L4L | BMC

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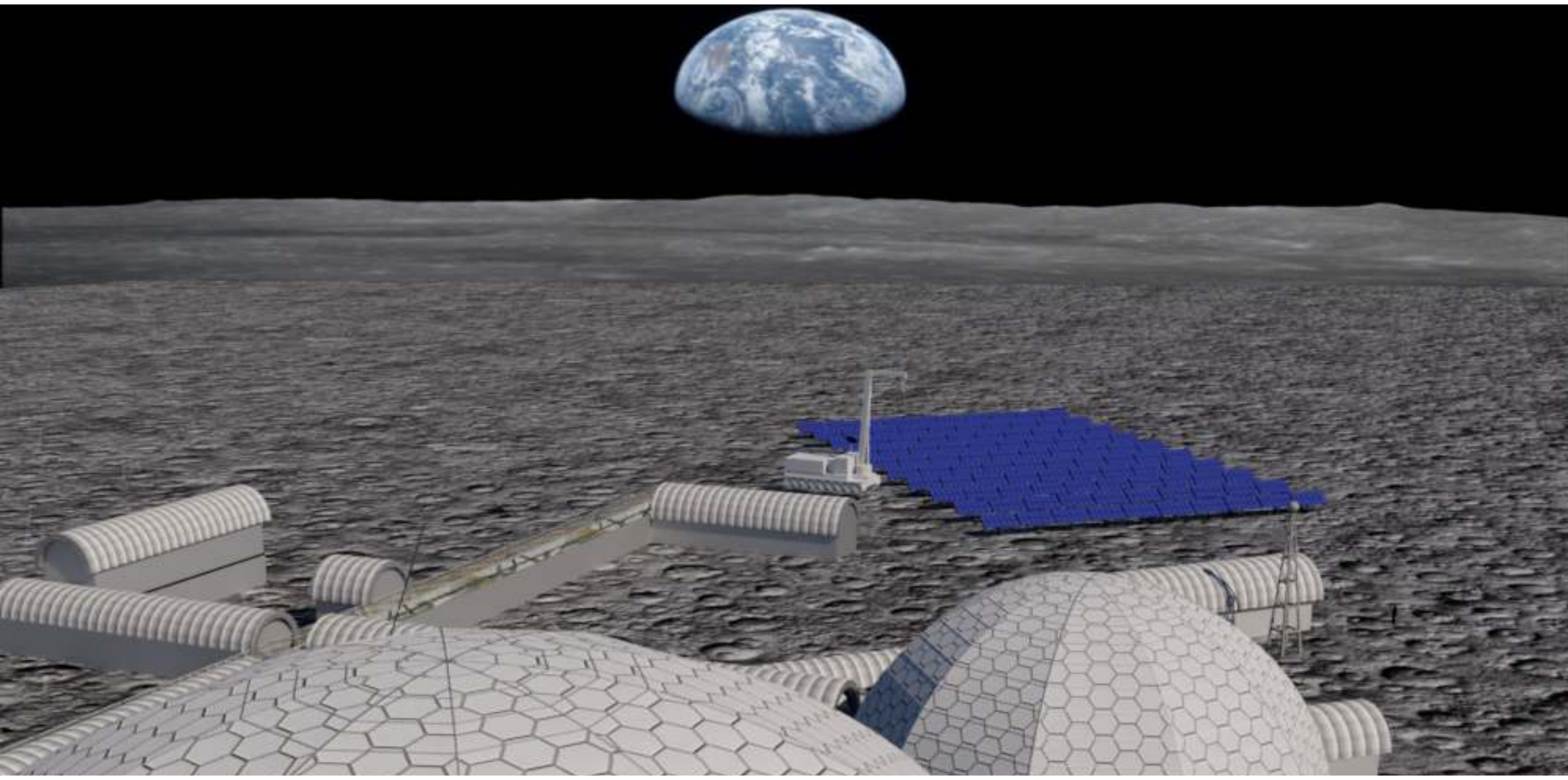

Luna for Living (L4L)

James Gibson
Alfie Marshall
Ben Reed
Freddie Nicholson
Shi Hong Kuang
Francesco Bartolini
Rohan Gathani
Tristan Mann-Powter
Charlie Franklin

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Introduction

Summary

We have designed Space Factory as a commercially viable moon base. There are many challenges in achieving this, and we have developed creative and realistic solutions to all these problems. In order to show these solutions, we have used a number of methods including flow diagrams, drawings and especially designing a full a 3D CAD model of the base, using professional architectural software, Autodesk Revit and Fusion 360.

Our Team

James Gibson

I was the project manager, so allocated other people their tasks and chose the general direction of the project. I also focused on the transportation element of the project, as well as energy and the commercial activity. In addition, I helped everyone with their work when they found something difficult or could not come up with a solution.

Ben Reed

I was team coordinator and oversight engineer for the project. I made sure that deadlines were being met (with a bit of encouragement!) I am interested in Mechanical Engineering, Electronics and Computer Science. I contributed towards Energy Sources, Base Design and Electronics within the Project.

Freddie Nicholson

I assisted the project manager in deciding the direction of our project. I am also responsible for most of the CAD work shown using Autodesk Fusion 360 and Revit. I primarily worked on projects to do with the overall base design and electronics. I also was responsible for most of the formatting in the document and converting all our equations to LaTeX. I am studying Physics, Further Maths, Computer Science and DT and enjoy working on electronics projects at home.

Charlie Franklin

I was primarily in charge of researching how to produce aluminium and other metals on the moon. I worked out the rate of output, the necessary energy requirements for that rate, and the design of the reactor to make it work. I also assisted with the process of producing nutrition for the colonists. I am studying Maths and Further Maths, Physics, Chemistry and Computer Science at A-level.

Shi Hong Kuang

I was in charge of researching mining on the moon. I designed CADs in Fusion 360 for the mining vehicle/crane, satellite transportation module, interior crane, electrolysis reactor and launch pad. I also worked on researching the technologies behind these projects. I am studying Physics, Maths, Computer Science and DT.

Alfie Marshall

I focused mainly on the mining aspect of the project, looking into how this would be possible on the moon, and aiding others with the designs. I also did some initial research into food production. I am studying Physics, Further Maths and Art at A level. I also designed our project logo.

Rohan Gathani

I focused on deciding how we would attain water on the moon, as well as how we would electrolyse it to get hydrogen fuel. I am an A-level student studying Further maths, Physics and Chemistry and I am interested in Mechanical Engineering.

Tristan Mann Powter

I was an odd-jobs man in the group. My work started off as looking into silicon extraction and how solar panels were created, but then I changed paths to looking at functions of the Base itself such as pressure sensors to alert people if the internal environment was not being maintained and some work on food production and worker diet. I'm in my first year of A-Level and am studying Physics, Maths, Further Maths and Chemistry. My current degree and career interest are Civil Engineering.

Francesco Bartolini

I started by looking at designs for the lunar rovers and how they could be used efficiently to further expand our knowledge of the terrain, and also contributed to the design of the final mining vehicle. I am studying Maths and Physics with a combination of languages and I am interested in astronomical missions and the future of lunar investigations.

Commercial Activity

Summary

The commercial activity that Space Factory will perform is to overcome what NASA calls “the tyranny of the rocket equation” and allow a cheaper option for launching satellites, fuel and people into orbit. The base will compete directly with launch companies, offering a cheaper way of getting commercial payloads into space, especially into orbit around the earth. Currently, the space industry is estimated to be worth $345 billion globally, and it is estimated up to $150 billion of that was spent on launches, with this figure only growing. This is a massive and highly valuable market, and one that Space Factory can at least partially capture. The cost of launching satellites into space comes from the fact that a very large delta V is needed to launch a rocket into space from earth, and it cannot be fully reusable because the atmosphere prevents the recovery of higher stages. It is much easier to get from the moon to low earth orbit, as the delta v is much lower, and there is no need to travel through the atmosphere, which can allow all vehicles to be reusable. This decreases costs massively and means that most satellites could be launched more cheaply from the moon, which is what Space Factory will do. It will also have the capacity to launch people into space, allowing for crew changes at the ISS to take place much more cheaply, and for human lead repair missions of satellites to become more common. The base can also build and fuel vehicles for exploration beyond the solar system, and NASA estimated that just being able to refuel from the moon would save them $10 billion dollars a year while undergoing a Mars mission. The goal of this base is to provide for the manufacture of fuel and satellites, as well as the launch of staff, as cheaply and safely as possible.

Why was this commercial activity chosen, how will it be carried out?

This commercial activity was chosen because it pursues the only real market of real value that the moon has an advantage in providing. There are other, very valuable materials such as Helium 3 and tritium on the moon, however there is only a small marketplace for either of these materials, meaning that providing them in large quantities would saturate earths markets, and cause a decrease in the price. Within the next ten years, there is not any possibility that nuclear fusion will become commercially viable and widespread, with the first reactor demonstrating commercial competitiveness, DEMO, not planned until 2060. Currently, the demand for these chemicals are in the order of hundreds of millions of dollars a year, not billions, so it is a marked too small to be worth pursuing. Furthermore, should these markets grow because of increased demand, both helium 3 and Tritium can be bread in a fission reactor, and while this is expensive at the moment, if the market were to grow, economies of scale would lower this cost, and make a base on the moon uncompetitive. Furthermore, these isotopes are only on the moon in trace quantities, so a gigantic mining effort would need to be undertaken to achieve large amounts of these chemicals, which would make the base extremely expensive.

Even worse is the suggestion that we could mine materials which are on earth in large quantities such as titanium or uranium. These metals are abundant on the earth, and the cost is extraction. While they will be in slightly higher concentrations on the moon, they have a price per kilogram simply too low for it to be worthwhile mining, and that would require a tremendous industrial effort.

Tourism is another suggested commercial activity, and if people were willing to pay enough, we could allow a tour of the facility, however the price per ticket would need to be very high, and there are very few people in the world who would be wealthy enough and keen enough to buy a ticket. This lack of interest is shown by the fact that no tourist has ever gone into space.

On the other hand, the space launch industry is very valuable, and will not be easily saturated. With the cheapest price per launch from earth at $10 000 per kilogram, it is possible to make great profit margins. The materials we would need to launch are also much easier to extract on the moon, with most of the satellites being made, by mass, from aluminium for the body, silicon for the solar panels and hydrogen and oxygen for the fuel. The assembly of the satellites on the moon may seem too challenging, with only 40 members of staff, however the most difficult parts of the electronics and sensors could be sent from earth. The rise of CubeSats has shown that more simple satellites can now compete with more complex ones because of advances in electronics and computing. Furthermore, advances in 3D printing of metals, which is expected to improve in the next 10 years, means that the body of a satellite can be 3D printed easily, and with the addition of fuel and solar panels, more than 75% of the mass of the satellite can be added on the Moon. The remaining complex electronics can then be added by the members of staff before launch into space, saving lots of money on a very expensive launch from earth. With a cost to reach the ISS of $70 million dollars per person, this can also be undercut by the Space Factory. This makes the role of supporting other commercial activity in space a very lucrative one, which is why it has been chosen.

In order to build the satellites, there will be several modules dedicated to the 3D printing of aluminium components, and there will be workshop space which will be fitted with equipment such as automated lathes in order to allow for components of satellites to be manufactured on the moon. These can then be brought to the main assembly hall for final construction and testing, and the components made on the moon can be combined with the more sensitive equipment from earth. The Satellites will be carried by a vehicle to the launch site, where they will be loaded onto the launch vehicle, which will carry the satellite into lunar orbit. This rocket will have a capacity of 10 tonnes, so no satellites above this size can be launched in one go and will instead need to be built in multiple parts and assembled in space.

Space Factory would also be open to accepting tourists if they are willing to pay a high enough price to make it economical, however this cannot be our main revenue stream, as we do not expect many people to be interested.

Earth to Space

Design of a Low Earth orbit launch vehicle

The task is to design a system that is able to economically and safely move payloads and people from Earth into low earth orbit (LEO). In order to reach LEO, an object needs a height of at least 150km and a speed of about 7800 m/s.

There are three principal ways that this velocity and height can be achieved. The only routinely used method is a rocket launch. Using the other two, a gun or a space elevator, are very tricky.

The problems with using a gun are numerous. A conventional explosive cannot be used because of insufficient power, and nuclear explosions would destroy the payload. A rail gun may work, but it would be very expensive to construct, and may require technology not available to us in the next 10 years. It would exert huge G forces on the payload as well, making it unsuitable for humans and most equipment. Simply using a rail gun for launching from the moon is too difficult, so it is impossible to do from earth. These problems rule this solution out.

A space elevator may seem an elegant solution to use the spin of the earth to give orbital velocity. However, no material has ever been developed with the strength to support its own weight, even without considering the weight of a payload. Materials strong enough to do this are not conceivable in the next 10 years. Even if they were, the cost of assembly would be prohibitive, and there would be great complications in powering the device through its assent. These problems make this solution impossible.

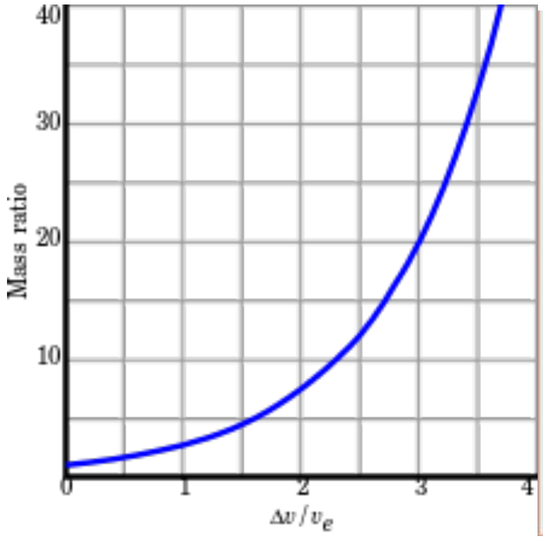
Rockets are used to launch objects into space because they can exert much lower G forces, and the technology has been present since the 50s. Therefore, a rocket must be designed.

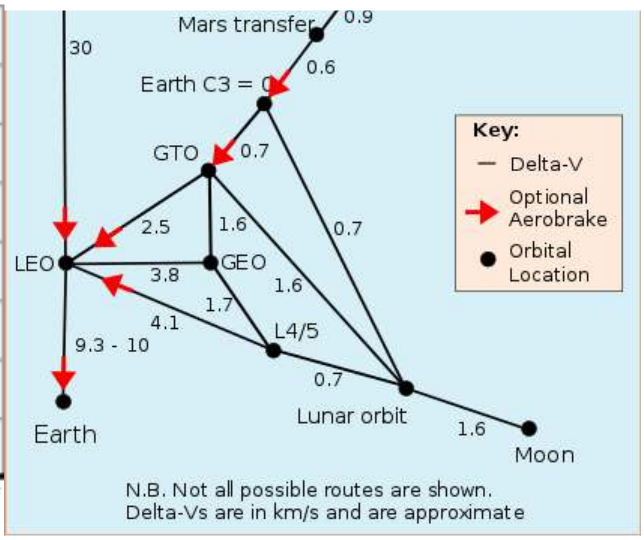
First, the specifications for a launch vehicle must be found. In these calculations, Δv is used. This is a measure of how much a rocket can change its speed. In order to reach LEO, a rocket must, with its payload, produce a Δv enough to reach LEO.
Δv can be calculated using the Tsiolkovsky rocket equation, or ideal rocket equation. It says that

Calculating the required Δv is complicated due to factors such as drag, gravity, trajectory and latitude of launch complex.

A simple guess can however be calculated. $7800 + lost \triangle v$ from gravity during launch + lost gravity from air resistance -450m/s if launching at the equator. If air resistance is assumed to have an effect of about 300m/s, typical of rockets, and losses due to gravity are around 1300m/s. This means that the rocket must be able to generate a Δv of very approximately 9000 m/s. This is roughly correct when compared to other rockets. This approximate number will be used in calculations.

$$\triangle v = effective\ exhaust\ velocity \times ln \frac{total\ mass}{dry\ mass}$$





The rocket equation and the graph above show that to make a rocket as small and therefore as economical as possible, the rocket should have a low ratio of dry mass to mass with fuel, and a high specific impulse.

Disposable rockets have the advantage that they save on weight as they have no features needed to return, allowing them to be smaller and cheaper. They also have a better safety record, and are easier to manufacture, often requiring less specialised materials. The downside is that if no components are reused, the operation cannot really scale with size, as each additional launch will cost a large amount of money, limiting the amount of payload that can economically be sent to space.

Reusable rockets have the advantage that they can launch much higher capacities over their lifetime, which has the potential of much lower costs. Problems include the cost of refurbishing the components being prohibitively expensive, the design being less efficient and safety being lower priority.

In order to launch enough mass to build a lunar base, a reusable launch vehicle is almost certainly necessary. Using the ISS as an example, over 400 tonnes was needed. The equipment which needs to be initially launched into space is listed later in this document, however this will need to be enough to support an initial crew of 20 and includes heavy equipment such as vehicles and a chemical reactor vessel. Although the exact mass of these cannot be calculated, it will be many hundreds of tonnes. Furthermore, a rocket, also detailed later, will need to be launched and fuelled to carry payloads to the moon, increasing the required mass further.

Furthermore, there will need to be further crewed missions regularly to replace the staff, and to bring up components and supplies as the mission continues. This means that if the rocket system is not reusable, the cost would be very high.

Comparing to the current heavy lift rocket, the SLS (space launch system), the limitations of disposable launch systems are clear, as the project has been heavily delayed, and there are only nine scheduled launches in the next decade, meaning that only about 800 tonnes could be launched at tremendous cost, and then it would be just as costly for crew changeover missions, with a cost of around one billion dollars per launch.

In comparison, the space shuttles launched about 100 times with a 30-ton payload capacity each time. This makes a total of 3000 tonnes to LEO, making a reusable system clearly superior for such a large payload requirement, and the need for many resupply missions.

The space shuttle faced two main problems, firstly safety. Two space shuttles were destroyed, both times resulting in 7 casualties. This is an intolerable failure rate for manned flight, so the system must be designed with a launch abort system and must not require the same large heat shield made of tiles used by the space shuttle, as it had very high refurbishment costs and was not very safe.

The second problem was the high cost. This was because of its huge size creating logistical issues, and because of refurbishment between launches. Reducing size and refurbishment while maintaining a launch capacity of 30 tonnes payload capacity plus people must be achieved.

The solution is to use modern technology, e.g. using computer controls and materials to design a more efficient and safe launch system by changing the design to something more like the Falcon 9 rocket currently in use.

The design is as follows:

First stage: 5 × RS 25 engines, with hydrogen oxygen fuel (793 000kg), 57000 kg of equipment including aluminium tanks, flight computer, titanium alloy grid fins, and is reusable.

Second stage: 3 × Vacuum adjusted merlin engines with RP1 and liquid oxygen fuel (17100 kg), carbon fibre structure, weighing 9000kg and is disposable.

This has two possible configurations, in payload launch mode where it can launch 40000kg of payload, or crew launch mode where it can launch 30000kg of payload and a 10000kg reusable capsule including a launch abort system.

This will be cheap to reuse as the main first stage and the crew capsule can be reused, and the second stage will be small and cheap. The crew capsule will require refurbishment between missions including a replacement heat shield to increase safety, while the main booster will have little refurbishment, keeping the costs low.

Another important design decision is the material choice, and there are many options.

Aluminium is a solid choice. It has a medium density compared to other choices, a high strength and relatively high heat resistance.

For the 1st stage which needs to be able to reland and therefore withstand high temperatures and be reusable, it is not possible to use carbon fibres which lose integrity with temperature and are therefore not suitable.

Steel has good resistance to temperatures and strength, but is too heavy for the first stage, and is not required because the re-entry will be a controlled descent using retro thrusters and grid fins to decrease speed, allowing aluminium to be used on the first stage. It is also a good metal for reusability because of its use in aircraft, so it is well understood unlike carbon fibre. For the second stage however, reducing weight is essential, so modern strong carbon fibre can be used, as it is disposable.

Another choice is for the engine. For the first stage, the RS 25 is very efficient with a high specific impulse, designed to be reusable and can be restarted easily. It uses hydrogen as fuel.

The Merlin engine is efficient, light and cheap to manufacture in large numbers. It uses RP-1 (high grade kerosene) as fuel.

Both are tried and tested engines, which is ideal because engine development is very expensive and often results in unsafe engines and can fall behind schedule, so using existing engines is a big advantage.

The RS 25 would however need to be developed so that it can throttle down further than its current 67% maximum thrust, otherwise landing would be very difficult as a single engine could launch the whole rocket.

The merlin engines would also have to be vacuum adjusted to maximise their efficiency, as they would be operating in low atmospheric pressure, however this is a common adjustment and is well understood.

Calculating the masses required using the ideal rocket equation.

$$\triangle v = effective\ exhaust\ velocity \times log \frac{total\ mass}{dry\ mass}$$

To do this logically, the second stage needs to be solved first. Assuming each stage needs to contribute 4500 Δv, the average exhaust velocity from the merlin engine is about 3000 m/s. To formulate the equation it needs a 10000 kg capsule as well as 30000 kg payload. This is on top of its own dry mass, which can be assumed to be $\frac{1}{20}$ th the total mass. Calling the mass of the 2nd stage $\boldsymbol{x}$, we can get the equation:

$$1.5 = ln \frac{20x + 800}{x + 800}$$

This can be simplified to

$$4500 = 3000 \times ln \frac{x + 40}{\frac{1}{20}x + 40}$$

Rearranging the log,

$$\frac{20x + 800}{x + 800} = e^{1.5} = 4.48$$

$$20x + 800 = 4.48x + 3580$$

$$15.5x = 2780$$

$$x = 180\ tonnes$$

This is only an approximate value. The calculation of the 1st stage requires the same process, except with an exhaust velocity of 4400 m/s because of the highly efficient RS 25 engines, and with a dry mass of 220 tones for the payload and 2nd stage, plus a dry mass of $\frac{1}{15}$ th of its total weight. This ratio is worse because it has to be reusable and is made of aluminium.

Furthermore, it needs to retain 30% of its Δv for use in a propulsive landing.

$$4500 \times 1.3 = 5850$$

Now the equation is:

$$5850 = 4400 \times ln\frac{x + 220}{\frac{1}{15}x + 220}$$

$$1.33 = ln\frac{x + 220}{\frac{1}{15}x + 220}$$

$$\frac{x + 220}{\frac{1}{15}x + 220} = e^{1.33} = 3.78$$

$$x + 220 = 0.252x + 832$$

$$x = 820\ tonnes$$

Because of the estimations which have been made, the mass of the second stage will be increased slightly to 850 tonnes. This is to include excess fuel, so that there is definitely enough capacity to get to low earth orbit.

This gives a payload of 40 tonnes, a second stage of 180 tonnes and a first stage of 850 tonnes, with a total mass of 1070 tonnes.

This mass is on the same order as other reusable rockets such as the Falcon 9, which has a mass of 550 tonnes and can launch about 10 tonnes to low earth orbit. This system improves on it because it uses more efficient engines, materials and is larger, giving a greater efficiency.

The dimensions of the rocket can also be calculated. The density of liquid oxygen is $1100\ kg/m^3$ and the density of liquid hydrogen is $70\ kg/m^3$.

The combustion equation is $O_2 + 2H_2 \rightarrow 2H_2O$

This means there are two hydrogen atoms for one oxygen. As a hydrogen atom weighs $\frac{1}{16}$ th of oxygen, $\frac{1}{16} \times 2$ means a 1:8 ratio of mass must be achieved. With 793000 kg of fuel in the first stage, that makes 88100 kg of hydrogen and 705000kg of oxygen.

$$\frac{88100}{70} = 1260\ m^3$$ of hydrogen

$$\frac{705000}{1100} = 640\ m^3$$ of oxygen

This gives a volume of fuel of $1900\ m^3$. An additional $1000\ m^3$ can be assumed because of space in bulkheads and for equipment. Assuming a radius of 7m which is appropriate for a rocket of this size, the height will be $h = \frac{V}{\pi r^2}$.

$$\frac{2000}{3.14} \times 3.5^2$$

$H = 52m$ for the first stage.

The same can be done for the second stage. RP-1 fuel has a density of $1000\ kg/m^3$, and has an oxidiser to fuel ratio of $\approx 1:2$. With a fuel mass of 171000kg, there will be 48000kg of LOX and 123000kg of RP-1.

$$\frac{48000}{1100} = 44m^3$$

$$\frac{123000}{1000} = 123m^3$$

This gives a volume of $167m^3$ for the second stage, which can be increased to 180 for equipment and empty space. If we assume the diameter decreases to 4.5m, the height can be found.

$$h = \frac{180}{3.14 \times 2.25^2}$$

$$h = 11.3$$

This diameter of 4.5m should be just large enough to fit the manned capsule and payload on top. If not, a larger faring could be fitted, if especially large payloads needed to be launched.

