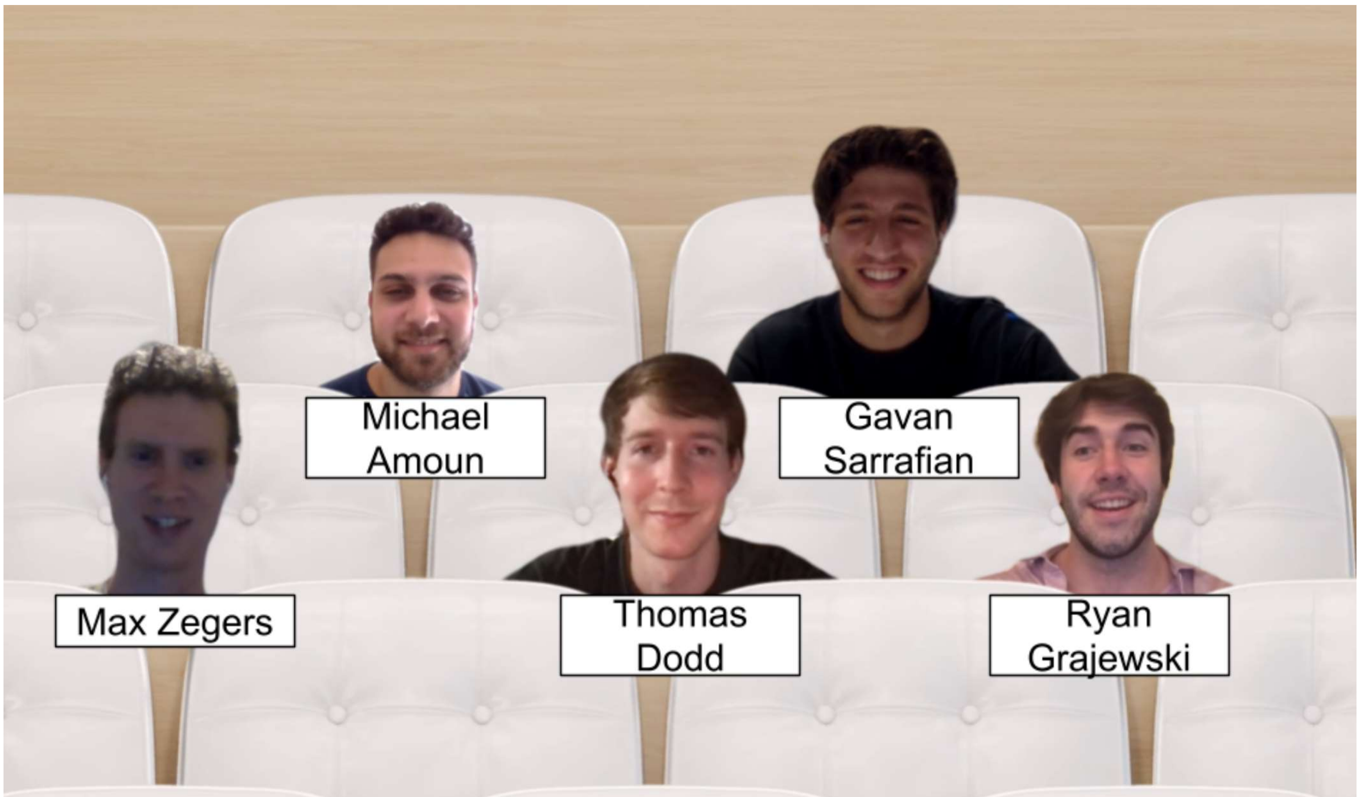
<u>Team Report 2</u>

Team: Space Cowboys
October 30, 2022



Professor: Dr. Julie Linsey

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1 | 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. Currently we are exploring three directions which relate to the identification of useful ore via spectroscopy technologies, establishing a robust pressure vessel to operate on the lunar surface, and utilizing the lunar environment to aid metal tempering/hardening processes.

First, we worked on developing the mission statement by brainstorming metaphors and analogies. Additionally, we reflected on the customers' needs by utilizing Green's CNA method. These methods helped us better understand the intent of our product, constraints around the project, and where to focus our research efforts. Furthermore, we generated function trees, black box diagrams, word trees, and a mind map to build on our initial ideas. These methods helped us visualize the potential functions our product could perform. Another milestone to developing our product involved completing a House of Quality (HOQ) by using the information obtained in the Green's CNA. We stacked up the customer requirements addressed in Green's CNA and listed the appropriate engineering requirements to meet these requirements. Each customer's needs were rated on its 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.

Our final phase of development began with sharing sketches, conducting research on related patents, and looking further into analogous domains and bio-inspired domains to spark novel ideas. As a team, we began down selecting until we were left with three main directions that are ripe for innovation. The three directions are identifying useful ore using spectroscopy technology, tempering/hardening metal by using the lunar environment, and developing a pressure vessel on the moon. Some challenges include, reducing the necessary maintenance and automating calibration, performing heat transfer without air, and achieving a tight tolerance while manufacturing on the moon, respectively. More research is being conducted to tackle this obstacles.

2 | Introduction to NASA's Big Idea Challenge

2.1 | 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.

2.2 | Mission Statement & Project Scope

- **Mission statement:** to design, model, and validate a highly innovative 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.

- **Product Description:** An innovative system that improves a critical facet of the refining process which transforms excavated lunar regolith into usable feedstock material for the lunar forge.

- **Key Business or Humanitarian Goals:** 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:**
    - 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.)
    - Uncharted innovative automation solutions for this application; vision tracking and sensing, shaker tables, bowl feeders, step feeders, etc.
    - Methods for increasing efficiency of manufacturing processes on the moon

- **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.

2.3 | Project Background

The task for this project is based on the NASA Big Ideas challenge. The current research area of opportunity is mining lunar regolith on the surface of the moon. Our objective is to research and locate a design conflict area that provides an avenue for creative and highly innovative design that progresses the lunar settlement missions forward. The lunar environment consists of many valuable ores and minerals that can be refined and transformed into usable infrastructure. The major intent is to design a product, method or device that aids in SITU refinement and manufacturing.

In order to sustain long-term human life on the moon, NASA has identified the need for a reliable method for producing metals for the purpose of manufacturing mission critical infrastructure on the moon. The desired end products or infrastructure include: storage vessels, extrusions, pipes, power cables, and supporting structures [1]. Many intricate steps are involved in transforming lunar regolith into these desired end products, so the project is expected to have a narrower scope surrounding one particular aspect of the metal production pipeline. This system in question will need to function in the lunar environment and utilize resources available on the Moon, including ilmenite and anorthite.

3 | Research Results

3.1 | Subject Matter Research Results

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.

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 [3],[4],[5]. Also, lunar dust, radiation from the sun, solar winds, and much lower gravity are other environmental factors worth noting [3],[4]. Additionally, extremely low temperatures of -253C and extremely high temperatures of 120C are present on the lunar surface [6]. 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 [8]. 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 already been undergoing experimentation. After exploring the refinement design space further, the sub-processes for identifying specific types of ore within regolith, separating ore types, and methods for treating metal have been noted as innovative areas ripe for innovation.

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.

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 refine Ilmenite into a usable feedstock where the usable metal output is Titanium or TiO_2. One potential 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 metal ore up t0 1650 C to achieve the liquid state, and this is typically done using a 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]. On the moon's 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. NASA has already begun researching energy sources to meet these constraints such as nuclear fission, or silicon photovoltaics [25]. Additional considerations will be to design a system that will function in the lunar environment; this includes but is not limited to, extreme temperatures, low gravity and high abrasivity.

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" [26]. 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 [26]. Vacuum Distillation, Sulfuric Acid Leaching, and Hydrochloric Acid Leaching are all other known ways to produce alumina [27]. 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 [27].

3.2 | Customer Needs Research Results

No.	Customer Needs Research Key Takeaways	Green's CNA Reference #
1	System must produce a usable product or by-product to continue down the metal production pipeline.	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.	e0-e9
3	System needs to be easy to install and operate either by astronaut or robot, or completely autonomously.	c3,c6
4	System should either be assembled on-site on the moon, or lightweight and compact enough to be transported from Earth.	c3

5	System should either be assembled on-site on the moon, or lightweight and compact enough to be transported from Earth.	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.	e7, e8
7	System intake volume should allow for adequate and beneficial output volume when considering time to operate	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 [7].

3.3 | Customer Needs Analysis (Green's CNA)

Ref. No	Context Factor	Question Prompts v1.0	Response Notes	Sources
HOW: Usage Application				
a0	task application	What specific purpose(s) will product be used for? How will the product be used?	The product will be used to extract or refine metal ore from bulk lunar regolith. The purpose it serves is part of the larger Lunar Forge functionality	1. https://bigidea.nianet.org/wp-content/uploads/2023-BIG-Idea-Challenge-Proposal-Guidelines.pdf
a1	task function	What major function(s) should the product provide?	The system should either extract usable metal ore from bulk lunar regolith, or refine those ores into further usuable components down the pipeline of metal production.	1. https://bigidea.nianet.org/wp-content/uploads/2023-BIG-Idea-Challenge-Proposal-Guidelines.pdf
a2	task quality	What quality of the primary function is needed?	The quality of the primary function should be medium to high. A good measure of validity is the efficiency with which the extraction or refinement process is performed.	1. https://bigidea.nianet.org/wp-content/uploads/2023-BIG-Idea-Challenge-Proposal-Guidelines.pdf
a3	transportation type & amount	How often, how far, and in what way will product be transported?	System parts will need to be transported from Earth to the moon. Occasionally the system might need to be moved depending on the enviornment or changes with other activites on the moon	2. https://www.nasa.gov/press-release/as-artemis-moves-forward-nasa-picks-spacex-to-land-next-americans-on-moon
a4	cleaning	How and where might the product be cleaned?	Exterior cleaning may be a consideration. Lunar dust can deteriorate the exterior of any structure on the moon due to its abrasive qualities, so cleaning in that form may be a factor. Internally, total system flush using specialized materials to clean the system throughput	3. https://history.nasa.gov/alsj/TM-2005-213610.pdf
WHERE: Usage Environment				
e0	surroundings	Where and in what type of surroundings will product be used? What in the surroundings might influence what the product must be like?	Moon's surface environment (nearly vacuum, no atmosphere), lunar dust, radiation from sun, low gravity	4. https://bigidea.nianet.org/wp-content/uploads/SLS-SPEC-159-Cross-Program-Design-Specification-for-Natural-Environments-DSNE-REVISION-H.pdf
e1	surroundings (sound)	How noisy are product surroundings? How much noise from the product is acceptable?	Noise is not a consideration	5. https://sservi.nasa.gov/?question=sound-moon#:~:text=However%2C%20the%20Moon%20is%20in.no%20sound%20on%20the%20Moon.
e2	weather/ climate	What weather/climate will product be exposed to?	Extremely low temperatures on Moon's surface (-253 C) Extremely high temperatures on Moon's surface (120 C)	6. https://www.space.com/18175-moon-temperature.html
e3	environment ruggedness	What objects and substances will product interact with? Will product be exposed to any unusual substances or conditions?	Lunar dust, high solar winds,	4. http://bigidea.nianet.org/wp-content/uploads/SLS-SPEC-159-Cross-Program-Design-Specification-for-Natural-Environments-DSNE-REVISION-H.pdf
e4	space (when in use)	How much space is available adjacent to product?	Nearly unlimited space, though location is constrained by distance from power sources (3.5Km). Must be able to function with other lunar forge components in the near surroundings. Potential space considerations for rocket transporting it to the moon.	7. https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf
e5	space (storage)	How and where will product be stored? How much space in transport vessel?	On the lunar surface. Transport vessel will likely be the Artemis series of spacecreft.	7. https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf
e6	thetics of surround	What are the surroundings of the site? Are there any hazzards to be aware of?	Lunar Enviroment, lack of gravity	4. http://bigidea.nianet.org/wp-content/uploads/SLS-SPEC-159-Cross-Program-Design-Specification-for-Natural-Environments-DSNE-REVISION-H.pdf
e7	naintenance & part cost & availability	What is the cost & availability of maintenance & parts?	Low maintenance availability. Replacement and maintenance cost will be high.	1. https://bigidea.nianet.org/wp-content/uploads/2023-BIG-Idea-Challenge-Proposal-Guidelines.pdf
e8	energy availability & cost	What is the cost & availability of possible energy sources (human, battery, gas, electric, biomass)?	NASA has a fission surface power project in the works that can currently provide 40 kilowatts of power - this is enough to power 30 households for 10 years. This device may provide power for the Lunar Forge base.	8. https://www.nasa.gov/mission_pages/tdm/fission-surface-power/index.html
e9	Coatings required	What types of coatings/barriers does the customer require? How will the product withstand corrosion and abrasion?	Coatings must conform to the standards stated by the customer/user. Coatings must withstand the temperature variation, abrasion resistance and durability stated in the attached source.	9. https://standards.nasa.gov/sites/default/files/standards/NASA/B-w/CHANGE-1/1/NASA-STD-5008B-Revalidation-w-Change-1.pdf
WHO: Customer Characteristics				

c0	user	Who will use the product? (Choose it? Buy it?) What user characteristics affect what the product must be like?	User: astronaught/scientist. Ultimate customer is NASA and BIG Idea Challenge judges	1. https://bigidea.nianet.org/wp-content/uploads/2023-BIG-Idea-Challenge-Proposal-Guidelines.pdf
c1	user skills & education	How experienced is the end user with the task?	The user will be unfamiliar with the task in the early stages. This is the first attempt at establishing a lunar forge. We expect the user to become familiar with the task once the operation is succesful and ongoing.	10. https://www.space.com/nasa-plans-artemis-moon-base-beyond-2024.html
c2	physical ability	Does the user have any physical conditions that may cause difficulty performing the task? (strength, control, range-of-motion, vision).	Range of motion and space suite dexterity are limited but improving (bulky gloves, limited vision range, etc.), lack of gravity	11. https://www.nasa.gov/feature/a-next-generation-spacesuit-for-the-artemis-generation-of-astronauts
c3	user tolerance for complexity	What is the most complex product the user is comfortable using? Must this product be less complex? How long is user willing to spend learning the product?	System should not be extremely complicated and should require minimal user time	1. https://bigidea.nianet.org/wp-content/uploads/2023-BIG-Idea-Challenge-Proposal-Guidelines.pdf
c4	relevant customs and practices	Are there any cultural practices or expectations related to this product?	Customer desires products that are innovative and ground breaking. Customer also desires products that are functional and inspirational. NASA also wants the U.S. to be a continued leader in space exploration in the international community.	12. https://bigidea.nianet.org/wp-content/uploads/2020/09/Artemis_Plan_NASAs_Lunar_Exploration_Program_Overview_September_2020.pdf
c5	xpectations: (purc	About how much will it cost to fund this project?	Limit of $180,000 to develop project	12. https://bigidea.nianet.org/wp-content/uploads/2020/09/Artemis_Plan_NASAs_Lunar_Exploration_Program_Overview_September_2020.pdf
c6	time expectations: setup & operation	About how much time is the user willing to spend to setup this product? To operate this product? How valuable is saving time?	Considering the user will have limited mobility in the spacesuit, we plan to design around this by making the product easy to setup and with minial assembly steps. The user will operate the machine between processes via a control module setup near the product. We plan to make as many of the process transititons autonomous in order to boost efficiency and save time for the user who will be busy with many other functions related to the Lunar Forge.	11. https://www.nasa.gov/feature/a-next-generation-spacesuit-for-the-artemis-generation-of-astronauts
c7	safety expectations	What product safety concerns does the user have? What safety features is the user expecting? What dangers must be avoided?	Safe thermal energy levels, precautions against flammability and combustion. See attached resource from NASA.	13. https://standards.nasa.gov/safety-quality-reliability-maintainability
c8	ırability expectatio	How long does the user expect the product to last?	10+ years, the system should continue to function from when it is built to future Mars missions planned in the 2030's	12. https://bigidea.nianet.org/wp-content/uploads/2020/09/Artemis_Plan_NASAs_Lunar_Exploration_Program_Overview_September_2020.pdf
c9	purchase context	Where and how might the product be purchased? How would the buying decision be made (research, referral, impulse)?	Purchased through research and government funding by large organizations. Selected through the NASA BIG Idea Challenge	12. https://bigidea.nianet.org/wp-content/uploads/2020/09/Artemis_Plan_NASAs_Lunar_Exploration_Program_Overview_September_2020.pdf

4 | Design Methods

4.1 | 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

4.2 | 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. <u>Scooping Litter:</u> Dirty job separating out waste from a main resource.

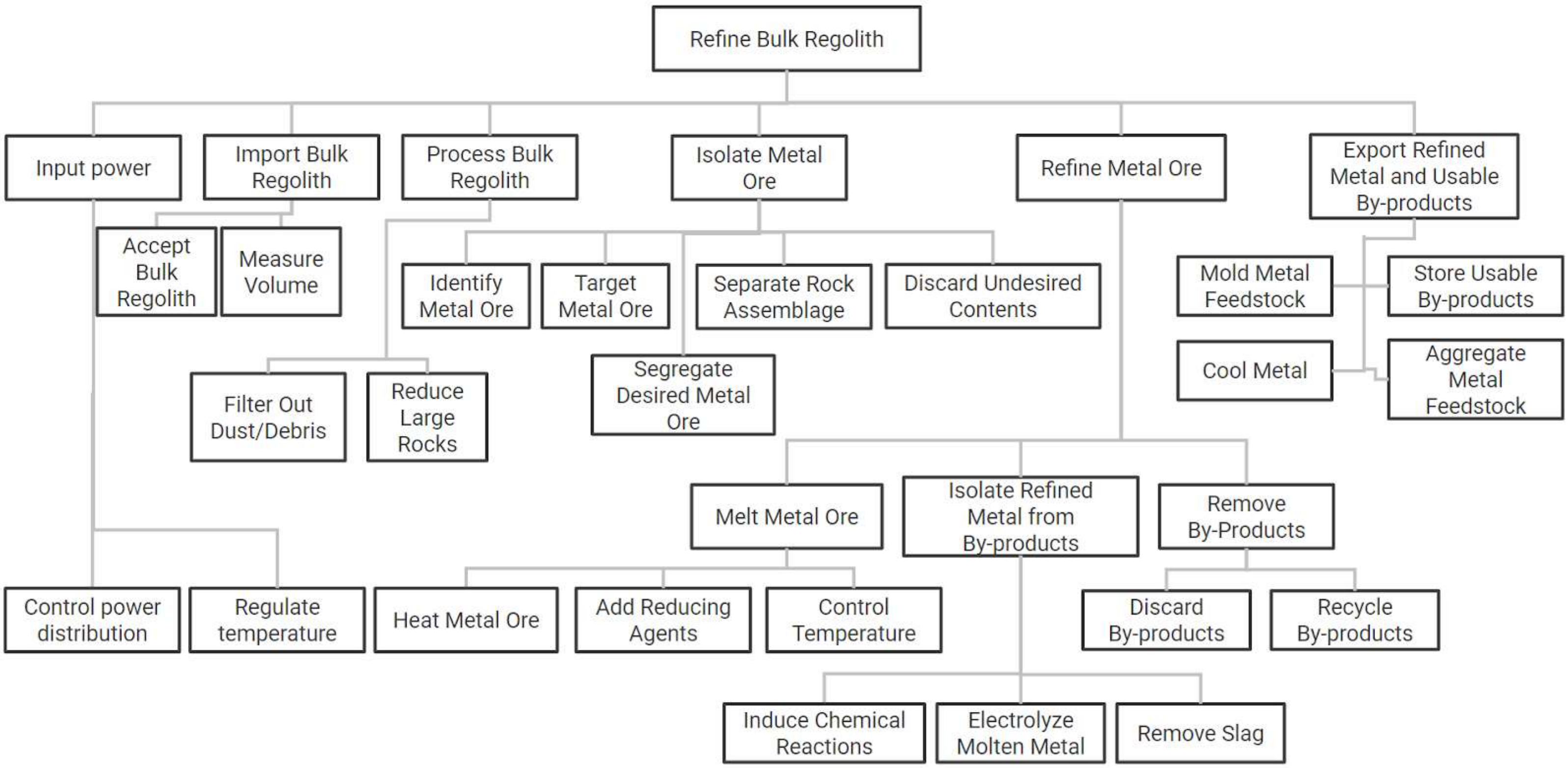
10. <u>A concrete recycler:</u> Used for separating steel rebar from waste concrete. This allows the separate materials to become useful for future projects.

- 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

4.3 | Black Box Model

- 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

4.4 | 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

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

	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 Failsafe s	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.

4.5 | 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

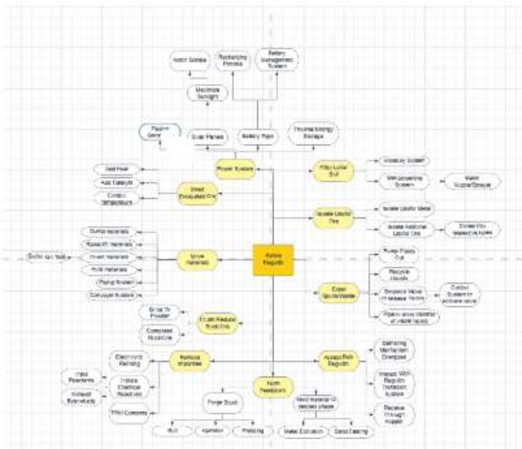
5 | Idea Generation

Our process for idea generation, the results of each process are at the end of the document:

1) **Mind Map–** we began by generating a mind tree which had each subject-area/sub-function that the system must accomplish as the secondary-level items.
2) **6-3-5 Sub-Function Design Development –** we divided up each sub-function from the mind tree as sub-function areas for which we generated ideas. Each team member generated 2 sketches belonging to different sub-functions, and then performed the 6-3-5 method. It is important to note that the SCAMPER method was indirectly used during this process as we added, subtracted, etc between each other's ideas
3) **Morphological Chart** - Using the developed ideas from the 6-3-5 method, we populated a morphological chart where different alternative design concepts were made for each sub-function.
4) **Word Tree** - Using general concepts that we generated, we used WordTrees to find different analogous domains. Each concept led to a more general term that we broke down to find alternative solutions that relate to similar current products and solutions in different technology fields.
5) **Analogous Domains** - The word tree helped generate new concepts through analogies, by searching for patents related to these concepts we were able to define some analogous domains.This information also helped us determine new analogies for each process.The analogous domains are:
    1. Food Processing
    2. Kitchen Tools
    3. Toys
    4. Outdoor Recreation
    5. Wood Working
    6. Vehicle Transportation
    7. Hose Connecting Devices
    8. Agriculture Harvesting and Picking
    9. Heating Devices from Lamps or Convection
    10. Window Furnishings

