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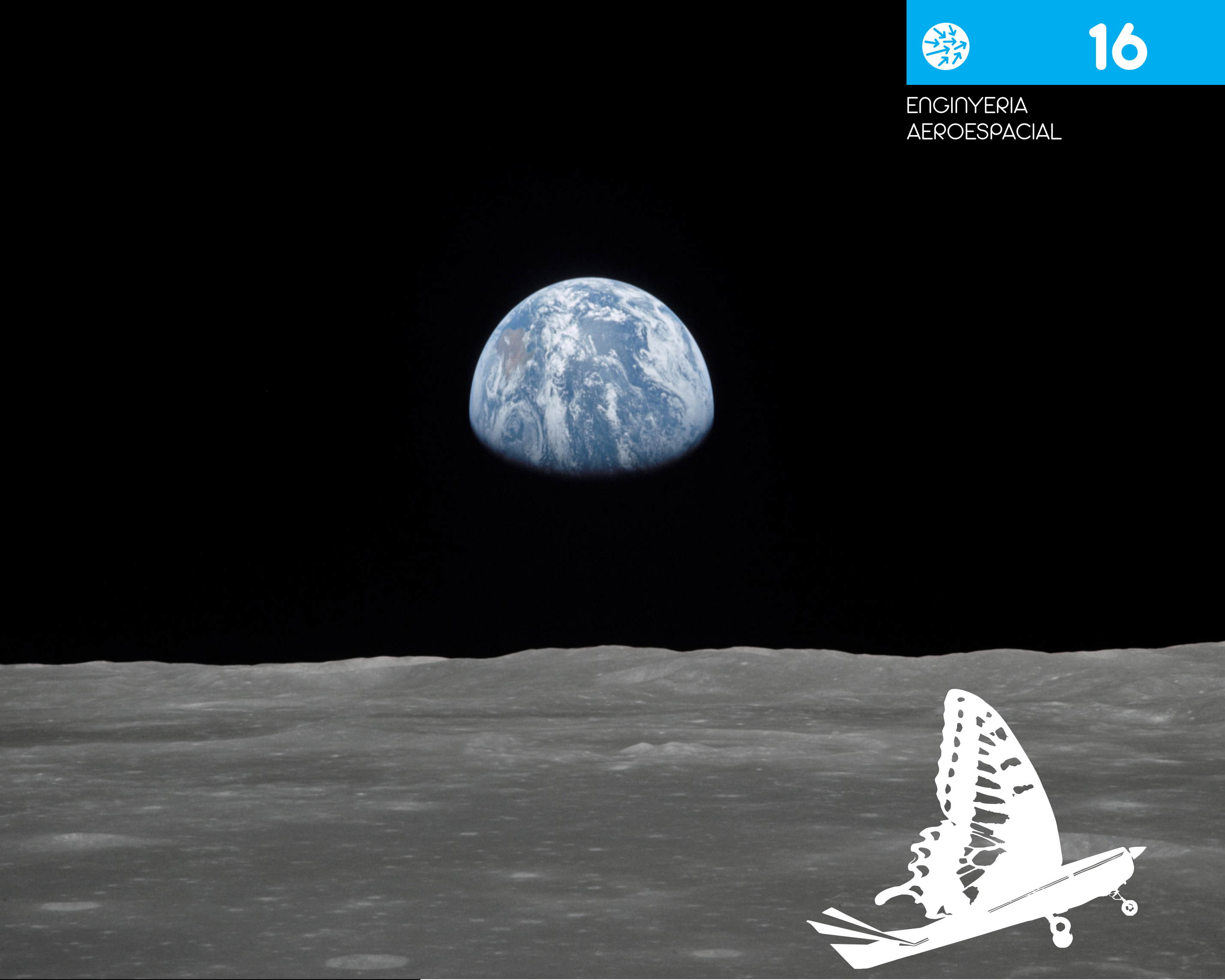

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The Moon: The Next International Space Station

Ignasi Casanova
Miquel Sureda

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© Image Credit: NASA. This view of Earth rising over the Moon’s horizon was taken from the Apollo 11 spacecraft.
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Contents

Nomenclature

CCAA	Common Cabin Air Assembly
CDRA	Carbon Dioxide Assembly System
CELSS	Controlled ecological life-support
DEM	Digital Elevation Model
ECLSS	The Environmental Control and Life Support System
EVA	Extravehicular Activity
I/R	Radiance Factor
LESI	Lunar-surface effective solar irradiance
LSI	Lunar-surface solar irradiance
MIS	Monthly Illumination Spectrum
MLS	Mostly Liquid Separator
OGA	Oxygen Generation Assembly
OGS	Oxygen Generation System
ORU	Orbital Replacement Unit
PEL	Peak of Eternal Light
PWD	Potable Water Dispenser
QD	Quick Disconnects
t	Time
UPA	Urine Processor Assembly
WHC	Waste and Hygiene Compartment
WPA	Water Processor Assembly
WRM	Water Recovery and Management
WRS	Water Recovery System

