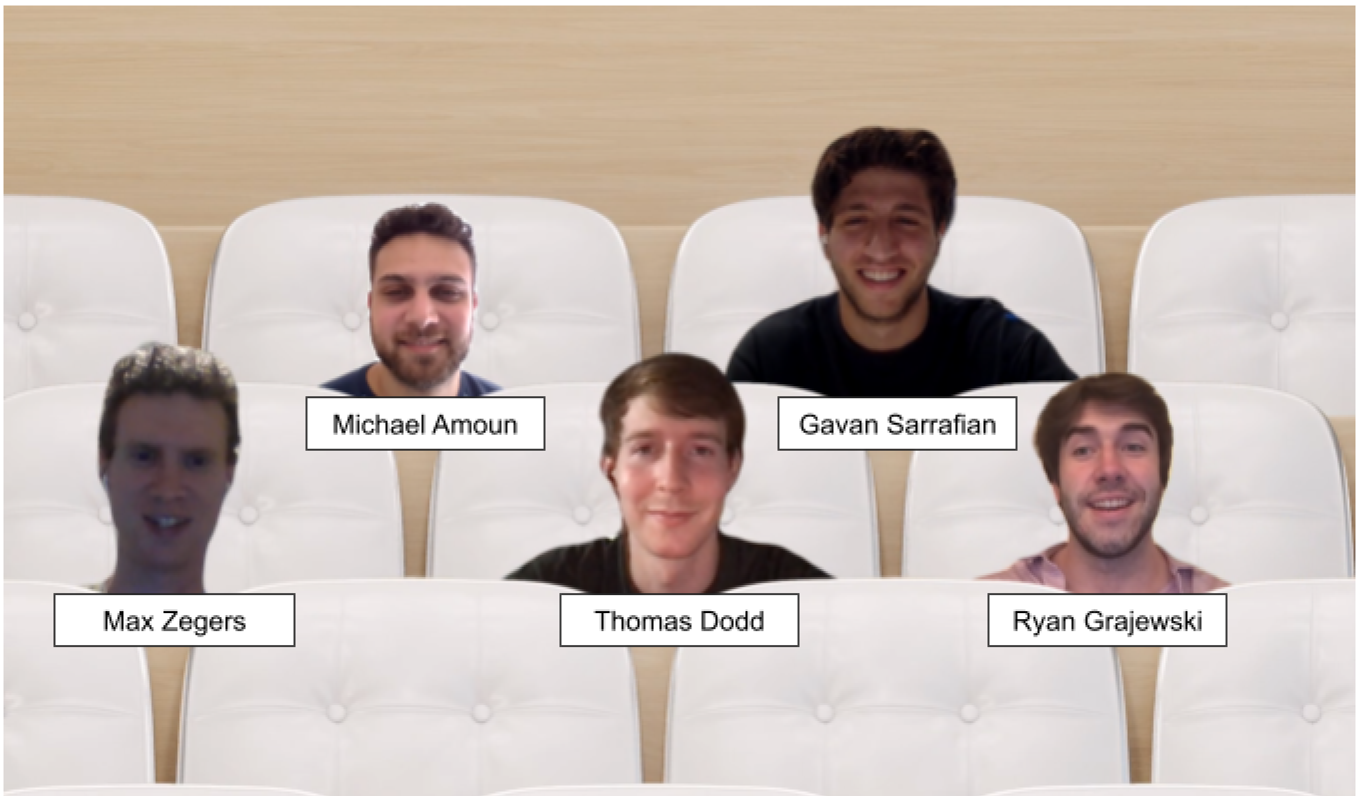
Team Report 1 (Due 09/25)

Team: Space Cowboys



Professor: Dr. Julie Linsey

Table of Content

Executive Summary:

NASA has launched project Artemis which has the goal of establishing a long-term presence on the Moon. Due to the high cost of transporting materials from Earth, one of the many challenges will be determining ways to use in-situ resources (ISRU) to create a sustainable environment. Our team, The Space Cowboys, have begun designing a product that will solve one piece of this problem; enabling the production of lunar infrastructure. Our product will extract Anorthite from bulk regolith and refine it through various processes in order to output aluminum extrusions. To achieve this, we had to research the problem to develop a fundamental understanding of the mission and science, quantify the customer needs, and structure the product's functions.

Our first approach involved creating a mission statement that revolved around the guidelines listed in NASA's 2023 BIG Idea Challenge. To fully understand our mission statement we worked together to generate creative metaphors and intuitive analogies. The metaphors focused on the user experience and were intended to spark emotions for our customer while the analogies were focused on the functions of the product. Additionally, we did an elaborate study of the customer needs using Green's CNA method. This methodology helped direct our research efforts which allowed us to consider factors related to our products' usage application, usage in the environment, and the characteristics of our customer. With all the information gained through discussion and research, we constructed a detailed function tree to summarize the individual actions involved in our overarching goal of refining bulk regolith. Engaging in this approach helped align our efforts moving forward and made the opportunity gap of our product clear.

The second approach consisted of completing a House of Quality (HOQ) and constructing black box diagrams centered around the function of refining bulk regolith. The black box diagrams helped us visualize the possible inputs and outputs of our system in order to achieve our function. For the HOQ, we developed the customer needs addressed in Green's CNA method and listed the appropriate engineering requirements to meet these needs. We then quantified the importance of each customer's needs by rating the relationship strength to the engineering requirements. Furthermore, we coded the correlation between the engineering requirements to themselves. Doing this helped rank the importance of each engineering requirement allowing us to distribute our efforts accordingly. This ensures we will adequately meet the customer needs during the future ideation steps.

Further development will be updated as additional research is acquired and idea generation sessions are conducted.