Assuming the 30-tonne payload has a density of $200\ kg/m^3$,

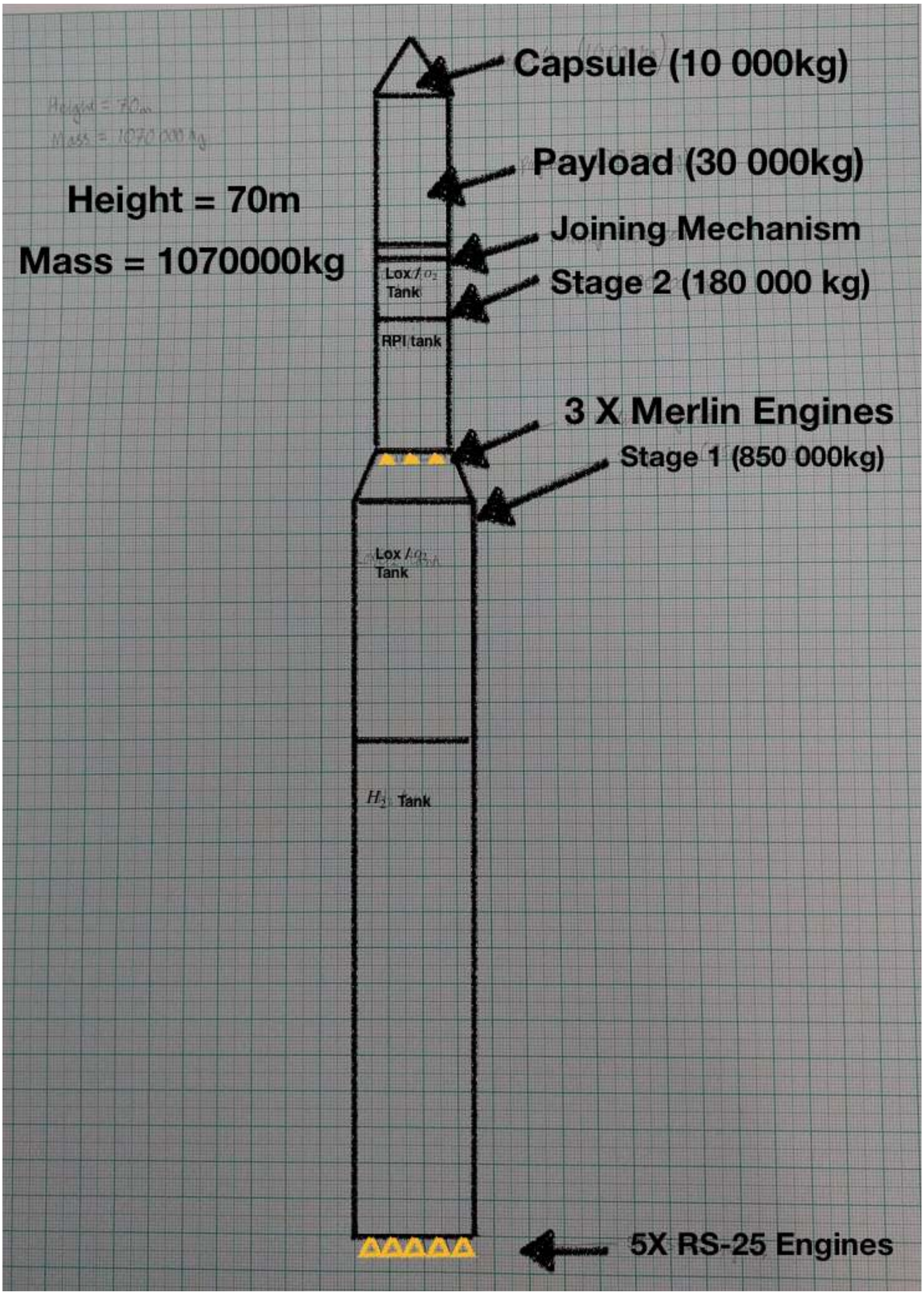
$$h = \frac{150}{3.14 \times 2.25^2}$$

This means a standard payload height will be 9m

The rocket will use normal launch control systems, being flown automatically by a flight control computer powered by batteries in the upper stage, which will also have a backup computer for redundancy.

A rocket of this size is not bigger than rockets which have historically been launched, so could be launched from the space center in French Guinea.

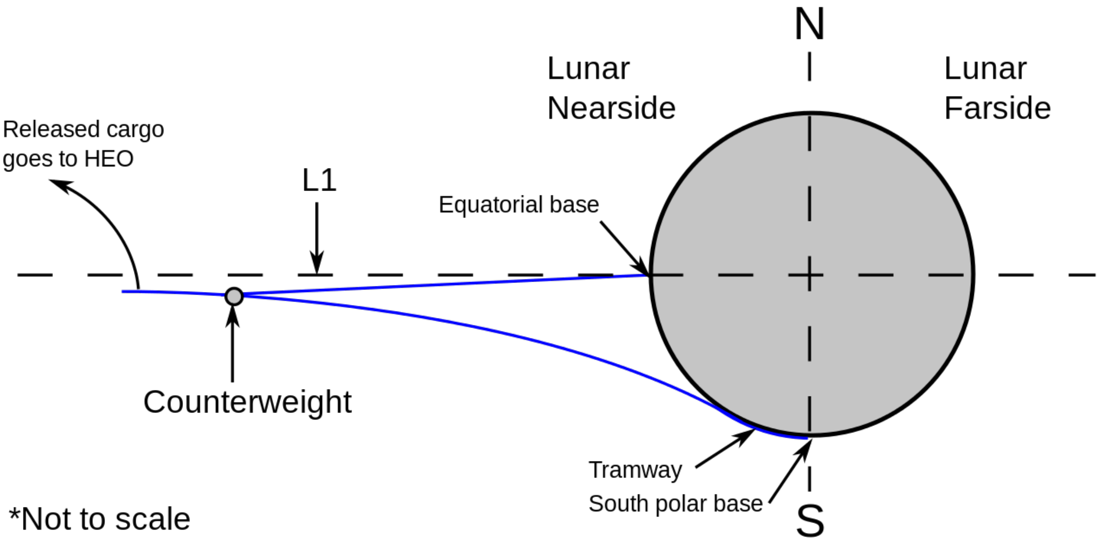
Here is a scale diagram of the completed launch system:



Moon to Lunar Orbit

This needs to be done very cheaply and efficiently in order for this project to work successfully, as the costs will need to be very low and the system will have to be highly reusable. There are several options to achieve this, which are a reusable conventional launch vehicle, a space elevator, railgun or a skyhook.

The first option is a space elevator, which is unfortunately not a possible solution. Despite the high efficiency and reusability, it would offer, especially considering that the end of a space tether could be placed at a Lagrange point, offering stability and ease of access from earth. The idea of a space elevator is made more difficult by the fact that the slow rotation of the moon means that it would need to be very long, which increases construction costs and means that it is placed under high strain, which would cause it to require special high strength materials such as Kevlar. They would also require the capture of a heavy counterweight, which is not impossible, however would present many challenges to acquire. The simplest way to get a counterweight to a space tether would be capturing an asteroid, however moving an asteroid of the tens of thousands of tonnes required to counter the large mass of the space elevator would be very difficult and require powerful rockets to move it into position. The only materials strong enough to make the tether such as Kevlar or polymers can only be made on earth, which increases construction costs as these would need to be launched into space. This makes the space elevator ultimately not worthwhile. It must be considered that it would be a huge project, having a length of over 3000 km, and its costs would be far higher than the base itself. This idea would be more complex than the skyhook, which is shown by calculation to be very difficult.



The second option is less well known, which is the skyhook. This is a method by which a payload could be lifted easily into orbit around the moon, with most of the advantages of using a space elevator, with fewer of the downsides. A rotating skyhook would orbit the moon while rotating and would simply require a payload to launch a few hundred meters upwards and catch a near stationary hook, which would then swing upwards. The reason it is near stationary is because it will be rotating in the same direction as the moons orbit. The photo included shows this principle. This option is unfortunately also untenable as it would be a project orders of magnitude larger than the construction of the base itself and would be tremendously costly. The problem is that in order for the tether to be moving fast enough relative to the surface, it will need to be either rotating very fast or be very long.

The moon rotates at over $1000ms^{-1}$, so the skyhook would need to be able to match that speed in the end. A sensible length which is often chosen for the most practical and smallest skyhook is 400km. This has a radius of 200km.

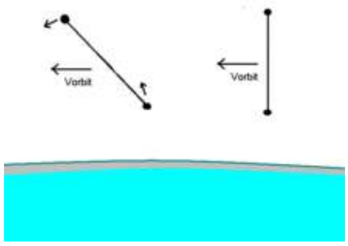
Centripetal force is equal to $\frac{mass \times velocity^2}{r}$

Subbing in the reasonable initial value of 40 000 kg for the mass at the end including a small reusable launch vehicle and payload, this requires a force of $\frac{40000 \times 1000^2}{200000}$ N

This is 200 000N.

Choosing the strongest possible materials, these have a tensile strength of 2000 MPa. This means that it would simply require a $\frac{1}{100000}$ of a meter squared (on centimeter squared) of this cable to hold the payload, which seems reasonable. The mass of the cable must be taken into account.

By approximating the mass of the cable at a radius of 100 km rotating at $500ms^{-1}$ relative to the center (an approximation which favours this concept), and including a density of $7g/cm^3$, this gives a mass of 140 000 kg, much higher than the initial payload. This will require the cable to have additional strength equal to $\frac{140000 \times 500^2}{100000} = 350000N$ This has more than doubled the force required, and by repeating this process, it is clear that this material would not hold the structure. While it is possible to make the cable out of advanced, lighter materials and the cable can be tapered in order to reduce mass, these materials would need to be fabricated on earth and shipped to the moon. At best, this would require thousands of tonnes to be shipped from earth, and it still does not negate the safety issue as if the cable were to break, through fatigue or through a collision with an asteroid, it would kill any passengers. Ultimately, this idea has to be rejected.



A rail gun can be easily shown to be a bad idea. Putting aside the massive size the huge power and cooling requirements as well as safety issues, it could not carry humans or anything with

any complexity, such as a rocket. In order to simply reach lunar orbit, a speed of $1600\ ms^{-1}$, which is easily achieved with a rocket, the length of the rail gun can be calculated. The highest G force that a person or rocket can be expected to survive during acceleration is 10G, which is already much higher than conventional rocket launches. Using SUVAT equations, with an initial

velocity of $0\ ms^{-1}$, a final velocity of $1600\ ms^{-1}$ and an acceleration of $100\ ms^{-1}$, using

$$v^2 = u^2 + 2as$$

$$S = \frac{1600^2}{2 \times 100}$$

$$S = 12800m$$

This is a tremendous length, and neglects and resistance, or gravitational losses, which would be high if launching at a low trajectory. It is more realistic to assume that the final speed needed is at least $1800\ ms^{-1}$ to make it to lunar orbit, which gives a length of rail gun at 16.2km, which is a huge size to build a large diameter and highly complex machine and would be incredibly costly. This launch would still be very violent and would cause the crew to lose consciousness, while only taking them to lunar orbit.

The power requirements for accelerating a 10 000 kg payload can also be calculated.

$$F = mA = 10000 \times 100 = 1000000\ N$$

$$Work\ done = force \times distance\ moved$$

$$= 1000000 \times 16200 = 1.62 \times 10^{10} J$$

Time taken is 18 seconds.

$$\frac{1.62 \times 10^{10}}{18} = 900\ Megawatts$$

This is the power usage of a city, and equivalent to a large power plant.

This power would need to be stored in gigantic batteries or super capacitor arrays and would take a long time to recharge without a huge power source.

It must also be considered that the only high velocity rail guns launch projectiles of a few kilograms, not many tonnes. Building at a larger scale would be very technically challenging and is not reasonable in the next ten years. This would all be costly to build and makes a rail gun completely unfeasible.

A reusable conventionally designed launch vehicle makes sense, as it is the only way humans have moved to and from the moon so far. The Apollo program did not use a reusable system as they only needed to travel to and from the moon a limited number of times, and the technology for reuse was limited. The Space Factory commercial idea relies on using a highly reusable and cheap launch and landing system so that the cost of launching from the moon is kept low enough to give the moon an advantage to the earth for launches. A conventionally fuelled launch vehicle would not be too difficult to design, as the much lower gravity of the moon and the lack of atmosphere makes it much easier to launch and recover vehicles to lunar orbit. The Δv change needed to travel between the lunar surface and lunar orbit is only 1.6km/s, which is comparatively low, so will not require especially large rockets or powerful engines, and will allow for a single stage using efficient rockets to make the journey from the lunar surface and back on one tank of fuel before refilling on the moon. This restricts the fuel choice for this rocket to H_2 and O_2 as these are the fuels which will be made on the moon. This is an acceptable choice as many rocket engines use this fuel source, however a hypergolic propellent is often seen as a more reliable choice and is the fuel type used for Apollo missions.

One problem is that the rockets would need to be large and powerful to lift heavy payloads, and much of the lunar base would be dedicated to maintaining and fuelling these rockets. They would also have engines too big and complex to be made on the moon, and they would not be able to receive extensive maintenance because of limited manpower on the moon, so the rockets would need to be replaced with ones from earth. It is very difficult to design a safe launch abort system for this rocket (one was not included on the Apollo vehicles) because the lack of atmosphere means that a capsule deploying parachutes cannot help the crew. This means that the crew would be fully reliant on the reusable system. This means that it would need to be designed with many redundancies, making it heavier and less efficient, and they would need to be retired if there was any sign of a fault, creating logistical challenges. This is however the only option to launch payloads of 10 tonnes, which would be either a crew capsule or a satellite. This limits the launch mass of satellites to 10 tonnes, above which satellites would have to be assembled in space.

A reusable launch vehicle could also do this process in reverse. Once a capsule is in lunar orbit, it can be reached by a fully fuelled launch vehicle and landed. This reusable rocket could be used to land all equipment to the surface of the moon, as soon as the capacity to generate the fuel is brought online. Before then, a disposable lander will have to be used. These could however be melted down and used to build more parts of the base once the furnace is operational.

The single stage launch vehicle can be designed using the same process as for the earth to LEO launch vehicle and the ideal rocket equation. There needs to be a ΔV change of 1600 m/s.

Because air braking is not possible as it is on earth, it can be approximated that twice this amount is needed for the full launch and recovery of the system.

$$1600 \times 2 = 3200 \triangle V$$

This number neglects losses due to lunar gravity, however they will be small as it is low, and the rocket will accelerate quickly.

Because the system will need to be heavy in order to be safe, and so that it has enough redundancy, fuel will only make up 80% of the mass. Therefore, with the mass the rocket without fuel or payload as X, the equation becomes:

$$3200 = 4500 \times ln\frac{5x + 10}{x + 10}$$

$$e^{0.711} = \frac{5x + 10}{x + 10}$$

$$X = 3.5 \ tonnes$$

This is the dry mass of the system without a 10-tonne payload of fuel. The engine will be a rocketdyne J-2 engine. This was developed for upper stages and has an exhaust speed of approximately 4500 m/s in a vacuum. It weighs 1.8 tonnes and produces 1000 000 N of thrust.

With a total mass, $5 \times 3.5 + 10 = 27.5 \ tonnes$, acceleration can be calculated.

$$F = ma$$

$$1000000 = 27500 \times a$$

$$a = 36.3 \ ms^{-2}$$

This is a survivable and appropriate rate of acceleration, of under 4G. The engine is throttleable and can be decreased in thrust as fuel is burned and will need a very low thrust for final landing, as the mass will only be 3.5 tonnes, and lunar gravity is 1/6th. Making the engine stable at this low thrust will require research and development, however, is achievable in the next 10 years. It will also need to be improved with increased reliability, and sensors which are able to detect if the engine is near failing so that it can be decommissioned.

The rocket will burn O_2 and H_2 in the same ratios as calculated previously. With a ratio of $8 : 1$ O_2 to H_2 by mass,

$$4x = 14 \ tonnes \ of \ H_2$$

$$\frac{14}{9} \times 1 = 1.6 \ tonnes \text{ of } H_2$$

$$\frac{14}{9} \times 8 = 14.4\ tonnes \text{ of } O_2$$

Using the same volume calculations done previously,

$$\frac{1600}{70} = 22.9m^3 \text{ of } H_2$$

$$\frac{14400}{1100} = 13.1m^3 \text{ of } O_2$$

$$Volume = area\ of\ circle \times height$$

$$Height = \frac{volume}{area\ of\ circle}$$

$$Height = \frac{36.0}{\pi \times 2^2}$$

$$= 2.9\ m\ in\ total$$

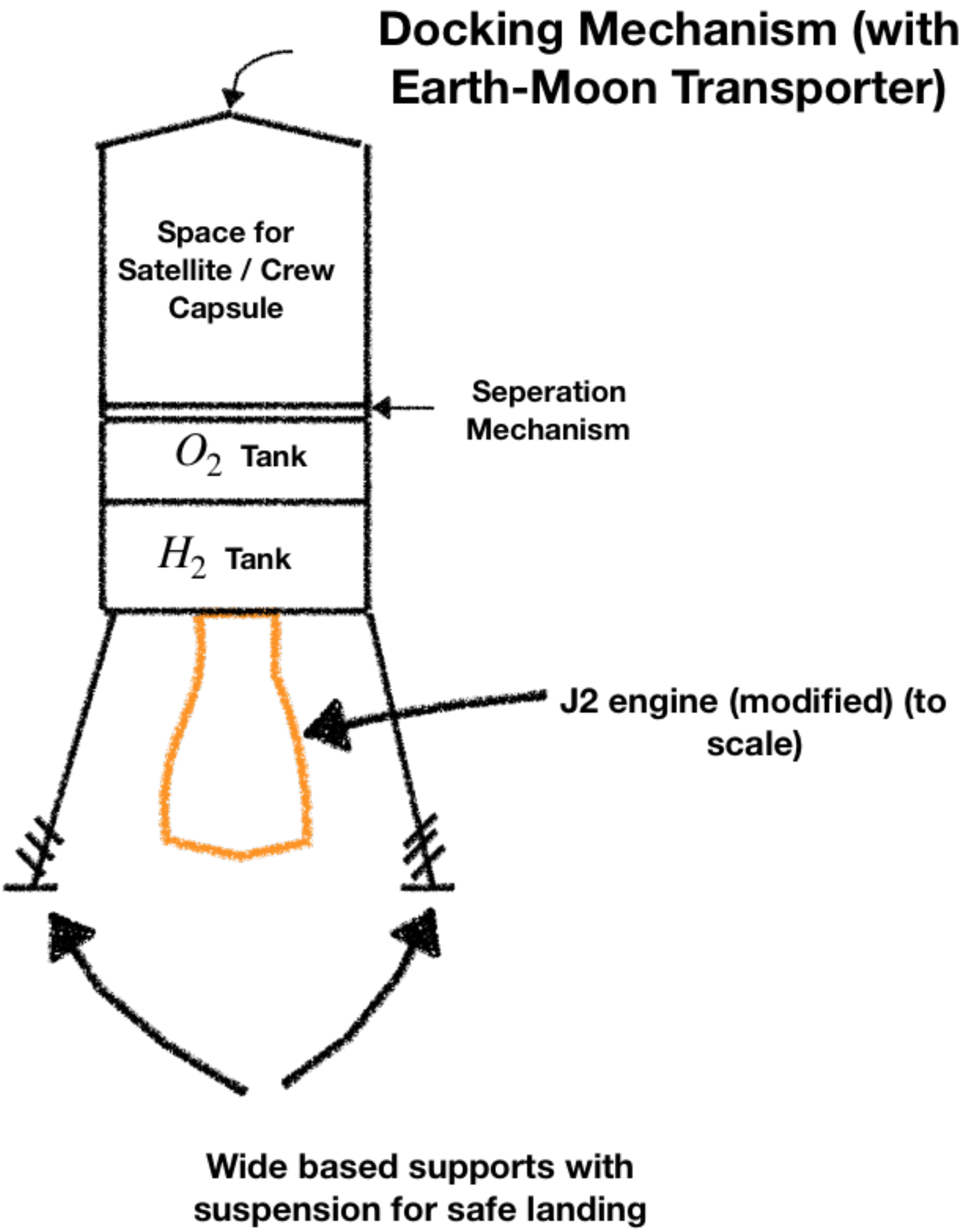
This means that the tanks need $\mathbf{36.0\ m^3}$ of volume. With a radius of 2m,

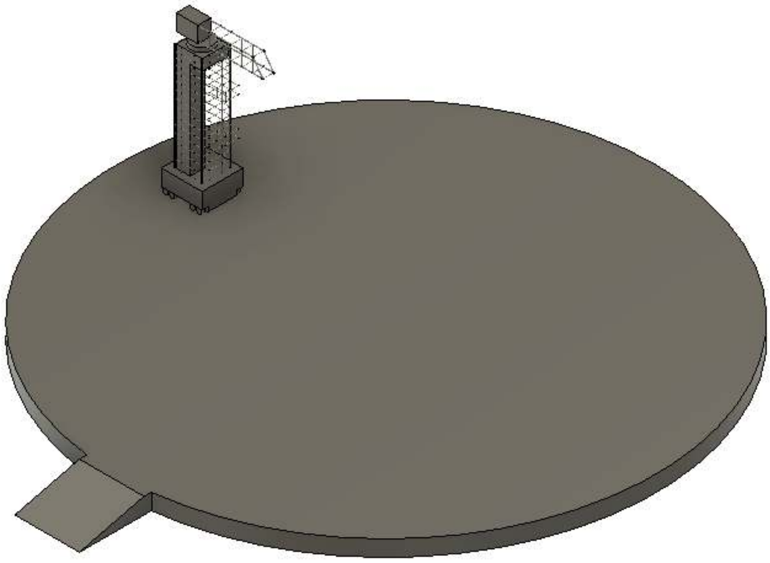
This large radius is chosen because aerodynamics do not need to be considered, and the launch system needs to be small enough to be launched itself into orbit by the earth to LEO launch system. It also needs to be wide enough to support a large satellite being launched, or a crew capsule.

Real image of J2 rocket engine preparing for test

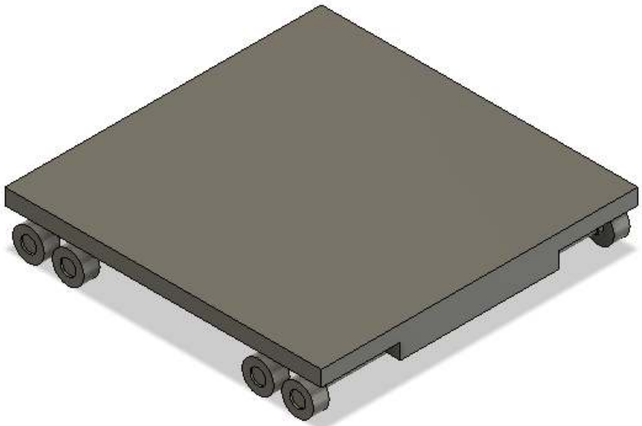
= 1m

Radius = 2.0m





This is a model of the launch pad for the rocket. It will take off from and fly back to this launch platform. It also shows a mobile tower which can fuel the rocket and move off the launch platform when a rocket is trying to land.



This image shows a small vehicle which can take satellites form the assembly hall and the launch pad, and then the crane vehicle can lift the satellite into place, making logistics more convenient. This platform could be dragged by another vehicle or have its own motors and batteries.

Lunar Orbit to LEO

Taking payloads between LEO and Lunar Orbit

In order to go between the earth and moon orbit, a rocket is needed. This needs to be as efficient and reusable as possible, in order to make it easy to move satellites to LEO and geostationary orbit from the moon, and in order to set up the base cheaply.

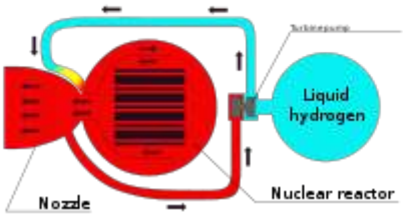
It is best to use an efficient and reusable rocket which can be refuelled from the moon, in order to keep costs and sustainability as low as possible. The most efficient type of rocket engine is the ion thruster, with exhaust speeds of 20000 - 50000 m/s, however it has several problems. They require electrical power to accelerate ions out of the thruster to propel themselves, which would require a large solar array to power them, making them heavy and low powered. This means that an ion rocket would be costly to assemble in space and would take a long time to go to and from the moon as it would have a low acceleration. The only fuel, xenon, would not be needed in huge quantities, and there are small amounts of xenon on the moon from radioactive decay and solar winds. This would however require the moon base to be capable of extracting the xenon, or require fuelling from the earth instead, which increases the number of costly earth launches. This makes an ion thruster too expensive and slow to be a viable option.

A conventional rocket negates these problems as it can be assembled from light engines in orbit and use hydrogen and oxygen which can be produced on the moon. They can also generate large amounts of thrust, leading to much shorter journey times. They are however less efficient, topping out with an exhaust speed of 4500 m/s, meaning that lots of fuel will need to be made on the moon and brought up to refuel the rocket, making it too costly.

A nuclear rocket is more efficient, with exhaust speeds in the range of 12000 m/s. It also only requires hydrogen as its main fuel, which is already being manufactured on the moon, through electrolysis of water. It is also able to produce higher thrust than an ion engine, leading to shorter journey times. A nuclear thruster will however be heavier than a conventional one and will also either need to be replaced or refuelled every few years when the nuclear fuel is spent. This must be done from earth as the nuclear fuel extraction and enrichment process is too complicated and expensive to be performed on the moon, as separating isotopes of uranium is a difficult industrial process, often requiring large numbers of centrifuges.

With nuclear rockets as the best choice, there is also a choice between liquid, solid or gas core nuclear rockets. Liquid and gas nuclear thrusters have the nuclear fuel in a fluid state, contained within the reactor. This provides the advantage of possibly being more powerful and efficient, however they are less well understood, as while solid core nuclear reactors have been used on earth for more than 70 years, fluid core ones have not been used, meaning that this technology is not reasonable within the next ten years. This leaves a solid core reactor as the best option.

The image below shows how one would work:



NASA and the US military have spent hundreds of millions of dollars researching nuclear reactors as many believe that they will be the best way to travel long distances and with large payloads in space. Furthermore, the idea of putting a nuclear reactor into space has been done before, with the Russians launching many satellites with nuclear reactors for electrical power. This does pose some risk on launch, as if the launch fails, nuclear fuel could be dispersed into the atmosphere. The nuclear fuel could however be launched with caution, with launch abort systems and parachutes so that nuclear fuel rods would be returned to earth safely. Once in space, the nuclear fuel rods could be placed into a graveyard orbit once spent, so they will not pose a long-term risk.

The earth to LEO launch vehicle is able to launch 40 tonnes, so this nuclear rocket should be able to carry 40 tonnes of payload to the moon. It should also be capable of carrying a 10-tonne satellite back from the moon to orbit around the earth, while only requiring to be fuelled while at the moon, from its reusable launch system.