→1

Space Exploration

Exploration has always instilled a deeply ingrained passion in humanity, intriguing us with the unknown and sparking a profound curiosity that has driven us to discover new lands. This drive led the Vikings to cross the ocean to reach England and compelled Columbus to discover the Americas, because they dared to explore. Before these discoveries, humanity believed they were alone in the world, that nothing but an infinite abyss existed beyond the sea, threatening to swallow whoever dared to cross its frontiers. Inarguably, the history of humanity is a saga of men and women trudging across every possible part of this Earth. The next logical step for our species now is to climb outward, beyond Earth.

For centuries, space travel has been the fantasy of artists, and works of science fiction that have been fascinated with the relationship between time and space. Their musings often served as a precursor to reality. Now is the time to convert this dream of so many into reality.

Our knowledge of space remains scant, despite the twentieth century's magnificent endeavours to migrate humanity above our atmosphere. The Russians were the first to successfully launch a satellite into orbit in 1957, when Sputnik paved the way for the first astronaut, Yuri Gagarin, to journey into space aboard Vostok 1 in 1961. The U.S. left humanity's footprints on the Moon for the first time in 1969, when the boots of Neil Armstrong and Buzz Aldrin traversed our nearest planetary body. From that moment forward, technology has evolved to levels we could only dream of then. Thousands of satellite constellations orbiting the Earth have transformed the way we work. Communications are faster; we can 'pinpoint a person's location at 1 m precision within 1 second; we can predict the weather; and our new generation of telescopes can view the universe from outside the atmosphere [1].

Because the space industry is costly, further exploration has been stymied. Governments are discouraged from spending money on even the most modest of missions. History has proven that every discovery of new lands brings new riches to humanity – so why should we stop exploring space? Studies of Earth's sibling planets, Venus and Mars, can inform us of our planet's future. The Sun, Jupiter, and Saturn could help us understand fluids at different temperatures and ways to produce clean energy [1]. Colonising other bodies in our solar system will lead to scientific advances that are unachievable on Earth, changing our view of the universe and allowing us to exploit these bodies and further improve our technology. Traveling to other bodies, learning, adapting: these are the next frontier for humanity.

1.1 Farming the Cosmos

By volume, very little appears to exist in what we aptly call space. Yet, the sheer quantity of resources we can exploit is immeasurable compared to those on Earth. The concept of farming resources tends to invoke thoughts of materials like minerals, rocks or metals, but the reality is that space is filled with energy, gases and even vacuum, among other untapped riches that await us.

The greatest generator of energy in our solar system is the Sun. By exploiting other bodies with thinner atmospheres in our celestial neighbourhood, we can extract massive amounts of energy. Bases on planetary bodies would be sustainable, allowing us to save that energy and send it to Earth. Energy and radiation would also benefit many experiments that could provide humanity with new vaccines and other scientific discoveries.

The largest water surface that we know of is on Earth, and finding it elsewhere in a liquid state is no easy task. Yet, a liquid water supply is of primary importance, because humans and all life that we know are water–based. We need it to grow and thrive. Having water in space is therefore essential to our survival if we are to create habitable societies in this new frontier.

Most planetary bodies in our galaxy have oxygen in some form or another that can be extracted. Humans obviously need air that is comprised mostly of oxygen in order to breathe, and though we cannot magically create it, we can extract it from rocks and liquids when not in its gaseous state. The necessary sources of oxygen exist and can be accessed for living in space and establishing settlements on other planetary bodies [2].

helium–3 is one chemical element that we know exists on the Moon and Jupiter. This element could produce energy through nuclear fusion and significantly reduce the by–product of harmful radiation that this process currently creates. Because they are easier to obtain, the elements Deuterium and Tritium are presently used for fusion, but these produce high amounts of radioactive waste that is problematic to dispose of. But helium-3 would mostly eliminate these problems [3].

Sending material to space from Earth is very expensive and currently not at all profitable, as the cost of launching large ships beyond our atmosphere can reach billions of dollars. Even sending parts for assembly in space would be prohibitively expensive. But what if there were no need to send material to space and it was instead drawn from somewhere else? Constructing bases, hangars, machinery, and other necessary facilities on other bodies like the Moon would be easier with materials that are farmed from the Moon itself or even asteroids. We would save billions in costs and materials while obtaining the same structures. What is more, there are a number of spaceships that are technologically feasible, yet most of them cannot be manufactured due to the cost of launching them into space. But manufacturing them beyond Earth's gravity would provide us with better and safer spaceships that could travel much deeper into space.

