STONKS

Space Transport Of NuKlear Substances

Blott Matthews Challenge

Contents

Introduction

Possibly the greatest achievement in mankind's history was the first time man walked on the moon in July 1969. The Apollo program, of which Apollo 11 was just one part, has led to technological innovation and development never thought possible less than a century ago. So, in line with the 50th anniversary of Neil Armstrong walking on the moon for the first time and NASA's new pledge to return to the moon by 2024, we propose a new idea for a human spaceflight program which would have the ultimate goal of mining the moon for Helium-3 for use back on Earth.

Space Transport Of NuKlear Substances, or STONKS for short, would be an international space program aiming to replace fossil fuels, an already outdated and dwindling source of energy, with Helium-3, which can be sold to private companies to be used for nuclear fusion. We will also set up a permanent lunar base capable of sustaining at least 20 crew at once as well as a transport system between Earth and the Moon which can reduce fuel usage.

Our plans for mining Helium-3 on the moon are nothing new; multiple papers have been written on the subject, and in as far back as 1988 NASA held a conference on the matter. Utilising the moon for its Helium is also more commercially viable than for other energy sources, such as solar. The vast costs involved in surrounding the moon in photovoltaic cells would be completely unnecessary when mining the lunar surface for Helium-3 is much simpler and more elegant.

Nuclear fusion will undoubtedly revolutionise our planet, and possibly guarantee the future of our species by delivering clean energy to the masses. Although the technology may not be there yet, sustained investment into fusion shows that it won't be long until Helium-3 will be one of the most desired elements on the planet: our plan is simply to capitalise from this demand.

Section 1

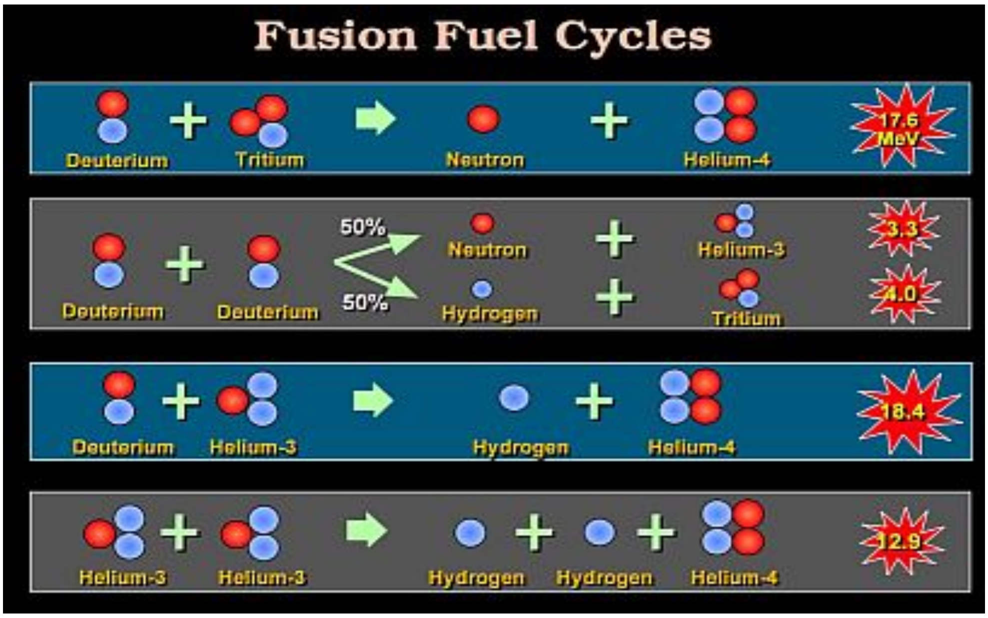
Commercial Activity

1.1. Nuclear Fusion

1.1.1. What is nuclear fusion?

Nuclear fusion is a reaction in which two or more atomic nuclei are combined to form one or more different nuclei and subatomic particles (neutrons or protons), therefore releasing energy.

Deuterium-deuterium nuclear fusion will be used, which combines a pair of deuterium atoms to form helium-3 and a neutron.



1.1.2. Advantages of fusion

- Abundant energy: Fusing atoms together in a controlled way releases nearly four million times more energy than a chemical reaction such as the burning of coal, oil or gas and four times as much as nuclear fission reactions (at equal mass). Fusion therefore has the potential to provide the kind of baseload energy needed to provide electricity to our cities and our industries.

- Sustainability: Fusion fuels are widely available on the moon and the supply should last for hundreds of years.

- No CO_2: Fusion doesn't emit harmful toxins like carbon dioxide or other greenhouse gases into the atmosphere. Its major by-product is helium-4: an inert, non-toxic gas.

- No long-lived radioactive waste: Nuclear fusion reactors produce no high activity, long-lived nuclear waste. The activation of components in a fusion reactor is low enough for the materials to be recycled or reused within 100 years.

- No risk of proliferation: Fusion doesn't employ fissile materials like uranium and plutonium. There are no enriched materials in a fusion reactor like ITER that could be exploited to make nuclear weapons.

- No risk of meltdown: A Fukushima-type nuclear accident is not possible in a fusion device. It is difficult to reach and maintain the precise conditions necessary for fusion—if any disturbance occurs, the plasma cools within seconds and the reaction stops. The quantity of fuel present in the vessel at any one time is only enough for a few seconds of fusion and there is no risk of a chain reaction.

- Cost: The power output of the kind of fusion reactor that is envisaged for the second half of this century will be similar to that of a fission reactor, (i.e., between one and 1.7 gigawatts). The average cost per kilowatt of electricity is also expected to be similar to that of fusion: slightly more expensive at the beginning, when the technology is new, and less expensive as economies of scale bring the costs down.

1.1.3. Types of nuclear fusion

Several types of nuclear fusion are theorised at the moment:

- Thermonuclear fusion: When matter is heated to a high degree (similar to the plasma state of matter), fusion may take place as a result of particle collisions with high kinetic energy. However, harnessing fusion energy in a controlled fashion by this process has not yet been achieved, although the energy in stars is obtained through this process.
- Inertial confinement fusion: In this process the reaction is carried out by heating and simultaneously compressing a fuel target.
- Beam–beam or beam–target fusion: In this method the fusion reaction takes place by accelerating one or both the nuclei. However, the fusion cross-sections are several orders of magnitude lower than that of Coulomb interaction cross-sections. Therefore, a major fraction of the energy is dissipated out in Bremsstrahlung radiation or ionization of the target's atoms.
- Inertial electrostatic confinement: This method employs a device with which an electric field is used to heat and confine the nuclei. We will primarily focus on this method because it is the most realistic and developed approach.

1.1.4. Solutions to contemporary issues

Net energy gain (NEG) is still negative. The highest ratio of energy efficiency was achieved by the Oxfordshire based JET tokamak in 1997 (two-thirds of the break-even point). However, a leap forward was made in 2017 by the Chinese EAST tokamak test reactor achieving a stable 101.2-second steady-state high confinement plasma, setting a world record in long-pulse H-mode operation, it was therefore estimated that sustainable nuclear fusion can be achieved within 10 years.

1.1.5 Helium-3

Helium-3, an isotope of helium, is an inert, nontoxic and nonradioactive gas. Helium is in fact present in the Earth's atmosphere however this is only in minute quantities (less than 0.0005 percent of atmosphere) as the helium isn't gravitationally bound to the Earth. Furthermore, only 0.000137 percent of this helium is actually helium-3. By far the most common source of helium-3 at present is the United States nuclear weapons program, of which it is a by-product. However, not only does detonating nuclear weapons have obvious environmental, political and economic issues, the supply of Helium-3 using this method is negligible compared to its required quantities in a fusion reactor.

1.1.6 Other commercial uses of Helium-3

- Medical application: Following inhalation, gas mixtures containing the hyperpolarized helium-3 gas can be imaged with an MRI scanner to produce anatomical and functional images of lung ventilation. This technique is also able to produce images of the airway tree, locate unventilated defects, measure the alveolar oxygen partial pressure, and measure the ventilation/perfusion ratio. This technique may be critical for the diagnosis and treatment management of chronic respiratory diseases such as chronic obstructive pulmonary disease (COPD), emphysema, cystic fibrosis, and asthma.
- Cryogenics: A helium-3 refrigerator uses helium-3 to achieve temperatures of 0.2 to 0.3 Kelvin. A dilution refrigerator uses a mixture of helium-3 and helium-4 to reach cryogenic temperatures as low as a few thousandths of a Kelvin.
- Helium-3 also absorbs neutrons. This property has resulted in its widespread use for neutron detection. Neutron detection has applications in security, industry, and science. For example, the US federal government uses radiation portal monitors and other neutron detectors at borders to prevent the smuggling of nuclear and radiological material. The oil and gas industry uses neutron detectors for well logging.

1.2. Mining

1.2.1. Composition of Lunar surface

Helium-3 is still relatively rare, even on the Lunar surface. In fact, it's estimated to account for 1.4-15 ppb in sunlit areas and up to 50 ppb in shadowed areas of the lunar regolith. However, Helium-3 will not be the only material that we will seek to mine as most, if not all, of the life supporting elements are in great abundance on the Lunar surface. Their respective abundances are detailed in the table below.

Element	Low-Ti Mare Soils	High-Ti Mare Soils	Highland Soils	KREEP Soils
O	60.26	60.30	60.82	60.47
Si	17.30	15.86	16.31	17.35
Al	5.56	5.70	10.66	6.48
Mg	5.53	5.70	3.84	5.39
Ca	4.44	4.60	5.92	4.43
Fe	5.85	5.29	1.90	4.47
Ti	0.66	2.01	0.17	0.62
Na	0.26	0.31	0.29	0.44
K	0.06	0.05	0.05	0.19
Mn	0.08	0.07	0.03	0.06

[a]The lunar regolith composition assumed for these simulations is that of Low-Ti Mare soils, and the variation across soil types is the percent of relative abundance by number. Averages taken from *Wurz et al.* [2007]; original data from *Papike et al.* [1982].

1.2.2. Mineable Area

To mine the moon, one must be able to determine which areas of the moon are mineable, and are not full of craters, ridges, rocks, and other obstructions. One way to do this is to take a map of an area of the moon and mark out all of the unmineable areas and then determine which areas are large enough to be mined. This trade study, dependent on the minimum feasible mine size and the capability of the miner to avoid objects, was done for the lunar mare: Mare Tranquillitatis by Cameron and Kulcinski.

This study looked at 27 high-resolution photographs, 2-meter resolution, taken during previous missions to the moon. These photographs spanned an area of about 100 square kilometres. Before mapping out these photos, Cameron and Kulcinski had to determine which features of the lunar surface are mineable. The main part of this research deals with craters and their associated ejecta halos, which may contain rocks that would be unable to be mined by our lunar miner.

Cameron and Kulcinski reported that the average depth to diameter ratio of fresh craters was 0.25 and that the average depth of the regolith away from craters larger than 12 meters in diameter was at least 3 meters. So, craters with a diameter of less than 12 meters should not have reached bedrock and therefore will not have rocky ejecta halos. Since most of the craters on the lunar surface are less than 12 meters in diameter, this leaves a good portion of the surface to be mined.

The distinction between fresh and old craters is quite substantial, since very old craters only cause slight undulations on the lunar surface and should have been exposed to enough solar wind volatiles to cover the upper 3 meters with regolith. But Cameron and Kulcinski took a very conservative approach with these types of craters since it is very difficult to distinguish between the old craters and the new craters based only on photographs, thus even the old craters were determined to be unmineable.

The next step in this paper was to determine how large the ejecta halos extended out from the crater rim. This could not be done only from the photographs since only rocks larger than 2 meters in diameter could be seen. For this, the advice of Harrison H. Schmitt was taken. Schmitt stated that if no 2-meter blocks of rock are found, the unmineable area is a circle centred on the crater with the diameter equal to the crater diameter. If blocks are only visible inside the crater, the unmineable area is a circle with a diameter twice that of the crater and if the blocks are outside of the crater, the unmineable area is a circle with a diameter three times that of the crater.

The analysis showed that the area covered by craters and ejecta halo ranged from 8.5% to 50.4% depending on the photograph, with the average being 16.4%. However, this does not mean that it is feasible to mine 83.6% of the area. It is not practical to mine very small areas since the effort to mine them would not be worth the relatively small number of volatiles recovered. So, Cameron and Kulcinski did a trade study on one of the photographs that covered approximately 27 square kilometres located east of the Apollo II landing site. They looked at two different minimum mine sizes: a 300-meter and a 400-meter square, shown in Figure 10-1. For the 400-meter square, only 15% of the area was mineable, while 22% of the area was mineable with the 300-meter square.

