BADMINTON SCHOOL

BMC

Badminton School Submission to
the 2020 Blott Matthews Challenge:

LUNA 4 LIVING

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Summary

Our challenge was to design a moon base, capable of self-sustainment and able to hold a maximum of 20 people. Along with transport, and a profitable commercial activity. Our resources had to be existing technology and we had to use real-life design concepts to enable the transport to carry all our resources and people. We collaborated and also worked separately to bring together our overall plan.

We decided upon not one, but two commercial activities; one being sponsored research for new scientific discoveries, utilising the lower gravitational forces to our advantage, the other an exclusive package holiday to the moon, with activities such as moon hikes, space painting, history of the moon, and also including sleeping and eating on the moon. Our base is to be located on the lunar south pole and the most self-sustaining it could possibly be, and we took this into account when researching and designing our project.

Acknowledgements

Firstly we would like to thank Richard Blott and Charles Matthews for such an amazing opportunity to partake in such a scheme like this one and for inspiring us to delve deeper into our passions and understanding of engineering.

We would also like to thank our Physics teacher, Mr Owain Hutchings for introducing us to this activity and overseeing our operations, and again, inspiring us to look into further detail about something we all love.

Lastly, we would like to congratulate each other on our achievements so far and we hope to continue working as a team in the future as we have had so much fun collaborating for this project.

Our Team:

Lucia Adams:

I am fascinated by this project as I am currently taking Mathematics, Further Mathematics, Physics, Chemistry and Computer Science AS. My main passion is Programming and Maths, with my hope to study Maths and Computer Science in the future. The part I have focused on is oxygen and energy production for our moon base. I have loved researching the possibility of having self-replicating systems which involve both robotics and maths. Meanwhile, it suggests solutions for energy consumption on earth to tackle global warming and help the environment, which is an area I feel strongly about.

Kiki Benson:

I am currently taking maths, further maths, physics and economics A-levels and I hope to study either economics or aerospace engineering at university. The competition aligned perfectly with my interests as I was able to apply some business techniques learnt whilst still learning about spacecraft. I really enjoyed looking at activities that could be carried out on the moon and the effects of microgravity.

Lyra Guo:

I am doing A levels in Maths, Further Maths, Physics and Chemistry. And my acquired knowledge of rockets in this project will hopefully be helpful for being an aerospace engineer or physicist in the future. As a member of the transportation team, my aim is to work with the other team members to bring people to and back from the moon safely. I researched extensively on rocket fuels and rocket systems, which matches perfectly well with my interest in physics and maths.

Julia Kim:

I am currently taking Maths, Further Maths, Physics and Chemistry for A-Level. In the future, I would like to pursue a career in engineering; I am keeping my options open for many different fields of engineering but my interest in nuclear engineering grew last summer after seeing a nuclear fusion reactor at Seoul National University. Thus, this led me to research in nuclear aspects of energy which could be used in our moon base. Furthermore, I have looked at the possibility of autonomous construction of the base as the most spoken topic in the science industry now is undoubtedly Artificial Intelligence and advanced robotics. The BMC gave me an opportunity to gain invaluable skills such as working collaboratively as a group and allowed me to research creatively.

Julia Kwok:

Hello! I'm Julia Kwok, and I study A-Level Maths, Further Maths, Chemistry and Physics. In the project I've been working on finding out a cost for launching the rocket and what trajectory it might take. In the future I would like to go to university to study (physical) natural science or mathematics, with the goal of getting a PhD or doing research in mind, but have not yet ruled out the possibility of becoming an engineer. This project interested me because I thought I could use it as an opportunity to learn more about how engineering projects are planned out and constraints identified through personal experience.

Claire Leng:

Currently I take Maths, Further Maths, Art and Physics. I am also doing an EPQ project focusing on the use of additive manufacturing in buildings and constructions. In this project, I focused on exploring the use of materials, designs, and structural components of commercial spacecraft. This project allows us to understand the fundamental theorem of engineering and materials. I especially enjoyed learning the characteristics of the materials and how they can be used in different parts of the spacecraft. I would like to explore more aspects of engineering in university.

Anfisa Rapotina:

I do Chemistry, Physics, Maths and AS level Computing. This challenge interested me, because I wanted to improve my teamwork skills as well as exploring my interest in investigating the universe. In the future I would like to do chemical engineering at university and as a career.

Orla Stewart:

I am currently studying Maths, Physics and Economics at A-level and I am interested in becoming a pilot or engineer someday, either as a structural/civil engineer or an aerospace engineer, so this project perfectly fitted my interests. Part of my role in our team was to oversee the whole project proposal like a project manager, however I also have an interest in structural engineering and design, so I took on the challenge of designing our moon base, in terms of researching the structure and materials.

Part 1- Commercial activity

Requirements:
"Propose a commercial activity to be undertaken on the Moon, describing the major components and processes and indicating in general terms how such activity might generate income and profit."

Introduction:

Coming up with an idea for a commercial activity was quite tricky for us as we had to take into account how economical, profitable and beneficial it would be. We came up with the ideas of mining, tourism and research labs.

Mining:

We looked at the possibility of obtaining metals and the chemicals on the moon and selling them on earth. We carried out our research and found out that the moon holds REMs (rare earth metals) and we realised that it would be profitable for us to mine these and sell them on earth especially because of the technological era we are in. These metals are present in smartphones, medical equipment, electric cars etc. China produces 90% of these and with its reserves estimated to last only 15-20 years from now, and with the growing technological market, obtaining this metal from the moon would be profitable. However, the United Nations outer space treaty does not allow anyone to claim ownership of the moon. This implies we may not be able to mine the moon commercially, in addition this would require heavy spending on capital, as we would need to invest in robots to mine as well as extract the materials.

Tourism:

We also considered the idea of organising package holidays to the moon. Customers would pay a fee that would have transport, activities and feeding involved. We took into account that gravity on the moon is 1.62 m/s^2 and realised that we could utilise this and come up with fun activities. However, after calculating the potential cost of these holidays we weren't sure of how profitable it would be, because if it's too expensive we would only have a limited range of customers. In addition space travel has a number of health implications.

Components of the holiday:

The trip would last a total of three days. The first day, being the day of arrival would mostly be about health and safety as well as learning how to walk and run on the moon. The second day would be participation in the activities and the last day would be packing up to journey back to earth.

<u>*Before Flight-*</u>

We firstly took into account the health and safety implications of moon travel and decided that the start of the holiday would be a training session, that would prepare organs and bones for the change in atmosphere, followed by safety briefings.

<u>*Upon Arrival-*</u>

Tourists would be given a tour of the moon base, another safety briefing as well as being made aware of the timetables and schedules.

The Activities-

- Capture the flag- This simple outdoor game plays on the fact that countries have planted their flags onto different parts of the moon. The game would be very enjoyable as the sensation of running on the moon would be much different to that of the earth as a result of the difference in gravity which would be very entertaining. The game would also be a good form of physical activity to prevent the deterioration of the bones.
- Bird Simulation- This activity would give our tourists the chance to fly. They would put on wings and fly around an enclosed space. How it would work, is the theory that will the lower gravitational pull of the moon, and the normal atmospheric pressure of the air on earth (101 kPA), they could generate lift using their wings. It would be good fun being able to float and fly around.
- Landscape Painting- The views on the moon would be much different from that of earth's and we would give people the chance to paint pictures of the view, whilst floating and bobbing around.
- Exercise- Whilst on the moon everyone would be required to complete a minimum of two hours of exercise, in order to prevent bone and muscle loss.

Fig.1- soft suit

Space suit research:

Requirements for space suit:

- Stable internal pressure
- Mobility
- Supply of breathable oxygen and elimination of carbon dioxide
- Temperature regulation
- Communication system collecting and containing solid and liquid body waste + shielding against ultraviolet radiation and particle radiation

Fig.2- A hard shell suit

Suit types:

- Soft suits typically are made mostly of fabrics. All soft suits have some hard parts, some even have hard joint bearings. Intra-vehicular activity and early EVA suits were soft suits. Advantage - no discomfort for the user (like 3 snow suits as one). However this suit is used in low pressure only, which requires pre-breathing exercises before use.
- Hard-shell suits are usually made of metal or composite materials and do not use fabric for joints. Hard suits joints use ball bearings and wedge-ring segments similar to an adjustable elbow of a stove pipe to allow a wide range of movement with the arms and legs. Main advantages: firstly, the joints maintain a constant volume of air internally and do not have any counter force, which means the astronaut does not need to exert to hold the suit in any position; secondly, hard suits can also operate at higher pressures which would eliminate the need for an astronaut to pre-breathe

oxygen to use a 34 kPa (4.9 psi) space suit before an EVA from a 101 kPa (14.6 psi) spacecraft cabin. But the joints may get into a restricted or locked position requiring the astronaut to manipulate or program the joint (which is not a problem - hard-shell space suit had a flexibility rating of 95%).

- Hybrid suits have hard-shell parts and fabric parts. For example, NASA's Extravehicular Mobility Unit (EMU) uses a fiberglass Hard Upper Torso (HUT) and fabric limbs. ILC Dover's I-Suit replaces the HUT with a fabric soft upper torso to save weight, restricting the use of hard components to the joint bearings, helmet, waist seal, and rear entry hatch. Virtually all workable space suit designs incorporate hard components, particularly at interfaces such as the waist seal, bearings, and in the case of rear-entry suits, the back hatch, where all-soft alternatives are not viable. Contain advantages and disadvantages of both, soft and hard-shell suits.

Fig. 3- A spacesuit in space

- Skin tight suits, also known as mechanical counterpressure suits or space activity suits, are a proposed design which would use a heavy elastic body stocking to compress the body. The head is in a pressurized helmet, but the rest of the body is pressurized only by the elastic effect of the suit. This mitigates the constant volume problem, reduces the possibility of a space suit depressurization and gives a very lightweight suit. Nevertheless these suits may be very difficult to put on and face problems with providing uniform pressure.

Fig. 4- Skintight suit

Research Labs:
We looked into the possibility of providing labs for medical research on the moon. Again, utilising the lower gravity and and so opening up possibilities for research that we may not be able to conduct on the surface of the earth.

Conclusion:
Space suits:
The best suit turned out to be the Hybrid suit. It was most appropriate for the activities we had planned and the most viable option.

The suit has a mass of 47 pounds (21 kg) without a life support backpack, and costs only a fraction of the standard US$12,000,000 cost for a flight-rated NASA space suit. The Apollo suit program cost about $90 million, and produced 60 suits of several types. The first group of 5 Block II (lunar) suits were delivered under a $5M contract. The PLSS was a separate $20M program.

A problem we encountered is that much of that was R&D, and not really an individual suit cost. IOW, while 60 suits were produced for $90M, a 61st suit would not have cost an additional $1.5M. It’s estimated that individual suit prices ranged from $90,000 to $400,000, with the A7LBs (the lunar suits) in the $250–400K range.

The overall cost, to design, develop, test and evaluate then certify and produce a spacesuit, the answer is around $300 to $500 million dollars. The recurring cost of copies would be less obviously around $10 - $15 million dollars.

Conclusion:
After weighing the pros and cons of the above, we decided to provide the holidays as well as carry out the medical research. The prospect of a holiday on the moon is an idea that is bound to generate a lot of income. However, after calculating the potential costs and how much we would have to charge consumers, we then agreed on offsetting this cost with the medical research labs. Similar to the way in which commercial airlines transport cargo, in order to make a larger profit, the medical research labs would help subsidize the costs of these holidays.

