Report 1131

How many rocket launches from Mahia Peninsula would it take to establish a lunar colony?

Introduction and summary

Establishing a interplanetary colony is one of the most exciting prospects for our future. Ever since man first landed on the moon in 1969, space technology has been advancing. With this, the idea of creating a viable lunar colony has become a reality. Recently, a new rocket launch site has been developed on the Mahia Peninsula. This offers the chance for New Zealand to become one of the world's leading rocket launch providers. New Zealand can become the premier destination to launch the world's first lunar colony.

It is quickly becoming possible to establish a colony on the moon. Recently China and Europe discussed collaborating to create a lunar colony[1]. It has no longer has become a race to the moon, but a race to establish humans there. Therefore, we will need to consider the resources that we need to achieve this ambitious goal.

Most of the resources consumed during a rocket launch are in the launch itself. The Saturn V, the most recent and only rocket to send humans successfully to the surface of the moon, ended up getting 16.4t to the lunar surface, despite having an initial mass of 2,970t[2]. Only 0.55% of the mass of the initial launch vehicle made it to the surface. Obviously, this makes it apparent that one of the major hurdles to creating a sustainable lunar colony is the amount of rockets required.

Colony

We are defining a colony as a population that will be able to survive without the need of any extra support from earth. Creating a colony like this will require a significant investment and time. A report by Lochran W. Traill, et al. in 2007 examined the theoretical minimum viable population (MVP) required for genetic stability of a human population[3]. This was done by averaging the past 30 years of data in reports made on MVPs for humans. The report found that approximately 4169 people were required to establish a viable population, capable of surviving without intervention and without a planned return to earth after any number of generations. We will take the number 4170 as our MVP, and split this into 2085 males and 2085 females to maximise gene pool and reproductive ability.

The colony is to be constructed in situ, using components and materials brought to the surface with each launch. The structure is to be mainly underground to reduce the impacts of radiation and micrometeorite damage.

Rockets

We will be using SpaceX's ITS (Interplanetary Transport System), an upcoming launch vehicle expected to be first tested in 2020[8]. SpaceX's rocket is perfect for our calculation as it utilises modern and future technology, which will allow for major efficiency improvements, as well as larger payloads to be launched into Low Earth Orbit (LEO). Other rockets such as Rocket Lab's Electron are not suitable as the LEO mass is only expected to be 150-200kg[18] which is hardly enough to launch a human. This means there would have to be a significant upgrade in infrastructure at Mahia but this is out of the scope of the question.

The ITS is a 2 stage rocket, and has 2 configurations of upper stage/payload[8]. One is the standard version with an "Interplanetary Spaceship" which has the main spacecraft used for transfer of crew and cargo to the destination, and the other is the "ITS Tanker" which is used to refuel the Spaceship in LEO. The system works by first launching a Spaceship into LEO, then it is refueled with multiple tanker missions to full capacity again. It then will then transfer to its destination via a Hohmman transfer Orbit. All components of the system are reuseable, including the large first stage booster. The important specifications for the Tanker and Spaceship stages are as follows:

Spaceship: Empty Mass: 150 tonnes, Fully Fueled Mass: 2100 tonnes, Specific Impulse: 382 sec, Normal Payload: 450 tonnes to Low Martian Orbit from LEO once fully refueled.

Tanker: Empty Mass: 90 tonnes, Fully Fueled Mass: 2590 tonnes, Specific Impulse: 382 sec, Normal Payload: 380 tonnes of fuel to LEO.

Both spacecraft are powered by Raptor Vacuum Engines with a specific impulse of 382 sec running on Liquid Oxygen and Liquid Methane. The first stage doesn't matter in this context as nothing is to be changed by it and any Δv cost increases due to a different launch site will be made up for by the second stages. The payloads are different from their normal loads as we would be going to the surface of the Moon, not Martian orbit. These will be calculated in the report.

Launching from Mahia Peninsula will also reduce the efficiency of the launch vehicle. This is due to being closer to the earth's axis. As the earth spins on its axis, each part of the surface rotates at a different velocity. At the equator, this effect is maximised as the distance from the earth's axis is at maximum. This is why rockets are often launched close to the equator. However, Mahia peninsula is far away from the equator and consequently will cause rockets to have to expend extra fuel in order to reach orbit.