Physical matter is not the only resource in space. The lack of matter is also a viable resource. The Earth's atmosphere interferes with most of our current telescopes, but establishing observatories or huge antennas on atmosphere-free bodies would advance our science immensely and deliver new knowledge on the workings of the Universe.

The advantages to farming our nearby resources are limitless, and it is time that we begin planning for this endeavour. The next step for humankind is to exploit that which surrounds us and advance as a civilisation. This means exploring deeper into space.

→ 2

The Moon

2.1 Earth’s Moon

It remains uncertain how the brightest and largest body in our night sky, the Moon, came into being. Many hypotheses have attempted to explain its formation, with the most popular theory positing that it was created when a Mars-sized body collided with Earth about 4.5 billion years ago and ejected a molten body that crystallised after 100 million years.

Life is possible on Earth thanks mostly to the Moon’s orbital position. It stabilises the climate and regulates the tides of ’seas and oceans. It also protects the Earth from meteorite impacts, even if the majority are not huge and would likely disintegrate in the atmosphere. Nevertheless, it serves as a shield for our planet [3].

The name ‘Moon’ is used with capital M to differentiate it from other moons in the space, like the moons of Jupiter or Saturn. To refer to it we use “lunar”, derived from the name on the Moon in Latin, Luna. With a radius of 1738 km, less than a third of the Earth’s, this mass of 7.353 10^{22} kg [4] orbits our planet at a distance of 384,400 km in synchronous rotation, meaning that the same ‘face’ (hemisphere) always faces the Earth, which is why we refer to the bright and dark sides of the Moon. Relative to the fixed stars, its orbit is 27 Earth days; but because our planet also moves and rotates, it takes 29 days to complete an orbit from our perspective.

2.2 Environmental Conditions

2.2.1 Gravitational Distribution

The lunar gravitational field is complex due to the non-uniform distribution of its mass and its irregular shape. Moreover, the gravitational field changes as a function of time, as does the Earth's (secular changes), but these variations are very small. Full knowledge of the lunar gravitational field is one key to understanding its internal structure, as well as topographic maps and the identification of lunar orbital disturbances that may affect the navigation of artificial satellites.

Multiple studies have been conducted on the Moon's gravity, some of them using the Doppler effect in data transmission between two satellites (Lunar Prospector Mission), four-way tracking data (SELENE) and laser altimeters (Lunar Reconnaissance Orbiter – LRO). In particular, the Lunar Gravity Model LGM2011 used the data obtained from the SELENE mission (SMG100i) and the LOLA (Lunar Orbiter Laser Altimeter) elevation data to compute the lunar normal gravity field. It also employed a forward-modelling procedure based on Newton's law of gravity (Newtonian forward-modelling) to obtain the gravitational acceleration map presented in Figure 2.1.

As seen in Figure 2.1, the mean gravity acceleration of the Moon's surface is 1.62486 m/s^2 (i.e., approximately 1/6 G), with variations of up to 1.6%, with the highest acceleration values occurring within the depths of craters.

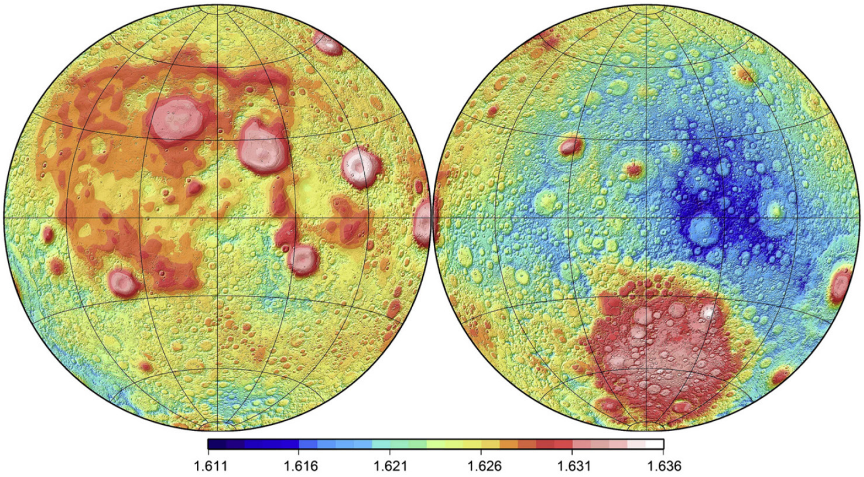


Figure 2.1
Gravitational acceleration at the lunar surface (m/s^2) from LGM2011 data [5].

Causes of Gravitational Distribution

The Moon's non-uniform mass distribution was identified and studied by the Lunar Orbiter Satellite programme, which detected large accelerations in the five nearside ringed maria between Sinus Aestuum, Sinus Medii and Mare Orientale. This phenomenon is of uncertain origin but caused by mascons (i.e., mass concentrations) with physical extensions of between 50 and 200 km [6].

