET chamber to read the temperature. These thermocouples are currently outfitted within the chamber. NASA is providing extra k-type thermocouples to us for prototyping and validation that have a range between 93.15 and 313.15 Kelvin, which is broader than the target range. This guarantees the range of temperatures we are targeting will be accurately read. Lastly, a manometer will read the last critical target, pressure. The chamber does have a pressure monitoring system that is more complex than a manometer, but for small scale validation purposes, a handheld manometer will be used that can read to 1.33e-5 Pascals.

* + 1. **Summary**

The targets listed above and in Appendix C are the goals for our system to set a measurement of performance. These targets will help us track our progress and success; they will also act as a reference point for benchmarking. Along with tracking our progress it will keep us aligned with customer objectives that need to be reached, while ensuring the project cost remains within a reasonable budget. These targets and metrics are subjected to change as prototypes are developed and tested.

## Concept Generation

* + 1. **Concept Generation Tools**

Concept generation is the process of generating possible solutions to a problem. A couple of tools used to generate concepts are morphological charts, anti-problem, and biomimicry. These tools are useful to produce larger and more robust ideas that are without bias and target the solution from different perspectives. This is especially beneficial because teams tend to stick to the original ideas even if they don’t provide the best solution to the problem. It is important to use these tools to aid designers in thinking out of the box and stimulate innovative solutions.

* + - 1. **Morphological Chart**

A morphological chart is a tool to aid idea generation in a systematic manner. The critical functions outlined earlier are split into an individual column. Under each function, different independent methods of achieving that function are listed. This creates a matrix of functions and possible solutions. Once the chart is complete, concepts are found by combining solutions from different functions, with one solution being selected from each function. This produces a systematic process and generates complete solutions that target each critical function. The morphological chart we used can be seen in Appendix D.

* + - 1. **Biomimicry**

Biomimicry is the mimicry of the models, systems, and elements of nature for the purpose of solving complex human problems. Essentially, copying nature to solve similar problems. To help search for ideas, AskNature.org was used to search some keywords like “cooling”, “space environment”,” and “water out of air.” Once the keywords are searched, articles pertaining to those keywords are researched to see if any systems or animals in nature can be mimicked to solve our project. Organisms that can survive in space were our focus in researching biomimicry.

* + - 1. **Anti-Problem**

The goal of anti-problem as a concept generation tool is to have the team try and solve the opposite problem. This in turn, can trigger viewpoints of the original problem from different angles with the intent to generate more possible solutions. For our project, our team tried to solve the anti-problem statement, “How do you keep regolith hot, dry, and at atmospheric pressure?” This led us to investigate insulation barriers and reduced kinetic energy further while generating concepts.

* + 1. **Concept Analysis**

During concept generation, the team generated 100 concepts, as can be seen in Appendix D. Out of these concepts, five were chosen as medium fidelity, and three were chosen as high fidelity.

* + - 1. **Low Fidelity Concepts**

Low fidelity concepts are concepts that are not feasible for reasons such as: time, technology, or cost constraints. Another reason a concept can be classed as low fidelity is because the concept does not meet a critical function. All concepts that are not listed in the next two sections are considered low fidelity and can be seen in Appendix D.

* + - 1. **Medium Fidelity Concepts**

Medium fidelity concepts are concepts that address most, if not all, the needs for the design but are not as attainable or complete as high fidelity.

Table 5. *Medium Fidelity Concepts*

|  |  |
| --- | --- |
| Concept # | Concept Description |
| 13 | Fins with LN2 running through regolith every square inch of base length. |
| 24 | Copper cooling coils are layered throughout the length of the box/cylinder to evenly cool the entire regolith sample, coils are retractable. |
| 34 | Flood box with cryogenic gas to drop temperature which freezes water out of air, then add to dry regolith before pumping down to vacuum. |
| 43 | Sample box surrounded by vacuum isolation jacket and 5 surface LN2 jacket. |
| 44 | Sample box placed on top of 1D LN2 cooling plate, surrounded by vacuum isolation jacket. |

The medium fidelity concepts selected for our project are concepts #13, #24, #34, #43, and #44. Starting with concept #13, we ruled this as medium because it only accomplished part of the solution. While it does provide a surface at where testing could be done, having fins at every square inch would make drilling and excavating the regolith bed a challenge. Also, it would not be cost or material efficient. For concept #24, the coils would have to be placed at every inch around the fixture and even through the middle. To make the coils retractable we would have to protect the motor from the dust coming off the regolith. Even though it is possible it would not be cost effective to order that amount of coils. Concept #34 is medium fidelity due to cooling with cryogenic gas requires more space and energy than cooling with a cryogenic liquid. Concept #43 would not be able to cool the middle of the regolith uniformly due to the regolith being a great insulator. The LN2 jackets would only cool once inch of regolith around the box. Concept #44 is a design that assumes that cooling is occurring during pull down where 1D heat conduction between regolith is not feasible. Since there is no air in a vacuum, there is no conduction occurring between air molecules and the regolith.