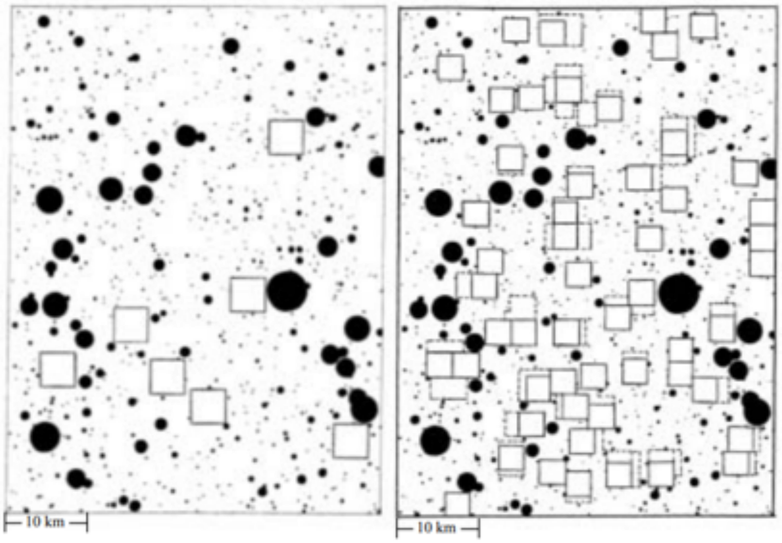


Figure 10-1. Mineable area with 12 meter and larger diameter craters with 400 meter squares (left) and 300 meter squares with extensions (right)[1]

They also looked at the mining possibilities if it was assumed that the miner would be capable of handling regolith with small areas of rocks, which will be within the capabilities of our miner. With this, they assumed that the craters of diameters between 12 and 24 meters could also be mined. They found that 22% of the area would now be mineable with 400-meter squares, while 56% of the area is now mineable with 300-meter squares, as shown in Figure 10-2.

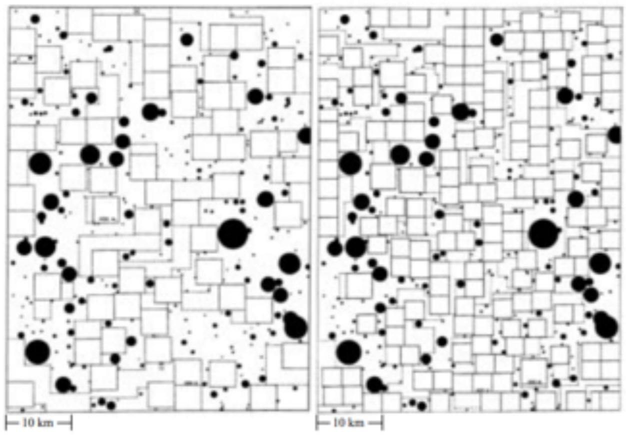


Figure 10-2. Mineable area with 24 meter and larger diameter craters with 400 meter squares (left) and 300 meter squares with extensions (right)[1]

Similar charts were prepared for three additional areas and it was found that for the Apollo II area, anywhere from 28 to 57% of the area could be mined. These calculations are done with a ten percent error due to the plotting on these charts by hand and therefore the inability to exactly replicate the results.

This is highly relevant information when calculating the total amount of helium-3 that can be mined. It is estimated that there are 1,100,000 tonnes of helium-3 available to mine from the lunar surface but this figure, assuming that the regolith is evenly distributed, falls to 560,000 tonnes (this also assumes even distribution of craters once the unmineable areas are discounted).

1.2.3. Design of miner

Three designs of lunar He-3 miners have been developed, the Mark-I, II and III. In general, these designs employed mature terrestrial mining technologies like bucket-wheel excavators, and conveyor belts, but also involved key design aspects required for large scale mining operations in the lower gravitational field strength of the lunar environment.

The first miner rendition, the M-1, was completed in 1988 and laid the conceptual groundwork for the much more detailed M-2 design. A conceptual illustration of the M-1 is provided in Figure 2. The last iteration of the M-2 design was completed in

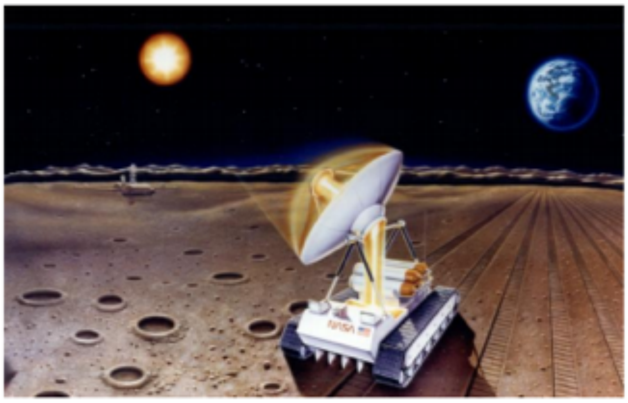


Figure 2. Illustration of the Mark-I Helium-3 lunar miner in operation

Figure 3. Illustration of the Mark-II Helium-3 Lunar Miner in operation

1994. The miner design involved more component level design work and also further discussed the requirements of the support infrastructure for the He-3 mining activity. An illustration of the M-2 can be seen in Figure 3. The M-3 is the most in depth of the three designs and was completed in 2006. It was essentially a detailed optimization of the M-2 for reduced mass and size in exchange for 75% more electrical power usage. A computer aided design model of the M-3 is shown in Figure 5.

Each miner was designed to return 33 kg of 3He to Earth each year after mining over a 1 km^2 area, assuming a 10 ppb He-3 grade (by mass). It has long been thought that the He-3 grade in the undisturbed Maria regolith should actually be closer to 20 ppb and with this in mind, the collection would be closer to 66 kg/yr as seen in Table 3. The mining process for the M-3 is largely the same as that of the previous M-2. The process starts with a bucket-wheel excavator (BWE) that continuously drops regolith onto a conveyer that brings regolith

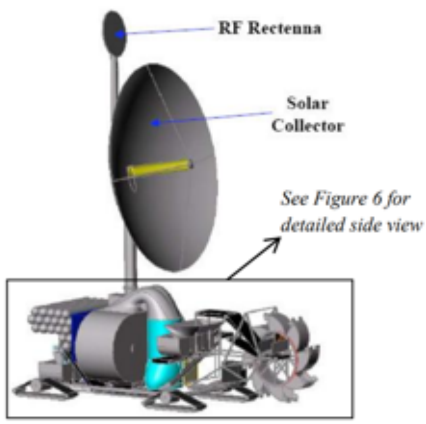


Figure 5. Model of the Mark-III Helium-3 Lunar Miner

into the miner. A BWE was used as the means of excavation because they are heavily used on Earth in the coal mining industry and have been considered one of the best options for large-scale continuous surface mining applications. The 4 m diameter BWE can take multiple cuts at different depths by pitching up and down relative to the miner. Taking multiple smaller cuts allows the use of a smaller and less massive BWE and also allows mining to be conducted below a depth of 3m, although this is not required for standard operation.

Selected Annual Miner Parameters	
^{3}He extraction (kg)	66*
Mining time (hr): *90% of lunar days*	3942
Excavation rate (tonnes/hr)	1258
Processing rate (tonnes/hr)	556
Excavation depth (m)	3.0
Forward miner speed (m/hr)	23
Area excavated (km^2)	1.0
Thermal process power (MW)	12.3
Power use (M-II, M-III) (kWe)	200, 350
Mass (M-II, M-III) (tonnes)	18, 9.9
Internal Pressure (kPa)	100, 15
Gas Storage Tank Pressure (MPa)	15, 20
Dimensions (LxWxH) (m)	19.7x10x10 13.6x5.4x4.8
*assuming 20 ppb ^{3}He grade, however only 10ppb was assumed in previous miner designs leading to a reported 33 kg of ^{3}He annually [8], [10]	

Table 3. Mark-II and Mark-III miner parameters (Credit: M.E. Gajda)

A conceptual depiction of the excavation process is shown in Figure 4. Once excavated, the regolith must be beneficiated (screened) to remove material unsuitable for processing. The excavated regolith is conveyed through a series of inclined sieves, a hopper, and powered screw conveyors. The constant flow of regolith into the hopper provides the inlet vacuum seal against gas loss, The particles larger than 250 μm are then separated by the sieves and screw conveyors. The particles smaller than 250 μm are brought into a fluidized chamber, where a stream of previously collected volatile gases (mostly hydrogen) carry only particles smaller than 100 μm into the miner's heater. This chamber is designed to flow gas upwards against a horizontal flow of regolith fines dropping off of a conveyor. This process allows the larger particles to fall onto a conveyor for waste regolith.

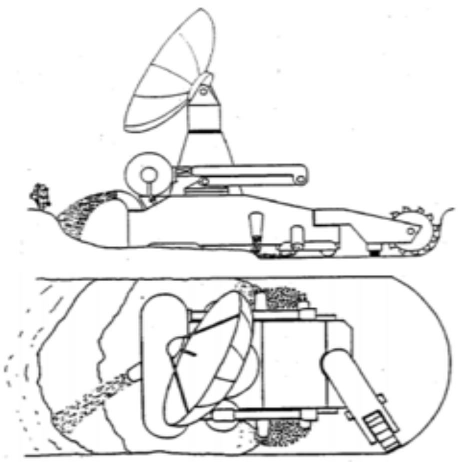


Figure 4. Side (top) and top (bottom) view illustrations of the Mark-II lunar miner excavating a 3m trench while collecting volatiles (Credit: I.N. Sviatoslavsky)

The heater in the miner is a heat pipe heat exchanger that uses sodium-potassium alloy as its working fluids and receives heat from a 10 m diameter solar concentrator on top of the miner. The thermal power is initially reflected from a larger 110 m diameter stationary solar concentrator as shown in Figure 3 and Figure 5. For efficiency, the thermal energy transferred to the regolith to release volatiles is reused by preheating incoming regolith with heated volatile deficient regolith. This occurs via heat transfer from the recuperator section of the heater to the preheater section. The use of heat pipes allows the regolith heating system to avoid any additional power conversion steps. Microwave heating has been discussed as a heating method but has not yet been adopted into the design.

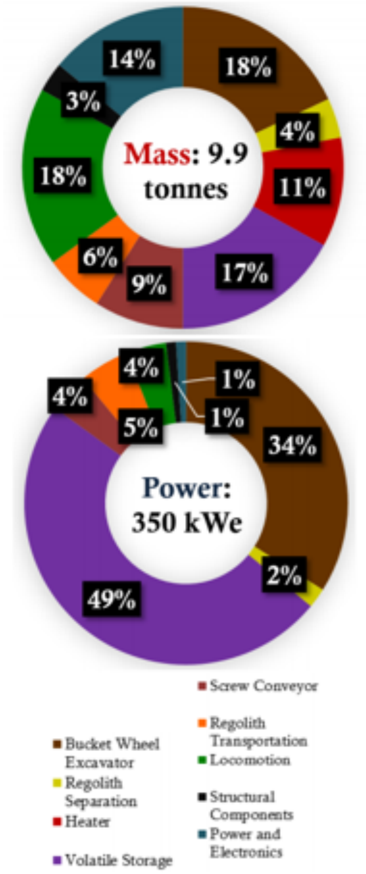


Figure 7. Subsystem mass and power distribution for the Mark-III lunar miner (Credit: M.E. Gajda [13])

After leaving the heater, the volatiles evolved from the regolith fines must then be separated from the regolith itself. This is done with an electrostatic separation device that attracts the regolith, allowing volatiles to pass through to storage tanks or back into the fluidized chamber. Through the use of 6 staged compressors and 3 intercoolers, volatiles are stored in tanks at the rear of the miner. Water and carbon dioxide are stored as liquid in one set of tanks while the rest of the volatiles are stored in gas tanks at 20 MPa. These filled tanks are to be carried away by another vehicle on the Moon for future gas separation and isotopic separation processing. Estimates for subsystem and total mass and power consumption for the M-3 miner are presented in Figure 7.

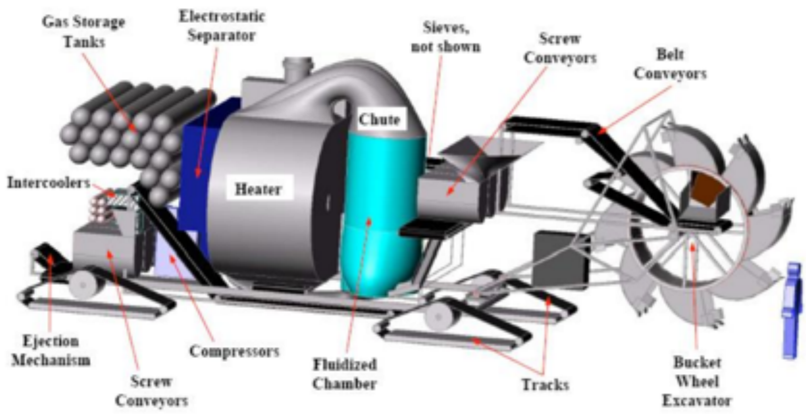


Figure 6. Side view model of the Mark-III lunar miner (Credit: M.E. Gajda [11])

Solar energy will be used to heat the regolith and indirectly power the miner through the use of RF (radio frequency) beaming, which limits mining operations to lunar days only, with any needed maintenance performed during the lunar night. This decision, along with the assumption that the miner will be operating during 90% of the lunar days, leads to about 4000 mining hours per year. These numbers lead to a required excavation rate of about 1300 tonnes of lunar regolith per hour to get 66 kg of He-3 per year and yield 69 kg/hr of lunar volatiles.

One way to reduce the power requirements of the miner would be to line the heater walls with thermophotovoltaics. Some of the heat from the heater would be converted into energy that could then be used for electrical power. This would cut down on the amount of beamed power that would be needed for the Mark III. Doing this would not adversely affect the performance of the heater since very little of the heat would be used by the TPVs while the rest would be waste heat used to heat the regolith. The most significant difficulty with this idea is that the backside of the cell will need to be cooled to allow for higher efficiencies.

1.2.4. Mining Operation

The mining operations will always be within 10 km of the basecamp. This limitation is set so that maintenance crews will be able to travel to and from the mine without endangering their safety. Even this distance is rather far since the farthest any of the Apollo rovers travelled was 20.1 kilometres. So, any new rover will need to be much more durable and capable of traveling for extended periods of time. This also means that the Mark III must be capable of traveling 10 km without the use of solar power. It is assumed that the rover must be able to return from the mine during the lunar night. The Mark III will also need this capability in case something goes wrong with the RF beaming system.