We can work out the relative velocity based on the latitude of the launch site using trigonometry. We will compare Pad 39A at Cape Canaveral with Mahia Peninsula.

Pad 39A Latitude = 28.608138°[23]
Mahia Peninsula Latitude = -39.258532°[22]

The max rotational velocity can be calculated by 24*6378 (earth's radius[21] times its rotational period)

$$V_{max} = 1669.791ms^{-1}$$[

$$V_{max} \cdot \cos\Theta = V_{site}$$

$$V_{39A} = 1669.791\cos 28.608138 = 1465.9ms^{-1}$$

$$V_{Mahia} = 1669.791\cos 39.258532 = 1292.9ms^{-1}$$

Next we calculate the orbital velocity for a parking orbit for the vehicle. The parking orbit we chose was 250,000m, as this is the parking orbit used with many spacecraft and is likely to be used with the ITS when it is finally launched.

$$G = 6.67 \cdot 10^{-11}Nm^2kg^{-2}, M_{earth} = 5.972 \cdot 10^{24}kg$$

$$r = (r_{earth} + r_{orbit}) = 6,621,000m$$

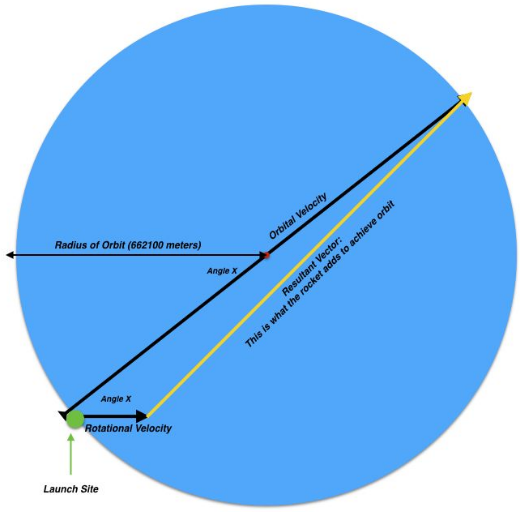
$$V_{orbital} = \sqrt{\frac{GM}{r}}$$

$$V_{orbital} = 7756.41ms^{-1}$$

The latitude of the site is equal to the inclination of the orbit (corresponding angle rule), angle X on the diagram. We can then work out the vertical and horizontal velocity components needed for each launch site.

$$\therefore \sin\Theta = \frac{V_{vertical}}{7756.414732}$$
$$\therefore \cos\Theta = \frac{V_{horizontal}}{7756.414732}$$

Then take the rotational velocity off the horizontal velocity (we are launching in the same direction as earth's rotation.



$$V_{resultant} = V_{horizontal} - V_{rotational}$$

Then combine the two vectors again to get the total velocity needed.

$$V_{needed} = \sqrt{(V_{resultant})^2 + (V_{vertical})^2}$$

$$\therefore V_{39A} = 6507.42ms^{-1}$$
$$\therefore V_{Mahia} = 6804.68ms^{-1}$$

Therefore we can calculate the difference in Δv between launch sites.

$$\Delta v_{difference} = 6804.68 - 6507.42 = 297.26ms^{-1}$$

The "Spaceship" that carries the cargo and people can hold up to 210000 kg of rocket fuel. This needs to be entirely filled before the rocket sets off to the lunar surface. Each refueling "Tanker" normally can take 380000 kg of fuel to LEO. These rockets are reusable and land back on the earth. However, as we are using Mahia peninsula as the launch site, we will need 297.26ms^{-1} of extra Δv to launch. This will reduce the amount of fuel that is able to be transported to LEO to refuel. This can be calculated using the Tsiolkovsky rocket equation.

$$\Delta v = V_e \cdot \ln\frac{M_0}{M_f}$$
$$\Delta v = 297.26ms^{-1}, V_e = 3747.42ms^{-1}, M_0 = 380000 + 90000 = 470000kg$$
$$297.26 = 3747.42 \cdot \ln\frac{470000}{M_f}$$
$$M_f = 434160kg$$
$$M_{fuel} = M_f - M_{vehicle}$$
$$M_{fuel} = 344,160kg$$

We can therefore work out how many refueling rockets will need to be launched to completely refuel the main vehicle.

