SD2905
Human Spaceflight

Malin Boije
Fabio Nassar
Simon Callbo
Florian Thuillet

A conceptual study of the life support system and the human aspects on a lunar base.

Red team, group 3

Abstract

Space exploration has started a long time ago. Even without cutting edge technology, the human race started to explore and study those luminous dots that float in the deep dark space. What was their motivation? Curiosity. Maybe the most important motivation of all, today it still helps us to keep pushing the barriers of knowledge. Lunar exploration is essential, mainly because it is one of the main celestial bodies that we have the closest relation. Before going to Mars, we need to explore the Moon. Building a lunar base is a subject of this project and what are all the cares that it is needed to achieve it. To develop this project, most of the information has been found by literature reviews. Mostly based on NASA files and the course lectures, the final project has shown to be a high quality summary of all the information needed to start your own lunar base. The project has been divided into subproject, where this report will present the life support system and human aspects. which has been divided into 4 parts: inside atmosphere, nutrition, medical aspects and thermal control. The aim of this paper is to provide information of how to maintain the human life in a Lunar Base. Different aspects of life support require different solutions. For example, the nutrition most important result was that the food demand of the lunar base could be reduced up to 30% by using a greenhouse. Or, for the medical aspects, an innovative solution for exercising in space is to use the FlyWheel Exercise Device. The challenge of this paper is to turn the unknown into a feasible and closed project. Even with all the difficulties, the final project has shown to be of high quality and feasible, from the economical and technological point of view.

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Introduction

Since the early 20th century the submarines were widely used in warfare and had to remain submerged for several months. In order for the crew to survive life support systems had to be developed. These consisted of air revitalization-and fresh water systems. More modern versions of submarines generate oxygen by electrolysis of water.

This experience would later benefit the development of life support systems for human spaceflight when space-travelers had to remain for long periods of time in space, where environmental conditions were even harsher and still are.

Today the life support systems are far more advanced and consist of air generation and revitalization system, water tanks, thermal control, medical aspects and nutrition which all need to work in microgravity while being exposed to radiation for up several months or even years.

In the future, when going into deep-space travels with humans, systems need to be closed loops since the possibility of resupply will not be feasible. These systems need to be able to sustain themselves, without the need of new resources. For example lunar greenhouses, which will demand an amount of power and turn it into food for the crew. In-situ resource utilization and development of new and more efficient power plants might be the key to make this possible.

Atmosphere

A manned base implies a basic need of breathable air, or at least oxygen, to ensure the survival of the crew. Since the crew can be up to six people (during transitions), it is necessary that the life support system is designed for such number of residents. As regards the air, it is preferable to provide it as an atmosphere containing nitrogen and oxygen with high majority than pure oxygen. Pure oxygen is poisonous for humans at a 1 bar pressure and causes a central nervous system condition (the Paul Bert effect) and a pulmonary condition (the Lorrain Smith effect). Furthermore, a little spark would set ablaze the entire base in a pure oxygen environment. The considered solution is an atmosphere composed of 72% of nitrogen and 28% of oxygen, with a pressure slightly below 1 bar, and the internal volume of the inflatable structure is around 720 m^3. In that particular part of the study, the presence of greenhouses has not been taken into consideration, due to their non-functionality potential. If the plants do not grow or any other problem occurs, the crew still needs oxygen. Moreover, during the

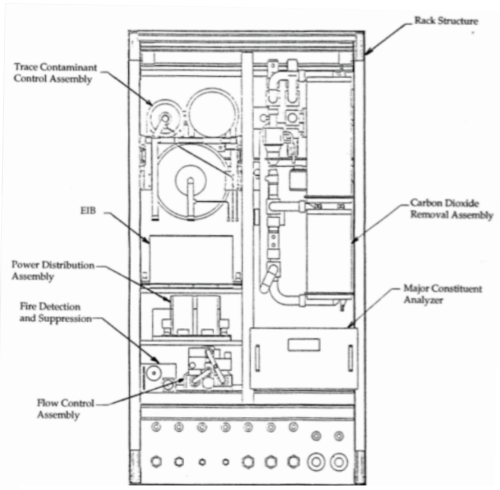

Figure 1 ISS Life Support Rack

early times of the base, greenhouses will not be installed or operational yet and the crew will still need an oxygen input.