Part 2- Moon Base

Requirements:
"Design a permanent Moon base capable of sustaining at least 20 persons, maximizing self sustainment. Costs need not be stated but solutions should seek to be economical i.e. not extravagant in use of resources."

Introduction:
When discussing what our moon base would consist of, we considered the structural materials of it, such as what the walls etc would be made out of, and the shape and size of the building, but we also discussed what we would do to make it comfortable for the people living in it and what facilities it would contain, all whilst being able to provide room for the commercial activities and living standards, such as a food preparation area.

Initial research:
Our initial idea was to have an inflatable building; easy to transport, repair, set up and sustain due to the large difference in pressure on the moon to what we are used to back on earth {1}. The high pressure of the earth compared to the moon inside the base would always assure that the structure would be maintained and the building inflated.
However, later on we realised that this high pressure could lead to an increased risk if something were to puncture the rubber like material leading to catastrophic situations of rapid depressurisation. We concocted this idea of the rubber inflatable base from some research and discovered it had pros and cons.
(The main ones are listed below):

Pros	**Cons**
Differences in pressure means an assured inflation of the building	Due to the high pressure, any minor tears, or major ones, would mean severe consequences and danger to health.
Easy to transport material (assuming designed and constructed on earth)	May not be big enough to capacitate 20 persons
Easy to construct/ inflate on the moon	Material may not be durable enough

When considering the material the base would be made out of we considered different factors such as how cost efficient it would be in terms of transport and obtaining the supplies to build it, and how we would build it. We also discussed whether there were any natural materials on the moon that we could use as a resource, which would cut out the factors of transportation and fuel costs.

One source of information suggested that we could align cuboid shaped inflatable rooms and connect them to create a giant settlement (Shown in Figure 1 below);

> ”One design uses inflatable “pillows” to create a cuboid shape (rather than the more natural spherical shape). Many of these pillows can be aligned and added on to create a growing settlement. They would maintain their shape by using high-tensile beams to battle against the bellowing membrane material. Protection from micrometeorites and solar radiation would be provided by regolith.” You can see an example of this in the diagram below in Fig. 5.

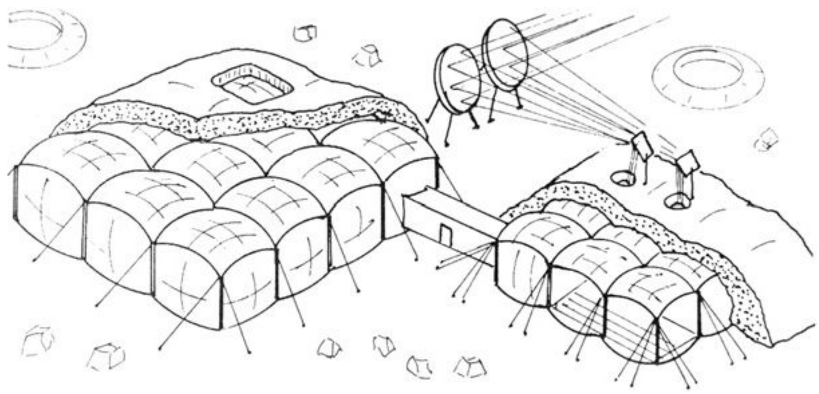


Fig.5- Inflatable lunar base covered in regolith (with cutaway)

Another particular limiting factor we discovered was that due to the lack of protection with no atmosphere on the moon, our moon base would have to withstand extremely penetrating radiation. We came up with the idea when thinking of our inflatable base, that we could cover the outermost surface with reflective material that can reflect or absorb the sun’s radiation levels.

One last idea we explored for living arrangements, was the supposed lava tunnels underneath the moon’s surface. “Ancient lava tubes under the lunar surface exist and may be utilized by colonists. Using natural cavern systems will have many benefits, principally that minimal construction would be required. Many advocates for this plan point out there are too many risks associated with above surface structures, why not use natural shelter instead? Lava tubes may be interconnected, allowing sizeable settlements, also, they may be easily sealed, allowing for pressurized habitats. Lunar colonists will also be sufficiently protected from micrometeorites and solar radiation.”. However we decided that this may not be the best option as it is not guaranteed that these tunnels have the structural integrity to withstand habitability and may not be the easiest option for our habitat as it may not be as accessible.

Generating energy:

Solar power

Research from Qian Xuesen (Laboratory of Space Technology China) has suggested that solar power generated on the moon can supply enough energy for lunar bases, with energy left to spare. Rocks and dust on the moon is largely comprised of silicon dioxide which can be used for photovoltaic cells and also glass for thermal systems.

In the 1970s, Dr David Criswell also promoted the use of lunar rocks and dust in the production of photovoltaic cells.
On earth, the arrays have to be thick and heavy enough to undergo the stress of weather whereas they can be extremely thin on the moon, which makes them more economically viable.

The main consideration to the generation of power on the moon is the mass of the power system that has to be transported to the moon. The most efficient proposal is to utilize the lunar materials. No materials would have to be taken into space other than the initial equipment, making this highly practical for transportation.

Furthermore, the conditions on the moon (no weather) means the potential production of energy on the moon is vastly greater than its equivalent on earth; so much that there is a research into constructing a lunar ring by the Shimizu Corporation in Japan, which could use microwaves to transmit the energy produced back to earth. The limitation here is that the proposed area of the base, unlike the epic length of the lunar belt, would experience darkness.
The synergism is due to the ultra-high vacuum environment on the surface of the moon, and there are materials present on the moon from which thin film solar cells could be made within this vacuum environment by direct evaporation.
By-products from some oxygen schemes (such as the above) include silicon and aluminium, which are specifically needed for the fabrication of thin film silicon solar cells. The pre-existing vacuum of magnitude 10^{-10} Torr allows for vacuum deposition of thin film solar panels without using vacuum chambers.
SRSs

"Self-replicating systems (SRSs) have been theorized since the beginning of the space race.In a concept with ties to biomimicry, SRSs are able to (just like any biological organism) replicate themselves out of the materials in their environment, plus a desired output.".

The idea of having an SRS would reduce launch costs and the output would increase exponentially over time. As we are dealing with a moon base that is meant to last for an extended period of time, this is extremely beneficial. The moon is an excellent construction site due to three main factors of: its direct elemental composition, its generally uniform composition and the ease of mining the top regolith layer. (5-15m)

If achieved, this could run at a very minimal cost, because little would need to be sent initially to the moon, but after generating enough power for our base, we could look into selling the power at a profit. We could transmit the electricity via two methods, laser or microwave transmission.

The SPS-Arbitrarily Large Phased Array (ALPHA) is summarized here, which is a design introduced by Artemis Innovation Management Solutions led by John C. Mankins.

"The basic concept of SPS-ALPHA is to form an exceptionally large space platform from an extremely large number of small, high modular elements, where only a small number of types of modules are used. In the case of SPS-ALPHA, the modular elements (of which there are eight basic types) are combined in various ways to comprise a number of functional assemblies."

The eight modular components referred to above are as follows:

- Hexbus - basic smallsat (small satellite) structural unit
- Interconnect - smallsat to bind structural components
- Hex Frame - deployable beams that provide the base structure for the reflectors and connect the reflector array to the power/transmitter array
- Reflectors and Deployment Module
- Solar Power Generation Module
- WPT Module
- Modular Push-Me/Pull-You Robotic Arms—used for self- construction
- Propulsion/Attitude Control Module

Fig. 6-SRS on the moon.

To form the SRS, minerals would need to be extracted from the regolith. The fully designed mineral extraction system may be similar to that presented in the paper '*Advanced Automation for Space Missions'*. At this point in time, there is no example of an SRS having been constructed and there is a lack of research on complicated SRSs. However as explained by the paper *'Lunar Based Self Replicating Factory'* by Lewis Webber, there is no known logical flaw in the concept and thus can be implemented as no new technology is required.

Webber pulls similarities between biology and SRS systems to argue for having a single species for each modular component of the SPS, rather than having one "city-scale SRS".

In terms of units for the SRS, it is highlighted by Webber that the system should break up the production of computer components to a species responsible only for that function, reducing resource consumption of other species in the production chain. Otherwise several units all have aspects where they repeat the same process. Webber also talks about the relationships between the units. Either a unit requires resources/components from another unit for only the purpose of self replication (Green arrow and top/bottom of boxes in Fig.7), or for self replication as well as component production, which is a lot more common (represented by arrows out of the side of boxes). Each arrow is representative of supply and demand. Two units, harvesters and transport units, are separate from the other units. As their main factor is speed, it would be inefficient to have the units replicate. Full notes can be found in his report.

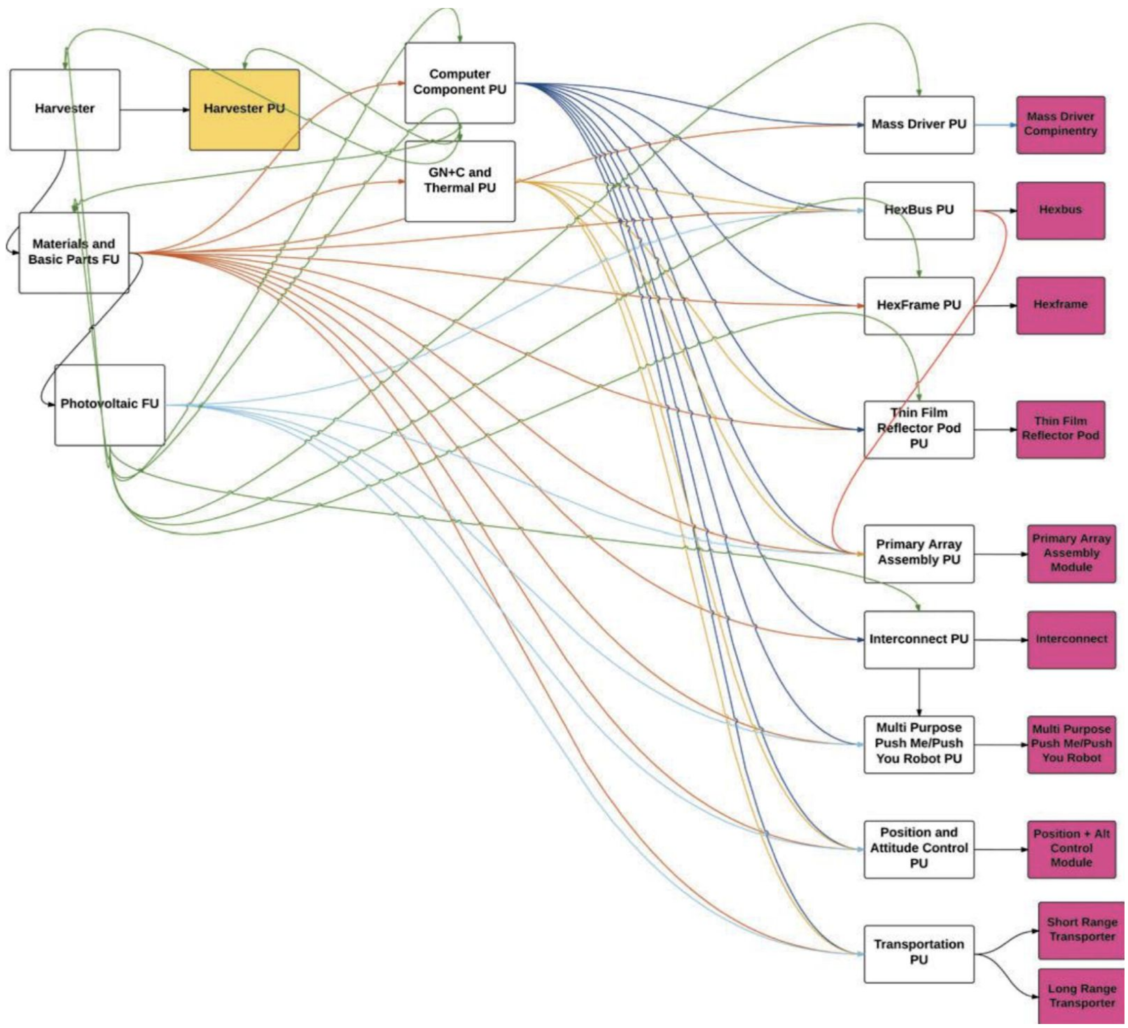


Fig.7 - Lewis Webbers' Unit system - NB "the pink boxes represent output products (SPS components), and the yellow square denotes a unique relationship configuration. FU, fabrication unit; PU, production unit."