2.2.2 Lack of Atmosphere

The Moon's atmosphere is a thin layer of surface boundary exosphere, which commonly exists on many planets and comets within our solar system [7]. NASA's LADEE mission sought to study the thin exosphere around the Moon. 0 km. From a low vantage point of 50 km apoapsis, the LADEE spacecraft detected Argon-40, a noble gas that condenses on the cold night side of the lunar surface [8]. The Neutral Mass Spectrometer (NMS) found three noble gases: helium, neon and argon [9].

Helium and neon are supplied by the solar wind. As the lunar surface heats up to over 117 C, this causes helium atoms to rise up and also results in some being completely lost to space. Nevertheless, the supply of helium particles is balanced by the solar wind [8].

Neon is also supplied by the solar wind, but in a small quantity. Being far heavier than helium, neon tends to remain in the exosphere. The only way for neon to escape the Moon's atmosphere is by photoionisation from the Sun's ultraviolet radiation causing the neon to lose an electron, but this process takes over 200 days. Due to the slow loss rate, neon can build up to the level of helium in the Moon's atmosphere [8].

The third noble gas is argon, which is formed by the decay of radioactive potassium-40. Potassium-40 is generally found on all terrestrial planets, as it remains deposited during their formation. Argon-40 behaves differently from the other noble gases in the Moon's atmosphere, as it condenses on the night side of the Moon, where temperatures drop to −173° C. As the Moon rotates, the Sun rises and the argon rises up to the exosphere. When it cools down, it settles in the potassium-40 abundant area mainly in the region of Mare Ibrium and Oceanus Procellarum. It has been speculated that there may be a connection between the surface potassium, atmospheric argon and the interior sources [8].

Sodium and potassium were detected by the Neutral Mass Spectrometer (NMS) and Ultraviolet Visible Spectrometer (UVS), which were used to measure exotic elements and their origins [9]. The solar wind causes sodium to be released from the surface into the exosphere through a process known as 'sputtering'. In this process, the solar wind's ions bombard the lunar surface and release materials like sodium, which has monthly cycle. This cycle is due mainly to micrometeoroids that vaporise grains in the lunar regolith. This causes an increase in the density of the exospheric sodium, which behaves similarly to potassium although they are excreted in different ways [8].

Vacuum Conditions on the Lunar Surface

Apollo 14 carried with it a device to measure the natural gas pressure of the Moon, although the readings were influenced by the rocket's landing and take-off. The results indicated 10^{-8} Torr of pressure during the astronauts' stay. One Torr (terrestrial atmosphere) is roughly equal to 10^{-3} Earth atmospheres. Days after the surface operations had finished, the measurements found between 10^{-12} and 10^{-10} Torrs, depending on the temperature [10].

Solar wind and the random motions of gas within it account for some of the pressure found by the Apollo 14 measurements. The solar wind can have pressure up to 10^{-11} Torr. The rest of the pressure is a result of outgassing on the Moon. Although much of the exosphere escapes the Moon, it is replenished by the release of neutral gas that is retained by gravity.

The Moon's low pressure has numerous implications for anybody planning to relocate there. At such low pressure, structural designs necessarily become more complex, heat transfer phenomena require innovative and more predictable materials, and consequences will be numerous for human biology. Inevitably, exploration on the Moon will be constrained by this low pressure.

2.2.3 Lunar Dust

Definition and Characterisation of Lunar Dust

As explained previously, the Moon's lack of atmosphere and weak gravitational force are two key characteristics that make it considerably different from the planet Earth in several aspects, such as the presence of lunar dust, its composition and its behaviour. Although the dust size may not seem significant enough to have any influence on a lunar base, it must be taken into account for many reasons.

Lunar dust originates from the soil known as lunar regolith. Most of this regolith remains on the surface because no wind exists in the lack of air. Nevertheless, due to the weak gravitational force, the tiniest dust particles rise from the surface and remain suspended a few meters above the ground, where they can affect everything they come in contact with.

Understanding the characteristics of lunar dust requires knowing the origins of the lunar regolith from which it comes. This soil contains a wide variety of particles such as rocks, monominerals, and glass fragments. It is approximately 5 meters deep in the mare areas and can even be as much as 15 meters deep in the highlands.

Due to the lack of atmosphere, the surface has been impacted by millions of meteorites and fragments from other space bodies, mostly asteroids. These impacts widen the variety of lunar regolith materials and cause these external particles to fuse together with those already present on the surface. This fusion is made possible by the presence of iron, which allows for different particles to melt. This mixture of native and external materials in the lunar soil is what forms the composition of lunar dust [11].