Air revitalization and oxygen production

A human's average consumption is 0.85 kg of oxygen per day and carbon dioxide's production is around 1 kg per day. To design or choose the life support system for the lunar base, the ISS can be a source of inspiration, see *Fig. 1*, since it uses the state-of-the-art space systems. Oxygen can be brought on the base from Earth in tanks (as cryogenic liquid or high-pressure gas), got from the space vehicles, or generated on board. The absorbed[1]. The systems, which are performing that are the Carbon Dioxide Removal Assembly and Vozdukh. A lot of other systems can be used to deal with carbon dioxide: molecular sieves, electrochemical depolarized concentrator, air polarized concentrator, solid amine water desorption and CO_2 membrane removal systems.

However, for a Lunar base, supplies from Earth must be minimized, and an interesting solution would be to get O_2 by discarding CO_2. The Sabatier reactor, see *Fig. 2,* could enable it, using the Sabatier reaction: $CO_2 + 4\ H_2 \rightarrow 2\ H_2O + CH_4$. Using the water electrolysis $2\ H_2O \rightarrow O_2 + 2\ H_2$, oxygen is produced as well as some

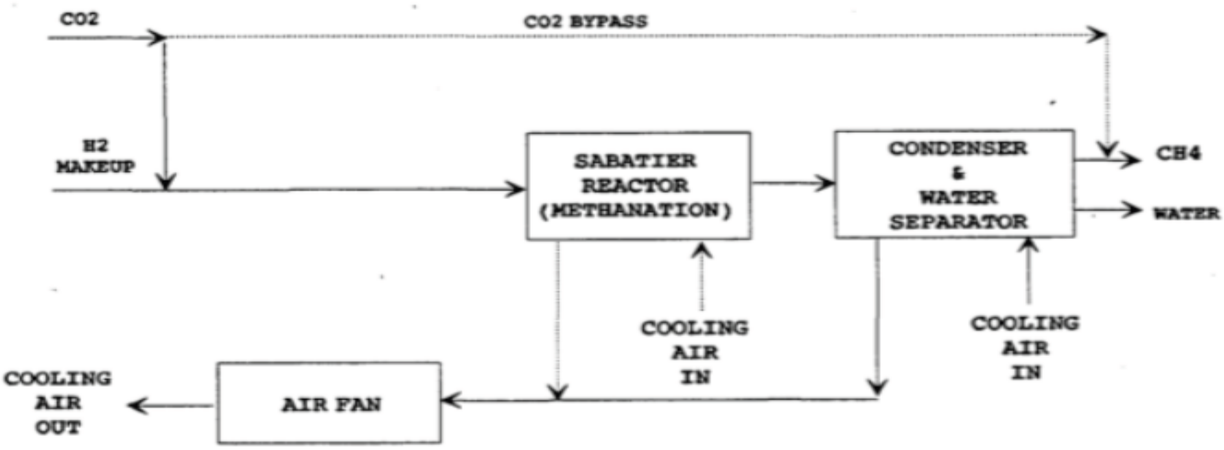

Figure 2 Sabatier Reaction

NASA's Oxygen Generating System (OGS) and the Roscosmos' Elektron perform the water electrolysis to provide oxygen to the station, whereas the Vika (Solid Fuel Oxygen Generation) can supply oxygen by burning solid lithium perchlorate. Superoxides (like the potassium superoxide KO_2) and ozonides (like the potassium ozonide KO_3) can as well be used to produce O_2 (and can remove some CO_2 in the same time). As regards the carbon dioxide, it is currently vented away of the ISS or

H_2. This H_2 is then used (and more H_2 that has to be brought) to react with CO_2 to produce water and methane. The water created by this process can be used once again for the electrolysis. Methane can be discarded, but it could also be a source of propellant, which would increase once more the appeal of this solution. The properties of the Sabatier reactor are 91 kg, 3 m^3 and 260 W, all per kg-day of CO_2 removal[2]. For a 6-people crew it would be 546 kg and 1.56 kW. A system, which would perform the water electrolysis, would also be needed. NASA's OGS (currently used on the ISS) has been chosen, because it is the last to be developed and the most efficient one for the time being. Its power consumption would be around 1 kW, and its mass around 100 kg. The global consumption of the whole system would then be around 2.5 kW.