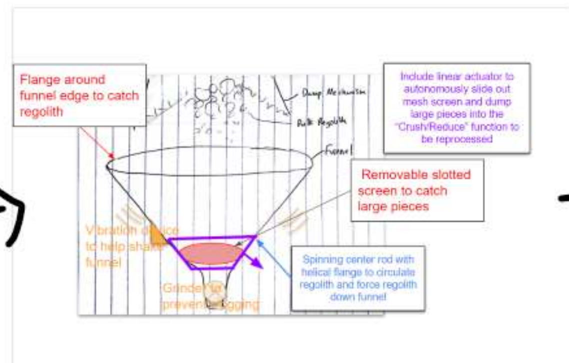
5.1 | Diagram of Methods Used

1. **Mind Map**

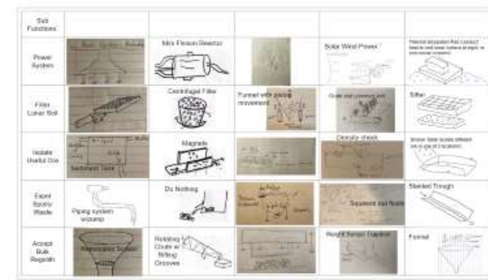


2. **6-3-5 Sub-Function Design Development**

2.5 **Indirectly used SCAMPER**

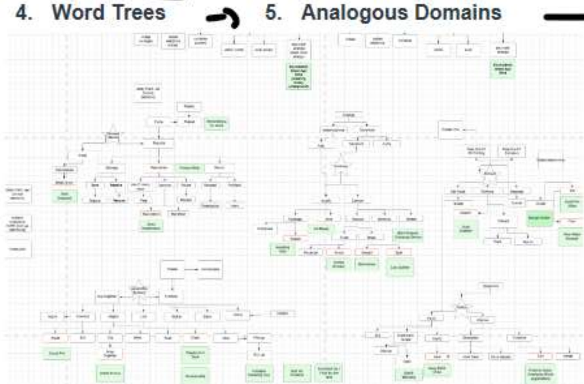


3. **Morphological Chart**



4. **Word Trees**

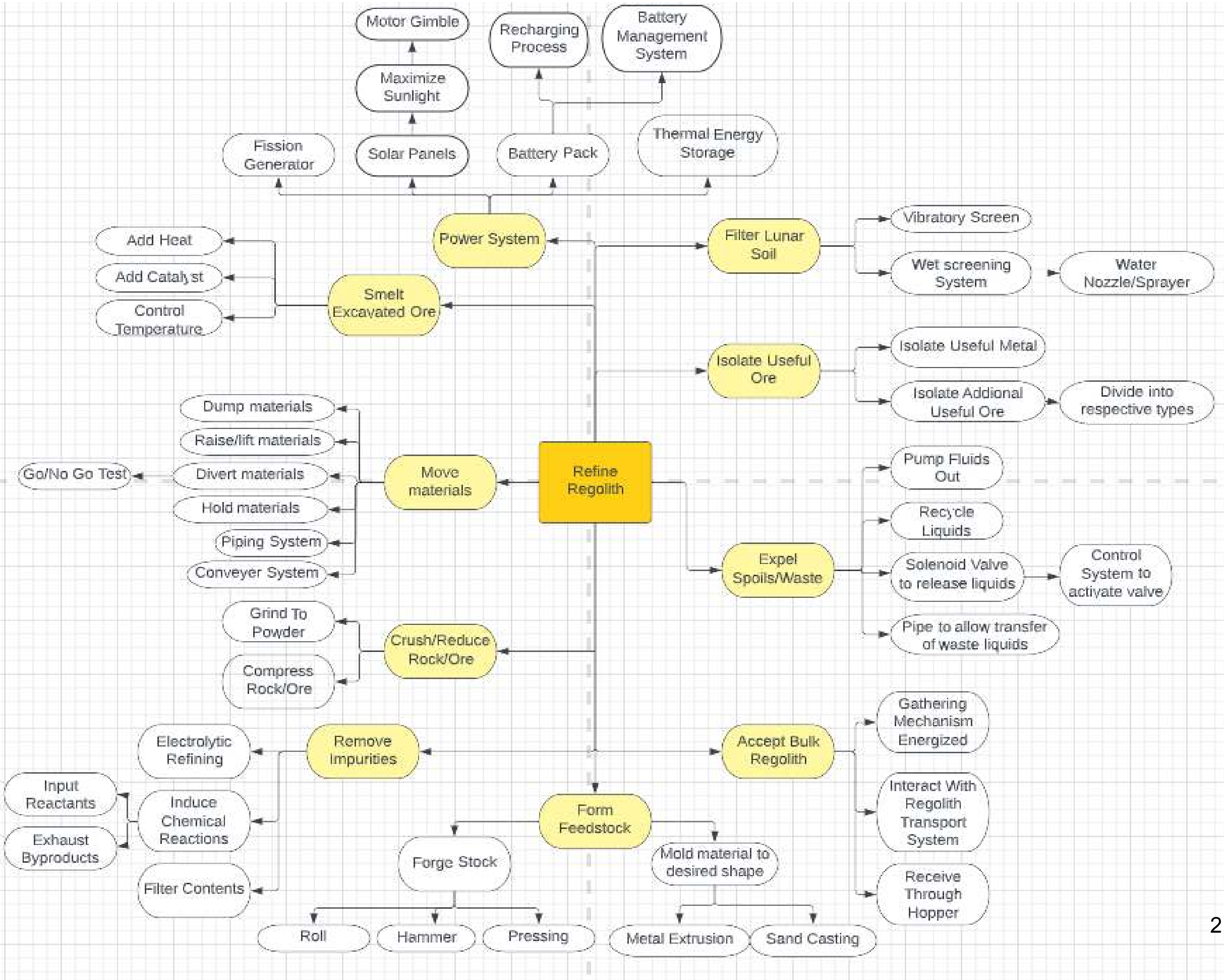
5. **Analogous Domains**



6. **Intuitive Analogies**

	Verb	Analogies
1	Break Down	Sink Disposal
2	Recondition	Shoe Restoration
3	Repurpose	Composting
4	Stretch	Aerating Taffy
5	Mold	Ice Maker
6	Grind	Coffee Grinder
7	Smash	Nutcracker
8	Split	Log Splitter
9	Split	Wire Stripper Crimping Tool
10	Detach	Fruit Grabber
11	Divide	Dough Cutter
12	Sift	Gold Pan Sifter
13	Filter	Fine Mesh Strainer
14	Braze	Crock Pot
15	Snap Together	LEGO Pieces
16	Chain	Continuous Track (Used on Tanks)
17	Chain	Continuous Track with Studs (Used on Snowmobiles)
18	Roll Up	Foldable Camping Tent

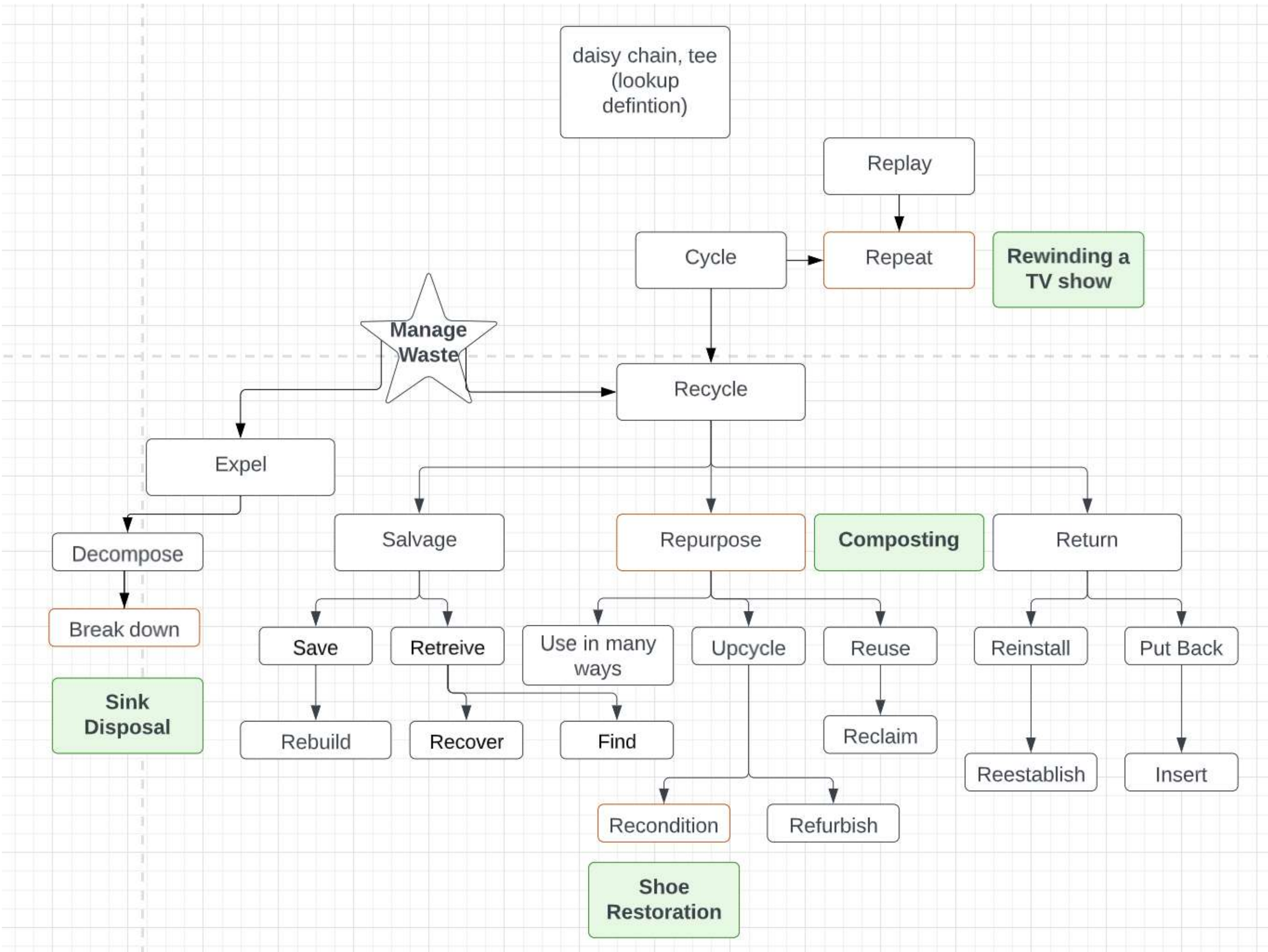
5.2 | Mind Map



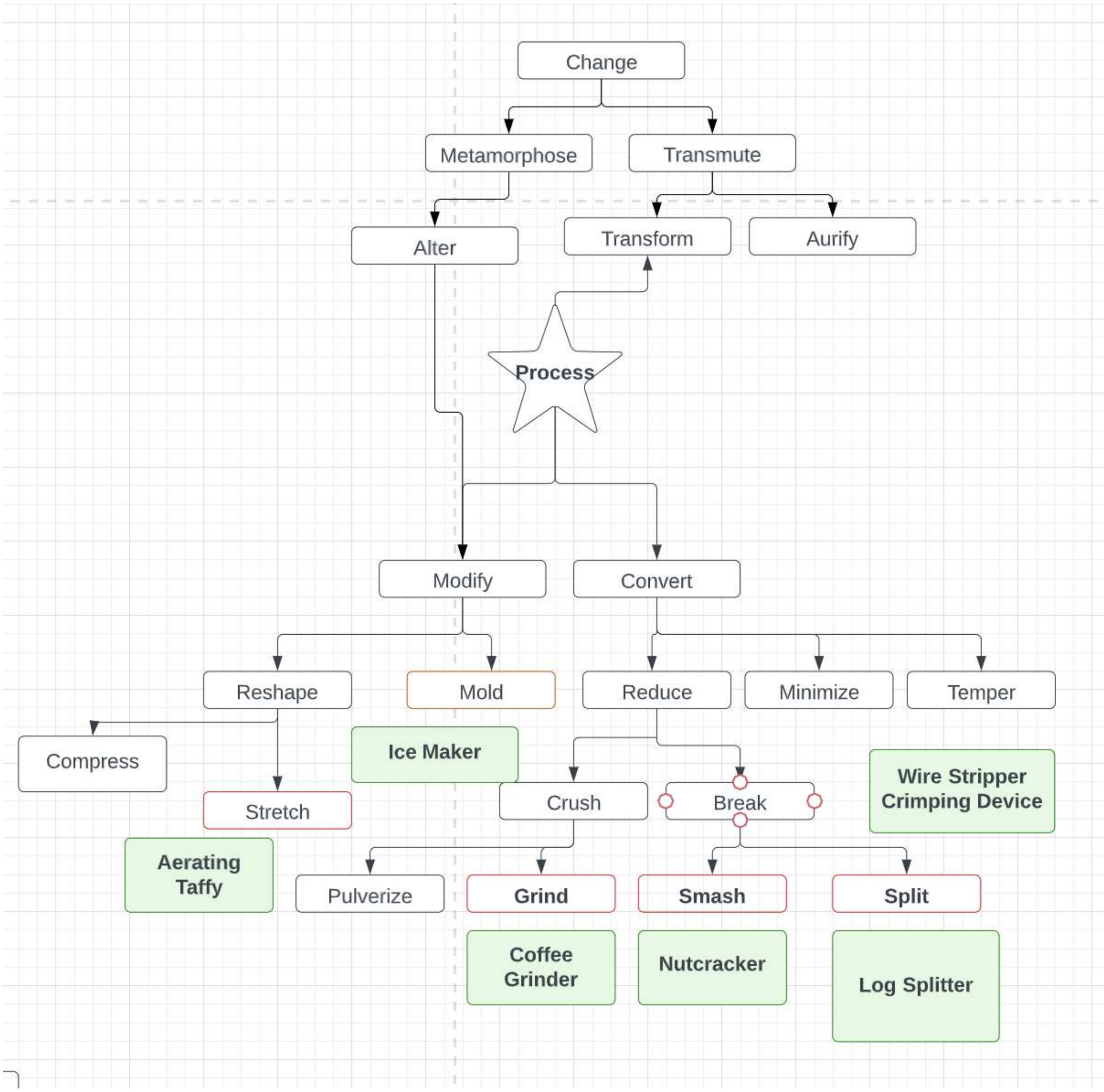
Refine Regolith
Power System
Fission Generator
Solar Panels
Maximize Sunlight
Motor Gimble
Battery Pack
Recharging Process
Battery Management System
Thermal Energy Storage
Smelt Excavated Ore
Add Heat
Add Catalyst
Control Temperature
Filter Lunar Soil
Vibratory Screen
Wet screening System
Water Nozzle/Sprayer
Isolate Useful Ore
Isolate Useful Metal
Isolate Addional Useful Ore
Divide into respective types
Move materials
Dump materials
Raise/lift materials
Divert materials
Go/No Go Test
Hold materials
Piping System
Conveyer System
Expel Spoils/Waste
Pump Fluids Out
Recycle Liquids
Solenoid Valve to release liquids
Control System to activate valve
Pipe to allow transfer of waste liquids
Crush/Reduce Rock/Ore
Grind To Powder
Compress Rock/Ore
Remove Impurities
Electrolytic Refining
Induce Chemical Reactions
Input Reactants
Exhaust Byproducts
Filter Contents
Accept Bulk Regolith
Gathering Mechanism Energized
Interact With Regolith Transport System
Receive Through Hopper
Form Feedstock
Forge Stock
Roll
Hammer
Pressing
Mold material to desired shape
Metal Extrusion
Sand Casting

5.3 | Word Tree

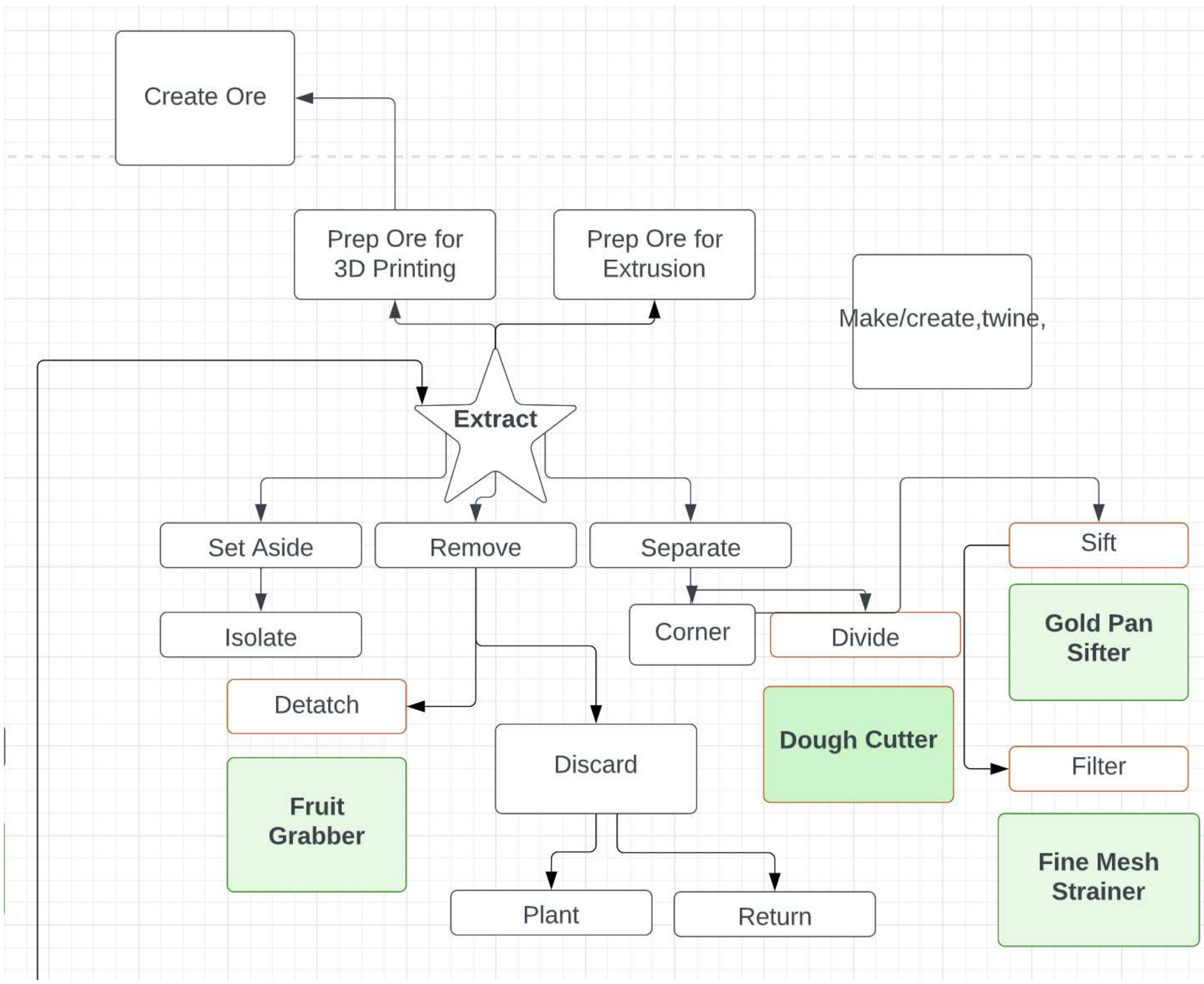
1) Keyword: “Manage Waste”



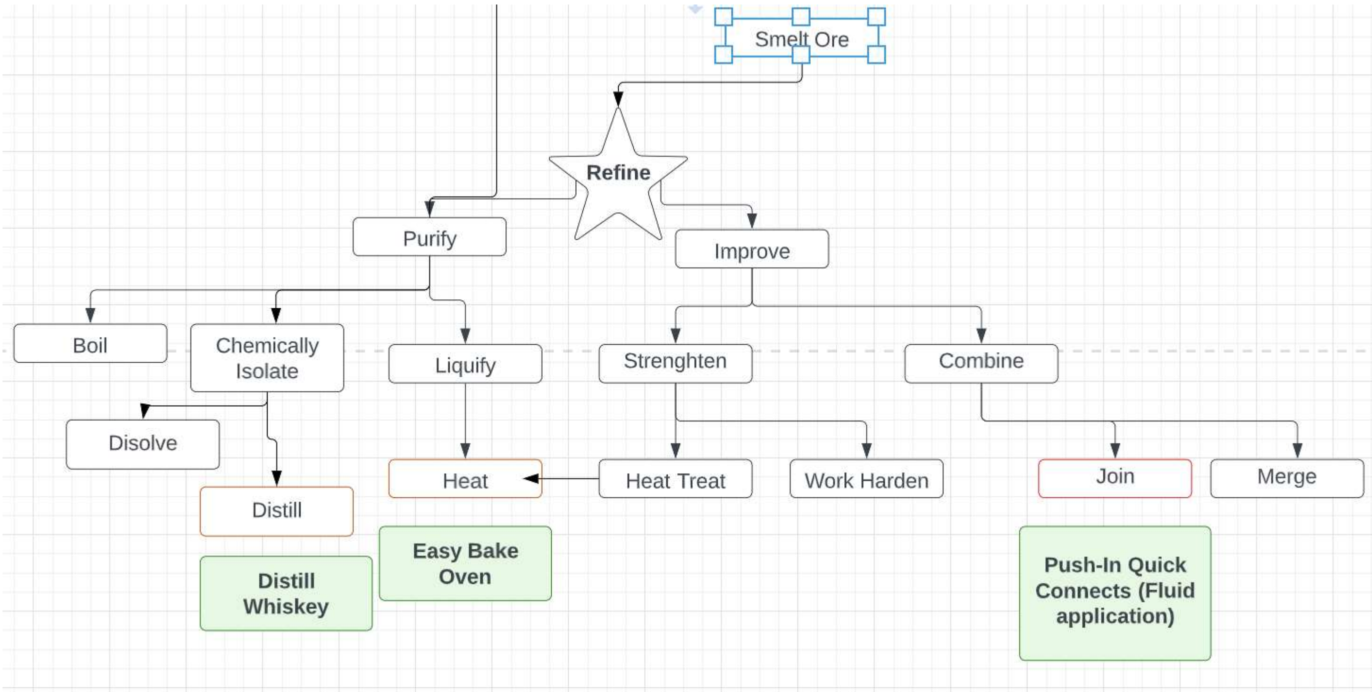
2) Keyword: “Process”



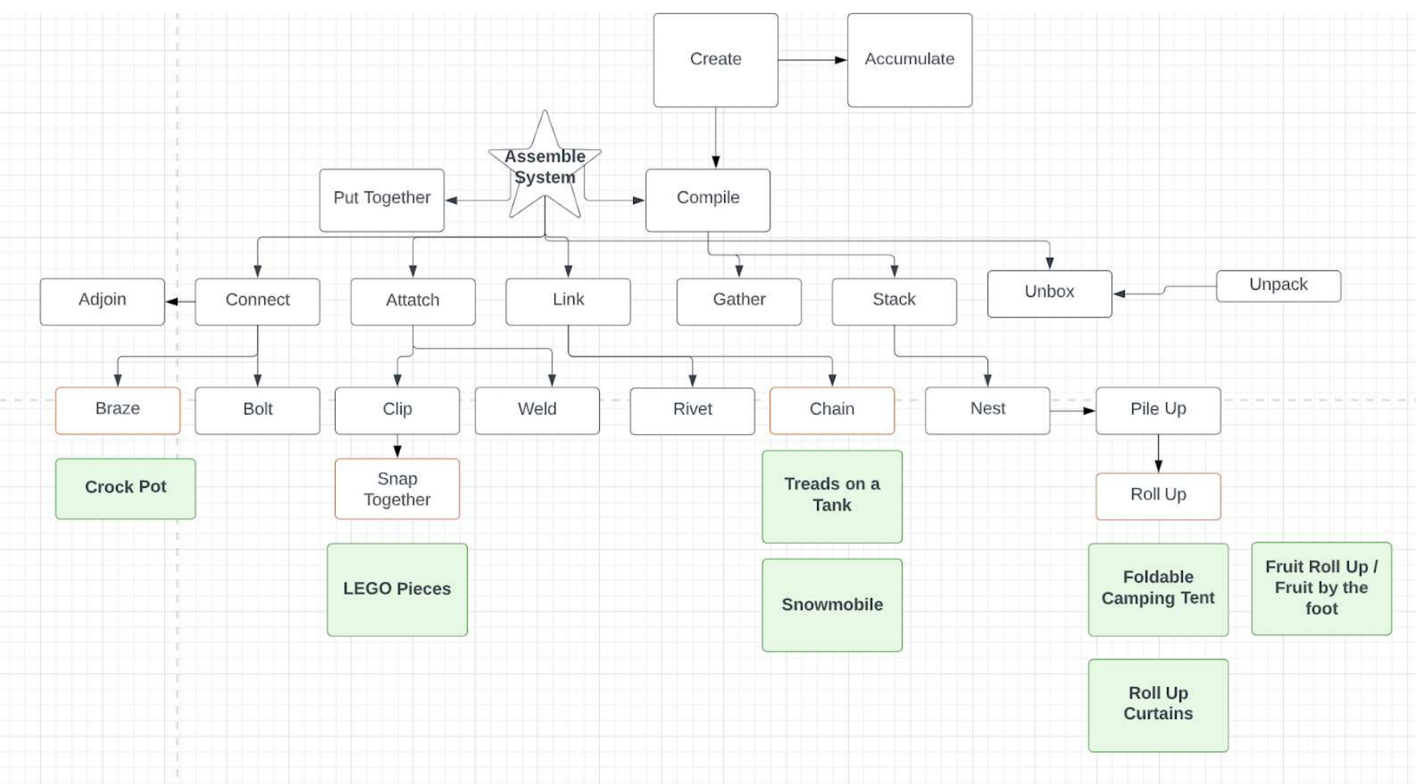
3) Keyword: “Extract”



4) Keyword: “Refine”



5) Keyword: “Assemble”