It is also assumed that there will always be a line of sight between the stationary dishes and the Mark III for the RF beaming to take place. The stationary dishes will either be mounted on the top of a hill or on a tower, or the mining area will be relatively flat without large hills or mountains. This will be mainly an issue of mine selection, which at this time focuses on the flat mare of the moon.

One challenge in mining the moon will be in deciding where to mine so that the bucket wheel will not encounter any large rocks that could potentially damage the buckets, bucket wheel, boom, motor, or any other part of the miner. The first step in avoiding rocks will be in the choice of the areas to be mined, as was described above. However, this will not ensure that there will be no rocks underneath the lunar surface that cannot be seen on the surface. Because of this, a type of look-ahead radar will be placed on the end of the bucket wheel boom. This radar will be able to scan the regolith in front of the miner to determine if there are any large rocks in the path of the miner. Rocks will be considered too large if any of the lengthwise dimensions exceeds 0.5 meters. Rocks with dimensions larger than this could become stuck in the bucket and damage the Mark III. If there are rocks too large for the Mark III to handle, then the miner will change its course to avoid them.

In the case of the radar not being sufficient, or the digging power suddenly jumping due to regolith inconsistencies, a clutching mechanism will be installed on the bucket wheel to ensure that none of the miner components are damaged due to this unforeseen mining obstacle.

Perhaps the biggest problem with mining on the moon is the fine regolith dust. This dust may get into the bearings and other mechanical components, cover optical components, and ruin electrical components via static charge. However, on the Apollo lunar rovers the wheel bearings and electronics were successfully sealed against any dust penetration, so this should not be a problem with the Mark III. Also, there will be frequent maintenance done on all of the components of the miner.

Next we will examine the issue of the miner's stability on relatively unmapped ground and unknown topography. Tipping is only a worry when the miner is not excavating since when in the mine, the miner will be on mainly level ground due to the level digging of the miner. At worst, the miner will be traveling up or down a slope of a few degrees, which will not be a problem at all. The only worry is when the miner is traversing from one mine to another or going to or leaving the main base. According to the Lunar Sourcebook, the angle of repose of the regolith, the maximum angle of displaced regolith, is about 400. In other words, the maximum angle of displaced regolith is 40°. However, the Mark III will be able to stay away from these areas and stick to the flatter areas of the lunar surface. To be safe, the miner will be limited to slopes of 30° or less. This should provide enough flexibility to easily get to and from the mine.

It has been posited that the miner should mine in a spiral pattern, thus the miner itself could directly transport the collected volatiles through a support arm to a refining facility inside the central station without the need for additional transportation vehicles. Additionally, the miner could receive electrical power to operate its excavation, mobility, conveyor and refining systems through a support arm. This mining technique would allow for volatile storage associated with each miner system. The feasibility of this approach rests somewhat on whether the support arm for the miner could operate as desired. The required bearing(s) at the central station and the length of the support arm could prove to be challenging to implement. The spiral mining concept has the capability to increase operational flexibility due to the multiple independent processing stations and the ability to reduce onboard mobile miner electrical power requirements. Schematics of the conceptual spiral mining architecture and the elements of an associated central processing station are shown below in Figure 8 and Figure 9.

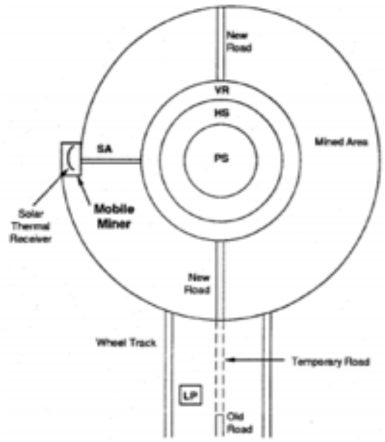


Figure 8. Schematic of a mobile miner operating while traveling in a spiral pattern away from a central station (Credit: H.H. Schmitt [15])

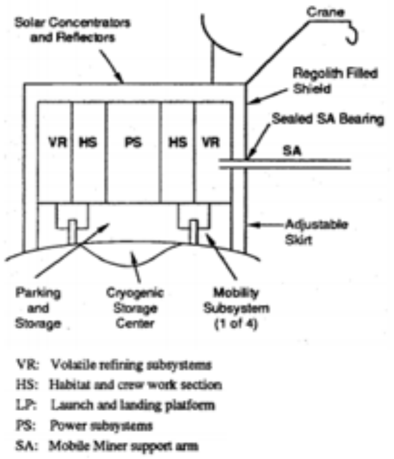


Figure 9. Schematic of central processing station for spiral mining concept (Credit: H.H. Schmitt [15])

Finally, as explained above, the Mark series of miners can process the regolith inside a mobile enclosure that refines, heats and discards regolith continuously. Large terrestrial coal mining machines, like the TAKRAF SR 8000 series can excavate around 16,000 tonnes of bituminous coal per year, dwarfing the processing rates of our miners. This suggests that there would not be an issue with mining millions of tonnes of regolith annually per miner, however the long-term effects of the lunar environment on excavating equipment have yet to be determined.

1.2.5. Extraction rate

The below table details our estimated extraction rates based on our Lunar miner and the best estimates for the average resource concentration in the lunar regolith.

Resource	Application	Estimated requirement for a 20 person base* (kg/annum)	Kg extracted / miner / annum	Mass evolved per tonne of regolith mined** (g)	Mass evolved per kg of He-3 evolved (kg)
Water	Life Support	23,376	108,900	23	3300
Oxygen***	Life Support	14,800	77,000	-	-
Nitrogen	Fertiliser	500	16,500	4.0	500
Hydrogen	Fuel	-	201,300	43	6100
Carbon Dioxide	Refrigerant	-	56,100	12	1700
Helium - 4	-	-	102,300	22	3100
Helium - 3	Fusion	-	66	0.014	1
Methane	Fuel	-	52,800	11	1600
Carbon Monoxide	-	-	62,700	13.5	1700

* Lunar base includes full scale mining operations, science-facilities, semi-closed life support system, and MMW nuclear power source.
** After beneficiation, 450kg of regolith is heated.
*** 0_2 obtained from electrolysis of regolith

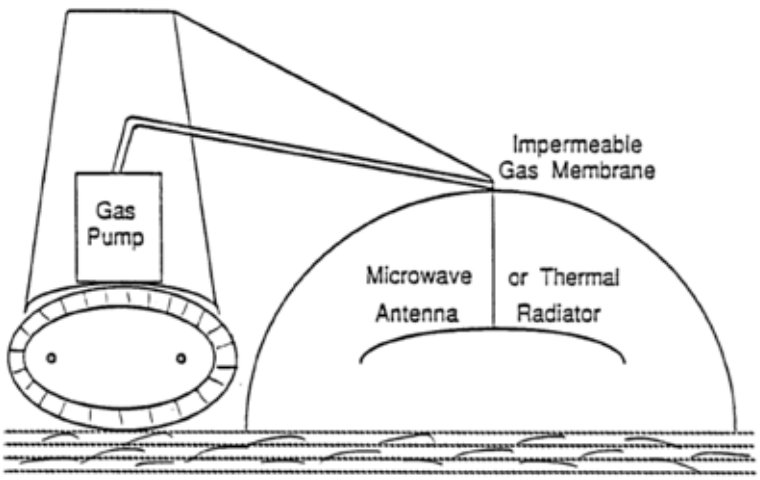
The ability to mine the moon is also essential for our lunar base. Otherwise, everything needed to support the base will have to come from earth, at an estimated cost of $2,720 per kilogram. Once the Mark III is up and running, the cost for living on the moon will be drastically less expensive since most of the needed elements for life support will be extracted from the regolith. The number of volatiles extracted is shown in the table above.

These numbers alone show the importance of using lunar volatiles to support our base on the moon. It has been estimated that using the miners would save an estimated 22 percent of the normal price to sustain a human over the first five years. Moreover, this calculation does not take into account the fact that the Mark III is nearly half the mass of the Mark II and that with the correct infrastructure in place, excess hydrogen and oxygen could be sold as rocket fuel or used to run fuel cells for local power, thus reducing the overall cost of mining.

On a side note, one possible extension of the Mark III miner is to reprocess the regolith fines to extract the metallic materials (Fe, Ti, Al, Mg, Ni etc.) contained in the regolith. This process would not be done on the Mark III, but the regolith fines could be conveyed to another machine that would be capable of extracting the metallics from the regolith. This would save energy since the metallic extracting machine would not need to excavate or beneficiate the regolith.

<u>1.2.6. In-Situ Volatile Release Concept</u>

The in-situ volatile release concept is an alternative concept for lunar He-3 acquisition that is potentially simpler and would drastically reduce the amount of regolith needed to be displaced. The concept is to apply heat to the regolith under an impermeable enclosure, without any continuous excavating, conveying or sieving processes. On an automated mobile platform, this concept was initially dismissed. A few heat transfer calculations found that a mobile in-situ volatile release system, providing heat by concentrated sunlight or by microwave energy to the surface regolith, would be inefficient in releasing and collecting the effluent volatiles from the subsurface. This conclusion was based on calculations that showed that it would take more energy and more time to collect an equivalent amount of He-3 compared with a continuously excavating miner. An illustration of this early dismissed concept is shown in the figure below.



The in-situ concept was revisited with an emphasis on reducing gas loss due to the isotropic diffusion of the released volatile gases underground. Eliminating the continuous mobility aspect of the in-situ extraction process, installing an underground gas barrier (dike), introducing a 1 atm hydrogen atmosphere under the extraction enclosure, and extending the heating elements into the subsurface yielded a much more viable approach compared to the initial in-situ concept.

The temperature profile for the “coldest” region, i.e. between heating elements at a 3m depth, is shown in Figure 11. This shows that approximately an entire lunar day (320 hours) is required to reach a high enough temperature (> 900 K) to extract around 90% of the deposited He-3. If moved after every lunar day (13 times / Earth year), three 100 m diameter enclosed areas, employing this in-situ process, could yield a total of 60 kg of He-3 per year, approximately as much as the miner. A conceptual illustration of an in-situ volatile extraction enclosure is shown in Figure 12. Each enclosure would include 8200 m^2 of fabric, 7800 embedded heat pipes, two solar collectors, core-drive boring machines, gas separation radiators, a helium isotopic separation system and service vehicles or robots to operate and move the entire structure.

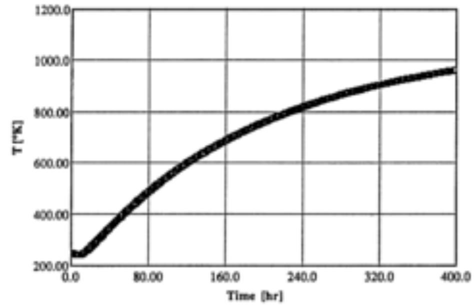


Figure 11. Lowest temperature (at 3 m depth) vs. time for a stationary in situ lunar volatile release enclosure using buried 0.5 m radius cylinders at 1073 K.(Credit: L.J. Wittenberg [18])

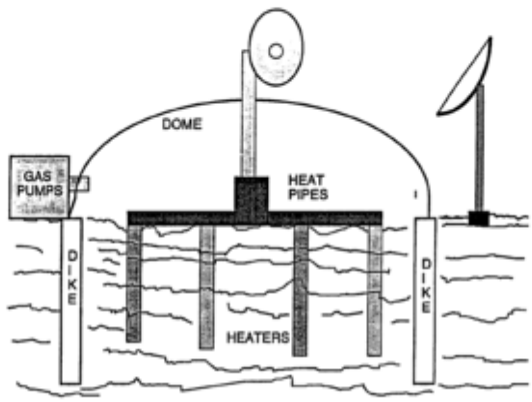


Figure 12. Conceptual design of an in-situ volatile collection with a stationary enclosure, heaters powered by solar energy and an underground barrier (dike) to prevent gas loss laterally (Credit: L.J. Wittenberg [18])

The mass of the entire in-situ mining operation was estimated at 174 tonnes, not including the crew accommodations required. The mass of regolith disturbed for this operation was estimated to be one millionth of that required for the excavator designs. In contrast, the mining operation based on the M-3 miner was estimated to have a mass of 10 tonnes without crew accommodations and, as previously mentioned, would require that 5 million tonnes of regolith be excavated.

If excavating large quantities of the lunar terrain turns out to be problematic for maintenance, environmental or political reasons, there would surely be an impetus toward less invasive volatile mining processes like the in-situ concept presented. Without the need to limit the excavated mass of regolith, the M-3 miner and its associated systems outperform the in-situ release concept in terms of total mining operation mass. Additionally, the energy payback for the stationary enclosure method, when the extracted helium - 3 is used for fusion power, is also less than ⅓ of that for the Bucket Wheel excavator designs (8.5 instead of 33). Trade studies around this particular in-situ volatile release mining concept may lead to improved performance, but at the present time the more “conventional” M-3 lunar miner design appears to be superior.