$$\frac{1950000}{344160} = 5.666 \approx 6$$

There will need to be an extra 6 rocket launches to completely refuel the main vehicle. Therefore there will need to be 7 rocket launches per lunar landing. We will now need to consider how much mass each "Spaceship" is able to transport to the surface. This can be done using the specific impulse equation and the Tsiolkovsky rocket equation. The extra fueled the "Spaceship" requires to get into orbit due to the extra

Δv requirement is accounted for, as we have calculated a full refuel of 1950 tonnes, as well as the excess of 0.3333 tanker loads.

$$V_e = I_{sp} \cdot g_0 \therefore V_e = 382 \cdot 9.81 \therefore V_e = 3747.42ms^{-1}$$ [4]

$$\Delta v = V_e \cdot \ln \frac{M_0}{M_f}$$

Using the Δv "map" [4] we can find the amount of Δv required to get the the Moon's surface from LEO is 5670 ms^{-1}

$$I_{sp} = 382s, M_0 = 2100000kg, M_f = 150000kg, \Delta v = 5670ms^{-1}$$

$$5670 = 3747.42 \cdot \ln \frac{2100000 + M_{payload}}{150000 + M_{payload}} \therefore M_{payload} = 400,760kg$$

This means that 19% of the LEO mass will make it to the Lunar Surface. This is a large improvement compared to the Saturn V, which only made 10.2%.

Lunar Base

The materials required to construct a lunar base, and then the people to inhabit that base, must be transported to the moon. A large amount of detail about the base is required in order to estimate the total payload required, and thus the number of launches required to transport it all.

Construction

For a population of 4170 humans, a large and complex base structure will be required. A minimum of 4170 rooms will be required to house each person, however this number should be increased to 4,200 at a minimum to allow for contingency, accidental population growth and repair/maintenance of rooms to be carried out. A NASA study[5] said that a minimum area for sustainable living for a person is 40m^2. This means that at a minimum, living quarters would have to be 6*7 metres to house a person, and 2 metres high. This would result in a floor area of 176,400m^2 for the population. Interconnecting hallways would then encompass another approximate 10000m^2 of floor area. Utility rooms for support systems would then require approximately another 10000m^2 of floor area. These are the water treatment system, heating and air filtration, and cooking/catering areas.

This results in a calculated total of 196,400m^2 of floor space. Due to the nature of these calculations, it is wise to allow extra floor space - therefore a ballpark estimate of 200,000m^2 of floor area should be sufficient for the entire base. This has an approximate size of 450m*450m in total.

The base must be constructed underground at a depth in excess of 10m. This will practically eliminate solar radiation, preventing it reaching the inhabitants on a continuous basis and causing genetic defects (which could invalidate our MVP estimate). It will also drastically reduce the amount of material required to construct the base. Rather than having to transport bulk building materials from earth, many building materials can be made on site using by-products of drilling out the underground structures. Insulation and interior panelling must be brought to the site, but only minimal structural elements will be required to stabilise the underground structure rather than to fully construct an entire building.
Insulation can be achieved by keeping the interior structure separate from the surrounding ground, supported by metal or concrete supports. The vacuum in the gap will result in efficient insulation without increasing mass of construction.

Each room is 7*6*2m, meaning the overall volume of a room is $84m^3$. A useful estimate for calculating the mass of construction, is the mass of various International Space Station modules. A NASA BEAM module[15], which provides $16m^3$ of interior space, weighs 1400kg. If each room has a volume of $84m^3$, then the approximate mass of the room's construction must be:

$$\frac{84}{16} = 5.25$$

$$5.25 \cdot 1400 = 7350kg \text{ Per Capita}$$

$$7350 \cdot 4170 = 30,649,500kg \text{ Total}$$

We can also assume that the farming structures have a similar mass profile to the BEAM modules[15]. Therefore, to create $38216m^2$ of usable volume:

$$\frac{38216}{16} = 2388.5 \text{ BEAM Module Equivalents}$$

$$Total = 2388.5 \cdot 1400 = 3,343,900kg$$

Finally, we can add together both values and get a total structure mass.

$$M_{Structure} = 30649500 + 3343900 = 33,993,400kg$$

Water

The WHO[6] states that 15 litres of water, per person per day, must be available for sanitation and drinking, to survive. This could be reduced by using more effective methods of sanitation, and an optimum temperature aboard the base.