If the Sabatier reactor is chosen, the base needs a H_2 supply to perform the Sabatier reaction. For a 6-people crew the mass needed is 200 kg per year, and it is a lot less than the mass of oxygen that would be needed without the Sabatier reactor, due to the huge difference between the molecular masses of hydrogen and oxygen. Cryogenic tanks are the best way to bring hydrogen to the Moon, because of their little sizes and their weights. To bring 200 kg of H_2 per year, 150 kg of tank is necessary. Depending on the choices made for the number of supply rockets sent to the Moon, the supply will be done every six months or every year.

Even if the Sabatier reactor implies a continual supply of hydrogen from Earth, it is a better solution than superoxides or ozonides due to the smaller mass of hydrogen but also because hydrogen is more common in nature (on the Moon or on Mars later) than potassium superoxide or ozonide.

Trace contaminant control

Since unfortunately one of the outputs of human beings is contaminant, the concentration of microbes has to be monitored and controlled. Indeed, contaminants are harmful for humans but also for equipment. Trace Contaminant Control is necessary, and can take the shape of particulate filters, activated charcoal, chemisorbant beds and catalytic burners. For a 6-people crew, it would weigh 600 kg for a size of 1.8 m^3, and would need 900 W. Alongside with the contaminant monitoring and removal system is necessary a major constituent analyzer to monitor nitrogen, oxygen, carbon dioxide, methane, hydrogen and water vapor. Furthermore, even if the problem is lesser on the Moon than on the ISS due to the gravity, a ventilation system is required to circulate the air and prevent asphyxiation of the astronauts.

Dust

Moreover, a system monitoring the quantity of dust in the air and dealing with it is necessary, because dust is a main issue on the Moon, and will also be one on Mars. Moon dust has to be dealt with at the beginning and at the end of EVAs, when the airlock is open. Changing of Environment Control and Life Support System filters is another way for the astronauts to be in direct exposure to lunar dust[3]. Space suits have to be perfectly washed after any EVA to prevent dust from penetrating into the base and contaminate air, because dust is harmful for equipment surfaces and mechanisms but also for the crew. Breathable dusts are at least toxic to the respiratory system and can be abrasive to the skin and eye. One of the solutions could be to remove the space suit in a three stage airlock after the EVA, using a magnet before removal to vacuum the suit. A local exhaust ventilation with a high efficiency particulate filter would additionally remove any lunar dust particle from the atmosphere of the base. Even if "Dust is the Number-One environmental problem on the Moon", no single solution has been demonstrated to be efficient enough at preventing dust contamination or at removing dust[4].

Gas periodical supply

Oxygen is consumed by humans' breathing but unavoidable leaks and EVAs also force to resupply the base in air (so basically nitrogen and oxygen), to maintain the pressure to its initial value. Those losses can be assumed at about 7% per year, and will require a periodical supplying from Earth. Some solutions have been considered to extract nitrogen from Moon's constituents, like regolith, but nitrogen stays an issue in order to establish a completely independent environment without any supply from Earth. The nitrogen and the oxygen needed to replace the losses due to the leaks will be brought to the base as cryogenic liquids, for the same reasons as for the H_2 supply. 45 kg of N_2 (plus 8 kg for tanks) and 20 kg of O_2 (plus 3 kg for tanks) have to be brought from Earth every year.

The perfect closed-looped environment would involve an independent production of O_2, like greenhouses, but this cannot be achieved yet, even if progress is being made in these fields. Another long-term solution would be the in situ resource utilization (ISRU), like the use of Moon-widespread regolith as evoked before.

Nutrition

Together with oxygen, water and food are the most basic resources needed to sustain human life. Even though these resources are abundant on the Earth, bringing them up is challenging. Not only for bringing up the mass, but also the care and costs needed to produce the food consumed in space is challenging. To better understand this process, we can look back in history. Whether those explorers are onboard a sailing ship or on the ISS, adequate storage space and transportation has always been a problem. Food needs to remain well preserved for a long time, to avoid nutrition deficiency or many other psychological effects on the crew.

Long time ago, humans discovered that food would remain edible for longer if it were stored in a cool dry place. In the space it is not different. The 3 most used processes to increase the life time of foods are: thermostabilization, irradiation and freeze-drying. Each one of these methods have very specific reasons. The thermostabilization raises the so called Shelf Life of the food, i.e the time that the product remains edible in the shelf, without a freezer. Irradiated foods, on the other hand, have much more shelf stability, which means that the acceptance of the food remains for much longer. At last, the freeze-drying process is used to inhibit microbial growth[5].