1.2.7. Calculated Details

Hourly excavation rate	1258 tonnes / miner
Hourly processing rate	556 tonnes / miner
Annual mining time	3942 hours
Annual mining rate	4,960,000 tonnes
Mass of He-3 per tonne of regolith	0.014 g
Annual mass of He-3 produced	66 kg / miner
Current market value of He-3	$1.41 million / kg
Annual value of He-3 per year (50 miners)	$4.65 billion
Total minable He-3	560,000 tonnes
Total value of minable He-3	$790 trillion
Annual He-3 to meet global energy demand	133 tonnes
Miners required to mine 133 tonnes per annum	2009
Weight of miner	100 kN
Dimensions of miner (LxWxH)	13.6 x 5.4 x 4.8 m
Power usage	350 kWe / miner

Section 2

Lunar Base

2.1. Design

2.1.1. Considerations

The lack of a protective atmosphere means there’s little protection against harmful cosmic radiation. This means moon inhabitants would have to construct buildings with walls sufficiently thick to block radiation from coming in and use cumbersome spacesuits when leaving the facility. The walls must also be strong enough to withstand the pressure differences between the outside and inside and to cope with the impact of micrometeorites–tiny specks of rock and dust crashing onto the surface at high speeds.

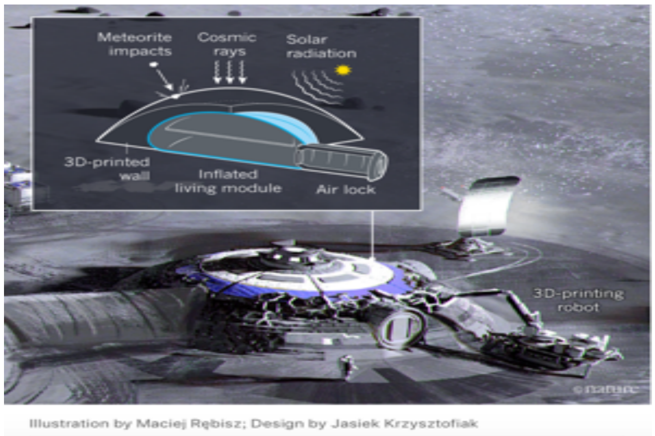
These considerations mean that, when we expand the first bases and start actually building structures on the moon, lunar concrete, which is a mixture of sulphur and cement will be a good option. This is because it’s nonporous, strong, and doesn’t require water, which is in short supply on the moon.

With a payload of approximately 22,000 kilograms (Falcon Heavy’s approximate payload capacity to the moon), steel-reinforced concrete will be a viable option as it is a synergistic composite material where the concrete provides high compressive strength and steel provides a high tensile strength, similar to the extracellular matrix of bones.

The moon has almost no atmosphere, therefore meteorites impact the surface at speeds close to 18 km/s - to put this into perspective, a bullet leaves a rifle at about 2 km/s. Although large meteorites are rather rare, a sufficient protection layer for micro-meteorite impacts is necessary. With a probability of 0.998 to have no fatal event during a lifetime of 10 years, a protection layer of 800mm is needed. This protection is achieved by offsetting the catenary structure radially by 800mm. The offset is radial as meteorites can impact the surface under any angle.

Due to the non-existence of an atmosphere or a magnetic field on the moon, space radiation on the surface is far higher than on earth. There are three types of radiation that reach the moon’s surface: solar wind, solar flares and galactic cosmic rays (GCR). Solar radiation will, in particular during solar flares, be one of the main drivers of our design.

2.1.3. Basic structure



Across top: small lunar rocket jeep, fence-like radio telescope, optical telescope dome, rocket hangar pit, commuter rocket, ore dump truck, ore mine.

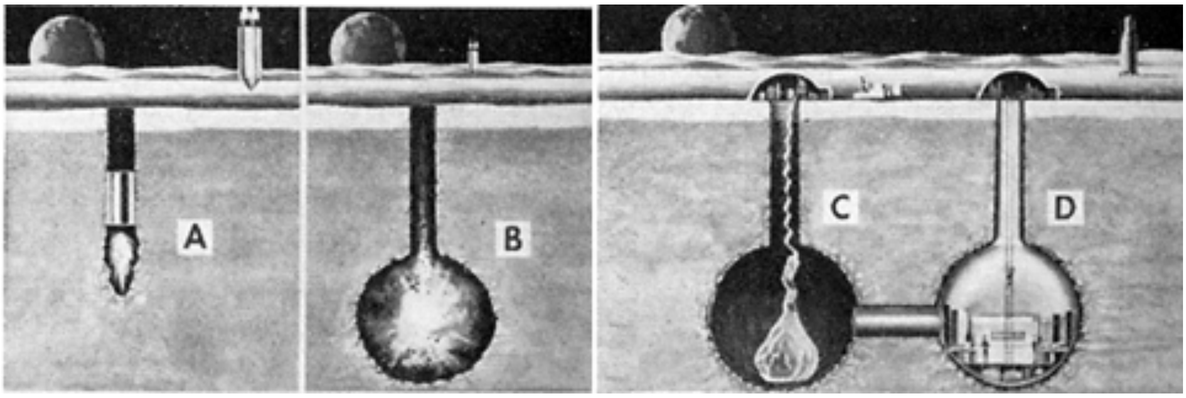
As stated in section 2.1.1, there are a multitude of pieces of necessary equipment which are crucial to the sustainability of a lunar base, and to the physical and mental health of the crew members.

The aforementioned need for shelter from cosmic rays and meteorites can be solved using inflatable or flat-packed living modules brought from Earth. These could be covered with materials such as regolith converted into bricks, or organic waste bound together by fungi. Ideal locations for our lunar base will harness natural cover, such as cliffs or caves.

2.1.4. Phase 1

To maximise the astronauts' productivity and also to minimise the possibility of any risk through the process of creating a fresh lunar bass, the construction of our lunar base will be set out in two phases. Phase 1 will be the construction of an initial section of our base. Phase 1 will be directed and controlled completely from Earth; this phase will finish before the 20 astronauts are sent to the moon creating a habitable space for initial settlement of the crew as soon as they land on the lunar surface

A projectile from Earth will carry special shaped charges to blast a shaft (A on the following diagram) on the Moon's surface. At a predetermined depth it will create a spherical chamber (B).

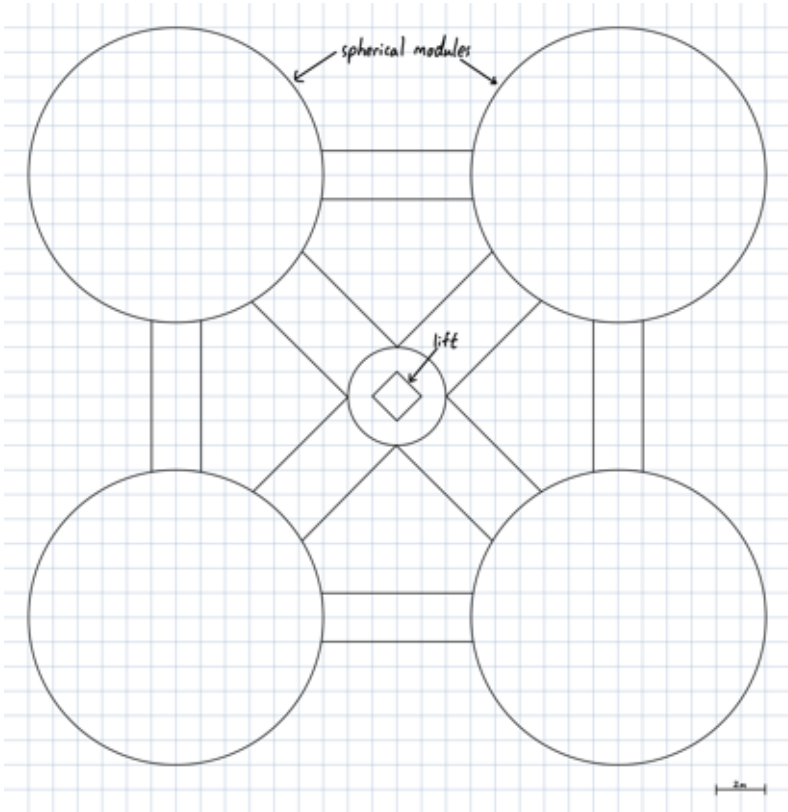


When the crew lands, an airtight membrane will be dropped into the chamber (C) and inflated, and equipment and supplies will be installed (D). The finished Moon base will consist of a series of pressurized chambers connected by tunnels. Surface structures will contain airlocks, according to the proposal made to the American Rocket Society by a researcher from General Electric's Missile and Space Vehicle Department.

For the starting base to be suitable for usage by our crew of 20 people, we will construct four shafts each with a diameter of 12 meters and at a depth of one meter. Each shaft will be separated by a 6 meter hallway with a diameter of two meters. The hallway between shafts will be drilled after the construction of the spherical shaft by a second excavator.

These four shafts will form a kite shape with a cross (see following diagram), each individual shaft contained by a double airlock system. Here, two sets of airtight doors are set at each entrance both between shafts, and between the outside and the base. At the intersections of the cross, there will be the main entrance where a 4 meter wide space for a lift and a ladder is fitted to another double airlock system which links directly to the outside of the underground lunar base. The igloo shaped surface extension will be constructed in Phase 2.

Walls of these circular shafts will be lined with steel reinforced lunar concrete with synergistic properties of compression and tensile strength. These steel materials will be brought from Earth along with the astronauts on the Falcon Heavy. Each tunnel is designed to be wide enough to facilitate the transport of material ranging from reasonably sized robotic machineries to tool trolleys



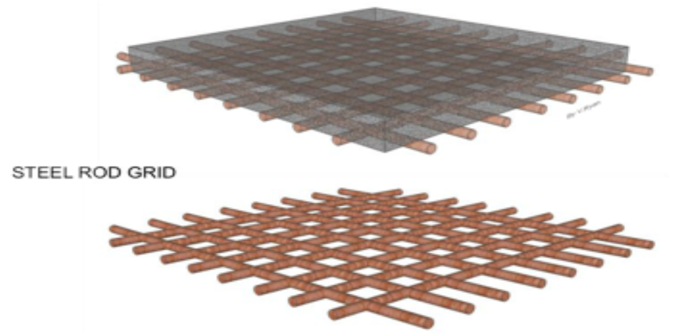
Visual outline of Phase 1 (from above)

2.1.5. Phase 2

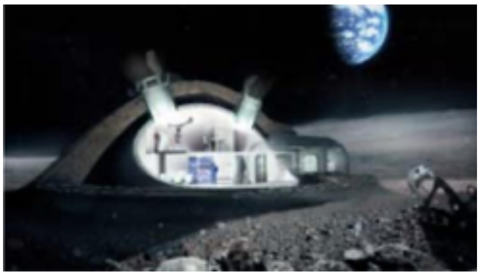
After the construction of the initial section of our base in Phase 1, Phase 2 will begin with the astronauts' arrival on the moon. Sent to the moon aboard the Falcon Heavy, are essential pieces of equipment for our programme. The Falcon Heavy will land on a designated landing pad 500 meters away from the base (see section 3.3.2). With the arrival of the lunar crew and the necessary equipment, Phase 2 of our lunar base will commence with a full system check-up of the base's structural integrity and the airlock systems.

Phase 2 will then proceed with the excavation of the lunar soil, again with a diameter of 12 meters, but these will be dug out as cylinders rather than spheres, with a depth of 8 meters.

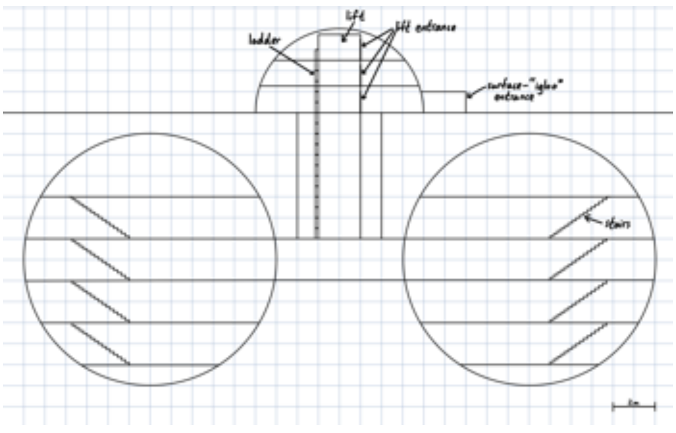
The walls of these cylinders, after the completion of their excavation, will be reinforced with steel reinforced concrete. Steel will be delivered along with the Falcon Heavy from Earth, and lunar concrete can be produced using the method described later in Section 3.3.2. The so called Lunarcrete reinforced steel walls will be constructed with a steel matrix made up of a steel rod grid as shown below, creating a 10 centimetre thick wall in each excavated cavity.



Other than the extension of the underground lunar base, a surface lunar outpost on top of the main entrance will be constructed as mentioned in Phase 1. This will be according to a design created by an industrial consortium comprised of Foster + Partners, Alta SpA, Monolite Ltd, and Scuola Superiore Sant'Anna.



This design proposes an assembly of two inflatable volumes (see figure A, next page), interconnected with ready-to-use cylindrical elements that also dorm air locks to the outside environment. The inflatables will be constructed to have a height of 8 meters in order to contain three levels. The overall shape of each inflatable will have continuous curvature so that it can withstand internal pressure. Note that these inflatables do not give any protection besides providing an atmosphere in pressure and conditioned space.



Phase 1 structure with surface "igloo" (side view)

The protection of the surface base will come from a dome shaped shell (Figure B, next page), constructed from a 3D printed regolith which uses a gantry system that is always of an order larger that the printed object. 3D printed regolith, like masonry, has a very low tensile strength. The geometry of the structure ensures that forces are primarily compressional. Therefore, a catenary structure was chosen to span the internal pressurised volume. In this way, mainly compression forces will be acting on the structure. Installation of facilities such as medical and research equipment will commence after the construction of each module.