In conclusion, the above section on SRSs, summarising and expanding on the paper written by Lewis Webber for our needs, shows that this is a very exciting concept that we would further research as is greatly practical and reduces cost, time and launch load.

Nuclear Power

Depending on the location of the base on the moon, the base can undergo up to 14 days in darkness, which raises issues with the proposed solar powered system. Although using solar power to generate electricity is a good idea, we are not able to rely on solar power on its own. Like we do here on Earth, we thought it would be necessary to generate energy from nuclear fission along with solar power due to its efficiency and reliability. NASA has developed a light-weight portable nuclear fission reactor called "Kilopower" - it can generate electricity up to 10 kilowatts for about 10 years. Considering 900 watts was about the maximum amount of energy we managed to get in the past with a nuclear system for space, Kilopower is truly remarkable. Furthermore, the development and construction of this project has cost less than 20 million dollars, which is significantly lower than hundreds of millions of dollars worth projects which were done in the past. This project began in 2013 in conjunction with the Department of Energy of the US' National Nuclear Security Administration and several other national research centres in the States. It has proved to be successful in March 2018, and its under development of mission concepts and the team is currently striving to reduce any possible risks, before transitioning to the Technology Demonstration Mission program in 2020.

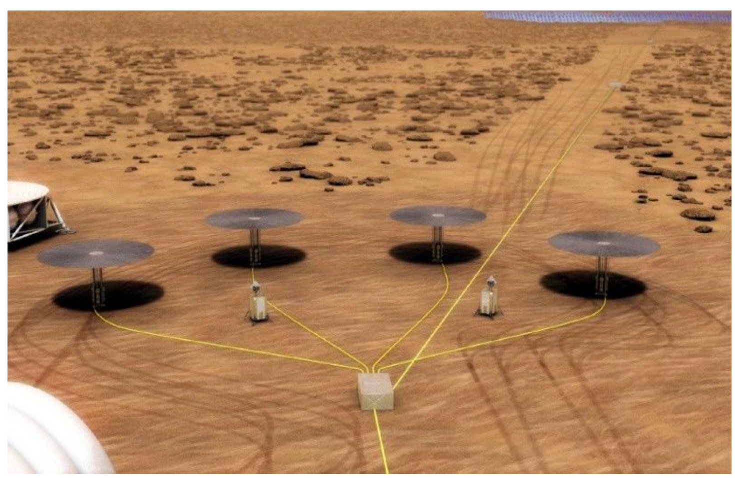



Fig. 8 (Left); **Fig. 9** (Right).

How does it work?

The Kilopower uses Stirling Technology, where it uses Uranium-235 reactor core to produce heat which is transferred up to the highly efficient Stirling engines via heat pipes from the reactor. This KRUSTY (Kilopower Reactor using stirling technology) is suitable for our purpose of generating energy in the moon as the size of the reactor core is only about a paper towel roll.

According to the lead engineer at Glenn who has been involved in the development of KRUSTY, Mark Gibson," Kilopower gives us the ability to do much higher power missions, and to explore the shadowed craters of the Moon" as we would "require a new class of power that we've never needed before".

But how reliable is it? In terms of reliability and efficiency, Kilopower is incomparable to any other power sources. One of the only reasons why one could disagree with the use of nuclear power despite its ability to generate large amounts of energy, would be the potential safety issues. In fact, it is much safer than other previous technologies - "launching a fission reactor is going to be several orders of magnitude safe" compared to the radioisotope systems in the previous years according to Gibson.

The chief reactor designer at NNSA's Los Alamos National Laboratory has also ensured against these doubts - "We threw everything we could at this reactor, in terms of nominal and off-normal operating scenarios and KRUSTY passed with flying colors,"

The KRUSTY experiment was conducted in 4 phases to ensure safety and ability to work in any conditions despite unexpected situations by conducting the experiment without power and in the environment where the power was increased incrementally.

<u>Thermal energy:</u>

The lack of convection on the moon means the heat from the sun remains in the regolith. We could use this and a mirror or lens to focus sunlight onto the regolith and use that to heat the base or generate electricity.

<u>In terms of storing the energy:</u>

The preferred system recommended in the 2009 NASA study was a photovoltaic solar array-powered cryogenic storage regenerating fuel cell system. NASA calculated that a five-kilowatt continuous delivery system would store 2,000 kilowatt-hours with a system energy density of 1.15 kilowatt-hours per kilogram. The study's alternate preferred system was a fixed orbit laser system, with a 16.1-hour orbit period that required a surface receiver installation with 525 kilowatt-hours of energy storage. The laser was powered and fired when it was both in direct sunlight and in direct line-of-sight with the Moon base.

Self-sustainment:

Oxygen production

43% of regolith is oxygen on average by mass. Harnessing the oxygen from the regolith could also give some useful byproducts such as various metals.

The paper "Oxygen Production From Lunar Soil" by Carlton C. Allen and David S. McKay, outlines the production of oxygen from various samples of lunar soil.
15 soils from the Apollo collection were reduced in flowing hydrogen at temperatures ranging from 900 to 1100 degrees celsius. The highest yields were from iron-rich mare soils and volcanic glass.

Different proposed processes of oxygen production include gas and solid interactions, silicate or oxide melt processes, pyrolysis, co-product recovery and aqueous solution reactions. One of the best researched methods is to reduce iron oxide using hydrogen gas. This consists of a two step process:
Firstly0-reducing iron oxides and liberate the oxygen to form water.

$$FeO + H_2 \rightarrow Fe + H_2O$$

Then the water is electrolyzed with hydrogen recycled to the reactor and oxygen liquified and stored.

The experiment carried out tested 15 various lunar soils which were specifically chosen to cover the chemical compositions in the Apollo collection. Samples mare soil 75061 and volcanic glass 74220 were reduced at temperatures between 900 and 1100 degrees celsius. The remaining solids were reduced at 1050 degrees Celsius. The table below shows the results.

Table 1. Lunar Soil Experiments at 1050°C

Sample	FeO (wt%)*	Weight Loss (%)
62241	5.5	1.0
73151	8.5	1.3
73241	8.5	1.5
14141	10.2	1.6
14148	10.6	1.9
76031	10.7	1.6
76131	11.0	1.8
10084	16.2	2.7
12032	14.1	2.2
72161	14.9	2.6
15013	15.0	2.4
15471	16.2	2.3
71131	17.5	3.3
75061	18.0	3.0
74220	22.9	4.1

Fig.10

Each sample was reduced in flowing hydrogen, which flowed past the samples at $122 cm^3 min^{-1}$. After 3 hours the hydrogen flow was stopped and the sample was cooled and weighed. Some samples lost weight before the introduction of hydrogen due to absorbed water vapour.
The results showed that oxygen yield is strongly and directly correlated to the solids FeO abundance, as shown by Fig. 11.

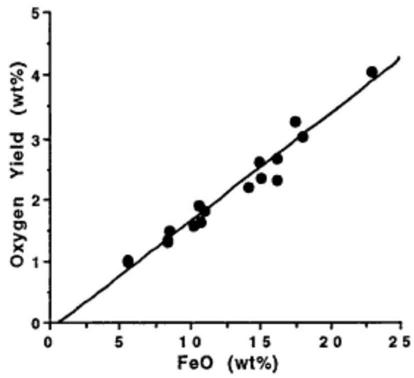


Fig. 11

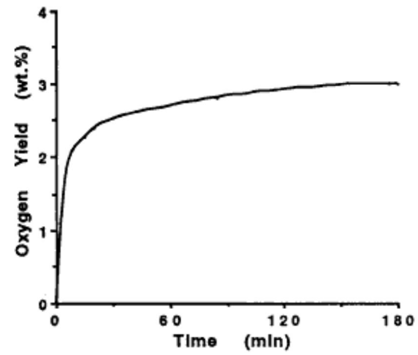


Fig. 12

The reaction kinetics are shown in Fig. 12. It shows the oxygen yield from a 1050 degrees celsius experiment on iron-rich mare soil 75061 which is representative of all the other experiments.
It shows that the reduction of the lunar soils is rapid, with 50% of weight loss occurring in the first 5 minutes. The reaction is thus complete within a rough time scale of 10 minutes.
The experiments were run at different temperatures and were only weakly dependent on this factor.

This allows assessment of oxygen yield from each of the major iron oxide bearing phases in lunar soil such as ilmenite, olivine, pyroxene, impact glass and volcanic glass.

Ilmenite was the most easily reduced phase in lunar soil. Even the largest grains of around 80um appeared to be reduced throughout. They also seem to be highly permeable to water and hydrogen at 900 degrees celsius and above.

Pyroxene had a minor reduction. The impact glass formed by micrometeorite impact undergoes significant reduction. Oxygen released from the volcanic glass sample is more strongly dependent on temperature, as shown by Fig 13.

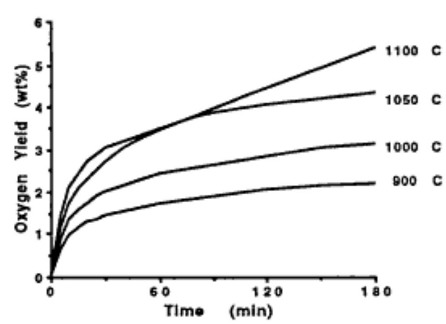


Figure 3. Oxygen yield from lunar volcanic glass 74220, reduced at 900-1100°C.

Fig. 13

The initial rate of oxygen release is slightly slower than lunar soils, and oxygen release continues for at least three hours.

Overall, it is shown that the oxygen yield can be predicted by the knowledge of the solid iron abundance and overall composition. Data sets of these values should be available covering the entirety of the moon, making this a dependable area of research. Deposits of iron-rich volcanic glass, the premier oxygen ore, can also be mapped.

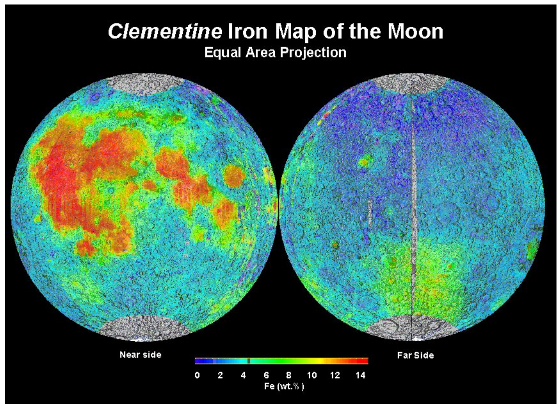


Fig. 14: FeO% map

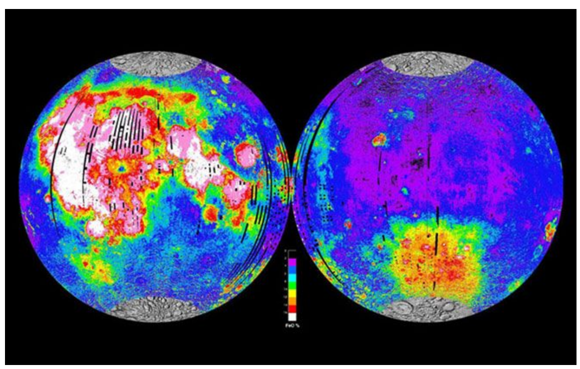


Fig. 15: FeO% map

In conclusion, production of oxygen from lunar materials is a practical method of obtaining oxygen. The yields are predictable and rapid, with most oxygen release being within tens of minutes.