Unfortunately, there are no nuclear reactors designed for this purpose, and designing a nuclear reactor is beyond the scope of this project, so I will simply estimate that, as modern small modular nuclear reactors can achieve 26 MWh of power weighing 20 tonnes, this power density could be repeated for a reactor in space, using technology available within 10 years. This mass excludes shielding, which would make the nuclear reactor too heavy to be efficient. In order to protect the crew from the gamma and neutron radiation that the reactor would emit while it is operating, the crew capsule, as well as any payload, will be at the end of a long boom, which will keep the crew safe. The radiation will drop off with the cube of the distance, so a distance of 150 m from the core of the reactor should be completely safe. This boom will weigh a negligible amount.

With a mass of 20 + 40 = 60 tonnes to go to the moon. This requires a Δv of 4800 m/s. Assuming an exhaust velocity of 12 000 m/s:

X is the mass of fuel needed.

$$\triangle v = 12000 \times ln\frac{60 + X}{60}$$

Using the rocket equation again,

$$e^{0.4} = \frac{60 + X}{60}$$
$$89.5 = 60 + X$$
$$X = 29.5 \ tonnes$$

of fuel needed for the journey, giving a total mass of 89.5 tonnes

In order for the rocket to make the trip from the moon, it would need to have another Δv of 4800 m/s.

When leaving the moon, it will need 29.5 tonnes of fuel, but not the 40-ton payload.

$$20 + 29.5 = 49.5$$
$$4800 = 12000 \times ln\frac{49.5 + X}{49.5}$$
$$X = 24.3 \ tonnes \ of \ fuel$$

The total fuel that the rocket will need to leave the moon with for this journey is 24.3+ 29.5 = 53.8 tonnes of fuel. This only when a 40-tonne payload needs to be brought to the moon.

In order to simply put a 10-tonne satellite into geostationary orbit, the amount of fuel needed is

Journey back

$$2300 = 12000 \times ln\frac{20 + x}{20}$$
$$X = 4.22 \ tonnes$$

Journey there:

$$2300 = 12000 \times ln\frac{34.22 + x}{34.22}$$
$$X = 7.23 \ tonnes$$

The total fuel required to place this satellite is 7.23 + 4.22 = 11.5 tons. This means that for each positioning of a satellite, there will need to be refuelling for the nuclear rocket. This will however be inexpensive, as the fuel will be made on the moon through electrolysis, and the launch vehicle taking the fuel from the moon to the rocket is fully reusable and autonomous.

The nuclear rocket itself will not need more nuclear fuel for years, as it will only be running at full power for a small amount of the time.

The reactor will need to heat 29.5 tonnes of hydrogen to thousands of degrees K.

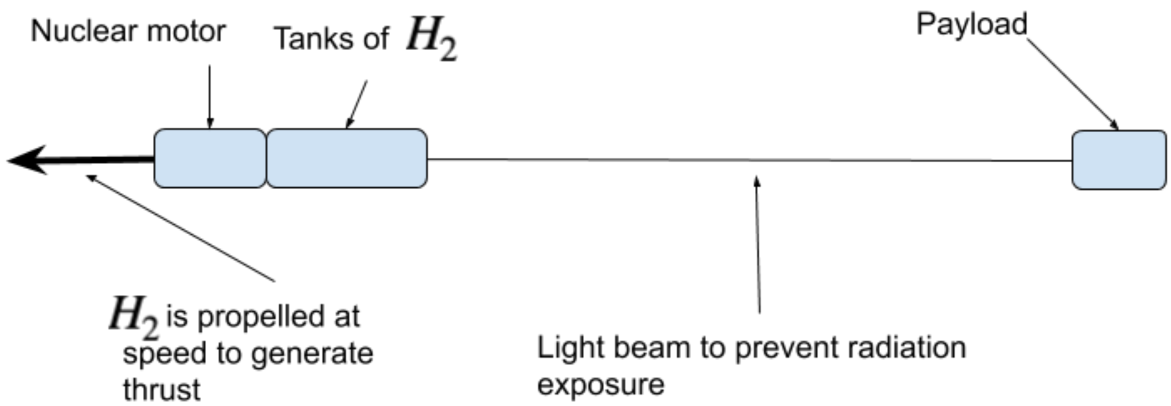
The specific heat capacity for H_2 is about 10 J/Kg per kelvin.

For a temperature increase of 1000 K,

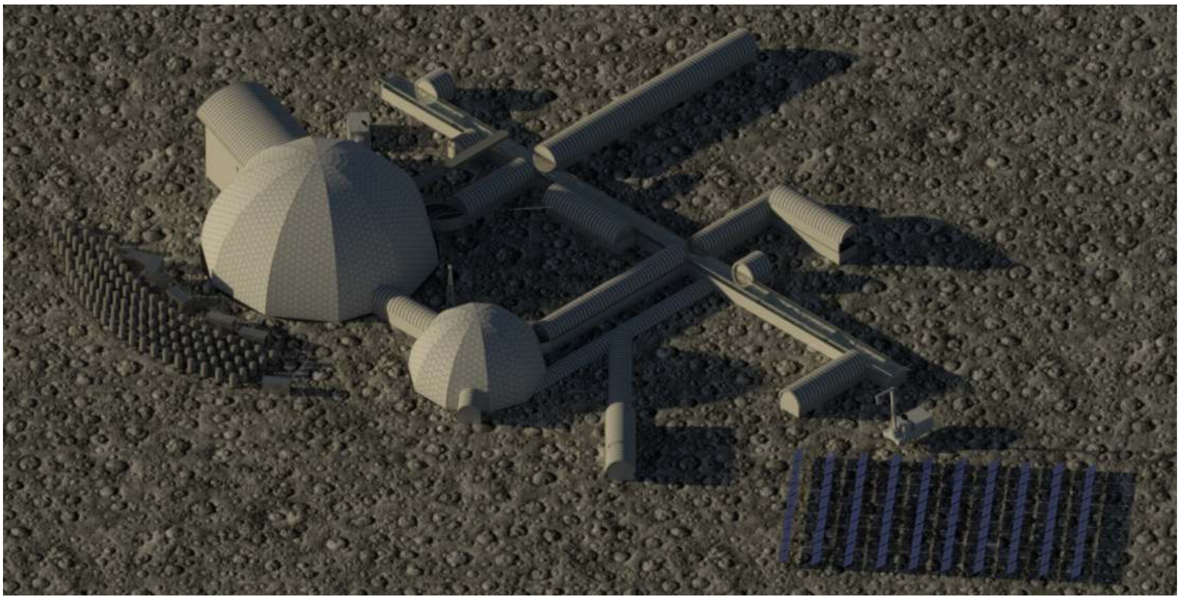
$$29500 \times 1000 \times 10 = 2.95 \times 10^7 J$$

This is not a very accurate calculation as there are many effects which have not been taken into account, however with a reactor of 20 MW, or 2×10^7 J per second, it would be able to fully fire the engines in 3 seconds. This is however not accurate, as the reactor has to be heated and it is not this efficient, however this proves that the reactor is powerful enough to generate thrust rapidly, allowing for short journey times between the moon and earth. The journey will not be too quick however, because that would require the engines to fire to decelerate the rocket, which would not be efficient.

Because the reactor is not real and the calculations are very approximate, only a rough sketch of the rocket can be provided:



Base Overview



A CAD model of our Base Design

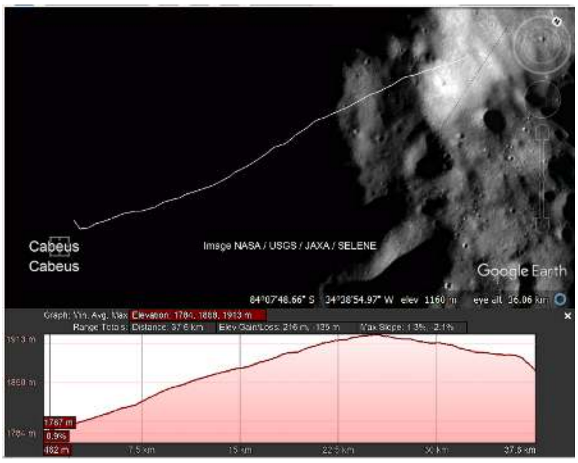
Fundamentally, this base needs to provide living space and life support for the 40 people who will be living there for several years at a time. The base will be made up mainly of easy to manufacture repeating modules, which can be manufactured on the moon and added over time in order to improve the base. There will also be two large domes which will provide more space for larger equipment, where the raw materials will be processed, and the satellites will be assembled.

Some of the base will need to be sent from earth (the first crew module, the parts for the large assembly hall, the chemical processing, solar panels the vehicles including the crane and the excavation vehicle. Once this is established, the base will be able to support a few people, and has limited capacity. It can however expand, adding more crew modules, building the main assembly hall for satellites, as well as adding more workshops and modules to grow food. After the base is fully established, it can then move on to its role as a place for building satellites and supporting activities in space.

Please note that CAD models shown in this document may contain assets/models that may seem unsuitable for lunar habitation. Unfortunately, due to time constraints we were unable to generate individual assets for specific lunar usage and therefore models are purely in place to demonstrate usage / scale of the various sections of the base.

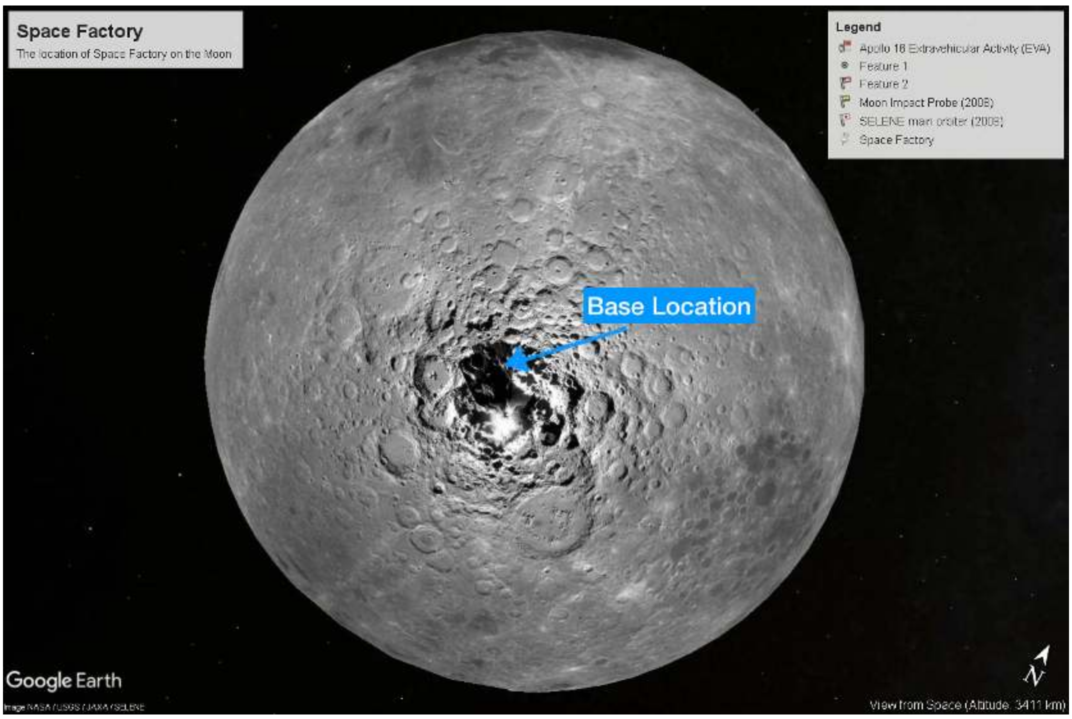
Base Location

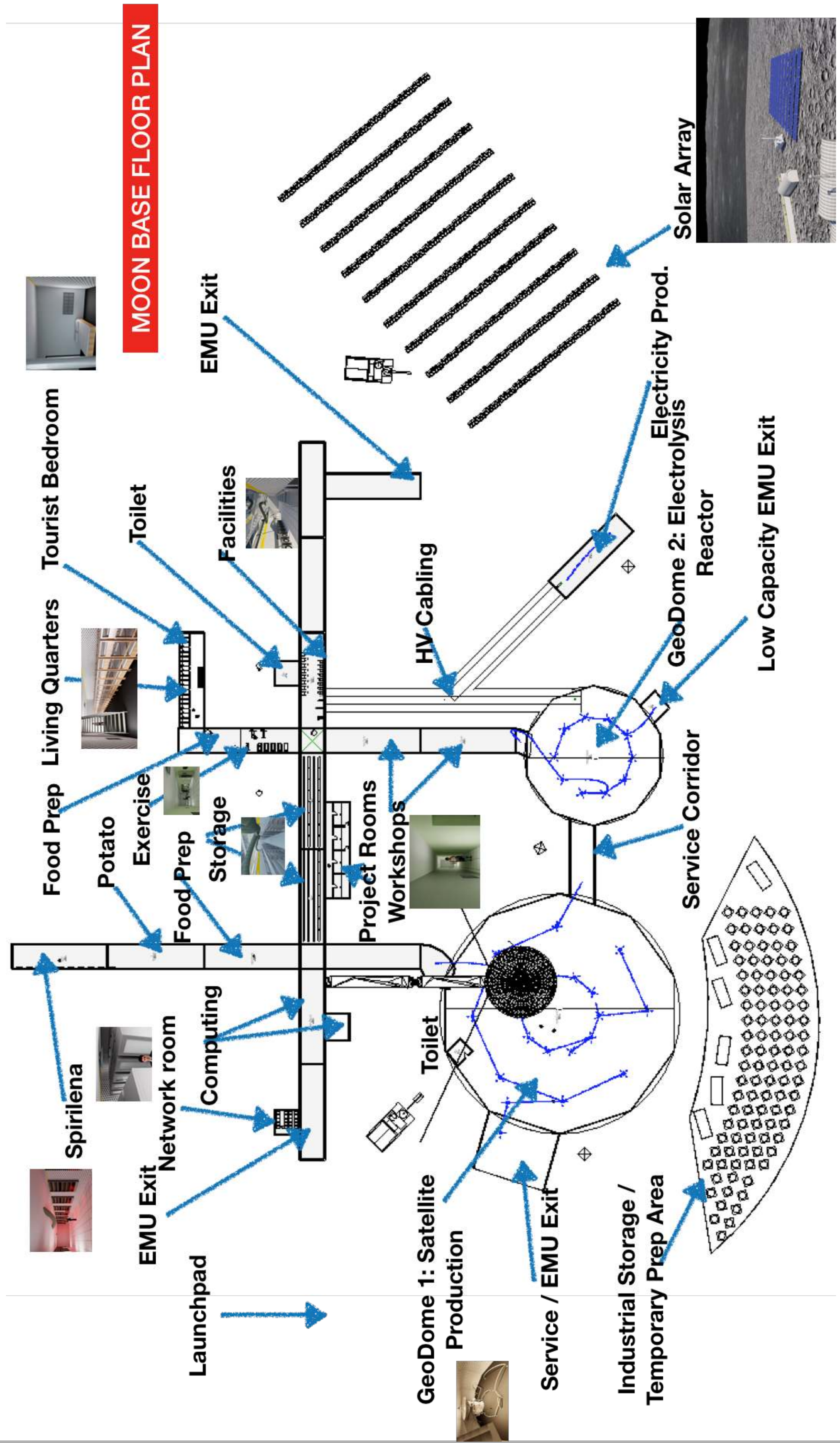
Through our research, we found that water was an essential resource which we could not do without. Therefore, we found the crater Cabeus contains tiny ice grains mixed in with soil that are fairly simple to extract. Unfortunately, it is within a shadow region (a permanent state of darkness) and therefore we found the closest flat spot nearby. which is around 20km away. This is where we will land and start our construction. This is located on the south pole of the moon.



This location is also in sunlight, so it allows us to harness solar energy.

The footprint of our base will be approximately 500m x 500 and the elevation of this ground as shown above is suitable for this usage. It only changed in height by 20m. The various components of the base will also have no fixed anchoring / foundation system as well to allow flexibility in the placement of modules. Instead a block foundation system will be used to support either side of each component.

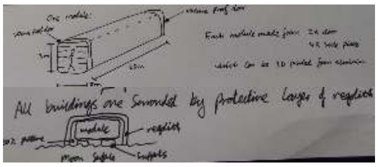



MOON BASE FLOOR PLAN
Tourist Bedroom
Living Quarters
Toilet
Facilities
EMU Exit
Food Prep
Potato
Exercise
Food Prep
Storage
Project Rooms
Workshops
HV Cabling
Electricity Prod.
Solar Array
GeoDome 2: Electrolysis Reactor
Low Capacity EMU Exit
Service Corridor
Spirilena
Network room
Computing
EMU Exit
Toilet
Launchpad
GeoDome 1: Satellite Production
Service / EMU Exit
Industrial Storage / Temporary Prep Area

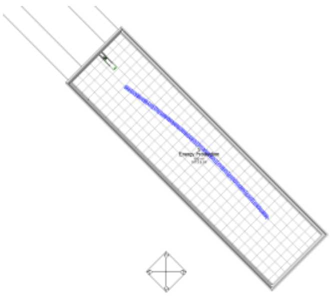
Modular System

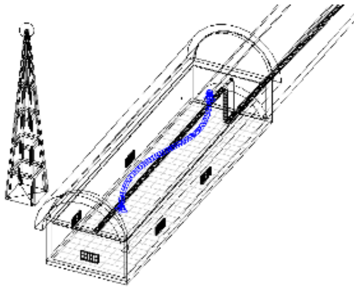
As you can see from the site plan above, the base is made up of several different components all consisting of a similar standard. Each module is individually pressurized.

Standard Module

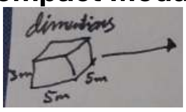


Dimensions: 5m x 3m x 20m
Volume: $300m^3$
Usage: A standard flexible module used the most around the base.

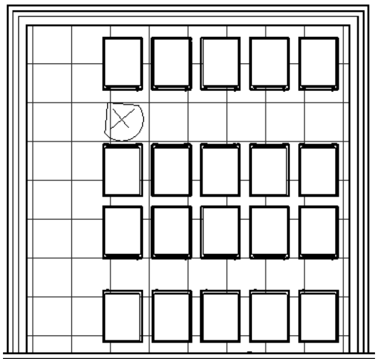


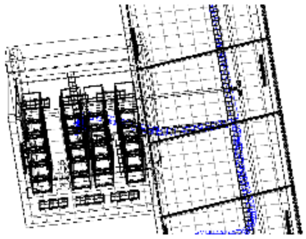


Compact Module

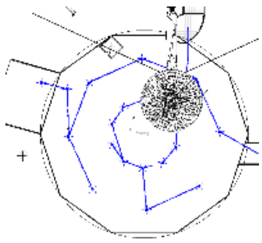


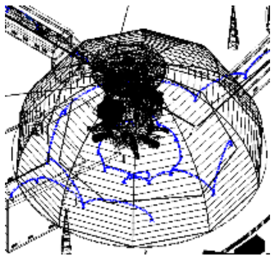
Dimensions: 3m x 5m x 5m
Volume: $75m^3$
Usage: A joining 'block' or facility room that is designed for connecting modules together and service rooms.



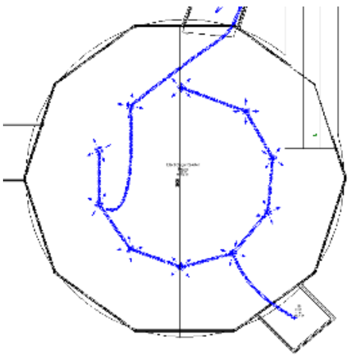


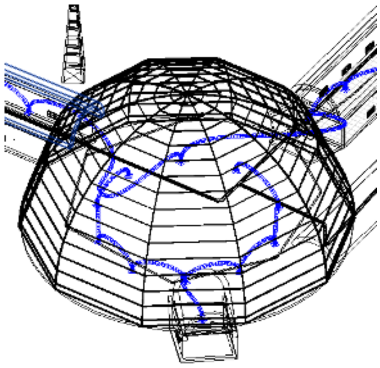
GeoDome 1
Dimensions: 25m x 25m x 25m + 15m x 15m x 15m
Volume*: $6750m^3$
A specialised module designed for the housing of our satellite production. There is also an external service area attached.





GeoDome 2
Dimensions: 15m x 15m x 15m
Volume*: $1767m^3$
A smaller specialised module designed for the housing of our electrolysis reactor and other projects.
***NB: Using volume of hemisphere**

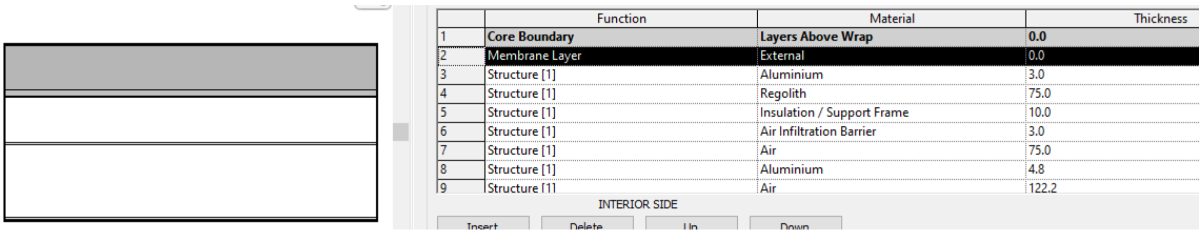




The advantages of using standard modules are clear. Efficiency during manufacturing and production costs are lowered. A universal system also allows for easy expansion and if a module is for whatever reason damaged. It is fairly simple to produce a replacement part. It also means the fitting of interconnecting parts such as airlocks and cable ducts is much easier.

Walls

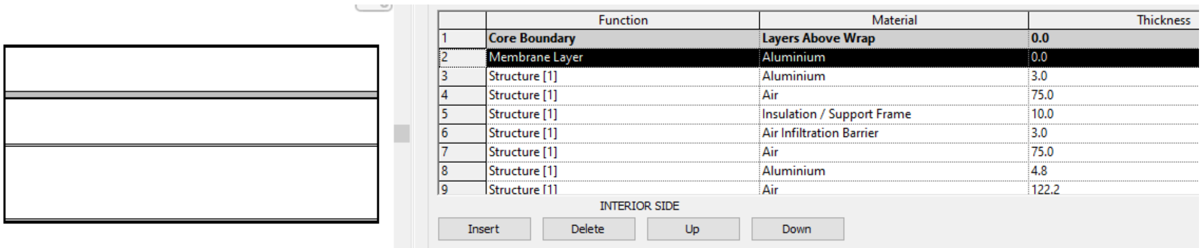
Space Station Wall



	Function	Material	Thickness
1	**Core Boundary**	**Layers Above Wrap**	**0.0**
2	Membrane Layer	External	0.0
3	Structure [1]	Aluminium	3.0
4	Structure [1]	Regolith	75.0
5	Structure [1]	Insulation / Support Frame	10.0
6	Structure [1]	Air Infiltration Barrier	3.0
7	Structure [1]	Air	75.0
8	Structure [1]	Aluminium	4.8
9	Structure [1]	Air	122.2

The universal wall used across the space station will be made of thin aluminium sheets similar to that of on the ISS and padded with regolith for radiation protection. Metal mesh materials are also placed within to make wiring / piping easy to fasten and organise. Hence the large percentage of the wall being air. Sensors and heating elements will also be placed every 3m to measure conditions and regulate heat as needed.

Internal Space Station Wall



	Function	Material	Thickness
1	**Core Boundary**	**Layers Above Wrap**	**0.0**
2	Membrane Layer	Aluminium	0.0
3	Structure [1]	Aluminium	3.0
4	Structure [1]	Air	75.0
5	Structure [1]	Insulation / Support Frame	10.0
6	Structure [1]	Air Infiltration Barrier	3.0
7	Structure [1]	Air	75.0
8	Structure [1]	Aluminium	4.8
9	Structure [1]	Air	122.2

An interior wall that is always within a module and cannot pass between modules to maintain segregated pressurization between modules. Designed for splitting modules into project rooms / personal areas. These are not fitted with electronics within by default but have the netting needed if required.

The use of Regolith within the walls

As the Moon has almost no protective atmosphere or magnetic field, astronauts would need shelter from cosmic rays and meteorites. The modules are designed with sufficient protection from radiation, as they include layers of Aluminium as well as regolith. This will block all alpha and beta radiation; however, some high-level gamma radiation will be let through. Micro meteorites will also be blocked by the structure, however it will not be able to block any sizable meteorites, so this poses a safety threat, and this is why modules are individually pressurised, in order to prevent a catastrophic loss of life across the base. The staff will be exposed to significant amounts of radiation when they are in space, and they will be required to wear dosimeters so that personal radiation dose is monitored, with those receiving too high levels of radiation being sent back to earth.

Regolith is an easy construction material to use and can be easily packed into the walls to provide extra protection. It can also be used to construct the flat launch and landing pad for the transport vehicles, as well as for foundations for the modules.

Staff

In order to make the base as efficient as possible, the staff in the base will be carefully vetted in order to ensure they are of peak physical and mental fitness, as the cost of bringing them back to earth will be high. Furthermore, people will need to be specialists, as they will need to operate and maintain a range of complex equipment. They must also be dedicated, as they will have to work very long hours in order to maximise efficiency. These requirements may seem very tough, however there is large demand to be an astronaut across the world, so there will probably not be any problems recruiting.

Electrical Power

Electrical Power on the Moon

In order for the moon base to operate, there must be a substantial source of electrical power. This electrical power must be present in small quantities as soon as the base is first established in order to power lighting, life support and communication equipment. As the base expands, the power supply must also be able to expand, increasing in its ability to supply power. The power supply must also be reliable, as a fault could cause the whole base to be evacuated, if the power cannot be brought back online.