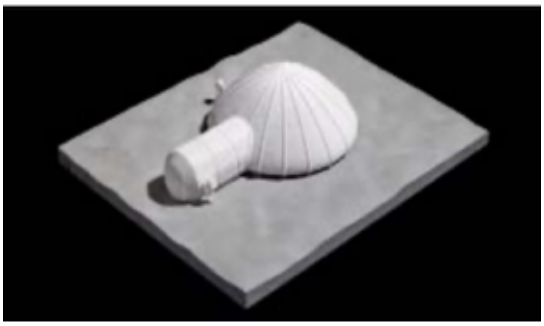


Figure A

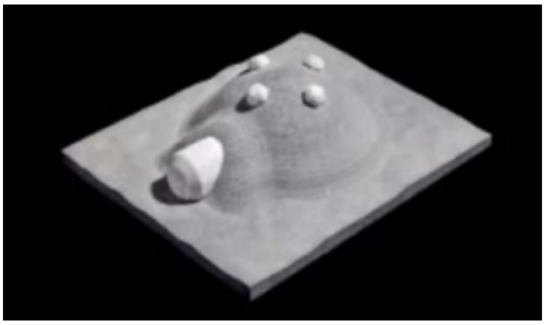


Figure B

One of the lightest space filling topological systems that can be found in nature are foam structures. Foams are often defined as a two-phase system, in which typically a high volume of gas cells are enclosed in a liquid or solid state. In this case we have loose regolith enclosed in a 3D printed closed wall cell system.

There are two main reasons why a closed wall foam system was chosen. Firstly, although the thickness of the regolith would protect from meteorites, it does not minimise the damage from such an impact. To absorb the impact of meteorites, a layered approach of solidified and loose regolith would be ideal to disperse the energy of the impact. Secondly, closed foams also have the advantage that any section through the structure delivers a structural platform. This is crucial as the regolith dome will be built up from horizontal layers. Each of these layers will need to be a platform from where the 3D printing robots can build the next layer.

A parametric model and script were developed by the Specialist Modelling Group at Foster + Partners to investigate the usability of foam as the internal structure of the regolith shield (Figure C). A structural feasibility study has been pursued, making some simplifying assumptions, by performing a structural analysis on a shell structure, a comparative Finite Elements (FE) structural analysis on small samples with different cell sizes and an analytical study comparing the cell structure with other materials.

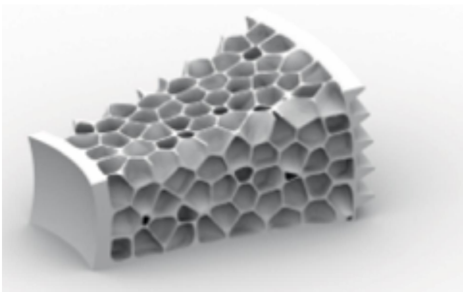
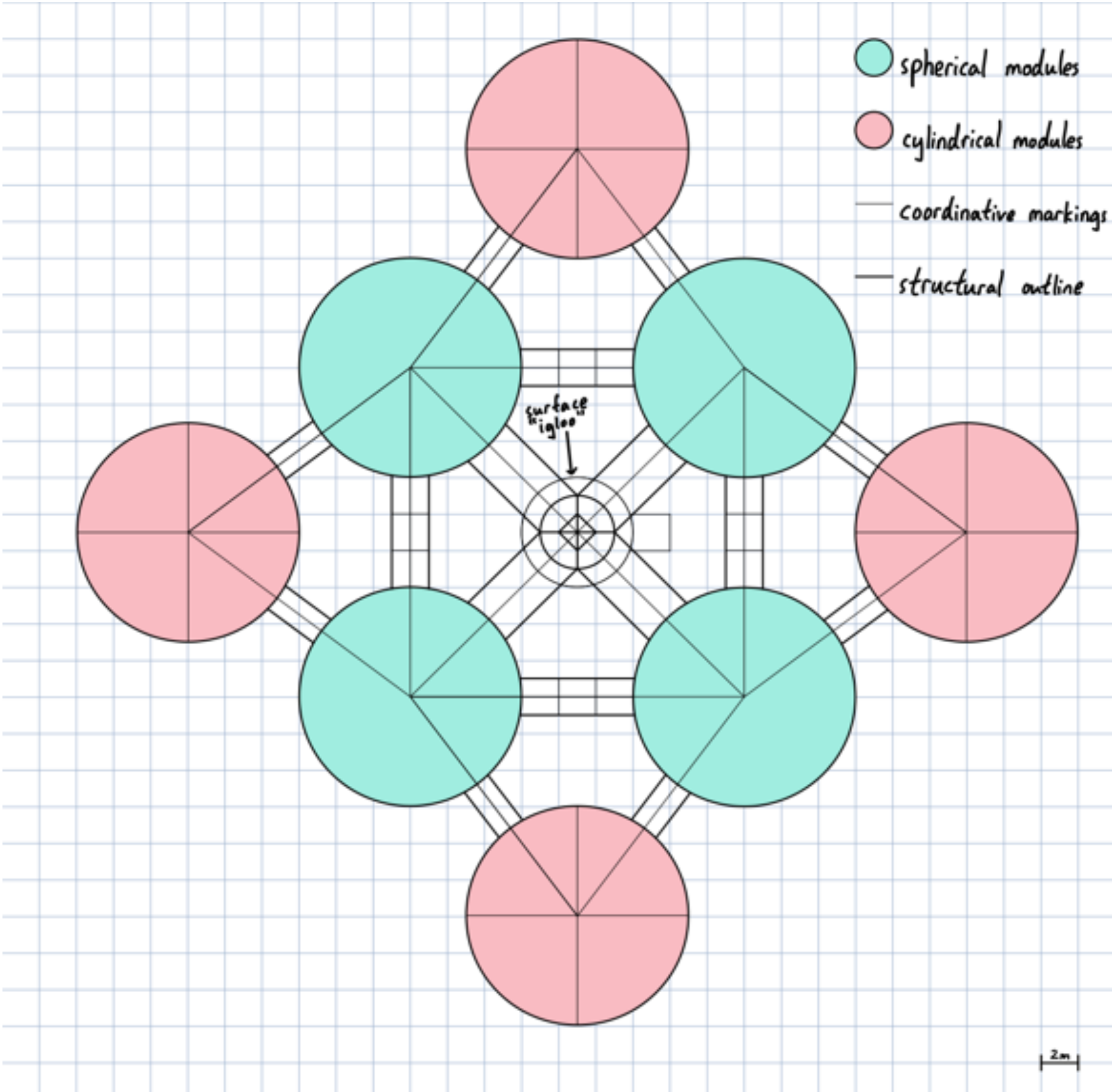
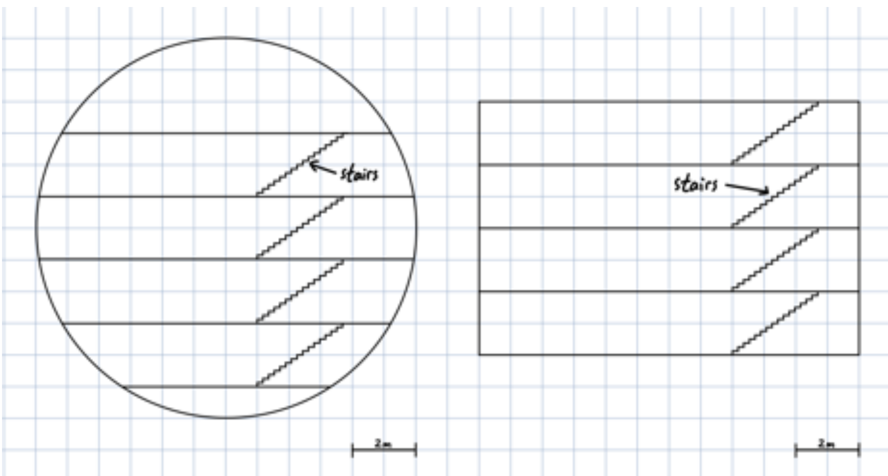


Figure C



Completion of the construction of Phase 2 (from above)



Sideways view of the spherical and cylindrical module

2.1.6. Location

A base on the equator would be the easiest site to land and launch from and would be in constant communication with Earth. However, lunar nights could prove a challenge for power.

A settlement in the polar regions offers access to icy deposits for mining, interesting geology and sunlit uplands, but shadowed terrain makes landing difficult, and Earth communications intermittent.

In conclusion we will build our first bases at the equator due to the easier landing conditions. After our team has settled, we will look into relocating at the poles to expand our mining and research projects.

2.1.7. The role of robotics

Japan's space agency wants to create a moon base with the help of robots that can work autonomously, with little human supervision.

The project, which has racked up three years of research so far, is a collaboration between the Japan Aerospace Exploration Agency (JAXA), the construction company Kajima Corp., and three Japanese universities: Shibaura Institute of Technology, The University of Electro-Communications and Kyoto University.

Recently, the collaboration did an experiment on automated construction at the Kajima Seisho Experiment Site in Odawara (Japan). A 7-tonne autonomous backhoe went through its paces at the site, executing procedures such as driving a specified distance and repeating routine operations.

The backhoe has been modified with onboard survey instruments and an automatic operation control console. The instruments that the tractor and backhoe are installed with autonomously measure the backhoe's position and direction, making it both remotely and automatically operable. Shielding the module with the surface material to protect it from meteoroids and radiation.

The backhoe is equipped with a suite of technologies to help it work by itself on the lunar surface, which is located about 2 seconds' radio distance away from Earth. In other words, any command sent from Earth would take about 2 seconds to arrive at the moon's surface. (The average distance between the earth and the moon is about 239,000 miles, or 384,000 kilometres). This means that any fine handling operations will be best performed if a human can control the machinery from the moon itself or from our Earth-Moon satellite (section 3.4), where delay is much lower.

2.2. Life support on the moon

2.2.1. Oxygen

In order for humans to respire on the moon while in the lunar base, a steady and reliable stream of oxygen is required. There are several options that can be explored to find the most elegant and simple solution, but it seems that one prevails above the rest.

Recently, scientist Dr Derek Fray (University of Cambridge), discovered a way to produce oxygen via the electrolysis of lunar rock (which will be mined by our lunar miners). A current is passed between two electrodes and through molten calcium chloride. Usually for this reaction both electrodes would be made from carbon, however, this would produce carbon dioxide. Therefore, Fray created a new material for the anode. Calcium titanate and calcium ruthenate were mixed to produce the new type of anode. The electric current removes the oxygen atoms from the cathode, they are ionised and dissolve into the solution. Because the oxygen ions now have a negative charge, they are attracted to the positive anode. Usually this anode erodes to produce carbon dioxide. However, due to the new electrode, which does not erode, only oxygen molecules are produced.

The average human requires roughly 740kg of oxygen per year, assuming the average human inhales roughly 9.5 tonnes of air in a year. Three, one-metre tall electrolysis reactors, could produce one tonne of oxygen per year. This would require three tonnes of lunar rock.

It would be sensible to retain a surplus of oxygen for each person on the moon, in case a reactor stops working, for example. Therefore, there will be three one-meter electrolysis reactors per person on the moon. Creating 1 tonne of oxygen per person in a year, since the average human uses 740kg of oxygen per year, there will be a substantial surplus of 260kg of oxygen. Although it would possibly be cheaper to reduce the number of reactors, in the event of an emergency this surplus is worthwhile. Due to the 20 astronauts that will have to be supported in this base at one time, 60 electrolysis reactors will be required.

2.2.2. Water

For 20 people to survive on the moon, they will require a minimum of 23,376 kg of water per annum. However, due to the harsh conditions on the moon it is recommended that the astronauts try to exceed this if possible. Fortunately, the miner will collect an expected 108,900kg of water per annum, that can be filtered and used for the needs of the lunar base.

The water will need to be filtered for it to be drinkable. This will happen via a step-by-step process which is similar to how water is filtered on Earth. Firstly, aluminium sulfate (the coagulant) is added to the water to bind with dirt and other unwanted particles and group them into larger particles (floc). The floc is then heavier than the other particles in the water, so it sinks to the bottom. The leftover liquid will then be passed through a filter made of sand, gravel and charcoal. This will remove any of the unwanted, dissolved particles. Then, in the final step, chlorine will be added to sterilise the solution and make it safe to drink.

2.2.3. Food

In order to produce our own food on the moon, we must be able to grow plants there, in controlled conditions. The plants will require substantial amounts of space to be able to provide enough food, and so the base must be made big enough to accommodate this. Many of the nutrients that the plants need to grow can be synthesised by our lunar miners, eliminating the need for more materials to be transported from Earth.

We will use a technique known as hydroponics – growing plants in water rather than soil, with LED lights providing artificial sunlight. This can be performed in an internal windowless room. A large amount of water is required in order for hydroponics to occur. The plants can be grown in hydroponic towers. In a system of 200 hydroponic towers, 250 gallons would be required. This roughly equates to 7039kg/annum of water. Again, this water can be sourced from the water collected by the miner. All nutrients for the water will have to be brought up from the Earth to begin with, however they will be very light so their impact on the launch is negligible. CO_2 is also required for the plants to grow. The CO_2 will be provided by the CO_2 produced through the astronauts' respiration as well as by synthesis from the aforementioned miners. This system of growing food will provide astronauts with all the carbohydrates and fibre required for a balanced diet.

To provide protein for the astronauts, a system of growing meat on the moon will be used. The meat can be grown in labs, simply from a muscle sample of the animal. Stem cells are taken from the animal muscle tissue. These would be frozen and taken up to the moon. They also have a negligible weight. On the moon the stem cells would be multiplied in petri dishes to allow them to differentiate into simple muscle fibres which would gradually develop into muscle tissue.

