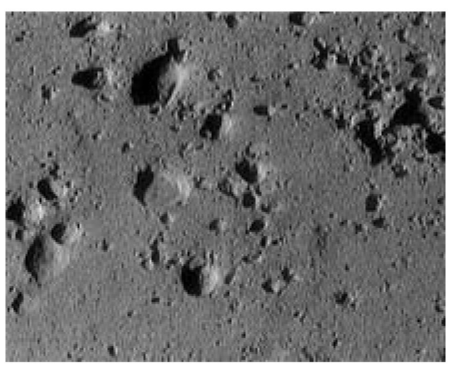
ME3302- Project: Extra-Terrestrial Manufacturing
Final Project Report
Team: Falcon 3 (ME19B063, ME19B067, ME19B093)

DRIVE LINK of project submission:
https://drive.google.com/drive/folders/1SaPHJt7Xf4enCx8rxaQW1ypBjSXcG98a?usp=sharing
contains:
1. Video recording of the presentation
2. 3D model of factory process parts-PDFs and STEP files
3. Report PDF
4. Presentation of the project
5. Factory Simulation (.spp file) on Technomatix Plant Simulation Tool

Proposed Product to manufacture: Oxygen from Lunar regolith

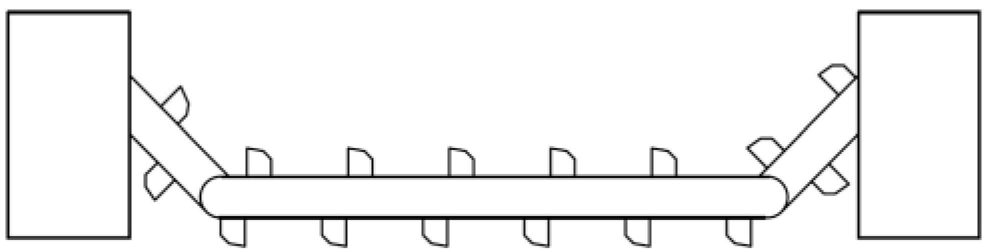
Raw material:

- The raw material utilized in the process of obtaining oxygen is **lunar regolith**. Regolith is the lunar soil present on the surface of the moon and is **formed due to meteorite impacts** which crushed and melted rocks present on the lunar surface and created tiny pieces of glass and minerals.
- It comprises **several different oxides of elements** such as Silicon, Aluminium, Magnesium, Calcium and so on. Traces of nonmetallic elements such as sulphur, carbon, hydrogen, neon etc. have also been found.
- The thickness of the regolith layer varies from approximately **4 to 15 m** on the lunar surface.
- Although grains of various diameters are found in the lunar soil, grains of sizes **20-500 μm are useful** for obtaining oxygen from the raw material. The remaining grains are characterized as rocks or dust, based on their diameters.

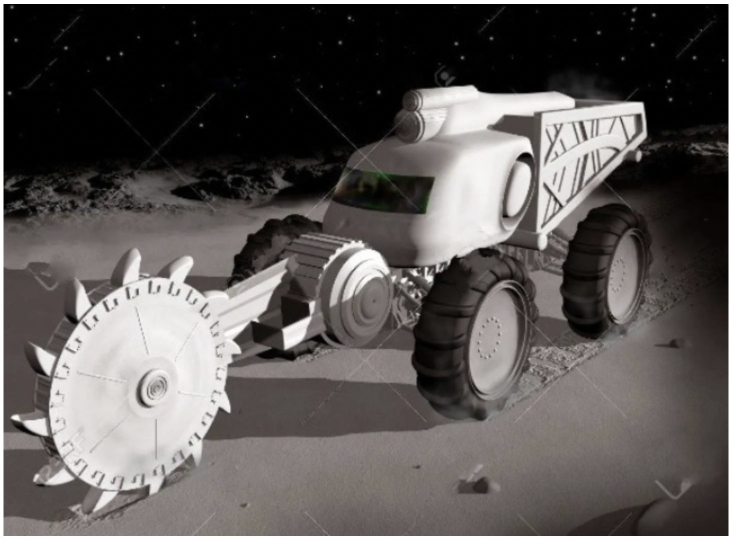


Collection/Mining of lunar soil:

