ANALYSIS OF ON SITE MOBILITY AND CREW WORK ON A LUNAR BASE

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Abstract

This report analyses, as the title suggests, the aspect of the onsite mobility and crew work on a lunar base. The analysis is conceptual and treats technologies that are currently in development and not yet implemented. The suggested technologies and systems are meant to make it possible for a crew to live on the moon, partially sustained by the moon with minimal resupplies. The rotation of one year serves as a benchmark for future missions to Mars and is limited by the effects of radiation on the astronauts. The result is presented as a summary of weights and cost for the needed equipment, along with the launch sequence of the equipment.

I. INTRODUCTION

"The moon – For millions of years it looked down on the Earth with its lopsided face and baffled mankind. Sooner or later we were going to want to take a closer look at it."

-James May

As suggested in the citation above, mankind is curious by nature. This is why, 40 odd years ago, Neil Armstrong joined the crowd of explorers that has pushed the boundaries and went where no one previously had been before, pushing the outside of the envelope. Since then 12 people has sat foot on the moon, the last in 1972 [1].

There are many reasons to why man should continue to explore the moon. Today NASA has almost 200 suggestions of what could be done on the moon, among these is to eventually enable a human settlement on the moon and to test technologies for future missions to Mars [2].

This report is written as part of a group project in the course Human Spaceflight, analyzing the feasibility of building a manned base on the surface of the moon and treats the subjects of "On-site mobility" and "Crew work".

The assumption is made that when the International Space Station is decommissioned in 2024, human space exploration will move to the moon. The moon base shall be operational for at least ten years and accommodate up to six astronauts at any given time. It has been decided within the group that the base will be located in the vicinity of the Moons South Pole.

II. On Site Mobility

In this section different solutions for transportation on the moon are presented. Manned and un-manned rovers for use in both short and long range are discussed.

A. Short and medium range

The short and medium range rovers are to be used for manned transportation, and to help transport equipment and cargo in the closest vicinity of the base.

1. "Classic" Rover

In order to conserve the oxygen carried by the astronauts in the space suit tanks, a classic rover, such as the one used in the Apollo missions can be used to travel short distances, see Figure 1.

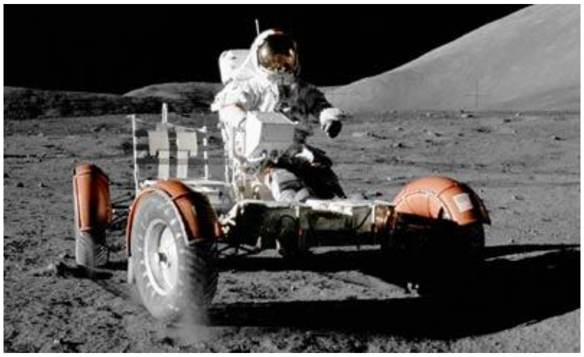

Figure 1 – Rover used in the Apollo program

2. Transportation from landing site

Regular trips between the landing site and the moon base will be made. Either just to transport astronauts or to move supposedly heavy cargo and supplies that arrives from earth.

A suggestion for an autonomous railway system has been studied. It could possibly save time and greatly reduce the amount of work needed from astronauts by doing some tasks in parallel. It is composed of a wagon or a car that will be towed with a cable operated by winches.

Due to the thermal expansion caused by the significant temperature variations on the moon surface it is not possible to build a railway track. Instead a road could be built using the same technique as when building the base. A road can be created from the moons regolith [3] by printing layers to smooth the landform between the base and the landing site.

If we assume the following data, it becomes possible to roughly estimate a design for the commute road:

- Distance between lunar base and landing site will be around 250 m.
- The largest rover or wagon that will be used will have a width of 4m and a safety margin of 1.5 m, the roads width will be approximately 6 m.
- The maximum cargo diameter is about 8 m so a landing circle area with a diameter of 15 m will be sufficient.