Figure 3 Exemple of meal on ISS.

Food in the Lunar Base

The kinds of food the astronauts eat are not mysterious concoctions but the food are mostly prepared on Earth with many commercially products available on the grocery store shelves. Diets are designed to supply each crew member with a certain number of each main nutrient. *See Fig. 3.*

The first step in calculation how much food each crew member needs during the mission is to find a way to determine how much food they will eat, this is done in *Table 1*. According to NASA, each astronaut chooses its own menu for the mission, respecting the value of 1.8 kg/day at max, of food, including its package. The daily necessary intakes of each crew member are normalized by ISS, seen in following table.

Nutrient	Daily intake
Calories	3000 kcal
Protein	0.8g/kg
Carbs	50%-55% of calories
Fats	25% of calories
Vitamins	All the spectrum
Liquids	~2000 mL
Minerals	Every mineral

Table 1 Daily intake for NASA crew members

Each kind of food can remain for a different time at the shelf, before spoiling or becoming unacceptable to eat. See *Table 2.*

Type of food	Shelf life
Meat products	3 years
Fruit and desserts	1.5 up to 5 years
Vegetable dishes	1 up to 4 years

Table 2 Shelf life of food types

A strong remainder is that the crew will be staying for a long time without fresh food, which can cause a bad psychological effect after a couple months. Since the Lunar Base is far away from the Earth, resupplying will be too expensive to be made often enough to provide fresh food. For this reason, a solution is to build a Lunar Greenhouse.

Lunar Greenhouse

Growing plants in an extreme environment is extremely important when talking about space. Without the Earth's gravity, unknown effects can occur since the research is in early stages. Happily, recent studies from the University of Arizona have shown that it is possible to grow some kinds of plants in the lunar gravity. Furthermore, they have even designed an almost fully autonomous lunar greenhouse that can provide fresh vegetables to the crew.

The green house to be used in space has been specially designed due to that. It uses the hydroponics method, which consists of growing plants using a nutrients solution in water. This method does not use any kind of soil, which is a great advantage. Most of the nutrients needed for the solution can be obtained by processing the urine produced by the crew, which can reduce even more of the dependence of resupply. A smaller portion of the nutrients must come from earth, but it can be easily stored for long periods in the base[6].

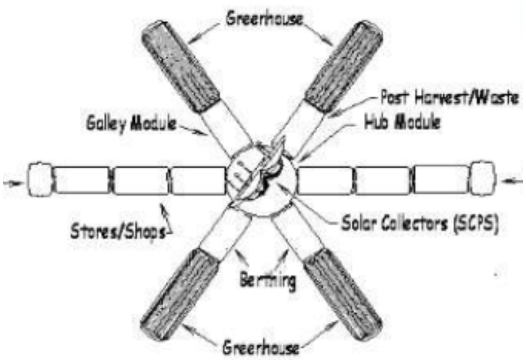

Figure 4 Schematic from above of the lunar green house

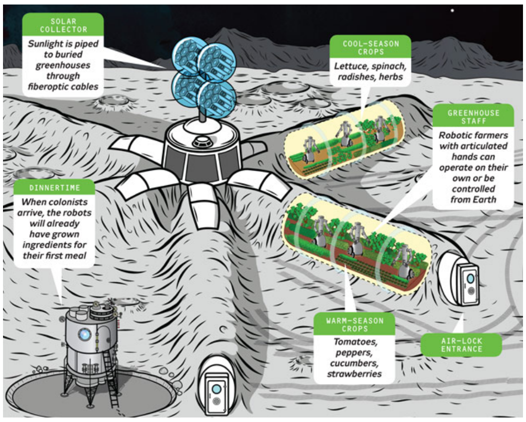

Figure 5 Green at the lunar base

The lunar greenhouses setup scheme

The greenhouse does not only provides fresh food and helps recycling the substances in a closed environment, it also works as a relaxing room for the crew, since growing plants is considered a very comfortable activity. As the scheme above shows, see *Fig. 4* and *Fig. 5*, the greenhouse will have its own solar panels to supply the internal lights. It will also need to be buried, in order to protect the interior from the solar radiation. The parameters of the greenhouse are shown in *Table 3*. The cost of each of the 4 greenhouses is about US$100.000.