Solar concentrators could provide the temperatures required to release the oxygen from the metal oxides. In theory, a reactor could use mirrors to channel sunlight to heat the moon soil to over 900 degrees celsius until it glows. This corresponds to the temperatures required for the oxygen production through the lunar soil.

However the process does require hydrogen which would have to be brought from the earth if lunar ice cannot be mined. However,using the $FeO+H_2$ reaction would mean that beyond the first batch of hydrogen carried to the moon, there is no need to

carry more hydrogen (which presents a risk on spacecraft due to its flammability) as it can be extracted by hydrolysis of water produced in the reaction.
A test completed in Hawaii in 2010 on simulated lunar regolith demonstrated that the process was feasible. However, tests to determine the effects of low gravity and vacuum have not yet been carried out.

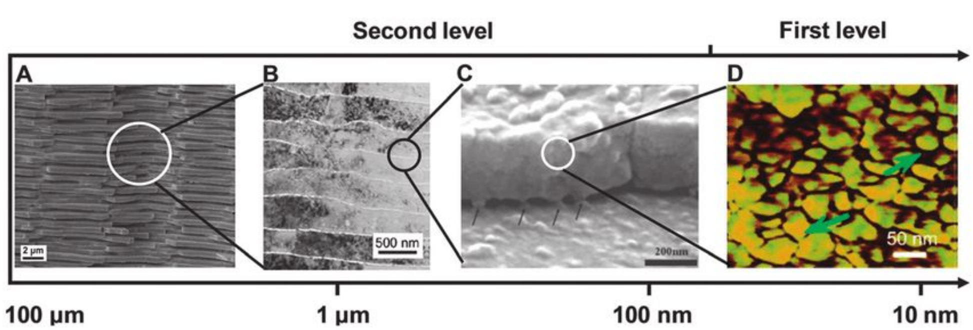
Materials:

A possibility of protection against the moon is using the natural resources on the moon. There is a substance called regolith on the moon, which can be used as a component to form a type of lunar concrete, called cast regolith. This material is supposedly high tensile, rigid and dense enough to protect against the cosmic radiation from the sun penetrating the moon. Using this has the advantage that it is already on the moon, so there would be less of an additional cost than if we used lead, which happens to be very heavy. As mentioned before, we would use the lead or cast regolith and coat the outer surface of the habitat in the protective material. (Fig. 5).

There is also a substance called Nacre, which is more commonly known as mother of pearl. This exists on earth already and is an organic-inorganic composite material which consists of layers of mineral and protein based substances. Previously, artificial nacre was made using layers of polymer, which were only soluble in organic solvent - this led to large amounts of waste that had to be disposed of once the procedure was done.

However, the University of Rochester has developed a more eco-friendly, and biologically-based method of creating synthetic nacre to avoid the usage of harsh chemicals by using bacteria called *Sporosarcina pasteurii* and *Bacillus licheniformis*, a calcium source and urea.

Nacre is extremely rigid and good at resisting compression, like concrete. Research done by the University of Michigan and Macquarie University in Sydney shows that the nacres binding organic layers disperse to areas with lower pressure, then the separated tablets consisting of aragonite rigidify, preventing crack formation and giving its ductile strength.



However, there is a problem - each layer is about 5μm thick but each double layer requires a day to form. Despite this, this project has a lot of potential. Further on, Meyer, the lead biologist in this research team, has suggested this could form a base for lunar bases and other planets as the materials needed are small amounts of bacteria and water, as the urea can be extracted from the urine of the astronauts. This would be ideal as it is cheaper and lighter by far compared to any other materials, which would also reduce the weight of the spacecraft for transport. Her lab is in process of developing a 3D printer that can print the bacteria and nacre, so that they could use nacre to form any 3D shapes.

Fig. 17- Appearance of Nacre

However, that leaves the question of if we were to build it out of materials such as nacre, how would we build it? JAXA, Japan's space agency is working on a solution for this question. It is developing a project to achieve the goal of autonomous construction of the moon base using robots which can be sent prior to the astronauts' arrival. This research, led by the Japan Aerospace Exploration Agency, is being done by the collaboration between Kajima Corp, a construction company, Shibaura Institute of Technology, The University of Electro-communications and Kyoto University.

Fig. 18

To start with, a backhoe which has been designed for its usage on the moon will be used. Motion recognition capabilities will be used to adapt to the construction site.

In course of the construction, the following steps are needed:

- **Site preparation** work for the module for human habitation
- **Excavation** - this stage can be skipped of minimised if we use the moon cave or a crater
- **Installation** and **initial construction** of the structure
- **Shielding** the module with the surface material to protect it from meteoroids and radiation
    - The shielding should be carefully done to prevent the oxygen from the inside of the structure to escape in case of puncture on the outer structure due to meteoroids.

By 2029, Toyota and JAXA aim to launch a moon rover for transportation of humans, in prep. Canada is on course to construct an autonomous robotic arm, “Canadarm3”. Some pictures below to show the different steps.

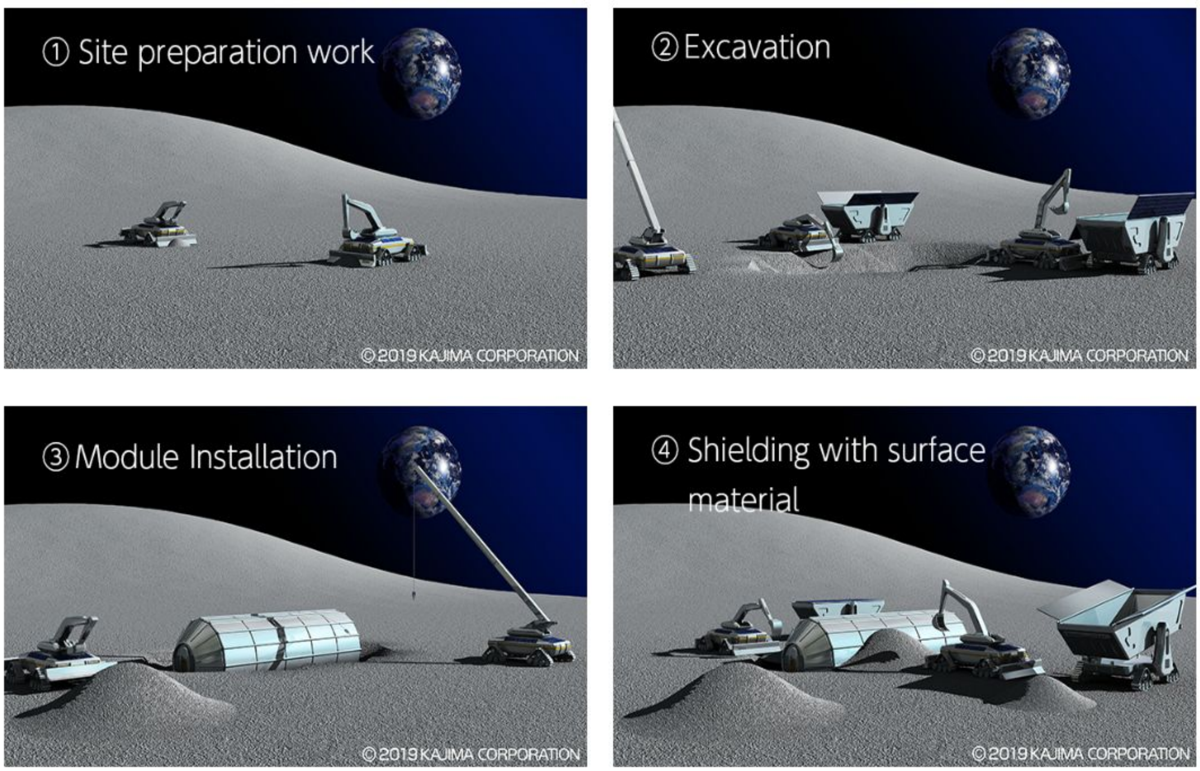


Fig. 19

Location:

When researching where to place our moon base, we had to consider many things such as:

- Where we will find water
- What other resources could we utilise around the area where we set up our base
- How much light will there be?
- How will the temperature differ with other areas of the moon?

After considering all of these factors, we have decided to prioritise factors such as water and natural resources to allow self-sustainment, along with the conditions of living such as temperature and light as our commercial activities involve the use of great power and exploring the resources. Through research and exploration we could provide crucial opportunities for scientific research on the moon, which could in turn, become a possible profit outlet and an additive to our commercial activity.

After a while, the moon's south pole became of great interest to us, as we discovered an article suggesting colonisation of the moon would start there. Through deeper research we discovered that it fit many of our criteria; water could be found in the form of ice deposits, there would be long periods of up to 200 earth days of light, and the temperature could be withstood by a human, being around -13°C.

Constant light for 200 days could be substantial enough for the base to be self-sufficient in energy by using solar energy and converting it into electrical energy in the long term, however at first it could be that we don't have the facilities or time to transport materials in the first few weeks of the project.

Water can be found in ice deposits located in craters at the bottom of the moon, as the sun's light and heat does not reach into these craters as their walls are often raised- blocking the sun that is skimming the surface of the moon at the south pole. As a result temperatures in these craters plummet to -248°C causing ice to form. If we could find a way to harvest this ice, our base could use it for many purposes, such as water hydration, irrigation for plants (leading to further self sustainment) and extracting hydrogen for fuel purposes as well. This water has also been untouched by the sun's rays and can give us an insight into the days of our early solar system furthering the possibility for more studies and scientific exploration.

The location of the south lunar pole is also of interest due to the magnetic crust being located near there, which, again, could be used for further experimentation and the possible development of new technology, which could also be profitable - all profits will be discussed in our financial section of our report.

Structure:

There were many shapes to consider when designing our habitat, from cubes to cuboids with rounded edges, to spheres and half of cylinders on their sides (like a hangar for aircraft). At first we presumed a half-cylinder on its side would be the best solution, with the barrel of the cylinder made more spherical as to reduce stress on vertices etc.

The arch of the cylinder would mean that there would be no weak corners to degrade its integrity. However we also discovered from our research that the sphere is also a very good shape to use. We will cover this later on in the *Set-backs* section.

Set-backs:

We encountered a few set-backs during our design of the building, tackling areas such as volume/space capacity, stress retention, and habitability. When creating our moon base we had to consider the volume it allowed vs the weight of the material it would take to be able facilitate this volume, or in other words, its surface area to volume ratio. The graph below shows the correlation between its mass and volume and it was found that a sphere is more structurally stable in terms of stress as it is all one curved surface so therefore the stress is equal in all places, and as there are not edges and vertices the overall pressure would be lower than a building with joints for example. The sphere, is proven to be the most "volumetrically efficient with the least surface area and mass for a given volume" as shown in Figure 20.