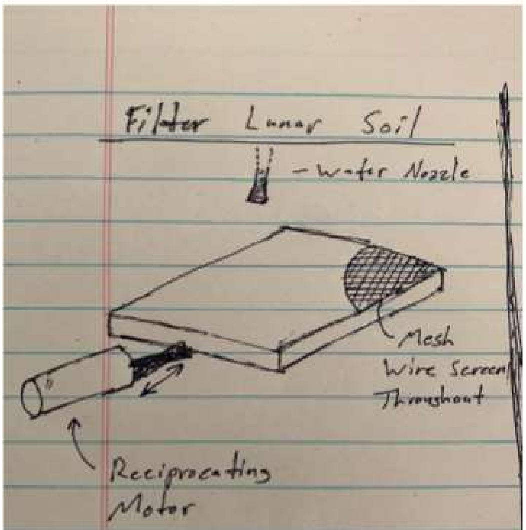


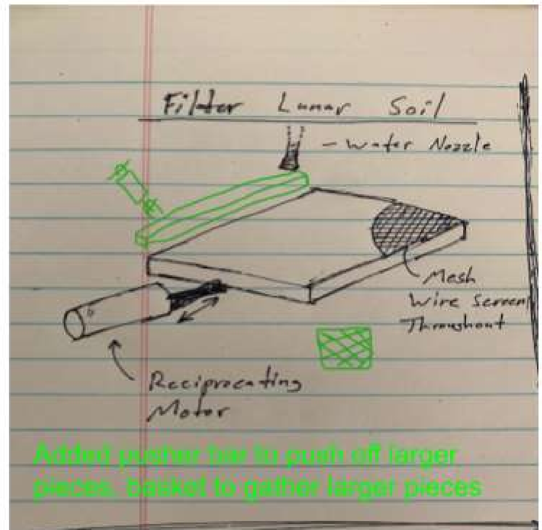
5.4 | Intuitive Analogies from Word Tree Method

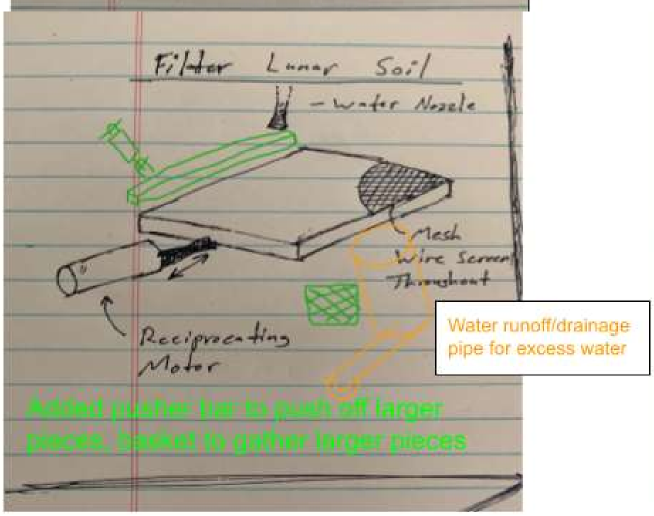
	Verb	Analogies
1	Break Down	Sink Disposal
2	Recondition	Shoe Restoration
3	Repurpose	Composting
4	Stretch	Aerating Taffy
5	Mold	Ice Maker
6	Grind	Coffee Grinder
7	Smash	Nutcracker
8	Split	Log Splitter
9	Split	Wire Stripper Crimping Tool
10	Detach	Fruit Grabber
11	Divide	Dough Cutter
12	Sift	Gold Pan Sifter
13	Filter	Fine Mesh Strainer
14	Braze	Crock Pot
15	Snap Together	LEGO Pieces
16	Chain	Continuous Track (Used on Tanks)
17	Chain	Continuous Track with Studs (Used on Snowmobiles)
18	Roll Up	Foldable Camping Tent
19	Roll Up	Roll-up Curtains
20	Roll Up	Fruit Roll-up/Fruit by the foot
21	Heat	Easy Bake Oven
22	Repeat	Rewinding a TV Show
23	Distill	Distill Whiskey
24	Acumular energia	Escondiendo dinero bajo tierra

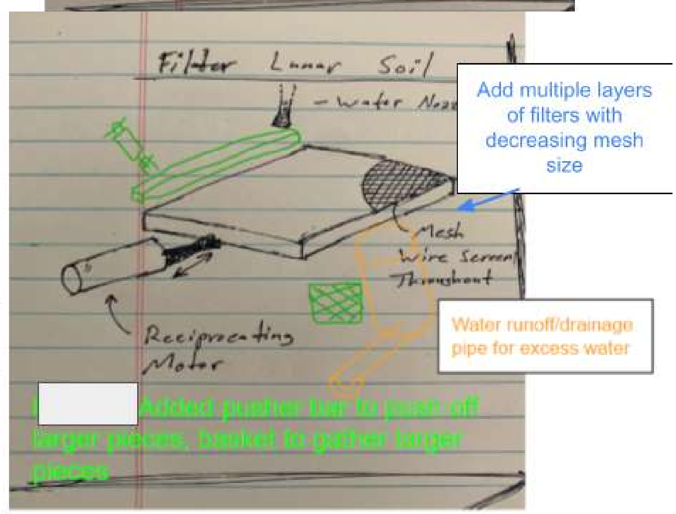
5.5 | 6-3-5 Method

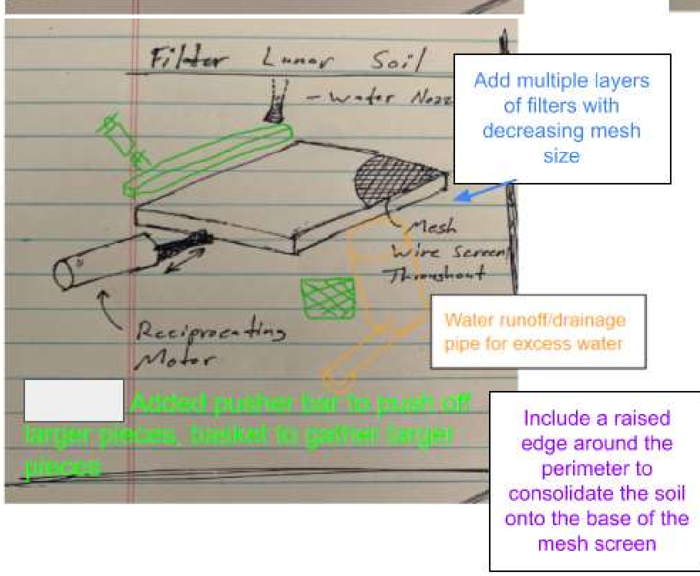
Filter Lunar Soil



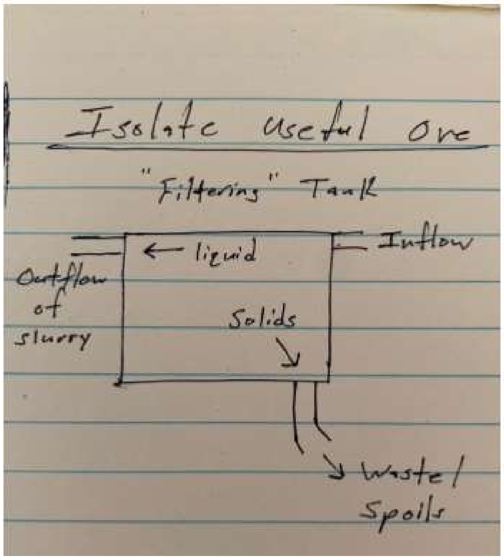


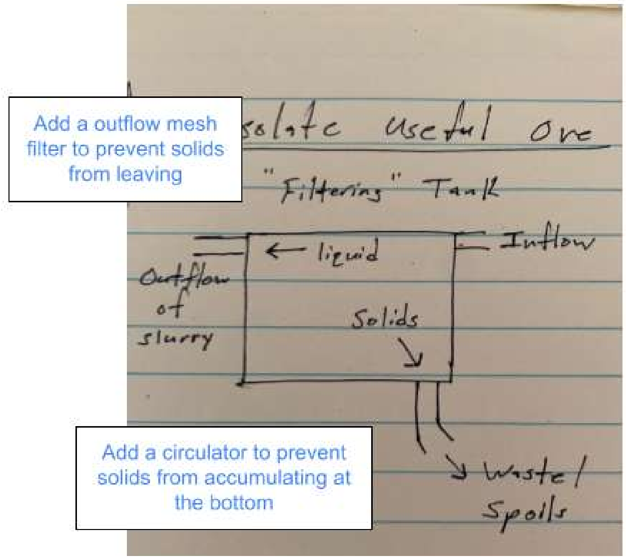


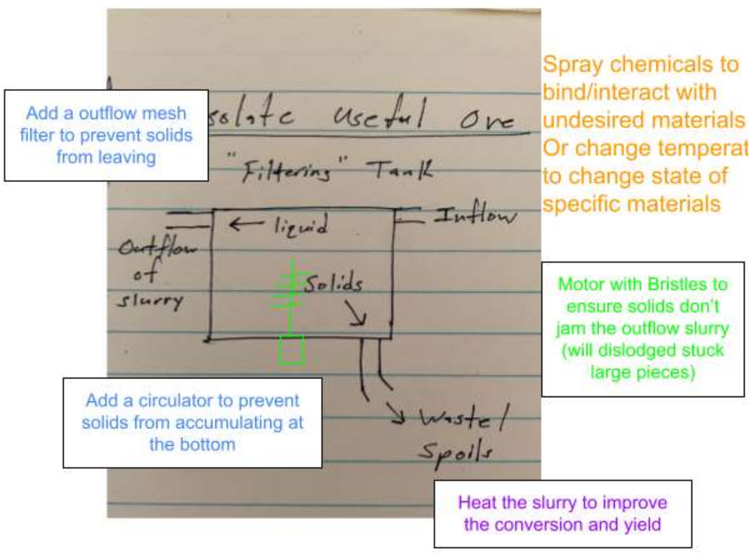


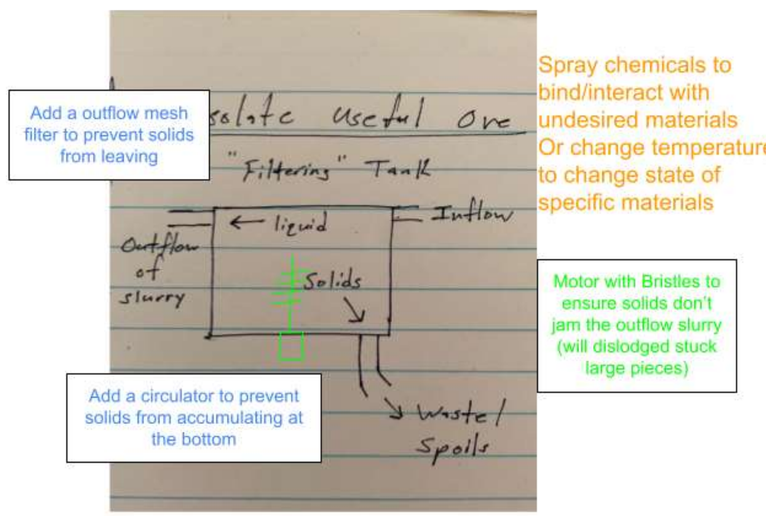


Isolate Useful Ore

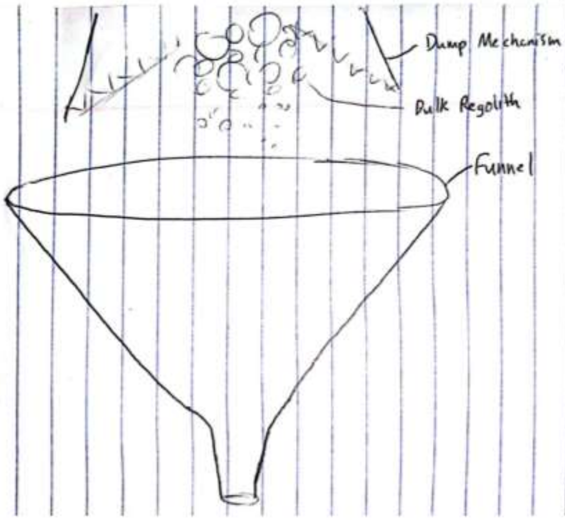


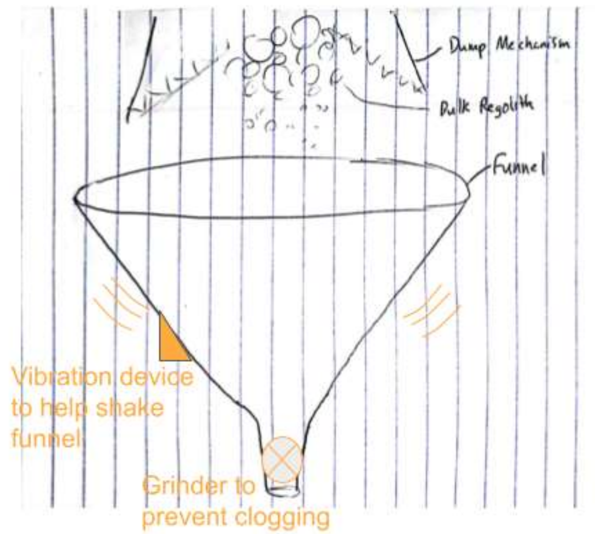


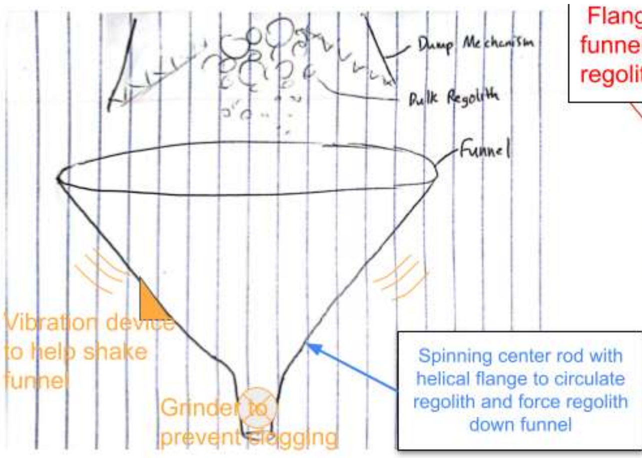


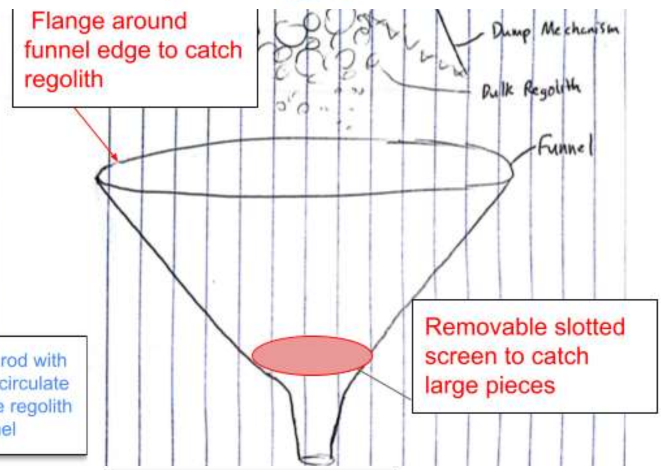


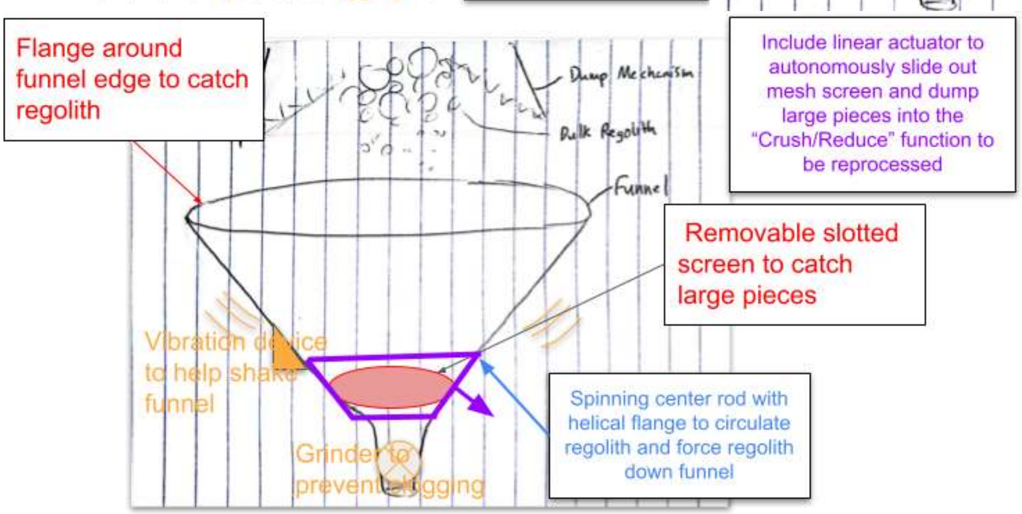
Accept Bulk Regolith



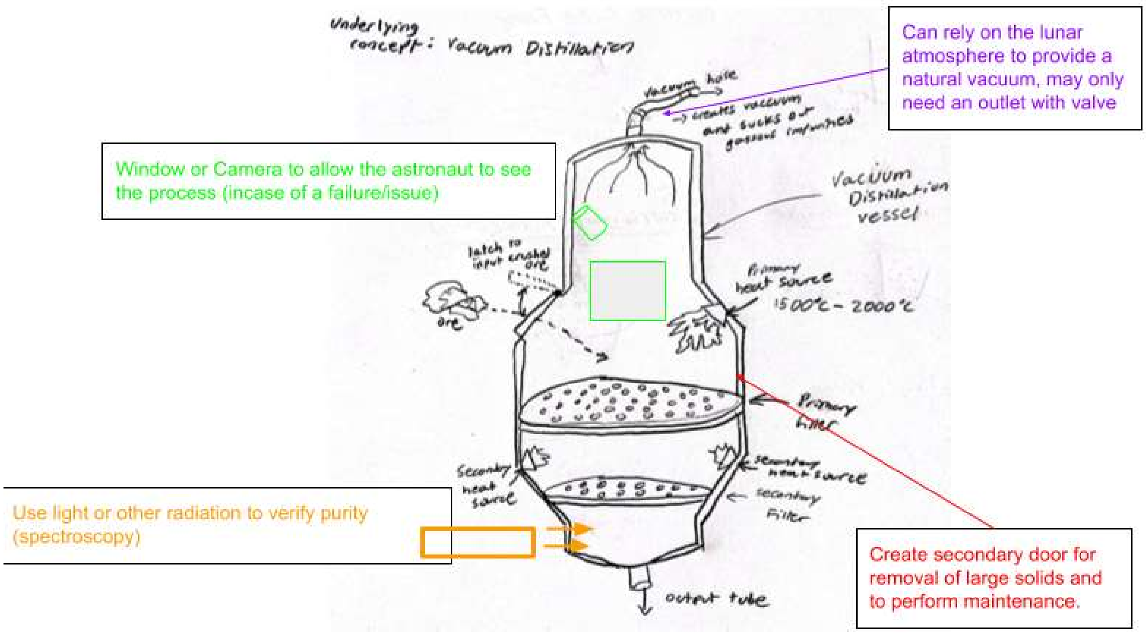




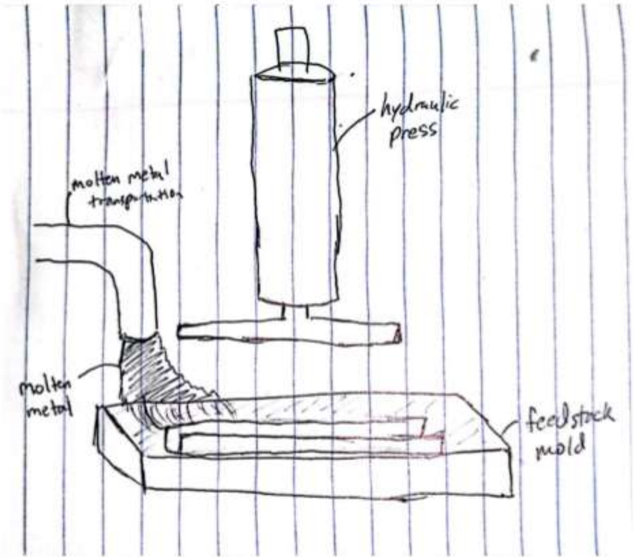


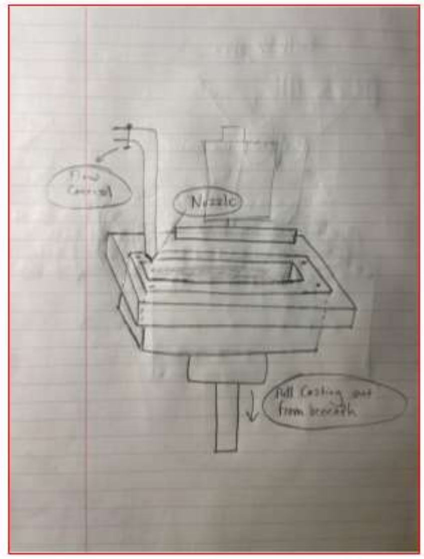


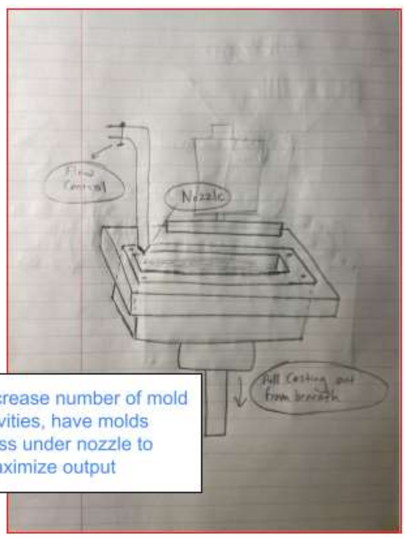
Remove Impurities



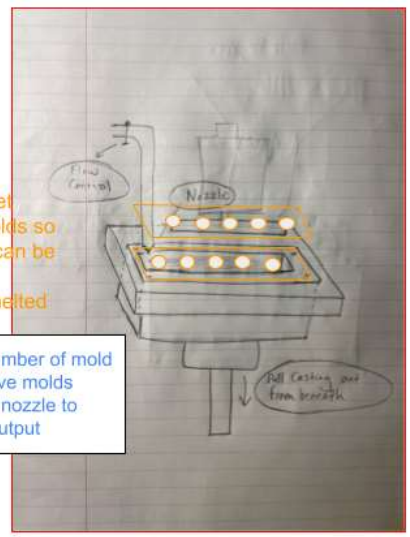
Form Feedstock





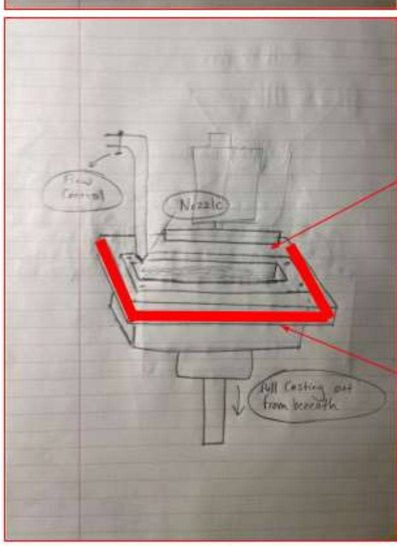


Increase number of mold cavities, have molds pass under nozzle to maximize output



Ball or pellet shaped molds so feedstock can be easily moved/remelted

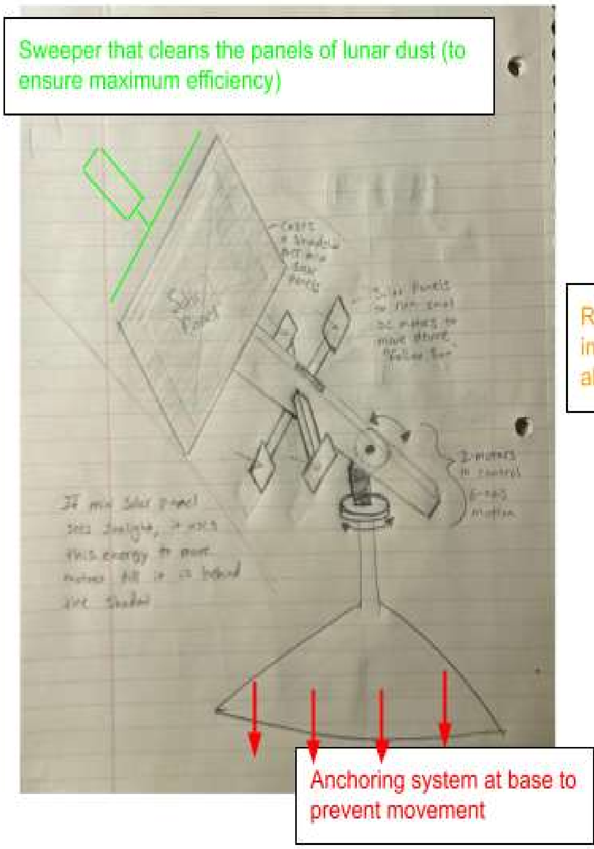
Increase number of mold cavities, have molds pass under nozzle to maximize output