Considering the assumptions stated above road will have a surface area of 270 m^2. If the road thickness is 0.1 m that means, the road construction will require 27m^3 of printed regolith. If we assume a that glue represent 10% of the volume and a density similar to the density of water, then this road requires 2700 kg of glue.

3. Unmanned transportation rover

Not all transportation of cargo can be done on prepared terrain so a rover capable of moving cargo in many different situations will be useful. NASA has been working on a prototype called ATHLETE, see Figure 2. It uses wheels on 6 limbs, with each limb having several joints and 6 degrees of freedom, that can both drive and to some extent climb over obstacles [4]. This rover is designed to be able to carry many different types of cargo and even be able to perform various tasks like drilling or digging in the moon surface. It could also serve as a transport for astronauts in special circumstances; for example for traversing very rough terrain or in some emergencies.

Figure 2 – The ATHLETE.

There have been a couple different versions of this prototype, but the mass for a final mission ready model can be estimated to be roughly 1000 kg ±200 kg, with a carrying capability in the order of 500 kg in Earth gravity.

A rover such as this one could be useful in all stages of a lunar base's lifetime, from initial construction to later base maintenance and lunar excursions.

B. Long and very long range

The rovers needed when making excursions far away from the base will be different from the ones described in II.A. This section discusses alternatives for such rovers.

1. *Autonomous rover*

For research or maybe to make a communication relay it may be advantageous to have a small autonomous rover that can perform some sampling of the moons ground or atmosphere.

Due to sustainability reasons it should be maintainable and use electrical power. A rover like Curiosity would be very useful and if it is sent in the first launch it could be used to check and control the base site before starting to build the base from scratch. A rover like RESOLVE, see Figure 3, is necessary in order to make sure that our technology to extract and process water on the moon is viable, as described in IV.D.1.

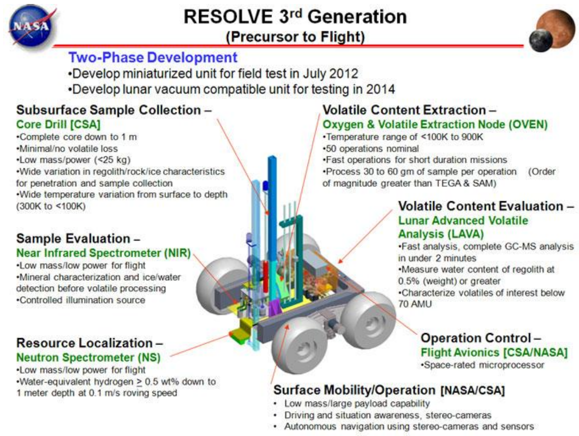

Figure 3 – The RESOLVE [5].

2. *Habitable rover*

Astronauts will need surface mobility to explore multiple sites across the lunar surface. Hence for such expeditions, a pressurized lunar rover may be considered such as the LER, see Figure 4, which can provide the astronauts main mode of transportation and also allow them to work without any restrictions imposed by spacesuits. The pressurized cabin of the rover will have a suit port that provides a faster way for the crew to get into their space suits and out of the vehicle.

Figure 4 – Testing of the LER [6].

Looking into the features of the rover, it will consist of a mobility chassis and the pressurized cabin module weighing 1000 kg and 3000 kg respectively. These two components could be delivered to the lunar surface pre-integrated, or as separate elements. The chassis can be driven by the astronauts even without the pressurized cabin by wearing the spacesuits and it can also be used to carry the cargo initially if required. The modular design of the rover allows various tools such as winches, cable reels, backhoes, cranes and bulldozer blades to be attached in case of special missions [7].

Various considerations are given to the rover while designing, which are as follows [7]:

Range of exploration

On the surface of the moon, travel range is limited by how quick the astronauts can get back to their pressurized environment. Hence explorative activities will be limited by the number of rovers. In case of rover break down at a position very far away from the base, then it becomes very difficult for the astronauts to get back to their base by foot. Therefore it will be useful to send an emergency rover along with the main rover so that it can act as a backup. The presence of rovers will expand the range of exploration to very far off distances from the base, thus increasing the scientific opportunities.