There are two main fundamental sources of power. This is either from the sun or from nuclear power. Nuclear fusion would be convenient as the nuclear fuel, hydrogen with deuterium and tritium isotopes is present on the moon. The problem is that nuclear fusion is not able to produce net power, and while that may change in the next 10 years, fusion will remain very complex. ITER, the fusion reactor expected to create a net output of power, weighs 23 000 tonnes, and that is using the most modern technology in superconductors. This means that a fusion reactor on the moon is not possible. A fission reactor is more plausible, such as the one used to transport payloads to and from lunar and earth orbit. A small reactor of this size could produce several megawatts of continuous power, which would be plenty, and would only weigh 20 tonnes. The problem is that while the reactor weighs 20 tonnes, the coolant loop and turbines as well as heat exchanges needed to allow the reactor to generate electrical power would weigh hundreds of tons. This means that the reactor could not be set up quickly, so cannot be used as the base begins operation. Furthermore, the reactor will require refuelling every few months as it will be running continuously, which means that the base will not be very independent. This is also not a completely reliable power source, as reactors need down time for refuelling and maintenance. This means that either a second reactor would need to be brought and set up, or a large store of power would need to be established for emergencies. Because it would require so much work to set up and so much material to be brought from earth, it would be too challenging.

Solar power is more promising, as it is the power source used historically in space. Photovoltaic cells are able to generate electrical power directly and reliably, without need for a massive setup. Furthermore, with the main component being silicon, they can be manufactured on the moon, allowing the setup to be expanded easily as more energy is needed, while also being the power source right from the beginning. A photovoltaic array would be a perfect solution, however lunar nights are 14 earth days long, and during that time, power will be much less, with only a few percent of the maximum being produced, and only when the earth is in the sky.

The base is placed near the south pole, but on some high ground so that there will be sunlight. The moon does not have seasons like the earth's poles do, so there is no season where it will be fully dark. In order to compensate for the low angle of the sun, the solar panels will need to be able to rotate, spaced far apart and at a high angle so that they face the sun head on. Solar cell technology has advanced rapidly, making them more efficient than a solar thermal system when it comes to weight and ease of establishment.

Solar panels should be able to achieve higher solar output than they manage on earth, because technology will be more advanced, and without the atmosphere, more light should reach the panels. The efficiency figure I will use in calculations will be 30%, and with the sun's light being about 1000 W/m^2, this makes 300W per square meter panel.

When the base is first established, its power requirement will be much lower than when it is fully operational. In order to estimate the power needed when the base is in operation, it will be assumed to be about that of the ISS, at about 75 kW,

In order to produce this,

$\frac{75000}{300} = 250m^3$ of solar panels will be needed.

The problem is that during the solar night, this power will also be needed, so power must be captured and stored overnight. This power is not all needed continuously, as much of it goes to scientific equipment which is not needed all of the time. I estimate that the power could be halved overnight, in order to reduce the need for energy storage. Initially, this energy storage will be done with lithium ion batteries brought from earth, as they are very energy dense, and are nearly 100% efficient. This means that $375m^3$of solar panels will be needed initially, and at 10 kg per panel, this is 3.75 tons of solar panels. There will also be about this much additional equipment to mount and rotate the panels, so they remain facing towards the sun, meaning 7.5 tons of equipment needs to be brought.

In order to provide 37.5 KW of power for the 14-day night, the energy stored can be calculated.

$$37500 \times time\ in\ seconds\ across\ 14\ days = energy$$

$$37500 \times (60 \times 60 \times 24 \times 14) = 4.5 \times 10^{10} J$$

Then energy density of lithium ion batteries, assuming small further efficiencies are found, is 300-Watt hour per kilogram. In joules, this is

$$300 \times 60 \times 60 = 1.1 \times 10^6 J$$

$$\frac{4.5 \times 10^{10}}{1.1 \times 10^6} = 40900Kg$$

of batteries, which will need to be brought from earth.

This is a large mass of batteries, and as the base expands, it must be possible to store the power using equipment which can be produced on the moon, otherwise it will be too expensive. It is possible to run less energy intensive equipment such as the reactor only during the day, however other energy intensive processes such as growing food will require continuous power.

Energy could be stored using equipment built on the moon in several ways. Gravity based methods will be ineffective, as the 1/6th gravity combined with low amount of water means that pumped storage will not be a viable method. Flywheels are often used as an easy method of storing power, however this is also not possible, as over many days, friction will cause too much power to be lost. The same is true of thermal systems, which are also not very efficient, as converting the heat energy into electrical energy is inefficient and would require a large amount of equipment. Hydrogen Fuel cells can also be considered, as we are already using electrolysis to split up water into hydrogen and oxygen. During the night, stored hydrogen and oxygen can then be combusted, releasing energy. This method is viable, and has been used in space missions before, however only for much smaller power supplies, and they were not recharged in space, instead being used as a one off. Currently, this is not very energy dense or efficient, and while it is subject to high amounts of research, it is not improving rapidly, so will probably not be suitable within 10 years. Furthermore, it would very much increase the demand for electrolysis, meaning that that machine would need to be much bigger and heavier. Energy storage has also been proposed using aluminium, which can be extracted on the moon. By oxidising and reducing the aluminium, large amounts of energy can be stored and then released. This is however not very efficient at the moment and has never been done on a large scale, so it is not a very good option.

The best option therefore is liquid air storage, which has been done on a large scale on earth. This method of energy storage works by cooling air down to below its boiling point so that it becomes a liquid. This can be done efficiently using a Stirling engine to cool the liquid. During the day, large amounts of oxygen, produced in excess by the metal purification process can be cooled to liquid oxygen, and stored under pressure, in the large banks of storage tanks outside the base. Once liquid, they can heat up a little, as the pressure will keep them liquid. Then, during the night, heat can be allowed back into the liquid oxygen. In lunar high ground, underground temperatures average about 220 K. This is high enough to exceed oxygens boiling point of 90K, so if necessary, the oxygen can be boiled by passing it through pipes in the ground. We can also use excess heat from the aluminium reactor, or from the remainder of the base.

As the oxygen boils, the oxygen will expand hundreds of times, and this can be used to do work on turbines, in order to generate electricity. This setup can be built on the moon, as it requires simple tanks, pipes and cooling equipment which can be 3D printed from aluminium, and simply assembled, with a few turbines being brought from earth. The efficiency of liquid air storage is not as high as batteries, with the most efficient systems only achieving 70% efficiency. This efficiency may improve in the next ten years; however, we cannot expect to achieve any more than that 70%, considering that compromises will be made to manufacture it on the moon. It is also relatively energy dense, with a size 140 times smaller than a pumped storage power plant. It also has energy density comparable to chemical energy storage, meaning that while the setup will be large, it will not be gigantic.

A final estimate for the overnight power requirement once the base is at full size is hard to accurately estimate. Most energy intensive processes will be stopped across the lunar night, leaving food (216kW), and general life support / systems, which is about two times the power usage of the ISS, at 150kW. This means that 366kW needs to be provided throughout the night. This will need an energy stored of

$$366000 \times 60 \times 60 \times 24 \times 14 = 4.4 \times 10^{11} J$$

Assuming the liquid air storage reaches the same energy density of the lithium ion batteries, the size of a system needed to store this energy is

$$\frac{4.4 \times 10^{11}}{1.1 \times 10^{6}} = 400000\ kg$$

This is a big system, however it will be made almost entirely from materials on the moon, so the costs will be low. Furthermore, it can be supplemented by the lithium ion batteries already on the moon, which can act as a backup in case of a fault.

During the day, We will need to take in enough energy to store away, including the 70% efficiency. To calculate the energy:

$$4.4 \times 10^{11} J \times \frac{1}{0.7} = 6.3 \times 10^{11} J$$

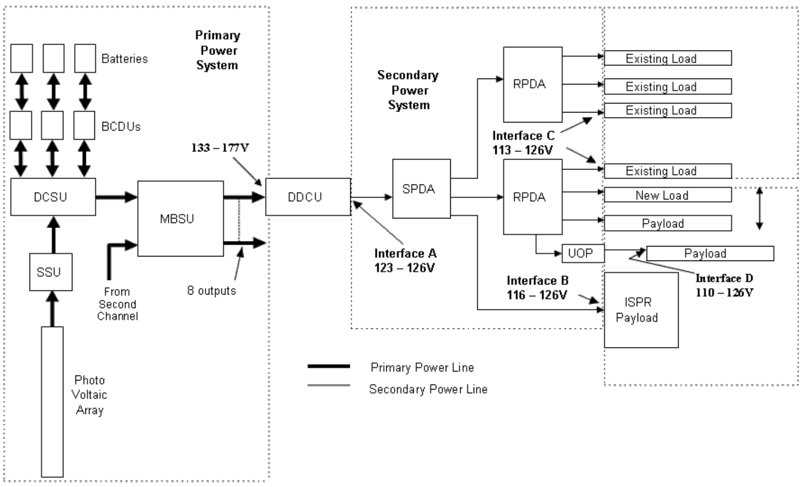
$\frac{6.3 \times 10^{11}}{60 \times 60 \times 24 \times 14} = 520\ kW$ is needed for storage overnight. We also need 1380 kW for the electrolysis, 540kW for the reactor and $4 \times 75 = 300\ kW$ for the general running of the base. This is four times the power to run the ISS and is a good guess. The power needed by some smaller systems is not included, so another 100kW will be added to the total. This brings daytime power demand to

$$520 + 1380 + 540 + 300 + 100 = 2840\ kW$$

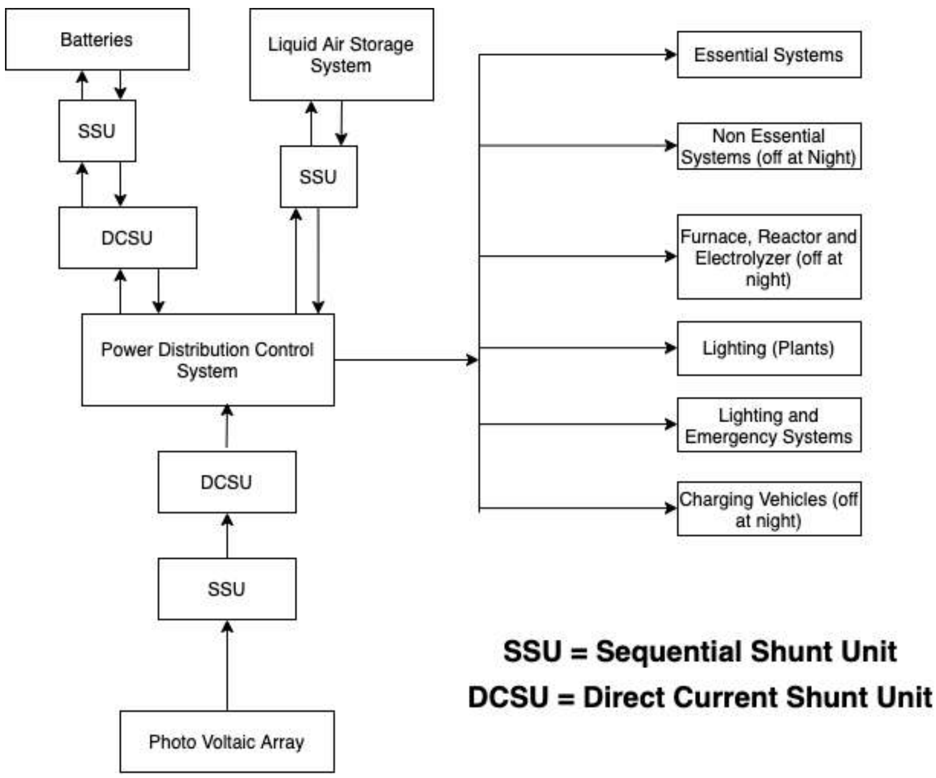
This will require many more solar panels. Using 1kW per square meter again, this means that:

$\frac{2840000}{1000} = 2840\ m^2$ of solar panels. This has a mass of 28 400 kilograms, which can be mainly made on the moon.

The energy produced by solar panels is at a very low voltage. It depends on the type of solar panel and its size, however 15V is typical. This is too low to run the base directly. The base will be provided with DC electricity at 110V. This is because AC is only used on earth because electricity needs to be increased to very high voltage for efficient transmission over long distances. The base will be small enough that DC at 110V will be quite efficient, as the longest distance will be only a few hundred meters, where losses will be minimal. This also saves weight, as most devices such as computers need DC power, so they will not need rectifiers, making them lighter and thus cheaper to bring to the moon, as well as more efficient. The liquid air storage system can also be made with DC motors, and so can all other motorised systems, so DC will not be a problem. Converting the 15V DC to 110V DC will require conversion equipment, which is nearly fully efficient. The ISS converts its low voltage electricity from solar panels into 160V DC and manages the distribution of power with the following setup:

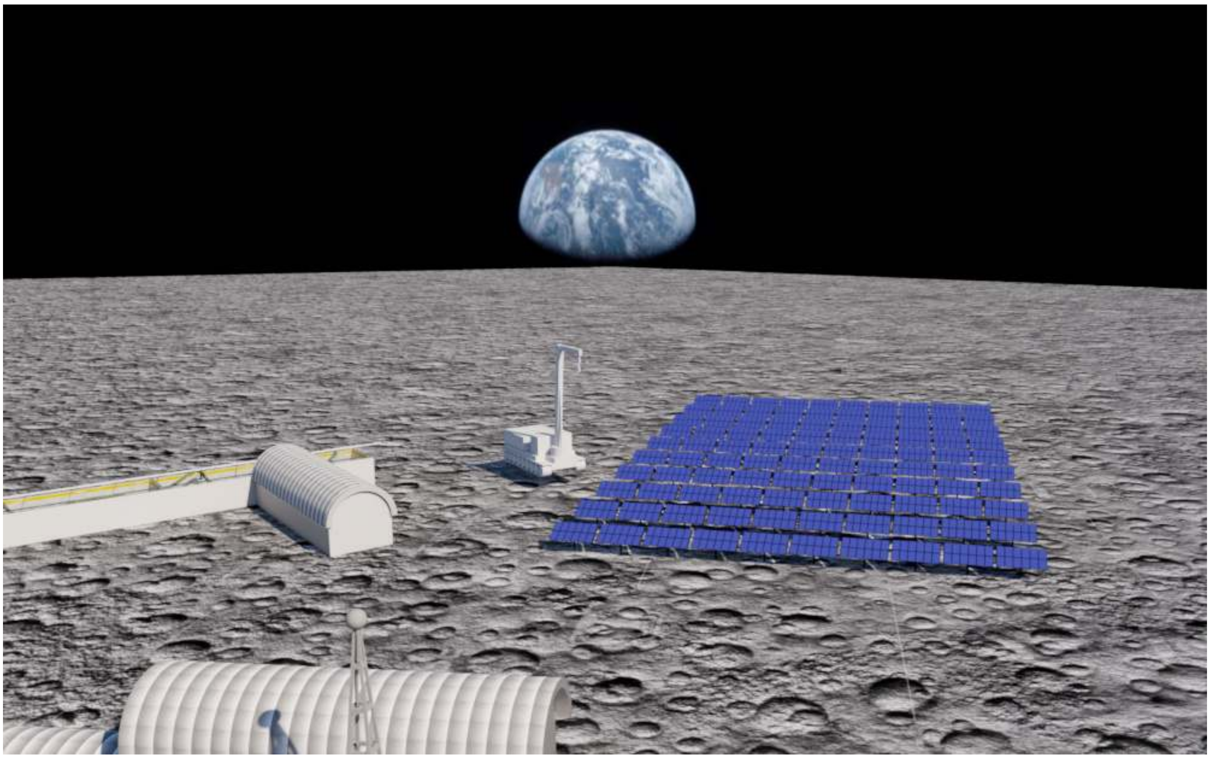


This level of detail is too complex to be replicated for this base, however a simpler version can be designed for the base, which will show the basic power system:



The SSU regulates voltage to keep a continuous, stable output voltage. The DCSU converts from different voltages.

The main power distribution control system will regulate where power goes, controlling the distribution of power through a series of relays. This system can be mainly automated as power grids are on earth, with some manual oversight from an earth-based control center.

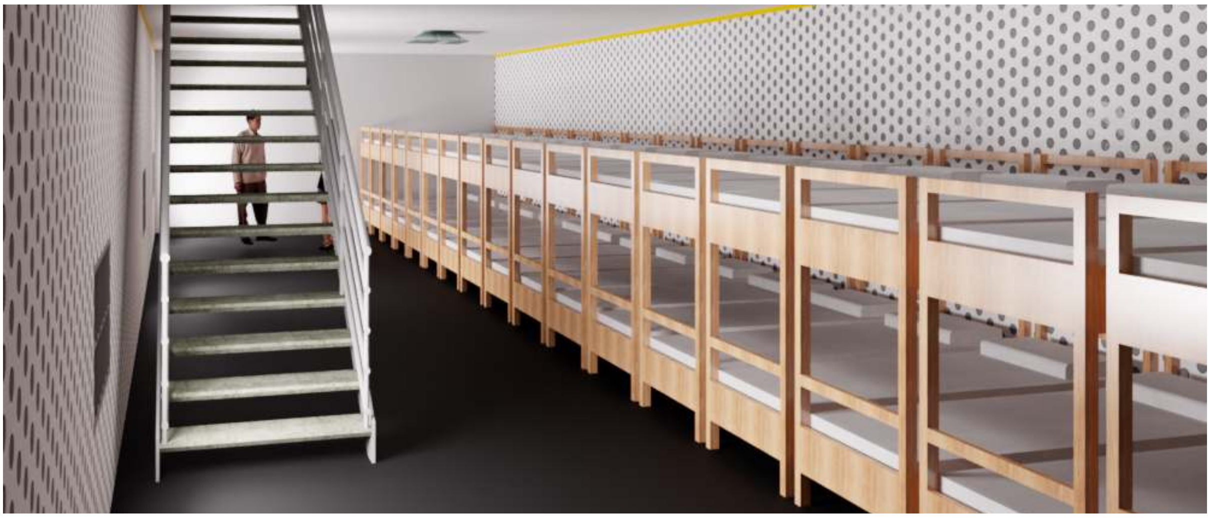


Our Lunar Bases's Solar Array

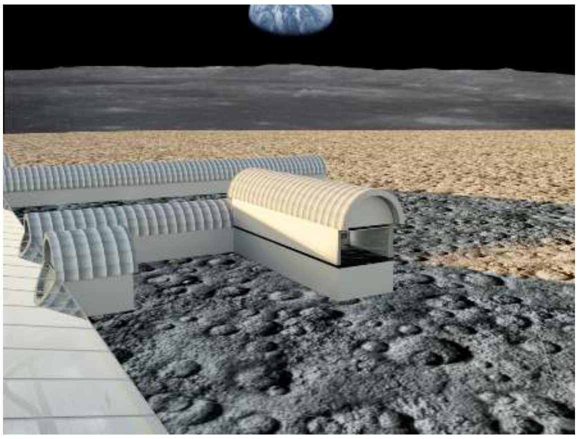
Base Tour

In this section, we will go over a few of the modules within the space base using CAD and review what activities take place in each part. People have been added for scaling reasons.

Living Quarters



A relaxing space for the inhabitants to sleep. Made up of 20 bunk beds on the first level and another 15 on the second, this area is flexible in the number of people it can sleep, and beds can be removed as needed. The area would also have desks / personal workspaces with ethernet connections to the left-hand side allowing access to internal video services and other entertainment platforms. The picture above is at max capacity. The real furniture would be as light as possible and made fully fire resistant.



Exterior View of Living Quarters

Tourist Bedroom

On the next floor up in the Living Quarters. There is also a Tourist Bedroom designed for special occasions. Tourism is not our main commercial activity, but it should not be ignored

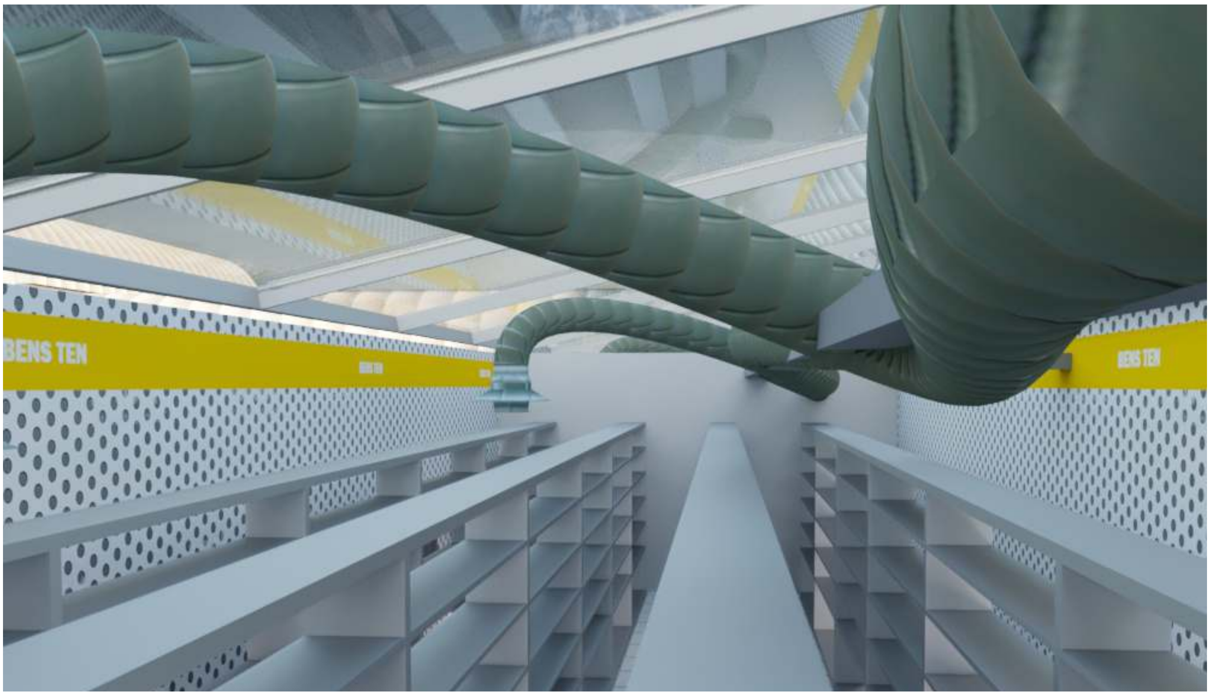
Project Rooms

As the scientists on board our station will be fully qualified in different disciplines, it would be inconsiderate to not allow them space to test out their own projects / potential future projects for our mission within the base. Therefore, we have 4 allocated project rooms within a module with GeoDome 2 being an additional space they can use if needed as the electrolysis reactor does not take up all the space.

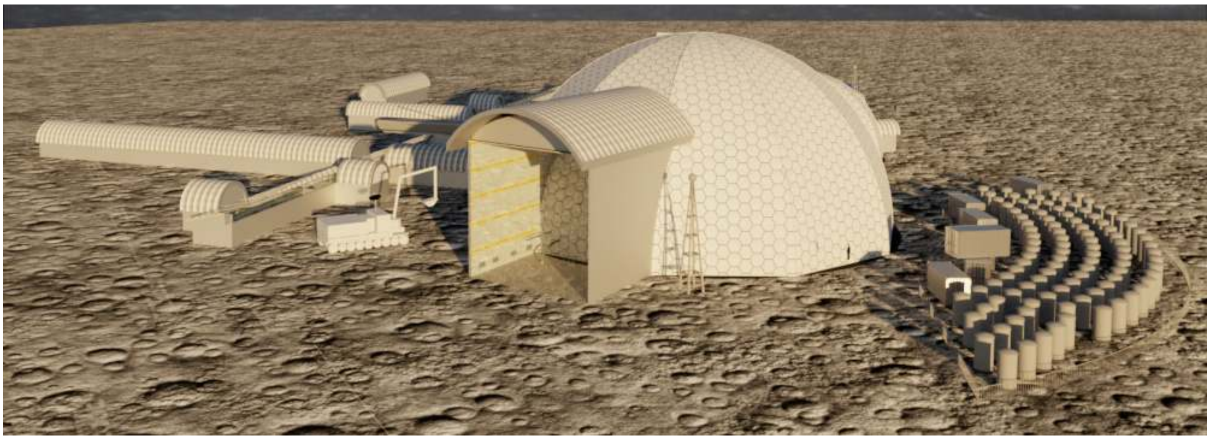
Facilities

Facilities is a general area for all kinds of industrial equipment such as washing appliances (perhaps not washing machines as pictured, although these will be used, as unlike the ISS, people will reuse their clothes in order to decrease costs and increase independence. To the back of the room you can also see the main inlet from the energy center outside. This is where maintenance activities and control panels for central control systems would also be housed. There is also a service ladder for accessing this corridor's cable, piping and air ducts.

Storage

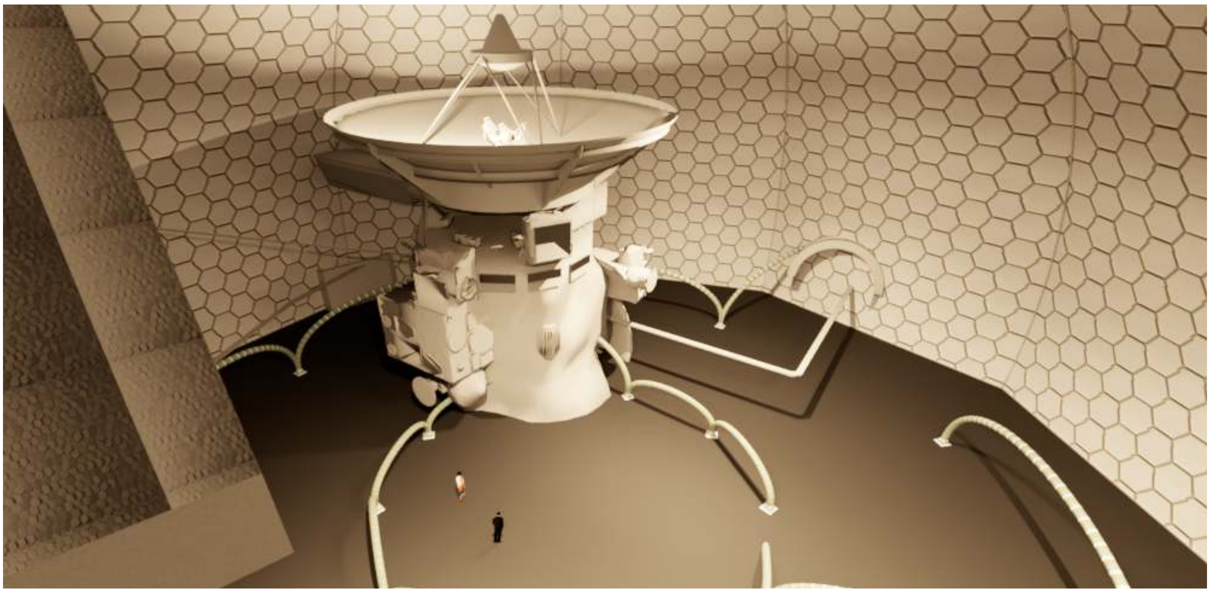


With several projects taking place on the base. It makes sense to have a centralised storage area, allowing quick and easy access to resources for projects and other use cases. Therefore, we have dedicated two internal modules to storage like the one pictured above. The stores will include space suits, emergency food, tools and spare parts.