At 15 litres per day, 4170 people would consume 62,550 litres of water. This would require that much water to be processed and returned to drinkable form every day. The University of Memphis Civil Engineering department estimates that a water treatment plant would consume 1800kWH per 1 million gallons of water treated. This is 3.785 million litres. As the amount of water used by a population of 4170 people is:

62550/3785000 = 0.017 of the 1 million gallons

Then the power usage would be approximately 30.6kWH per day for a single plant providing water to the entire facility. This is 1.275kW, or 0.0003kW per capita.

Lighting

A 500 lumen light is sufficient to provide adequate lighting for a $5m^2$ space. Typical LED efficacies are in the order of 100lm/w[9] resulting in a power usage of $1W/m^2$. If humans are to maintain approximately a 24 hour day/night cycle, the lights will be on, on average, 50% of the time. To make the system more efficient, it would be wise to separate the day and night schedules of the station's inhabitants into distinct groups, to maintain a more constant average power usage. This minimises the total peak power usage.

Power usage of Farming

To provide consistent hydroponic lighting, a LED lighting system would be used. The efficacy of this system would be lower than that of a regular LED lighting system due to the type of LEDs used, which would be optimised to provide more infrared light to help the plants. This would therefore approximately be 50lm/w.

For an area of $38255m^2$, lit by 2W LED modules for every $1m^2$, the power usage would be 76510W, or 76.51 kW at a 100% duty cycle to maximise plant growth.

Heating

The base will be heated by the same system that provides air filtration. This system would dissipate an average power of 0.1kW into each room continuously to maintain a constant temperature. This means a 100% duty cycle and will maintain a constant temperature.

Power Total

Energy for the lunar base will be provided through the use of nuclear power. We are assuming that as part of the lunar base, energy would be required for the following purposes (in no particular order):

Power usage per capita

Purpose	Notes	Parameters	Avg. Power required
Lighting	Minimal LED lighting to be used in all rooms within base.	A single 5W LED module per $5m^2$ room. Used for half of the day on average.	5W per person, 50% duty cycle
Personal devices	Modern tablet device, powered by station power.	Average device consumption of 10W. Used ⅕ of the time.	10W per person, 20% duty cycle
Cooking	5kW[19] cooking facilities	Used once daily for 1 hour	5kW, 5% duty cycle

Average power usage per capita (W):

$$5 \cdot 0.5 + 10 \cdot 0.2 + 5000 \cdot 0.05 = 254.5W$$

Overall base power usages

Heating and Air filtering	Central heating and air filtration system for entire base.	10kW system for 100 rooms (0.1kW/room, continuous)	420kW, 100% duty cycle
Communications	Communications to earth	Central communications modules. Efficient system with an average use of 1kW, including a 100W transmitter[11].	1kW, 100% duty cycle
Transport (lunar vehicles etc.)	Electric vehicles to be used for transportation. Must be charged from base.	Vehicles would take 10kW charge. Would be charging 5% of the time due to infrequent usage.	10kW, 5% duty cycle
Food preparation	Cooking of vegetables.	100 5kW cooking systems.	500kW, 10% duty cycle
Farming	Hydroponic lighting	$19108m^2$ * $2W/m^2$ LED lighting system.	76kW, 100% duty cycle
Melting ice	Average temperature of -50°C near the Shackleton crater. Heating 50L ($50,000cm^3$) of ice per day to 0°C to use as input to	5kW heater[12]. Melts ice in several hours.	5kW, 10% duty cycle

	closed loop water recycling system.		

Average Power usage for base systems (kW)
$420 + 1 + 76 + 10 \cdot 0.05 + 500 \cdot 0.1 + 5 \cdot 0.1 = 547.5kW$
Therefore the total power usage of the station is 547.5kW, plus 4,170 multiplied by the average power used per capita.
$547.5 + 4170 \cdot 0.2545 = 1,608.765kW$
Full sunlight doesn't reach the Shackleton crater, due to low latitude near the south pole as well as the long day night cycle of 27.32 days. To use solar power, large amounts of solar panels, as well as batteries, would be needed to have a working electrical system. A more effective alternative is to use a nuclear reactor. A nuclear reactor is compact and produces power all of the time, with high reliability. Nuclear fuel can also be obtained from the moon[7]. A nuclear reactor would have to be sized to the total power usage, given expected growth, and a 20% derating for safety reasons. A set of batteries may be employed to keep basic systems running during reactor maintenance. The main power consumption of the central heating system would be switched off for this time.