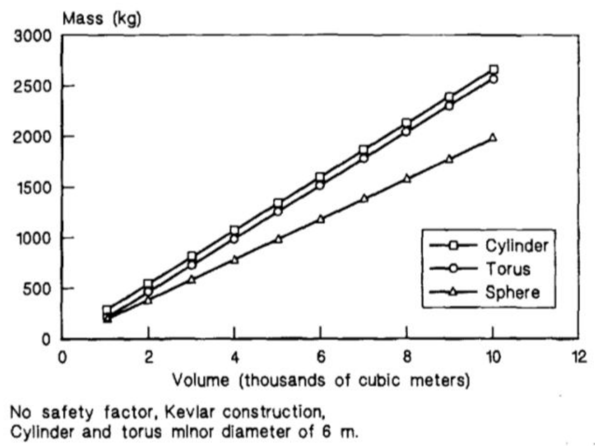


Fig. 2. Mass vs. volume for sphere, cylinder, and torus.

Fig. 20

Final Plan/ conclusion:

Our final plan was formed a few weeks before the deadline; we decided to go with the inflatable base idea, as it theoretically had more positives than negatives. Although the idea of arriving and being able to utilise the lava tunnels sounded appealing, this was a risk to us as we were not certain on the conditions of these tunnels. As for the protection against radiation we decided to follow through with the idea of the lead coating on the surface of the habitat, as although it is heavy to transport, in the long term, it is dense enough to protect from micrometeorites and has radiation absorbing properties. It is also in plentiful supply on earth and is using existing technology.

As for the shape of the moon base, we discovered one last design that we decided was the most feasible option. We would keep the shape and structure of the base to be spherical, continuing with an inflatable design and place the habitat in a crater of appropriate size (which would be scouted out before by using rovers and cameras. The sphere would have different layers/ platforms for different purposes. The lower levels would experience cooler temperatures as they have less exposure to sun and radiation. These levels would most likely be used for storage, and possibly be viable for lab conditions (for experimentation). Middle layers will be used for general operations and guest quarters, and eventually the possible farm inside, where we can grow our own organic material to be even more self-sustaining and upper levels could be used for crew quarters. A version of this is shown in Fig. 21 below:

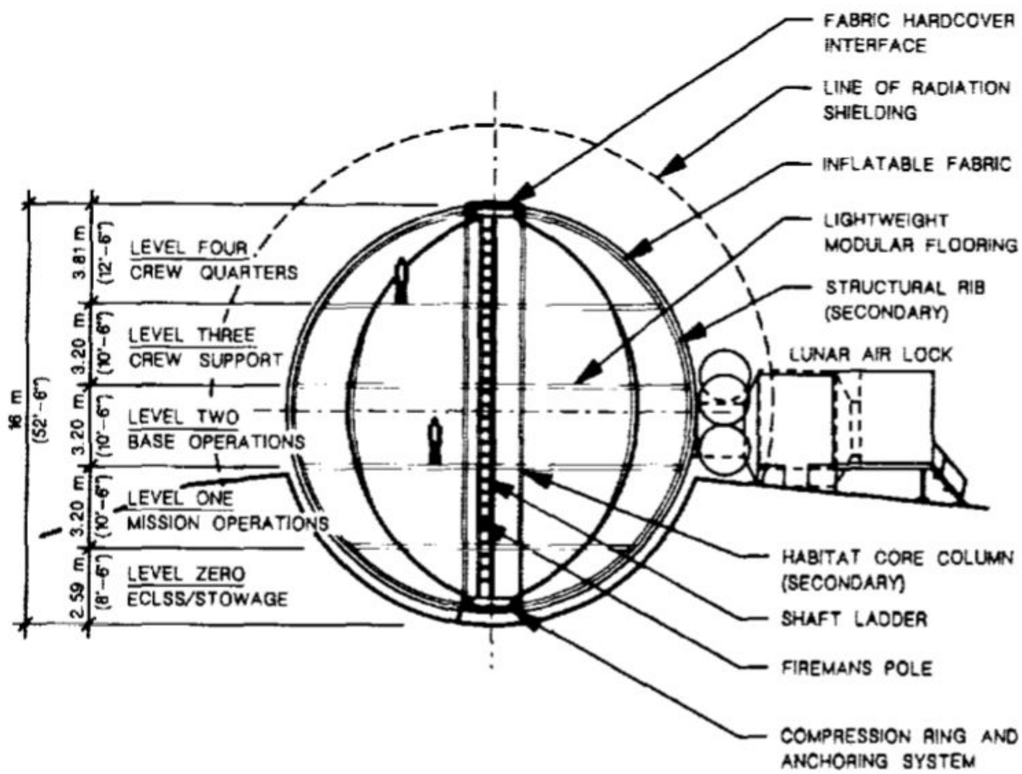


Fig.21: Cross section of the inflatable lunar habitat

Our final source of energy would be a mix of nuclear and solar energy, as we believe that solar energy is not enough for us to sustain ourselves. As previously mentioned, there is a significant period of darkness in most places in the moon, however due to the fact we are located at the south pole where there is more light, these periods will be shorter, so we suggest that we would maybe phase out nuclear energy as it can be very dangerous to generate/ operate on.

Part 3- Transport

Requirements:

"In support of the requirements of Parts 1 & 2, design a transportation system for carriage of people and materials to / from the Moon on a regular basis (i.e. what is required is a proposal enabling multiple trips rather like a ferry service). The transport system should be capable of carrying a load of at least 2500 Kg between the surfaces of Earth / Moon in either direction. Costs need not be stated but solutions should seek to be efficient and economical."

Introduction:

Using already existing technology we have decided to use a rocket as our source of transport. A spacecraft is a machine designed to be put into space, and it is mainly used for observing the Earth, communication, navigation and space exploration. The designing of the rocket stands a very important role in the transportation process. As research shows, a spacecraft must be able to fit inside a rocket fairing and the rocket must have enough power to lift it into orbit. This suggests that high loading strength is required. The shape of a spacecraft mainly depends on the rotation and spinning of it in space. For example, Meteosat, is a satellite that spins and has a drum shape.

Main design:

For the spacecraft, the following parts are essential and must include:

- shape
- size
- configuration

As this spacecraft will be used for commercial purposes which will take passengers, there will be a requirement for seating capacity, entrance and exit hatches, communication and electrical systems, and life support.
For the shape of the spacecraft, some aerodynamic and other characteristics of the configuration should be taken into account, besides the structural stress, high speed and heat tolerances must be monitored. The following pictures show the current designs of manned spacecrafts.

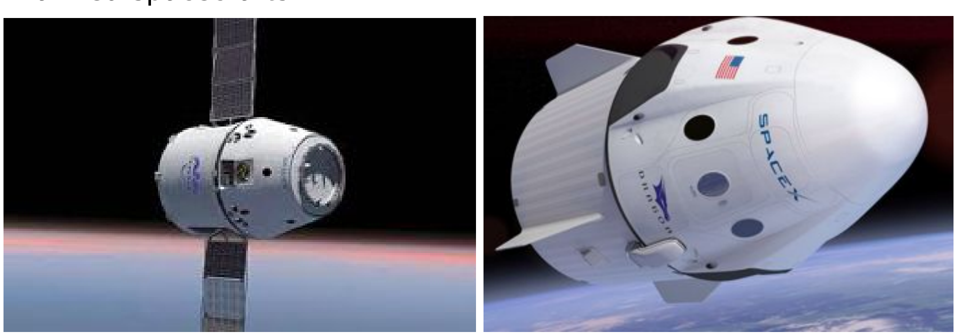


Fig.22

Currently, the spacecrafts are mainly sphere shaped, as this is the most weight-efficient design for balancing the internal pressure. A sphere provides the most internal volume whilst having the smallest possible mass. It also has a small cross sectional area, and makes the biggest blast wave. The blast wave is what slows the capsule down and it is better to be as big as possible. Inflatable and other expandable spacecrafts are also very practical by making stuff larger in space than at launch.

However, even though the sphere shape is the best and the most weight-efficient design, the cylindrical shape is the easiest to manufacture. This is because most construction techniques are currently based on metal plates, and the sharp edges made through this process are less optimal than the sphere shape to withstand internal pressure. Despite this, it is beneficial to have artificial gravity induced by rotation in space for a long stay, and therefore, cylinders and torses are good options as they are easy to inflate.

The spaceship capsules are designed to have a round shape. This shape allows slowing down of the atmosphere from 8km/s to 0 km/s. This design can also lower the friction of passing through the atmosphere as the cross sectional area is smaller.

Materials:

To obtain the most from the materials for space structures, the materials have to have minimized mass; high stiffness and high strength to withstand loads; accommodate payload and equipment; high reliability; low cost; high accessibility and manufacturability.

As research shows, the most widely used material for spacecraft façades are composite materials. A composite material is a composition material which is made from two or more constituent materials with significantly different physical and chemical properties. When these materials are combined, a material with both characteristics are produced. Composite materials are currently being used widely, not only in the aerospace industry, but also in the construction industry. It is being preferred for its high strength and durability. Also, it is lighter and less expensive compared to the traditional materials.

Composite materials, such as aramid fibre, are used for its heat resistant characteristics and strong synthetic fibre structure. Aluminium alloy is also widely used in the aerospace industry. It is reasonably priced, and provides both high strength and high stiffness. These characteristics are tremendously important, as the spacecraft will need to survive through both extreme heat and cold. The lightness and sturdiness also makes this material appeal to the aerospace industry. Aluminium lithium alloy is one of the examples. Aluminium lithium alloy has 10% or more weight-saving over standard aerospace alloys. It is also used in the Super lightweight Tank (SLWT) for the Space Shuttle, with a weight saving for 7,000 lbs.

For our spacecraft, we will also consider a material named Graphite Fibre (Polymer matrix composites). This type of material also has high strength and high stiffness, with an approximately weight saving of 25-50% in the spacecraft.

We have also creatively considered to use some ‘future’ materials in the construction of spacecraft. We want the material to be ultralight, flexible and printable electronic components. We considered that this material could possibly be 3D printed parts that are made from advanced polymers and metals. However, this is only a ‘future’ possible solution for the spacecraft. To make this material into use, we would need to consider the feasibility and practicality of using it.

Propellants:

Helium 3

Due to the frequent exposure of solar wind on the Moon’s surface, there is an abundant source of Helium-3. Helium-3 is not radioactive and furthermore, it does not produce any harmful waste products, yet it is a reliable source to be used in a fusion reactor which could lead to production of safer and cleaner nuclear energy.

Helium-3 is extremely rare on Earth unlike on the moon – this is because we have the protective atmosphere around the earth which prevents the helium-3 from penetrating into the surface, whereas the moon doesn’t have any atmosphere so the lunar soil absorbs the helium-3 emitted by the sun via the solar winds.

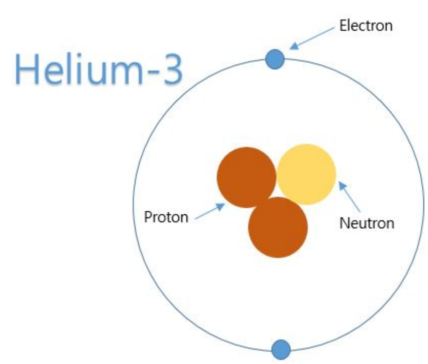


Fig.23

According to an Artemis Project paper, if we fill one space shuttle cargo with helium-3, its net value is about 3 billion dollars for a tonne which has a potential to power a year worth energy for the whole United States.