* + - 1. **High Fidelity Concepts**

High fidelity concepts meet all the needs for the design and have a high potential for success.

Table 6. *High Fidelity Concepts*

| Concept # | Concept Description | Visual Representation |
| --- | --- | --- |
| 45 | Sample box placed on top of cooling plate, then translating mixer geos through regolith to uniform the temperature | A diagram of a rectangular box  Description automatically generated |
| 46 | LN2 drip lid that recirculates boiled cold nitrogen gas through grate | A drawing of a typewriter  Description automatically generated |
| 48 | Retractable auger that mixes regolith mass with LN2 in augur to provide even cooling. It is matched with a removable lid with thermal couples attached to the bottom. | Top of Bed View. Bottom of Lid w/ Thermal couples  A black and blue design on a white background  Description automatically generated |

The high-fidelity concepts selected for our project are concepts #45, #46, and #48. Concept #45 involves placing the regolith sample inside an open box on top of a cooling plate. A mixer is simultaneously moving through the sample in the box to help reach a uniform temperature. This is a high-fidelity concept because it hits all critical functions, is technically possible, and could be cost and time effective, depending on the material and cooling rate. Concept #46 attacks cooling in a different manner but still as possible and as efficient as concept #45. Concept #46 requires an LN2 drip at the top of the PLANET chamber that would recirculate the boiled nitrogen gas (-196 °C) through the chamber and a bottom grate. This process would be slow, but it would thoroughly cool the regolith, be energy efficient, and not interfere with the high vacuum system. Concept #48 involves placing retractable augers horizontally that mix and circulate the regolith at low speeds. The auger would have LN2 piping along its length so as the regolith is mixing, conduction is happening, and the regolith is becoming cooler.

## Concept Selection

After determining our five medium fidelity concepts and three high fidelity concepts, different tools will be used to help narrow down and select a final concept. These selection tools include binary pairwise comparison, house of quality, Pugh chart(s), and the analytical hierarchy process (AHP). The benefits to using selection tools include eliminating confirmation bias, allowing concepts to be quantified, and ensuring the concepts are ranked on the same criteria. This certifies the final selection chosen objectively based on the design needs and not designer bias.

* + 1. **Binary Pairwise Comparison**

Binary pairwise comparison (BPC) is a concept selection tool that allows a team to compare and rank the list of concepts against each other. To create a BPC, the customer needs are listed in both the column and row headers to form a matrix. If the need in the column is more important than the need in the row, it receives a 1. If the requirement is less important, it receives a 0 in that cell. The corresponding cell across the diagonal of the matrix will then receive the opposite value. The values are then summed up and used as an importance weight factor in the House of Quality tool. To save space on table size, table 7 shows the customer requirement with an assigned number to be used throughout the BPC. From the BPC in table 8, it was determined that uniform cooling throughout regolith, and maintaining water composition were the most important weight factors.

Table 7. *Legend for Customer Requirements*



Table 8. *Binary Pairwise Comparison*

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* + 1. **House of Quality**

The House of Quality includes the list of customer requirements as rows, the importance weight factor next to it, and the list of engineering characteristics as columns. The purpose is to turn the project requirements into design specifications and analyze which requirements are critical to the design. The correlation between customer requirement and engineering characteristic is rated 1,3, or 9. A 1 represents no relationship, a 3 represents a minimal relationship, and 9 represents a highly significant relationship.

Each column is totaled and then summed for a raw score. The final column sum is divided by the raw score to get a relative weight for each engineering characteristic. Finally, the characteristics are ranked in importance with the highest relative weight being 1 and the lowest being 10. From the House of Quality, it was determined that coolant carries the highest weight and ease of use carries the lowest. Understanding how important each engineering characteristic is allowing us to stress which engineering characteristics are critical for the design. The top 6 characteristics were kept for further calculations. This cutoff was determined because the drop off between characteristic 6 and 7 was significantly larger than the drop off from 5 to 6. Our House of Quality can be seen in table 9 below.