- The process of excavation of lunar soil follows a similar process as that of excavation on earth. But the difference lies in the **lower gravitational force on the moon** and the **lower mass of the soil**.
- Alongside, the soft soil surface coupled with low gravity would make it increasingly difficult for traditional heavy machines to dig out lunar soil. Hence, **excavators must be of lower mass and size**, in general, than that of earth.
- Another factor which needs to be taken into account is the **presence of sharper and larger grains/rocks** which can result in wear and tear of parts of excavators.
- Lunar excavators obtain lunar soil in the range of a few hundred metres of the plant, else the operation of the latter may get disturbed due to the eruption of dust during the digging process.
- For the said purpose, a **bucket chain excavator** with an attached bridge is proposed. The design of the same is shown below. They offer advantages over other excavators in terms of **greater mass flow rate and the greater area of removal per operative cycle**.



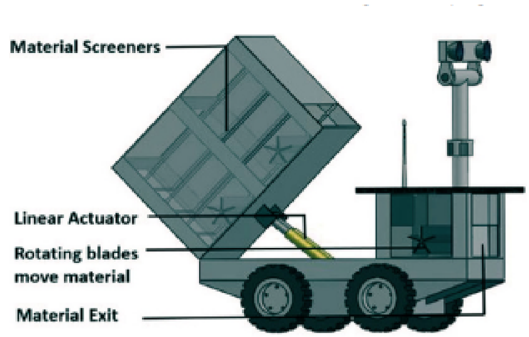
- The long horizontal bar with multiple buckets scrapes the soil from the surface. The **two side beams help in varying the depth of excavation**. Additionally, these beams provide for some inclination during the process of excavation.
- One major advantage of the above setup is that it can be positioned in one place with one side of the bridge being fixed and the other moving in a semicircular motion to dig the soil.
- The bucket which has been held fixed till the excavation is completed is now released and it hits the plates. This results in the collected raw material being thrown off into the collection vessel. This system of collecting excavated material **offers a significant advantage over regular excavation on earth as the low value of acceleration on the moon would decrease the pace of the process**.
- The speed of the system should be in the range of **0.3-0.5 m/s** to prevent the material from being thrown out.



Transportation of raw material to processing plant:

- Any design for transportation of raw material from the excavation site to the processing plant needs to satisfy one criterion specifically, along with lower mass and size- **it should be capable of shifting its location frequently**, as the topmost centimetres of the lunar soil would be excavated in each cycle of excavation and hence the rover with the excavator will have to move to a different location after each cycle.
- Therefore, we propose the use of **wheeled rovers with bucket chain excavators**. They offer advantages such as ease of movement, high flexibility and easy teleoperation.
- For the given purpose the rover will be provided with a suspension for all the four wheels and independent steering. Such a setup will permit the rover to drive sideways or move in any direction conveniently.
- But a significant disadvantage of wheeled rovers is the damage caused by lunar dust to the wheels, joints and motors.
- This can be overcome by **providing the wheels with a flexible and protective cover that the cover protects them from dust and extreme temperature variations**. Simulation-based tests done on NASA's VIPER rover have shown drastic improvements in the clogging of dust.

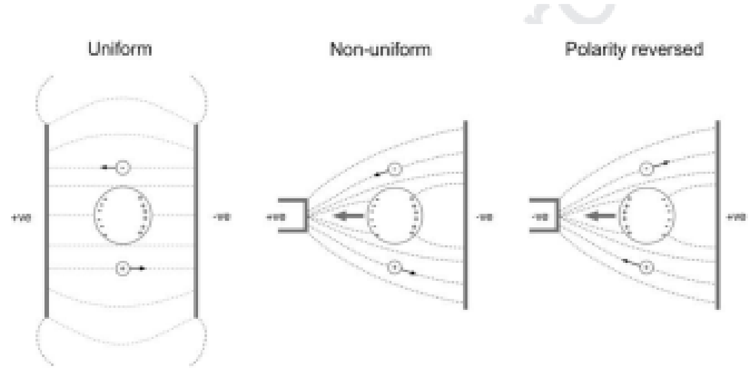
- Tests are also being done to find similar technologies for protecting the electric motors of the rover. It is proposed that each motor be surrounded by three layers of the seal.
- The excavator will also comprise a container or dump truck for the rover to place the collected regolith in.