Introduction:

This project is part of NASA's BIG Idea Challenge, which is looking for new technologies and designs related to a lunar forge. This will aid in processing lunar regolith into resources for developing infrastructure on the moon as part of NASA's Artemis mission [1]. The Artemis mission is the first step to developing a permanent human presence on the Moon as well as a future jumping off point for humans to reach Mars [2]. There are several processes available for development within the lunar forge project: prospecting for ore, refining ore into usable metal, feedstock forming, extrusion methods, and testing of metals.

This project will focus on refining metal from bulk lunar regolith because metal refinement is an essential first step in the production life cycle of lunar metals used for structural components. Through extensive research into many processes along the metal production pipeline, this design space was selected as the most inspiring and impactful opportunity to progress the lunar settlement missions forward. Similar refinement systems exist on Earth for resources found on Earth, but this project must be adapted to new challenges presented by the lunar environment [20]. The lunar forge must function on the moon's surface while being both durable and economical, and must be designed to meet NASA's regulations. The scope of this project is limited to the NASA Big Idea Challenge and its guidelines for a successful proposal. This report describes the initial design techniques used to develop a novel system aimed at the process for refining lunar regolith into a usable resource as part of the overall metal production pipeline.

Mission Statement:

To design, model, and validate a system for use on the moon that accomplishes a targeted process along the metal production pipeline using bulk in situ regolith as a material input. The processes that have been elected for exploration comprise ore extraction from bulk regolith and beneficiation/refinement.

Product Description (single, concise focused sentence):
An innovative system that refines excavated lunar regolith to extract feedstock material for the lunar forge.

Key Business or Humanitarian Goals (schedule, gross margin/profit or break-even point, market share, advancement in human needs):
To reach the limit of existing metal extraction sources by accessing the useful naturally occurring materials of the moon.

Primary Market (Brief phrase of market sector/group):
The primary market for this system is aerospace technology research and development industries aimed at sustainable metal production for use in future space exploration missions. NASA and all lunar forge constituents/contractors operating the metal forge pipeline.

Secondary Market:
Materials excavation and forging occurring in harsh environments on Earth. (Ex: Highly abrasive, low energy availability, extreme temperature, and low pressure environments).

Key assumptions or uncontrolled factors (e.g.cannot be determined at beginning or will require significant effort later for validation):
- Assume we are working with current status and plans for the lunar forge and the Artemis program.
- Assuming the payloads will land safely on the moon.
- Assume that the environmental conditions are as described by NASA

Stakeholders (1-5 word statements of customer sets):
NASA, astronauts interacting with the forge, future generations of humans living on different planets, future engineers/lunar or mars missions.

Avenues for Creative Design:
- Method for obtaining the metal from the regolith (magnetic field, sensors, etc.)
- How much regolith can we process and how fast can we process it
- Uncharted innovative automation solutions for this application; vision tracking and sensing, shaker tables, bowl feeders, step feeders, etc.

Scope Limitations (List of limitations that will bring back the design team from "solving the world's problems"):
- Virtual Group Members/Meetings
- Duration: 1 Semester
- Cost Limit: $200/person
- Limited to the moon
- Limited to the software tools and online resources available to Georgia Tech students
- Limited to the scope described in the NASA BIG Ideas challenge.

Project Background:

It has been nearly 50 years since the last Apollo mission landed humans on the moon. Over the past decade, there have been technological advancements that paved new ways to imagine future space exploration. One recent technological advancement is the increase in privately owned space companies successfully accessing space in cost-effective ways. One such company named SpaceX has accomplished various feats like successfully docking NASA astronauts at the ISS and drastically decreasing the cost per launch by landing their Falcon boosters back on Earth for reuse. Additionally, newer companies such as Relativity Space, are further improving the manufacturing cost by utilizing new technologies in additive manufacturing to print their rocket's structure and engines making space travel more accessible than ever. These advancements as well as others have propelled our generation in a modern day space-race to establish a presence on the moon and one day on the martian surface of Mars.

In Greek mythology, Artemis is the sister of Apollo. Artemis is NASA's present day mission with the goal of establishing a long-term human presence on the moon. In order to sustain long-term human life on the moon, NASA will need a reliable method for producing metals for lunar infrastructure including pressure vessels, piping, and support structures [1]. This project will need to function in the lunar environment and utilize resources available on the Moon, including ilmenite and anorthite.

3.1 | Subject Matter Research Results

Extensive research pertaining to the NASA Big Ideas Challenge was conducted to better understand the usage application, the usage environment, and related solution requirements. For this project, the scope of our research was limited to areas pertaining to the lunar environment as the context of the design problem, as well as areas related to the metal refinement/beneficiation process that is part of the overall metal production pipeline.

An understanding of the lunar environment is critical before tackling the design problem itself. Our research results relating to the lunar environment yielded valuable information regarding the surroundings, weather/climate, available physical design space or storage, parts, maintenance, energy availability, and cost. The moon's surface environment is nearly a vacuum with no atmosphere. Also, lunar dust, radiation from the sun, solar winds, and much lower gravity are other environmental factors worth noting. Additionally, extremely low temperatures of -253C and extremely high temperatures of 120C are present on the lunar surface. Regarding energy availability, NASA has a fission surface power project in the works that can currently provide 40 kilowatts of power, which is enough to power 30 households for 10 years. This device may provide power for the Lunar Forge base.

Our usage application research showed that the greatest opportunity for impact on the progress of the Lunar Forge missions is the design space pertaining to refinement and beneficiation of lunar ore in the metal production pipeline. The primary function of the system should extract metal ore from bulk lunar regolith or refine those ores into usable components down the pipeline of metal production. This design space was identified as opportunistic because it is the one aspect of the metal production pipeline that currently does not have an operating solution – other processes like additive metal manufacturing have been a hot topic for lunar research whereas metal refinement has been a slightly neglected area. Continuing from this, the system will need to be transported from Earth to the moon and occasionally the system might need to be moved depending on the environment or changes with other activities on the moon. Finally, exterior cleaning may be a consideration as lunar dust can deteriorate the exterior of any structure on the moon due to its abrasive qualities.