Table 9. *House of Quality* A table with text and numbers

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* + 1. **Pugh Charts**

The five medium fidelity and three high fidelity concepts mentioned previously can be compared in a Pugh Chart to evaluate the strength of their functions. The concepts are set in the columns, while the highest engineering characteristics from the House of Quality are used in the rows. To being a Pugh Chart, a datum is selected that allows us to benchmark all the concepts against a baseline concept. The chart uses plus (+), minus (-), and satisfactory (S) to determine compared strength. This rating system allows us to translate qualitative data, like concepts and requirements, into quantitative data. We can then weigh the criteria and choose, based on the charts, the best option. Table 10 shows our first Pugh Chart. As our datum, we used the cooling plate with no mixer concept. Then we compared that concept to the other 7 concepts based on the top 5 weighting engineering characteristics. For our first Pugh Chart, concept #46, the drip lid with a recirculation pump had a total of +3, being the highest concept from this iteration. Another concept, the drip lid with a regolith mixer, ended with a +2. We decided all concepts with a positive score from the 1st iteration of the Pugh Chart would move to the 2nd.

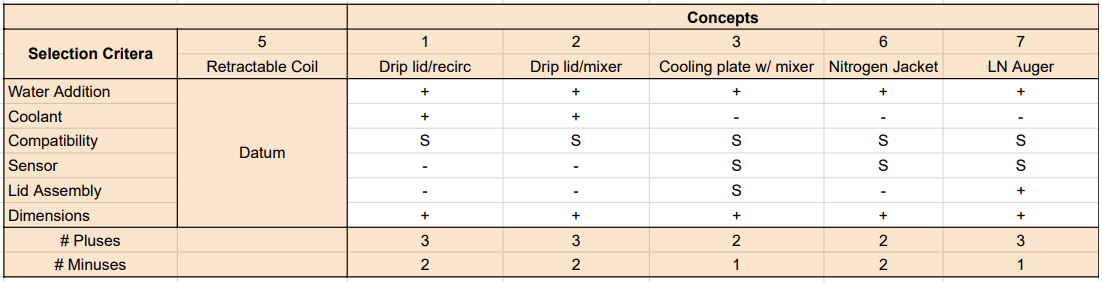
Table 10. *Pugh Chart: 1st Iteration*

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The 2nd iteration of our Pugh Chart can be seen in table 11. For this iteration, we used concept 5, the retractable coil as the datum because it scored a -2 on the first iteration. Once the chart was completed, it was determined the liquid nitrogen auger, concept #48, had a +2, the highest score on this iteration. The only concept to be neutral was concept #43, the nitrogen jacket concept.

Table 11. *Pugh Chart: 2nd Iteration*



Our final Pugh Chart can be seen in table 12. Using concept #43 as the datum, we wanted to compare the two highest concepts from previous iterations: concept #48 vs. concept #46. By carefully going through each engineering characteristic and how the design performs against the datum, concept #48 scored a +2, while concept #46 scored a +1. These final data points will be used during the final rating matrix to select a final concept.

Table 12. *Final Pugh Chart*

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* + 1. **Analytical Hierarchy Process**

The Analytical Hierarchy Process (AHP) was used to determine which of the engineering characteristics are the most significant to the success of the project. As previously mentioned, only the top 6 characteristics from the House of Quality were considered. The process involves putting each engineering characteristic against the others and ranking their importance. The ranking system uses numbers 1, 3, 5, 7, 9 where 1 represents that the characteristics are of equal importance and 9 represents that the criteria is much more important than the opposing characteristic. The opposite corresponding cell of the matrix would receive the inverse of the previous score given. Cells of the matrix comparing the same criteria are given a 1. These rankings are then summed down vertically. The initial rankings were then normalized with respect to the previous sum. This involved dividing each cell by the sum of its column. The rankings were then checked for bias by conducting a consistency check. A consistency ratio less than 0.1 deemed the ranking nonbiased, but any number larger than this showed that the rankings were biased and needed to be reconsidered. Table 13 below shows the initial AHP matrix for our engineering characteristics.

Table 13. *Engineering Characteristics AHP Matrix*

*A table with numbers and letters

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The same process was used to compare the final three designs from our concept Pugh charts with respect to the top 6 engineering characteristics. These charts along with the normalized matrix and consistency check for the criteria matrix are shown in Appendix E.

* + 1. **Final Concept Selection**

After using the analytical hierarchy process to find the characteristics that are the most prevalent for our design, we compared our top three design concepts with each characteristic. The table shown below is our Final Rating Matrix which includes: the regular and transposed final rating matrix, the criteria weights, and the rankings of our top three concepts.