Astronaut protection

The pressurized cabin is heavily shielded and can withstand any kind of solar particle events, suit malfunctions or even medical emergencies.

Rapid Ingress/Egress

The LER concept of the rover enables the astronauts to go out for a moonwalk at moment’s notice. The suit-port, see Figure 5, present at the back of the pressurized cabin allows them to enter and exit their spacesuits without bringing the suits inside. It in turn minimizes the wear and tear on the suits and also help in keeping the internal space dust free.

Figure 5 – The space suits on the backside of the cabin [7].

Field Science capability

Due to the presence of the pressurized cabin, the flexibility of switching between spacesuits and plain clothes acts as a beneficiary factor. Although the astronauts will have to go into the external environment, see Figure 6, to have a closer look at the surface, some of the activities may need delicate work which cane done inside the cabin itself. Being able to sit comfortably and look at the geological formations without the restriction of the bulky gloves and continuous exertion of suited walking enables them to better research on site. Thus the cabin can also serve as rolling science lab for studying any samples or any other kind of research.

Power

Like electric cars here on earth, this rover is powered by batteries. NASA is trying to come up with a lightweight battery system, the aim of which is not only to reduce weight but also create high efficiency allowing them to last longer.

Figure 6 – Showing the field science capability [8].

Other concepts the lunar electric rover depends on are the fuel cells, lightweight structures and materials, braking system, active suspension and thermal control systems, etc.

Thus to sum up this concept, this kind of rover can be extensively used for the transportation of astronauts. It is highly useful during the initial stages of the lunar base mission as it can transport them to the base site from the landing site.

C. Communication

Communication forms one of the important aspects of the mission because it is essential for the astronauts to be in constant touch with the rest of the crew members on moon as well as the mission control center on earth.

The current design of the spacesuits involves the astronauts to wear a Communications Carrier Assembly (CCA) or "Snoopy Cap". This assembly consists of the fabric hat fitted with microphones in the ear area for listening and boom microphones in front of the mouth for speaking. These caps are worn under the helmet and visor that surround an astronaut's head [9].

So the radio signals are sent to their headsets, which then translate the signal into sound. While on the field, the astronauts can communicate with the base in this way and their communication can also be relayed back to earth [10].

The communications carrier assembly, while being effective, has some limitations such as non-adjustable caps once worn, boom microphones interfering with the feeding and drinking mechanisms during long duration missions outside the base or spacecraft.

To improve upon these limitations, NASA has been working to upgrade the suits in such a way that it will be fitted with integrated audio system. This new system is where the microphones and earphones are removed from the CCA and integrated into the structure of the space suit itself. This implies that there are no moving parts to disrupt an astronaut's movements or become dislodged during the activity.

Sound quality can be impacted negatively because the microphones are integrated inside the suit and are present a bit farther away from the astronaut's mouth and hence due to this reason there is a possibility of interference.

To solve this problem, a multi-channel noise reduction concept is implemented where advanced filters are used to isolate the sound of speech [9].

III. Equipment and Tools

In this section the equipment needed to perform work and research is described. Amongst these are the space suits for EVA, and the research equipment.