- Simultaneously we also propose that the **lunar excavator rover possesses photovoltaic cells (PVs)** alongside the container for energy storage.
- The collected lunar regolith is next placed in the beneficiation chamber. The rover has the capacity of excavating and collecting **100 kgs of regolith in 5 minutes**.

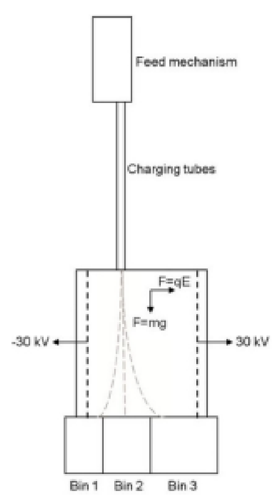
<u>Beneficiation</u>:

- Before conducting chemical reactions (hydrogen/carbothermal reduction, molten salt electrolysis) on the collected regolith, the **feedstock needs to be made uniform**. Beneficiation is the **process by which the collected raw material is enriched for suitable minerals and classified by size**.
- Size classification is important for electrolysis as larger particles with a lower work function may contain the same amount of charge as smaller particles with a higher work function.
- Terrestrial beneficiation processes generally use gravity or liquids, such as froth flotation. Such methods are difficult to use on the surface of the Moon as liquids are not present in enough quantity, and the low gravity does not aid in gravitation based methods. Therefore, magnetic and electrostatic techniques are suggested to use for lunar-based beneficiation.
- In electrostatics based techniques, **changes in the Coulomb and/or dielectrophoresis forces** are utilised. This technology separates the particles based on the difference in their surface charges. Particles are polarised in a non-uniform electrostatic field which creates dielectrophoresis forces.
- Electrostatic separation can be performed by manipulating the Coulomb and/or dielectrophoresis forces. The effect of an electrostatic field on charged(small) and neutral particles(large) is shown below. The **electrophoretic force** can be experienced by charged particles in both **uniform and non-uniform fields**. On the other hand, **dielectrophoretic force** is experienced by the neutral particle in non-uniform fields.



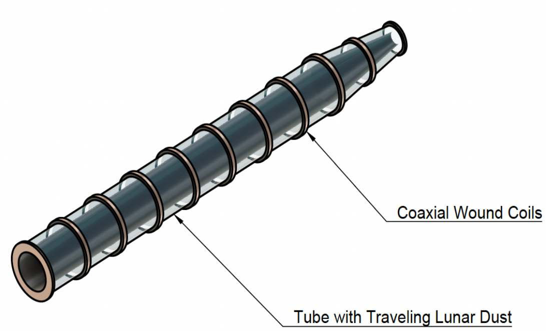
Difference between the interaction of a uniform and non-uniform field with charged and neutral particles.

- Therefore, a difference in the size of particles results in different forces being exerted on them, which in turn causes particles to get deflected in different directions, helping in the separation of the particles.
- Alongside, **Coulombic separation techniques** can be used. Positively charged particles are repelled by the positive electrode and attracted to the negative electrode, and vice versa. The particles contain surface charges before entering the electric field. The differences in the magnitude of the Coulomb force due to differences in surface charges enable separation.
- Another method utilised in beneficiation is **tribocharging and free fall separation**. Particles of different types or sizes come in contact and charge is transferred. Next, these charged particles are allowed to **free-fall through an electrostatic field and the deviated paths of the particles are used to separate them**. The figure for the process is shown below.



Transportation/Material handling between processing steps:

- The conveying distance between different processes in a production plant **is a few meters**. Various systems have been analysed for the same.
- Individual rovers, like the ones described for excavation and transportation of regolith to plant, may be used but they possess some significant disadvantages- relatively low speed, and difficulty in maintenance because of the abrasive lunar dust, especially at the wheels. But if **several rovers are connected together in a chain-like system** they can form a continuous conveying system. The design of the rover can be modified by adding a belt conveyor instead of dump trucks. A major disadvantage of such a system is its high weight.
- More traditional terrestrial methods such as **scrapers, and screw conveyors** are more suitable for short distances than for longer conveying. But, they possess some crucial problems such as high friction in carrier parts as well as many mechanical parts. They also do not possess high flexibility.
- One possible solution could be a **railway or ropeway system**. For the former, the rails will be placed on supports so that there is half a meter distance from the lunar surface. This way the rails are not impacted by contact with the lunar soil, as well as the non-uniform depth of lunar soil. Additionally, a semi-flexible conveying path can also be modelled, with mobile supports. Despite these advantages, there are some prominent drawbacks of heavy infrastructural requirements and challenges in maintenance.
- A similar ropeway system can be developed with a high payload capacity, is above the lunar surface, and has fewer maintenance problems. The negative aspects of this system are the same as with the railway.
- A more unique system for conveyance on the Moon is proposed - **electromagnetic conveying**. This system consists of many coaxial wound coils placed at equal distances from each other. The interconnected coils form a series of tube sections. **Electronic impulses are passed through these coils at regular intervals resulting in a force that causes the regolith to move from one coil section to the next one.**
- Advantages of the system: This system requires low maintenance and has no mechanical moving parts. The material will not clog the conveyor in case of an emergency stop. One significant disadvantage is that the required energy is considerable.

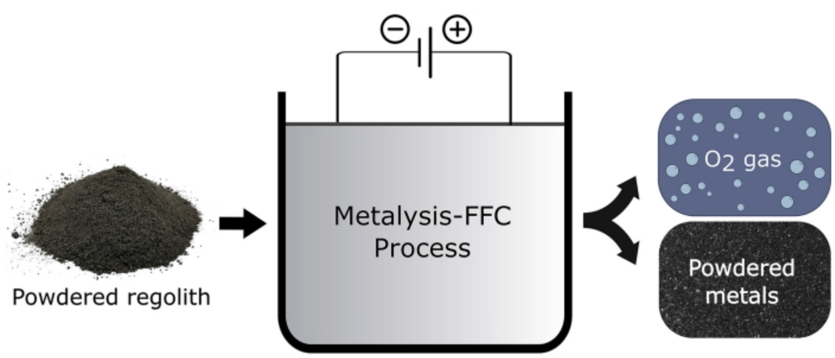


Energy systems for processing:

- We propose the usage of **solar energy** to power rovers and processes in production plants.
- **Tracking based solar concentrators, adjustable mirrors and fibre optics** will be used to track the sun and concentrate sunlight on regolith to melt or heat it. The usage of fibre optics would also result in a reduction of transmission losses from collection to point of delivery.
- The concentrated heat can be used to generate electricity using PV cells or to melt lunar regolith in brick molds, which would further be used to melt regolith for the electrolysis process.
- Another alternate source of energy is **nuclear fission energy**. The raw materials(radioactive substances, materials for plants) can be carried to the moon and plants can be set up on the lunar surface.

Production of oxygen using molten regolith electrolysis:

- After obtaining beneficiated lunar regolith, an electrochemical process takes place in a specially designed chamber.
- The **raw material is submerged in molten salt ($CaCl_2$) and heated to 950°C**. A current is then passed through it, causing the oxygen to migrate and collect at an anode, along with the formation of a mixture of metal powders.



- The oxygen produced is removed using an exhaust pipe and is subsequently stored for further usage.

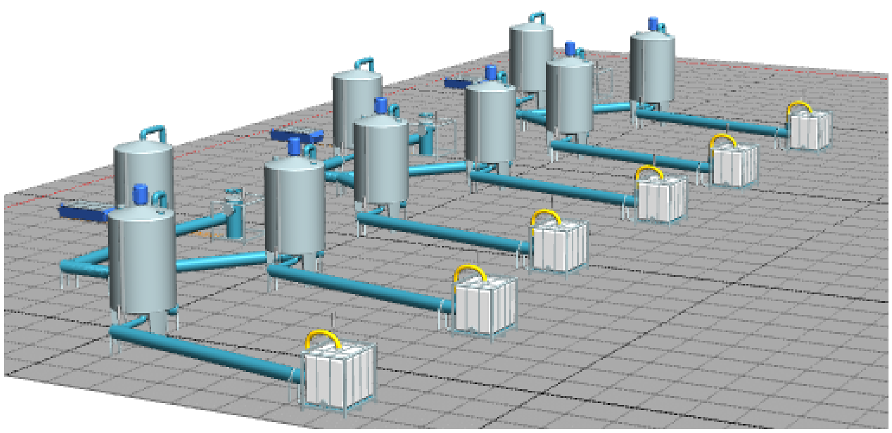
Automation in the plant:

- The processing plant is a **fully automated and flexible automation manufacturing system**, as it requires very little human intervention once set up.
- The rovers for transportation and collection of regolith and the automated electromagnetic conveyance system contribute to decreased human intervention in the system.