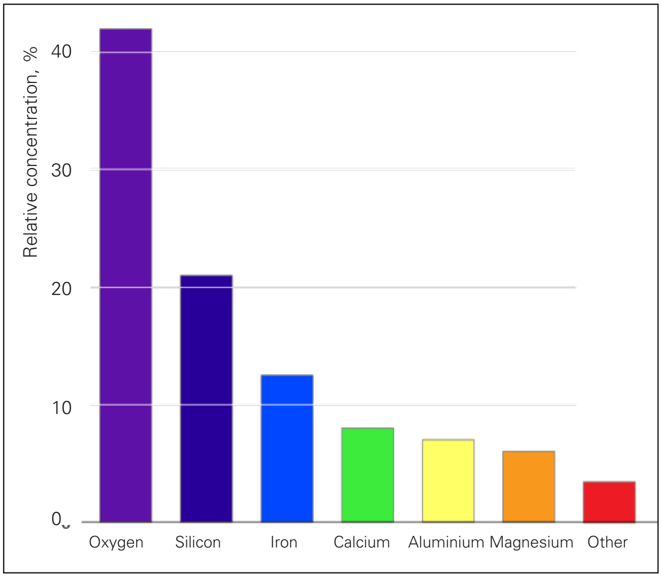


Figure 2.2
Composition of the lunar soil [11].

Interestingly, the Sun's bombardment of X- and UV-rays on the lunar surface gives dust particles a positive charge, while the solar wind has an opposite effect on the non-illuminated face: the dust particles there are given a negative charge. These two facts contribute to the dust becoming suspended, as both charges cause the particles to separate from the surface from a few meters up to a few kilometres. Because the negative charge is even greater than the positive, the movement of the dust particles is even more significant on the dark side of the Moon [12].

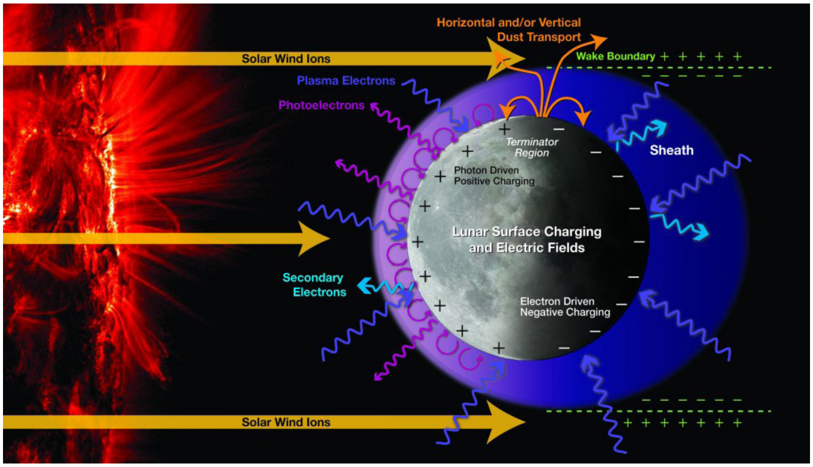


Figure 2.3
Effect of the solar wind on the Moon's surface [13].

Effects of Lunar Dust over Time

Whether during the building of the settlement or when exploiting the Moon's resources after completing the settlement, it will be impossible to avoid interacting with lunar dust.

The Apollo missions reported various issues involving lunar dust.

Most all of these involved dust coating the astronauts' EVA suits and being unintentionally introduced into the Lunar Module. This dust not only produced breathing and ocular discomfort for the astronauts, but it also affected the normal operations of various equipment, such as camera lenses, bearings and visors [14].

The lunar dust was difficult – if not impossible – to brush off the outer fabric of the suit, and it left scratches in the bearings between the suit gloves and arms and between the helmet and neck.

What is more, the reactivity of the dust remains unknown. Because it exists in near-vacuum conditions, grain surfaces are covered with chemical bonds that could be very reactive, meaning that exposure to this dust could interact with our organs in unknown ways with potential toxic effects [15].

The health issues associated with lunar dust have been investigated in recent years with NASA creating a team dedicated to this issue. The Lunar Airborne Dust Toxicity Advisory Group (LADTAG) set exposure limits for lunar dust on the basis of research findings, such as the 2013 study on lunar dust toxicity in inhalation-exposed rats. This study was limited to 180 days of intermittent and continuous lunar dust exposure of, respectively, 0.4 and 0.006 mg/m^3 [16].

It has also been determined that the low gravity environment would make it easier for these dust particles to penetrate deeper into the lungs and create deposits, which could be dangerous over long-term periods. Dermal irritation and injuries to the respiratory tract from ultra-fine particles will also be an issue [17].