It could be extracted by heating the moon dust to about 600 decrees after digging the surface of the moon and we could bring it back to the earth and use it as fuel on the earth. This could result in huge profit.

However, there are difficulties in implementing this in real life: from the transportation of helium 3 from the moon to the earth to the efficiency of this process. A physicist from the university of Oxford, Frank Close has commented that "Helium 3 has no relevance for fusion" as "deuterium reacts up to 100 times more slowly with helium 3 than it does with tritium which means we would need higher temperature in the reactor than others – this would be difficult as nuclear fusion technology is still in process of development and obtaining high temperature in fusion reactors is very hard.

Despite these contrasting views, we thought that Helium-3 is worth looking at and has a potential of being the possible resource which we could mine on the moon for energy production on the earth as the science and technology are getting more advanced at a faster rate than ever.

Chemical propellants:

For the purposes of travelling to the moon, a rocket must have a source of energy to enable it to overcome the gravity of the earth.

This source of energy is supplied by chemical propellants combusting exothermically, much of which is stored in a fuel tank that detaches itself from the main body of the rocket shortly after take-off. Each section of the rocket also has a store of fuel for after the main tank is detached; in later stages this fuel is mainly used for helping the rocket to reach the desired escape and orbital velocity.
Rocket engines perform best in outer space because of the lack of air pressure on the outside of the engine.
Some rocket fuels carry oxidiser because the amount of oxygen available in space is not enough to support the burning of the fuel.

Desired property of propellants

High specific impulse is a measure of how effectively a rocket uses the propellant. By definition, it is the total impulse (or change in momentum) delivered per unit of propellant consumed. High values of specific impulses are obtained by exhausts having high-temperature (a large combustion enthalpy) and low molecular weight (so combustion products should contain simple, light molecules – like hydrogen, oxygen, fluorine, carbon or light metals for example aluminium, beryllium or lithium.)

High specific energy or density is another important property. If a fuel is denser and can release more energy per unit volume, a smaller volume of it will be needed and so a smaller, lighter tank can be used. These two factors need to be considered together. For example, liquid hydrogen is energetic and its combustion gases are light. However, it is a very bulky substance, requiring large tanks. The dead weight of these tanks partly offsets the high specific impulse of the hydrogen propellant. Volatile propellants must either be avoided, or kept at high pressure to prevent unnecessary evaporation, as their density would decrease.

Suitability/ease of operation with the designed engine. Some fuels may not interact in a desirable manner with existing engine designs or cause problems when burned.

A fuel should ideally be readily available or easy to produce and have a low production costs while maintaining the safety of the production method to ensure that there is an economically viable source of propellant. For some propellant, to obtain an adequate amount, an entire new chemical plant must be built. And because some propellants are used in very large quantities, the availability of raw materials must be considered.

Other criteria

Some are not adequate as coolants for the hot thrust-chamber walls. Others exhibit peculiarities in combustion that render their use difficult or impossible. Some are unstable to varying degrees, and cannot be safely stored or handled.
Potential harm to the environment, animals or the human body: excessively toxic/harmful/explosive/unstable/highly-reactive chemicals producing toxic exhaust should be avoided.

Unfortunately, almost every propellant that gives good performance is apt to be a very active chemical; hence, most propellants are corrosive, flammable, or toxic, and are often all three.

Types and evaluation of propellant and their assessment

Solid chemical propellants

Double-base propellant

The most common double base propellants combine the explosives nitroglycerine and nitrocellulose, plus additives in small quantities to form a colloid. There is no separate fuel and oxidizer. The molecules are unstable, and upon ignition break apart and rearrange themselves, liberating large quantities of heat. These propellants lend themselves well to smaller rocket motors. They are often processed and formed by extrusion methods, although casting has also been employed.

Composite propellant

Separate fuel and oxidized chemicals are used, intimately mixed in the solid grain. Solid rocket propellants are prepared as a mixture of fuel and oxidising components called 'grain' and the propellant storage casing effectively becomes the combustion chamber. Because the oxidizer has no significant structural strength, the fuel must not only perform well but must also supply the necessary form and rigidity to the grain. Ordinarily, in processing solid propellants the fuel and oxidizer components are separately prepared for mixing, the oxidizer being a powder and the fuel a fluid of varying consistency. They are then blended together under carefully controlled conditions and poured into the prepared rocket case as a viscous semi solid. They are then caused to set in curing chambers under controlled temperature and pressure. The most common solid propellant is ammonium perchlorate mixed with powdered aluminum that is held together in a rubberlike matrix.

Liquid

Liquid propellants use fuels together with oxidisers.
Most fuels, with the exception of hydrogen, are liquids at ordinary temperatures, and are usually quite tractable substances. Hydrogen, however, exists as a liquid only at extremely low temperatures. So it is very difficult to handle and store. Also, if allowed to escape into the air, it can form a highly explosive mixture. It is a very bulky substance, about one-fourteenth as dense as water. Nonetheless, it offers the best performance of any of the liquid fuels.

Fuel: kerosene, liquid hydrogen, alcohol, hydrazine and its derivatives

Some of the best oxidizers are liquified gases, such as oxygen and fluorine, which exist as liquids only at very low temperatures; this adds greatly to the difficulty of their use in rockets.

Oxidizer: liquid oxygen, nitric acid, nitrogen tetroxide, liquid fluorine, hydrogen peroxide

Liquid oxygen is the standard oxidizer used in the largest United States rocket engines. It is chemically stable and noncorrosive, but it's extremely low temperature makes pumping, valving, and storage difficult. If placed in contact with organic materials, it may cause fire or an explosion.

Nitric acid and nitrogen tetroxide are common industrial chemicals. Although they are corrosive to some substances, materials are available which will safely contain these fluids. Nitrogen tetroxide, since it boils at fairly low temperatures, must be protected to some degree.

Liquid oxygen (LOX) and highly refined kerosene (RP-1). Used for the first stages of the Atlas V, Falcon, Soyuz, Zenit, and developmental rockets like Angara and Long March 6. This combination is widely regarded as the most practical for boosters that lift off at ground level and therefore must operate at full atmospheric pressure.

Table comparing solid and liquid propellants

	Solid propellants	Liquid propellants
Advantages	Maintenance and instant readiness. Easy to store, transport and handle. Reliable, simple. Contain their own oxidizer. Low cost Have high density, therefore thrust.	Higher specific impulse Capable of being throttled, shut down, and restarted. Only the combustion chamber of a liquid-fueled rocket needs to withstand high combustion pressures and temperatures. Several practical liquid oxidizers are available which have better specific impulse than the ammonium perchlorate.
Disadvantages	require carefully controlled storage conditions, and may offer handling problems in the very large sizes, since the rocket must always be carried about fully loaded. Require protection from mechanical shocks or abrupt temperature changes that may crack the grain. Casting large amounts of propellant requires consistency and repeatability to avoid cracks and voids in the completed motor. are intolerant to cracks and voids and require post-processing such as X-ray scans to identify faults. Have lower specific impulse. Once ignited, solid propellants burn continuously, limiting the number of applications. contain sensitive high explosives that can detonate under high shock loads, high temperatures, or other conditions.	Storable oxidizers tend to be extremely toxic and highly reactive, while cryogenic propellants must be stored at low temperature and can also have reactivity/toxicity issues. Liquid oxygen (LOX) is the only flown cryogenic oxidizer - others such as FLOX, a fluorine/LOX mix, have never been flown due to instability, toxicity, and explosivity. Liquid-fueled rockets require potentially troublesome valves, seals, and turbopumps, which increase the cost of the rocket. Turbopumps are particularly troublesome due to high performance requirements. They require more complex engine systems to transfer the liquid propellants. low density

Chemicals that we are going to use

The research on storing hydrogen as solid without compression by Dr Enass Abo-Hamed can potentially be used in our rockets. Her method is to pack hydrogen in an intricate 3D-printed aluminium tube. Hydrogen remains stable in this extremely light tube and only starts reacting when a 'coolant' is pumped through, warming them up and releasing the hydrogen gas to the fuel cell.

Because electrically powered rockets are still in development, we can pump the warmed hydrogen into the combustion chamber to mix with the oxidiser to produce a huge thrust. Hydrogen can release huge amounts of energy, and almost the only concern is that it is hard to store. So when this hydrogen storage technique gets tested and widely recognized, we can use it for our moon travel, providing that we can get oxygen and hydrogen from water or other available sources.

Although the proposed technique is viable, we think for now, it is probably safer and easier to use the more traditional kerosene and LOX for first-stage rocket, and liquid hydrogen with LXO in the second stage. We have to keep in mind that hydrogen is highly flammable and that different fuels require entirely different rocket engine designs.
But nonetheless we can still use hydrogen and oxygen in smaller engines to generate electricity in the spacecraft or on the moon base.

Rocket trajectories

There are many factors to consider when launching a rocket; one of the more important is its trajectory. The trajectory of a rocket must be carefully considered to optimise the amount of fuel to carry (if more fuel is brought, more fuel must be brought on top of that to ensure that the rocket can carry its own weight-this is therefore an exponential relationship, so the amount of fuel needed increases quickly, not to mention the extra that must be bought to supply the engine with adequate fuel if it doesn't run at maximum efficiency!). Additionally, as short a journey as possible should be chosen to minimise travel times, as a longer trip would allow for more opportunities for things to go wrong as well as negatively impact morale.

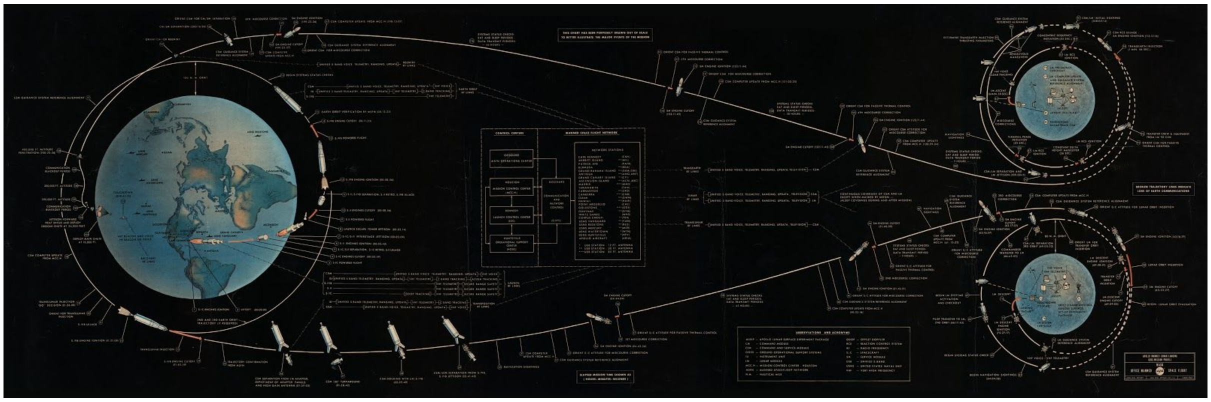


Fig.24-Graphic of the launch and trajectory of a rocket

The procedure would have involved several steps; firstly, the initial launch, in which a rocket would carry a fuel tank. but a large amount of fuel still remains necessary due to the enormous amount of energy needed to escape the gravitational pull of the earth. {1}