Table 14. *Final Rating Matrix*

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* + 1. **LN2 Drip Lid with Nitrogen Gas Recirculation**

From the results of Table 14, the concept #46 “drip lid/recirc” has met the criteria from our previous charts the best. This concept is assumed to be used for water addition and cooling before vacuum. The fixture first flows in liquid nitrogen into a top drip lid. The LN2 then spreads out and drips into the regolith mass uniformly. Conductive heat transfer occurs with the LN2 and regolith. In most applications, expended LN2 would normally vaporize off and escape out of the system. However, this concept uses the vaporized nitrogen gas that is –196 °C to further cool the system, increasing cooling efficiency and reducing the necessary amount of total LN2. This nitrogen gas is pulled out from the top layer of the bed using a recirculation pump and is forced into a bottom section underneath the mass of regolith. This nitrogen gas is then forced up through the regolith further cooling it. The bottom of the main regolith bed is perforated and will have a layer of canvas-like material allowing the flow of gas but keeping the regolith separated. Because vaporizing liquid nitrogen expands to almost 700 times the volume, the closed cooling system will need to be frequency depressurized with an automatic pressure valve. A slow drip of LN2 into the system will allow for maximum heat transfer to occur between the nitrogen gas and regolith before the gas is vented. A specific flow rate can be calibrated for optimizing both time and efficiency.

This concept was selected as it best fulfills the important characteristics decided by the AHP matrix in Table 13. Conclusions from this chart showed that coolant, sensors, and water addition were the most important characteristics required of the device. Concept #46 will require more sensors for gas flow rate and controlling the recirculation pump, further complicating the project. However, this concept likely has the highest capacity for cooling efficiency as it uses both liquid and gaseous nitrogen. For ease of water addition to the regolith mass, the drip lid used for LN2 could first be used to uniformly and precisely add the necessary water content to the system. Therefore, this concept will best meet the needs of the customer and provide the most advantageous solution to the problem.

|  |  |
| --- | --- |
| Closed view of Fixture | Sliding lid partial open on fixture |
| Expanded view of Fixture | Bottom view of the exploded assembly |

## A close-up of a document Description automatically generated1.8 Spring Project Plan

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# Chapter Two: EML 4552C

## 2.1 Spring Plan

### Project Plan.

### Build Plan.

# Appendices

# Appendix A: Code of Conduct

This document will serve as the team contract for Team 519 during the entire Senior Design period lasting from the Fall of 2023 through the Spring of 2024.

**Mission Statement**

Team 519 is devoted to generating the best solution to the project: Retain Water Ice in Regolith at Vacuum, sponsored by NASA MSFC. The team will utilize engineering experience and previous courses from the FAMU-FSU College of Engineering throughout the design process. In addition to solving this vital problem, the skills and experience developed throughout the project will build a foundation for future engineering applications.

**Outside Obligations**

All previously disclosed obligations shall be respected and honored. In the event of new outside obligations, the member should inform the team through the Microsoft Teams chat. The Microsoft Teams calendar should also be updated. If a member constantly fails to notify the group of outside obligations, or fails to honor other members’ obligations, the team member will be addressed. Team meetings are a high priority for all members. If a member cannot attend a meeting, they should notify the group as soon as possible. If a member repeatedly misses meetings without notification, they will be addressed.

Specific member obligations are as follows:

**Trent Walker**: Work (Wednesday/Friday/Saturday Nights starting at 5:00PM)

**Luke Leibkuchler**: TA (Tuesday/Thursday 12:30PM-2:15PM), Club Baseball (Schedule will be provided to entire team once it is available)

**Kevin Hernandez Lichtl**: Work (Flexible hours, Scheduled Project Meetings)

**Katherine Mesa**: Work (Flexible remote hours, typically during business hours), Travel (Interviews, Pre-booked vacations)

**Megan Reid:** Work (Monday/ Wednesday 9:30AM – 3PM, Friday 3-5PM), Church (Sunday until 2PM), Second job (occasionally Saturday or Wednesday nights – notice will be given as soon as possible)

**Team Roles**

Team roles should be flexible throughout the duration of the project, and self-assigned based on areas of expertise and interests. Work not related to a specific role will be assigned on a case-by-case basis.

|  |  |
| --- | --- |
| **Team Member** | **Team Role** |
| Kevin Hernandez Lichtl | Astronautical Engineer |
| Luke Leibkuchler | Systems Engineer |
| Katherine Mesa | Fluid Test Engineer |
| Megan Reid | Design Engineer, Test Engineer |
| Trent Walker | Thermal Fluids Engineer |

**Communication**

Microsoft Teams text chat is the primary form of communication. A Microsoft Teams meeting will be used for virtual meetings. If a team member is unable to attend a scheduled meeting, they will notify the team 24 hours in advance. If a member misses a meeting, other members can fill them in with their personal meeting notes/minutes. If a team member cannot be reached for an entire week, they will be addressed. Responses are expected within 24 hours.