To prepare for a return to or settling on the Moon, Taylor et al. [14] compiled an interesting list of lunar dust properties that must be addressed before returning:

- Abrasiveness on and penetration into friction-bearing surfaces
- Pervasive coating of seals, gaskets, optical lenses, windows, etc.
- Settling on all thermal and optical surfaces, such as solar cells
- Physiological effects on humans, especially the lungs, lymph system, and heart

In order to survive in the settlement, it is crucial to mitigate all these properties and to define procedures for maintaining the facilities clear of lunar dust.

Reducing and Avoiding the Effects of Lunar Dust

Dust was not considered a major threat until the first lunar landing mission, upon which it became immediately obvious that the dust was dangerous and had a hazardous effect on space suits.

It was difficult to remove the dust from the lunar module, and the filtration system was insufficient for the task. Apollo crews reported ongoing problems: wrist and suit hose locks became difficult to operate during Apollo 12 while suit fabric became abraded and leak rates increased; the Apollo 14 crew's mission was impeded by helmet visor scratches that decreased visibility; and the Apollo 15 crew was hampered by difficulties with connecting and disconnecting the PLSS PGA [18].

In order to avoid such problems in the future, NASA came to the following conclusions:[18]

- All systems and interfaces with other systems that come into contact with lunar dust must consider the effects throughout the entire design process.
- Dust management must be incorporated into the Concept of Operations and Requirements.
- Every person who works on NASA's Constellation lunar missions must be mindful of this problem.
- Cost-effective solutions should be developed with a combination of common sense existing technologies and promising, innovative technical solutions.

The relatively large amounts of iron particles, particularly in the $< 50\ \mu$m portion of the lunar soils, provides possibilities for eliminating dust from many surfaces such as solar cells, seals, lenses, windows and breathing filtration systems. Normal magnetic separation is impractical, because the material just clumps together. In order to manipulate dust on the Moon the 'high-gradient magnetic separation' method was developed. Basically, the dust passes through an open matrix of metallic material. The larger particles get trapped and the coarser ones seep through. When the filter is full, the magnetic field can be turned on and filter manually cleaned. Industrial magnetic separation is performed in water slurry and it is currently being tested as an air- filtering system for the lunar base [19]

Woven fabric was used as a basic material in the Apollo program, but research has shown 'there is evidence that retention of these contaminating particles on the space suit is promoted by interaction between the dust particles and the weave of the space suit fabrics.' Future space suits should be made with an alternative material or, if using woven fabrics, with appropriate surface coatings to keep particles from entering and penetrating the fabric weave. The one-time-use lightweight coverall garment for protecting the space suit's outer systems and surfaces was proposed as a viable financial and practical solution. Such a garment should be able to cover all parts of the space suit. After a moonwalk, it should be capable of easy disposal and, thus, prevent dust contamination of the habitat. The ED-XRF (Energy-Dispersive X-Ray Fluorescence) was developed to assess the amount of latent lunar soil on the space suit and, after calibration, it also assesses the damage to the space suit after Moon EVA. The sealed 360-degree wrist rotation bearing used on the Apollo missions has been found not to be compromised by the dust and could serve as a baseline for future space suit design [20].

2.2.4 Temperature and Heat Transfer

The temperature of the lunar environment varies drastically from day to night, based on location. The day-night cycle of the Moon spans 28 Earth days: 14 of them in sunlight and 14 in darkness. At the equator, the temperature variation reaches an approximate maximum with a lunar noon temperature of 374 K, and a lunar night temperature of around 120 K. Moving away from the equator, the decrease in solar radiation intensity during the day-time leads to lower maximum temperatures according to latitude. Figure 2.4 displays the relationship between latitude and temperature across the day-night cycle. This relationship is described by the following equation, which takes into account the varying solar flux at different latitudes: $T_{Moon}(K) = 373.9\ (\cos\theta)^{0.25}(\sin\theta)^{0.167}$ [21]

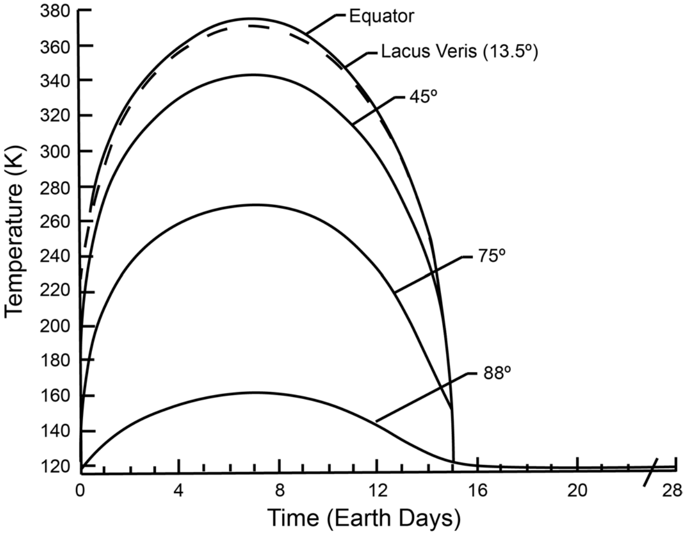


Figure 2.4. Moon surface temperature profile at different latitudes [21].