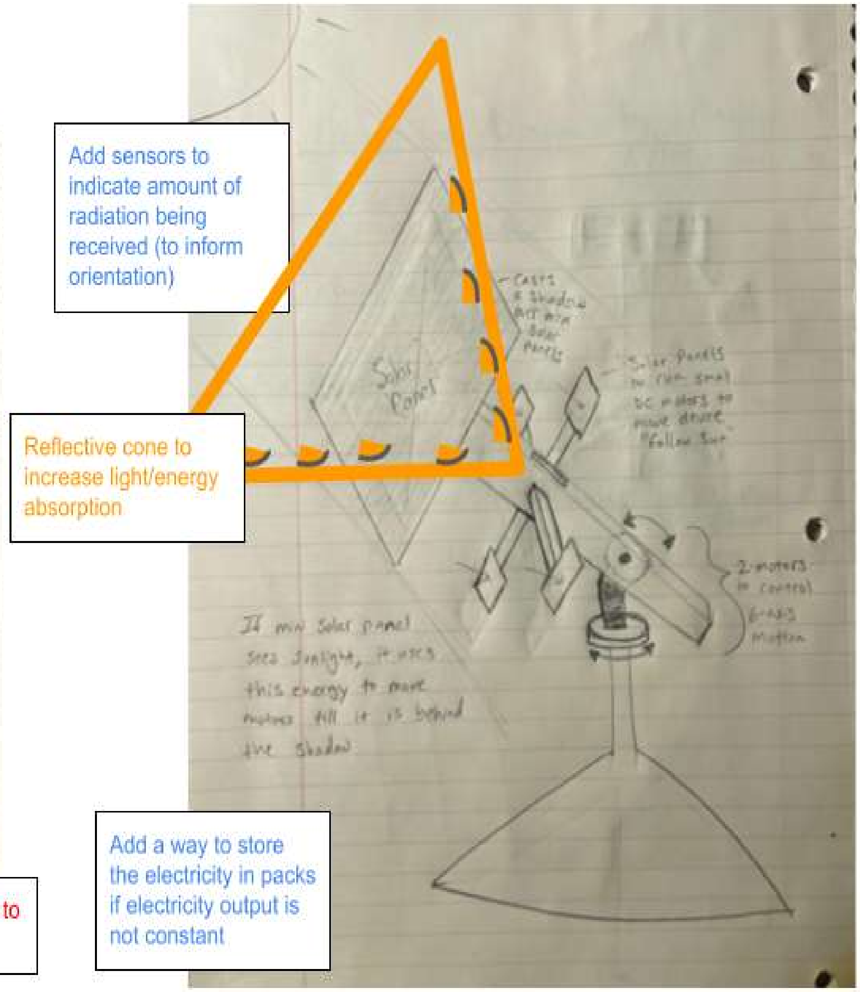


Create upper shell for mold

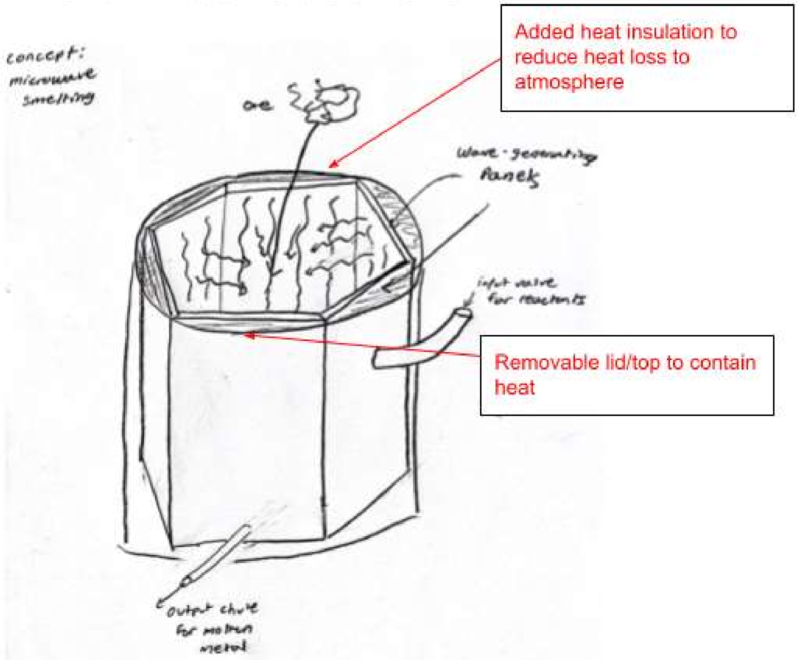
Machine cooling jacket into mold

Power System

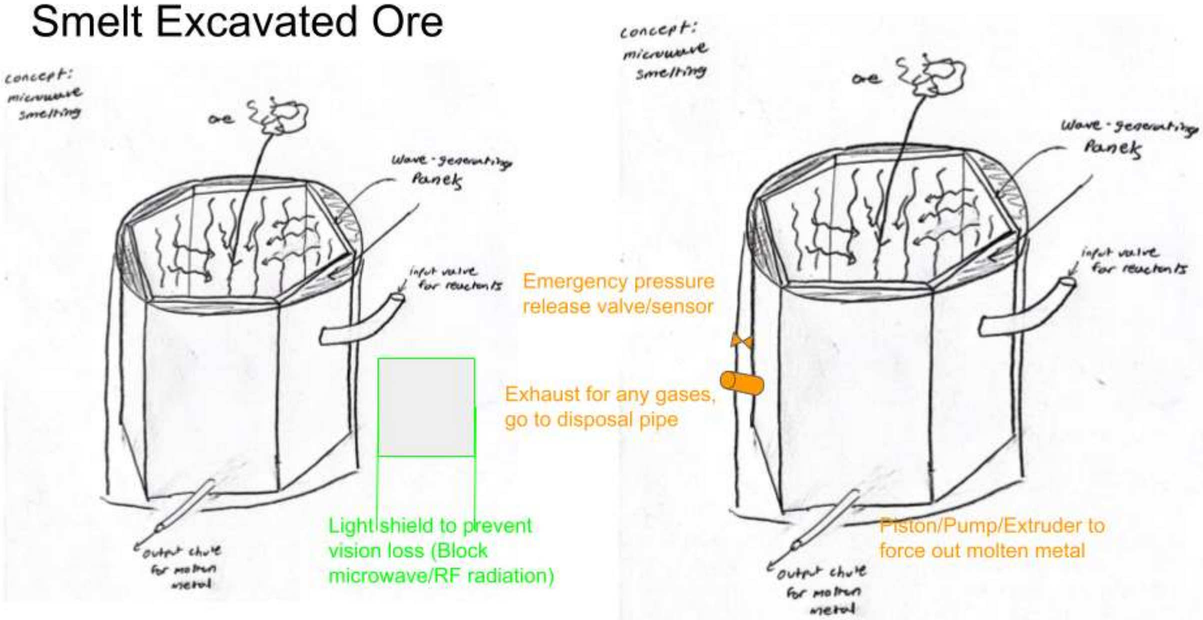




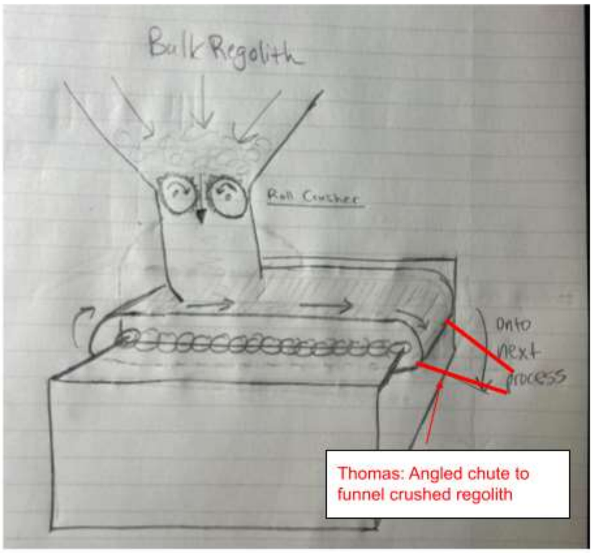
Smelt Excavated Ore

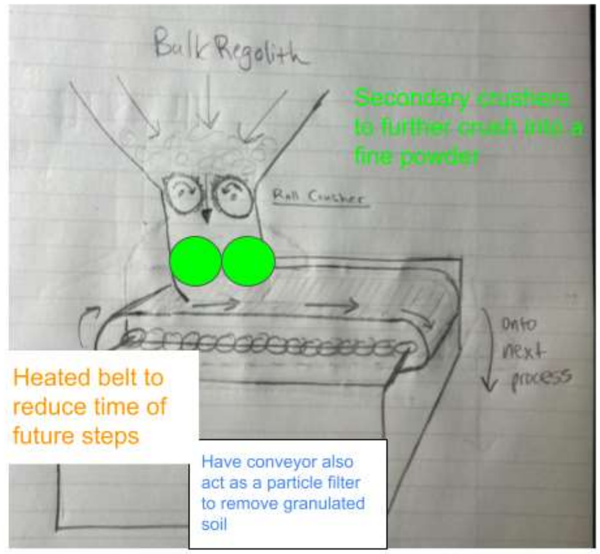


Smelt Excavated Ore



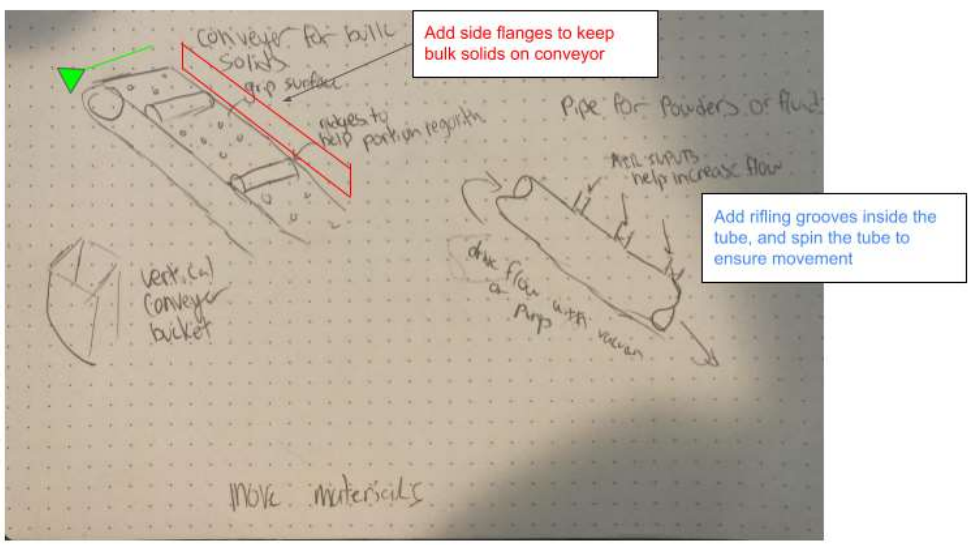
Crush/Reduce Rock or Ore



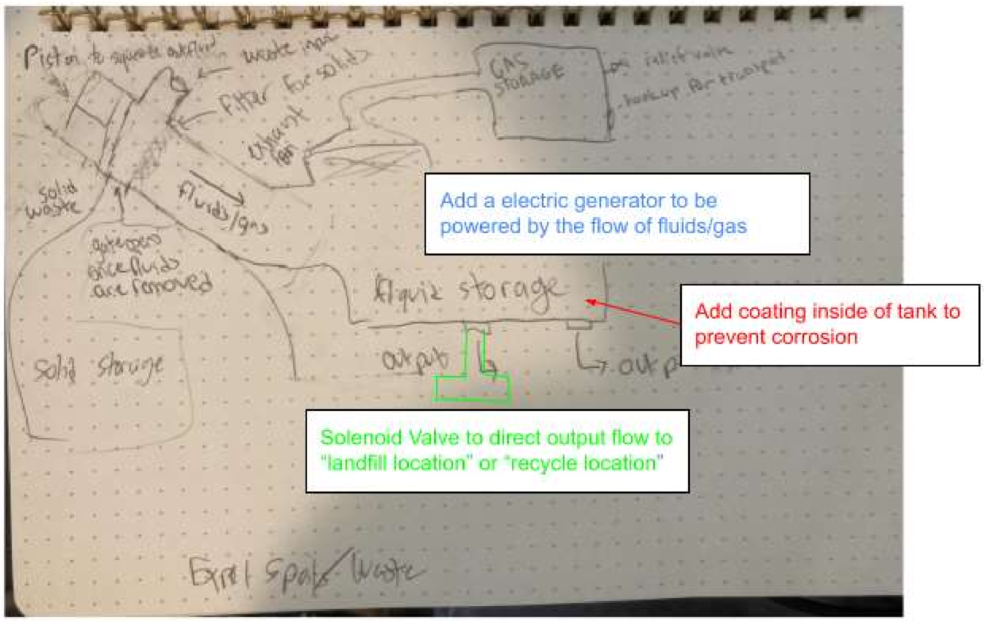


Move Materials

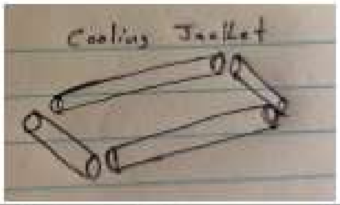
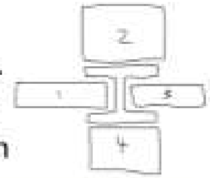
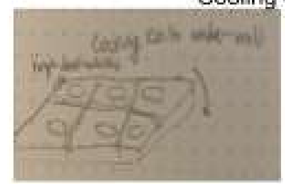
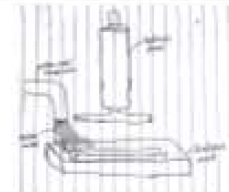
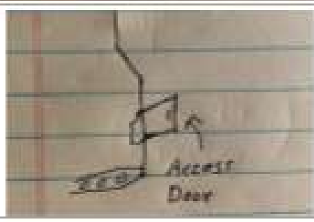
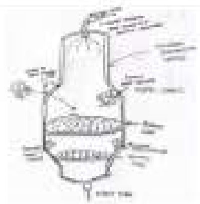
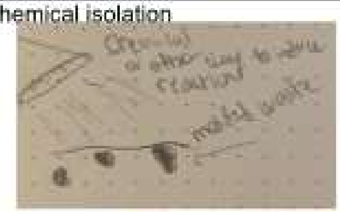
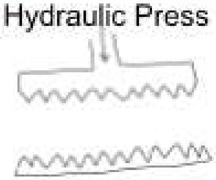
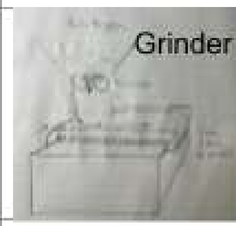
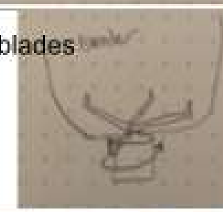
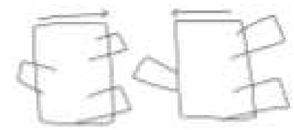
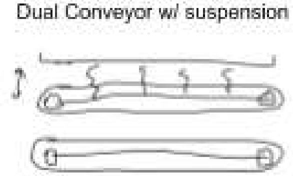
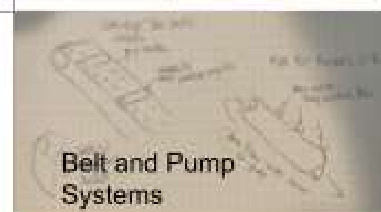
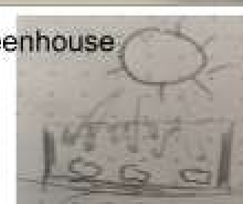
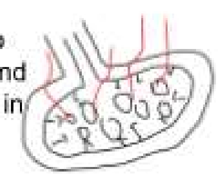
Added automated air curtain, air jet filter large chunks into a different system
Can also be used to sort different sizes

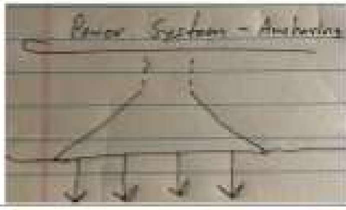
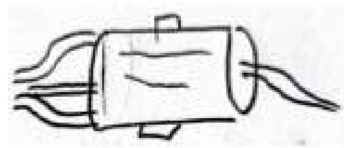
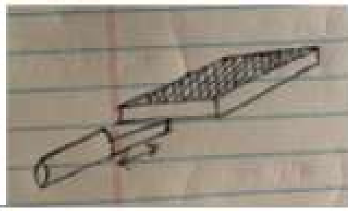
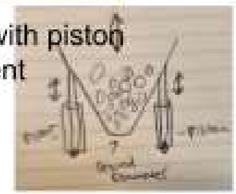
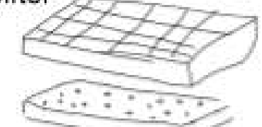
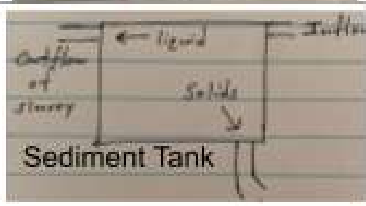
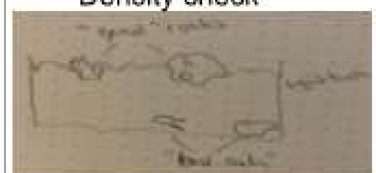
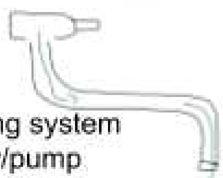
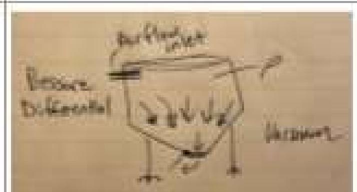
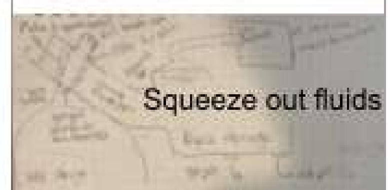
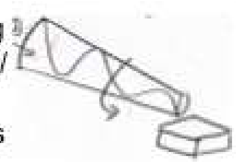
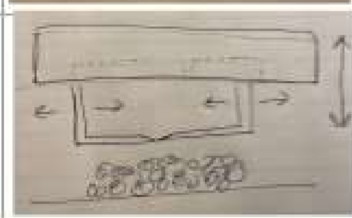
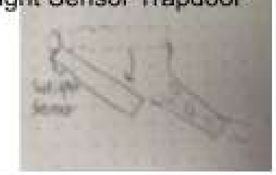
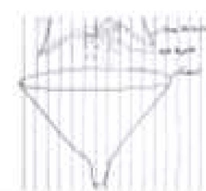


Expel Spoils/Waste



5.6 | Morph Matrix

Sub Functions					
Form Feedstock		Rotating Cylinder Casting Drum 	Quad roller for I-beam formation 	Cooling coils 	Press w/mold 
Remove Impurities		Vacuum Distillation 	Liquation 	Chemical isolation 	Magnets to remove unwanted magnetic metals during certain parts of the process 
Crush Reduce Rock or Ore	Hydraulic Press 	Vibrating Circulator w/ Abrasive 	Grinder 	Blender blades 	Massive Tire Crusher 
Move Materials		Vertical System (Use Gravity) 	Dual Conveyor w/ suspension 	 Belt and Pump Systems	Step Feeder (singulate & move materials at the same time) 
Smelt Excavated Ore	Hot Plate 	Wave Energy to Melt Metal 	Thermal heater bar (direct contact with ores) 	Greenhouse 	RF Coil to heat up and smelt ore in small batches 

Sub Functions`					
Power System		Mini Fission Reactor 	Solar Panel System 	Solar Wind Power [1] 	Thermal dissipation Pad (conduct heat to cold lunar surface at night, to cool power systems) 
Filter Lunar Soil		Centrifugal Filter 	Funnel with piston movement 	Grate and conveyer belt 	Sifter 
Isolate Useful Ore	 Sediment Tank	Magnets 		Density check 	Shaker Table (isolate different ore in one of 3 locations) 
Expel Spoils/ Waste	 Piping system w/pump	Do Nothing 		 Squeeze out fluids	Slanted Trough 
Accept Bulk Regolith	 Removable Screen	Rotating Chute w/ Rifling Grooves 		Weight Sensor Trapdoor 	Funnel 

5.7 | Prior Art Patent Search

	Applicable Patents & Prior Art		
No.	**Title**	**Patent No.**	**Link**
1	Polishing Apparatus	US 9039492	https://patents.justia.com/patent/9039492
2	Process for the Recovery of Value Metals from Metals from Material Containing Base Metal Oxides	US 7329396 B2	https://patents.google.com/patent/US7329396B2/es
3	Process for the extraction of aluminum from aluminum ores	US 4069296A	https://patents.justia.com/patent/4069296
4	Quick disconnect and release hose couplings	US 6354521	https://portal.unifiedpatents.com/patents/patent/US-4451069-A
5	Methods and Devices for Evaluating the Contents of Materials	US10494919B2	https://patents.google.com/patent/US20180306031A1/en
6	Blast Furnace Operation Method	EP2431484B1	https://patents.google.com/patent/EP2431484B1/it
7	Method of producing aluminum from bauxite or its sludge	RU 2626695C2	https://patents.google.com/patent/RU2626695C2/en?oq=Method+of+producing+aluminum+from+bauxite+or+its+sludge+RU+2626695C2
8	Rock picker with storage conveyors	US4345655	https://patentimages.storage.googleapis.com/50/d2/37/554edfc21451ce/US4345655.pdf
9	Beneficiation of Values from Ores with a Heap Leach Process	US20180369869A1	https://patents.google.com/patent/US20180369869A1/en
10	Method for Separating Mineral Impurities From Calcium Carbonate-Containing Rocks by X-Ray Sorting	US8742277B2	https://patents.google.com/patent/US8742277

11	A kind of ore crusher	CN209423711U	https://patents.google.com/patent/CN209423711U/zh

1.) **Enclosed polishing apparatus (US 9039492)**

Abstract: An enclosed polishing apparatus include a housing, a fixing seat, a guiding mechanism, and a chain-driven polishing mechanism. The housing includes a bottom housing and a top housing connected to the bottom housing. The fixing seat is securely placed in the bottom housing. The guiding mechanism is placed in the top housing above the fixing seat. The polishing mechanism is movably mounted on the guiding mechanism above the fixing seat. The polishing mechanism is driven and guided by the guiding mechanism to follow a desired polishing contour on a workpiece.

Why?: This apparatus can help inspire ideas related to the refinement process of Anorthite ore. It is also mechanically powered which will benefit our design.

2.) Process for the Recovery of Value Metals from Metals from Material Containing Base Metal Oxides (US 7329396 B2)

Abstract: A process for leaching a value metal from oxidic materials, Such as a lateritic nickel ore, comprising the step of leaching the ore with a lixiviant comprising a cationic salt (e.g., magnesium chloride) and hydrochloric acid is disclosed. An oxidant or additional metal chloride (such as that which results from the leaching operation) may be added. In one embodiment, the process comprises recovery of a value metal from ore comprising the steps of leaching the ore with a lixiviant; separating a value metal-rich leachate from the ore in a first Solid-liquid separation; oxidizing and neutral izing the value metal-rich leachate so obtained; and separating a solution of magnesium chloride from the leachate so obtained in a second Solid-liquid separation. In another embodiment, the lixiviant solution is regenerated from the Solution of magnesium chloride. In a further embodiment, regeneration of the lixiviant Solution includes a step of producing magnesium oxide from the solution of magnesium chloride.