**Dress Code**

For formal presentations, business attire should be worn by all members. This does not include jeans, but a dress shirt with slacks or khakis. For Engineering Design Day, however, suits and ties should be worn. There is no formal dress code for informal team meetings. For sponsor meetings, business casual is expected.

**Attendance Policy**

Team members are given 3 meeting skips per semester. Otherwise, attendance is expected at all meetings, especially meetings with the project sponsor. If a member is unable to attend a meeting, they should contact the team via the Microsoft Teams chat. Meetings will take place in person during the allotted senior design class time. Monday, Wednesday, and Sunday meetings can be scheduled as needed. The team can also agree to meet remotely if necessary. Members are encouraged to attend meetings outside of the agreed upon days if scheduled, but not required.

**How to Notify the Group**

The primary communication outlet is Microsoft Teams chat. The text group chat can also be used for more urgent matters. If extremely urgent communication is needed, a phone call can be used either to the entire group, or to an individual member.

**How to Respond to People in Professional Meetings**

When responding in professional meetings, all communication will be respectful and punctual. If there is any unclear information, team members can ask questions, or fill in any remaining information via email, zoom, or the Microsoft Teams chat. More demanding means can be used if necessary. Responses are expected within 24 hours.

**What Do We Do Before Contacting Dr. McConomy or TA’s**

In the event of any disagreements, a team member will first have a 1 on 1, respectful conversation with the other member. This is highly encouraged, to improve the overall team morale. If this does not solve the problem, an entire team meeting shall be held. All members are encouraged to attend these meetings. If the meeting is not successful, a Teaching Assistant will be contacted. Only if the TA is not capable of solving the issue, will Dr. McConomy be contacted.

**At What Point Do We Contact Dr. McConomy**

If a member is not in contact with the team for an entire week and does not attend team meetings, Dr. McConomy will be contacted. An extended absence is extremely urgent, which calls for direct contact with Dr. McConomy.

**What Do You Want Dr. McConomy to Do When You Come**

The team would advise Dr. McConomy to email the missing member, and CC the rest of the team.

**How to Amend**

If a member has a possible amendment to the code of conduct, a team vote will be conducted. The amendment will need to get a 3/5 majority vote to be added.

**Vacation Days**

Vacation days should be group focused. If a member must take a vacation day for personal reasons, they must communicate with the group. The team will decide what to collectively use the vacation days for with a majority vote.

**Code of Conduct Acknowledgment**

Each member of the team has discussed and read this contract and agrees to uphold everything provided in this document.

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# A diagram of a company Description automatically generatedAppendix B: Functional Decomposition

# Appendix C: Target Catalog

Table 1. *Target Catalog*

| Function | Metric | Target |
| --- | --- | --- |
| Maintain regolith water composition | Water composition (%) | Water composition should stay between 4-10 |
| Cool entire regolith mass | Temperature (Kelvin) | Temperature should get down to between 173.15 K and 203.15 K |
| Maintain high vacuum pressure within the fixture | Pressure (Pascal) | Pressure should get down to a range of 1.33e-4 to 1.33e-5 |
| Collect and display water moisture | Water Composition (%) | Between 0 and 20 |
| Collect and display temperature within the regolith mass | Temperature (K) | Between 93.15 K and 313 K |
| Collect and display pressure within the fixture | Pressure (Pa) | Gathers and displays pressure data between 1.33e-5 and 1.01e5 |
| Collect and display coolant flow rate | Flow rate (m^3/s) | Gathers and displays flow rate data, approximately 100 |
| Needs to fit within the PLANET chamber | Volume (ft^3) | The fixture needs to fit within a 4ft x 8ft x 1ft volume |
| Fixture can be transported in and out of the chamber | Rating 1-10 | Fixture needs to be transported and given an ease of transport rating of at least a 6 by all users |
| Fixture withstands cryogenic temperature and high vacuum pressure | Cycles | Can last 80 cycles of 173.15 K and 1.33e-4 Pa |
| Fixture allows flow of coolant | Flow rate (gal/hr) | 500 gal/hr of liquid nitrogen flows in fixture |
| Fixture utilizes materials invisible to microwave radiation | Frequency (GHz) | Materials do not get affected by electromagnetic waves between 0.3–300 |
| **\*Users should be able to operate the fixture after team’s instruction** | **Number of Training Sessions** | **The user should be able to operate the fixture after 2 sessions** |
| **\*The fixture should be compatible with experiments outside of the scope of this project** | **Number of Experiments Compatible** | **At least 2** |
| **\*Fixture should be easy to assemble and set up** | **Number of Personnel** | **Two users required to assemble fixture** |