Additionally, the Moon is not a perfect sphere, as features in the lunar environment were created by events such as meteorite impacts. With lunar regolith acting as an excellent insulator (possessing an average thermal conductivity of

0.004 W/m·k), these features can offer very good thermal protection by blocking the solar and galactic radiation from reaching the shaded surface, thus preventing heat from effectively conducting from sunlit areas to those in shadow. As a result, regolith areas in shadows also experience significantly lower temperatures even during the sunlight hours. Indeed, craters near the lunar poles may provide locations that are always in shadow, with temperatures that are in fact below the abovementioned 120 K [22]. Figure 2.5 displays the brightness temperature at local noon +0.5 hours across the entire Moon's surface, taking into account the effect of geological features.

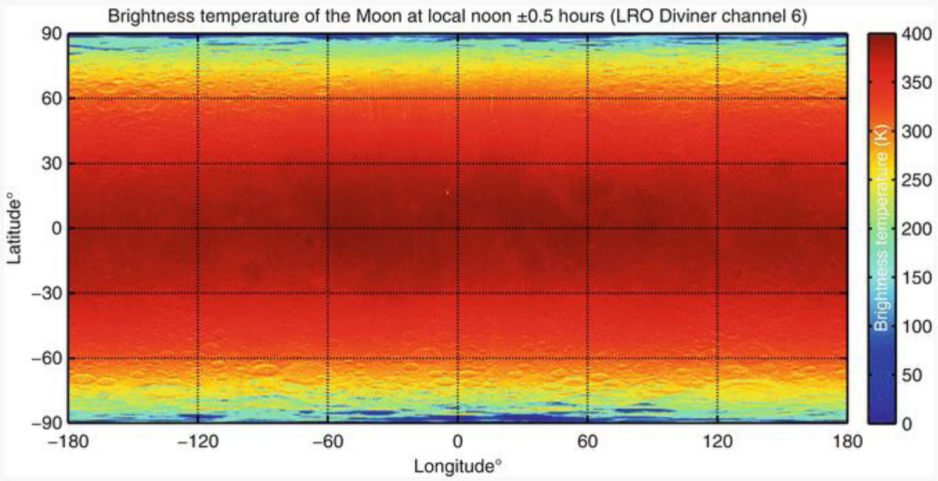
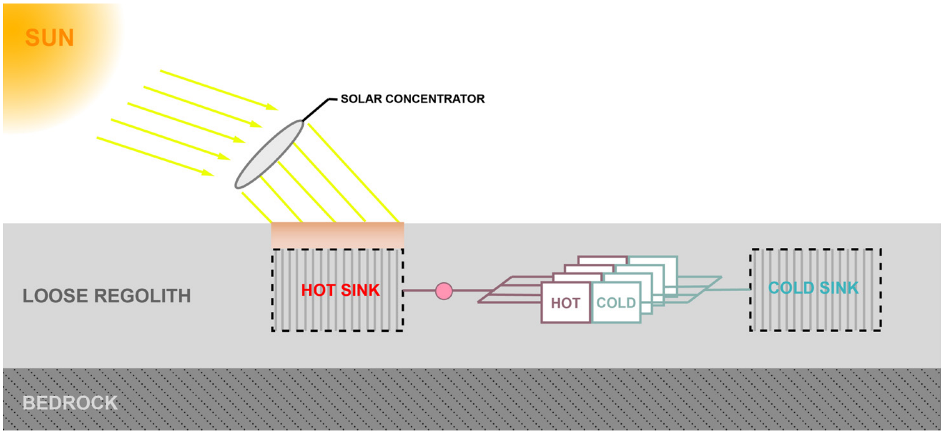


Figure 2.5
Moon brightness temperature at local noon +0.5 hours [22].

The Moon's atmosphere is extremely sparse compared to that of Earth. Indeed, it is so sparse it can technically be considered an exosphere, with just 100 molecules per cubic centimetre. This is a billion times fewer molecules than the amount found per cubic centimetre on the Earth at sea level [23]. Due to the lack of molecules, heat transfer in the Moon's atmosphere essentially does not occur through conduction or convection, but instead solely through radiation. Radiation is a steady but slow way of transferring energy through the emission of electromagnetic waves. The time taken for heat transfer to occur on the Moon is therefore significantly greater than on Earth – with the cooling rate calculated to be at least 6 times slower [24]. Due to radiation being the primary source for heat transfer, daytime temperatures are controlled by the reflective ability (albedo) of the surface. Night-time temperatures are governed by the ability of the material to gradually radiate the heat accumulated during the day.