Greenhouse info	
Oxygen produced	0.62kg/day
Food produced	1.37kg/day
Power needed	4.2 kW
CO_2 consumption	0.22kg/day
Labour demand	36min/day
Mass total	1021 kg
Fertilizer needed	0.0129kg/day
Water consumption	4.3 kg/day
Size	2.1x5.5 (circular)

Table 3 Green house production

The chosen produced vegetable in the greenhouse must have 3 major characteristics: able to be produced in hydroponics, high productive and high water percentage in its composition, see *Table 4*.

Plants to be grown	**% of water in mass**
Lettuce	95%
Cowpea	79%
Strawberry	92%
tomatoes	94%
cucumber	96%
sweet potatoe	77%
	average 83%

Table 4 Percentage of water in mass of many different vegetable [7]

Waste dealing

In a closed environment waste is an enormous problem. There are no trash trucks in space and you cannot simply throw it away. The wastes will accumulate and someday you will need to get rid of it.

According to a recent report from NASA, the amount of trash produced by each crewmember is about 0.6 kg/day. For long-term missions, the amount of trash produced can be up to more than 1000kg in a year. So, the need to deal with the wastes is evident[8].

Happily, there are many ways to deal with wastes. According to the same report, 25% of the wastes composition is water and 50% is personal hygiene wastes. This shows that by simply dehydrating the wastes can reduce the amount of trash produced significantly and still recycle the water. Another potential fate for the wastes is recycling the materials and, if it's not possible to recycle, just storage.

Results

Resupplying a lunar base is no joke, and will need to be avoided to reduce the costs. For this reason, all the measures have been taken to reduce its number to the minimum possible.

For the first 3 months there will be no greenhouse, since it is under construction and the food will need to be brought with the water needed to rehydrate and feed the crew. For this reason, the first supply will need to be much bigger than the later ones. The first supply until the base is built will be of approximately 986 kg of food and water. After this period, only one resupply of 988 kg for each 6 months, mainly of food, will be needed. This reduction of about 50% is due to the greenhouse and the fact that the water can be recycled in the lunar base. The greenhouse produced up to 30% of the food demand by the crew, which is extremely beneficial. In a close future, this number may be greatly increased. With better technologies there can be even better greenhouses that produces not only vegetables but, who knows, maybe insects to provide protein to the crew.

The related costs of nutrition parts come mostly from the food and water. Each day, the cost to produce the food for each crewmember is about US$350. This high number is due to the extremely careful processes related to the production. The greenhouse itself will cost roughly US$500.000.

Medical aspects

Exercise

The recommendation on the ISS today is 2 hours of exercise, including both resistance and aerobic exercise. The biggest different regarding this countermeasure action is the gravity. On ISS there is almost 0G but on the lunar surface there is 1/6G. One could think that the time of exercise should be reduced, but since no people have been on the moon for a longer time the exercise time are recommended to be the same as on ISS. When astronauts have been on moon for a longer time and data have been achieved, there is an opening for decrease the exercise time if the astronauts' health can be guaranteed.

The fact that one of the purposes of the base is to prepare the astronauts for future deep flights, devices suitable for that purpose will be chosen. One resistance exercise device provided for resistance exercise is the Advanced Resisted Exercise Device (ARED). This device is a considerable spacious device, which is not suitable for deep space flights. Another more suitable resistive exercise device is a FlyWheel Exercise Device (FWED). See *Fig. 6*[9]. The FWED can provide the same peak load as ARED. At the moment NASA is developing a second generation of this device, which will allow aerobic exercise as well, the aerobic mode will be similar to a rowing motion. As the second-generation design is complete, the device will be brought up to the station.

Artificial gravity is another approachable solution to counteract microgravity environment. These types of solution is very big and heavy weighted, and one aspect for deep space travels, is the fact that the space crafts needs to be small and light weighted[10]. Hence, artificial gravity, at the moment, is not a suitable solution. Today the long-term effects are not clearly established, and more research is needed in order to guarantee the astronauts health. However, the moon base may be a great place for further research, and later on also a place for permanent use if the results show that this is viable.