The two existing and abundant metal ores available for the refinement/processing design space are Anorthite and Ilmenite. The NASA BIG Idea Challenge description document provides some helpful background on these two metal ores[1]:

Ilmenite Ore ($FeTiO_3$)	**Anorthite Ore ($CaAl_2Si_2O_8$)**
● 4th most abundant mineral on the lunar surface ● Likely candidate for oxygen production with the byproducts being iron and titanium dioxide ● Is paramagnetic and can be sorted via magnetism ● Iron can be extracted as a byproduct and converted to feedstock ● Titanium Dioxide is another byproduct and can be reduced to titanium and oxygen ● Titanium can be used to form wire feedstock for Electron Beam Fabrication (EBF)	● Very similar chemical properties to Bauxite found on earth - can be used as a substitute in the lunar environment ● Can be separated from lunar highland regolith using mechanical methods ● Aluminum can be extracted as a usable byproduct using similar methods to aluminum refinement on earth ○ Various chemical and electromechanical methods can be used to produce refined aluminum

There are several unique system requirements pertaining to the refinement process of both of these ores. Part of these system requirements can be extrapolated from the processes that exist on earth for refining similar metals.

For Ilmenite, extensive documentation exists on how to extract and refine titania slag from Ilmenite ore found in South Africa. On the lunar surface, Ilmenite is one of the most abundant minerals, having been produced as part of lunar magma at around 1200°C [23] There are two primary routes that can be taken to upgrade Ilmenite into a usable feedstock where the usable metal output is Titanium or TiO_2. For our purposes, Titanium is a less desirable metal output than iron, but understanding the general process requirements is helpful. A first process is ilmenite smelting, which takes place in a liquid state and yields a titania-rich slag and molten iron as byproducts. For this process, the system is required to heat the metal ore up to 1650°C to achieve the liquid state, and this is typically done using an electric furnace in order to provide the adequate energy input [24]. A second process involves Synthetic Rutile which utilizes solid-state reactions to produce metallic iron and rutile. Iron can then be extracted via leaching[24]. The takeaways from research on these processes is that ilmenite smelting is very energy intensive and can be rather unstable depending on the amount of input energy and carbon available to react with. In the context of the lunar surface, energy and carbon are two things that are not abundant. Thus, the major consideration here is how to balance the energy constraints with the need to produce a large amount of metal feedstock for other parts of the metal production pipeline.

Anorthite is closest in composition and chemical properties to the metal ore Bauxite that is found here on Earth. Processes used to generate aluminum feedstock from Bauxite are also heavily documented, and while Anorthite is not typically used to produce Aluminum on Earth, it is being considered due to the depleting levels of Bauxite. From NASA's "Space Resources and Space Settlements" research document, the most researched and viable process from extracting aluminum from anorthite is the "lime-soda sintering process" [25]. However, This process is incredibly resource dependent, and for every 1 mole of anorthite, 3 moles of $CaCO_3$ and 1 mole of Na_2CO_3 are required as consumable reactants [25]. The Lime-soda process also requires a significant amount of water if leaching methods were desired as the final extraction method. Other processes are currently being researched such as the use of Alumina production to arrive at aluminum as the end product. Vacuum Distillation, Sulfuric Acid Leaching, and Hydrochloric Acid Leaching are all other known ways to produce alumina [26]. The takeaway from these lesser-used methods is that Anorthite may be an attractive metal to focus efforts on for this project due to the lower temperature requirements compared to Ilmenite. A drawback, however, is that these processes typically require some form of carbon recycling method which would add further complexity to the overall system design [26].

3.2 | Customer Needs Research Results

1. System must produce a usable product or by-product to continue down the metal production pipeline.
    a. Reference Green's CNA a0
2. System needs to be capable of operating in the extreme environment on the moon's surface, including precautions for lunar dust abrasion, low temperatures, and minimal available energy sources.
    a. Reference Green's CNA e0-e9
3. System needs to be easy to install and operate either by astronaut or robot, or completely autonomously.
    a. Reference Green's CNA c3, c6
4. System should either be assembled on-site on the moon, or lightweight and compact enough to be transported from Earth.
    a. Reference Green's CNA c3
5. System should run off available energy sources on the moon.
    a. Reference Green's CNA e8
6. System should be safe to operate, and safe to operate autonomously without hazard to the operator or any other processes along the metal production pipeline.
    a. Reference Green's CNA e7, e8
7. System intake volume should allow for adequate and beneficial output volume when considering time to operate
    a. Reference Green's CNA a0, a1

Customer Characteristics helped define important end user factors such as the user, the user skills, physical ability, time, and safety expectations. The end user is the astronaut or lunar scientist, and the ultimate customer is NASA and BIG Idea Challenge judges. The user will be unfamiliar with the task in the early stages, but should become more familiar performing the tasks after repeated usage. Additionally the users' range of motion and space suite dexterity are limited. Safe thermal energy levels, precautions against flammability and combustion are critical customer safety expectations. Mission length of over 10 years is expected, with the understanding that the system should continue to function from when it is built to future Mars missions planned in the 2030's.

Customer Needs Analysis (Green's CNA)

******PASTE GREENS TABLE HERE**** (WHEN COMBINING PDFS)******

Metaphors:

1. Netflix for lunar metal ores: Netflix changed the way people consumed entertainment – rather than driving to a Blockbuster and renting a movie, they became available on-demand. This product removes the need to "drive" to earth for metal ores.

2. A Microwave: microwaves make getting a bite to eat quick and easy by using microwave meals, which cuts down on food prep time and cost. This product cuts down the cost and time which is currently required for obtaining metal products on the moon.

3. A Camera Lens: Enables the researchers and lunar forge team to see refining methods and systems from a new perspective. A photographer uses various lenses to capture new perspectives and new views.

4. A Car Headlight: Car headlights enabled people to travel without sunlight. This product will enable lunar colony expansion without the need for Earth's supplies.