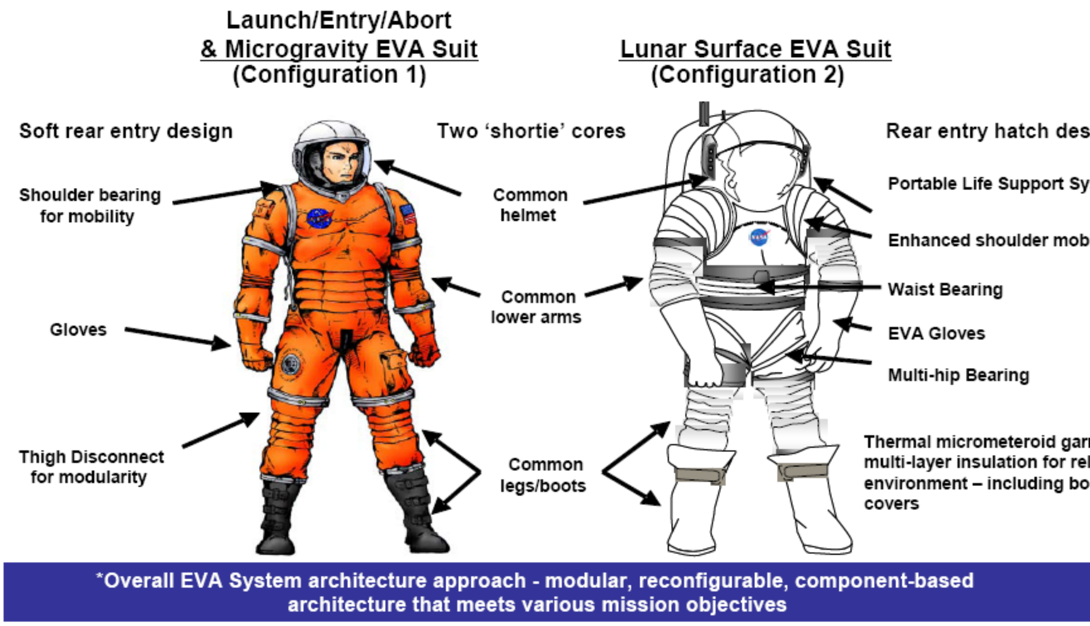

Figure 7 – The Constellation Space Suit [28].

A. Space suits

There have been many design concepts for new modern space suits; NASA currently has combined many of those ideas into the Constellation Space Suit project. The Constellation space suit is designed to be versatile and comes in two configurations, see Figure 7.

Configuration 1 is made of mostly soft materials and is designed for launch, landings and limited microgravity EVAs.

Configuration 2 is the designed for a lunar mission with extra durability and improved cooling systems. It can carry a life support backpack that can connect to the umbilical from vehicles or other machinery for longer missions. It also features a heads up display and high tech communication equipment. Configuration 2 bases some of its design on the Mark III space suit concept, which features a mix of hard and soft materials, high pressure and rear entry [11]. The high pressure has the benefit of making astronauts able to go on EVA without having to worry about decompression sickness or perform long pre-breath preparations to reduce the amount of nitrogen in their blood and joints. The rear entry function is vital to the design of the Lunar Electric Rover, where the space suits are doubling as air lock and connect to ports on the back.

For the future there are hopes for designs where pressure is applied through mechanical counter pressure, this would allow for flexible skintight suits and would allow much more mobility in space environments. MiT are working on the “Bio suit” [12] but any functional suits are still a long way off, with both reliability and temperature control being major hurdles to overcome.

B. Tools

Like on the International Space Station, astronauts will have some tool package with general tools adapted/designed for weightlessness or low gravity. Such design implies at least one tether on each tool but also a thermal resistance for a very large range temperature. For some scenario or emergency case some kind of specific can be required like air lock tools or door lever in order to help astronaut to do their work.

C. Research equipment

The research equipment can be improved or upgraded after most supply missions or crew rotation. However, it would be best to limit any major changes. Therefore it is necessary to continue as ESA has been doing for ISS, i.e. try to invent equipment that scientists might have use in the future, without necessarily giving it any predefined mission.

Medical research and monitoring equipment is however a must-have in order to monitor the crew's health and be able to take preventive action if needed.

Detectors and telescopes are also necessary in order to better study the incoming radiations and therefore necessary to better protect the crew.

IV. Crew Work

This section treats the major aspects of the crew work on the base. The schedule, the composition of the crew and their tasks, involving research and maintenance is discussed.

A. Schedule

During the astronauts stay on the moon their schedules will need to be planned in detail to ensure efficiency regarding their duties, but also to satisfy all human needs. These needs are both psychological as well as physiological. The effects of long duration space flight are largely unknown as the longest spaceflight performed by a human is 438 days [13].