2.2.4. Medical

Astronauts will need to be able to provide basic first aid on the moon. To do this they will require a room in which to carry out emergency operations and other requirements. One of the 20 people staying on the moon at any one time must be a trained surgeon and be able to carry out these operations in the event of an emergency. Basic x-ray equipment will be installed in the moon base as well.

Medical Kits:

Command Module Medical Kit:

This medical kit was carried in the Apollo command module. It contains bandages, eye and nose drops, sleeping pills, and self-injectors to treat motion sickness and pain.

Lunar Module Medical Kit:

Small medical kits like this one were also carried in the Apollo lunar module. They contain sleeping pills, aspirin and other pain relief medication, eyewash, and bandages.

Survival Equipment:

The survival equipment shown here was carried on the Apollo 11 mission. The survival kit provided 48 hours of survival supplies for the three-man crew, if rescue was delayed. The supplies fit into two rucksacks.

Apollo Survival Rucksack

This is the first of the two rucksacks flown on the historic first lunar-landing mission, Apollo 11, in 1969. It includes three water containers, one radio beacon with spare battery, three pairs of sunglasses, six packages of desalted chemicals, one desalter kit, two survival lights, one machete, and two bottles of sunscreen. The second rucksack (not pictured) contained a three-man life raft, a sea anchor, and three sun bonnets.

Apollo Dual Life Vest

Each astronaut was provided an inflatable life vest for use after splashdown. This dual life vest kit was carried aboard Apollo 11.

Apollo Survival Light

Two of these multi-purpose units were carried in the Apollo survival rucksack to be used in case there was a delay in being rescued after splashdown.

Section 3

Transport System

3.1. Storage of Helium

3.1.1. Considerations

As our mission primarily revolves around the transport and usage of Helium-3, we need a sustainable and sure method of transporting it. We have decided that it is best to store the Helium as a liquid as this is what research has shown to be the most suitable method.

Helium-3, due to its weak interatomic attractions between the He atoms, has a boiling point of 3.19K. As this is an extremely low temperature, we would struggle to keep this inside a rocket or on the earth without a serious amount of cooling under normal atmospheric pressure. This would be very costly, so instead we would store it in high pressure canisters for transportation. Using the equation $P_1 / t_1 = P_2 / t_2$, if we increase the pressure that the helium is stored at, the temperature to store it as a liquid will decrease, hence increasing the efficiency.

3.1.2. Solution

Research suggests that it would be possible to store the Helium in such canisters. These canisters will be able to hold liquids and gases up to pressures of 17,000KPa. This would dramatically drop the temperatures required to store the Helium in a liquid phase, and therefore the cost.

Using the formula: $P_1 / t_1 = P_2 / t_2$ we can find the temperature required to keep the helium as a liquid at 17,000 KPa is
$P_1 / t_1 = P_2 / t_2$
101 KPa / 3.19 K = 17,000 KPa / t_2
31.661 = 17,000 KPa / t_2
t_2 = 537 K

This value is far higher than we want and therefore a lower pressure will be needed. If we were to keep the Helium-3 at room temperature (294 K) a pressure of 9310 KPa in the canisters would be needed to be kept constant.

$P_1 / t_1 = P_2 / t_2$
Atmospheric pressure / boiling point of He = pressure in canister / room temperature
$101 / 3.19 = P_2 / 294$
$P_2 = 9310$ KPa

The canisters that we use will be able to withstand this pressure. A slightly higher pressure may be needed to ensure that all the helium is in liquid phase (940KPa). The fact that we now have a way of storing the helium at room temperature without any cooling will make transporting the He significantly simpler.

Another problem that we encountered when drawing up ideas for the transportation of Helium was that the canisters will be exposed to great range of temperatures, from the surface of the moon (127 degrees centigrade to -173 degrees centigrade) to being stored inside a rocket. Therefore, the canisters will need to be insulated well enough to maintain the He-3 at a constant temperature.

We also looked into other contemporary ways of storing Helium; one such successful method used cryogenic vessels to store the helium. Cryogenic vessels are super-insulated vacuum vessels which keep the contents at a safe pressure and temperature. They use the same multilayer insulation that NASA uses on their astronaut suits. Each layer reflects 95% to 98% of all infrared radiation. The multilayer insulation is composed of many of these reflective layers each spaced out by a pocket of insulating air. This will help keep the contents of the canisters at a stable temperature no matter what the environment is like.

100 x 0.05 x 0.05 x 0.05 = 0.0125% of radiation that penetrates three layers of insulation, where 0.05 = the percentage of infrared radiation that gets through each layer and 100 = the initial amount of infrared radiation.

With just three layers of this insulation, a maximum of 0.0125% of the original infrared radiation will get through to the Helium. This value can be further reduced by adding more layers of insulation. Each layer only has a thickness of around half a millimetre and is made up of polyester film. Therefore, it will not add too much extra bulk or weight to transport. Furthermore, the density of Helium is 1/8th the density of liquid water, which will make the transportation of the cylinders much easier.

3.2. Rockets

3.2.1. The Falcon Heavy

The project requires significant transportation of both materials and astronauts, as well as the movement of Helium-3 back to Earth. Based on the latest research we concluded that the Falcon Heavy and Starship currently being developed by SpaceX were best suited for this role.

For a fee of $90,000,000 SpaceX will build a Falcon Heavy rocket and launch it from our own launch site. This is a necessary fee since the Falcon Heavy allows us to carry up to 22,000kg (seconded only by the legendary Saturn V Rocket) of various cargo such as He-3, resources for the Lunar Base and more inhabitants. This is also ⅓ the price of the next most powerful rocket being flown today, the Delta IV Heavy. The Falcon Heavy has no less than 3 cores consisting of 9 engines each, therefore being powered by 27 Merlin Engines, thus creating a maximum upthrust of 22,819,000N, which is roughly 845,000N per engine.

845,000N x 27 = 22,819,000N

The Falcon Heavy rocket is the most powerful rocket flying today by a factor of 2, which is why we deemed it necessary to spend $90m. The fact that the Falcon Heavy rocket is capable of carrying 22,000kg of Payload to the moon at a time, and the addition of 7 people, further validates our choice in the Falcon Heavy.

The Falcon Heavy rocket, being 70m high and 12.2m wide, will prove rather difficult to fit onto a landing stage (see section 3.3). The regular Falcon rockets launch at the Kennedy Space Centre, from Launch Pad 39A. For example, in 2019, SpaceX launched 12 Falcon rockets, proving that the size of the Falcon Heavy is in fact viable. He reliability of the Falcon series of rockets is also vital for us.

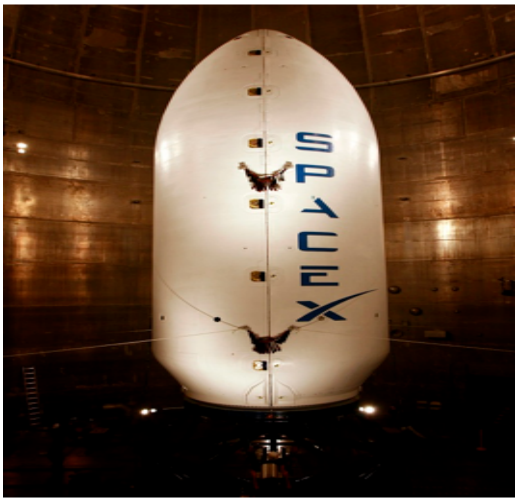
Another reason why the Falcon Heavy is the ideal rocket for this role is because the side thrusters, which have a total of 18 engines all together, can be ‘recycled’ after use. After the stage separation at 148 seconds after launch, the booster rockets attached to the side of the Falcon Heavy eject and enter a new course of trajectory. The Second stage of the Falcon Heavy Launch gives up to 934,000 N of upthrust in a vacuum and has a burn time of 397 seconds. The boosters initiate a re-entry sequence, and they fall back down to earth in a calculated manner using parachutes and prior landing location planning. These boosters can reliably be used over and over again and there have been several Falcon Heavy and Falcon-9 launches from reusable engines. This makes the Falcon Heavy an appealing rocket to us since we want to minimise our environmental impact by promoting reusability within our operations.

3.2.2. Anatomy of the Falcon Heavy

The Payload:

Payload capacity = 22,000kg

The Payload, which lies at the top of the rocket, is made of a strong composite structure designed and built internally within SpaceX. It consists of Aluminium honeycomb core with carbon-fibre face sheets, which make two half shells therefore making a full shell at the end of the construction process. The Payload can carry the rocket cargo to low Earth orbit (LEO) as well as geosynchronous transfer orbit (GTO). The generous size of the Payload structure allows us to maximise the He-3 shuttling volume. It stands at 13.1m high and 5.2m wide (diameter).



The Dragon Spacecraft:

Pictured left is the SpaceX Dragon Spacecraft which was designed with the Falcon rockets in mind. As such, this individual spacecraft, which is 8.1m high with a diameter of 4.0m, can be attached to the top of the rockets and allows multiple people to be transported as well as valuable cargo.

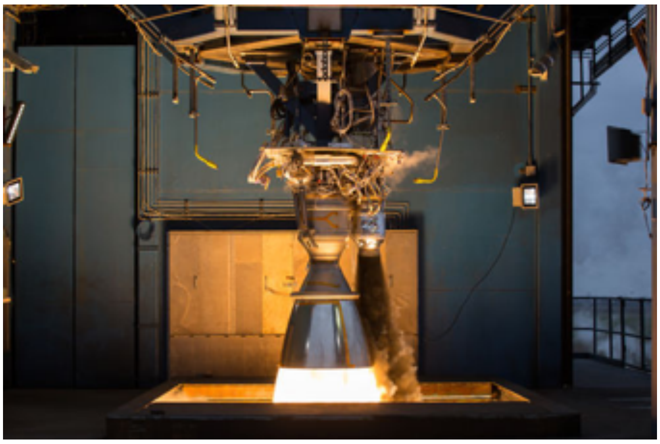
This Dragon Spacecraft has a launch payload mass of 6,000kg and a return payload mass of 3,000kg, which gives us the flexibility to work with. The trunk volume of $37m^3$ means that up to 7 people can be within the Dragon Shuttle at a time.

The Booster tanks and Landing Legs:

The Falcon 9 Heavy tanks are made of a highly durable alloy of aluminium and lithium. This alloy is used because it is stronger and lighter than its composite metals. Inside, there is the Liquid Oxygen and the Rocket-Grade kerosene. These tanks are designed and built in the SpaceX facilities. The landing legs are also made by SpaceX.

The landing legs of the Falcon rockets deploy after the first stage separation and they allow for the safe return of the rocket to earth. This is a major point of us using the SpaceX rockets since the renewable nature of the rocket allows us to meet our target of being environmentally friendly. The construction materials are carbon laced with more of the aluminium-honeycomb structure used in the payload.

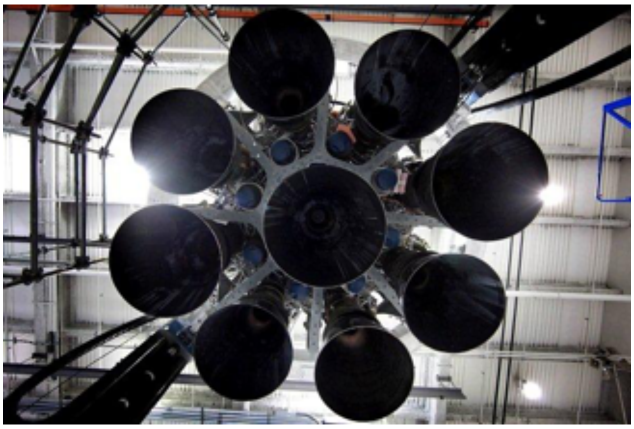
The Merlin Engines and the Octaweb Structure:



These are the Merlin engines which power the Falcon Rockets. They are also developed in house by SpaceX and they have taken a lot of inspiration from previous successful designs from history.

The Merlin 1D engine is capable of producing 845,000N of thrust through utilisation of the Liquid Oxygen and the rocket grade Kerosene. This figure rises to 914,000N in the vacuum of space without air resistance. The Power-to-Weight ratio of the Merlin engines is what helps the Falcon Heavy be one of the most efficient rockets today. The Power-to-Weight ratio of the engine alone stands at over 150 to 1.

The Octaweb structure on the bottom of the Falcon Rockets are a huge improvement on the older and less aerodynamic 3 x 3 structure. The structure carries the same 9 rockets, arranged differently, consisting of 8 boosters round the edge of the rocket, with a single centre booster in the middle. This structure greatly simplifies the design and assembly of the rocket.



So, we will be using the Falcon Heavy rocket to shuttle supplies and goods, and the Dragon shuttle will allow us to provide transport between the earth and the moon. Overall, the combination of the two rockets provides a seamless balance of cargo capacity and passenger count.

3.2.3. SpaceX Starship

Considering we have access to technology and innovations up until 2030, we concluded that a potential future investment could be in the SpaceX Starship, which was unveiled in 2018. Upon completion, the SpaceX Starship will be 100% reusable with the capacity for up to 100 passengers, and an excess of 84,000,000 N of thrust, potentially making it the most powerful rocket ever.

Starship, which comes with two separate sections, is 118m high and 9m wide. The upper reusable section of the rocket can be launched on its own, providing itself with 12,000,000 N of thrust which is supplied from the 6 Raptor Engines (methane / liquid oxygen propellant) which are the latest engines developed by SpaceX.