5. A Make-Over Salon for Moon Rocks: people enter a salon wanting a make-over, and leave looking and feeling new and confident. In the same way, this system takes in bulk moon rocks and refines them so they leave as new, confident, and usable metal ores.

6. Curbside Pickup: The convenience of curbside pickup will be relatable to our product as the rest of the lunar base will have the usable materials ready to use at minimal effort or travel.

7. A Hawk Searching for Prey: Hawks hunt for small prey while flying at high altitudes. To humans this is very impressive and is similar to how our system will search for valuable metals.

8. Self Driving Car: A futuristic system that can accomplish a complex task with little input. The technology is improving but is not perfect yet, but could improve how people travel. It has the possibility to drastically improve the efficiency of a lunar colony if done correctly.

9. An Amazon Factory: Over the last decade, Amazon has become the leader in selling and shipping products to customers. This metaphor speaks to our system's ability to continuously and autonomously extract metal from regolith, similar to how you can imagine an Amazon factory is constantly shipping out products day in and day out.

10. Eating Mardi Gras/King Cake: It's exciting to find the prize (plastic baby) in the cake that you want to find while eating it. If you don't get the prize you still get to eat cake. The system will go through regolith with a chance of finding something valuable, if not still benefit from any potential raw materials.

- These metaphors help capture the emotions needed for this design project
- The final product will drive human expansion in space, so it must be innovative and exciting
- The design must also captivate potential judges

Intuitive Analogies:

1. A Fish Net for Lunar Resources: Searching a large area or large volume of water for a limited number of valuable fish.

2. Catching a Lobster: Throwing out a trap and hoping you come up with something valuable. The trap helps secure something specific

3. A Gold Mining Sifter for Moon Rocks: gold miners would use Sluice Boxes to pan for gold nuggets among larger rocks. This system can be thought of as a sluice box for extracting usable ore.

4. Pasta Strainer: removes the needed pasta from the unwanted water

5. Separating Oysters and Pearls: Pearls possess a much higher value than the oysters meat and shells and many oysters often searched in high volumes to locate the rare and valuable pearls.

6. The Cotton Gin of Lunar Natural Resources: A revolutionary and innovative new tool to provide a separator solution for a previously manual task.

7. Egg Separator: Device separates the yolk from the egg whites to allow for the use of each element of the egg individually

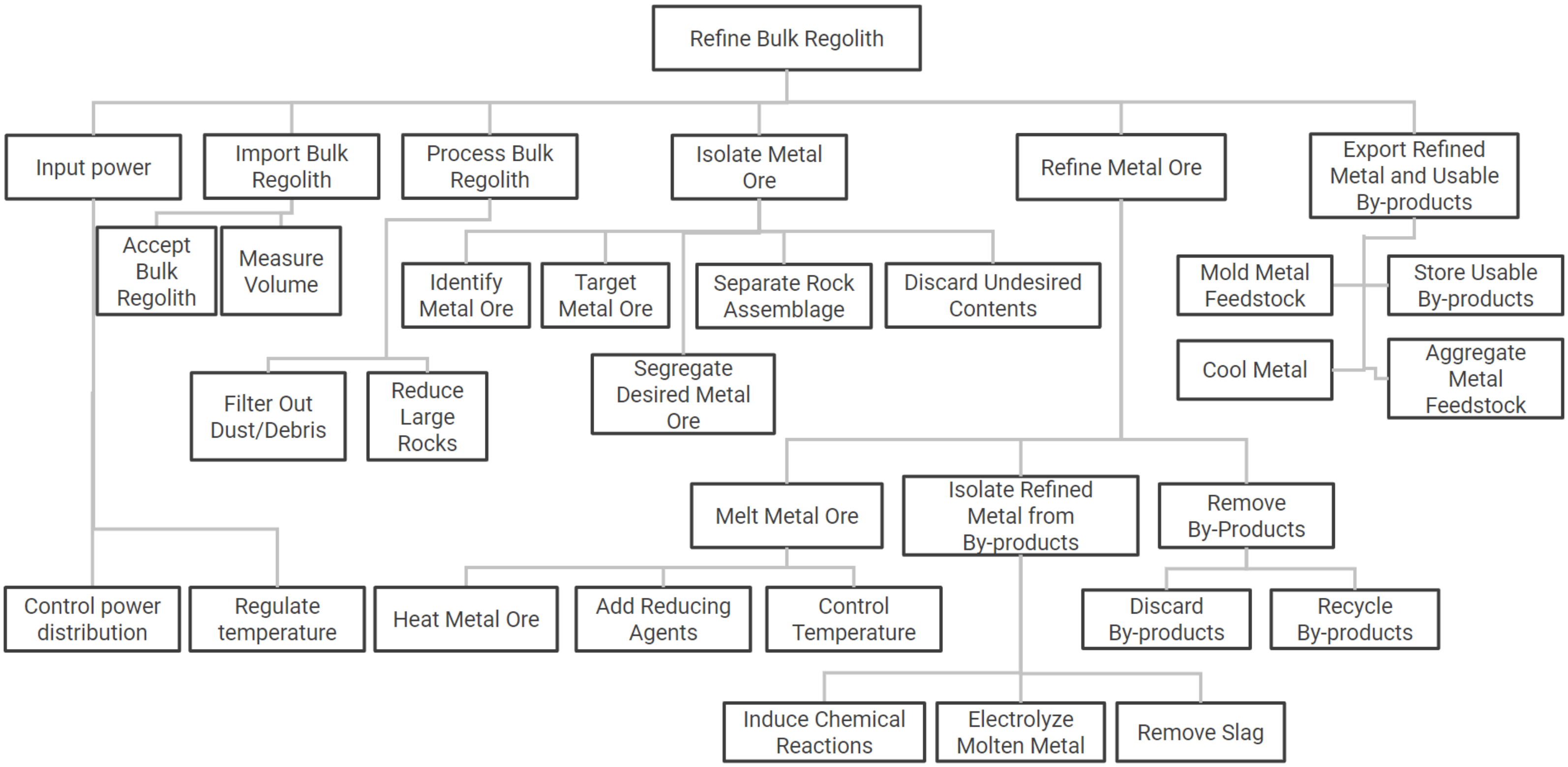
8. Camping Stove: A tool that you can bring while camping or traveling away from civilization to make/process food without needing to go back and forth between the woods and civilization.