1. Baseline schedule

The schedule used by the astronauts on the International Space Station can serve as an outline. There are some major differences between living on ISS and the moon. Examples are micro gravity versus 0.17 of the Earth's gravity on the moon [14], and the length of a day, 90 minutes on the ISS [15] compared to 29.5 Earth days when living on the moon [16]. Considering these differences, this schedule takes into account all tasks that is needed to be performed, including rest and exercise [17] and is constructed to work in an environment very different from the one on Earth. The daily schedule varies depending on the duties, and if the astronauts are on duty or not. When broken down, the schedule can be divided into six basic chores: wakeup and pre sleep, preparation and briefing, work, exercise, sleep, and flex time. The time allocated for these chores is presented in Table 1.

During wakeup and pre sleep the astronauts have time to take care of their personal hygiene, do housekeeping duties and eat breakfast [15]. The preparation and briefing allows for a conference with mission control to go over the planned schedule for the day. After this it is time to work. This involves doing routine maintenance of the station and performing research and doing experiments. The workday is planned including flextime, allowing for delays and short breaks between the scheduled works. Just like on Earth during midday there is time for lunch and a lunch break. It is vital that there is time exercise every day. Without exercise, in zero gravity, the skeleton and mussels would deteriorate and astronauts would not be able to walk or stand when returning to earth [15]. Lastly the sleep is scheduled to allow for sufficient rest and recovery.

	Working day	Off-duty
Wakeup/Pre sleep	03:30	03:30
Preparation/Briefing	01:20	00:15
Work	05:20	00:20
Exercise	02:30	02:30
Sleep	08:30	08:30
Flex time	02:50	08:55

Table 1 – Basic schedule for an astronaut on the ISS, which could serve as baseline for the astronauts on the moon base.

B. Crew rotation

The crew rotation is mainly linked with health criteria because astronauts are exposed to solar and cosmic radiation, which limit their mission duration around 300 days. But the crew rotation can also be dependent of the mission requirements, for example if a specialist is needed to repair a robot or something else that requires extended EVAs and exposure to radiation staying period of an astronaut can be reduced to permit the exchange of crew members.

C. Composition of crew

The composition of the crew will be of great importance to avoid complications regarding the mission. According to [18], heterogeneous crews have lower rate of conflict than homogeneous ones, larger crews have fewer conflicts than smaller ones, and conflicts tend to decline with increasing mission length. Taking this in consideration the capacity of the moon base should be utilized to its maximum as much as possible, rotating the half the crew at the time creating an overlap between crews, hence keeping the crew as heterogeneous as possible.

The "third-quarter phenomenon" is a phenomenon that suggests that the rate of conflict amongst crew members is the highest during the third quarter of a mission [18]. Along with an increase in conflicts, the crew members also experiences mental issues. It is believed that these issues arise when the crew realizes that the work is only halfway completed, and that a long period of the mission still remains. These issues are essential to both the health of the crew and the success of the mission [19]. The third quarter phenomenon was observed during the "Mars500" study, and it was suggested that more attention needed to be given to the third and fourth quarters of the mission and that scheduling of tasks could be used as a countermeasure to this phenomenon [20].

1. Pilot

In a crew, the pilot is one of the principal persons to fulfill the mission because he is in charge of the trajectory control and the landing procedure. For this mission, it is compulsory to have at least one experienced pilot in order to ensure a safe landing on the moon's surface. But also in case of an emergency, which can imply evacuation, he has to be capable to bring the team back to Earth. That means to perform an emergency lift off from the moon and a re-entry procedure. They are also qualified to perform extra vehicular activities.

2. Researcher

In this project of building a moon base, the possibilities and challenges of research are quite huge. The main aim is to prepare a mission to colonize Mars, but in the same time the base provides possibilities to do research. Some areas of interest are finding water on a new planet and find the way to exploit it. There is also the challenge of creating propellant on another planet by using the material present in the ground without all the facilities available on Earth.