The total estimated average power usage of the base is 1.61MW. To allow for higher peak power demand and a 20% derating of the reactor, a sensible size is 2MW.
A reactor designed by General Electric for use by the U.S. military, the S8G, produces 220MW of power and has a mass of 2,750,000kg. To produce an estimate for the mass of a 2MW reactor, this power to mass ratio can be scaled down to a 2MW reactor.

$$\frac{220}{2750000} = 8 \cdot 10^{-5} MW/kg$$

And for 2MW:

$$M_{Production} = \frac{2}{8 \cdot 10^{-5}} = 25,000kg$$

Battery mass:
To allow the base to run at the same 2MW rating of the reactor, for one hour of maintenance, a contingency of 2MWH of battery power is sufficient. In an emergency, the power usage of the base could be far reduced to allow longer maintenance.

$$2MWH = 2,000,000WH$$

Maximum Lithium-Ion battery density is 265Wh/kg[17]

$$\therefore \frac{2,000,000}{265} = 7547.17kg$$

Finally, we can calculate the total mass of the electricity system.

$$M_{Electricity} = M_{Production} + M_{Battery} = 32,547.17kg$$

Farming

Food is one of the hardest things to create sustainably on the moon. We will need to calculate how much each human needs to consume in order to maintain a healthy diet and enough calories. We have decided farming on the moon is the only sustainable way to feed the colony. We came with a diet to fill as many nutritional areas as possible while being only plant based to make it easy to produce:

Per 100g	Calories	Protein	Carbs	Fat	Fibre	Mg	Iron	Vit C	Vit A	Vit B-6	Calcium	Potassium	Sodium
Potatoes	77	4%	5%	-	8%	5%	4%	32%	-	15%	1%-	12%	-
Broccoli	34	5%	2%	-	10%	5%	3%	148 %	12%	10%	4%	9%	1%
Spinach	23	5%	1%	-	8%	19%	15%	46%	187%	10%	9%	15%	3%
Soybeans	446	72%	10%	30%	36%	70%	87%	10%	-	20%	-	51%	-
Marrow Stem Kale (x3)	32	6%	1%	-	16%	6%	2%	58%	100%	10%	23%	6%	-
Lentils	116	18%	6%	-	32%	9%	18%	2%	-	10%	1%	10%	-
Peanuts	567	52%	5%	75%	36%	42%	25%	-	-	15%	9%	20%	-
Corn (x2)	365	18%	24%	7%	-	31%	15%	-	-	30%	-	-	1%
1.1kg	2089	>100	>100	>100	>100	>100	>100	>100	>100	>100	47	>100	5

The lack of Calcium can be addressed through small dietary supplements, such as ingested tablets. These tablets can be created through the refinement of lunar rock, due to the high calcium content of the rocks.[14] Sodium can be recovered from sodium based ionic compounds located in ice collected for water.

The plants will also have to have time to grow. This means we will have to have multiple times the amount of crops needed for a day growing. This means there will always be some crops that have matured[20].

Potatoes = 90 days, Corn = 60 days, Spinach = 50 days, Broccoli = 120 days
Spinach = 90 days, Peanuts = 120 days, Lentils = 80 days, Kale = 80 days
Soybeans = 60 days

$$Average = \frac{90+60+50+120+90+120+80+80+60}{9} \approx 84$$

If we assume there are on average 4.5 “plants” per m^2, with a edible mass of 2.5 kg per plant[13], we can find the food mass per m^2:

$$2.5 \cdot 4.5 = 11.25kg$$

1.1kg of food is needed per day for a female, and 1.375kg is needed for female.

$$1.1 \cdot 2085 = 2293.5kg$$

$$1.375 \cdot 2085 = 2866.88kg$$

Therefore the total food required for the colony per day = 5160.375kg

Because on average the plants take 84 days to grow, we must have 84 days worth of growth at different stages on going at all times. The total mass of all these plants is:

$$5160.375 \cdot 84 = 433,471.5kg/cycle$$

This is the amount of food which has to be growing at any one point in time to sustain the colony. Two cycles of nutrients and seeds will be taken in order to start off the farming system.

$$M_{Growing} = 2 \cdot 433471.5 = 866,943kg$$

If we allow for 1 m for height of growing room for plants for roots and leaves, we can calculate the total volume of the farming infrastructure:

$$\frac{433471.5}{11.25} \approx 38225m^3$$

This can then be used to calculate the mass of this structure.