3.) Process for the extraction of aluminum from aluminum ores. (US 4069296A)

Abstract: Aluminum may be recovered from various raw materials including kaolinite, alunite, coal ash and slag, and both raw and spent oil shale, by contacting such materials with an aqueous solution of hydrofluoric acid, followed by removal of the insoluble residues remaining suspended in solution and the precipitation of hydrated aluminum hydroxide from the clear solution by basification with an alkaline agent.

Why?: This patent teaches methods that can be used during the extraction process for aluminum. While the exact process may not apply directly, if Anorthite is chosen as the ore in question it will be very helpful as background.

4.) **Quick disconnect and release hose couplings (US 6354521)**

Abstract: A quick disconnect and release hose coupling is disclosed where the socket will disconnect and release from a plug if the hose connected to the hose coupling is pulled with sufficient force. A quick disconnect female socket used in the hose coupling includes a body portion and a movable sleeve. The hose coupling includes an end conduit that is adapted for coupling to a hose. The end conduit is connected to an intermediate conduit, and the intermediate conduit is connected to the body portion of the socket. The hose is in fluid communication with the socket through the end conduit and intermediate conduit. The intermediate conduit also permits the end conduit to move relative to the body portion. A mechanical coupling is attached to the end conduit and to the sleeve of the socket such that when the end conduit moves relative to the body portion the mechanical coupling moves the sleeve relative to the body portion. Accordingly, pulling on the end conduit or the hose attached to the end conduit will retract the sleeve so as to disconnect and release the hose coupling from the plug.

Why?: This helps during the “on lunar surface” assembly process for the system. As many parts of the system will need to be assembled, this provides a quick and easy route for assembling fluid passages on the lunar surface for the astronauts.

5) **Title: Methods and Devices for Evaluating the Contents of Materials (US10494919B2)**

Abstract: Methods for determining the hardness and/or ductility of a material by compression of the material are provided as the first aspect of the invention. Typically, compression is performed on multiple sides of a geologic material sample in a contemporaneous manner. Devices and systems for performing such methods also are provided. These methods, devices, and systems can be combined with additional methods, devices, and systems of the invention that provide for the analysis of compounds contained in such samples, which can indicate the presence of valuable materials, such as petroleum-associated hydrocarbons. Alternatively, these additional methods, devices, and systems can also stand independently of the methods, devices, and systems for analyzing ductility and/or hardness of materials.

Why?: This patent teaches different methods for identifying materials through chemical and physical tests. This is done by pressurizing a material until gasses are released and then analyzing the gas to determine information about the substance. Similar techniques can be used to help identify the correct materials in the regolith.

6) **Blast Furnace Operation Method (EP2431484B1)**

Abstract: The present invention relates to a method for operating a blast furnace using carbon iron composite (ferrocoke), produced by briquetting and carbonizing a mixture of coal and iron ore, as blast furnace feed for the purpose of stably performing a low-reducing agent ratio operation

7.) **Method of producing aluminum from bauxite or its sludge (RU 2626695C2)**

FIELD: chemistry.
SUBSTANCE: method comprises grinding of mixture to produce a powder and calcination of the mentioned powder at a temperature ranging from 600°C to 800°C to produce basic calcined material, containing aluminum oxide and optionally at least one oxide selected from the group consisting of titanium oxide and iron oxide, mixing of the basic calcined material with a carbonaceous material to produce a mixture; carbochlorination of the mixture with chlorine gas at a temperature ranging from 600°C to 1000°C to produce a gas stream, containing aluminum chloride and optionally at least one chloride selected from the group consisting of iron (III) chloride and titanium chloride, condensation of the gas stream to produce chloride condensate, comprising aluminum chloride optionally at least one chloride selected from the group consisting of iron (III) chloride and titanium chloride, optionally comprises processing of the chloride condensate for fractional separation of aluminum chloride and optionally at least one chloride selected from the group consisting of iron (III) chloride and titanium chloride, and carrying out of aluminum chloride electrolytic process in electrolysis cell to produce metallic aluminum.
EFFECT: lowered carbon dioxide and perfluorocarbon gasses emissions and increased energy efficiency of the process.

Why?: This patented process is applicable to excavated ore from the lunar regolith. This process details the extraction of the pure aluminum from the collected raw ore. Bauxite, found on earth, is a near equivalent ore of Anorthite found on the lunar surface. It will aid in the chemical division of individual mineral components to enable further refinement.

8.) **Rock picker with storage conveyors United States Patent 4345655**

Abstract: A rock picker has a plurality of high capacity conveyors, one of which is used for storing rocks during the picking operation. The conveyors quickly unload the stored rocks into a truck or at some other desired location. The storage conveyor is arranged so that it does not take up any substantial amount of space greater than the rock picker frame, but yet is sufficiently large in capacity so that it can store a large number of rocks as they are picked. Loading conveyors are sequentially placed so that first and second normally continuously operating conveyors load into the third storage conveyor in sequence. A storage hopper is provided at the input end of the storage conveyor, and the conveyor is intermittently operated to carry the rocks from the hopper in a layer along the length of the storage conveyor. When the storage conveyor is loaded with rocks, the storage conveyor is run to discharge the rocks off one end.

Why?: A regolith storage system and transportation system will be paramount in processing of lunar regolith. Whether we want to move regolith from one process to another, or if we want to store it, this is a great patent that shows how rocks can be moved around and stored using a conveyor and hopper respectively.

Additionally, this is a mobile system that would be able to move around on the lunar surface. It also introduces some new ideas that we have thought of before in ideas generation, but in a more finalized product (such as using a blower to blow the rocks into certain bins)

9) **Beneficiation of Values from Ores with a Heap Leach Process (US20180369869A1)**

Abstract: This invention relates to a process for recovering value metals from sulphide ore , including steps of crushing ore in a primary crusher (14) to a size of about 40 cm and less , passing the crushed ore through one or more of the following pre - beneficiation processes such as bulk sorting (16) and screening (20) followed by coarse floatation (46 / 50) , or gravity separation or magnetic separation . A waste stream (54) from the pre - beneficiation process / es with a particle size greater than 100 um is stacked in a heap (26) and subjected to a heap leach . This integrated process utilizes the pre - beneficiation techniques best suited to the characteristics of a particular orebody ; and during the pre - beneficiation simultaneously creating a low grade stream that yields significantly higher recoveries than achievable by normal heap leaching of low grade run of mine ore.

Why?: This patent teaches the leaching method of beneficiation. This is directly related to the extraction and refining process and will be extremely helpful in understanding how the current processes are conducted.

10) **Method for Separating Mineral Impurities From Calcium Carbonate-Containing Rocks by X-Ray Sorting (US8742277B2)**

Abstract: The present invention relates to a method for separating mineral impurities from calcium carbonate-containing rocks by comminuting the calcium carbonate-containing rocks to a particle size in the range of from 1 mm to 250 mm, separating the calcium carbonate particles by means of a dual energy X-ray transmission sorting device.
Why?: This patent teaches a method for identifying the desired metals as well as a means for evaluating the purity of the final products. Even though this patent is indented for calcium carbonate, similar techniques can be used for this project. X-ray or other light transmission can help identify what is in the regolith that comes into the system as well as what is left after refinement.

11) A kind of ore crusher (CN209423711U)

Abstract: The utility model discloses an ore crusher. Relating to the technical field of ore processing, the device comprises an outer support bracket, a crushing bin and a crushing bin are arranged on the outer support bracket; a feeding hole is formed in the top of the crushing bin; discharging opening is formed in the bottom of the machine body, a feeding hole is formed in the top of the crushing bin; discharging opening is formed in the bottom of the machine body, the feeding hole is communicated with the discharging hole; an ore crushing mechanism is arranged in the crushing bin; an ore crushing mechanism moving up and down is arranged in the crushing bin; movable sealing plates are inserted into the feeding opening and the discharging opening; the two movable sealing plates are connected with linear driving mechanisms; the linear driving mechanism comprises a driving gear driven by a motor, two driven gears meshed with the driving gear and two racks meshed with the two driven gears respectively. One end of each of the two racks is connected with one movable sealing plate, the two movable sealing plates can regularly and intermittently open and close the channel, intermittent ore control is achieved in the crushing process, and ore blockage is prevented.

Why?: This patent teaches a mechanism that can crush ore. This is a critical part of the ore intake process and will help guide how the refinement process begins.

5.8 | Bio-Inspired Design Concepts

	Bio Inspired Designs		
No.	**Biological Inspiration**	**Biological Function Words**	**Sub-Function Area**
1	Mantis shrimp	Breakdown, crush, particulate, cleave	Crush/Reduce Rock/Ore
2	Stingray Jaws	Crush	
3	Radula of Patella Limpets	Crush, Breakdown	
4	Fiddler Crabs' Setae (hairs)	Filtrate, segment	Isolate Useful Ore
5	Blue Whale's Teeth	Filter	
6	Human Kidneys	Filter, Recycle, Extract	
7	Metal-Toxicity Adapted Fungal Strains	Leach, breakdown, convert	
8	Web-Producing Spiders	Collect, form	Form Feedstock
9	Honey Bees' Wax Cells	Heat, Form, Create	
10	Bombardier Beetles' Combustion Chamber	Temperature, Heat, Scald	Smelt Excavated Ore

11	Click Beetles	Temperature, Heat, Power	
12	Gray Whales	Temperature, Heat, Regulate	
13	Thorny Devil Lizards		
14	Atlantic Puffin	Collect, Absorb, Digest	Accept Regolith
15	Ants Musculoskeletal System	Orient, position, slide, tunnel, transport	Move materials
16	Snake Scales		
17	Arthropods		
18	Baby Birds' Fecal Sacs	Waste	Expel Spoils/Waste
19	Oriental Hornet	Energy, Absorb, Store	Power System
20	Flowers' Ability to Follow the Sun	Absorb, Energy, Convert, Power	

Function:

"Crush/Reduce Rock/Ore"

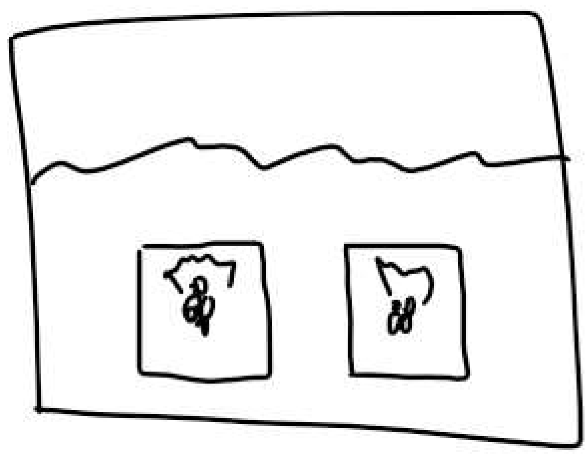
Biological Function Words: Breakdown, Crush, Particulate, Cleave

1) **Mantis shrimp [30]**

Biological Strategy: "Cavitation bubbles are created when an object moves through water at very high speeds and creates extreme velocity gradients in the flowing water. Under the right conditions, this produces a cavity or bubble in which the pressure is so low that the water vaporizes. When the bubbles collapse under higher surrounding pressures, they emit energy in the form of sound, light, and heat waves. The whole process occurs in a matter of milliseconds."

Bio Inspired Solution: This may be used to create an immense amount of power in order to crush regolith. This solution may be more difficult to carry out because it would require the transportation of water to the moon. If water was a by-product of a different process in our system this could be used to submerge the regolith in water and use cavitation to generate high amounts of energy to break up the material.

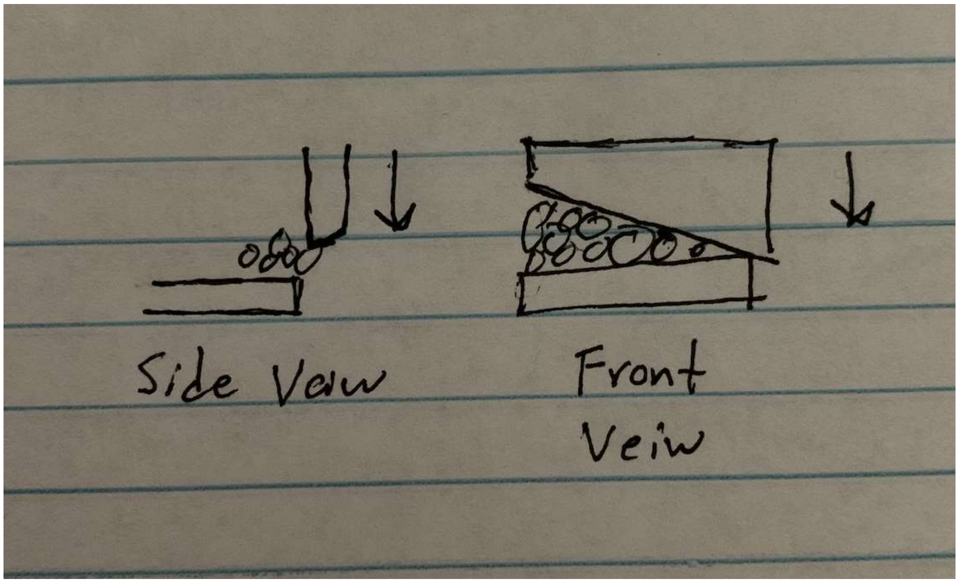
If the regolith is submerged in water and placed in a cavitation chamber, a similar method can be used to transfer kinetic energy to the regolith and break it down to smaller more usable pieces (see image below).



2) **Stingrays - Jaws Designed to Crush Food to Aid Digestion [31]**

Biological Strategy: Freshwater stingrays use blunt jaws to process the hard shells of their prey/food. The kinematics of the stingray jaws include an asymmetric crushing action to shear the insects, crustaceans, fish etc. to optimize the force applied by the muscles.

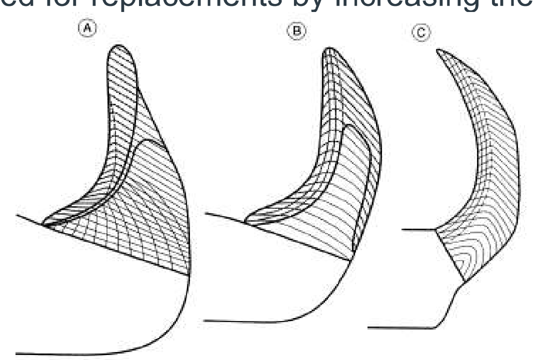
Bio Inspired Solution: The angles and motions inherent to the stingray's crushing jaws can be applied to an ore crushing device that optimizes our available energy on the moon. An angled gravity-fed chute with hardened crushing jaws below can be used to process regolith into smaller pieces to give better access to the bauxite ore. Rocks and minerals are more easily separated with shearing and tension forces rather than compressive forces.

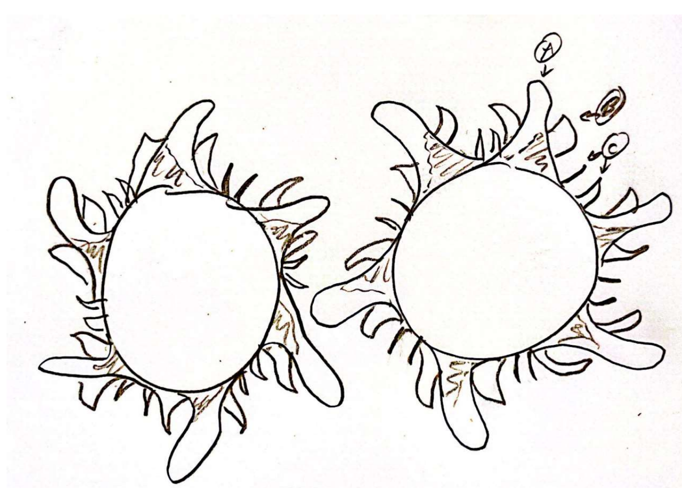


3) **Radula of Patella Limpets - Teeth Composition and shape prevents wear [32]**

Biological Strategy: These limpets have a special mineral composition of their radula (which is the specialized feeding apparatus inside their mouth) made of magnetite cutting tips. "It is shown that shape, internal structure, positioning and material characteristics concertedly function in minimizing the rate at which the teeth wear down and in maintaining optimal cutting behavior."

Bio-Inspired Solution: This bio-inspired design would utilize the shape, internal structure, and positioning strategy employed by the Patella Limpets for use in an ore-crushing apparatus with rotating jaws. The jaws would be lined with teeth that mimic the Patella Limpet's Radula, enhancing the longevity of the system and reducing the need for replacements by increasing the resistance to wear.





Function:

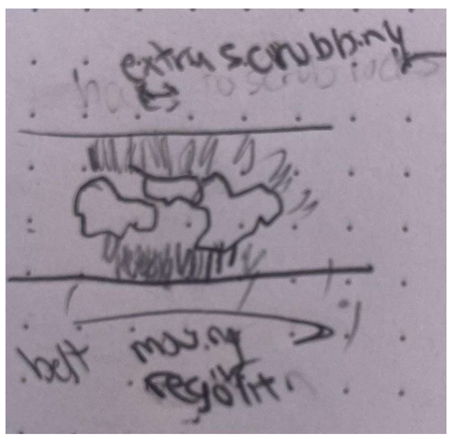
“Isolate Useful Ore”

Biological Function Words: Filtrate, Segment, Divide,

4) **Hair-Like Structures Filter Fine Materials Fiddler Crabs [33]**

Biological Strategy: These crabs use small stiff hairs called setae on their feeding appendages to hold and scrub sand and other sediments.They then eat what was scrubbed off. This can be a potential technique for isolating the desired ore by using brushes/bristles to hold and scrub rocks until the desired ore is left.

Bio Inspired Solution: In one potential solution hair like materials are placed either at the entrance of the system or along sections that move the regolith. The hairs then scrub large chunks of moving regolith, removing fine particles from the regolith. This can make it easier to identify and process the desired resources from the bulk regolith. This solution can be incorporated at multiple stages in the design to help remove fine particles or residue.

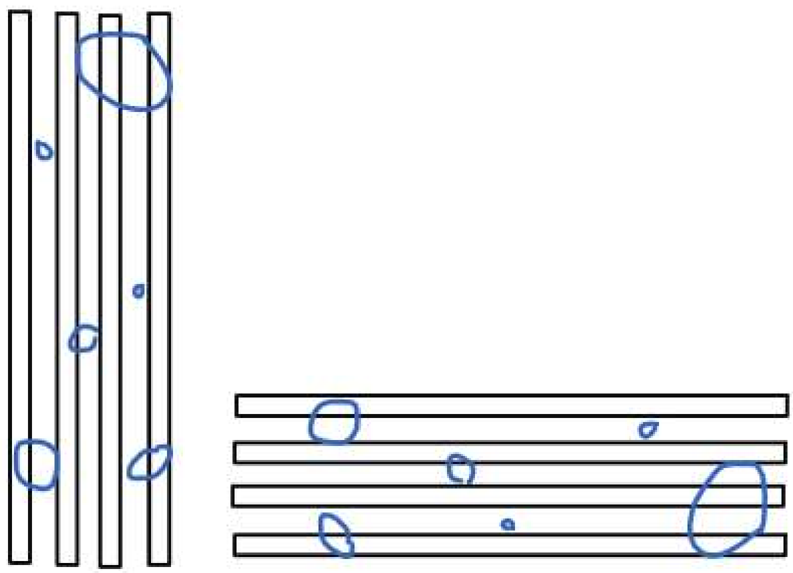


5) **Blue Whale “Feathered” Teeth Filter Food [34]**

Biological Strategy: The blue whale has integrated keratin filters that help to filter small plankton and other small fish from water. “Whale baleen consists of numerous thin plates attached to the upper jaw, each with fringes that capture tiny organisms and shuttle them toward the animal’s throat.” These vertical filters isolate the useful items that the whale wants, with minimal effort.

Bio Inspired Solution: A similar filter structure might be useful for filtering out smaller ore from larger ones. We can use vertical beams/bars/plates, similar to the plates on the inside of the jaw of the whale to separate small rocks from big rocks. Though this seems like a very simple solution, it is a very inexpensive and energy efficient way of isolating useful ore in our system. Overall this simplistic bio-inspired solution can be very efficient in isolating useful ore on the lunar surface.

Vertical or Horizontal “rails” can be used to obstruct large regolith (blue large), and let other small pieces through (blue small).

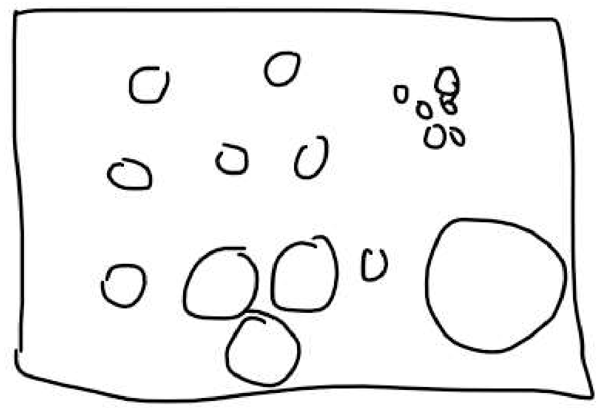


6) **Kidneys Filter and Recycle Waste in the Human Body [35]**

Biological Strategy: Human kidneys filter blood to extract useful minerals and substances that are useful for everyday functions. The primary filtering occurs in glomerulus which is a porous that causes small molecules that are considered waste to pass out of the bloodstream while larger molecules, like proteins, remain in the bloodstream. The liquid waste is then expelled from the body.

Bio-Inspired Solution: This mechanism can be applied to our system to remove impurities from the molten bauxite ore using solvents and other chemicals to aid in the breakdown of individual minerals. Dissolved minerals in a solution could be passed through a chamber with ported walls to separate the pure bauxite from the unwanted regolith components.

A filter screen isolates different sized regolith in different regions (large ores in one location, smaller ores in another). See image below.



7) **Bio-Leaching of Aluminum from Low-grade Bauxite using Adapted Fungal Strains [36], [37]**

Biological Strategy: The process of using organic materials to break down metal ores is known as bioleaching. For the context of aluminum extraction, Marine-derived fungi Aspergillus Niger and Penicillium Simplicissium have been known to produce unique organic acids like citric, oxalic, and gluconic acid that allow them to decompose low-grade metals like Bauxite (which contains alumina like Anorthite). Fungal strains that have been adapted to the high metal toxicity of aluminum could be used as an energy-reducing alternative to the traditional Bayer process used to extract aluminum from bauxite.

Bio-Inspired Solution: This bio-inspired design solution would make use of these adapted fungal strains in order to carry out the energy-intensive process of extracting alumina from anorthite ore (the Bayer process is the equivalent method used for Bauxite on Earth). These fungal strains could be introduced to small batches of crushed anorthite ore in order to form a pulp in which the fungal strains would leach non-alumina components. The result would be an aluminum dense pulp which could go on for further treatment.

Fungal extraction of alumina can be seen in the process below, where the extraction process takes place in the middle and a desired alumina sludge is formed on the left.

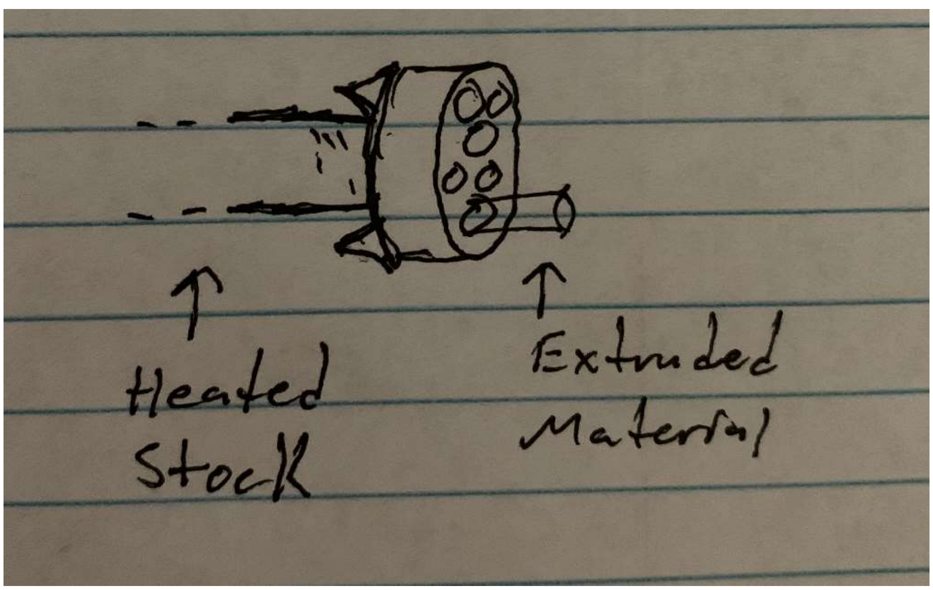
Function: “Form Feedstock”

Biological Function Words: Bond, Fuse, Build, Bind, Link

8) **Spider Producing Webs [38]**

Biological Strategy: Spiders produce webs from accepting liquids and using proteins to produce a strong and flexible web strand. The spider collects resources from its environment to produce a useful web material with a variety of desirable properties. The liquid web solution is passed through a lattice-style structure. The material is able to form into a solid once divided into the smaller diameter strands. The web is designed to have the correct tensile strength, ductility, adhesion etc.