9. Scooping Litter: Dirty job separating out waste from a main resource.

10. A concrete recycler: Used for separating steel rebar from waste concrete. This allows the separate materials to become useful for future projects.

- This analysis helps get a better understanding of the functions of this design in a simple way
- Each analogy is on a different topic, but still paints a picture of what the design needs to do
- The design must separate one thing from something else and be able to process that "one thing" on the moon

Function Tree:



- The function tree helped develop a clear vision of what the final design needs to do. It also helps to clarify the scope of what we need to design for.
- The clear understanding of the functions will be useful in the ideation phase, where we will develop solutions to each phase of the refining process.

House of Quality:

Engineering Requirements (correlation matrix)

Engineering Requirements	# of human input steps	Max Thermal Expansion / Contraction of Components	Heat Dissipation	Minimum Input volume (amount of regolith it can accept)	Required Power Input	metal output volume	Cost of prototype (proposal) development	Functional lifespan	Maintenance intervals	# of Failsafe Measures	Overall System Dimensions	Volumetric Repeatability of output metal	Average Component repair cost	Resist ionizing radiation energy	Time Required for Assembly Process	Cycle time	Overall System Weight	Refinement Repeatability of output metal	Handle varying quality of regolith	# of loading cycles until failure	Mininum Internal (for smelting)Operating Temperature
# of human input steps																					
Max Thermal Expansion / Contraction of Components																					
Heat Dissipation																					
Minimum Input volume (amount of regolith it can accept)																					
Required Power Input																					
metal output volume																					
Cost of prototype (proposal) development	+	⊕			⊕																
Functional lifespan		⊕	⊕		⊕		⊕														
Maintenance intervals	+						+	⊕													
# of Failsafe Measures	-				+		+	⊕	-												
Overall System Dimensions			-				+														
Volumetric Repeatability of output metal				⊕		+		+													
Average Component repair cost		+	+				+	+	-	-	+										
Resist ionizing radiation energy							+	⊕	+												
Time Required for Assembly Process											+		-								
Cycle time	-			+	+	+			-	+		-									
Overall System Weight							⊕				⊕				+						
Refinement Repeatability of output metal						+					-					-					
Handle varying quality of regolith				+		+						+				+					
# of loading cycles until failure		+		-				⊕	⊕				+	+		+		+	+		
Mininum Internal (for smelting)Operating Temperature		⊕			+			-						+							
Direction of Improvement	↓	↑	↑	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	○	↓	↑	↓	↑	↑	↑	↑

Engineering Requirements

Customer Requirements	Importance (1-10)	# of human input steps	Max Thermal Expansion / Contraction of Components	Heat Dissipation	Minimum Input volume (amount of regolith it can accept)	Required Power Input	metal output volume	Cost of prototype (proposal) development	Functional lifespan	Maintenance intervals	# of Failsafe Measures	Overall System Dimensions	Volumetric Repeatability of output metal	Average Component repair cost	Resist ionizing radiation energy	Time Required for Assembly Process	Cycle time	Overall System Weight	Refinement Repeatability of output metal	Handle varying quality of regolith	# of loading cycles until failure	Mininum Internal (for smelting)Operating Temperature
Controls are intuitive	4	◎																				
Functions in lunar environment	10		◎	◎		◎			◎	○	Δ				◎					◎	○	Δ
Durable	8		◎	◎					◎	◎	○		Δ		◎			○	Δ	○	◎	○
Easily transported	7					Δ	Δ					◎				○		◎				
Simple Setup/assembly	7	Δ								○		○				◎						
Minimal power requirements	10		Δ	Δ		◎	◎	○					Δ				○	○	Δ	○		○
Volume (ore extracted and refined)	9				◎	○	◎					○	◎						◎	○	○	○
Safe to operate	6	○	Δ	Δ				○			◎					Δ						Δ
Low Cost	2	Δ	○	○		◎	○	◎		Δ		○	○	◎		Δ	Δ		○		○	○
Reliability	6		○	○					◎	◎	◎		◎		○		○		◎	◎	◎	
Quick Cycle Time	7	Δ			○	○	○						○				◎	○	○			
Simple to repair	6	○							○	○						○						Δ
Targets		XXX Steps	XXX	XXX BTU/hr	XXX m^3	XXX kW	XXX m^3	$180,000	XXX years	XXX years	XXX Failsafes	XXX m^3	+/- 5% Volume Yield	$	100 MeV - 1 GeV	XXX hrs	XXX metal/hr	XXX kg	+/- 5% Purity Yield	>= 75% useable material	XX Cycles	XX Celsius
Absolute Importance		88	202	202	102	253	205	66	234	197	142	117	180	18	180	110	113	138	180	225	189	109
Relative Importance (%)		2.71	6.22	6.22	3.14	7.78	6.31	2.03	7.20	6.06	4.37	3.60	5.54	0.55	5.54	3.38	3.48	4.25	5.54	6.92	5.82	3.35
Rank		19	5.5	5.5	18	1	4	20	2	7	12	14	10	21	10	16	15	13	10	3	8	17

Key	Value	Symbol
Relationship Matrix	Strong (9)	◎
	Medium (3)	○
	Weak (1)	Δ
Correlation Matrix	Strong positive correlation	⊕
	Positive correlation	+
	Negative correlation	-
	Strong negative correlation	⊖
Improvement Direction	Positive direction	↑
	Negative direction	↓
	Stays the same	○