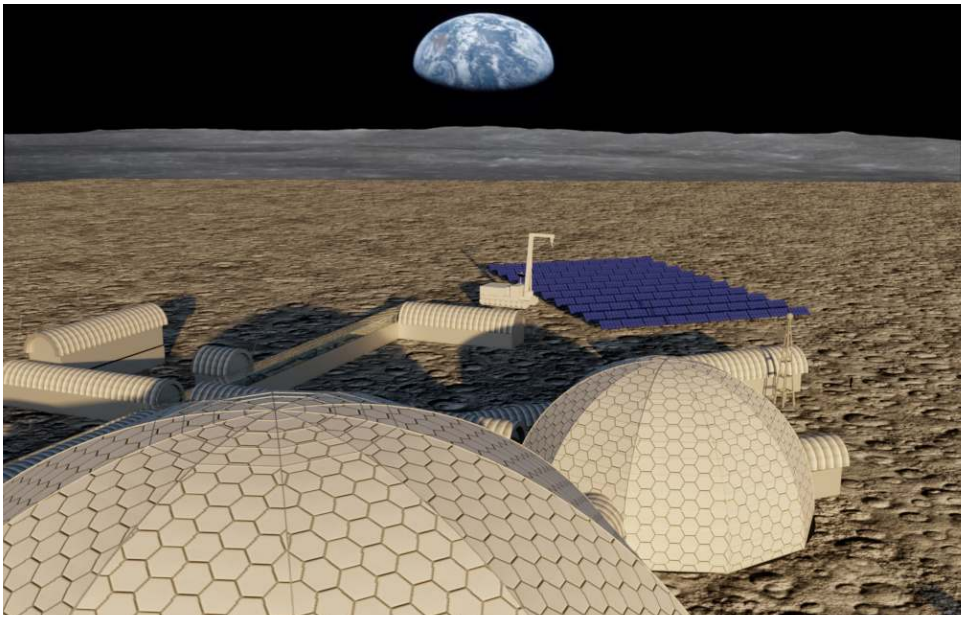


Additionally, for larger objects and when we first land on the moon for construction, we will need an area to store these larger, more industrial objects. Therefore, we would construct a railed off type area (pictured here to the right) with all the materials needed for construction. A launchpad would also be placed to the left. Eventually as the base is built, the area will be replaced by tanks for the liquid air storage for the energy project and storage of other fluids required for manufacturing and research.

GeoDome - Satellite Production



GeoDome 1 is a massive engineering challenge. It will be used as the main production facility for our satellites. It also houses the second toilet facility. It is 25m tall allowing for construction of big satellites and other large scale projects that we may want to produce on the moon, such as assembling more modules or vehicles. As GeoDome 1 is such a large space, the appropriate infrastructure for Lighting, Air Exchange and Electricity will need to be put in place. The energy needed for one bulb to light the entirety of GeoDome 1 is 25 000W which is not possible and therefore an array of spotlights will need to be sorted. Possibly 250x100W LED spotlight lamps placed around the edge of the dome. As you can see from above more gas exchange has been put in place to accommodate the large space and to prevent carcinogens from the production line getting into the human lungs.



Workshops - Component Manufacture

As well as the main assembly hall, components for satellites will need to be made in the workshop modules nearby. These workshops will have all of the equipment necessary such as metal 3D printers, a small furnace, lathes, CNC machines and work benches. This is where the staff will spend most of their time and this is where all of the components including solar panels will be made. Because the moon has 1/6th gravitational field strength, it is easier for people to carry components around, and carts can be used to carry the largest components. This space can also be used to fix broken pieces of equipment, in order to increase the bases efficiency and independence.

Exercise Area

The inhabitants will be in a gravitational environment that is abnormal for them, because the moon's gravitational field strength is only 1/6th that of earths. Because of this, we will need to make sure to provide the facilities needed in order to cater for these side effects. One known symptom from astronauts on board the ISS is muscle fatigue when travelling back to earth. Therefore, we are supplying exercise equipment such as treadmills. Although clearly the typical weight bench pictured above would not be effective and potentially dangerous, exercise equipment which relies on elasticity will be needed, as is used on the ISS.

Materials Processing GeoDome

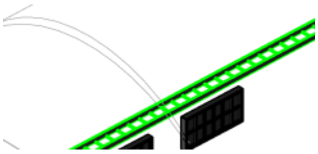
The second, smaller GeoDome will contain equipment too large to fit into the normal modules. This is primarily the chemical reactor for producing aluminium and silicon, and the electrolyser for producing oxygen and hydrogen. This area will also need to have some conveyor belts to carry material as it is unloaded from the mining vehicles, as well as machines to pulverise the rock, as well as separate and remove ice from the rock. There will also need to be several other machines which have not been designed in detail which have been brought from earth in order to perform functions such as sintering, and separation of products, in order to make the rocks into usable raw materials.

System Design

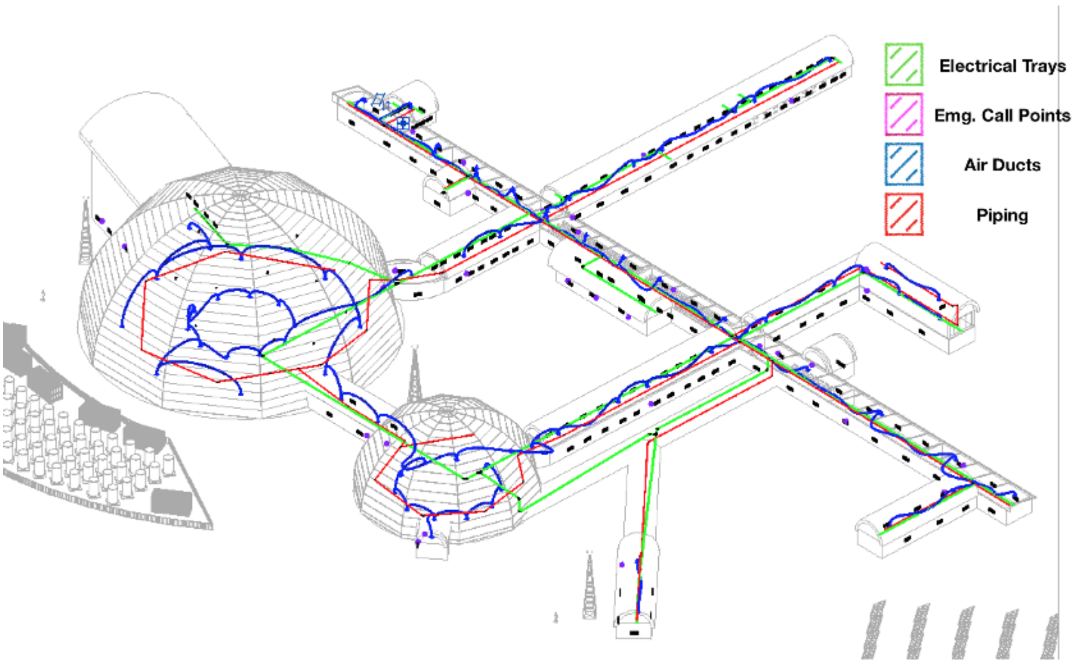
You may have noticed from previous photos the round flexible green ducting running along the ceiling. This is one of our four essential systems that are running across the entire base. Every module has a universal connection pattern which allows them to be easily chained together.

These four integral systems to the base are: Electricals (including ethernet wired connections, sensor links and any kind of other electrical application), Piping for liquid transfer (all modules have water), Air Ducting for transfer of processed air and Fire / Disaster Alarm connections. These systems are all essential for safe and effective running of the base and hence backup links are put in place and whenever a connection is broken, the internal computing system will flag up to the appropriate engineers that something needs attention.

Electricals are all placed in cable ducts like this:



These are very useful as they allow flexibility in what kind of cables are run and allow for easy mounting of electrical components such as network radio equipment aka WiFi access points. Pictured below is an overview of all systems throughout the base.



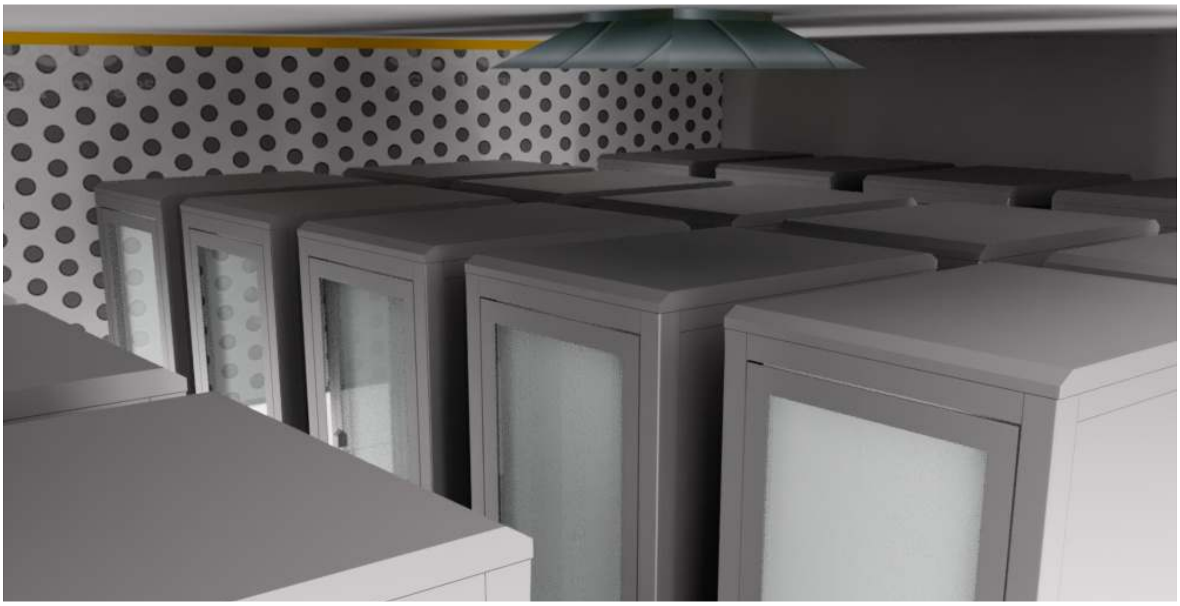
Systems Overview generated from CAD

Electricity

The electrical supply and distribution will be carefully monitored in order to prevent the outbreak of an electrical fire as the result of a fault. This can be done using computer systems.

Connectivity

Networking, Connectivity and IoT (Internet of Things)



A CAD model of The Moon Base's Main Network / Server Room

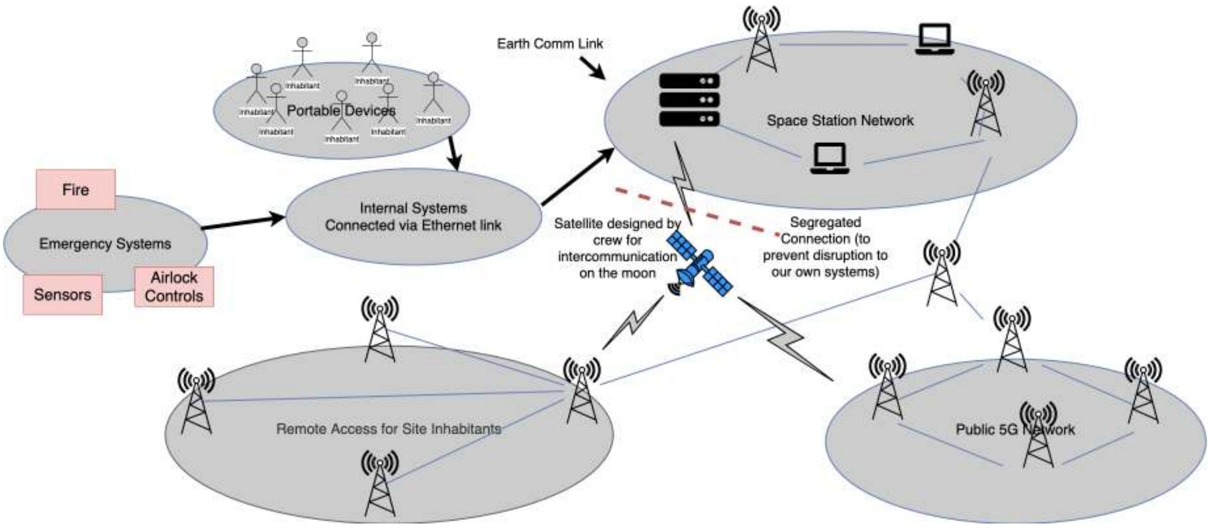
In order to maximise efficiency, and to allow control processes to be moved out from the base and to control rooms on Earth, we need to seek better connectivity than what is already offered on the International Space Station. Internet access will need to be readily available for all inhabitants allowing them to access crucial resources quickly and efficiently.

Furthermore, we hope to connect our various internal systems within the habitat to allow for a smarter environment which can be computer controlled to ensure maximum efficiency in energy and labour.

Getting a Fast and Reliable Internet Connection to the Moon

Currently the speed on the International Space Station is 600Mbps which is substantial, as it is enough to support 20 people. 600Mbps is approximately 13 times as much as a household broadband connection in the UK. However, as we look towards the future and as technology develops we are going to require an even better speed link if we are going to be able to perform the large scale research, and allow future redundancy. For perspective, the Large Hadron Collider at CERN produces one petabyte of collision data per second. However, after processing this amount reduces to around 3GB per second. Although we will not be generating this amount of data, the base will have thousands of sensors which will need to be analysed by crews on the ground.

It is important to consider the bandwidth that we would require on the station therefore we are going to do a simple calculation. We will assume for this number that we are at max capacity in all cases (usage, number of devices).



A Network Map of all Lunar Communications

40 x Inhabitants
1 Portable Computer per Person - intended for work related activities - sending files and data. Approx. 40mb/s
1 Portable Handheld per Person - for VoIP communication amongst the space station using a Push to Talk (PTT) style system. Also has access to all internal systems. Approx. 15mb/s

16 x Servers
For storage of all lunar data including and not limited to:

- Research Data similar to that of CERN
- Redundancy Servers setup in RAID 1 to prevent loss of data due to disk corruption.
- Cache to prevent constant streaming from Earth servers.
- Tape Servers for long term storage.

We estimate that within the first five years of usage we will require approx. 10GB/s internal and 500mb/s external (earth link)

We will also have an expansive IoT setup within the base with various sensors all connected together regulating various features of the base such as temperature and pressure. These sensors will be adjusted constantly over time and need rapid communication with output devices to ensure the conditions are just right. There are approximately 15 standard modules and two larger modules. If there are sensors every 2m then $\frac{2}{20} = 10 \ Sensors$ in each module.

$(10 \times 15) + 100 = 250$

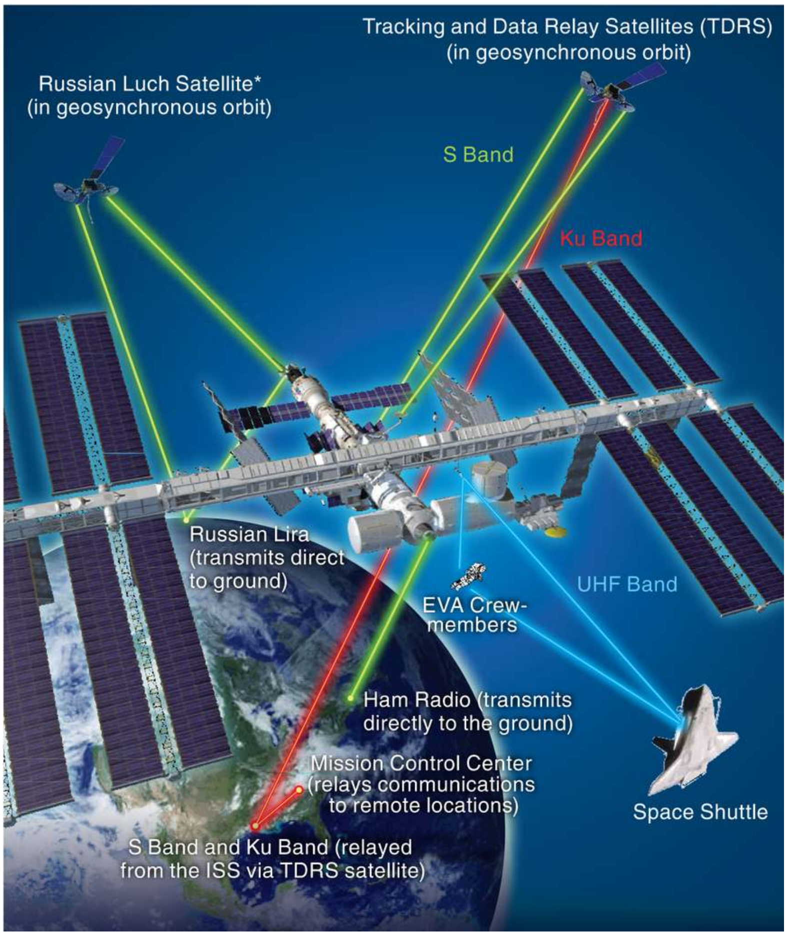
Each module will use about 1mb/s internal connection so bandwidth internal will be 250mb/s.
There is no need for external connections.

Total internal: $40 + 15 + 10000 + 500 + 250 = 10{,}805$ **mb/s**

Total external: 500 mb/s

Ways of Receiving an External Connection

The connection on the ISS is currently provided by a multitude of satellites providing a link between the station and earth. The bandwidth of the system is not bad however the link speed is slow with each connection to the earth having to travel 22,000 miles. However, the moon is approximately 238,900 miles which would significantly increase the latency / ping. The radio connection to the ISS is known as the Ku band and S band (12-18 GHz and 2-4 GHz) respectively.



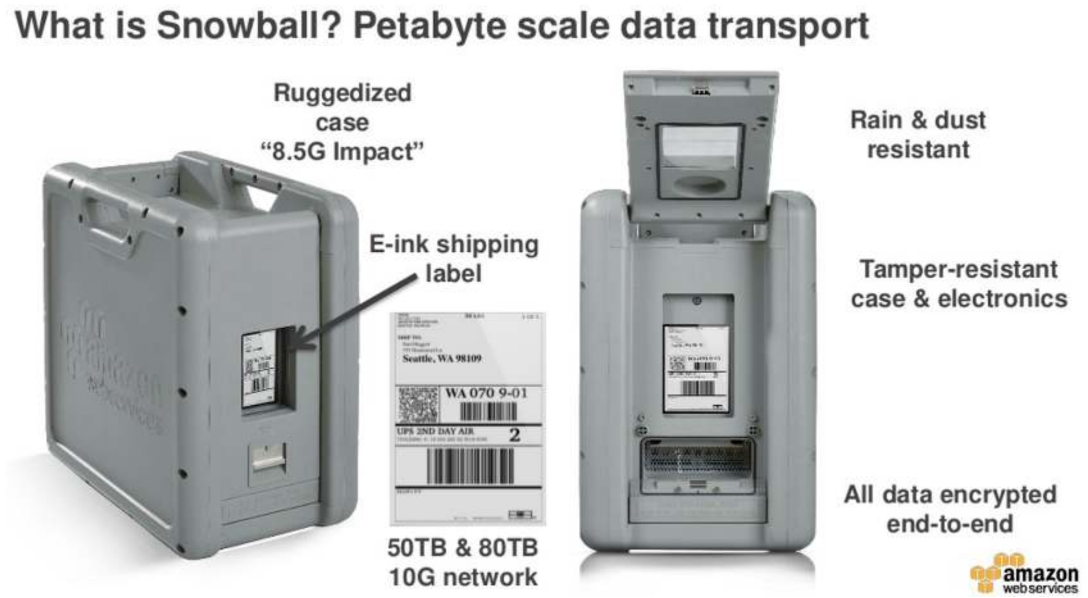
Infographic showing the various communication bands used on the ISS

Calculations can be performed to express why the latency of the ISS's internet connection is so large. However for our purposes latency is not that big of an issue and therefore this solution could work for our needs even though currently at this moment in time the ISS only receives a speed of 600 mb/s, developments in satellite technology are constant and we would hope that in the next 10 years we will have overcome this limitation put in place and increase the range perhaps by using a different band.

However, Lasers are another possibility. NASA is currently running a Laser Communications Relay Demonstration (LRCD) project which will allow us to have a greater bandwidth and speeds up to 10 to 100 times faster than what is currently used. It is being labelled as potentially being revolutionary for space comms that could offer up to gigabit-per-second data rates!

LCRD

There is also a slightly old-fashioned way of manually shipping the data using space grade equipment that holds capsules of data that are manually sent in shipments from earth. Of course these being shipped for the sole purpose of data transfer could be tremendously expensive but in the long run if we are running shipments regularly with earth, such as returning crew, then there is no reason not to if it is possible to transfer up to a petabyte of data which would take a lot longer over the connections we would have in the next 10 years! Pictured below is Amazon Web Service's enterprise grade 'Snowball' capsule used for businesses with big data needing to exchange it quickly and securely.



Amazon Snowball

Relaying our Internal Network across the Moon Habitat

5G has been in the news recently for being the next generation of mobile connectivity. If we are going to have portable handheld devices, and other electrical devices that talk over wireless signals we need to make sure we are using the latest technology to allow us to run our applications and IoT network. 5G unlike 3G to 4G isn't just a massive step up in speed, it is also a completely redesigned protocol in some cases allowing for Peer to Peer networking allowing devices to talk to one another instead of going to a centralised tower. The use of peer to peer networking for our IoT sensor network is a game changer and could significantly reduce the load on our internal ethernet network and offer advantages in other areas.

Additionally, the portable handheld devices the crew will be using will be much smarter and also the Peer to Peer networking will be useful for our Push to Talk application as the radio will not need to be in range of a tower in case of emergency / system failure. This is very helpful, as it allows for problems to be instantly relayed to the staff, making the base simpler and more efficient.

Programmable Logic Controllers

Programmable Logic Controllers (PLCs) are ruggedized computers designed for use within embedded applications such as Smart Buildings. There are several different manufacturers and models for PLCs all offering different features and different capabilities. With the development of our Lunar Habitat, we want to make sure that we are doing our best to run the environment with little user intervention. This is where smart technologies with PLCs combined with various types of sensor can become particularly powerful. Below are some examples of different use cases for PLCs within the Space Factory.

Programmable Logic Controllers mounted on a cable tray connected via Ethernet

Programmable Logic Controllers come in several different specifications, but our main requirements would be an Ethernet interface to allow it to be plugged into our internal systems network and some kind of serial communication port to allow us to connect heating elements and sensors as required.

To supply a PLC (presuming it runs at 5V and 2A) with electricity we should consider the amount of heat that will be produced from resistance.
This a power requirement of:
$5 \times 2 = 10W$ which is small enough that there are no cooling requirements, and these computers can be left on all the time.