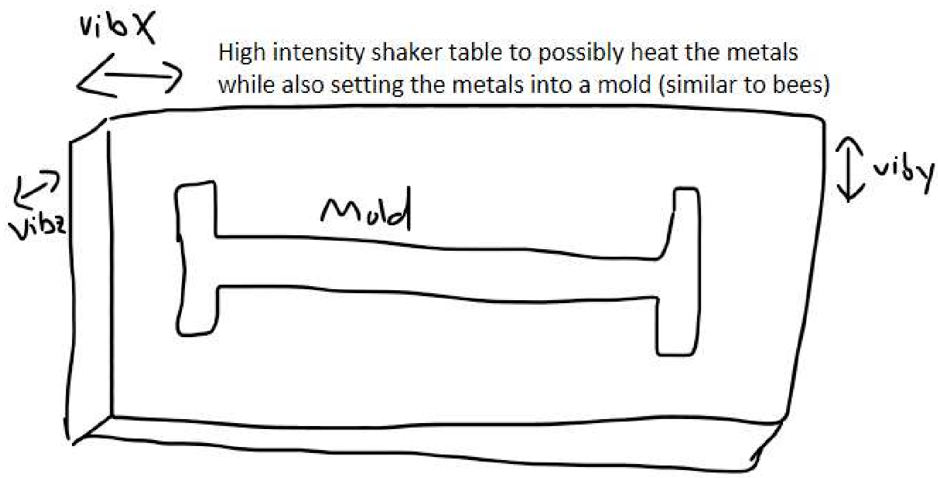
Bio-Inspired Solution: This phenomenon can be applied to developing methods for aluminum extrusion to form feedstock on the moon. In the same way that the spider's abdomen contains sieve-like structure, the purified aluminum ore could be passed through a series of smaller extrusion ports of a die to induce proper cooling and create extrusions that are more easily transported and handled.



9) **Honey Bees Generate Heat to Mold Cylindrical Wax Cells, then Surface Tension Pulls the Cooling Wax Into Hexagons [39]**

Biological Strategy: Honey bees make wax and shape it while using heat. Bees use vibration to generate enough heat to allow the wave to reach temperatures over 100F. This lowers the viscosity of the wax making it easier to mold the shape of wax. After the wax cools the “surface tension rebalances, and the structure tightens into a hexagon shape”.

Bio-Inspired Solution: A similar process might be applicable for forming the feedstock of metal materials on the lunar surface. Vibration might be an inspirational way of heating metals to allow them to increase in temperature, thus increasing viscosity, then allowing the metals to cool to shape.



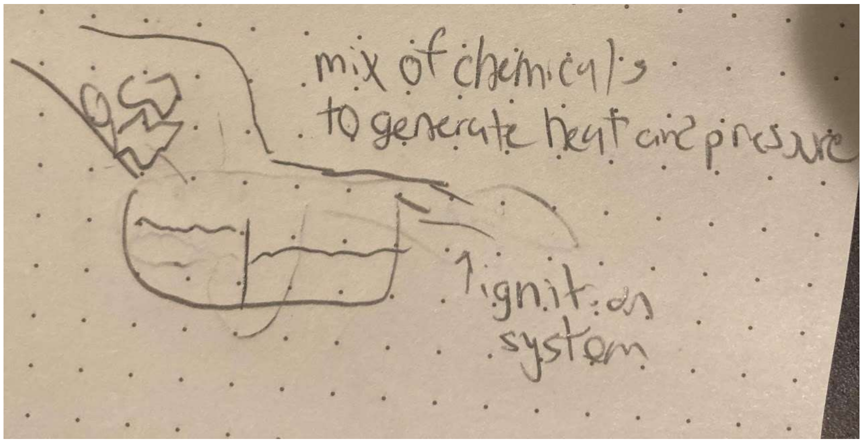
Function: "Smelt Excavated Ore"

Biological Function Words: Temperature, Heat, Power, Store Power, Energy, Regulate

10) **Combustion Chamber Sprays Scalding Liquid [40], [41]**

Biological Strategy: Bombardier beetles are able to spray a chemical p-benzoquinones at around 100 degrees celsius by combining hydroquinones, hydrogen peroxide and enzymes in special chambers. The reaction removes oxygen from the hydrogen peroxide which then reacts with the hydroquinones. This releases heat and the oxygen acts as a propellant for the spray. The unique heart shaped chamber and chemical reaction creates a potential ignition for high temperature systems.

Bio-Inspired Solution: A similar type of reaction could rapidly generate a lot of heat to begin the smelting process. This would most likely not be able to sustain high enough temperatures for long enough to smelt the metal, but it could be a low resource method to jumpstart any necessary heating as an ignition system. Different chemical reactions could generate more heat or different by-products to help reach higher temperatures. Additionally this could help inspire solutions for other functions like expelling waste or purifying the metal. A rapid, high temperature and high pressure chemical reaction could remove undesirable materials in the process through an exhaust system.



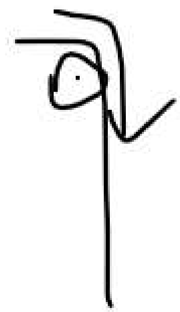
11) **Click Beetles: Energy Stored Amplifies Power of Click Beetle's Jump [42],[43]**

Biological Strategy: Click Beetle's are known to have the ability to propel themselves in a powerful jump off a surface. They achieve this large jump by temporarily deforming its external cuticle, which acts to store energy elastically below the muscle until a trigger point is reached and the energy is released in the form of amplified work. These beetles are able to achieve a power amplification factor of over 1000.

The power amplification phenomenon demonstrated by these Beetle's may provide some significant inspiration into a bio-inspired design relating to several facets of this design problem, including the problem of energy consumption required for smelting. Raising the temperature of any substance to its melting point inherently requires a large amount of power. The method the Click Beetle uses to amplify the power of its jump may have an interesting application in amplifying the power output of the apparatus used to smelt ore.

Bio-Inspired Solution: This bio-inspired design solution would make use of the Click Beetle's energy storage phenomenon by slowly accumulating energy elastically and then releasing it all at once to provide a significant burst of energy to a mechanism that will aid the heating process of the ore. The mechanism would require a method to convert elastic potential energy into thermal energy.

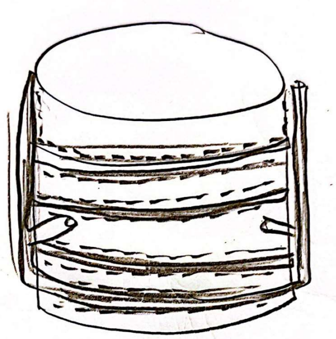
Energy can be stored in a pulley, similar to a beetle's jump.



12) Gray Whales: Arteries in Tongue act as Efficient Heat Exchanger for Thermoregulation [44],[45]

Biological Strategy: Despite its outer layers of blubber, the Gray Whale's tongue is left exposed to the ice-cold waters it lives in when it opens its mouth to feed. To negate any rapid heat loss to the cold waters flowing through its mouth, the Gray Whale's tongue has a vast network of blood vessels and arteries that carry blood in a unique way, acting as a highly efficient heat exchanger which keeps the internal body temperature regulated. These blood vessels are grouped in planes, where very long and small-diameter arteries extend the length of the whale's tongue, each being tightly surrounded by smaller blood veins. The larger artery carries blood out to the tongue while the smaller veins carry blood back to the Whale's heart – this process allows the warmer blood in the arteries to minimize the heat loss from the veins and regulate the inner temperature of the tongue.

Bio-Inspired Solution: Working in the lunar environment poses similar heat dissipation challenges, especially considering the smelting process where it is important to minimize heat loss in order to save energy while increasing the temperature of the ore. This bio-inspired design makes use of the highly efficient heat-exchanger structure that the Gray Whale Employs. Surrounding the smelting cavity with an array of these multi-layered heat-exchanger "veins" could work to minimize the level of heat dissipation away from the system. The larger arteries of the system could surround the smelting cavity, carrying the high-temperature exhausts produced from the smelting process. The smaller veins would process the more cooled exhaust fumes away from the system or recycle them back into the smelting cavity to be reheated.

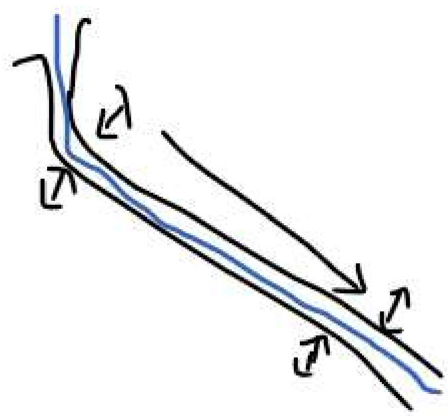


13) **Grooves on Spikes of Thorny Devil Lizard Provide Drinking Water by Drawing Condensed Dew to Mouth by Capillary Action. [46]**

Biological Strategy: Thorny devil lizards can “gather water against gravity without using energy or a pumping device”. Channeled surfaces on the lizard's mouth use capillary action (where the liquid is elevated depending on the relative attraction of the molecules of the liquid) to accept the standing water. “reduce the energy consumption required in collecting and transporting water by pump action (e.g., to the tops of buildings), and provide a variety of other inexpensive technological solutions such as managing heat through evaporative cooling systems, protecting structures from fire through on-demand water barriers, etc.”

Bio-Inspired Solution: Having a concept for gathering water or accepting materials without using energy is critical to a lunar mechanism. Since minimizing energy use is critical for a lunar mission this will be a very useful bioinspired mechanism. Additionally, using a system that manages heat through evaporative cooling systems will be an inexpensive way of accepting liquids into the system while using little energy.

A trough or passage can be used for energy movement with expansions and contractions, without the presence of gravity on the moon. Shown below both sides of the trough will expand and contract as needed.



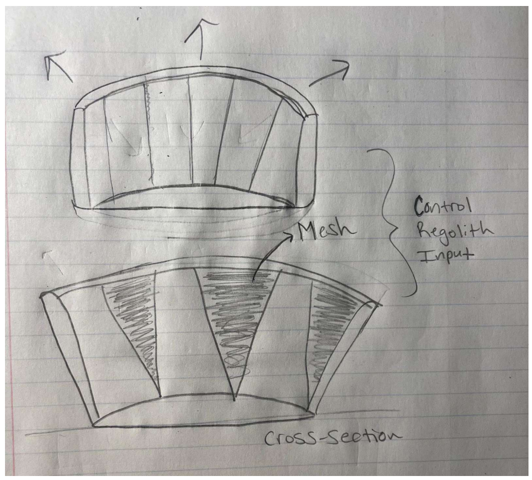
Function: “Accept Regolith”

Biological Function Words:Collect, Absorb, Digest, Deposit

14) **Atlantic Puffin Unique Beak Design [47]**

Biological Strategy: Puffins make shallow dives into water in search of large numbers of small fish. They are able to carry a large number of fish because their jaws are hinged at multiple points. They also have soft stretchy flesh that holds the upper and lower jaws of the puffin together. Additionally, the inside of their upper jaw has a texture which allows them to hold prey inside their mouth while searching for more food. This unique jaw/beak design allows for puffins to preserve their energy as each trip and dive for food takes up a lot of energy.

Bio Inspired Design: This design can be mimicked in our product when collecting/accepting bulk regolith. If we can optimize and control the amount of regolith we accept, we can reduce the amount of energy consumed per cycle.



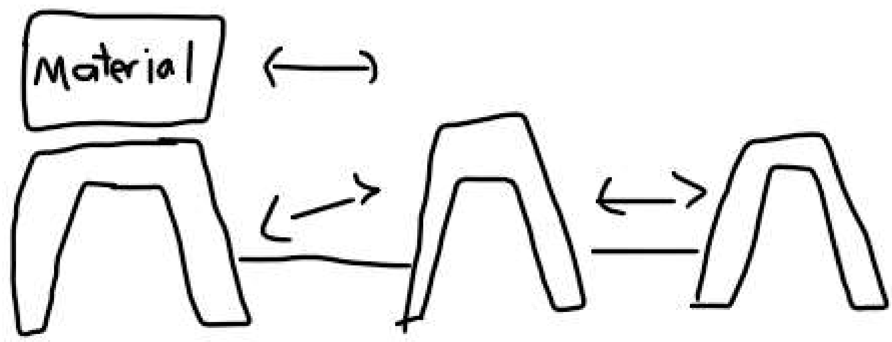
Function: "Move Materials"

Biological Function Words: Orient, Position, Slide, Tunnel, Transport

15) Ants Musculoskeletal System Allows for Lifting Extreme Weight [48]

Biological Strategy: The musculoskeletal system of an ant allows for ants to lift up to 5000 times their own body weight. Due to the exoskeleton geometry of their head and neck, it allows them to support much more weight that researchers believed was possible. This phenomenon allows them to move large volumes of useful food and building materials to support everyday functions. Researchers also indicate that this feature of the ant's body can be optimized in low gravity environments. This design found in nature could be applied to individual regolith transport devices to more efficiently move materials from one site to another.

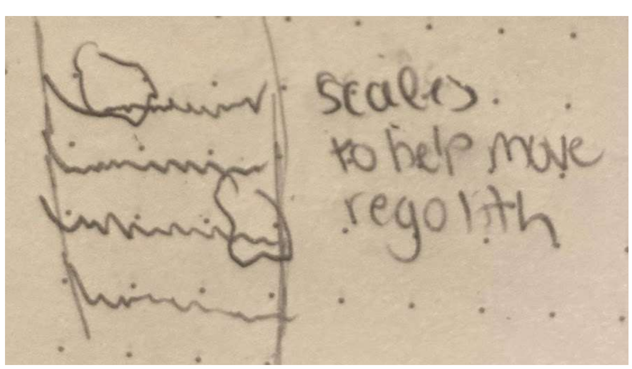
Bio Inspired Design: This design found in nature could be applied to individual regolith transport devices to more efficiently move materials from one site to another. Rather than rely on electric motors, hydraulic pumps and other systems, the transportation devices could include locking lugs that engage at a specific time to ensure that the load does not fall. This would utilize the geometry of the device rather than consume additional energy. Sketch below shows a lug system that would passively expand and contract while moving and supporting material dependent on which direction the material is moving.



16) Snakes: Scale Shape Enables Limbless Movement [49]

Biological Strategy: Snakes are able to easily move across sandy or rugged surfaces due to a combination of their slithering motion and unique scale patterns. The snakes move through high friction to help grip a surface and propel themselves forward and through low friction to help slip over surfaces and reduce damage. These seemingly contradicting features allow for effective movement over long periods of time. The scales have different patterns on the macro and micro scales to enable the snake's movement.

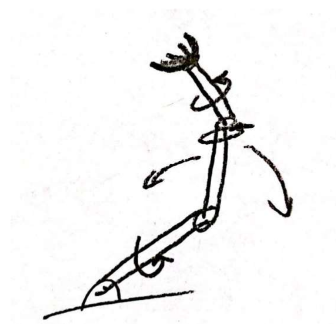
Bio-Inspired Solution: This idea could also be applied to the movement of regolith and other materials in the system. A unique pattern of "scales" could be applied to belts, slides or other tubes to help facilitate the movement of both large rocks and small sand particles throughout the system.The scales can effectively grip the regolith and prevent clogs or jams from too much material. The scales could also help increase durability of the overall system and reduce the need for maintenance.



17) Arthropods: Multiple Joints Allow Circular Movement [50]

Biological Strategy: Crustaceans have grouped two or three limb hinges on their limbs to allow for movement along different planes. This results in full circular movement of the limbs. Without this feature, the movement would only be allowed in one plane.

Bio Inspired Design: Using a similar method, we can prioritize the mobility of our product when transferring materials from one process to another. Another example could be designing a simple robot arm that autonomously analyzes the regolith in various stages and can pick and place any regolith that is jamming the mechanical processes (grinding, etc.). The added mobility will allow 6-degrees of freedom making it easy to pick and place in various locations.



Function: "Expel Spoils/Waste"

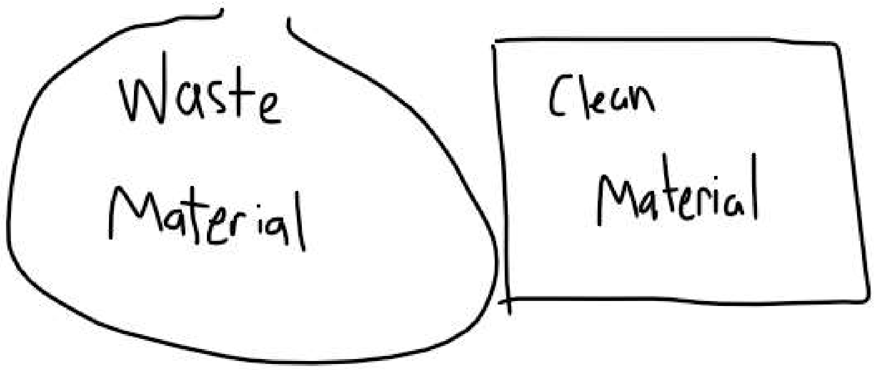
Biological Function Words: Breakdown, Dispose, Excrete, Displace, Discharge, Waste

See "Combustion Chamber Sprays Scalding Liquid" (BID 10) [40]

18) Fecal Sacs Produced by Baby Birds Enable Parents to Maintain a Clean Nest by Easing Clearance of Waste. [51]

Biological Strategy: Baby birds expel all of their waste (urinate + feces) in one action. Rather than expelling waste directly next to the nest the adult bird (mother) takes the waste sacs far away from the nest. This is because having the wastes next to the nest or inside the nest attracts predators. The baby birds keep all their wastes in sacs that are stored inside the nest. These sacs hold all the waste and are transported somewhere else to expel away from the nest once larger enough.

Bio Inspired Design: A similar method of containing wastes can be useful for our lunar forge as it will clearly separate the wastes from the wanted materials. Additionally, rather than having potential wastes in the "nest"/"forge", where they can contaminate clean materials, a system can be put in place to transport/launch the waste away from the forge. Isolating waste from wanted materials will be critical to our design, additionally finding a disposal method that moves unwanted waste away from the forge will be beneficial to the over function of the forge system. All in all this bio-inspired design helps inspire us to use a “sac-like” method for containing all unwanted liquid/solid wastes in one location prior to expelling/transporting to a different location for recycling or discarding.



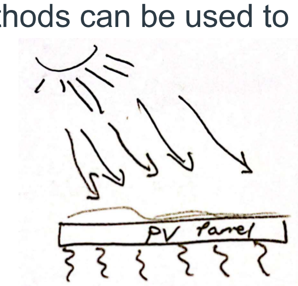
Function: “Power System”

Biological Function Words: Solar, Photosynthesis, Power, Energy, Synthesize

19) Oriental Hornet: Pigments Absorb Solar Energy [52]

Biological Strategy: These hornets absorb sunlight exposed to their outer layer. They are able to harvest solar energy due to the brown and yellow pigments on their outer layer. There are multiple layers of each color (30 of brown/15 of yellow). The brown layer is also covered in grooves that act like gratings to trap light. Additionally, the yellow layer is covered in bumps which increase the effective surface area for absorption. The solar energy is stored and converted into electrical energy which is held between the inner and outer layers of the yellow stripe. This energy is then used for physical activities like digging or flying. It is also used to regulate temperature.

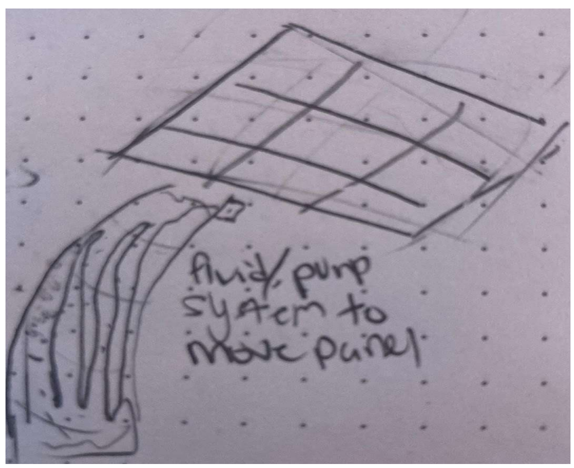
Bio-Inspired Design: Similar mechanisms may come in handy when trying to maximize our source of energy and methods of acquiring said energy. Solar energy is a useful source of energy on the moon and these methods can be used to trap and enhance the intensity of solar energy for our solar panels.



20.) Water Pressure Helps Flowers Follow the Sun [53]

Biological Strategy: These flowers bend towards the direction of the sun so they can maximize exposure. Hormones called auxin in the flower move away from the light and help stiffen certain parts of the flower.. This allows the flower to bend towards the light due to changes in water pressure a. This allows the flowers to absorb as much light as possible at little energy cost.

Bio-Inspired Design: A similar technique can be designed to power the regolith smelting system. A flexible stem connected to a solar panel can be moved by changes in pressure of a fluid. This allows the panel to follow the path of the sun. While the flowers use a hormone to help regulate the pressure, the system could use pumps or mechanical means in combination with a light sensing control system to help regulate the pressures and positions. This will cost some additional energy, but this should be offset by the increased solar exposure.



6 | Design Concept Descriptions and Down-Selection

6.1 | Round 1 Down-Select

Concept	Reason for Elimination
Sifting/Mechanical filters	Limited room for innovation
Conveyor belts	Simple solution that is common in non-lunar environments. There isn't as much room for innovation
Electrolytic Refining	Many existing solutions, limited room for innovation
Material movement	Solutions for this have already been explored. There are many examples of various all-terrain rovers
Accept bulk regolith	Many processes on earth exist, so much harder to find something groundbreaking
Grinding and crushing regolith	Little change to process on the moon, crushing and grinding has limited room for innovation
Piping transport system	Broad idea with too many factors and issues. Probably not feasible for this project

6.2 | Additional Research for Round 1 Down-Select

<u>1st Down Select:</u>

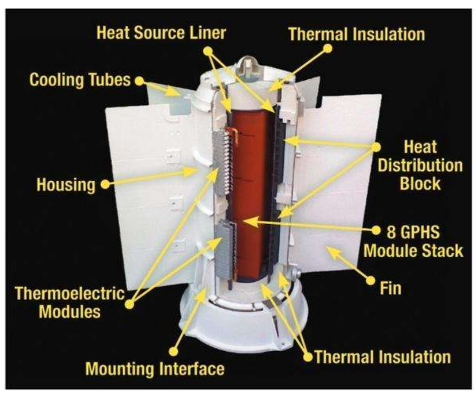
- **Innovation Topic/Area**
    - Concepts worth pursuing from idea generation phase or new concepts worth further exploration

<u>Reasoning:</u> [explanation on why the above topics are believed to be areas ripe for innovation]

- **Power Source**
    - Nuclear Fission
    - Heat transfer to ore

<u>Reasoning:</u> NASA is currently working on generating better ideas to harness nuclear fission [54]. There is room to innovate this because the lunar forge project will require a generally large amount of sustained power in order to be successful. More research will be conducted on methods of storing energy, harnessing nuclear fission, and current solutions NASA has already developed to determine ways we can further innovate.
<u>Additional Research:</u>

- Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is a generator that was created by NASA and the Department of Energy [55]. It works by taking the natural decay of radioisotope materials and converting their heat into electricity. Electric voltage is produced when you join two dissimilar and electrically conductive materials together. This machine was used to power the Curiosity rover and assisted with power generation for other NASA projects.



Model of an MMRTG, including its internal General Purpose Heat Source (GPHS) modules

- NASA conducted an experiment in Nevada to prove out the abilities of a new nuclear reactor power system [56]. The system is called Kilopower, and it is capable of providing up to 10 kilowatts of electrical power [56]. This project will be essential for future moon missions and looking deeper into how this system operates, we can locate areas for improvement.