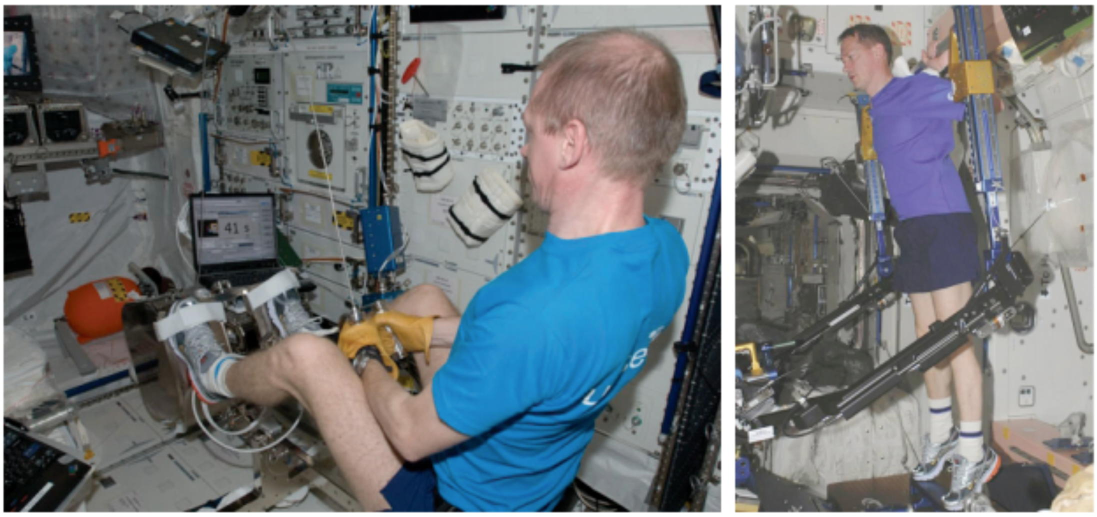

Figure 6 ESA astronaut Frank De Winne performs resistive exercise. To the right : ARED. To the left: LWED

Another established counter-measure exercise device is a load bearing treadmill, which provides effective aerobic exercise. There are a lot opportunities when choosing aerobic exercises, but one major advantage with the treadmill is the fact that the astronauts remember how to run in a 1G environment. Suppose an accident happens with the vehicle directly after landing and the astronauts need to run away from the landing site, if the muscle memory of running has not been used, running can be very hard for the astronauts.

Aerobic exercise is a monotonous action, where the performer needs to work out during a longer time. This type of workout can easily be tedious, therefore, more alternative to aerobic exercise will be brought up to the base. As already mentioned, the FWED with rowing mode and the treadmill will be brought to the base, as a third complement a bike will also be brought up. To have more opportunities for aerobic exercise, hopefully, the astronauts will be more motivated to do their mandatory exercise.

Skinsuit

At the moment ESA is working with project of a skin suit, see *Fig. 7*[11], the suit will be put into space for the first time in 2015, during Andreas Mogensens mission where he will evaluate the suit from a functional perspective[12]. Hopefully the results

Figure 7 Demonstration of Skinsuit

permit the suit to be applicable and useful for space mission and to the lunar base. The aim of the suit is to counteract the lengthening of the spine and reduce low back pain for the astronauts.

Family conferences

One major issue is the psychological stress astronauts are exposed to during long-term missions. In order to motivate and support the crew during long time of isolation, mandatory family conferences will be scheduled once a week. As the design of the base, including all communication systems, will offer continuous contact with earth more calls will be possible. The reason of having at least one conference is scheduled, is to make sure these are completed, as this is an effective way to keep the astronauts motivation and happy mood during the whole mission. Of course preparatory actions is also an important aspect to keep the astronauts in a good psychological state.

Ground support and medical devices

The complexity of having a manned base in space forces the crew to be medical trained before their mission takes off. This training includes how to maneuver medical devices, first aid, and some basic medical procedures. However, if something would happen during their time in space, there must be access to medical professional on ground. The ground control must have a medical team monitoring the astronauts continuously during their mission, and be able to identify risks and communicate with the astronauts what they need to do in order to counteract an accident. To minimize the risk of an accident to happen, preventive work must be done, i.e. medical check ups. The medical devices on the base must be workable in moon environment. One major requirement is that no radiation equipment can be brought to the base. As many imaging systems include radiation, however, this is not applied on MRI and UltraSound (US). The application for the two systems is quit different, as it is possible to imaging bones in a MRI but in an US. The US can image soft tissue, as well as a MRI. However, the MRI is very big and applies a strong magnetic field, which may disturb other system on the base. US is a more suitable solution for a lunar base due to many factors. It is smaller, more lightweight, less time consuming and the risks of bone fractures are not that high on the moon as on earth.