The detachable and optional second stage of the rocket, the Super Heavy extension, provides much more power to the Starship. The Super Heavy uses 24 to 37 Raptor rocket engines to provide 72,000,000 N for lift off thrust, which is critical for taking large masses to and from the moon. Up to 100 tonnes can be transported with the rocket at full power. The payload section of the Starship is 19m high and 9m wide, allowing 1208.73m^3 of storage space ($V = \pi r^2 h$)

As announced in May 2019, Starship will use three sea-level optimized Raptor engines and three vacuum-optimized Raptor engines. These sea-level engines are identical to the engines on the Super Heavy booster. Transport use in space is expected to utilize a vacuum-optimized Raptor engine variant to optimize specific impulse (Isp) to approximately 380 s (8,300 mph; 3.7 km/s).

Starship is planned to eventually be built in at least three operational variants:

- Spaceship: a large, long-duration spacecraft capable of carrying passengers or cargo to interplanetary destinations, to LEO, or between destinations on Earth.
- Satellite delivery spacecraft: a vehicle able to transport and place spacecraft into orbit or handle the in-space recovery of spacecraft and space debris for return to Earth or movement to another orbit. In the 2017 early design concept, this was shown with a large cargo bay door that can open in space to facilitate delivery and pickup of cargo.
- Tanker: a cargo-only propellant tanker to support the refilling of propellants in Earth orbit. The tanker will enable launching a heavy spacecraft to interplanetary space as the spacecraft being refuelled can use its tanks twice, first to reach LEO and afterwards to leave Earth orbit. The tanker variant, also required for high-payload lunar flights, is expected to come only later; initial in-space propellant transfer will be from one standard Starship to another.

Characteristics of Starship are to include:

- Ability to re-enter Earth's atmosphere and retro propulsively land on a designated landing pad, landing reliability is projected by SpaceX to ultimately be able to achieve "airline levels" of safety due to engine-out capability.
- Rapid reusability without the need for extensive refurbishment.
- Automated rendezvous and docking operations.
- On-orbit propellant transfers between Starships.
- Ability of reach the Moon (and Mars) after on-orbit propellant loading
- Stainless steel structure and tank construction. Its strength-to-mass ratio should be comparable to or better than the earlier SpaceX design alternative of carbon fibre composites across the anticipated temperature ranges, from the low temperatures of cryogenic propellants to the high temperatures of atmospheric re-entry.
- Some parts of the craft will be built with a stainless steel alloy that "has undergone [a type of] cryogenic treatment, in which metals are ... cold-formed/worked [to produce a] cryo-treated steel ... dramatically lighter and more wear-resistant than traditional hot-rolled steel."
- Methalox pressure fed hot gas thrusters for attitude control, including the final pre-landing pitch-up manoeuvre from belly flop to tail down. Initial prototypes are using cold gas nitrogen thrusters, which have a substantially less-efficient mass efficiency, but are expedient for quick building to support early prototype flight testing.
- A thermal protection system against the harsh conditions of atmospheric re-entry. This will include ceramic tiles, a double stainless-steel skin with active coolant flowing in between the two layers or with some areas additionally containing multiple small pores that will allow for transpiration cooling.) Options under study included hexagonal ceramic tiles that could be used on the windward side of Starship.
- A novel atmospheric re-entry approach for planets with atmospheres. While retro propulsion is intended to be used for the final landing manoeuvre on the Earth, Moon, or Mars, 99.9% of the energy dissipation on Earth re-entry is to be removed aerodynamically, and on Mars, 99% aerodynamically even using the much thinner Martian atmosphere.
- As envisioned in the 2017 design unveiling, the Starship is to have a pressurized volume of approximately 1,000 m^3, which could be configured for up to 40 cabins, large common areas, central storage, a galley, and a solar flare shelter plus 12 unpressurized aft cargo containers of 88 m^3 total.
- Flexible design options; for example, a possible design modification to the base Starship—expendable 3-engine Starship with no fairing, rear fins, nor landing legs in order to optimize its mass ratio for interplanetary exploration with robotic probes.

3.3. Launch

3.3.1. Earth

The Launch Pad on earth needs some consideration. The colossal size of the Falcon Heavy (70.0m x 12.2m) and eventually Starship needs to be accounted for when using a launch pad. The SpaceX company predominantly use the Kennedy Space Centre Launch pad 39A whenever they launch a Falcon rocket. Hence, this will be used when lifting off from earth as it has already been tested with the rockets that we will be using. This will prevent any unnecessary wastage of resources testing how will are going to lift off from the Earth.

3.3.2. Moon

On Earth, launch pads typically have exhaust plume tunnels or trenches beneath the launch pad to redirect the majority of the heat from the exhaust plume of a rocket. Huge jets of water are also used to transfer the heat as well as acoustic shock suppressors. Concrete is the main material that will be used in the construction of the launch pad due to its strong heat resistance.

As we will not be able to bring any significant amount of concrete to the moon, we will need to find an alternative to concrete for building a launch pad on the moon.

The aforementioned “Lunarcrete”: an alternative to concrete made on the moon from lunar regolith and the main material for our base, will once again be employed for our Lunar launch pad. It is very similar to concrete offering similar properties:

Compressive strength of Concrete: 30-70 MPa
Compressive strength of Lunarcrete: 40-80 MPa

Temperature Coefficient of Concrete: $7x10^6$ / K
Temperature Coefficient of Lunacrete: $5x10^6$ / K

Temperature Coefficient shows us how a material changes its physical properties in relation to a change in temperature. From the results above, it is clear that both materials offer suitable properties for the construction of buildings, as well as launch pads for rockets.

Lunarcrete has been previously made by researchers using regolith brought back to Earth. Steam is used to cure a dry aggregate composed of the lunar regolith. Scientists have suggested that this steam can be obtained by mixing hydrogen with lunar ilmenite at 800 degrees centigrade. This reaction would produce titanium dioxide, iron and water. These by-products, in particular the iron, can be used to reinforce the structures that will be created out of the lunarcrete such as the lining of our underground base as well as the launch pad itself.

3.3.3. Launch procedure

Lift-off and ascent

- First-stage powered flight lasts approximately three minutes, with commanded shutdown of the nine first-stage engines based on remaining propellant levels.
- The second stage burns an additional five to six minutes to reach initial orbit, with deployment of the fairing typically taking place early in second-stage powered flight.
- Subsequent operations are unique to each mission but may include multiple coast-and-restart phases as well as multiple spacecraft separation events.

Spacecraft separation

- After reaching the spacecraft injection orbit and attitude, the Falcon vehicle issues a spacecraft separation command, providing the electrical impulses necessary to initiate spacecraft separation.
- Indication of separation is available in second-stage telemetry.

Contamination and collision avoidance

- If a contamination and collision avoidance manoeuvre is necessary, the second stage performs the manoeuvre shortly after separation.
- A contamination and collision avoidance manoeuvre is provided as a standard service for individual primary payloads.
- For multi-manifested and secondary payloads, please contact SpaceX regarding collision avoidance requirements.

Post launch reports

- SpaceX will provide a quick-look orbit injection report to the customer shortly after spacecraft separation, including a best-estimate spacecraft separation state vector.
- A final, detailed post-flight report is provided within eight weeks of launch.

Disposal

- SpaceX makes every effort to mitigate space debris by responsibly passivating and disposing of hardware on orbit.
- Customer-specific requirements on disposal may impose modest reductions to the performance specifications

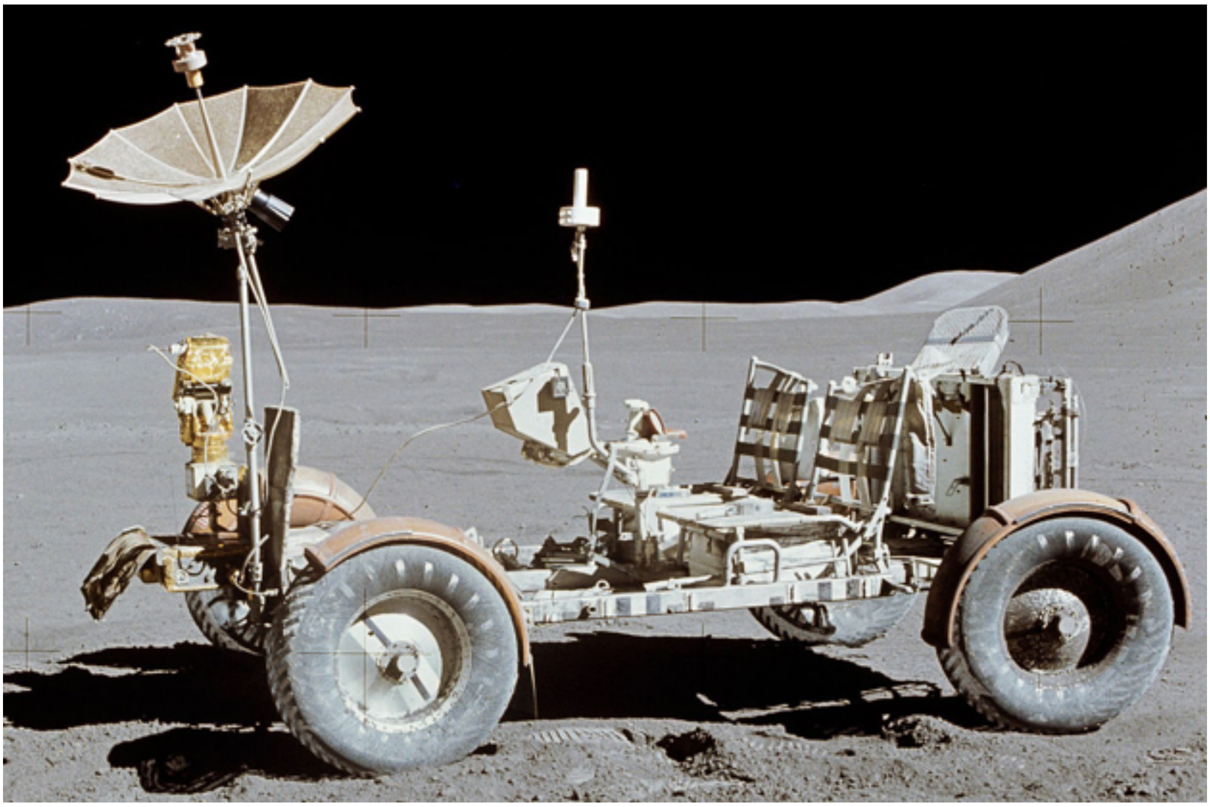
Below is the Launch procedure for the Falcon Heavy rocket as outlined by SpaceX.

Mission Elapsed Time (s)	Event
T-3	Engine start sequence
T+0	Lift-off
T+67	Maximum Dynamic Pressure (22,819,000N)
T+145	Main Engine Cut-off (MECO)
T+148	Stage Separation
T+156	Second-Engine Start-1(SES-1)
T+195	Fairing Deploy
T+514	Second-Engine cutoff-1 (SECO-1)
T+3086	Second-Engine Start-2 (SES-2)
T+3090	Second-Engine cutoff-2 (SECO-2)
T+3390	Spacecraft separation

3.4. Lunar rover

3.4.1. Considerations

Whilst on the moon we will require methods of transport capable of traversing at least 20 km in order to service the Mark-III lunar miners. During the Apollo missions three such Lunar Roving Vehicles (LRVs) were operated (see figure below). Each vehicle was electric powered (by two 36-volt primary silver-zinc batteries) and designed to operate in the low-gravity vacuum of the Moon, allowing the Apollo astronauts to extend the range of their surface extravehicular activities to up to 92km. The three LRVs that were driven on the Moon travelled a maximum distance of 20.1 km (Apollo17).



The LRVs were designed primarily as crew transport vehicles with a limited amount of science payload (moon rocks) capability. Several lessons were learned from the LRV operations on the moon. First, ground speed could not exceed 10 mph in most situations. The ⅙ g environment allowed the vehicle to lose contact with the surface when moderate bumps were encountered at approximately 9 mph, resulting in a momentary loss of control. Second, the lunar dust behaved much like wet sand on Earth and tended to stick to the surface of the rover's wheels. Moon dust is extremely abrasive and dust mitigation measures must be taken to prevent excessive wear at any place where dust can enter. The dust also has an adverse effect on the properties of heat radiators. Within a very short period of time, dust would cover the LRV radiators and the efficiency would drop precipitously.

Additionally, the Apollo astronauts noted that with the open frame design of the rovers, it felt as though a person could fall out of the vehicle while traversing a steep slope. A review of Apollo Lunar Rover operations indicated room for improvement in ride, suit interfaces, and reliability. Apollo mission reports indicate the vehicle performed well during operations but driving on cross slopes was described as feeling “very uncomfortable” by the operators. Suit interfaces for the Apollo LRV also posed challenges for astronauts attempting to sit in the driving seat. The chief problem was the rigidity of the suit torso and the difficulty in bending at the waist, as required for sitting. Lastly, rovers designed for the return to the lunar surface will be required to have a much greater lifespan, a longer range, and be rechargeable.

Owing to these limitations the conclusion was reached that a new Rover design would be required in order to maximise the efficiency of our astronaut’s time.