\*Needs in bold are not explicit functions

# Appendix D: Concept Generation

Table 1. *Morphological Chart*

|  |  |  |
| --- | --- | --- |
| **Water Comp** | **Cooling** | **Open and Close** |
| Pre-soak | Cooling Coils | Four bar mechanisms |
| Dry first then faucet drip | Agitator | Sliding hatch door |
| Top Sprinkler | Solid nitrogen block | No hatch |
| Grate fill | LN jacket | Manually removable lid |
| Capture water from atmosphere | Helium gas |  |
|  | Pump LN through a cooling plate |  |

List 1. *Concept Generation List – 100 Ideas*

Concepts

1. Mix regolith with water in a concrete mixer and add to box before pressurization.
2. Recirculate liquid nitrogen through regolith during pressurization.
3. Cooling coils flowing with liquid nitrogen along inner walls of regolith bed.
4. Cooled centrifuge circulates the regolith while being pressurized.
5. Solidify Nitrogen block on bottom of bed for 1D heat transfer.
6. Flood helium gas through test bed to cool without turning into liquid and changing regolith composition.
7. Place water bears on regolith in chamber, turn on and have the water bears expel water. To rehydrate, turn off chamber.
8. Sprinkle LN2 and vibrate box to mix.
9. Cylinder container as LN2 is pumped in and it rotates almost like washer machine.
10. Cylinder with opening and closing mechanism that pumps LN2 through coils.
11. Rectangular fixture with opening and closing mechanism that pumps LN2 through coils.
12. Mechanical rake that moves the regolith, moving back and forth along the fixture.
13. Fins with LN2 running through regolith every square inch of base length. (**Medium fidelity)**
14. Top lid with cake-mixer-like mechanism to mix regolith and LN2.
15. Elevated regolith bed, with retractable mixers underneath.
16. LN2 sprinkler system to cool regolith bed.
17. Insertable perforated piping that injects LN2 into regolith mass.
18. Mole-robot that digs around and detects areas of high temperature and squirts LN2.
19. Regolith is placed into the fixture in gradual layers, LN2 is sprinkled in cooling each layer, rake machine smooths out mass.
20. Reduce/ have no moving parts once in chamber to reduce kinetic energy and thus reduce temperature increase.
21. A retractable mixer on the side of the box that will mix the regolith during cooling and retract out of the box for further testing
22. Fixture is placed on a vibrating bed that will shake the regolith while LN2 is being pumped through the fixture to provide an even cool
23. Copper cooling coils are layered throughout the length of the box to evenly cool the entire regolith sample
24. Copper coiling coils are layered throughout the length of the box/cylinder to evenly cool the entire regolith sample, coils are retractable (**Medium fidelity)**
25. Retractable layered coils in a cylinder, cylinder rotates to mix up regolith
26. Cylindrical fixture placed on a cooling plate with LN2 filled coils within
27. Two rotating helical screw-like cylinders with LN2 blowing out of pores in the cylinder which move and cool the regolith.
28. Fixture placed on a LN2 cooling plate. The fixture has a retractable floor that will open and close to directly expose the regolith to the plate.
29. Regolith is placed in a LN2 filled cube. LN2 is pumped out after desired temperature is reached and prior to pump down procedure.
30. Conveyor belt that moves regolith through LN2 sprinklers and deposits in bed
31. Create watertight bed and flood regolith with LN2
32. Flood box with LN2 then drop regolith sample bed into liquid Nitrogen
33. Inject blocks of solid nitrogen within regolith mass, insulate using aerogel layer for minimal heat transfer
34. Flood with cryogenic gas to drop temperature which freezes water out of air, then adds to dry regolith before pumping down to vacuum. **(Medium fidelity)**
35. Rotating fins that can lower into regolith to mix the composition and maintain temperature
36. Fixture with hundreds of vertical fins that have a cryogenic fluid flowing through them (like a CPU cooler).
37. Fixture with retractable horizontal fins with cryogenic fluid flowing through them.
38. Bed is divided into sections and individually filled with LN2 flowing through dividers
39. Bed flooded with liquid nitrogen and vacuum chamber is turned on to prevent heat transfer
40. Regolith and LN2 are flowed through individual pipes that merge and then are deposited into regolith bed
41. Snake coil with LN2 inside but separated every 1 square inch to make room for drilling.
42. Vacuum chamber is sealed and its LN2 cold shroud is used to slowly cool regolith.
43. Sample box surrounded by vacuum isolation jacket and 5 surface LN2 jacket **(Medium fidelity)**
44. Sample box placed on top of 1D LN2 cooling plate, surrounded by vacuum isolation jacket **(Medium fidelity)**
45. Sample box placed on top of cooling plate, then translating mixer geos through regolith to uniform the temperature (**High fidelity)**
46. LN2 drip lid that recirculates LN gas through grate **(High fidelity)**
47. LN2 drip lid that recirculates LN gas with mixer to make temp uniform **(High fidelity)**
48. Retractable auger that mixes regolith mass with LN2 in augur to provide even cooling. **(High fidelity)**
49. Greenhouse idea that traps cold temperature but doesn’t' let heat in.
50. Regolith is pre-soaked with water, cooled with a solid nitrogen block, and has no hatch.
51. A top sprinkler distributes LN2 from a manually removable top, an agitator mixes regolith
52. An open top fixture cools regolith by flowing cold helium gas through mass
53. A top sprinkler is used to provide water to the regolith sample, LN2 is pumped through a cooling plate, the hatch is manually removable.
54. Water is dripped into dry regolith at constant rate to maintain composition, placed on block of solid nitrogen to keep cool. A sliding hatch door is used.
55. Top sprinkler is used on the regolith sample, with an agitator device to thoroughly mix the sample. A sliding hatch door is used.
56. A water capture device is put on top of the regolith to catch any water from the air inside the fixture. A LN cooling plate, along with a sliding hatch door.
57. Grate fill system is used to provide water to sample. A solid nitrogen block is used with a manually removable top.
58. Water is dripped into a dry regolith mixture, flooded with helium gas for cooling. A four-bar mechanism is used for a hatch door.