Fig.25- Slingshot maneuver animation

However, the earth rotates, so the rocket will gain a *horizontal* velocity when launched due to the gravitational pull of the earth. If the launch is timed correctly to give the rocket time to travel *around* the Earth (possibly the early morning), it is possible to use Earth' gravitational field to change the rocket's velocity and heading. Such a maneuver, commonly referred to as a 'slingshot' is useful as it both allows humanity to send spacecraft to places which would be impossible to reach if we relied solely on human technology and to reduce the cost so that space missions do not become prohibitively expensive. gravitational slingshot is also useful to reduce fuel for shorter trips, which is useful as even just one extra pound of fuel carried can incur high costs (SpaceX's rockets, which are priced at $2500/pound, are considered a low cost per unit weight already). The two main ways a gravitational slingshot can reduce costs are:

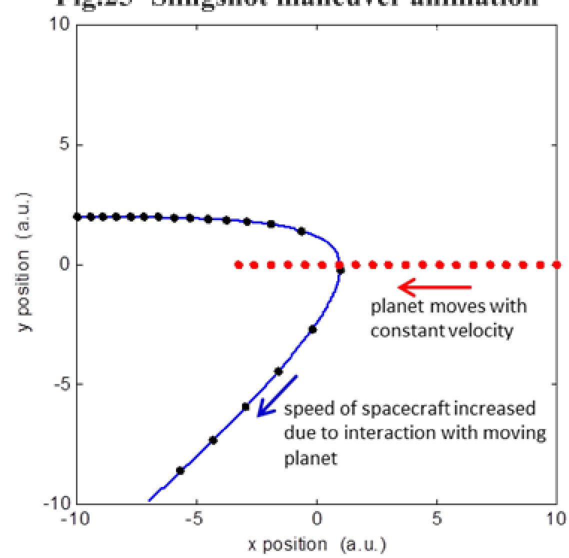


Fig.26- Graphic showing effect of slingshot on spaceship

1) By using a gravitational slingshot to accelerate the rocket to a speed where it can break out of orbit, the amount of fuel needed to achieve breakaway velocity is decreased. This is possible due to the fact that the planet-spacecraft interaction is elastic and therefore kinetic energy- and by extension momentum- is conserved. Thus, when the spacecraft slingshots around the moving Earth, some of the earth's momentum is transferred to the spacecraft {1}. However, the earth's mass is so enormous its change in velocity is negligible; but as the rocket's mass is much smaller, it experiences a large change in velocity ($\Delta p = m\Delta v$, so mass is inversely proportional to change in velocity if momentum is constant)
2) The slingshot can change the direction that the rocket travels in; varying the distance from the Earth to the rocket at which the slingshot is done changes the direction and magnitude of the force on the rocket from the Earth's gravitational field and thus the angle through which the rocket 'turns'; this reduces the amount of fuel reserved for changing direction/for the thrusters.

One must also carefully consider the return trajectory. Earth's atmosphere is a dense, fluid medium which one can consider to be similar to water at orbital velocities. If one extends this comparison, if the reentry angle is too steep, a spacecraft will experience forces on the fuselage that will cause frictional forces so great the fuselage will ignite, incinerating the craft; if the angle is too small the craft will bounce off the atmosphere and into space. Thus, there needs to be a carefully calculated reentry angle{3} to prevent either scenario from happening, which happens to be about 1-2 degrees below the horizontal (for a shuttle; relaunchable rockets have not been fully developed and so there is no data for this yet).

Stresses and strains

A rocket will undergo a lot of different forces when it is accelerated into the atmosphere, travels through space and returns. To simplify the thought process involved, one can model the spaceship as carrying no payload, and break the analysis up into 3 phases:

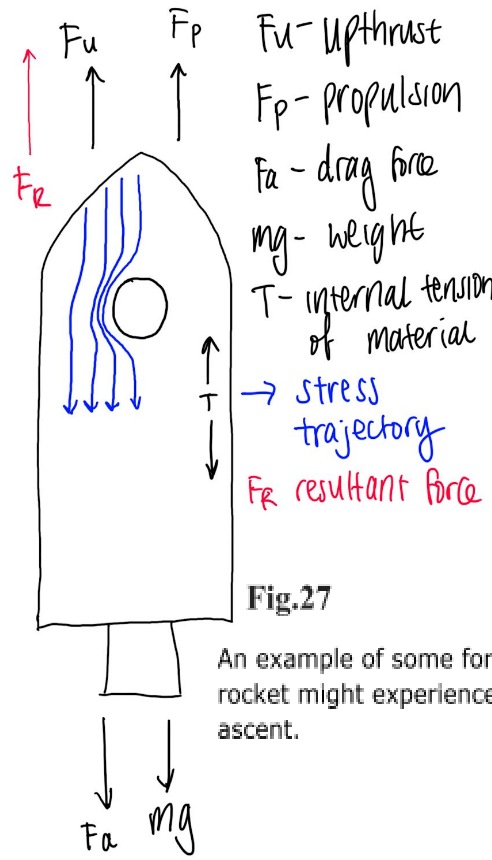


Fig.27

An example of some forces that a rocket might experience during ascent.

1) The takeoff/escaping the gravitational field

At the beginning, the acceleration and mass of the rocket are very large so the rocket experiences large forces. There are large compressive forces on the hull especially from air pressure as well as a large driving force; the rocket itself, as it is travelling through a fluid, experiences an upthrust{4}. The rocket also experiences a drag force acting on it. The material the rocket is made from also has its own internal tension.

As the rocket rises higher and higher in the air, the mass of the rocket would decrease because fuel would be burned and the exhaust ejected- the rocket would therefore experience a larger acceleration. Additionally, due to the thinner atmosphere at higher altitudes, the rocket itself would experience smaller external pressures.Thus, as all materials deflect when strained[3a], the deflection would increase as the resultant outwards force would increase due to the smaller internal pressures. the material chosen would need to deflect a small amount given the outwards pressure from the air within the rocket- implying that it should have a high stiffness/ Young’s modulus.

2) Outside the atmosphere

There is no external pressure from the atmosphere outside it, so the stress on the material from the internal pressure is at a maximum; this results in the material deflecting. The outer edge of the material will extend and the lower side contract; additionally, temperature differences may cause uneven extension and contraction. This uneven stress and strain on the material may leave the craft vulnerable to breaking apart as different parts experience different forces; additionally, if there are holes or windows, the stress trajectories{5} of the material are ‘squashed’ together, with the point of highest concentration at the deepest point of the crack. The concentration of the stress at the tip of the crack can raise the local stress multiple times relative to the original stress placed on the material, resulting in the material being prone to cracking and therefore the crack expanding. The stress factor at the crack tip is defined by the equation: $stress\ at\ tip = s(1 + 2\sqrt{\tfrac{l}{r}})$ {6}; where s is the original stress, l is the length of the crack and r is the radius. One can use this equation to understand that for any hole in a material, the stress concentration at the tip of such a hole is at a minimum of 3 times greater than the overall stress experienced over the whole material. Note that such a situation only occurs when l=r, meaning for a circular hole. For a hole that has sharp corners (e.g. a square hole), the stress concentration can be much higher than 3 times. Thus, if the design of the spaceship includes windows, these should be round to lower the stress on the hull material by as much as possible. Additionally, the hull can receive reinforcement across its horizontal axis to ensure that the deflection is not excessive.

3) Reentry

Upon reentry the spacecraft may experience rapid deceleration leading to large amounts of stress being placed on parts of the spacecraft in contact with the atmosphere. The spacecraft will also experience an external pressure from the atmosphere. As a result, there will be a large number of different forces applied from different directions on its material, and so care must be taken to choose a material for the hull that can resist forces applied in multiple directions simultaneously and is strong in many directions.

Launch systems:

Reusable launching systems

Before one even considers launching a rocket, a budget must be set for the rocket itself. It is no secret that such a large scale engineering project has a large price tag; NASA's 1981-2011 space shuttle program alone cost 199 billion US dollars (averaging out on 6-7billion/ year). Thus, the importance of properly pricing one's space missions cannot be overstated. Those working on any engineering project must also be aware that costs are likely to rise as errors arise and the project continues; inflation must also be taken into account. Thus, the actual price of a project is likely to (well) exceed the original projected cost. As a result, it may be worth reusing rockets to save money. According to Elon Musk, if one can figure out how to reuse rockets like airplanes, the cost of access to space will be reduced by as much as a factor of a hundred. For example, the first ever commercially successful reusable orbital-class launch system Falcon 9 carries a list price of about $54-60 million, with the cost of fuel only being 0.4% of the total. The majority of the launch costs come from building the rocket, which flies only once.

The Luna for Living project is a commercial activity that requires taking customers to and back to the moon an indefinite number of times. Thus, a good way to reduce cost is to use reusable rocket launch systems. However, using the SSTO (single stage to orbit) might be too ideal for the moment.

As we already know, most of the weight of the rocket is fuel, and as the fuel is burnt to push the rocket upwards, the fuel tank gets empty. The empty tanks do not contribute anything but to add weight to the launch, so staging is used to separate the empty tanks when they have burnt to completion to make it easier for the rockets to achieve the orbital velocity by removing the weight of the empty tanks.

Most rockets are designed to burn up on re-entry, or splash down into the ocean. The expendable rockets are so widely used because of the low production cost, simpler in design and greater fuel efficiency compared to reusable rockets, but it also has a significantly high pre launch cost.

Reusable launch vehicles are under development with the aim to reduce the pre launch cost. The system SSTO I just mentioned is a concept that once the spacecraft is sent into its trajectory, all the launch vehicles then re-enter the Earth's atmosphere and land to be refuelled so that it can be used again later.

Reusing launch vehicles is very difficult. It takes aerospace companies like SpaceX decades to develop a reusable first-stage and expendable second-stage. And not to mention that reusing both stages, is very hard because by then the rockets will be travelling at orbital velocity.

So why is reusability so hard to achieve? Many clever people have tried to develop reusable rockets but still decide to stick with expendable systems.

One of the reasons is because of the high gravity and thick atmosphere on Earth, and the fact that the rocket will need to operate in vacuum, transonic and other harsh circumstances,would require more advanced, likely composite material and engine technology. Such expensive technologies and materials would likely increase the price tag of such a project by a significant amount. As a result of these factors, a balance must be struck between having an exorbitant initial construction cost and a high repair cost. Additionally, not all spacecraft that have been designed with reuse in mind were or are reusable easily, or cheaply. For example, the space shuttles used in the space shuttle programme had to undergo repairs, bringing up the cost of the launch to between $450 million-$1.5 billion per launch. Another reason is that we need to find an extremely precise balance between the masses of the propellants, the supporting vehicle and the payload. With expendable rockets, you get only about 3% of lift-up weight to orbit (about 90% being propellants). So when you add a lot of things to the reusable rocket (like thermal protection, strength the stages, extra fuel and engines for landing, more complex systems) that would add weight to that vehicle, the payload needs to be reduced further (by about 30%). You might end up with no room to fit other essential or important systems or a weight that makes the spacecraft simply too difficult, or in the worst case scenario, unviable to launch. On the flip side, if nothing goes wrong, the cost of relaunching- which would just be refuel costs- would amount to about $200,000 (USD), a decrease of nearly 300 times compares to the cost of building and launching a new rocket.

But even with these difficulties, Elon Musk thinks 'reusability is fundamental to the breakthrough in access to orbit or beyond' and his settlement to Mars. So SpaceX is continuing research on Starship, which is going to be a spacecraft with a two-stage reusable rocket. If Elon Musk thinks that such a rocket may be possible, then we also think that we could use such a rocket in the Luna 4 Living project.

Reusable rocket landing

SpaceX rockets are designed not only to withstand reentry, but also to return to the launch pad for a vertical landing.