Radiation

Radiation is another importance aspects from a medical perspective. To protect the astronauts from radiation exposure, the base must be constructed with radiation shielding material, as well as the space suits for EVAs. The radiation exposure must also be measured and monitored during their time in space.

Thermal control

Being on the Moon means not only the research equipment has to endure extreme temperatures, but also the crew working and living there.

At the South Pole, near the Shackleton crater the temperature can go as low as -183°C at the crater floor due to it being permanently darkened and near its crust where the base will be established the temperature can rise to 123°C[13]. It is therefore a challenge to maintain a comfortable working environment for the crewmembers and an efficient working temperature for the electronics. Lunar days are roughly 28 days long for at least 80% of sunlight, which means about 24 days of sunlight and 4 nights of darkness. Besides the extreme temperatures of the Moon, the electronics and the laboratory equipment, greenhouse, Sabatier reactor etc. used will generate an estimate 2-3.5kW amount of excess heat which is about a fraction of seven of what the International Space Station (ISS) is generating[14]. It is a matter of thermal insulation and distributing heat over a longer period of time. This problem is solved using a clever design of the lunar base see *Fig. 8*, an active thermal control system (ATCS) and a two-phase hybrid loop system see *Fig. 10*.

Concept

Thanks to the clever design by the Lunar Base Construction Team the amount of material, tubes, fluids, pumps and tanks can be reduced significantly which will not only reduce the amount of payload carried from Earth but also ease up the complexity of designing and building the thermal control system on the Moon. The design is presented in *Fig. 8.* The exterior

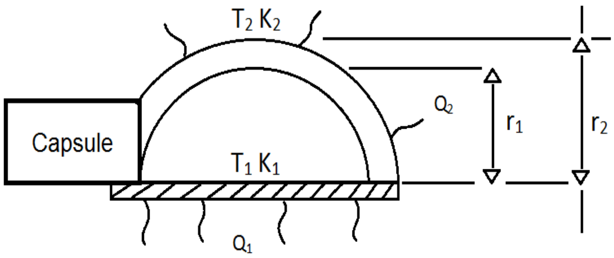

Figure 8 Lunar module.

consists of regolith and binder, 1.5 meters thick; the floor consists of compact regolith. The capsule is wherefrom the crew will work during arrival and before they fully inflated and pressurized the module. This is mainly to protect the lunar base from the harmful solar radiation but it also has other advantages such as being a thermal insulator.

From *Fig. 8* Q [W] is the rate of exchange due to conduction, T [K] is the temperature, k [W/mK] and r is the radius of the sphere. Index 1

and 2 stand for the floor of compact regolith and the regolith-sphere respectively, hence 1 is for indoor and 2 is for outdoor.
From this and Fourier´s Law of Conduction [15] it is possible to calculate the rate of heat that accumulates due to conduction:

$$Q_1 = \pi k_1 r_2 r_1 \ (T_1 - T_2) \qquad [W]$$

$$Q_2 = 2\pi k_2 r_2 r_1 \frac{T_1 - T_2}{r_1 - r_2} \qquad [W]$$

Parameter	Input	SI-Unit
T_1	295.45	K
T_2	396.15	K
k_1	$4.0 \cdot 10^{-3}$	W/mK
k_2	$8.8 \cdot 10^{-3}$	W/mK
r_1	5.5	m
r_2	7	m
Q_1	48.7	W
Q_2	142.8	W
Q_{Total}	191.5	W

Table 5 In data taken from [16]

From *Table 5* it is noted that an estimated of 191.5 W of heat will warm up the lunar module due to conduction during daylight assuming 135°C outdoor temperature.

This is negligible compared to excess heat that will be generated due to all the electronics and laboratory equipment which is about 2.5-4kW[14], it is only about 4.8% to 7.6% of total excess heat. Even though it might be good to insulate the lunar module even further by having two layers of regolith with binder and in between having a thin layer of vacuum surrounded by an Aluminum matrix, see *Fig. 9* This will not only help bearing the structural load of the base but also reduce the amount of excess heat that needs to be removed.