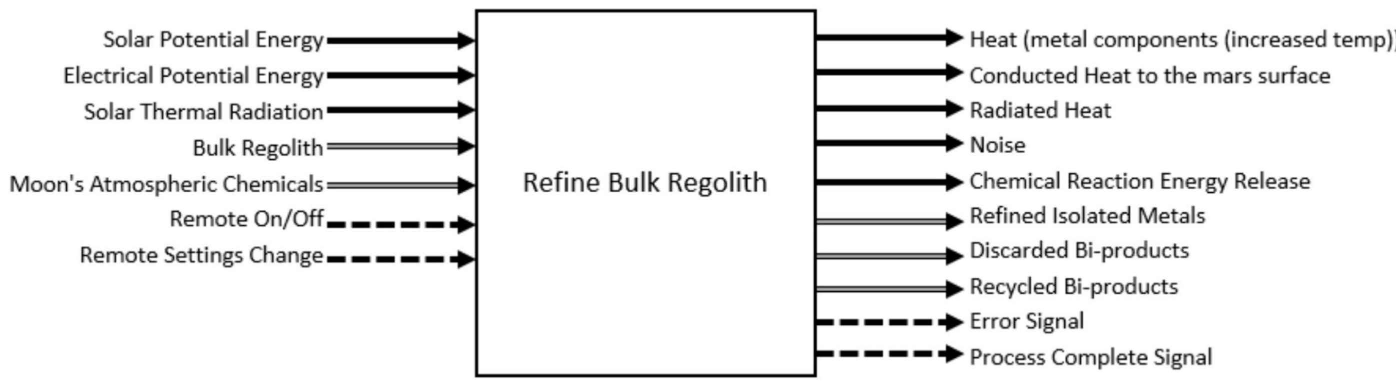
- The House of Quality helped identify what engineering requirements will be most critical to the design. The required system power, the functional lifespan, and the ability for the system to handle a range of regolith are some of the most important requirements.
- This analysis also helped us understand how all of the requirements relate and provides a roadmap for optimizing the system in the future.
- It also helped analyze the system through the eyes of the customer. This ensures that the design will focus on what needs are most important to the customer.

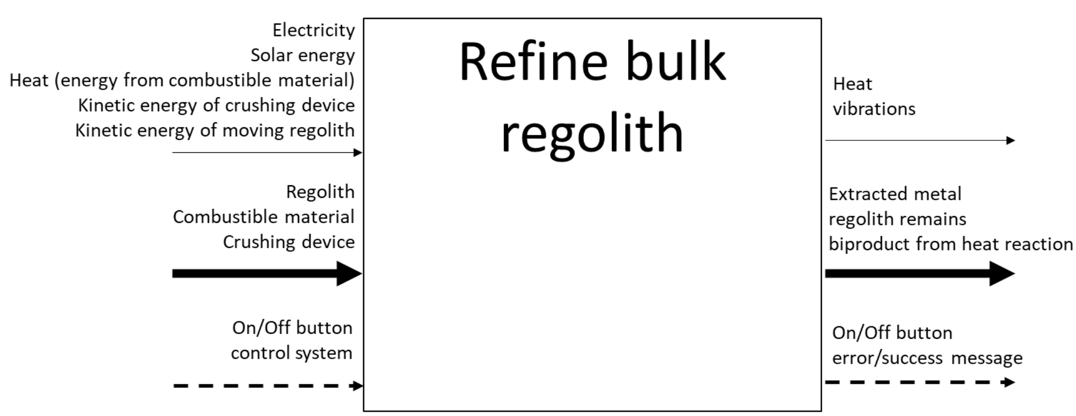
Customer Requirements/Engineering Specifications:

No.	Customer Requirement
1	Controls are intuitive
2	Functions in lunar environment
3	Durable
4	Easily transported
5	Simple Setup/assembly
6	Minimal power requirements
7	Adequate Production Volume (ore extracted and refined)
8	Safe to operate
9	Low Cost
10	Reliability
11	Quick Cycle Time
12	Simple to repair

Engineering Specifications				
No.	**Engineering Requirement**	**Metric**	**Source #**	**Source**
1	# of human input steps	qty		Undefined value. Dependent upon final design
2	Max Thermal Expansion / Contraction of Components	m/°C		Undefined value. Dependent upon final design
3	Heat Dissipation	BTU/hr	16	https://lunar.gsfc.nasa.gov/images/lithos/LROlitho7temperaturevariation27May2014.pdf
4	Minimum Input volume (amount of regolith it can accept)	m^3	17	https://curator.jsc.nasa.gov/lunar/letss/regolith.pdf
5	Required Power Input	kW	18	https://journals.sagepub.com/doi/pdf/10.1177/09544100211029433
6	metal output volume	m^3		Undefined value. Dependent upon final design
7	Cost of prototype (proposal) development	$180,000	1	https://bigidea.nianet.org/wp-content/uploads/2023-BIG-Idea-Challenge-Proposal-Guidelines.pdf
8	Functional lifespan	XX years	7	https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf
9	Maintenance intervals	XX years		Undefined value. Dependent upon final design
10	# of Failsafe Measures	List	19	https://www.machinedesign.com/news/article/21829303/safety-in-automation
11	Overall System Dimensions	m^3	20	https://hackaday.com/2021/12/13/mining-and-refining-from-red-dirt-to-aluminum/
12	Volumetric Repeatability of output metal	+/- 5% Volume Yield		Undefined value. Dependent upon final design
13	Average Component repair cost	US$		Undefined value. Dependent upon final design
14	Resist ionizing radiation energy	100 MeV - 1 GeV	21	https://www.nasa.gov/centers/ames/research/technology-onepagers/radiation-effects-materials.html
15	Time Required for Assembly Process	hrs		Undefined value. Dependent upon final design
16	Cycle time	metal/hr		Undefined value. Dependent upon final design
17	Overall System Weight	Kg	20	https://hackaday.com/2021/12/13/mining-and-refining-from-red-dirt-to-aluminum/
18	Refinement Repeatability of output metal	+/- 5% Purity Yield		Undefined value. Dependent upon final design
19	Handle varying quality of regolith	>= 75% useable material		Undefined value. Dependent upon final design
20	# of loading cycles until failure	XX cycles		Undefined value. Dependent upon final design
21	Minimum Internal (for smelting)Operating Temperature	Max temp of process	22	https://pubs.geoscienceworld.org/msa/ammin/article-abstract/65/3-4/272/41130/The-melting-and-breakdown-reactions-of-anorthite?redirectedFrom=PDF