Automated Robotics Projects

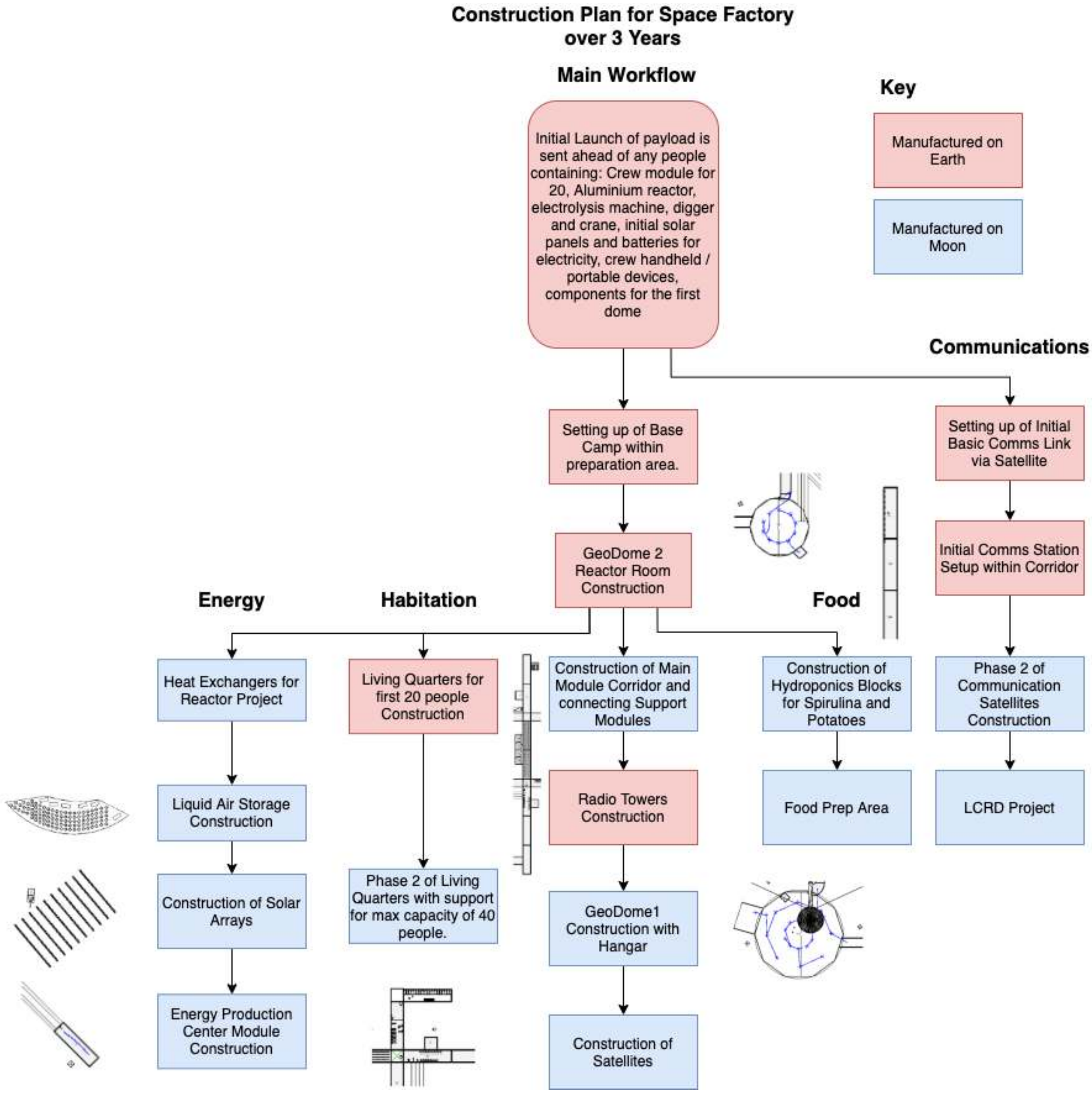
Our initial robotics project will be the diggers and cranes mentioned in another section, however with the aid of PLCs and other kinds of microcontrollers there is room for expansion in the following IoT areas:

- Food Production
- Environment Analysis Projects - Rovers
- Small Scale Mining Operations for Research
- And more…

Construction Plan

The Space Factory is a huge project to undertake and therefore we have come up with a draft construction plan to work out the timings and workflow when building our moon base from initial landing through to the construction of our first satellite.

The reason that this scheme is necessary is because the mass of the base as a whole is too great to be efficiently brought from earth. By building much of the base on the moon, once



basic functions are established allows for the mass that needs to be brought from the moon to be massively reduced. For the first few years, the staff will work on building the base, before satellite and fuel production begins as a commercial activity.

Food

Food could be grown hydroponically in sheltered greenhouses lit by LEDs. Plants recycle waste and turn carbon dioxide into oxygen so would form an essential part of a life-support system.

CAD Representation of a Hydroponics Room with Spirulina and specialised LEDs for Growth.

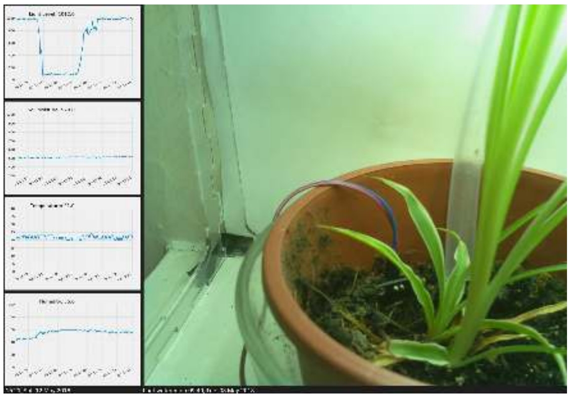
Initially, food will be shipped from the earth to the moon, and the ability to become self-sufficient on food is one of the last elements to be added to the base. This is because food can be shipped inexpensively from earth, as is currently done with the ISS. This does however create an ongoing cost, and food is one of the most important factors needed in a self-supporting moon base. By growing food independently, this removes the need for chemical CO_2 scrubbing, as well as increasing self-sustainability. The moon base will then be part of a closed ecosystem. Therefore, the plants would need to recycle organic waste and turn carbon dioxide into oxygen to breathe. Crops that grow well in confined spaces and that are packed with the nutrients that degrade most in storage such as $vitamins\ C_1, K$ and potassium are necessary. Food such as spirulina are the best for this as they provide a rich calorie and nutrient supply at the same time.

On the moon astronauts would grow plants in water under white and red LEDs which they can tweak to alter the mineral and vitamin composition of the plant. It would be possible to grow plants in soil made from the lunar Regolith as well as some added nutrients, however this is not as efficient as growing plants using hydroponics. Using soil from the Regolith would save transporting mass to the moon, however like growing in the earth on Earth, it is not as efficient, and plants take longer to grow than if Hydroponics are used.

Seeds can be grown easily with materials from Earth like water, air, soil, and an electric heating system for warmth. It is also more efficient to have the seeds in close proximity. Lunar night is a massive problem for plants as without ample sunlight surface temperatures decrease to -52 degrees Celsius. So, without a sufficient heating system the plants will freeze. Vacuums make the water in plants cells rush out and dissipate as vapour making a freeze-dried flower. For this reason, the plants will be inside the pressurized area of the base, so will be kept at the correct temperature and pressure.

In order to grow food, a greenhouse would contain LEDs for the most efficient generation of light. This would be placed in one of the standard aluminium modules, which provides ample protection from radiation and is well insulated. This setup would be operated autonomously, with the temperature, levels of nutrients, PH and water all being controlled by simple autonomous computer systems to maximise yield.

A prototype self-regulating plant system using a Raspberry Pi computer (would be replaced by a PLC)



An image from a camera module with graphs from the various sensors.

The electricity for the LED lights would be provided from the main energy grid. The CO_2 for the plants will be perpetually present in the air of the base, because as the food is eaten, the people will respire, and exhale the CO_2. This provides a natural negative feedback loop in the space stations air ducting system which will keep ideal concentrations of CO_2, as the plants will grow faster with more CO_2. Water will be extracted back out of the air as it condenses, and from the recycled urine of the staff. Nutrients can also be recycled from excrement, allowing for the cycle to be self-sustaining.

Use of Spirulina

Spirulina is a blue/green microalga which grows in salty water such as the sea on Earth and various salty lakes. It was harvested by aztecs for nutrition and it is still used today on a regular basis in West Africa where it is made into dry cakes. Spirulina grows in microscopic spirals (hence the name) but they stick together which makes it easy to harvest large amounts at once. In recent years, people have been attempting to promote spirulina as a treatment to various metabolic and eclectic health problems yet there is insufficient scientific evidence to back up these claims. There are still great benefits of spirulina due to its broad and dense range of nutrients. Spirulina's main claim to fame is it's 60-70% protein composition in its dry mass.

Spirulina also contains a variety of minerals in varying amounts. In order to receive a balanced diet of nutrients, another food source must be used. Another high calorie food such as potatoes can be used, as these are the most efficient, and they are also an easy plant to grow.
Spirulina Nutrition Statistics:

	100g Spirulina Contains:	Reference Intake for Adults	100g Potato contains
Calories	290 Kcals	~ 2000 Kcals	87 Kcals
Protein	57.5g	50g (Minimum)	1.9g
Fat	7.72g	70g (Limit)	0.1g
Carbohydrate	23.9g	225 (Minimum)	20.1g
Sugars	3.1g	90g	0.9g
Fibre	3.6g	30g	1.8g

If we have 0.6 kg of flavoured Spirulina combined with 0.4 kg of 1 potatoes to provide variety each day, as well as providing more nutrients per calorie. We reach the calorie, protein and fibre requirements as well as avoiding too much sugar and fat.

$$Calories : 290 \times 6 + 87 \times 4 \approx 2030\ Kcals$$

$$Protein : 57.6 \times 6 + 1.9 \times 4 \approx 350g$$

$$Fat : 7.72 \times 6 + 0.1 \times 4 \approx 47g$$

$$Sugars : 2.1 \times 6 + 0.9 \times 4 \approx 220g$$

$$Fibre : 3.6 \times 6 + 1.8 \times 4 = 29g$$

These numbers are all very close to the respective minimums and maximums. Peoples diets will be monitored very closely, in order to ensure they remain at peak energy, and additional vitamins can be supplemented easily, in order to keep people healthy. Furthermore, a small amount of food can still be imported in order to increase variety.

This will keep workers well fed as well as being an easy to grow source of oxygen for the closed system.

Space and energy requirements

The amount of spirulina is easy to calculate, as it is able to increase by mass by 25% per day. With 40 people needing 0.6 kg each, that means that per day, the mass of spirulina produced must be:

$$0.6 \times 40 = 24kg$$

The total mass that must be cultivated is four times that, at about 100kg. Because it can grow so rapidly, only a small initial amount needs to be brought from the moon. If only 1kg was initially brought, the mass over time is:

$$Total\ mass = Initial\ mass \times 1.25^{number\ of\ days}$$

In order to get 100kg from 1kg,

$$log_{1.25}100 = 21\ days$$

This will not take long. The more complex ingredient is the salt for the water, which would be difficult to extract on the moon, so must be brought from earth. The salt concentration needs to be at about 40 g/liter to maximise yield.

In a compact setup on a large scale, 100 grams of spirulina per day can be extracted from $1m^3$. This means that in order to have 24 Kg / day, there must be $240m^3$ of tank space. This is enough to be fit into a module, with room for harvesting equipment, lighting, etc.

For maximum yield, there needs to be 40 g/liter of salt in the tanks. There will be a total of 9600 kg of salt needed for the whole project. This will need to be transported from earth, and is not an inconsiderable expense. It is however about the same as transporting 25kg per day for a year, so growing food on the moon will soon become economic. Furthermore, 240 tonnes of water are needed, as well as an additional module. In order to light the spirulina, lighting is needed every meter, as the spirulina has a dark colour and will absorb light. Lighting needs to be at about 500 watts per meter squared. This means that

$$500 \times 240 = 120\ KWh$$

are needed to light the spirulina, round the clock. The tanks will also need to be heated to 34 degrees C in order to maintain maximum yield. This is potentially dangerous as it could cause the growth of bacteria dangerous to humans. For this reason, the tanks should be kept as sterile as possible, and it may be necessary to use antibiotics. Filtered air will be bubbled through the tanks in order to maintain carbon dioxide levels.

The growth of potatoes is even more intense on resources. Each potato weighs about 100g, so 4 potatoes are needed per person per day, making 160 potatoes. Using very approximate numbers, one can grow 70 potatoes per square meter, and they take 70 days before they harvest. This means that

$$\frac{160 \times 70}{70} = 160\ m^2$$

This means that a module with a floor area of

$$3.5 \times 18 = 63m$$ (including a corridor for access)

$\frac{160}{60}$ means that 3 layers are needed, allowing them to be 1m apart, giving plenty of space for the plants to grow. These will require $600\ w/m^2$ round the clock, making 96 kWh.

Seed potatoes will need to be brought, as well as several tonnes of starter nutrients, however not as much as the spirulina. They will also require several tonnes of water, however less than the spirulina, and that can be made on the moon. The container for these things can also be manufactured on the moon.

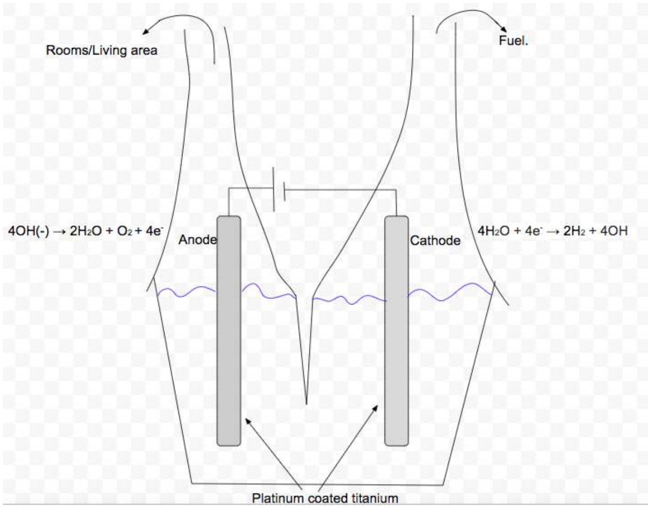
This food setup will allow for sustainability, while only taking two modules, and 216 kWh of power. This is a good extension to the base once the main function of the base is established, in order to decrease long term costs.

Electrolysis of Water

In order to fuel our many endeavours on the moon, we will need lots of hydrogen. Hydrogen is not very abundant on the moon in its natural form, and there are not many accessible compounds that contain it. The way we have decided to acquire hydrogen is by using the only substantial source of it, water.

There is lots of water in the crater nearby. NASA crashed a probe into the crater in order to sample it and has found that it was made up of 5% ice. This is possible because the crater is in permanent darkness, so ice can exist, probably brought by meteorites millions of years ago. There are billions of tonnes of ice estimated to be in this crater, and it will be excavated and brought to the base by the mining vehicle. On arrival, the mining vehicle will dump the rocks from the lowlands into the materials processing area, and as the ice melts it can be removed as pure water.

Using hydrolysis water can be split into hydrogen and oxygen. This will release hydrogen and oxygen, which is also useful in the base.



In order to electrolyse water, we will need two rods, the anode and the cathode. On a commercial scale, steel is normally used for this reaction as it is cheap and works effectively, however if we were to use steel it would quickly become very expensive as we can't manufacture steel on the moon, and it needs to be replaced very often. The best solution to this would be to use platinum coated titanium electrodes. Whilst these would still need to be replaced, they last much longer than steel or graphite, increasing the bases ability to sustain itself and lowering costs.

Once electrolysis has started Hydrogen will gather to the cathode where we will need to store it. To do this, we will channel it into a separate area where we will have pressurized tanks of hydrogen. From here, hydrogen can then be used as fuel in satellites or in the moon to lunar orbit launch vehicle, which requires 1.8 tons of hydrogen per launch.

In order for electrolysis to work we will need DC current. The ideal voltage for this is 1.23V, which can be achieved easily by stepping down the 110V base mains electricity. If we use a good electrolyte like H_2SO_4 along with our platinum coated titanium cathode and anode our electrodes will last for a long time and this will be quite economically effective.

In order to electrolyse one mol of water theoretically requires 237 kJ of energy. This would release two mol of water, which weighs 2 grams. In order to get a kilogram, this must be 500 times as much.

$$237\ 000 \times 500 = 118.5\ MJ$$

We would like to collect 1000kg of hydrogen every day, during the lunar day. The process will be stopped at night because it is so energy intensive.

$$118.6 \times 10^6 \times 1000 = 1.19 \times 10^{11}\ J$$

To convert this into power;

$$\frac{1.19 \times 10^{11}\ J}{60 \times 60 \times 24} = 1380\ kW$$

This makes the electrolysis of water the most energy intensive process done of the base.

Metal Extraction

Much of the lunar surface (especially in the lighter-coloured highlands) is made up of anorthosite. Roughly 90% of anorthosite is made up of a plagioclase feldspar known as anorthite (or calcium aluminosilicate). This is a mineral with repeating unit $CaAl_2Si_2O_8$. All of the components of this are useful:

Anorthosite

- Al is light, strong and conducts well, and is therefore used a great deal in satellites - very useful for our commercial activity.
- Ca is an even better conductor than Al, though more reactive (reacts with cold water) but still useful in dry environments.
- Si is useful in semiconductors and transistors - used to make computer chips and will be used in satellites.
- O_2 is useful for our colonists to breathe, and for liquid air energy storage.

Aluminium is the component that we are most keen to get however, as all of the others will be produced in excess.

The best method for extracting aluminium metal from anorthite is the FFC Cambridge process.

Anorthite can be extracted from anorthosite by grinding it finely and using magnetic separation to remove the mostly iron-based impurities. We can import the machinery required to crush and sinter the anorthite. Then the anorthite powder can be sintered (amalgamated) into a flat disk with a hole in it, known as the preform. These disks are stacked onto a metal cathode, and this is placed in a molten calcium chloride bath at 800-1000 ºC with an inert platinum anode.

The setup for the electrolysis as it is performed on Earth - the preform is on the right, having been slotted onto a metal rod to connect to the power supply.

At the cathode, the oxygen is stripped out and the anorthite is reduced to its metal components. The oxygen forms O_2 at the inert anode. (Note: we have not found a reliable source that says what the material used for the anode is. Our best guess is platinum.)

Calcium is soluble in molten calcium chloride, so it dissolves. This therefore needs to be distilled out during the process. Aluminium metal melts at bath temperatures, while silicon does not. The molten aluminium, which is more dense than molten $CaCl_2$, sinks to the bottom of the bath, where it can be tapped off. The remaining cathode is a very porous sponge of silicon metal.

The process on Earth takes place in an argon-rich atmosphere so that oxygen in the air does not re-oxidise the metals. Argon is not present on the Moon, so we will have to import our own inert gas. Argon is used on Earth because it occurs naturally in Earth's atmosphere at around 0.9% of the composition, so it is easy to obtain. Helium has the same effect as argon, though less abundant on Earth, but it is much lighter ($4\ g/mol$ rather than 40 for argon) so would be a much better lunar alternative as it is cheaper to import. Helium is also even more inert than argon. But the reason we use a noble gas on Earth is because it is hard to remove oxygen on Earth, while on the moon it is trivial to let the process run in a vacuum. However, this might have unwanted side effects, such as sublimation of the calcium chloride bath. Therefore, we have decided that we should keep pressure around the reaction.

There are several benefits to this process. First, it is in development. The company Metalysis is currently using the FFC Cambridge process, mainly to produce titanium, as the only real alternative - the Kroll process - is an expensive and slow batch process. Therefore, further technological advances may come within the next 10 years to make the FFC process more efficient. This process also requires only one product to be recycled - the calcium chloride - so recovery is quite simple. We can use an inert electrode, meaning that we produce more than enough oxygen gas for our colonists to breathe. Another benefit is that it produces far more oxygen than our colonists could possibly need to breathe - we can use much of the excess for energy storage and will vent the rest. Finally, it can run at a much lower temperature than most electrolysis processes (800-1000ºC, compared to e.g. the Hall-Heroult Process - for aluminium extraction on Earth - at 1400ºC).

The main downside to this process is that it must reduce all metals in the anorthite (i.e. the silicon and calcium, as well as the aluminium). This means that the process will take more energy than simply extracting the aluminium. However, these metals can also be usefully used for the lunar base, and later for the satellites; silicon for semiconductors and chips, and calcium for conductors. Also, chloride ions may be removed with the metallic sponge at the end of each batch and be lost from the system, and chlorine is non-renewable on the moon (only present as a trace). However, we can import more cheaply (because losses are small).

Maths

Anorthite has a M_r of 278.

Element components	Ca	Al	Si	O
Molar ratio	1	2	2	8
Relative molecular mass / g mol^{-1}	40	27	28	16
Mass ratio $= mol \times M_r$	40	54	56	128
Mass of element produced per tonne anorthite $= mass\ ratio \times \frac{1000}{278}$	144	194	201	460

We estimate $50\ m^3$ capacity for our relatively small reactor will be sufficient.

Density of $CaCl_2$ at bath temperatures, ρ(t) = ρm - k(t-tm)

t = 900ºC, ρm = 2.085 g cm^{-3}, k = 0.000422, tm = 775 ρ(900ºC) = $2.085 - 0.000422(900 - 775)$ = 2.03225 g cm^{-3} = 2030 kg m^{-3} (3sf)

$$2030\ kg\ m^{-3} \times 50m^3 = 101500\ kg\ CaCl_2$$

$$\frac{20300000\ g}{111\ g/mol} = 914400\ mol\ CaCl_2$$

The main constraint to this process is that at bath temperatures, calcium is only 3.09 mol% soluble. So, per tonne:

$$\frac{144000g}{40\ g/mol} = 3600\ mol\ Ca$$

$$914\ 400\ mol \times 3.09\,\% = 28\ 250\ mol$$

$\frac{28250}{3600} = 7.85$ batches, so 7.85 tonnes are processed per batch.

Element	Ca	Al	Si	O_2
Mass of element produced per tonne anorthite (kg) ($= mass\ ratio \times \frac{1000}{278}$)	144	194	201	460
Mass produced per batch (kg) ($= mass\ ratio \times \frac{7850}{278}$)	1130	1520	1580	3610

For 7.85 tonnes of anorthite, 9.81 tonnes anorthosite must be processed and separated, producing 1.96 tonnes of waste.

We need to produce around 3 tonnes of aluminium per day, during the lunar day, so we will do two batches per day.

There is 4m of molten salt in the reactor from the bottom.

The density of anorthite rock is 2730 kg/m^3. Assuming that the density of the powdered and sintered preform is 90% of its original density, the density of the preform is 2457 kg/m^3.

$$\frac{7850kg}{2457\ kg/m^3} = 3.2\ m^3$$

If we make the cathode 3.5m tall (so it doesn't touch any untapped molten aluminium on the bottom, which would be a less resistant pathway for the current, so the electrolysis would be much less efficient), then

$$\text{Cross-sectional area} = \frac{3.2\ m^3}{3.5\ m} = 0.91\ m^2$$

$$Radius = \sqrt{\frac{0.91}{\pi}} = 0.54m$$

Therefore, the preform has a diameter of 1.08m. This will be useful later on when designing the reactor.

Power requirements for the reactor

Enthalpy of formation of anorthite = $-100 \pm 1.5\ kJ/mol$

$$Ca_{(s)} + 2Al_{(s)} + 2Si_{(s)} + 4O_{2(g)} \implies CaAl_2Si_2O_{8(s)}$$

The reaction occurring here is the reverse of this, so the enthalpy of the reaction is +100.1 kJ/mol. However, this does not include the enthalpies of fusion for Ca and $2Al$, as they are in liquid form.

$$2 \times \triangle H°_{fus}(Al) = 2 \times 10.7 = 21.4\ kJ/mol$$

$$\triangle H°_{fus}(Ca) = 8.5\ kJ/mol$$

Both of these are going to a higher energy state, so this makes the reaction more endothermic. $\triangle H°_r = 100.1 + 21.4 + 8.5 = 130\ kJ/mol$ For 28 200 mol anorthite, this is 3 666 000 kJ.

Note: this does not take into account entropy change of dissociation. This is actually quite large, given how we are going from a solid crystal to its four constituent elements, one of which is a gas and two are liquids. However, we cannot calculate it because there is no data for the standard entropy of anorthite. Also, since entropy increases during dissociation, energy is released from the process, so the energy we need is less than we have assumed, so we can simply store or radiate the excess.

Alternative method

In the reaction, 16 electrons are transferred.

$$16 \times F = 16 \times 96\ 500 = 1\ 500\ 000\ C/mol\ anorthite$$

$$\frac{7\ 850\ 000\ g\ anorthite}{278\ g/mol} = 28\ 200\ mol\ anorthite$$

$$1\ 500\ 000\ C/mol \times 28\ 200\ mol = 42\ 300\ 000\ 000\ C$$

to process 7850 kg anorthite.

$$E = redox\ potential \times 42\ 300\ 000\ 000\ C$$

Standard Reduction Potentials:

$$Al^{3+} + 3e^- \implies Al$$ has potential -1.66 V

$$Ca^{2+} + 2e^- \implies Ca$$ has potential -2.87 V

We couldn't find standard reduction potentials for the other two reactions. The closest we could find were:

$$O_2 + 4H^+ + 4e^- \implies 2H_2O$$ has potential +1.23 V

$$Si + 4H^+ \implies SiH_4$$ has potential -0.14 V

Since redox potential assumes that the electrolyte is an aqueous solution, these potentials are not valid here - they would have different values to those for molten calcium chloride. We consulted with a chemist who said that this method is difficult to calculate and inaccurate, so we will be solely using the figures determined by the enthalpy of the reaction (= 2 820 000 kJ) for the energy required. However, we still account for the inefficiency of electrolysis.

Assuming that efficiency is around 40% (because current efficiency is usually about 90%, and also a little more than 50% is lost to the surrounding air):

$$\frac{3\ 666\ 000}{0.40} = 9\ 165\ 000\ kJ$$ for the batch.

Calcium boils at 1484 ºC, so the Ca-saturated salt must be heated around 400 K. The specific heat capacity of molten $CaCl_2$ is 102.5 J mol^{-1} K^{-1} (we think, but this is according to an unreliable source), so

$$102.5\ J\ mol^{-1}\ K^{-1} \times\ 183000\ mol\ CaCl_2\ \times 400\ K = 7500000\ kJ\ per\ batch.$$

Then we need to add the latent heat of boiling off the calcium. We can't find figures for the enthalpy of solution in $CaCl_{2(l)}$, so we'll just use the enthalpy of $Ca_{(l)} \implies Ca_{(s)}$, which is 153 kJ/mol. There is 1 mole of Ca produced per mole of anorthite, so there is 28200 mol Ca to boil off.

$$153\ kJ/mol \times 28200\ mol = 4\ 320\ 000\ kJ$$

So, in total, for each batch of anorthite we process, we need:

9 165 000 kJ to electrolyse the anorthite

7 500 000 kJ to heat the bath to calcium's boiling point

4 320 000 kJ to boil the calcium off

Giving a total of 21 000 000 kJ (3sf). This process occurs every twelve hours, but three are needed to let the bath cool down again for the next batch after distilling out the calcium. However, we can average it out by storing the excess energy. Therefore, average power requirement is:

$$\frac{21\ 000\ 000 kJ}{12 \times 3600} s = 486\ kW$$

Add 50 kW to be safe, as (for example) electrolysis might be less efficient than we calculated due to surface effects, to give a total power requirement of around 540 kW.

However, each batch, we need to cool down the bath again.

This means we need to dissipate 750 000 kJ every 12 hours.

$$\frac{7500000\ kJ}{(12 \times 3600)s} = 174\ kW$$

This heat will be injected into the heat exchanger array.

We can vent the calcium gas, because we don't need most of it, so we don't have to worry about dissipating the heat from condensing and freezing that.