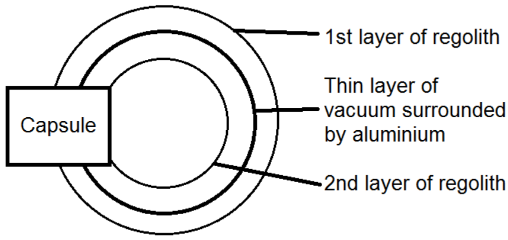

Figure 9 Two layers of regolith with a thin layer of vacuum in between, which is surrounded by aluminim.

Active Thermal Control System (ATCS)

The ATCS uses fluids that are mechanically pumped through a two-phase hybrid closed-loop circuit in order to achieve the following three functions: heat collection, heat transportation and heat rejection, see *Fig. 10*. Unwanted heat is handled in two ways, namely through cold plates and heat exchangers. Both of these use closed-loop circuits which circulate ammonia on the outside of the habitat in order to cool it down to a desirable temperature. Since the ammonia will get heated it has to circulate through radiators on the exterior of the habitat, releasing the heat by radiation to space that will cool the ammonia as it flows through the radiators.

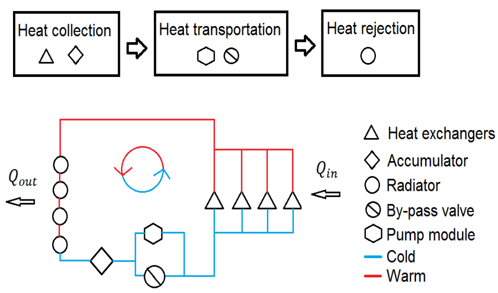

Figure 10 Two phase hybrid loop system.

As can be seen from *Fig.10* there will be a total of 4 radiators and 4 heat-exchangers, or cold-plates to be exact. These will be controlled automatically by a pump-module which will set the rate of the ammonia and water that will circulate. It is also possible to control this rate manually by using the by-pass valve by letting in/out pressure to change the chamber pressure of the pump and the loops. The Accumulator will work as an energy storage where intermediate cooled liquids will be stored and circulate ones they reached the right temperature. For the cold plates the Main Bus Switching Unit (MBSU) is used.

Figure 11 MBSU Cold plate.

The cold plate seen from *Fig. 11* [17] is the same type that is currently being used on the ISS. It weighs 49.4 kg and can remove about 1kW of heat.

As for the radiators the Photovoltaic radiators that are used are also in use on the ISS. Each one can reject about 1kW and weighs about 74 kg. In total the ACTS will be able to reject about 4kW of heat into space considering the same efficiency of the ACTS used on ISS. What can be noted is that the lunar dust will reduce their efficiency unless they are cleaned.

Conclusion

Taking into consideration every part separately, the Moon base seems workable and effective. The whole life support system has been designed in this report and there are some guarantees from past utilization in space for many of these systems. However, since no base has ever been built on any extraterrestrial celestial body, it remains difficult to know if every system will work as perfectly as it should, and the dust issue remains as the biggest obstacle for long stays on the Moon.

Appendix

Summary of Air and CO_2 removal

Gas	Mass (kg)	Tank mass (kg)	Total mass (kg)
Nitrogen N_2 (base)	648	58	706
Oxygen O_2 (base)	202	24	313
Dihydrogen H_2 (Sabatier)	200 /year	150 /year	350 /year
Oxygen O_2 (emergency – 1 month)	153	15	168
Nitrogen N_2 (leaks – EVAs)	45 /year	8 /year	53 /year
Oxygen O_2 (leaks – EVAs)	20 /year	3 /year	23 /year

System	Mass (kg)	Power (kW)
Oxygen Generating System	100-150	~1
Sabatier reactor	546	1.56
Trace contaminant control	600	0.9

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Summary of Air and CO_2 removal

Gas	Mass (kg)	Tank mass (kg)	Total mass (kg)
Nitrogen N_2 (base)	648	58	706
Oxygen O_2 (base)	202	24	313
Dihydrogen H_2 (Sabatier)	200 /year	150 /year	350 /year
Oxygen O_2 (emergency – 1 month)	153	15	168
Nitrogen N_2 (leaks – EVAs)	45 /year	8 /year	53 /year
Oxygen O_2 (leaks – EVAs)	20 /year	3 /year	23 /year

System	Mass (kg)	Power (kW)
Oxygen Generating System	100-150	~1
Sabatier reactor	546	1.56
Trace contaminant control	600	0.9