Black Box Diagrams:





- These black diagrams assisted in the identification of energy, material, and signal flows into and out of the system
- By comparing and contrasting the five diagrams the team can identify the sources of energy to be utilized and the signal methods to interact with the system
- The black box diagrams were helpful because they helped us come to an agreement on the desired output material

Conclusion:

Refining lunar regolith is a novel process that is not currently being done. NASA is working to fill this opportunity through the Big Ideas Challenge. The initial steps of the design helped identify what is needed for the final design to meet both the customer needs and the limitations of the project. Techniques like Green's CNA and the House of Quality specifically aided in the understanding of our customer needs and how to quantify their importance when stacked up against our engineering requirements. Through this, we concluded that the three most important engineering specifications for our design are the required power input, functional lifespan, and our product's ability to handle varying qualities of regolith. Following Green's Customer Needs Analysis, extensive research was conducted to better understand the design problem. An understanding of the lunar environment was critical prior to tackling the design problem itself. Moreover, a better understanding of the ores in the lunar bulk regolith was essential to better understanding the solution requirements.

Furthermore, other techniques like the black box diagrams and function tree were useful in summarizing the actions needed to successfully achieve our goal of extracting Anorthite from bulk regolith and refining it into valuable in-situ materials. While generating our list of metaphors, we reflected on how we wanted our customers' experience to be when interacting or thinking about our products' capabilities. Reflecting on this allowed us to brainstorm creative phrases that would capture this emotion. These emotions were related to what one would feel when witnessing an innovative, easy but complex, and versatile product. On the contrary, when generating the analogies we were focused on the physical functions of our product. Some of our products' functional properties that we wanted to portray are to obtain, separate, provide, and refine. Through these exercises we were able to accurately distinguish between how we want our product to be experienced through the customer's perspective as well as how we wanted our product's physical function to be interpreted.

The next steps in this project will involve brainstorming solutions that can perform the defined functions while still meeting the customer needs and project limitations. This will be done using mind maps, the 6-3-5 method and morph matrices. Once a comprehensive list of ideas is generated, the team will narrow down solutions and then begin a technical evaluation to get a feasible solution.

Team Member Contributions:

All methods were completed during group meetings. The descriptions included for each section were completed by the following members:

Executive Summary: Gavan Sarrafian
Introduction: Max Zegers
Mission Statement: Ryan Grajewski, Thomas Dodd
Project Background: Gavan Sarrafian, Michael Amoun, Max Zegers
Metaphors: Completed as a team
Intuitive Analogies: Completed as a team
Research Results: Michael Amoun, Ryan Grajewski, Thomas Dodd
Customer Needs Analysis and Green's CNA: Completed as a Team
House of Quality: Completed as a Team
Black Box Models: Michael Amoun (1), Max Zegers (1), Ryan Grajewski (1), Gavan Sarrafian (1), Thomas Dodd (1)
Function Tree: Completed as a Team
Metaphors: Completed as a Team
Engineering Specifications: Completed as a Team
Conclusion: Max Zegers, Gavan Sarrafian, Michael Amoun
Resources: Michael Amoun & Max Zegers formatting, All team members contributed different sources
Team Contract: Thomas Dodd

APPENDIX

Resources:

1 https://bigidea.nianet.org/wp-content/uploads/2023-BIG-Idea-Challenge-Proposal-Guidelines.pdf
Title: "NASA Big Idea Challenge", Author: NASA, Date of Access: September 11, 2022

2 https://www.nasa.gov/press-release/as-artemis-moves-forward-nasa-picks-spacex-to-land-next-americans-on-moon
Title: "As Artemis Moves Forward, NASA Picks SpaceX to Land Next Americans on Moon", Author: Brian Dunbar, Last Edited: April 22, 2021, Date of Access: September 14, 2022

3 https://history.nasa.gov/alsj/TM-2005-213610.pdf
Title: "The Effects of Lunar Dust on EVA Systems During the Apollo Missions", Author: James R. Gaier, Published: March 2005, Date of Access: September 14, 2022

4 https://bigidea.nianet.org/wp-content/uploads/SLS-SPEC-159-Cross-Program-Design-Specification-for-Natural-Environments-DSNE-REVISION-H.pdf
Title: "CROSS-PROGRAM DESIGN SPECIFICATION FOR NATURAL ENVIRONMENTS (DSNE)", Author: NASA Published: August 12, 2020, Date of Access: September 14, 2022

5 https://sservi.nasa.gov/?question=sound-moon#:~:text=However%2C%20the%20Moon%20is%20in,no%20sound%20on%20the%20Moon.
Title: "Sound on the Moon", Published: August 25, 2010, Date of Access: September 14, 2022

6 https://www.space.com/18175-moon-temperature.html
Title: "What is the temperature on the moon", Author: Doris Elin Urrutia, Tim Sharp, Published: February 28, 2022, Date of Access: September 12, 2022

7 https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf
Title: "NASA's Plan for Sustained Lunar Exploration and Development", Date of Access: September 14, 2022

8 https://www.nasa.gov/mission_pages/tdm/fission-surface-power/index.html
Title: "Fission Surface Power", Author: Jennifer Harbaugh, Date of Access: September 14, 2022