Earlier in the project, when we were considering processing a single batch of anorthite each day, we thought we might be able to use the energy released by cooling the 1484ºC bath back to around 900ºC as an alternative source of energy during the lunar night (14 terran days). So we could run the reactor for the first part of the lunar day, then distill off the calcium later in the day, and then through the night the cooling bath would heat a water reservoir around the reactor, which we could use to supplement our main (solar) energy income. However, on balance this would make the reactor far more complex and would not supply anything like enough energy to sustain the whole base for more than a few hours. We also had to greatly increase the output of the reactor, and to do that we now run multiple batches per lunar day, rather than just one, so in the end we decided to simply dissipate the heat by injecting it into the heat radiator array.

Reactor design

The best material to build the reactor from is titanium, with heat-resistant brick lining.

- Titanium has a low density for a metal (4500 kg/m^3), so it is cheap to import the reactor parts.
- It melts at 1670º - this is almost 200º hotter than the necessary temperature to boil off the calcium, so it is safe if the electrolyte somehow gets through the brick.
- It is strong, so it is able to support the weight of all its contents.

The reactor will be cylindrical in shape.

It needs to have at least 50m^3 capacity to contain the electrolyte.

It needs to have a balance between not too high and thin, so that there isn't too much of a temperature gradient and there is enough room for the electrodes, and not too low and wide, to minimise heat loss to surface air, and surface effects which reduce efficiency of electrolysis.

On balance, we decided to give the reactor an internal diameter of 4m.

$$Circular\ area = \pi\frac{4}{2}^2 = 12.57m^2$$

$$Height = \frac{volume}{area} = \frac{50\ m^3}{2.57\ m^2} = 3.98\ m$$

So the calcium chloride will come up to a height of around 4m. There will actually be 4.5m internal height, so that there is excess space in case of accidents (e.g. if the oxygen pipe gets blocked, the pressure build-up will be reduced).

The bricks will form a layer 25cm thick, followed by a further 10cm of titanium. The titanium layer may sound thin but remember that titanium is a very strong metal.

$$Volume\ of\ a\ hollow\ cylinder = \pi(r_l^2 l_1 - r^2 l_2)$$

$$For\ bricks,\ volume = \pi(2.25^2 \times 5.0 - 2^2 \times 4.5) = 7.3m^3$$

$$Mass = volume \times density = 7.3m^3 \times 1915\ kg/m^3 = 14000\ kg\ (2sf)$$

$$For\ titanium,\ volume = \pi(2.35^2 \times 5.2 - 2.25^2 \times 5.0) = 3.4\ m^3$$

$$Mass = volume \times density = 3.4\ m^3 \times 4500\ kg/m^3 = 15000\ kg\ (2sf)$$

The electrodes need to be inert and have a high enough melting point that they do not melt at bath temperatures. For these reasons we will use platinum. The two electrodes will need to have a wide diameter so that they have low resistance, so that there is the maximum possible voltage across the electrolyte.

If we assume a 5cm diameter for the anode:

$$Volume = \pi r^2 l = \pi \times 0.025m^2 \times 3m = 0.00785m^3$$

$$Mass = volume \times density = 0.00785m^3 \times 21450\ kg/m^3 = 168.5\ kg\ Pt$$

$168.5\ kg\ Pt = \ \$5.36\ million$, which seems like an extremely high price, but it is acceptable compared to the necessary price of transporting all the necessary, massive equipment to the moon.

For the hole in the top:

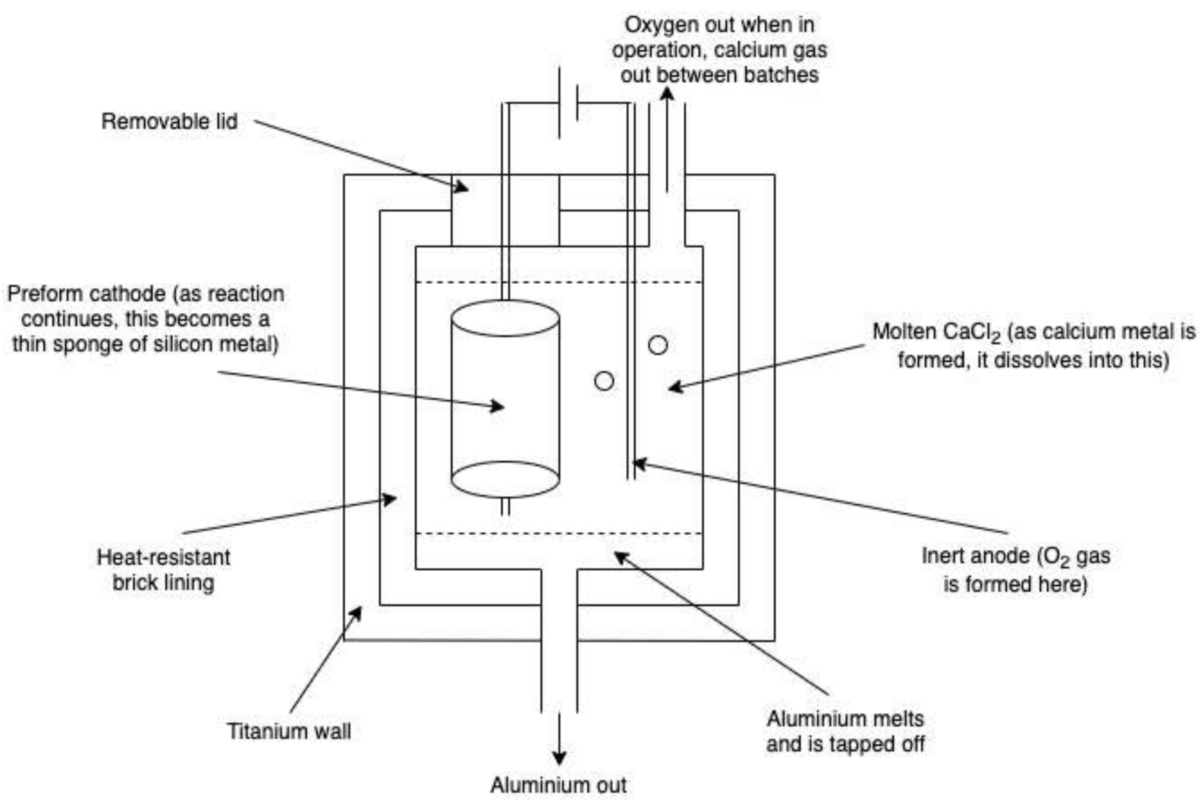
Diameter of preform = 1.08m, so to be safe diameter of hole = 1.15m.

$$Area = \frac{\pi d^2}{4} = 1.04m^2$$

$$Mass\ of\ brick = 1.04m^2 \times 0.25m \times 1915\ kg/m^3 = 500kg\ (2sf)$$

$$Mass\ of\ titanium = 1.04m^2 \times 0.10m \times 4500\ kg/m^3 = 470kg\ (2sf)$$

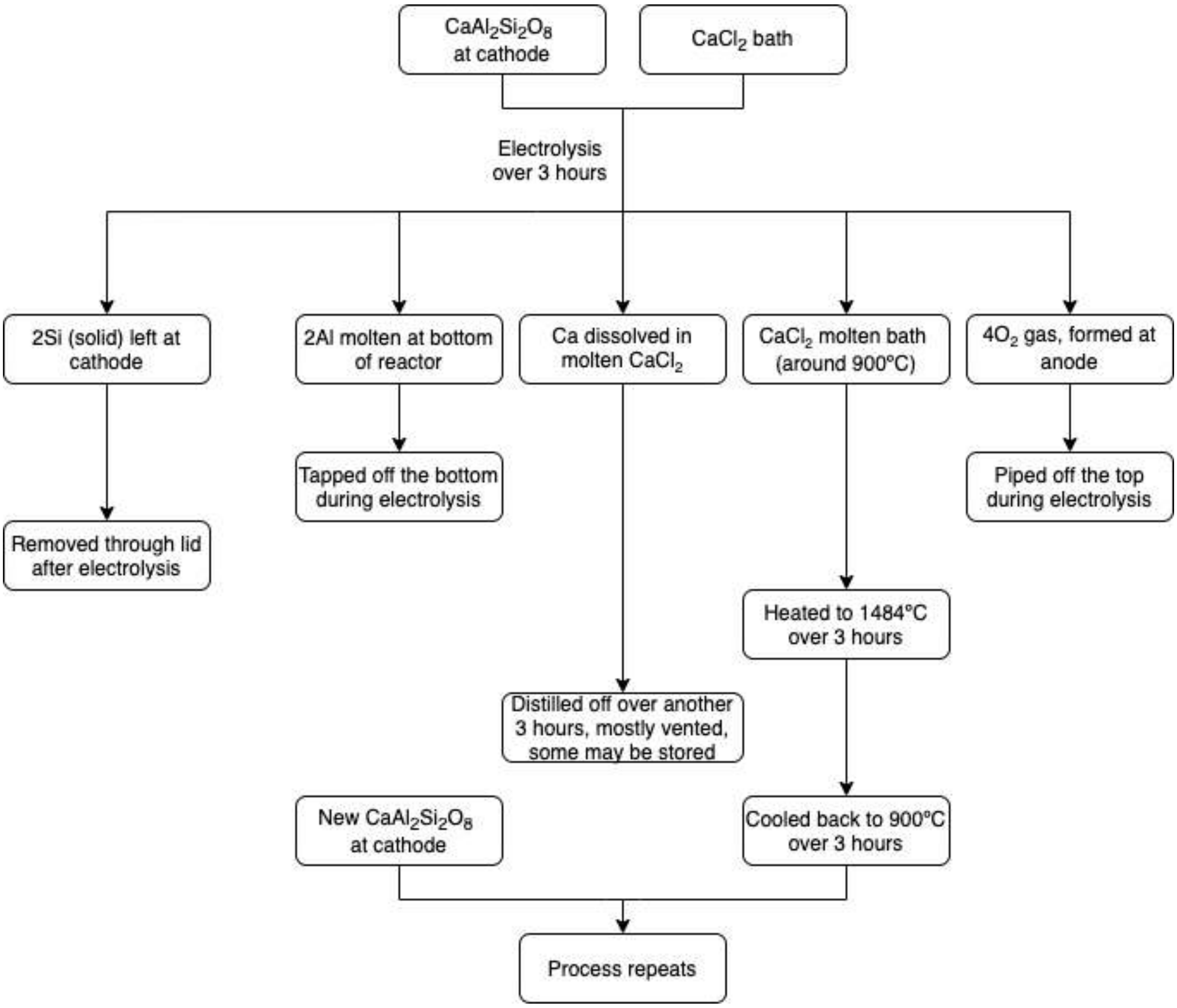
So, the lid will be around 1 tonne in mass.



Cross-section of the reactor. Not to scale.

CAD model of the reactor. Not to scale.

Final Process Diagram



Thermal control

In order to radiate heat energy from the base, including the 174 kW to condense the aluminium, as well as energy from other parts of the base, especially the energy storage system which will generate large amounts of heat when it is being charged. For this job, heat radiators will need to be used. These can be made out of aluminium, and can be laid out across the ground, in a more shaded position. If there is not enough naturally shaded area, the digger can be used to create some mounds of regolith to cast a shadow. This would not be too difficult, because the extreme latitude will mean that shadows are always long. These are not shown in the 3D model of the base. For the sake of calculations, we will assume that the power needing to be dissipated at maximum is 500kW.

The rate of black body radiation is described by Stefan-Boltzmann Law, which is:

$$Energy\ radiated = Stefan\text{-}Boltsman\ constant \times T$$

Because temperature is to the fourth power, increasing it will allow for a massive increase in energy radiated. A good running temperature for the heat radiators would be 400K, however it can rise above this safely, as the melting temperature for aluminium is 930K.

$$P = e\sigma A(T^4 - T_C^4)$$

$$Power\ radiated = emissivity \times Stefan\text{-}Boltzmann\ Constant \times Area \times (Temperature)^4$$

The vacuum of space will be assumed to have a temperature of 3K.

The emissivity of anodised aluminium = 0.77.

Anodised aluminium means that its surface has been partially oxidised, so that it is darker. This improves its emissivity without requiring black paint to be brought to the moon, so these radiators can be made on the moon. This is an industrial process that should be easy to perform.

$$A = \frac{500000}{0.77 \times 5.67 \times 10^{-8} \times (400^4 - 3^4)} = 450m^3$$

A setup with 450m^3 of aluminium panels will be able to radiate lots of power into space, as just a small further increase in temperature will significantly increase the rate of radiation of energy. The aluminium sheets can be very thin as depth does not increase their ability to radiate. At a thickness of 2mm, $2 \times 10^{-3} m \times 450\ m^2 = 0.9\ m^3$ of aluminium.

Density of aluminium = 2700 kg/m^3

$$0.9\ m^3 \times 2700\ kg/m^3 = 2.4\ tonnes\ of\ aluminium$$

needed for this setup.

Some of this can be brought from earth, and some can be manufactured in a first few, slower runs of the reactor. These radiators will also allow for temperature control of the entire base, as any excess heat can be dumped onto this array, especially during the lunar night when the reactor is not operating so the array will be cooler.

Mining on the Moon

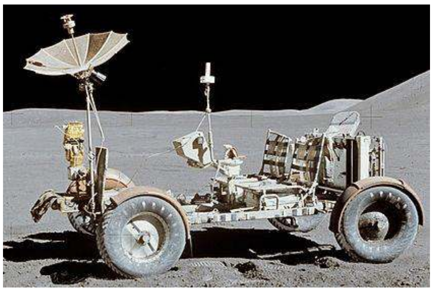
What will be mined?

Many things will be needed to be mined on the moon. Firstly, water ice which is found in abundance near the poles is necessary for providing the source of hydrogen and oxygen needed for fuel. This will be found about 20 miles away from the base in the crater which we are positioned near. We will also mine regolith, from which aluminium will be extracted, which can be done in the lunar highlands where the base has been built.

The mining equipment will be delivered to the moon fully manufactured, as many of the parts such as steel and rubber cannot be made easily on the moon, and because mining equipment cannot be made without anything having been mined yet.

Mining Vehicle

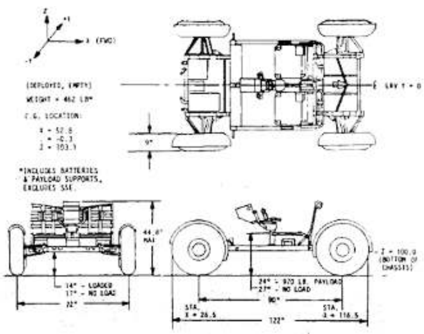
Example: Lunar Rover



Each rover weighs 210 kg (on Earth) without any payload. It could carry a maximum payload mass of 490 kg including two astronauts, equipment, and lunar samples. It had a top speed of 13 km/h.

Power was provided by two 36-volt silver-zinc potassium hydroxide non-rechargeable batteries

This rover was used in the last Apollo missions, so it is the best model of a Lunar Rover to be developed and successfully used by NASA.



Blueprints: An analysis

This rover looks very structurally weak, with a thin, simplistic chassis. This chassis would not be great at holding large weights, so it is not ideal for supporting large amounts of mined material.

We could improve the chassis by reinforcing it with more metal beams.

The wheels are also not ideal for mining, as they are very thin, therefore they do not have a large surface area. A larger surface area would be more useful for better mobility over rough ground, which is useful when mining.

Ideas taken from lunar rover

This rover, unlike a mining vehicle, is designed for exploration with its light-weight nature, giving it a relatively high-top speed. However, its load is very small, so for our context, we will need to improve on the design to increase the load. After analysing the blueprints, it is clear that the chassis and wheels are in need of improvement.

Our Vehicle

After looking at an example of a lunar rover, we have discovered that there are positives about that design, but we will also need to modify it for our purposes.

Mining Methods: Drill + Explosives

Explosives:

- Dynamite:
    - Dynamite is commonly used in mining. It only requires a deep hole to be drilled before placing the explosive underground. A stick of dynamite is 20cm long and has a diameter of 3.2cm.

To detonate dynamite, a combination of heat and pressure is required. Usually a fuse is lit.

Dynamite is made up of an absorbent material (like sawdust) soaked in nitro-glycerine:

- Nitro-glycerine is made from nitrating glycerol using nitric or sulphuric acid
- Glycerol can be found in various vegetables (soybean)
- If we can do both processes, then we can make dynamite in space.
- However, the growing of such vegetables will cost nitrates, which are never returned due dynamite being non-renewable. Therefore, we can import the dynamite directly, as it will be more economically viable to produce it on earth, than to waste resources of materials and time that are very valuable on the moon.

We cannot use a traditional fuse, because we can't light a flame in space due to the lack of oxygen. Therefore, we can use an electrical detonator fuse, in which the wire is surrounded by a layer of explosive material at the detonator end. A current sent through the wire would lead to electrical resistance building up, and the wire would then heat up. This heat would ignite the flammable material on the detonator end, which would set off the primer and in turn set off the explosives.

- C4:

- C4 has a slightly greater velocity than dynamite - dynamite has a detonation velocity of 7300 m/s, whereas C4 has a detonation velocity of 8040 m/s. This difference would not make an enormous change in terms of the volume of material broken up. However, the main difference between the two is to do with the sensitivity of the explosives. C4 is an insensitive explosive, meaning that it needs a high energy shock wave to detonate. This must be a physical shock wave, not electrical. This means that we wouldn't be able to use it on the moon as we are planning to use an electrical detonator fuse.

- TNT:
    - TNT is not dissimilar to dynamite, although there are some main differences. TNT, although it is more stable, is harder to detonate, and is not quite as powerful as dynamite.
- Having looked at dynamite, TNT and C4, we have decided that dynamite is the best option, as C4 is not viable due to its insensitive nature, and TNT is less powerful and more difficult to detonate.

From normal explosions, the power comes from the force of waves going through the air as well as through the ground, blasting material in a radius. Since there is no air on the moon, this could pose a problem. However, we thought that, if we replace the drilled earth and cover the explosives with rock, the explosive force could send vibrations through the solid material all around, and this could cause the damage and break up the rock.

Drill

In order for explosives to be planted onto the moon, a vertical downwards facing drill is required. This drill would dig deep into the ground, making a deep hole. At the bottom of this hole would be where the explosives are planted.

Now to determine the diameter of the drill, we must first work out how much dynamite is required to excavate 2 cubic meters of stone, as this is the maximum capacity of our storage compartment. We would be drilling 1m deep, because that means the explosion radius will be 1m above and below the bottom of the hole, excavating 2 cubic meters of stone.

Since the moon was originally a section of the Earth hundreds of millions of years ago, hence the Pacific Ocean, the density of stone on the Moon should be very similar to the density of stone on the Earth, so we will assume that they are similar. This gives a value of 2.196g/cm^3, however, we want this value in kg/m^3 so that we can find the volume in m^3.

Density of SiO2: Converting g/cm^3 to kg/m^3

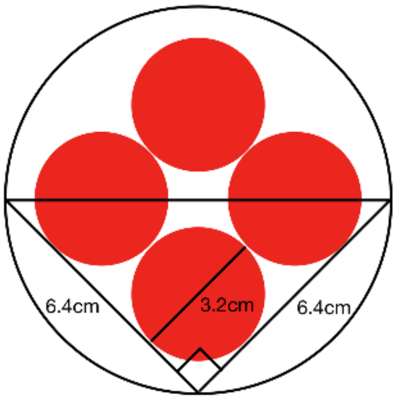
$$\rho = \frac{m}{v}$$

$$\rho = \frac{2.196\ g}{1\ cm^3}$$

$$\rho = \frac{2.196 \times 10^{-3}}{1 \times 10^{-6}}$$

$$\rho = 2196\ kg/m^3$$

Now since 1 stick of dynamite will break down 1000kg of SiO_2, and since the density of SiO_2 is 2196kg/m^3, the volume of 1 stick of dynamite will be:



$$v = \frac{m}{\rho}$$

$$v = \frac{1000\ kg}{2196\ kg/m^3}$$

$$v = 0.455\ m^3$$

This is the volume of rock that a single stick can excavate.

Now we must find out how much dynamite is required for 2m^3 of SiO_2, as this is the maximum capacity of our storage compartment:

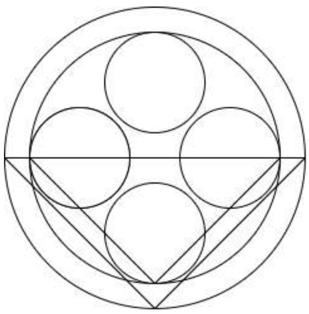
$$1\ dynamite\ sticks = 0.455\ m^3$$

$$4\ dynamite\ sticks \approx 2m^3$$

Now since one stick of dynamite has a diameter of 3.2cm, with four sticks of dynamite, we can find the diameter of the drill. We do this with the $diameter \times 2 = 6.4\ cm$ twice as shown in the diagram and the Pythagoras theorem $a^2 + b^2 = c^2$:

$$6.4^2 \times 2 = 81.92\ cm^2$$

$$\sqrt{81.92} = 9\ cm$$



This is not a fully accurate estimate, but this will allow a little extra space.

While you could save space in drilling holes by decreasing the diameter, as shown in this diagram, we have decided that we will keep our measurements. This is because any other diameter measurements are difficult to determine, as we have used the dynamite stick diameter to find the diameter of the drill hole.

The drill is powered by a high power and high torque electric motor similar to that of what is seen on construction sites in the form of bore hole drills. Hence the requirement for a dense battery to provide enough power to control all the core systems of the digger. The drill head will have a rated power of approx. 200 kW and spin at a max 105rpm.

The volume of each hole drilled = the volume of the drill

$$V = \pi r^2 h$$

$$V = \pi \times 0.09^2 \times 1.00$$

$$V = 0.025\ m^3$$

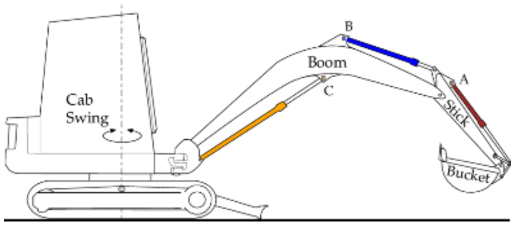
Excavator + Storage

To excavate using explosives, an excavator is required. In industrial mining, two separate vehicles are used, an excavator and a transportation truck. Once the charges are detonated, and the desired material is broken up and scattered, the excavator collects the material and places it in the storage unit of the truck.

Since resources will be scarce on the moon, making two separate vehicles for one task would be inefficient. This is because when making copies of our mining vehicle, we would have to make two separate electrical engines, batteries and chassis each time, wasting materials that could be used in satellite production. In order to save resources and time, we could combine the two vehicles into one. The vehicle would have an excavating arm, and a storage unit, therefore it could do the excavation process all by itself.

The Excavator

Excavators are powered by hydraulics, shown in the diagram to the right (A, B, C), which require fluid for their systems to function. Now since the moon has ice, we will be able to melt down the ice into water, which we will use as the fluid in the hydraulic system.



The compact excavator is the best example to examine, due to its small size, making it suitable for our space vehicle. I will base the excavating arm of our design on the excavating arm of the compact excavator.

Excavator force calculation example

If the smaller cylinder on the excavating arm has a radius 0.02m, it has an area of $0.02^2 \times \pi = 0.0013\ m^2$

The bigger cylinder has a radius 0.05m, so an area of $0.05^2 \times \pi = 0.0079\ m^2$

If a force of 500N is exerted by the crane:

$$P_1 = \frac{F_1}{A_1}$$

$$P_1 = \frac{500}{0.0013}$$

$$P_1 = 380\ 000\ Pa$$

$P_2 = 380\ 000\ Pa$ because pressure is the same at all points in a liquid

Therefore $F_2 = P_2 \times A_2$

$$F_2 = 380000 \times 0.0079 = 3000\ N$$

This calculation shows the power of hydraulics, as a force of 500N has been converted to a force of 3,000N. This demonstrates how we can use hydraulics to carry large amounts of moon material and place it into the storage area, and it will lead to an efficient mining operation.

The Storage Unit

The unit has to both keep the materials inside from floating out, and it has to keep the ice collected cool, to prevent it evaporating and being lost to space.

To do this, an automatic plate double door will be used. Once the unit is full, the door closes. To ensure the door properly closes, an electronic system that detects the height of the materials would need to be implemented. It would close the door once the materials are at a specific height.

To unload the materials, the vehicle would have a tipping mechanism, similar to that shown in the picture on the right. It would be powered by hydraulics, like the excavator, using water from the moon as its liquid.

Wheels

We are using continuous track for the wheels, because of the large surface area they provide. This will allow for great support of weight so that we can implement heavier parts, like a vertical drill, frontal excavator, storage compartment and heavy battery. The track also helps the vehicle cross rough terrain, which is useful when mining, due to the rough surface of mined ground. The tyre of the continuous track will be made of steel plates.

Powering the vehicle

Both the tipping mechanism of the storage system and the crane will be powered using hydraulics, as explained above, and the wheels will be powered using motors; we will be using 1 motor to power the wheels, as although more motors would generate more power, we are limited on how much energy we can produce.

The energy for the vehicle will be provided using lithium ion batteries, although we are also looking into aluminium ion batteries, as there is a source of aluminium on the moon, so we may start by using lithium ion and then convert to aluminium ion when we have mined enough using our vehicle.

Different parts of the vehicle require different amounts of energy:

- Drill
    - 200kW
- Excavating Arm + Continuous Tracks + Storage Compartment + Doors
    - 54kW
    - I got this figure from the specification for the 313 GC, a CAT excavator that I based the excavation arm and tracks on. The power usage should therefore be very similar.