59. A top sprinkler is used to water the sample, and a nitrogen block is used for cooling. A four bar will open and close the fixture.
60. Cool regolith bed slowly with liquid helium and insulate outside with aerogel layer
61. Evenly sprinkle in LN2 and mix with an agitator. Hatch motion is provided by a four-bar linkage.
62. Regolith is presoaked and an agitator device is used to stir the mixture while cooling. There is no hatch on this design.
63. Dry Regolith and faucet drip water to desired content. Regolith cooled by pumping LN2 through a cooling plate. A four-bar linkage will open and close the fixture.
64. Water is provided to sample through a grate filling system on the bottom surface of the design. Liquid nitrogen is pumped through a cooling plate and a manually removeable hatch is used.
65. A pre-soaked regolith mixture is placed on top of a solid nitrogen block in a sealed box. A four-bar linkage is used to open and close the hatch.
66. Water is provided to sample through a grate filling system on the bottom surface of the design. There is no hatch on this design and a solid nitrogen block is used for cooling.
67. Faucet drip is used to add water to dry regolith and then regolith bed is placed on top of cooling plate with LN2 inside. No hatch door is attached.
68. Water is sprinkled into the sample and LN2 is pumped through a cooling plate on the bottom surface of the fixture. A four bar is used to open and close the hatch.
69. Regolith is presoaked to desired water composition and a solid nitrogen block is used for cooling. The hatch is manually removable.
70. Grate fill system is used to provide water to the sample. An agitator is used to mix the regolith to cool the entire sample, and a sliding hatch door is used.
71. A faucet will drip water into the sample. Helium gas will be pumped throughout the sample for cooling, and there will be no hatch on the design.
72. A sprinkler system will wet the regolith sample and a nitrogen block will be used for 1D cooling. The hatch on the design will be manually removable.
73. The regolith will be presoaked, and a cooling plate will be used to cool the sample. The plate will have LN2 pumping through it and a sliding hatch door will be used.
74. Fill bed of regolith from the bottom with liquid nitrogen then placed on a solid nitrogen block in a fixture with a manually removable top.
75. Water would flow through grates into regolith and a cooling a plate would have LN2 flowing through to cool it. There is no hatch in this design for easy access to sample.
76. Start with dry regolith and during pump down trickle water into soil and use a solid nitrogen block to cool with a four-bar mechanism to open the door to allow experimentation.
77. Open fixture with sprinkler like water source using a rotating circular rake to mix regolith.
78. Trapping moisture and using a funnel to direct the water towards regolith and using a drill like mixer to agitate the soil and have a removable hatch
79. A grate fill system is used to soak the regolith. A solid nitrogen block is used to cool the sample and a four-bar linkage is used to open and close the fixture.
80. A dripping faucet is used to wet the sample and an agitator is used to mix the sample during cooling. A four bar is used to open and close the fixture.
81. A sprinkler is used to soak the regolith and a sliding hatch door is used. A solid nitrogen block is incorporated to cool the specimen.
82. The regolith is pre-soaked to the desired water composition. Helium gas is used for cooling with a manually removable top.
83. A faucet drip is used to soak the sample, and a cooling plate with LN2 pumped through it is used for cooling. A sliding hatch door allows access to the sample.
84. Water is dripped into the specimen, and a helium gas pumping system is used for cooling. This design has a manually removable top.
85. A sprinkler and a cooling plate are used for water composition and cooling needs. The plate has a LN2 pumping system within it and a slider hatch door is used to open and close the fixture.
86. A device is used to capture any outside moisture from the air within the chamber to keep constant water composition levels. A solid nitrogen block is used for cooling, and a four-bar mechanism is used for motion needs.
87. Sample is pre-soaked, and a cooling plate pumped with LN2 is used. The hatch is manually removable.
88. A grate fill system is used for water composition, and a LN2 cooling system cools the sample. A sliding hatch door allows for easy access to sample.
89. The sample is dried, and water is added through a faucet drip. A solid nitrogen block cools the sample, and there is no hatch to allow for sample access.
90. The sample is pre-soaked with water and placed on a nitrogen block to cool. A sliding hatch door provides access to sample.
91. A grate fill system is used to add water. There is no hatch to allow sample access and a LN2 cooling jacket is used.
92. A device is placed over the sample to ensure no excess water condenses into the regolith, with a sliding hatch door. An agitator is used during the cooling process for evenly distributed temperatures.
93. Pre-soaked regolith is placed in the sample bed on top of a cooling plate containing LN2. A four-bar linkage opens and closes the fixture.
94. A sprinkler is used to apply water to the specimen, and a LN2 cooling jacket ensures the sample gets evenly cooled. This design does not use a hatch to allow for easy specimen access.
95. A device is used to capture excess water in the fixture, and a LN2 cooling jacket cools the specimen. A sliding hatch door allows for access to specimen for further experiments.
96. The sample will be pre-soaked with water and will be cooled by an LN2 cooling jacket. No hatch will be used with this design.
97. A grate filling system will provide water to the regolith, and the sample will be cooled by an LN2 cooling jacket. A sliding hatch door will allow access to the specimen.
98. A sprinkler is used to provide moisture to the specimen, and an LN2 cooling jacket will provide the cooling. A sliding hatch door will allow access to the sample.
99. Regolith is dry first then mixed as faucet drips water ice, then put on cooling plate with LN2 inside. Fixture has a manually removeable top.
100. Grate fill is used to add water ice to regolith mixture and a LN2 cooling jacket is used to cool it. Fixture has a manually removable top.
101. Person sits on top of regolith bed and hand mixes 😉(EXTRA EFFORT!!!)