- Alongside, sensors and actuators present for the beneficiation and electrolysis plants make the system automated. Humans are required for the initial set up of the plant after which occasional status monitoring by teleoperation/physically checking the plant will be required.

Design of factory and factory layout:

- **Process layout** is found to be most appropriate for the product we intend to manufacture as the method to manufacture is divided into several processing steps and the product we plan to manufacture has no variety (apart from the final stage of its use as oxygen in cylinders or for propellants).
- The basic layout of the factory is as follows: Regolith Collecting Rovers deposit the raw material at the collecting station from where it is transferred to the beneficiation plant via electromagnetic conveyance. At the beneficiation plant, the regolith is classified by size and made uniform. Powdered regolith is transported to the electrolysis chamber via pipes, which use electromagnetic conveyance. Power obtained from solar energy or nuclear fission is used to run the electrolysis chamber and melt the regolith. Oxygen and alloys are obtained from the chemical process and are stored in separate cylinders for further usage.
- A representative image of the factory is shown below.



Teleoperation methods to control the manufacturing process:

- A human-rover teaming strategy using **artificial intelligence (AI) aboard the rover and a human operator** could be used to monitor the excavation process. An interface may additionally be provided for the system to shift from AI to Human instructions depending on the situation.

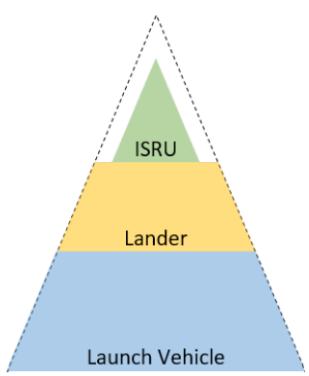
- The human operator would bring in advantages of **human cognition**. The data connection between the rover and mission controller must be continuous and reliable.
- Operation of the rover will require navigation and path planning. **Telemetry** can be utilised to visualize the path.
- The human operator will require visual data obtained from LiDAR cameras or any such equipment installed on the rover to monitor the robot's movement occasionally.

Safety Measures for manufacturing in space:

- As mentioned earlier, the **wheels and motors should be covered with protective covers** and seals, to prevent glass pieces & agglutinates or harder rocks and dust respectively from damaging the rovers.
- Safety features need to be more automated in nature so less human intervention is needed. For the same, the process plants must be equipped with **interlocks and sensors** like float and limit switches for electrolysis.
- Process plants like beneficiation chambers and electrolysis cells will be equipped to respond to take corrective action against a safety hazard.

Manufacturing metrics and economics:

Economics:



Several assumptions were made as an actual implementation will likely require a greater cost than what is estimated here. It was assumed that the landers and ISRU (In situ resource utilisation) plant are autonomous and highly reliable. Development costs are incorporated in the estimates described in the following sections, but the mission duration begins at some point in time when the ISRU systems are fully operational on the lunar surface.

Launch Vehicle: The launch vehicle chosen is a **Nominal Commercial** with a **Payload to TLI** of **15 tonnes**. The cost is $200M per launch vehicle

Lander Vehicle: The lander vehicle delivers cargo to the lunar surface. For cost calculation, the Inert Mass Fraction is assumed to be 0.25.

A stage's "inert mass" is the total mass of the stage minus the mass of the propellant and that of the payload.

Lunar lander costs were estimated with the Project Cost Estimating Capability (PCEC) cost estimating tool, commonly used by NASA. A third-degree polynomial in inert mass was made to fit a set of cost estimates and then used for the Cost Estimating Relationships (CERs) for the Design, Development, Testing, and Evaluation (DDT&E) and unit production costs.

$$\text{Cost (FY19 \$M)} = a m_{\text{inert}}^{3} + b m_{\text{inert}}^{2} + c m_{\text{inert}} + d$$

$\mathbf{m_{inert}}$ = 0.25*15 tonnes = **3 tonnes**

Cost Estimation of Lander Vehicle with m=3000 kg

- DDT&E (Design, Development, Testing, and Evaluation) = 25.947+220.5+690+3990 = $4926.447M - **Fixed Cost**
- Unit Production = 9.747+70.29+212.1+243 = $535.137M - **Variable Cost**

The values are obtained by substituting appropriate a,b,c, and d values

ISRU Systems: *In Situ Resource Utilisation* systems, designed and manufactured on Earth, are loaded into a multi-functional lander vehicle and launched by the commercial launch vehicle.