3.4.2. The Design

The design of our next generation of Lunar Rover is largely inspired by NASA’s “Lunar Electric Vehicle”. On the surface of the moon, travel range is limited primarily by how quickly astronauts can get back to a safe, pressurized environment in the case of an emergency. During the Apollo program, exploration was confined to the distance astronauts could expect to walk back in their spacesuits if their rovers broke down – about six miles. The planned presence of two or more LERs on the Moon would extend that potential range to more than 150 miles in any direction as even in the midst of challenging terrain, emergency shelter and support is less than an hour away. This greatly extended range will enable increased more miners to be serviced whilst also ensuring maximum safety.

Functional Requirements:

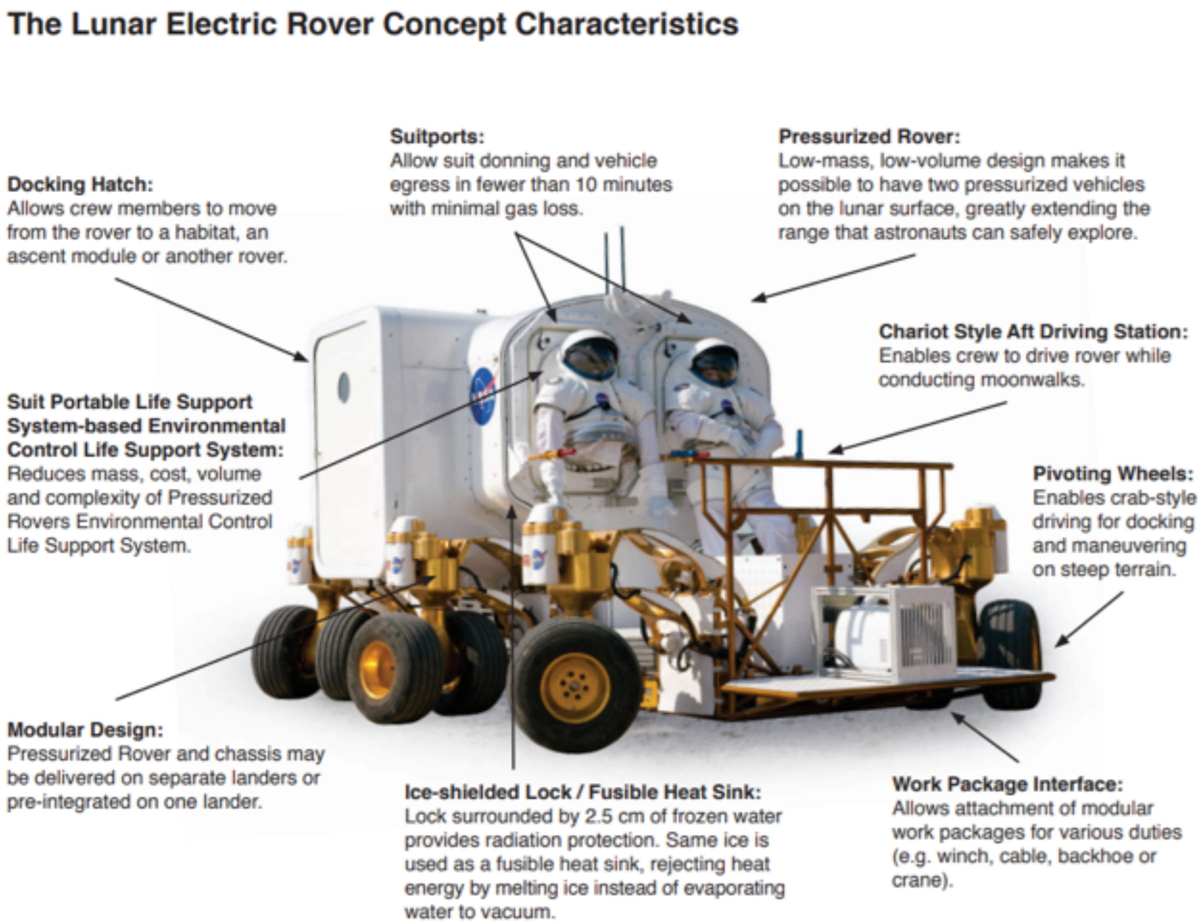
- The LER must be able to hold a crew of two, but can support a crew of four in an emergency
- It can travel at about 10 kilometers per hour
- The mobility chassis wheels are able to pivot 360 degrees, allowing it to drive in any direction

LER Specifications:

Weight: 3000 kg
Payload: 1000 kg
Length: 4.5 m
Wheelbase: 4 m
Height: 3 m
Wheels: 12x99 cm in diameter, 30.5 cm wide

Chassis Specifications:

Weight: 1000 kg
Payload: 3000 kg
Length: 4.5 m
Wheelbase: 4 m
Height: 1.3 m
Wheels: 12x99 cm in diameter, 30.5 cm wide



As detailed by the above figure, the rover will take advantage of multiple cutting edge technologies including regenerative brakes, active suspension and the latest onboard software.

Each rover consists of a mobility chassis and a small, pressurized cabin module. These two components can be delivered to the lunar surface pre-integrated or as separate elements. Astronauts can drive the mobility chassis without the pressurized cabin, by riding in the rotating turrets whilst wearing their spacesuits; the chassis can also be used to carry cargo. The modular design allows various tools – winches, cable reels, backhoes, cranes and bulldozer blades – to be attached for special missions. And the chassis can pick up and reposition solar-powered charging stations, communication relays and scientific packages.

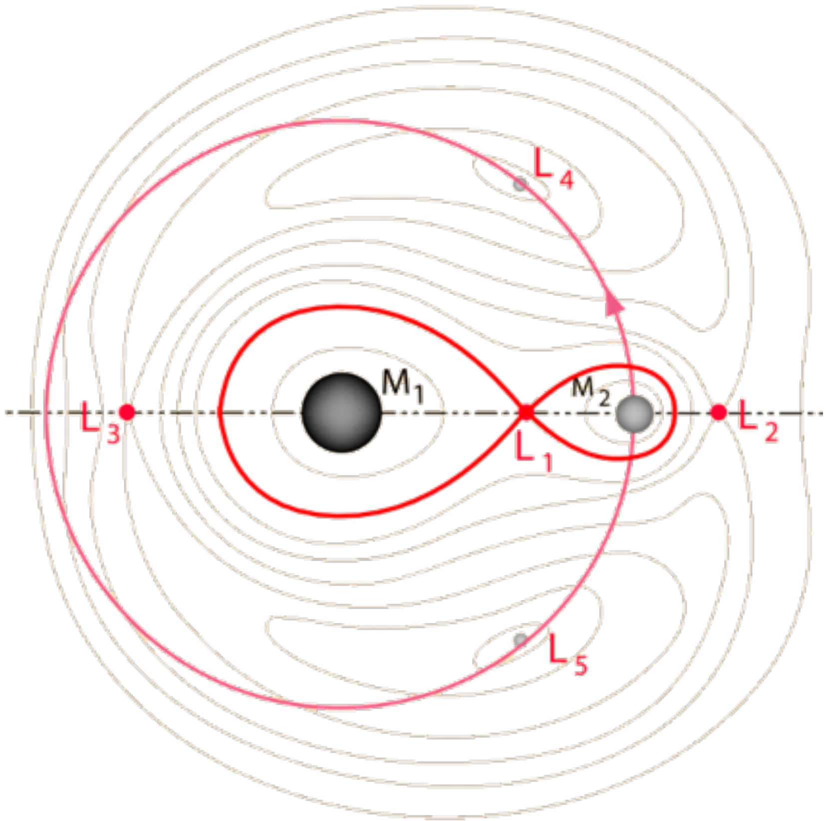
The total weight of the rover comes in at three tonnes and it has an operational payload of a further one tonne. The Rover is designed to hold a crew of two but can support up to four crew in an emergency. Thus, we will require a minimum of ten Lunar Electric Vehicles to safely maintain the lunar base and the Mark-III miners.

3.5. Satellite

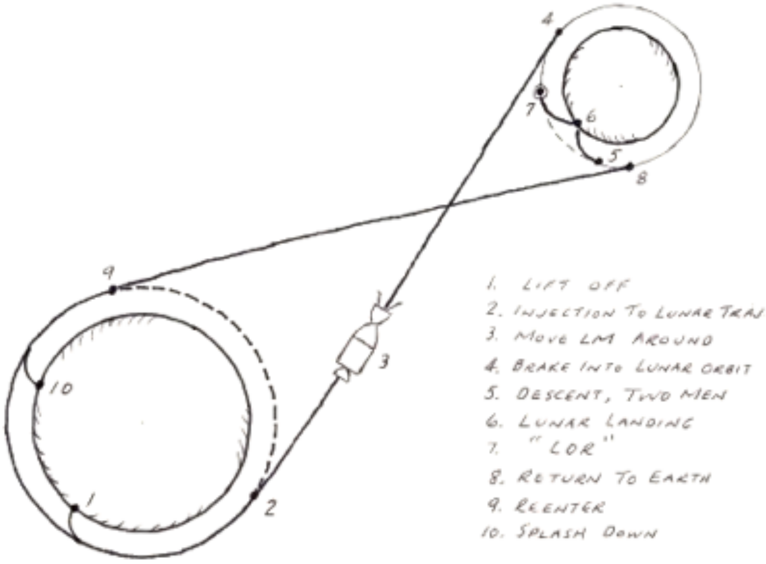
3.5.1. Lagrange concept

As this program will require many flights to and from the moon in both the establishment of a lunar base and the mining of Helium-3, a lot of our money will go into the launching and fuelling of our spacecraft. This fuel expenditure will also have its toll on Earth's environment, which consequently would contradict one of our main goals of this project: being environmentally sustainable.

With this in mind, we considered an idea to launch a satellite in permanent orbit between the Earth and the Moon in order to reduce fuel costs and to maximise the supplies brought to and from the moon. This would hopefully reduce the total number of launches necessary and therefore our toll on the environment (for example the Falcon 9 rocket releases 336,552kg of CO_2 per launch). After some initial research, we discovered that a permanent satellite of this type couldn't simply follow an elliptical orbit without either going miles out of the way in every direction or falling off of its orbital course. Thus, we landed on the idea to have a lunar cycler orbit centring on Lagrange point 1 (L_1 in the image below): a point between Earth and the Moon where net gravitational forces are zero. Apart from minor adjustments in the satellite's orbit every few years, it would require very little maintenance, and the only major cost would be building the satellite, as we could launch it using our own launch pads.



This idea was, in fact, used by Apollo 11. The difference between our orbit and Apollo 11's is that ours is a Lissajous halo orbit. This means that the orbit decays over a much longer time, allowing us to use much less fuel to keep the satellite on course. In addition to this, the nature of the orbit means the satellite would be in direct sunlight for almost all of its time, so solar energy could be harnessed to keep it running for even longer.



NASA's Lunar Orbit Rendezvous (LOR) for Apollo 11

This would allow us to send the Falcon Heavy up with its payload to meet the satellite's orbit above Earth, dock, then send the rocket back down to Earth to be used again in future missions, leaving the payload and its crew on the satellite travelling to the moon. Once close to the moon, it would undock and make its descent onto the lunar surface. On the return journey, the same rocket would simply dock with the satellite above the moon, and undock at Earth, where it would land at the same launchpad from which it took off.

<u>3.5.2. International partnership</u>

In terms of an international partnership, we have plans to make this satellite much like the International Space Station, allowing astronauts of all nationalities to use the facility with the goal of reducing carbon emissions on journeys to the moon and potentially beyond. It could also be a place to conduct scientific experiments that cannot be done on Earth - again like the ISS. The hope is to unite the world over the pressing issue of global warming, and seeing as more countries such as China and India are becoming interested in space travel, we have good reason to ensure that the future of space exploration doesn't become one of the planet's major polluters.

Conclusion

To conclude, our plan has tackled our goal of reinstating humans on the moon and commercially mining the lunar surface for Helium-3 to be used in nuclear fusion. We set out to ensure these targets were met in a cost-effective, sustainable and elegant manner and we believe that these pivotal criteria have been met.

Our transportation system, which comprises of the Falcon series of rockets, takes advantage of the latest innovations in aerospace engineering to ensure maximum cost efficiency and minimum environmental impact. The additional permanent satellite is also designed to further international cooperation, ushering in a new age for space travel.

The Lunar base will be created with innovation at its centre and will look to reinvent the more conventional methodologies of habitation. Sustaining our team of 20 astronauts was the priority throughout its conception and this will be achieved by using the lunar mining operation to evolve the essential, life-sustaining, volatiles. The base will also be predominantly underground as protecting the astronauts from radiation and lunar meteorites was a key challenge. In order to maintain a healthy diet, this necessitated the use of hydroponics and stem-cell cultured meats as natural sunlight would be highly limited.

The commercial aspect of the mission focused solely on the mining of Helium-3 from the lunar regolith, and its subsequent processing, to be transported to nuclear fusion reactors back on Earth. This process will be conducted using the new generation of Mark-III Lunar Miners, which are each capable of excavating 66 kg of Helium-3 per year. This Helium-3 would then have an estimated market value of at least 1.41 million USD per kg, making us significant revenues. The safety and potential power output of nuclear fusion will turn the climate emergency around, thereby allowing humanity to return to a path of mutual coexistence with nature.

We believe that we have laid out a comprehensive plan to establish an entirely new infrastructure linking the Earth and the Moon, but without the innovation of the Apollo Program scientists, none of this would be possible.

Authors

Max McNally - Team leader, Satellite
Euan Baldwin - Team coordinator, Mining, Lunar rover
Frank She - Nuclear fusion
Greg Northwood - Storage of helium, Launch pad construction
Matthew Hoult - Transportation, Launch pad design
Ludo Wilson - Life support on the moon
Jeroan Yip - Base design
Winston Li - Base design

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