# Appendix E: Concept Selection

Table 1. *Legend for Customer Requirements*



Table 2. *Binary Pairwise Comparison*

A table with numbers and letters

Description automatically generated

Table 3. *House of Quality* A table with text and numbers

Description automatically generated with medium confidence

Table 4. *Pugh Chart: 1st Iteration*

A screenshot of a table

Description automatically generated

Table 5. *Pugh Chart: 2nd Iteration*

A table with numbers and letters

Description automatically generated

Table 6. *Final Pugh Chart*

**A screenshot of a computer

Description automatically generated**

Table 7. *Engineering Characteristics AHP Matrix*

*A table with numbers and letters

Description automatically generated*

Table 8. *Normalized Engineering Characteristics AHP Matrix*

A screenshot of a graph

Description automatically generated

Table 9. *Engineering Characteristics Consistency Check*

*A table with numbers and a number of objects

Description automatically generated with medium confidence*

Table 10. *Concept Comparison Matrix*

*A table of information

Description automatically generated with medium confidence*

Table 11. *Concept Normalized Comparison Matrix*

*A table of numbers and symbols

Description automatically generated with medium confidence*

Table 12. *Concept Consistency Check*

A screenshot of a spreadsheet

Description automatically generated

Table 13: *Final Rating Matrix*

*A table with numbers and symbols

Description automatically generated*

Table 14: *Alternative Value Chart*

A screenshot of a graph

Description automatically generated

# References

**There are no sources in the current document.**