Vertical landing can often be achieved using parachutes or propulsion. SpaceX initially tested using parachutes, but the stage did not survive the re-entry into the atmosphere. SpaceX subsequently switched its focus to developing a powered descent landing system —a fully vertical takeoff, vertical landing (VTVL) rocket. The first stage will return tail-first for a powered descent and the second stage with a heat shield, reentering head first before rotating for a powered descent. The first stage landing is when after stage separation, the booster flips around, a re-entry burn, controlling direction to arrive at the landing site and a landing burn to effect the final low-altitude deceleration and touchdown.

After various tests, since 2017, Falcon 9 rockets have been routinely landed and recovered.

Moon landing:

After the travel from the Earth orbit to the Moon orbit, our spacecraft will need to land on the moon. The Apollo Mission about 50 years ago carried crew to the surface of the Moon successfully, so we can adopt the same approach.

The spacecraft of the Apollo Mission consists of two parts – the Command and Service Module (CSM), the mothership, and the Lunar Module (LM), the lander. Both modules contain the life support system and carries engines and fuels.

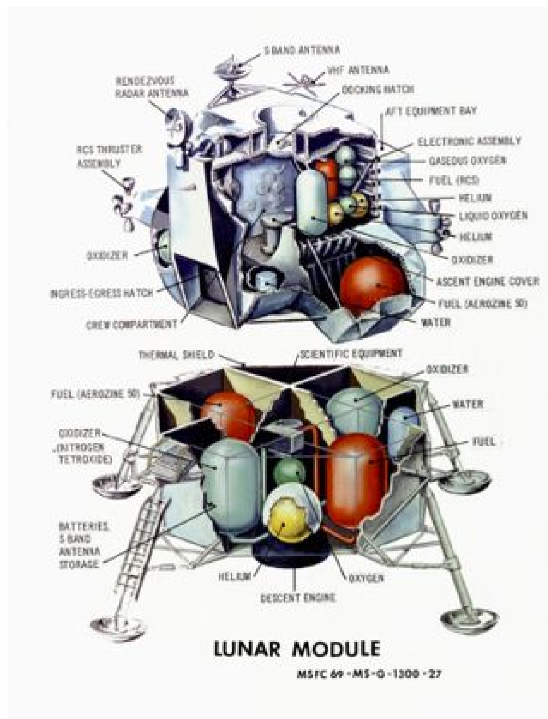


Fig.28- Lunar Module

After separating with the third stage rocket, the spacecraft stays in the Moon orbit so that everything about the LM is checked, and the CSM and LM are docked nose-to-nose to allow astronauts flied in the CSM can make their way into the LM. Once everything is checked, the astronauts separate the LM from the CSM and head to the Moon. The CSM then stays in the orbit serving as the communication link between the LM and the mission control back on the Earth. Some people need to stay in the CSM to do this job.

The LM is also made up of two parts – the Ascent stage and the Descent stage. For Moon landing, the Descent stage fires its engines to orient and land. The landing was first controlled by the computer on the CSM, which makes sure the vertical and forward velocity approaches zero. And finally the landing was manually manoeuvre by the astronaut on LM, to avoid crashing on craters and other surface formations.
Now the astronauts are safely landed!

We can use the same system – CSM and LM to land our customers. When landed, our crew will give instructions on how to get to our Moon base.

Leaving the Moon

After the astonishing tour on the Moon, it is also our responsibility to bring the customers safely back to Earth. The first step is to leave the Moon and get into the Moon orbit.

In the Apollo Mission, the astronauts go back into the LM. The Ascent stage of the LM fires engine to leave the Moon. Incidentally, because the gravity on Moon is so small, the escape velocity is 2.38 km s-1. While the Earth's escape velocity is 11.2 km s-1. (Escape velocity is the velocity required to escape the gravitational pull.)

The LM then leaves the Moon's atmosphere and into the orbit, where it is docked with CSM so that the astronauts sit back in the CSM. The LM is allowed to crash back to the moon and the CSM leaves the Moon orbit when it is ready and then heads towards the Earth.

Re-entering the Earth's atmosphere

Objects, like meteorites, which enter the Earth's surface will burn because of the supersonic speed. So we need to prevent our spacecraft from burning.

Objects burn at a low altitude because of friction with the air molecules. But in the upper atmosphere where there is little air, the burning is caused by the pressure wave at the surface of the head.

To avoid burning, the capsule will need to be coated in an ablative covering that protects the spacecraft underneath by burning itself during re-entry. There are two factors that dominate whether the spacecraft re-enters successfully – the shape of the capsule and the angle of re-entry.

Research has shown that the blunt shape lowers the head load. Because the air molecules cannot get out of the way quickly, they serve as a cushion and make re-entry more stable, keeping the shock wave and hot gases away.

The angle of re-entry also needs to be precise, usually 40 degrees. A steep angle will increase friction and the chance of burning up. A shallow angle will not re-enter, the spacecraft will just deflect like a stone across a pond.

After the re-entry, the parachutes will deploy at a suitable time. The spacecraft with humans on board will then rest on land, at sea or actively captured by our recovery team.

Safety procedures:

As rocket travel is still quite dangerous, we are going to incorporate several safety systems from launch to ensure the space travel as safe as possible.

Tests

Before the flight, all equipment on the rockets should be tested again and again. This includes the engines, the parachutes, the heat shielding, all the systems, etc. This ensures that we are launching it once it is prepared, and that we are able to deliver safe space travel experiences to the tourists.

Launch countdown

- Rocket check, verify for propellant loading
- LES armed
- First stage propellant loading: rocket grade kerosene, LOX,
- 2nd stage propellants
- Engine chill-down prior to launch
- Computer begin final prelaunch checks
- Propellant tank pressurization to flight pressure begins
- Launch directors verifies to go for launch
- Engine ignition and lift off

The engine chilldown is an important part if we are using cryogenic propellants, like liquid oxygen and liquid hydrogen. As the propellants are so cold, pumping them directly to the engine at normal temperature will cause problems, such as cavitation (vapour bubbles produced in the stream). So by allowing small amounts of the cold propellants through the system until the engine gets to a low working temperature is essential.

Launch escape systems (LES)

The Launch Escape System (LES) or Launch Abort System (LAS) is a system which is already in wide use to get the crew involved in human spaceflight away from the problematic part of the rocket as quickly as possible when something lethal happens to the rocket during launch or even on the launch pad.
In this Luna for Living program, we are transporting many tourists up to the moon and back, so a reliable LES is necessary, for the safety of the people on board and to attract more tourists.

The LES often contains a space capsule placed at the top of the rocket, ready to be ejected from its launch vehicle anytime when emergent. The situations are mostly

rocket explosions caused by the highly flammable fuels carried by the rocket, or booster failure.
The space capsule is often a spacecraft containing payload – crew and storage – and their own thruster engines. It also needs to be controlled by an automatic rocket failure detection and a manual activation.

Typical stages of LES:
Fault or failure detected, manually activate the LES.
Space capsule is quickly jettisoned from the launch vehicle/rocket using the LES engine.
After burning to completion, the abortion system is shut down.
The rocket recovery team would collect the debris if the rocket exploded.
After the LES engine is shut down, the spacecraft would passively coast to apogee – the highest point in its arc.
Further separation might take place at apogee according to the spacecraft design to get rid of the trunk from the crew capsule. The trunk contains storage, gears and usually solar panel.
Capsule reorient itself using the smaller regular engines.
Parachutes deploy (first drogue chute then the main chute) when conditions are met to softly and safely land on ground or water.
The on-land rescue team approaches and retrieves the spacecraft in time.

The Life support system

The life support system in human spaceflight is a group of devices that help a human being to survive in space, without the protective Earth shielding.
A life support system will need to have the following functions:

- Regulate air – provide oxygen and absorb carbon dioxide
- Supply water and food
- Maintain the correct body temperature and pressure
- Deal with the body’s waste products and vaporous emissions from the body
- Shield against harmful external influences like radiation and micro-meteorites
- Monitor oxygen level, temperature, pressure.
- Fire detection and suppression

Setbacks:

<u>Materials</u>

There are however a few challenges we will need to overcome with our materials for spacecraft. According to NASA, the hydrogen environment will be one of the main threats for the material. Hydrogen embrittlement, is a process of diffusion of hydrogen atoms into metal. This process can potentially cause the material to be more brittle and prone to cracking. This reduces the toughness of the materials, encourages crack growth and causes it to stress and deform. Hydrogen can also react chemically with elements that are presented in a metal, which then forms inclusions which can degrade the properties of a metal, furthermore, this can even cause blisters to appear on the metal surface. The most common mode for hydrogen embrittlement is when hydrogen is absorbed by a material that is relatively unstressed, such as the components of the shuttle's main engines before they experienced the extreme loads of liftoff and flight, and this is known as internal hydrogen embrittlement.Similarly as mentioned, internal hydrogen embrittlement can potentially make materials unable to survive under high stress.

Embrittle can also affect material to deform and be stressed when it is immersed in hydrogen, and this effect is known as hydrogen environment embrittlement. This occurs in pressurized hydrogen storage vessels, and the vessels are simultaneously being stressed while in contact with hydrogen. This causes reduction in ductility and strength. According to NASA, the reaction between hydrogen and titanium alloys can occur internally and form brittle titanium hydride. The chemical reaction of hydrogen with other elements that are present in the metal is through the hydrogen reaction embrittlement process. This forms inclusions that can degrade the properties of metal, and cause blisters on the metal surface. Despite that, one way to avoid this is by choosing naturally resistant materials when possible. As this process is not also realistic, engineers had a few experiments with coating and plating on the material, to protect the metal from any contact with hydrogen. Currently, the most effective barrier to hydrogen found is gold plating. However, developing and making this into commercial use will cost a lot. An alternative for this plating is copper plating, which provides the same level of protection as gold, as long as a thicker and heavier layer is applied.

Another challenge will be the space environment. Space has a vacuum environment, which means it is a space without any matter or air. This environment can cause some materials to outgas, which then turn affects any spacecraft component with a line-of-sight to emitting material. Another potential challenge is thermal cycling in Space, which is a process of cycling through two temperature extremes, and typically at relatively high rates of change. This process causes cracking, crazing, delamination and problems relating to thermal expansion in the material.

Conclusion:

Reusable launching systems

Reusable rockets are only valuable if the frequency of launches is great enough to outweigh the cost of developing and utilizing the technology. We need to be aware that refurbishing and recertification can sometimes be more expensive than manufacturing new engines.

For our project, we will need to fly frequently with around 10 customers each time. So the money we make from the tourists should be able to outweigh the cost of the reusable rockets. Therefore it might be more cost effective to use reusable rockets.

Appendix:

Maths and science notes

{1}(*Moon- 3 × 10^{-15} atm [0.3 nPa] compared to Earth: 101,000 Pa [101 kPa]*)
{1}: Assuming g doesn't change and is equivalent to 9.81 (3sf); and that standard orbital height=20,200 km= 20,200,000m; assuming the launch mass of this rocket= launch mass of Saturn V = 3,038,500 kg; GPE needed to reach that height is $GPE = mg\Delta h$ =20,200,000 x 3038500 x 9.81 = 6.02 x 1014 J. That's a lot of energy.
{2} Note that a stationary planet has no momentum and therefore if the planet does not move a gravitational slingshot does not work.
{3} This angle is referred to as the 'flight path angle' and is given the symbol γ (gamma).
{4} Archimedes' principle- weight of air displaced is equivalent to upthrust on rocket

{5} Imaginary 'paths' through which stress 'spreads' from one molecule to the next
{6} Inglis' equation for stress.

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