3. Engineer or Technician

An engineer and technician are essential in achieving the challenge represented by a lunar base. Their qualifications are required in order to assembly some part of the base or at least do the maintenance of the base. They give to the team a critical look on the technical aspect.

D. Research & Operations

1. Water extraction

In order to be able to stay longer on the Moon and go further in our human deep-space exploration, it is necessary to have sufficient water to sustain the crew. According to the principle of In-Situ Resources Utilization, the aim is then to be able to produce water locally. As shown by previous measurements, there is a nonnegligible amount of water on the Moon [21]. However, this water can be found trapped in ice form or in the regolith. An important aim at the beginning of the lunar base mission will be to develop the ability to extract and process this water.

In order to make sure we are able to sustain ourselves with water on the Moon, the following procedure can be followed:

- **Step 1:** During the first launch, along with the elements necessary to build a lunar base, a rover similar to RESOLVE should be sent on the Moon. Its mission will be to extract a small amount of water in order to make sure that this extraction is made efficiently.

- **Step 2:** Once the extraction process has been verified and/or improved, the bigger scale extraction devices can be sent to the Moon. More precisely, a Water Processing and Storage Package (WSP) capable of processing and storing an important quantity of water (around 4000 kg) should be sent along with a rover able of extracting and transporting large quantities of lunar soil containing water. The WSP would be working on the energy plants already built during the previous launches and would need around 1 kW per day to process and store the water.

- **Step 3:** Once the Moon crew is certain that the first package is working well, other similar packages should be sent for the sake of safety and redundancy.

According to a previous study [22], where these steps have been considered, this equipment should be able to extract 150 metric tons of water per year once fully operational (with at least 3 packages).

An important question in this process is the location of these packages. In order to minimize the transportation of energy to the WSP, and therefore the possible loss of energy, it is preferable to install the WSP next to the power generator plants. This implies that the excavating rover will have to cover a greater distance to go from the bottom of the crater to these plants. However, this location will also enable an easier recharging of the rovers batteries and an easier check-up of the rovers' overall status. Furthermore, the road to and from the crater can be made smoother using the 3D printers to level out the way.

2. Oxygen & Fuel processing

Once water can be efficiently extracted and stored, it is possible to use it for other uses than immediate consumption. It is possible to extract oxygen and hydrogen in order to process fuel for further use. The procedure to implement this processing should follow the same pattern as for water extraction:

- **Step 1:** Use the RESOLVE rover in order to make sure that the processing methods are efficient on the Moon.

- **Step 2:** The bigger scale processing devices can then be sent to the lunar base. A Water Electrolysis and Fuel Storage Package (WEFS) capable of processing and storing an important quantity of fuel should be sent. A rover extractor previously used to bring material to the WSPs could be used to transfer water from the WSP to the WEFS.

- **Step 3:** Once the Moon crew is certain that the first package is working well, other similar packages should be sent for the sake of redundancy.

The oxygen processed would here be used for the fuel consumption. It might therefore be useful to consider another source of oxygen for the base. This source would be regolith. Regolith actually contains around 40% of oxygen, and it can be extracted using a hydrogen reduction of lunar metals (aluminum for instance) [23]. This extraction should also be progressive as for the previous procedures.

The location of this equipment should close from the water and power sources, but because of the nature of the material stored, it would be preferable to leave a safety distance in the unlikely event of an incident. This equipment could even have its own independent power source. Any incident would then not affect the rest of the base operations.

3. Lunar Research

The moon base will be built after the end of ISS's life, consequently, all the research driven on the ISS should be pursued, like the micro-gravity research. Even though Mars has a stronger gravity field than the Moon, it is still far from the gravity conditions on Earth. The effects of low gravity are indeed not yet well known, therefore the research on the effects of the Moon's low gravity, along with the previous results with micro-gravity, will be an important step in preparing a Martian base.