9 https://standards.nasa.gov/sites/default/files/standards/NASA/B-w/CHANGE-1/1/NASA-STD-5008B-Revalidation-w-Change-1.pdf
Title: "PROTECTIVE COATING OF CARBON STEEL, STAINLESS STEEL, AND ALUMINUM ON LAUNCH STRUCTURES, FACILITIES, AND GROUND SUPPORT

EQUIPMENT", Author: NASA, Published: May 31, 2016, Date of Access: September 14, 2022

10 https://www.space.com/nasa-plans-artemis-moon-base-beyond-2024.html
Title: "NASA unveils plan for Artemis 'base camp' on the moon beyond 2024", Author: Meghan Bartels Published: April 03, 2020, Date of Access: September 14, 2022

11 https://www.nasa.gov/feature/a-next-generation-spacesuit-for-the-artemis-generation-of-astronauts
Title: "A Next Generation Spacesuit for the Artemis Generation of Astronauts" Published: October 8, 2019, Date of Access: September 14, 2022

12 https://bigidea.nianet.org/wp-content/uploads/2020/09/Artemis_Plan_NASAs_Lunar_Exploration_Program_Overview_September_2020.pdf
Title: "NASA's Lunar Exploration Program Overview", Published: September 2020, Author: NASA, Date of Access: September 14, 2022

13 https://standards.nasa.gov/safety-quality-reliability-maintainability
Title: "8000 - Safety, Quality, Reliability, Maintainability", Date of Access: September 14, 2022

14 https://www.aispacefactory.com/lina
(Company: AI Space Factory) Title: "LINA THE FIRST HUMAN FOOTHOLD ON THE MOON DEVELOPED IN COLLABORATION WITH NASA", Date of Access: September 14, 2022

15 https://www.youtube.com/watch?v=AIrH01N9AsE
Video Title: "HASSELL + EOC presents MARS HABITAT" Uploaded/Published: March 12, 2019, Date of Access: September 14, 2022

16 https://lunar.gsfc.nasa.gov/images/lithos/LROlitho7temperaturevariation27May2014.pdf
Title: "North Pole", Author: NASA, Date of Access: September 21, 2022

17 https://curator.jsc.nasa.gov/lunar/letss/regolith.pdf
Title: "Lunar Regolith", Author/Source: NASA Lunar Petrographic Educational Thin Section Set C Meyer - 2003, Date of Access: September 21, 2022

18 https://journals.sagepub.com/doi/pdf/10.1177/09544100211029433
Title: "Generating and storing power on the moon using in situ resources", Author: Alex Ellery, Date of Access: September 21, 2022

19 https://www.machinedesign.com/news/article/21829303/safety-in-automation
Title: "Safety in Automation", Author: Dan Hornbeck, Date of Access: "September 21, 2022"

20 https://hackaday.com/2021/12/13/mining-and-refining-from-red-dirt-to-aluminum/
Title: "MINING AND REFINING: FROM RED DIRT TO ALUMINUM", Author: Dan

Maloney, Published: December 13, 2021, Date of Access: September 21, 2022

21 https://www.nasa.gov/centers/ames/research/technology-onepagers/radiation-effects-materials.html
Title: “Space Radiation Effects Materials”, Author: NASA, Date of Access: September 21, 2022

22 https://pubs.geoscienceworld.org/msa/ammin/article-abstract/65/3-4/272/41130/The-melting-and-breakdown-reactions-of-anorthite?redirectedFrom=PDF
Title: The Melting and Breakdown Reactions of Anorthite at High Pressures and Temperatures, Published: 1 April 1980, Date of Access: September 21, 2022

23 http://eps.berkeley.edu/~wenk/TexturePage/Publications/1971-Lunar-ilmenite-CMP.pdf
Title: Lunar Ilmenite (Refinement of the Crystal Structure), Published: 29 October, 1970, Date of Access: September 23, 2022

24 https://www.saimm.co.za/Journal/v108n01p035.pdf
Title: Ilmenite Smelting: The Basics, Published: 1 February, 2008, Date of Access: September 23, 2022

25 https://ntrs.nasa.gov/api/citations/19790024054/downloads/19790024054.pdf
Title: Space Resources and Space Settlements, Published: 1979, Date of Access: September 23, 2022

26 https://lunarpedia.org/w/Lunar_Aluminum_Production#:~:text=Anorthite%20could%20be%20directly%20reduced,Aluminum%2C%20Calcium%2C%20and%20Silicon.
Title: Lunar Aluminum Production, Published: 10 April 2019, Date of Access: September 23, 2022

Team Contract:
ME 6102
Fall 2022
21 September 2022

Group Members:
Michael Amoun, Thomas Dodd, Ryan Grajewski, Gavan Sarrafian, Max Zegers

Preferred method of communication
- Group Messaging via Groupme for general communication

Preferred method of meeting
- MS Teams for general meetings, extended communication and decision making

File storage for team reports, team homework and all of team files
- Google Drive (sent to GT email accounts on September 7^{th})

Decision-making policy
- Majority Agreement, and,
- No major oppositions from team members

Participation
- All group members are expected to participate weekly during Teams meetings and provide an equal share of contribution to all group based assignments.

Expectation for attending group work meetings
- Attendance is expected for weekly meetings unless team members communicate a conflict in advance of the meeting.

Expectation for Class Meetings
- In-class group members are expected to meet in class at the scheduled class period time frame. Any absences should be communicated in advance of class.

Meeting Frequency
- Team meetings will occur once weekly on Wednesday's at 7pm and additional meetings will be scheduled as needed.

Team Communication with Professor
- One team member will email Dr. Linsey and copy all team members on email.
- In class members (Ryan and Thomas) will ask questions as needed during class.

Group Signatures:
(Please sign and date)

Michael Amoun: 09/19/2022
Ryan Grajewski 09/19/2022
Gavan Sarrafian: 09/19/2022
Thomas Dodd 09/20/2022
Max Zegers 09/19/2022