The system mass was split into 4 subsystem masses: structures, tanks, thermal control, and environmental control and life support (ECLS).

In addition to this Front-End Loaders and Haulers for excavation of lunar regolith and the Fission Power System for power are included in the cost estimation.

Calculating the cost:

- Structures = 269.88 + 88.233 = $358.113M - **Fixed Cost**
- Tank = 142.484 + 22.351 = $101.551M - **Fixed Cost**
- Thermal Control = 129.6816 + 0.0365833*t + 51.72236 + 0.000741667*t = $0.0044*t + $181.41396 M - **Fixed and Variable Cost**
- ECLS = 513.9 + 92.1675 = $606.0675M - **Fixed Cost**
- Front-end Loaders and Haulers = 473.3 + 32.27*50 = $2086.8M - **Fixed Cost**
- Fission Power Systems = 1726 + 530*10 = $7026M - **Fixed Cost**

The number of units of Front-end Loaders and Haulers was calculated as follows:

- **0.19g** of O_2 is released for **1 kg of regolith**
- Therefore the number of kgs of regolith to be excavated for $\mathbf{10^5}$ **kgs** of oxygen in one year is $526315.729*10^3$ kgs
- This is excavated over 365 days therefore the kgs of regolith that should be excavated per day is 1441960.9037 kgs of regolith
- **Each electrolysis cycle takes 8 hours (bottleneck process)** and therefore in a day 3 cycles can be done. Per cycle, we need 1441960.9037/3 = 480653.633 kgs of regolith

- **Each rover takes 5 mins to mine** the same and **can mine 100kg** of regolith therefore the number of rovers required is = [(480653.633*5)/(8*60)]/100 = 50 rovers

The number of units of fission power systems is calculated as follows:

- **One plant produces 10,000kg of O_2, annually** however we need 10^5 kgs of O_2 and hence we need **10 plants**

We assume 10^5 kgs of oxygen as a requirement based on the average amount of oxygen required in propulsion and for human use

To break even we need to find t such that

Total Fixed Cost + (Total Variable Cost)*t = (Cost of transporting 10^5 kgs of oxygen)*t
$15486.39249M + $535.1414M * t = $5400M * t

t = 3.1833 years

RHS of the equation is obtained from the assumption that transportation of 1kg requires $54,000.

Metrics:

1. Regolith Throughput is given by the following equation:

$$\eta_{O_2} \equiv \frac{m_{O_2}}{m_{regolith}} = \sum_i (w_i) \left(\frac{MW_{O_2}}{MW_{oxide,i}} \right) (r_{mol,i})(e_{frac,i})$$

Here η_{O2} represents the amount of oxygen extracted per kg of regolith, $r_{mol,\ i}$ is the ratio of the number of moles of oxygen per mole oxide i, w_i is the weight of oxide *i* in regolith $MW_{oxide,\ i}$ is the molecular weight of oxide i and $e_{frac,\ i}$ is the fraction of oxide i that is electrolyzed in each batch.

The fraction of each species that is electrolyzed depends on the operating temperature and the weight of oxide i depends on the type of regolith

2. We can also use metrics such as **Cycle Time**. Cycle time can be calculated as max(T_{mining} , $T_{electrolysis}$, $T_{beneficiation}$, $T_{handling}$). Based on the bottleneck model since the **bottleneck process** is the **electrolysis process** the total cycle time is equal to **8 hours ($T_{electrolysis}$).**

References:

1. Protection of wheels from lunar dust
2. Excavation and Conveying Technologies for Space Applications
3. Molten Regolith Electrolysis reactor modelling and optimization of in-situ resource utilization systems

4. Solar Energy Systems for Lunar Oxygen Generation
5. Lunar Regolith Excavator
6. Moon-exploring astronauts could get oxygen and fuel from lunar rocks
7. Oxygen- NASA's Space Launch System
8. Teleoperation Strategy