- **Storage Vessel**
    - Pressure vessel to protect against corrosion and abrasive damage
    - Vacuum on the moon

<u>Reasoning:</u> Listed as a current need in the NASA Big Ideas prompt. Ample areas for innovation regarding rust prevention, temperature control and protecting materials from the lunar environment.

- **Smelting Ore**
    - Controlling temperature
    - Controlling pressure
    - Adverse environment
    - Detect changes
    - Methods of adapting thermodynamic cycles for use in the lunar atmosphere

  Reasoning: While methods of smelting ore have been around for a long time we believe there are innovative solutions to be found for smelting ore in the lunar environment. In order to smelt ore, we need to maintain a steady operating temperature and pressure. One challenge to innovate on would be accurately controlling the large range of temperatures on the moon in order to smelt ore. It would require a powerful heating and cooling system and a robust detection system to record and send signals to the product.
  Additional Research:

    - We will need to research Cryocoolers, Thermal Control Systems (TCS), and methods of heating/cooling on the lunar surface [57]

- **Manage Spoils/Waste switch to Optimize Byproducts**
    - Capture useable resources from waste
    - Methods for converting byproducts of one process into useful inputs for others

  Reasoning: By-products of the refining process could be captured and used for an energy source or used for alternate manufacturing processes. Could include gasses, liquids, and solids. Especially because energy and primary materials are scarce on the moon, the ability to reuse exhausted resources as inputs for secondary processes would massively contribute to the sustainability of a lunar settlement. Any innovation that improves the sustainability or efficiency of a process is valuable.
  Additional Research:
    -

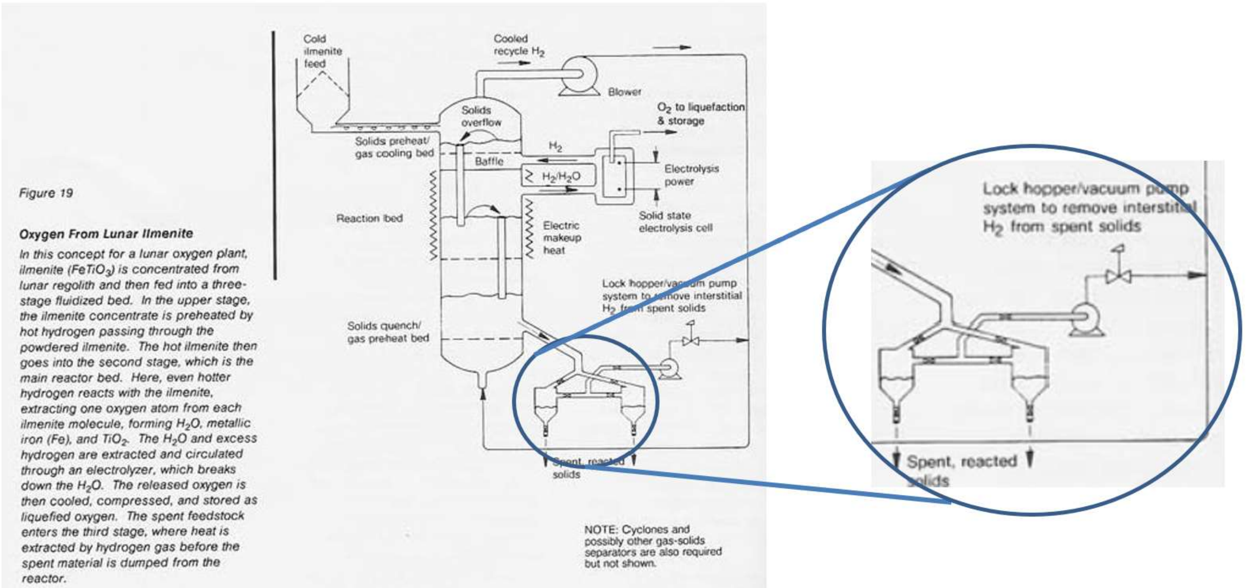


Figure 19

Oxygen From Lunar Ilmenite

In this concept for a lunar oxygen plant, ilmenite ($FeTiO_3$) is concentrated from lunar regolith and then fed into a three-stage fluidized bed. In the upper stage, the ilmenite concentrate is preheated by hot hydrogen passing through the powdered ilmenite. The hot ilmenite then goes into the second stage, which is the main reactor bed. Here, even hotter hydrogen reacts with the ilmenite, extracting one oxygen atom from each ilmenite molecule, forming H_2O, metallic iron (Fe), and TiO_2. The H_2O and excess hydrogen are extracted and circulated through an electrolyzer, which breaks down the H_2O. The released oxygen is then cooled, compressed, and stored as liquefied oxygen. The spent feedstock enters the third stage, where heat is extracted by hydrogen gas before the spent material is dumped from the reactor.

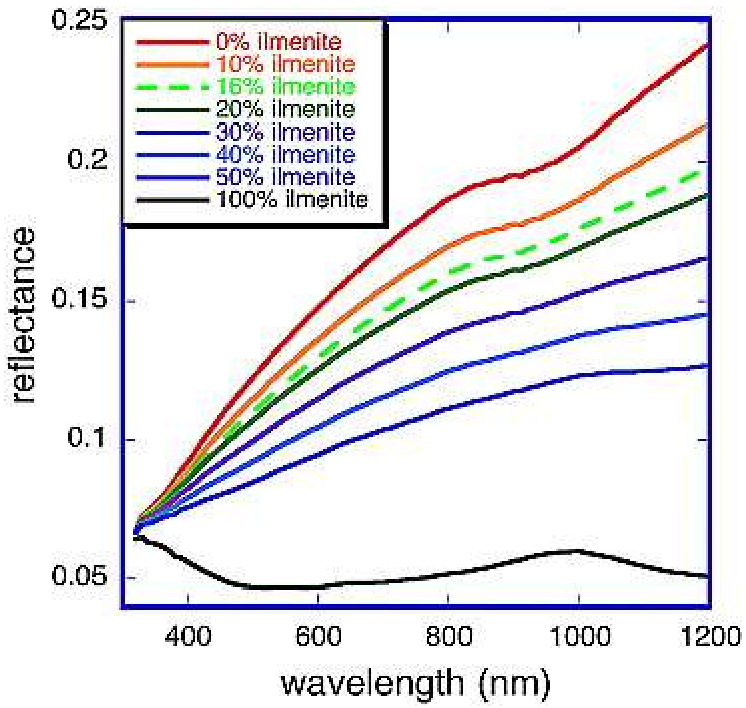
- Both these images are from “Processing Lunar Soils for Oxygen and Other Materials” [58]. They describe the process flow of refining anorthite and ilmentic soil found on the moon. Highlighted in the right image is a particular process that could be ripe for innovation - using the moon’s vacuum atmosphere to isolate and remove spent solids. This link sites cyclonic separators as devices that could be implemented to achieve this goal.

- **Identifying and Isolating Useful Ore**
  - Spectroscopy and machine vision to detect material composition and wavelengths [59]
  - Automated system using a series of magnets and air curtains to Isolate magnetic materials from non-magnetic materials as a pre-step
  - Mechanical methods for quickly and accurately targeting desired materials in batches of mined regolith

<u>Reasoning:</u> An automated system for identifying and isolating useful ore can increase the efficiency and throughput of the process. The existing methods for identifying material composition such as spectroscopy require frequent calibration and maintenance which inherently excludes process automation [59]. Thus, there exists the opportunity to improve or adapt this method with the goal being a continuous process. An automated magnet system presents an avenue for innovation when targeting Ilmenite ore as it is known to have magnetic properties due to its ferrous composition. Electromagnets could be explored as a passive, mechanical solution. Additionally the idea of using air curtains and jets to orient ore into certain locations has major room for innovation.

Additional Research:

- Spectroscopy can be useful for identifying ilmenite and other resources by observing reflected wavelengths from materials [60]. However it requires high maintenance and frequent calibration. This can be automated to better meet the needs of the BIG Idea's Challenge. Additionally with ilmenite the spectral features increase as particle size decreases. It becomes easier to identify fine ground ilmenite in lunar regolith. The system must be able to identify potential resources while still being able to extract and process the materials.



Previous research on identifying ilmenite (shown above) in lunar soil has already been done, the process will need to be modified so it can be used in the isolation and smelting process on the moon [60]. These techniques can also be used to determine overall quality of any final product.

- Pertaining to the Beneficiation process of mechanically separating (isolating) lunar ore, the above link describes several methods for passively (no power input) identifying ores. The link is part of a series of web pages that describe different processes that could be used for isolating ores [61]. A few of the many methods described include making use of physical properties like magnetism, specific gravity, and other methods such as electrostatic separation.

- **Drying/cooling system that utilizes lunar temperatures and pressures**
  - Used in conjunction with water or other liquid washing system

- Offers faster and more efficient drying than using heat or blowers
- Water vapors could be captured, collected and reused (if possible)
- Keep water in liquid form when desired

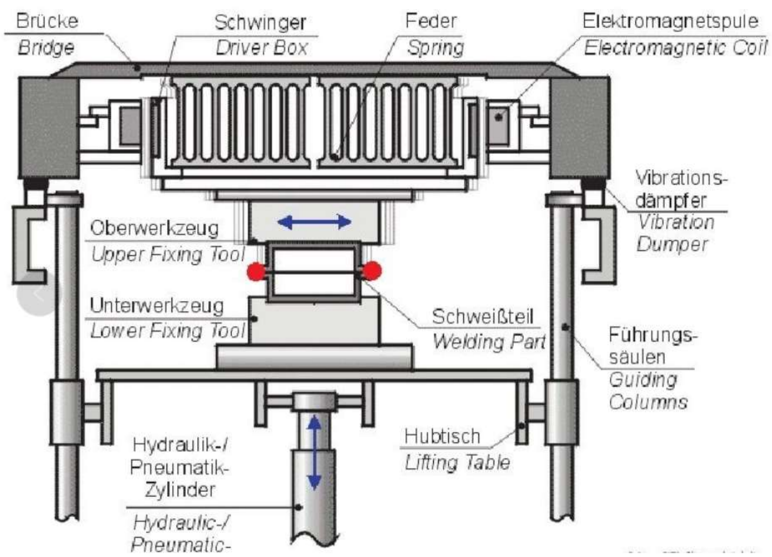
Reasoning: After hot-forming metal, several processes are often used to temper and quickly solidify the metal into its desired final state. These processes involve raising the temperature to a critical level followed by controlled cooling by convection to air or quenching in cooled water, neither of which are readily abundant on the moon. Thus there is value in pursuing innovative techniques that could use the surrounding lunar environment to dry or quench feedstock materials without requiring air or water.

- **Form Feedstock**
  - High intensity vibrational mold to form feedstock into auto-adjustable molds
    - High intensity vibration heats up material to allow for decreased viscosity
    - Flowing material is set into custom, auto-adjustable molds/dies
  - Very low energy necessary to power

Reasoning: Currently no system exists for generating feedstock from lunar ores while on the moon’s surface. Though on the surface might not seem like there is much room for innovation, the team has found many innovative amble ideas. There is room for innovation in the methods of forming feedstock because there are possible methods that have not been implemented yet on earth, such as using vibration for forming metal. Bees use vibration to form their hives. A vibrational mold might be a new innovative bio inspired design. Additionally, the idea of an automated test bed that changes the shape of mold prior to pouring molten metal might be a new way to form Feedstock that hasn't been implemented. While innovative, these are also useful for the lunar surface because of the low energy usage constraints.

Additional Research:

- The patent information below highlights a process that is similar to the process that could be used in this innovative feedstock forming process. Using vibration to heat treat metals could be a useful way of improving the mechanical properties of certain metals. While using vibration to heat up metals for heat treating is possible from the patent below, this similar process can be used on forming the shape of a metal with a lower metal point (aluminum rather than steel) [62]. Though vibration aging is used to reach the feedstock to certain temperatures for heat treatment, additional vibrational intensity could be used to further heat the metal and allow it to flow into a mold [63]. The mechanical design of such a system will be looked at further in the next homework, but an inspirational concept is shown below [63].



Next Steps:

- Continue research on potential power sources that are accessible or attainable on the moon. Research the most efficient sources that are useful for powering the lunar forge.
- Identify and further investigate innovation opportunities regarding storage vessels on the moon that protects ore from the lunar environment.
- Research more metrics and details on the lunar environment.
- Research useful chemical processes for processing ore.
- Identify new opportunity gaps in each down-selected concept. Look for specific problems that need to be solved
- Sketch new solutions
- Use a rating based matrix to further down-select ideas
- Research and evaluate alternatives with Pugh Chart

6.3 | Round 2 Down-Select

Originally we started with a pugh matrix to determine the best solutions to move forward with. Then we narrowed down the solutions to the three most feasible to complete in the semester, while using the design criteria shown in the leftmost column. After further analysis and discussion, it was determined that the main driving factors in the chart below were the ability to complete such a project in the timeframe of the semester or timeframe feasibility.

	Solution 1	**Solution 2**	**Solution 3**	**Solution 4**	**Solution 5**	**Solution 6**	**Solution 7**	**Solution 8**
Ranked 1 - 5 (5 is most optimal, 1 is least optimal)	**Lunar Storage Vessel**	**Adapt Smelting for Lunar Environment**	**Nuclear Fission**	**Converting Byproducts**	**Ore Identification via Spectroscopy**	**Isolate Ore via Magnets**	**Tempering/Hardening Metal Mechanism Using Lunar Environment**	**Form Feedstock w/ high-intensity vibration mechanism**
Cost of Development (5 = very low cost)	4	2	1	4	4	4	3	2
Minimal Power Requirements (5 = low power required)	5	2	2	3	3	3	5	2
Design/Proof of Concept Feasibility (5 = easier to prove/design)	3	1	1	2	2	4	4	2
Transportability (5 = easy to transport)	3	2	1	2	5	2	4	2
Magnitude of Impact on rest of Metal Production	2	5	5	1	4	4	2	5

Pipeline (5 = Vital to Prod. Pipeline)								
Utility to other processes (5 = high utility)	4	4	5	3	2	1	4	1
Longevity (5 = Long lasting)	3	3	2	3	3	4	4	2
Safety (5 = More Safe)	4	2	1	4	5	3	5	4
Reliability (5 = More reliable)	5	2	3	3	2	4	3	3
Innovation (5 = very innovative)	2	5	3	4	4	1	4	4
Sum	**35**	**28**	**24**	**29**	**34**	**30**	**38**	**27**

After the team recognized this bias toward completing the project in this timeframe, we reorganized the chart above. The reorganization shows the removal of requirements that are not yet able to be analyzed at this point in the design process (cost of development, longevity, safety) [highlighted in red above]. Additionally as stated above, a row was added for time frame feasibility.

	Solution 1	**Solution 2**	**Solution 3**	**Solution 4**	**Solution 5**	**Solution 6**	**Solution 7**	**Solution 8**
Ranked 1 - 5 (5 is most optimal, 1 is least optimal)	**Lunar Storage Vessel**	**Adapt Smelting for Lunar Environment**	**Nuclear Fission**	**Converting Byproducts**	**Ore Identification via Spectroscopy**	**Isolate Ore via Magnets**	**Tempering/Hardening Metal Mechanism Using Lunar Environment**	**Form Feedstock w/ high-intensity vibration mechanism**

Design/Proof of Concept Feasibility (5 = easier to prove/design)	3	1	1	2	2	4	4	2
Magnitude of Impact on rest of Metal Production Pipeline (5 = Vital to Prod. Pipeline)	2	5	5	1	4	4	2	5
Utility to other processes (5 = high utility)	4	4	5	3	2	1	4	1
Innovation (5 = very innovative)	2	5	3	4	4	1	4	4
Timeframe Feasibility	5	1	2	3	5	3	5	1
Sum	**16**	**16**	**16**	**13**	**17**	**13**	**19**	**13**

From the refined Pugh chart above we can see the three most optimal options to move forward with are the “Lunar Storage Vessel”, “Ore Identification via Spectroscopy”, and “Tempering/Hardening Metal Mechanism Using Lunar Environment”. The following section will go into further detail on design innovations for these three options, as well as sketches.

We determined that the “Lunar Storage Vessel” option had a lot of room for innovation as we could use the materials present on the lunar surface to construct the vessel (ores to create or film of 3D printing). Additionally, the ability to implement automated calibration for lunar ore spectroscopy could be an innovation that could improve current spectroscopy machines on earth. More detail about the Tempering/Hardening Metal Mechanism Using Lunar Environment can be seen in the section below.

6.4 | Design Concept Descriptions after Round 2 Down-Select

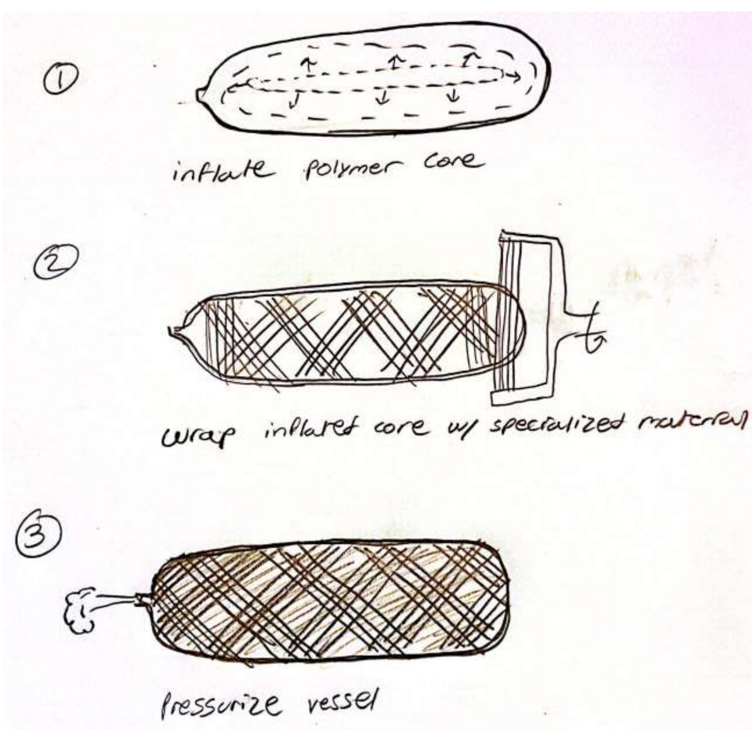
Lunar Storage Vessel:

Current Issues:

- Manufacturing of storage vessels (currently done via casting on earth)
- Production of a reasonable sized vessel on the lunar surface
- Achieving tight tolerance needed for an airtight vessel using lunar manufacturing techniques
    - Possibility for 3D printing the lunar vessel
- Maintaining quality of stored materials
- Time to manufacture
- Protecting product against the harsh lunar environment
    - Large temperature gradients
    - Resisting lunar and solar winds [64]

Areas for Innovation

- Use an initial inflatable polymer body
    - Body is inflated and then wrapped with metal stands
- Use of a wrapping method using two idle rollers (similar to package wrapping)
    - Turn regolith into a film that is malleable to be used a wrap
    - Use Iron ore, because of the higher ductility
        - Better suited material for pressure vessel
- Use of 3D printing to create end caps for the storage vessel
- Chamber with values that allow for variable liquid or gas flow
- Inspiration: **[65]**



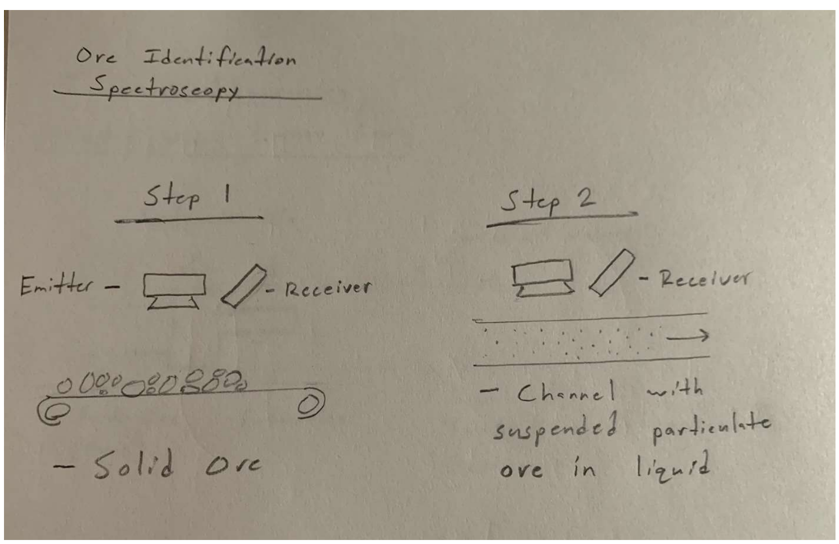
Spectroscopy:

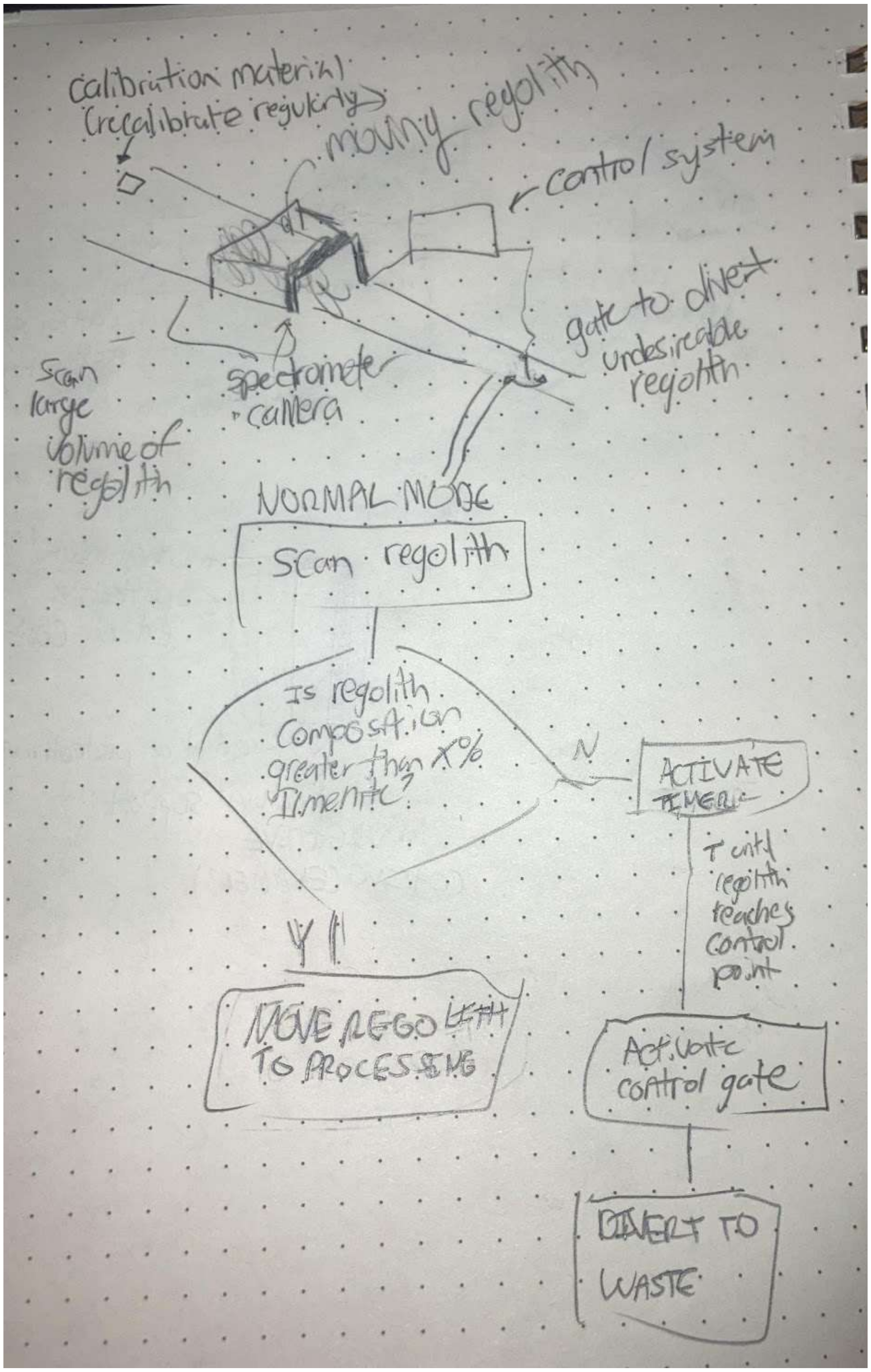
Current Issues:

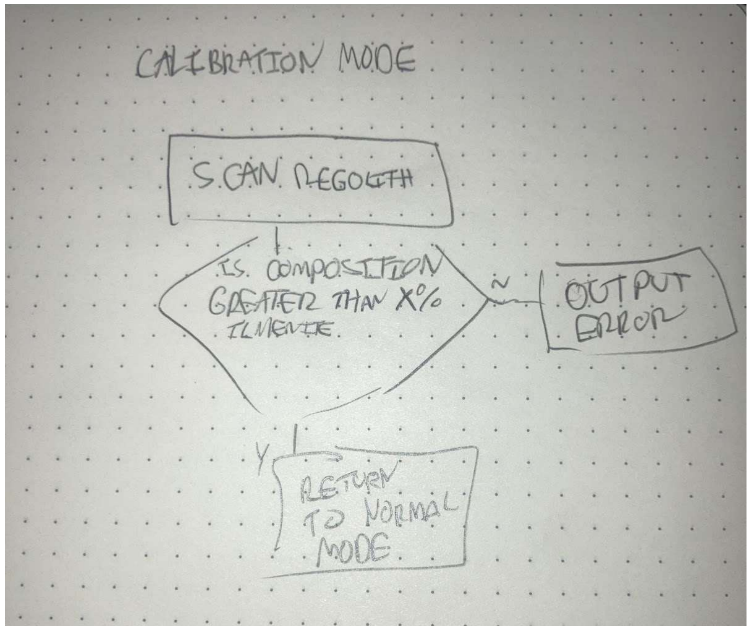
- Calibrating it (constant check ups)
    - Automate calibration
    - Control substance
- Inputting the substance
    - What size
    - Weight
    - Multiple materials within one chunk of regolith
    - What phase of the process do we apply it
- Optimal Operating environment
    - Could be an assumption
    - Or how do we control the environment to best suit our device

Areas for Innovation

- How to automate calibration
- How to separate different ore types once they have been identified
- How to adapt




calibration material
(recalibrate regularly)
moving regolith
control system
gate to divert undesireable regolith
spectrometer camera
Scan large volume of regolith
NORMAL MODE
Scan regolith
Is regolith composition greater than X% Ilmenite?
N
ACTIVATE TIMER
T until regolith reaches control point
Y
MOVE REGOLITH TO PROCESSING
Activate control gate
DIVERT TO WASTE



Tempering/Hardening Metal Mechanism Using Lunar Environment:

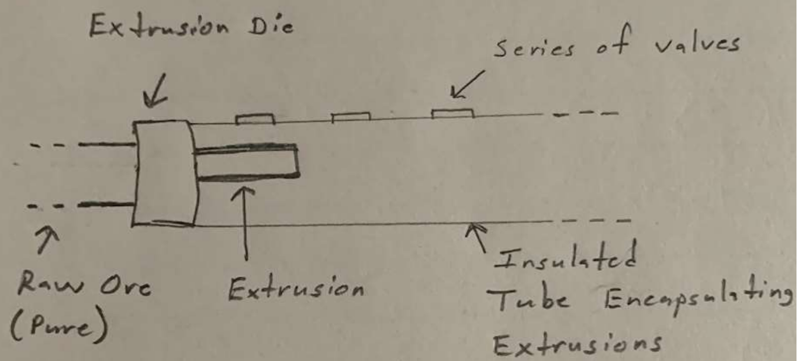
Current Issues:

- The temperature and duration of each phase of a tempering/hardening process is very specific - being on the moon it will be a challenge to meet these requirements
    - Will research specifics related to these metal processes
- How to use air quenching? (Requires oil/water/other liquid)
    - There isn't an atmosphere
- Perform heat transfer without air
- Water easily evaporates at most lunar temperatures

Areas for Innovation:

- Use of heat exchanger with flowing liquid to perform conduction on materials
- Use of liquid nitrogen to quench hot product and achieve desired material characteristics
- Automated Product Handling Device to transfer materials from heating to water quenching location
    - Use of a robot arm to move product within the device
- Shaker Table to translate products from the heating station to quenching station
- Super-cooled gasses or liquids that can create a source of convection

Tempering / Hardening Metal Using Lunar Env



- Valves can be opened/closed to allow variable air flow to the part.

6.5 | Preliminary Proof of Concept and Proof of Concept Plans

Lunar Storage Vessel Proof of Concept (Calculations can be found in last section “Proof of Concept for Vessel Structure”:

Proof of Concept for converting lunar regolith to thin steel films [66]:

Since this is a process that has been created on earth, we can translate this into a small scale model if the project gets accepted for the NASA BIG IDEAS challenge. Since limited time is available for the Fall semester the team will opt to focus on other aspects of the problem. For this concept, we are assuming that we already have formed the lunar ore into the rolls of thin film that we need, using the same process that is used on earth. This already established process uses lasers to heat small amounts of metal powder into the desired film thickness.

Proof of Concept for forming thin steel films into a Cylinder

- Our team drew inspiration from a shipping package wrapping machine [67]. .
- Our team will plan on using a similar process to form the cylindrical portion of the lunar storage vessel. After design calculations are finalized, a thickness of carbon steel film will be selected to design around. Once specifications are determined, a Computer Aided Model and Manufacturing Instructions will be created for the conceptual design of the Lunar storage vessel. Our Plan is to design around the structural calculations for the vessel and pivot the manufacturing process as needed.

Proof of Concept for metal 3d printing on the moon [68]

Since a metal 3D printing process already exists, SLS, Selective Laser Sintering can be used to manufacture the endcaps of the vessel on the moon. Laser Sintering 3D printing works by laying a “100-120 micron” layer of powdered metal (steel) on a bed. Then a laser “sinters” the metal to form it into the design shape [68], [69]. By grinding the desired lunar ore (steel) in other processes leading up to the 3d printing, this thin layer of powdered ore can be made. With RF connectivity back to earth, NASA engineers can use this SLS machine to create storage vessel end caps and iterative designs for other parts of the lunar forge [69]. Companies such as Relativity Space have already shown that it is feasible to print large vessels (rocket engines) using this type of manufacturing process.

Proof of Concept for Pressure Vessel Structure [70]

We will use formulas for simple pressure vessels to determine a recommended material from our dimensions [70]. Though there is an extremely thin atmosphere on the moon, for the sake of these calculations we will assume no air pressure on the lunar surface. Since the dimensions of the desired vessel are rather large, and all that is needed is isolation from the lunar surface a low internal pressure of 5 psig will be used to encapsulate internal parts. To harvest the parts that are necessary for lunar storage, we need an ID of at least 2 feet, and a length of about 6 feet [70].

Typical Metalized films are 78.4 microns or approximately 3 thou (.003 in) [71]. With the assumption that a thickness of around ¼ in of material is needed for this application we will need .25/.003 = 83 layers [71]. This can be adjusted as we further establish our proof of concept in the future. For further simplification, the poisson's ratio can be estimated to be that of aluminum 0.33. An estimate of 0.3 can also be used for steel, but we compare this once we determine the necessary yield stress to see which will result in a desired stress.

$$\frac{t}{ID} = \frac{1}{2}\sqrt{\frac{3(3 \cdot m + 1)P}{8 \cdot m \cdot \sigma_{yield}}}$$

Using the equation above we will solve for yield stress to determine viable materials for the conceptual design [72]. So, where thickness t is 0.25 in, ID is 24 in, m = 1/v = 3.03, P = 5psig.

solve	$\frac{0.25}{24} = 0.5\sqrt{\frac{3(3 \times 3.03 + 1) \times 5}{8 \times 3.03\,\sigma}}$	for	σ

Result

$\sigma = 14385.7$

Solving for sigma, we get a required PSI of 14.4 ksi [73]. This gives us a range of materials to choose from, though for space applications a Factor of Safety of 1.5 is the minimum requirement, with most opting for Factor of Safety of 2 and above.

Then the yield strength of steel (from source below) is 448 MPa or approximately 65 ksi (65000 psi). Our internal pressure P was chosen to have a low pressure of 5 psig, pumps and plumbing in the system can be used to pressurize the inside of the vessel, similar to space vacuum chambers.

For steel the FOS (Factor of Safety) [74]:

$$FOS_{STEEL} = \frac{\sigma_{yield}}{\sigma_{result}} = \frac{65}{14.4} = 4.51$$

$$FOS_{AL6062} = \frac{\sigma_{yield}}{\sigma_{result}} = \frac{5}{14.4} = 0.347$$

$$FOS_{AL6061T4} = \frac{\sigma_{yield}}{\sigma_{result}} = \frac{16}{14.4} = 1.111$$

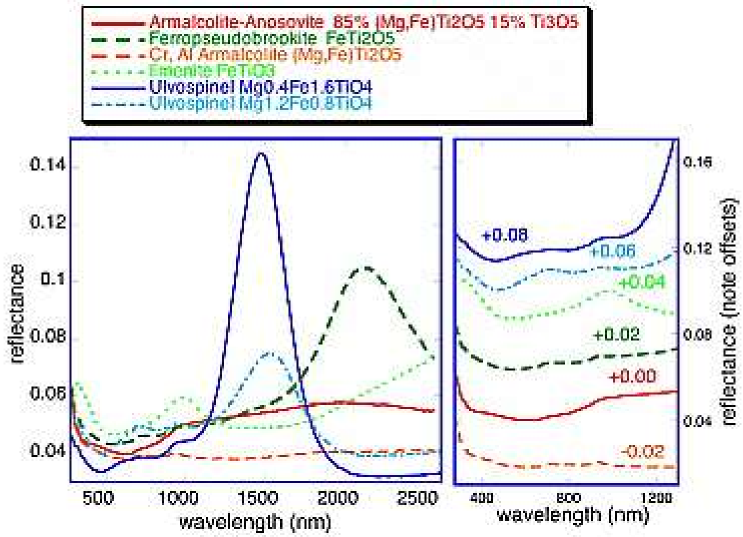
$$FOS_{AL6061T6} = \frac{\sigma_{yield}}{\sigma_{result}} = \frac{35}{14.4} = 2.431$$

From these FOS results, we can see that if we want to use aluminum for this design we should use a tempered aluminum such as common 6061-T6 [75]. A steel film will allow for a higher FOS.

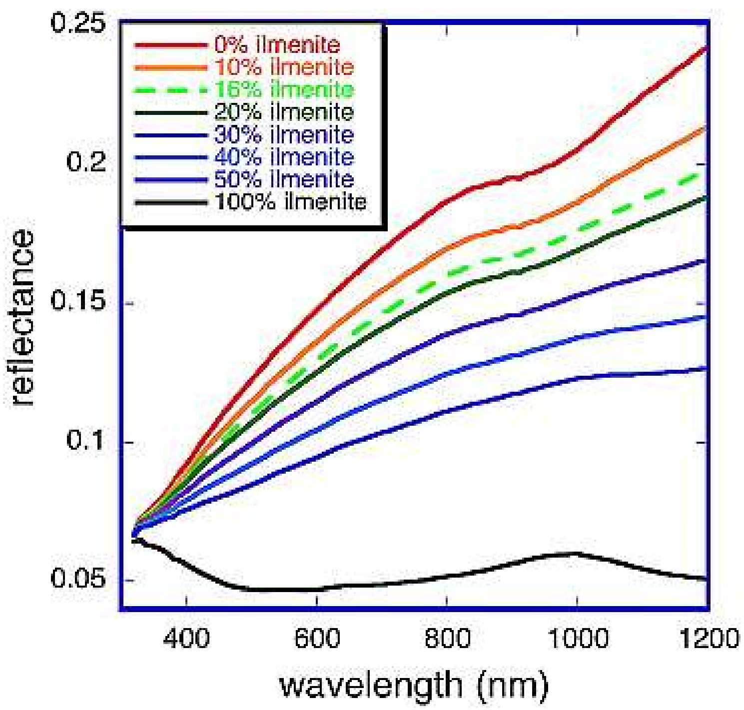
All in all, we plan on using the equation above to optimize our CAD (Computer Aided Design) Model of the pressure vessel. From our findings either a steel of aluminum film will be feasible given our assumed dimensions and pressures above. The final steps in the proof of concept of the pressure vessel will entail a CAD modeled design and MI (Manufacturing Instructions) showing the finalized (not assumed) number of layers, finalized material decision, dimensions, desired internal pressure, and manufacturing steps.

Proof of Concept for Spectroscopy:
Spectroscopy is already being used to identify the composition of lunar regolith by observing the reflectance of light against materials and comparing the information to known data [76].

Most research done so far involves a rover scanning regolith on the surface or work done in a controlled lab environment [77].
If spectroscopy is used to identify the desired minerals in the lunar regolith, it must constantly evaluate the composition of the regolith. Additionally the system must be able to automatically calibrate to ensure the spectrometer is properly evaluating the regolith. We will assume that at this phase, the bulk regolith is partially processed and the spectrometer will be scanning a predetermined volume of powdered minerals and determining if there is enough material for the sample to be viable for further processing. At regular intervals there must be a control sample to keep the spectrometer calibrated and alert an operator if maintenance is needed. This can be done at multiple stages of processing regolith, by acting as an initial filter to help determine if the regolith is worth processing or as a means of quality control before forming feedstock. The process can be adapted depending on what materials are desired.
This system will need to be modeled using software such as Matlab or Simulink. Using empirical data on the reflectance of various metals including ilmenite we can evaluate reflectance at various wavelengths to get an approximation of the amount of desired material in a sample as shown in the graphs below [62]. In order to calibrate the spectrometer, the system will scan a known material with multiple wavelengths and ensure it is within one standard deviation of the expected reflectance. If not the system will recalibrate. Once a sample is scanned it will be filtered and move onto the next step of the process.



Armalcolite-Anosovite 85% (Mg,Fe)Ti2O5 15% Ti3O5
Ferropseudobrookite FeTi2O5
Cr, Al Armalcolite (Mg,Fe)Ti2O5
Ilmenite FeTiO3
Ulvospinel Mg0.4Fe1.6TiO4
Ulvospinel Mg1.2Fe0.8TiO4
reflectance
wavelength (nm)
+0.08
+0.06
+0.04
+0.02
+0.00
-0.02
reflectance (note offsets)
wavelength (nm)



0% ilmenite
10% ilmenite
16% ilmenite
20% ilmenite
30% ilmenite
40% ilmenite
50% ilmenite
100% ilmenite
reflectance
wavelength (nm)

Plan for Proof of Concept for Hardening/Quenching Metal Mechanism Using Lunar Environment:

The ability to temper and harden metal on the moon is vital for constructing support structures. The hardening process involves heating a metal to a critical temperature and then rapidly cooling in order to create stronger grain boundaries [77]. Adapting this process for use on the moon is highly innovative because the resources used to quench or rapidly cool hot metals on earth like cold water, oil, and air are not abundantly available on the moon. Thus, using resources available on the moon as the cooling agent is the crux of this design concept. It happens that the moon has an abundance of untapped nitrogen captured in lunar regolith which could be used as a heat transfer medium to facilitate quenching [78].

This design concept will utilize nitrogen gas extracted from lunar regolith to rapidly quench heated metals via a convection process. The proof of concept model for this idea will focus on the quenching process for heat-treated aluminum, and once validated, can be expanded to include quenching for iron. The driving concept that is to be validated at this stage of development is two-fold: 1) whether the process requirements are feasible to use nitrogen as a convection agent at the temperatures required by the metals on the moon, and 2) whether it is feasible to assume there is enough nitrogen gas available on the moon for use.

The advantage of using a gas to quench material is that the cooling is performed more uniformly, it eliminates the need for a process to exhaust or recycle the cooling agent, and the cooling agent is much easier to produce on-site[79]

Design Concept Model:

1. A piece of aluminum is heated to its critical temperature between 300℃ and 410℃ [80]
    a. For sake of scope of this design concept, we made the assumption that there will be an adequate apparatus to heat the aluminum alloy to these temperatures judging that similar heating processes are needed to arrive that the aluminum alloy in the first place.
2. Once the aluminum is heated to its critical point, it is transferred to the quenching apparatus.
    a. The desired end-state of this product would have this process be automated by robots or conveyors, not requiring humans to do the physical transfer.
3. Blast nitrogen gas over the exposed heated metal and convect heat away from the aluminum quickly.
    a. This requires identifying the optimal pressure, velocity, and time needed to reduce the aluminum to the desired end temperature. This step is where

the validation of this concept will be performed, as the failure of this step means failure of the entire concept.

4. Remove the quenched metal from the convection apparatus and either repeat the process for a higher degree of hardening or finalize the metal.

For preliminary proof of concept, we will employ several heat transfer equations to determine whether nitrogen's thermal properties are sufficient for cooling an aluminum alloy in the desired time [81].

surface temp, nitrogen temp

heat transferred → $$Q = (T_s - T_N)\,h\,A$$

convection coeff., surface area

$$T_s = \frac{1}{A}\int T\,dA$$ → assuming uniform temp through, so $T_s = T_{s,avg}$

$$T_N = \frac{T_{n,in} + T_{n,out}}{2} \Rightarrow \text{avg}$$

heat transfer $$Q = (T_{N,out} - T_{N,in})\,C_p\,m$$

specific heat of nitrogen, mass flow rate

$$\therefore\quad (T_{N,out} - T_{N,in})\,C_p\,m = (T_s - T_N)\,h\,A$$

desired convection coeff. → $$h = \frac{C_p\,m}{A}\left(\frac{T_{N,out} - T_{N,in}}{T_s - T_N}\right)$$

These equations, along with more in-depth calculations for heat transfer involving turbulent flow, will be used to create a convection model. The proof of concept model that will be generated will be a Matlab model used to calculate the optimal parameters required to quench aluminum alloy - the parameters in question that will be identified will be nitrogen gas pressure, velocity, starting temperature, as well as distance the spray nozzle can be from the aluminum workpiece.

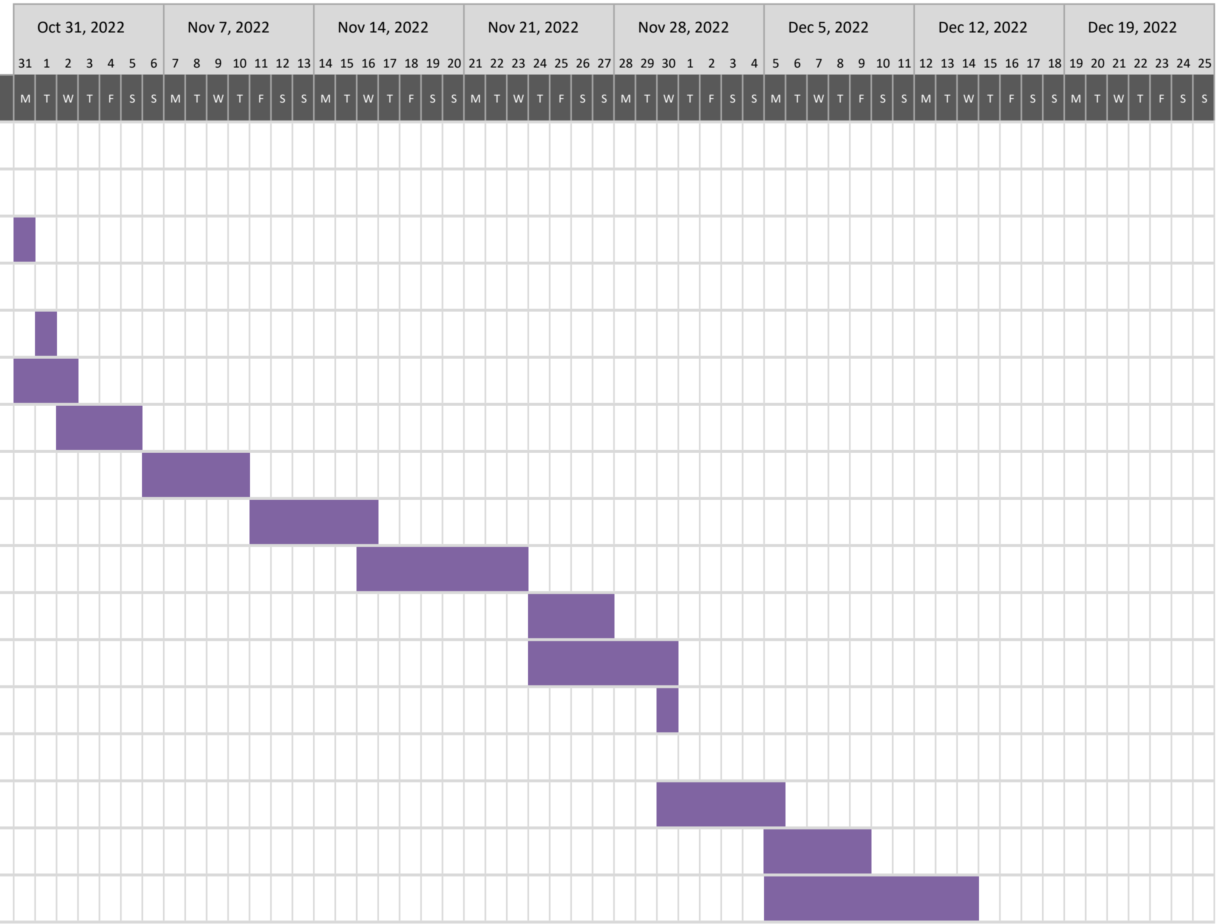
The goal with these equations is to validate the possibility of using nitrogen as an alternative quenching agent while still being a viable option in terms of time it takes to cool the metal.

Me 6102 - Schedule Update - Space Cowboys

Michael Amoun,
Thomas Dodd,
Ryan Grajewski,
Gavan Sarrafian,
Max Zegers

Sun, 10/30/2022
1

TASK	PROGRESS	START	END
October			
Complete Report 2		10/30/22	10/30/22
Continue Research and Evaluation of Solutions		10/29/22	10/31/22
November			
Watch Video - JPL Concept Formation - Induvidual		11/1/22	11/1/22
TRIZ Assignment (Due Nov 2nd)		10/31/22	11/2/22
Proof of Concept Consultations and Computations		11/2/22	11/5/22
Continue Down Selections		11/6/22	11/10/22
Proof of Concept Modeling		11/11/22	11/16/22
Evalution of Final Concept and Start Final Presentation		11/16/22	11/23/22
Thanksgiving Break & Work on Presentation		11/24/22	11/27/22
Continue Final Presentation Slides & Begin Final Report		11/24/22	11/30/22
Final Presentation Due 11/30		11/30/22	11/30/22
December			
Present Final Presentations		11/30/22	12/5/22
Continue Compiling Sources, Data, and Equations		12/5/22	12/9/22
Continue Final Report		12/5/22	12/14/22



7.0 | Conclusion

Refining lunar regolith is a novel and broad process. Using various design tools, the team went through a process of broadening and then narrowing down different solutions and ideas related to the problem. Initial steps such as the use of the black box model, defining metaphors, and developing a house of quality from customer needs allowed the team to clearly understand the context of the problem. Idea generation then allowed the team to explore new directions. This expansion of ideas helped highlight new areas for innovation that were missed during the early phases of the design process. Research done into both man made, and biological designs helped narrow down ideas that were both feasible and innovative. A critical review of the ideas allowed the team to filter down a wide set of over sixty broad ideas, into three well defined paths for an innovative solution.

The next steps in this project will involve developing a proof of concept model to verify the results of the design process. This could be limited to a combination of calculations and computer modeling due to the restrictions of the team. The team will also need to critique the design process so far to ensure that the best directions were chosen and potentially identify any missed ideas.

6.5 | 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
Diagrams of Methods Used: Completed as a Team
Mind Map: Completed as a Team
Word Trees Completed as a Team
Intuitive Analogies from Word Tree Method: Each member completed ~4 Analogies, and reviewed as a Team
6-3-5 Method: Completed as a Team
Morph Matrix: Completed as a Team
Prior Art Patent Search: Completed as a Team
Bio Inspired Designs: Each member completed ~4, and reviewed as a Team
1st Design Down Select: Completed as a Team
2nd Design Down Select: Completed as a Team
Plan for Proof of Concept: Michael Amoun, Max Zegers, Ryan Grajewski, and reviewed and adjusted by entire team
Conclusion: Max Zegers, Gavan Sarrafian, Michael Amoun
Gantt Chart: Thomas Dodd
Resources/Appendix: 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

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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 7th)

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