However, over the course of the days which the crops will take to mature, an alternative, temporary source of food will be needed. Soylent will be the choice of food, which is a powder based meal that provides all the required nutrients, minerals and vitamins needed to sustain a healthy diet[16].

1 male requires on average 2500 calories, while a female requires on average 2000 calories.

1 scoop (43.5g) = 200 calories

$$\frac{2500}{200} \cdot 43.5 = 543.75g/day$$ for males

$$\frac{2000}{200} \cdot 43.5 = 435g/day$$ for females

Assuming that it takes approximately 3 days for the passengers to finish the journey to the lunar surface. The total time they will consume soylent will be this time plus the time it takes before the planted crops started yielding.

$$Days = 3 + 84 = 87$$
$$0.54375 \cdot 2085 = 1133.71875kg$$
$$0.435 \cdot 2085 = 906.975kg$$
$$1133.71875 + 906.975 = 2040.69375kg/day$$
$$M_{Temporary} = 2040.69375 \cdot 87 = 177,540.36kg$$

Therefore, when we combine both expendable food and the sustainable food we get a final food total. We have added in the mass of the food that is growing as this will require nutrients to grow. This can come from minerals extracted from moon rock as well as human waste once the colony is active, but there would need to be an initial amount brought over from earth in the form of fertiliser and seeds.

$$M_{Food} = M_{Temporary} + M_{Growing} = 1,104,483.36kg$$

Humans

Humans also have mass which will need to be considered. We have used an average male mass of 80 kilograms and an average female mass of 65 kilograms.

$$\frac{4170}{2} = 2085$$

$$2085 \cdot 80 = 166800kg$$ of males

$$2085 \cdot 65 = 135525kg$$ of females

$$Total = 166800 + 135525 = 302,325kg$$

Total Mass

$$Mass_{Total} = M_{Structure} + M_{Electronics} + M_{Food} + M_{Humans}$$
$$Mass_{Total} = 33,993,400 + 32,547.17 + 1,104,483.36 + 302,325$$
$$Mass_{Total} = 35,432,755.53kg$$

Evaluations & Further Assumptions

Overhead

- ➢ We have assumed a 20% overhead on the mass of the base. This is to allow for other infrastructure and items such as furniture, tools, space suits, communications equipment, rovers, refineries, 3D printers, mining machines/tunnel machines, etc. To calculate the actual mass of these items would be very difficult due to the scale of the colony, and some what impossible due to the unknown that is technological development let alone the time it would take. While this may have some inaccuracy, it is better than not accounting for it at all.

Rockets

- ➢ The rocket used to create the moon base is the SpaceX ITS, as of 05/08/17
- ➢ All components and technology can be developed within the near future.
- ➢ The failure rate for rockets is approximately is 0.79% for manned missions[10]. However, failure doesn't necessarily mean a complete loss of vehicle or life, just a failure to complete the full mission parameters, but for simplicity we will assume all on a failed launch is lost.

Lunar Base

- ➢ The base will be located at the Shackleton Crater due to the large amount of ice and other resources/materials.
- ➢ Built underground to avoid the risks of radiation to equipment and people.
- ➢ Food is 100% plants grown on site to allow for easy production.

Conclusion

Our total mass for our lunar colony, including humans is 35,432,756kg. However, including a 20% overhead we get:

$$35,432,755.53 \cdot 1.2 = 42,519,306.64 \approx 42,519,307kg$$

For every 400,760kg transported to the lunar surface, 7 rockets are launched from the Mahia Peninsula.

$$Num_{Payloads} = \frac{Mass_{Total}}{Mass_{Payload}}$$

$$Num_{Payloads} = 106.1 \approx 107$$

For every payload going to the moon, 6 extra fueling rockets are required. Therefore 7 rockets per payload to the lunar surface.

$$Num_{Launches} = 107 \cdot 7 = 749$$

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