Radiation

A more important continuous field of study will be the effects of radiation. Since the Moon is not protected by a magnetic field, neither the crew nor the equipment will be spared by the radiation if left unprotected. Therefore a database of health and status evolution should be kept in order to better understand those effects. The crew should focus on trying new protection systems, for them and for the different equipment. If successful, those improvements will be of a considerable help for the Martian missions, since Mars receives less radiation from the Sun, the amplitude of the radiation decreases as r^{-2}, where r is the distance to the Sun.

Biology

Another useful research field is the behavior of plants in deep space. It would be beneficial to future deep-space missions to be able to grow plants in proximity of the human crew. The benefits would be plenty: Using photosynthesis the plants could help process oxygen and diminish the amount of carbon dioxide; taking care of plants could improve the physiological health of the crew; plants could be used as nutriments. Pursuing NASA's X-Habitat program on the Moon could be a first step to grow plants on the Moon. The ROGR program [24] seems promising in this sense and could be tested on real deep-space conditions. With the help of a mechanical gardener, fully automatic, the crew would be able to use all extra space in the base to grow some small plants. These robots could be modified to work on the greenhouse so that the crew members would not need to tend to the greenhouse. However, the crew members should still be able to tend to the plants by themselves since it can be mentally and psychologically beneficial [25].

Radio astronomy

Another possible and promising field of study is radio-astronomy. Since the moon doesn't have a flock of satellites, clouds nor a magnetic field, radio-astronomy could be done without any major disturbances. Some studies have already shown that having a radio-telescope on the far side of the moon would enable the study of objects 100 to 1000 times fainter than the James Webb space telescope [26].

V. RESULTS

The main results from the report are presented as a summery in Table 2. The results are discussed further in sections VI and VII.

Launch	Equipment	Purpose	Mass [kg]	Cost per unit [$]
1	RESOLVE: Regolith and Environment Science and Oxygen and Lunar Volatile Extraction	Autonomous very light rover to perform analysis: test the extraction of water process and the dissociation of water into H+O2	250	1 000 000 000
2	Excavating Rover	Big rover dedicated on mining operation	2300	1 700 000 000
	ATHLETE	All terrain exploration and transportation	1000	2 000 000 000
	Water process and storage unit	Process water on bigger scale from material brought by the Excavating rover	1200	3 200 000 000
3	LER	Big manned rover to perform long range trip and do some experiments If needed, only the chassis can be sent (1000 kg) for transportation operations	3000	4 000 000 000
	Crew	4 crew members	400	-
	Space suits	5 space suits to perform EVA	670	10 000 000

Table 2 – Result summery.

VI. DISCUSSION

The assignments of the crew members, the pilot, researcher, technician, is merely a distinction, and in reality these assignments are shared nearly equally between the members crew.

The suggestion of overlapping crews will not be possible to be realized in this mission as crew rotations will take place once a year [27]. Instead the crew size and heterogeneity of the crew, could be managed to decrease conflict within the crew.

The rovers used in case of man expedition on moon are the LEVs which are regarded the best design so far for the astronauts. While exploring the moon, the need for reaching out to far off places away from the base arises. Although there is a simple way to just send in the autonomous rovers to do the job but in some cases it requires the human touch for which the LEVs are actually designed for. The surface expedition could be very far from the base and sometimes due to unexpected events, there is a possibility of malfunctioning rovers. Hence, due to this reason, it might be a very good idea to have a backup rover which can be used by the astronauts to return safely to the base without any problems.

VII. CONCLUSIONS

The most significant approach to the lunar surface transportation and other mobility activities are the rovers. The presence of rovers like the LEV's, ATHLETE, RESOLVE, etc. as discussed earlier will contribute to a much safer method to work in the lunar environment.

As this report is very conceptual the technologies treated may not be fully operational at the time when the base is to be built.

The assumption is made of it being possible to find and utilize the water on the moon when founding the base. As this assumption is not yet demonstrated, it needs to be proven before a mission strategy involving the excavation of water as a primary objective to make the base sustainable, is implemented.

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