The total power in use is 54kW, so in a day, assuming it is 12 hours a day, it will use:

$$54 \times 12 = 648\ kWh$$

Also, the 200kW drill will be in use for 15 minutes every day as an estimate, will use

$$200 \times 0.25 = 50\ kWh$$

So, the total is $648 + 50 = 698\ kWh$

In the lithium ion batteries, which we are using to store the energy, there is a 100-kWh battery capacity. Therefore the vehicle would need to be recharged 6 times a day, which would take well under 12 hours, so the vehicle could keep being used for longer than 12 hours if necessary, although mining is not the main focus of the project so it may not be worth it to use vast amounts of energy on it.

This is quite a small amount of energy compared to the other pieces of equipment on the base and will not pose much of a challenge.

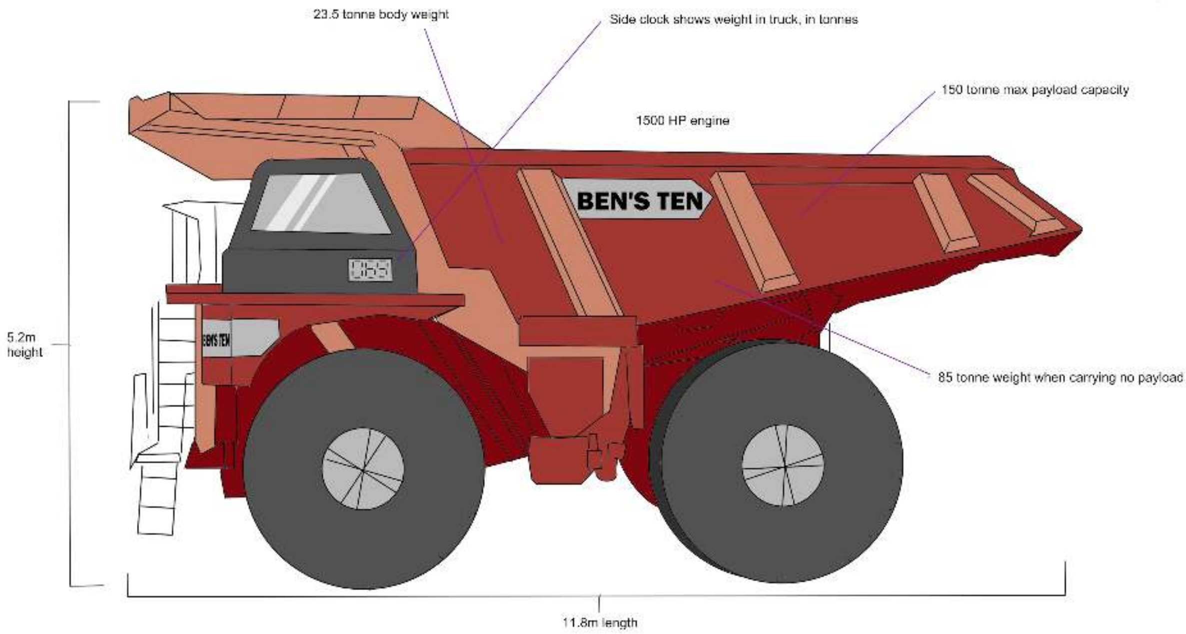
Automation

The vehicles would use radar technology and GPS to determine what obstacles are in front of them, and so that they can be set on a course. Search teams could be sent out to look for places where there are more abundant sources of metals and other materials, and then this could be set via GPS, or the vehicles could bring back samples and the metals could be extracted, to find where the best places to mine are. Once they are found, similar places would be set, and the mining operation could happen at a fairly rapid pace.

One problem with mining on the moon is that humans should be exposed to the moon's atmosphere for minimal amounts of time, as it is a harsh environment. Therefore, self-sufficient and automatic robotics would need to be put in place so that the mining machines could be run with little human interaction.

Because driverless technology is however limited, the vehicles will also be monitored, and initially driven by crews on the ground, who are connected by the radio communications link established by the base. This will have a latency of a few seconds; however, this will not be catastrophic.

Initial Design (Not Used)



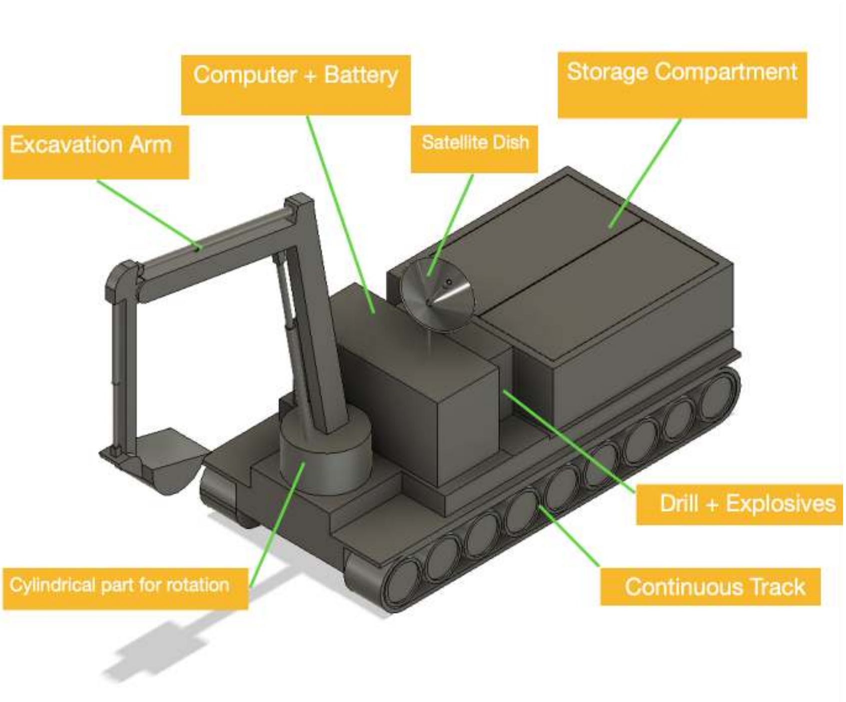
Above shows the first design that we came up with. We designed it to be similar to mining trucks on earth, and there are a number of problems with it. Firstly, it is far too big, and we would struggle to carry enough parts to carry this to the moon and construct it there. The size is also unnecessary, as we don't need to mine a large amount of materials. The wheels are also not suited to the environment of the moon, as they don't have a large surface area so it would not cope with the moon's harsh landscape. For this design there would also need to be a second vehicle, to dig the moon rock. It would also struggle to break through the rock with just an excavator.

Final Design

We looked at the problems of the first idea, along with all of the ideas above, and thinking about the limitations and possibilities for this mining vehicle, we used CAD to create a design. It shows how all of the pieces will fit together, and what it will look like when it is built. The vehicle is 10m long, 5m wide and 4m tall (not including arm and satellite dish). Considering the arm, the vehicle is 7m tall.

Using a GPS system to map out a route, the vehicle will travel to a designated area rich in useful resources. The satellite dish establishes a connection to the team operating on Earth, so that its route can be observed, and changes can be made if there are any problems with the route.

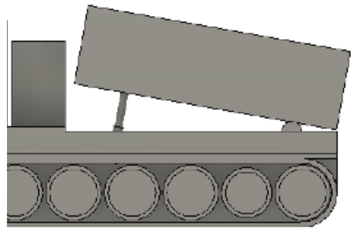
Once the vehicle travels to the source of the desired material, the drill will drill a 1m deep hole, where dynamite is then dropped by an automatic dropping mechanism found at the bottom of the vehicle. The vehicle will distance itself 20 meters from the hole, to ensure that the vehicle is not damaged by any flying debris. The dynamite is attached to an electrical detonator fuse, so it is detonated by the vehicle, by sending a current through it.



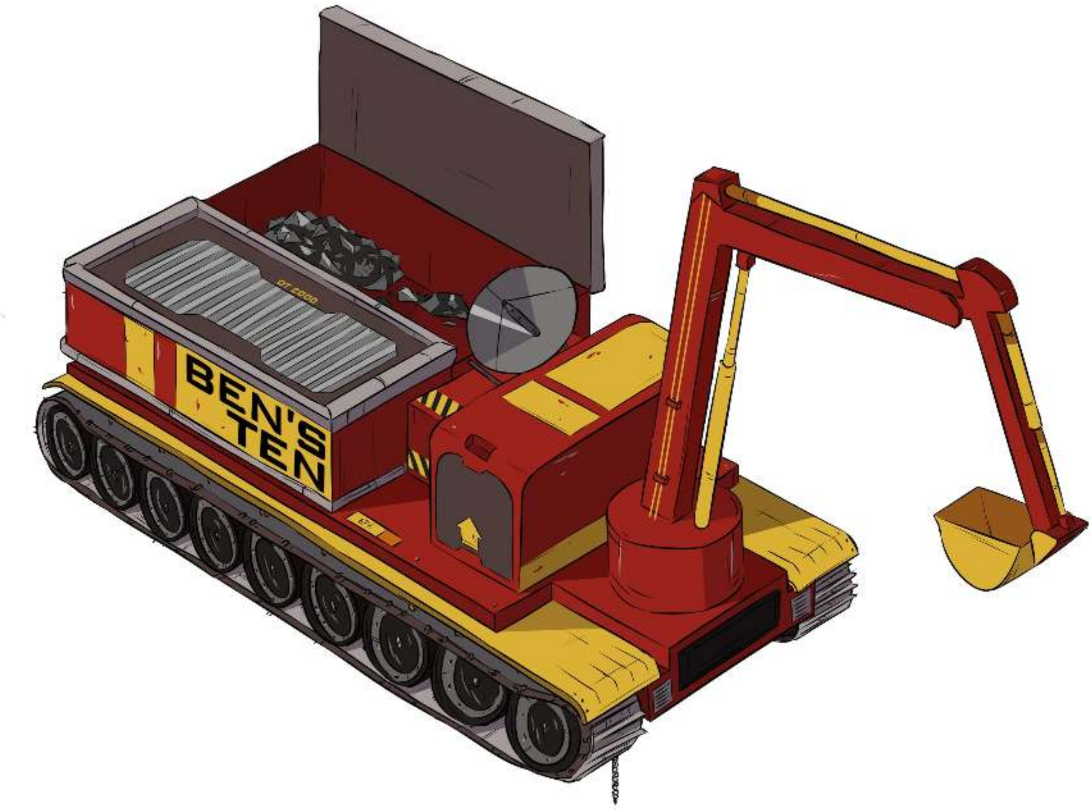
CAD design of Excavator

The excavation arm, as stated earlier, is based on the compact excavator, hence the triple hydraulic system seen below. The arm will be automatically controlled by a computer system inside the large box compartment. It will be programmed specifically to excavate material in front of/below it, which will be detected by a sensor that informs the arm of large masses of material to excavate. The arm is also attached to a cylindrical mechanism, so that it can turn 180° back to the storage compartment where it will release the moon material.

Before the arm turns around, the doors on the compartment facing upwards will automatically open up, so that the arm does not collide with the door as it opens. The doors will stay open at 90° until the storage compartment reaches a maximum capacity, which is detected by more sensors on the inside of the compartment. The doors close, and the vehicle travels back to base, where it must unload its contents. When it stops, the automatic doors at the back will automatically open. Then, the hydraulic mechanism on the bottom of the storage compartment will activate, and the material will fall out of the compartment due to the angle of the compartment.



Final Drawing



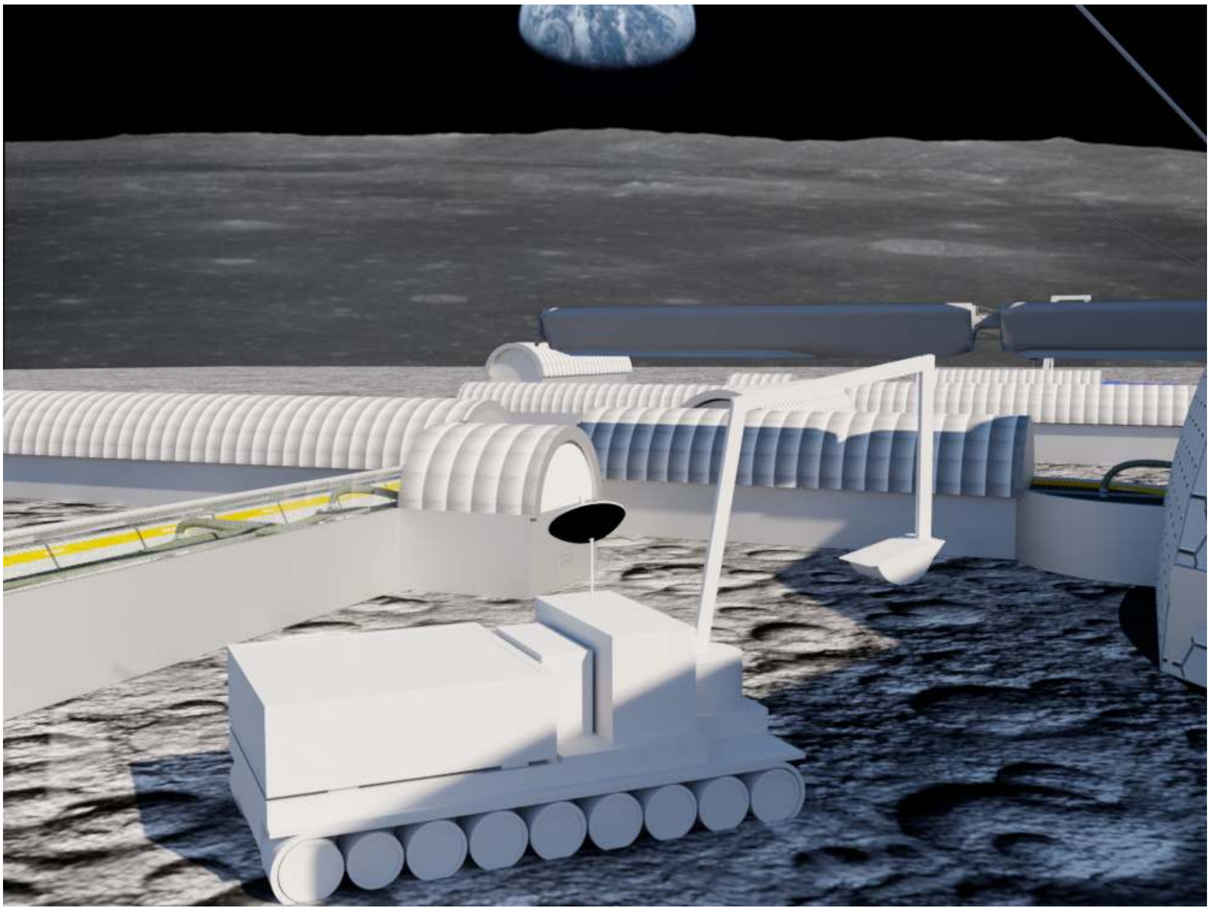
Hand-Drawn Excavator

Above is a final drawing of our mining vehicle, showing what it would look like when constructed. It shows the finer details of the design, and how it would be painted. We have illustrated the metal protective cover and how the steel sheets of the wheels would look, as well as a panel to show how much of the payload has been filled up.

Crane attachment

Instead of making a second vehicle for a crane, we have decided to make an attachment to the body of the mining vehicle. This would, much like the choice to combine the excavator and storage compartment, save resources. If demand for vehicles was too high however, a second vehicle could be sent.

The crane has a hydraulic mechanism at the bottom, and at the top can slide back and forth. The crane's hook is also extendable, as it is connected by a metal wire. The crane is to be used for construction of our moon base. It can be attached/detached at the base of the cylindrical turning part.



Above shows what the vehicle would look like next to the lunar base. It shows the scale of the vehicle when compared to the base

Safety Within the Base

With 40 inhabitants on board the station, we will need to ensure that precautions are put in place to ensure that no harm can come to any of the inhabitants. This will involve the use of safety features such as Airlocks throughout the entire station. These will close very rapidly automatically once depressurisation happens in any module and will hopefully save the lives of many of the staff. They will also close automatically in order to prevent a fire.

Airlocks

Airlocks will be slotted into our modular space base using a part that is specifically designed to slot into the connecting slot of each module. This will allow the use of the internal electrical system that is universal for the side of each module to be used, allowing for easy installation and diagnostics in the case of failure.

Of course, for an airlock to serve its purpose of protecting those on the inside from rapid depressurisation we will need to implement two of these airlocks within an exit to the outside to make them effective. These emergency exits will need to also have enough Extravehicular Mobility Unit gear to sufficiently evacuate the nominal amount of people within an area. In case of an emergency, a rocket will be left standing by to evacuate people. It is however very unlikely that the whole base would be destroyed, so people can walk around to parts of the base which are still intact.

Pressure Calculations

The pressure on the moon is incredibly small - close to vacuum. In the following calculation we will work out how much force will be applied to an exterior airlock door.

$$let\ pressure\ on\ moon, P_m = 0.3 \times 10^{-10}$$

$$let\ area\ of\ airlock, A_{AL} = 2\pi 1.2^2 = 9.0477868423$$

$$P = \frac{F}{A}\ hence\ F = PA$$

$$P_m A_{AL} = 9.047 \times 0.3 \times 10^{-10} \approx 2.71e - 10N$$

Now lets calculate the pressure from the interior of the station

$$let\ pressure\ on\ moon, P_m = 101.3 \times 10^3$$

$$let\ area\ of\ airlock, A_{AL} = 2\pi 1.2^2 = 9.0477868423$$

$$P = \frac{F}{A}\ hence\ F = PA$$

$$P_m A_{AL} = 101.3 \times 10^3 \times 9.047 \approx 917000N$$

As you can see from the above, the difference in pressure and force between the exterior and interior of the airlock is a great deal which could lead to a potentially catastrophic disaster if proper safety features were not put in place in the airlock. The equipment that we would fit the space station out with would also be highly susceptible to pressure changes like this and gives even more reason to implement proper electrical systems, which fail safe in case of a power loss or software malfunction.

Airlock Contingency Features

Safety features will need to be implemented into the airlocks construction to ensure that operation is safe for our inhabitants. An example of a threat we need to alleviate is the possibility of a pressurisation leakage. We will use pressure seals between the polycarbonate panels to ensure that this does not happen and implement a dead lock system that checks before operation that the pressure levels are at normal levels. Airlocks will also be fitted with other sensors that will automatically send out a signal on our internal IoT network on board the station to inform inhabitants that an alert needs attention.

Polycarbonate and ABS Usage throughout the Space Station

A safe and reliable choice of material needs to be made to ensure that our station is fit for emergency procedures such as a fire.

Polycarbonate is used currently on the ISS station and in the aviation industry. It is ideal for use cases where there is the possibility of thermal expansion. If for whatever reason the station doors were susceptible to fire/another source of extreme heat. Polycarbonate performs excellently under these conditions and would be able to remain intact. With a specific heat capacity (c) of **1.2–1.3 kJ/(kg·K).**

ABS, **Acrylonitrile butadiene styrene**, would due to its ease of manufacturability using vacuum forming and strength. It is also very lightweight, making it ideal for transport across the station.

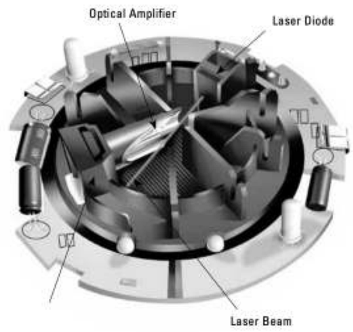
Aluminium is lightweight and there are many different alloy types such as 2219-T6 aluminum which is used on the International Space Station. We are extracting our Aluminium from Regolith which is explained in more detail in the electrolysis section. For this reason, it will be the main design material.

Fire Prevention Systems

Fires on the base station pose a real threat to inhabitants within the space station. Due to the complex ventilations systems that will need to be implemented to regulate pressure and oxygen levels smoke could quickly pass across the station very quickly posing the issue of carbon monoxide poisoning and rapid loss of visibility.

All artifacts that will be placed on the space station will need to be tested according to the highest safety standards and fire testing methods to ensure they are safe for use on the base. There will of course be exceptions for certain items that are critical to the research / running of the station, but these will be tightly regulated and checked for risks often. NASA currently tests under the MISSE scheme and we would use a similar approach.

Smoke Detectors would be placed throughout ventilation ducks to detect any foreign particles that should not be present. Unlike standard smoke detectors that work off a slightly unreliable light-based system, we will use laser detection modules that are estimated to be 100x more accurate than a standard detector.



Fires also behave differently in space due to the convection within a space station. This will cause the fire to slowly absorb oxygen from the surrounding area and gradually move. This makes them dangerous as they can last longer and cause greater damage.

Fire Spread Calculation

It would be useful to know how quickly a fire will spread along a corridor.

$$let\ speed\ of\ fire\ (peak), v_p = 0.03\ m\ s^{-1}$$

$$let\ length\ of\ corridor, x\ =\ 10\ m$$

$$v\ =\ \frac{\Delta x}{\Delta t}$$

$$\Delta t = \frac{\Delta x}{v}$$

$$\Delta t = \frac{10}{0.03} \approx 333s$$

A fire would take approximately 5 and a half minutes to spread along a stretch of corridor according to this calculation. However, there are several flaws with following this style of calculation as it does not take into account the flammability of different materials or the corridor conditions. Although, it does still give an indication at the kind of speed a fire would spread.

Disaster Detection Systems

Life on the moon, like Earth, will have unexpected disasters. Although most of the natural disasters which occur on Earth which also occur on the moon such as Earthquakes aka Moonquakes have a much weaker strength. The chance of a collision from a foreign object should also be considered for the construction of the base. There are lots of different types of ways a Moonquake could occur from a meteorite hitting the surface causing a ripple effect or a deep earthquake that occurs 700km below the surface.

To help prepare the crew for such an event. The base will be constructed with no real fixed fitting to the ground meaning that if an event did occur, parts of the station would not be damaged by the distortion of the moon surface. Pipes and ducting will also be constructed using flexible materials to prevent connections being broken. Cabling will also need to be constructed out of an alternative to PVC such as silicon outer casing as PVC is highly flammable.

Ducts will be fitted with sensors every 3m in each module including seismometers, the laser smoke detectors pictured above, CO_2 sensors, pressure and temperature. These will be wired on a dedicated network to segregate the safety of the inmates staying on the station. Furthermore, fuel is stored in tanks a distance from the station, so in the case of an explosion, there will not be devastating effects.

Electrical Design

Sensors - Pressure

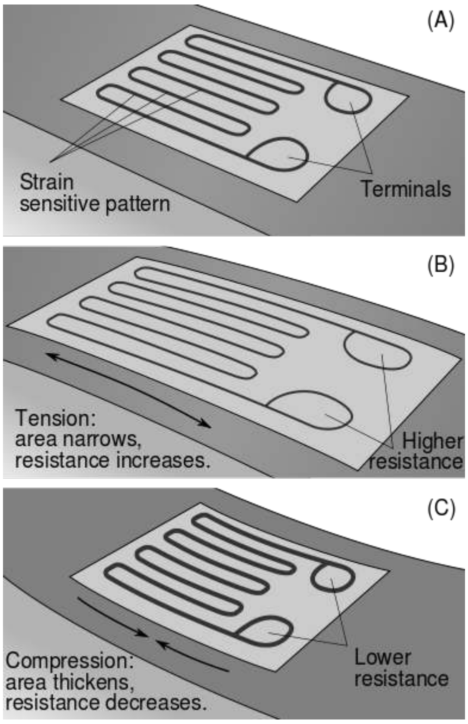
Humans are adapted to the surface pressure on Earth which is 1 ATM or 1.013 bars. The air pressure on the surface of the moon is almost nothing at 3 x 10-15 bars

One option is to have a pure oxygen environment; however, this is much less safe for more than one reason. The rate at which we inhale oxygen would exceed our blood's ability to transport it away and around the body. This excess inhaled oxygen then binds to lung proteins and can start attacking the central nervous system which can eventually be fatal. This only occurs over a long exposure and if the pressure is too high, however is a potential issue. Another weakness of a pure oxygen environment, as discovered by NASA, in 1967 with Apollo 1, was just how flammable the atmosphere became. A fire which started from an electric fault spread around the entire rocket in a matter of seconds due to the pure oxygen environment. This shows that pure oxygen environments are hazardous in high concentrations and pressures.

In order to mitigate these problems, compressed liquid nitrogen will be brought to the moon from earth. This means that there will be a simulated earth-like environment, which is safest. Furthermore, this is also the best environment to grow plants for food production.

The key issue then is sustaining this atmosphere inside the moon base and ensuring there are no leaks in the walls of the moon base. The image to the right shows the basic principle of the walls of the moon base. There are three layers to the walls of the moon base, and this is further detailed in the base overview. This creates two airtight layers, and a medium pressure will be used to fill the inner layer. This means that if either airtight layer failed, it would be detected but not life threatening. This detection will be performed by pressure sensors which will be placed at regular intervals and will be connected to the main computer system. This provides safety, as there is a high level of redundancy.

The main types of pressure sensors use a strain gauge. This is most often as thin slip of foil (2-10 mm squared) which is attached to some metal or polysilicon film. A constant current is passed through the foil and the voltage is measured. The film and foil acts like a diaphragm in a way that, as pressure in the room changes, it contracts. The image to the right shows a natural strain gauge at 1 ATM (A). When the diaphragm contracts, the film is stretched so there is greater resistance in the foil and a lower voltage (B). When the diaphragm is further relaxed by lower pressure, the resistance is decreased, and a larger voltage is read.



Resistance can be simply calculated using the equation V = IR or, for a more accurate result, the circuit can be connected to a Wheatstone bridge. The variety of pressures a pressure sensor can work at is defined by its gauge factor. This defines how much the strain on the foil will affect the electrical resistance in the foil circuit.

The pressure in the cavity will be 0.1 ATM so, if pressure sensors detect a larger pressure, we know there is a leak from the inside of the base to the cavity and if the detected pressure is lower than 0.1 ATM, we know there is a leak to the outside. Alarms can then be sounded, and staff can respond by installing temporary patches over where the leak has been found, while wearing space suits for safety. If pressure change is rapid, air locks can seal, and doors can shut.

An accurate pressure sensor which can detect changes from 0-1000 mbars costs between £200 and £600.

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