Once the surface is out of direct sunlight, the cooling rate is therefore sensitive to the thermal inertia of the upper layer of regolith. It is also dependent on the heat-retention properties of blocky material with large surface masses [22]. Differences in cooling rates can therefore give an indication of the surface distribution of large rocks and boulders on the Moon. The insulating properties of the surface regolith can also in fact be used as part of a heating system during the night-time. During the day, solar radiation concentrates on a patch of lunar soil and forms a heat sink, heat that may be used to run machinery. Additionally, at night, the excess heat in the sink may be tapped into for keeping equipment/habitats warm. The setup of this method is shown in Figure 2.6 [25].

Figure 2.6. Energy generation/storing system utilising lunar regolith [25].



2.2.5 Light

Condition of Solar Radiation on the Moon

Sunlight that reaches the lunar surface is constant, intense, and virtually inexhaustible. It delivers 1365 kW/m^2 to the lunar surface when the Sun is directly overhead (orthogonal to the lunar surface) [26].

Solar radiation is an exterior heat source of the Moon and represents a key resource for returning to the Moon [27].

Solar light controls the variation in lunar-surface temperature during the lunation, and it also changes the thermal radiation properties of the lunar surface.

The main techniques used to study and explore the Moon are multispectral imaging, thermal radiation imaging, and microwave radiation measurement. Signals received by these instruments, however, are affected by reflections of the solar radiation and emissions from the lunar surface. At the same time, solar radiation must also be considered when designing heat control.

Another aspect for studying solar radiation on the Moon is lightning. Due to the fact that the spin axis of the Moon is nearly perpendicular to the ecliptic plane, different conditions for lightning occur at the lunar poles. For instance, areas with low elevation may never be directly illuminated by the Sun, while other areas may be permanently illuminated.

This phenomenon is closely related to the presence of hydrogen, which has been detected near the lunar poles [28] in areas that are generally in permanent shadow. In addition, the temperature in these permanent shadow areas is low enough to retain water ice and other volatiles accumulated throughout the age of the solar system. The Moon's axis of rotation has been stable for at least 2 billion years [27].

In short, the profile of solar illumination over the Moon is an important factor for site selection, as it will heavily affect landings and other human activities there.

Theoretical Model and LESI Changes

In order to describe and facilitate understanding of the solar radiation that strikes the Moon, this section presents and analyses the results obtained by the theoretical model described in Chapter 15 of Li et al. [27].

First, let us consider that the solar constant (solar radiance at 1 AU) varies between 1361.8 and 1369.2 $W \cdot m^{-2}$ while also taking into account the limiting conditions of perihelion, aphelion, perigee and apogee in the Sun-Earth-Moon system. Bearing these in mind, the lunar-surface solar irradiance ranges from 1308.9 $W \cdot m^{-2}$ to 1425.7 $W \cdot m^{-2}$, with a range in excess of 100 $W \cdot m^{-2}$ at the equator.

Li et al.'s simulations [27] focus on changes in LESI (lunar-surface effective solar irradiance), which is the Sun's radiant power reaching the Moon's surface at different selenographic latitude and longitude over a month and at an 18.6-year lunar cycle.

Their simulation results showed that, because of the axial tilt of the Moon, the sub-solar latitude changes from about 1.5°S to 1.5°N in a year. In addition, for a given selenographic longitude, the solar incidence angle increases from the sub-solar latitude to the Moon's two sides. Figure 2.7 depicts the simulated LESI on the prime meridian over a month. Here, it is easy to see how LESI on the prime meridian achieves the maximum value near the lunar equator in the latter half the month. Other data that can be extracted from this figure are the sub-solar latitude's slight variations over the month in the southern hemisphere, leading to some differences in LESI between the lunar south and north poles.

When focusing on a whole year, we can see in Figure 2.8 how the movement of the Moon causes the monthly and yearly maximum LESI to vary with latitude. The maximum monthly LESI has a larger value near the lunar equator and decreases toward the poles.

Comparing the changes in LESI between the hemispheres also reveals an opposite tendency: the maximum monthly LESI at low latitudes is greater than those at high latitudes. A similar trend can also be observed when studying the whole 18.6-year lunar cycle. The maximum monthly LESI has a larger value near the lunar equator and decreases from the equator to the poles. The opposite occurs in the northern and southern hemispheres. However, the variation in the maximum annual versus the maximum monthly LESI has an opposite tendency at different latitudes: it is much lower at low latitudes than at high latitude, as depicted in Figure 2.9.

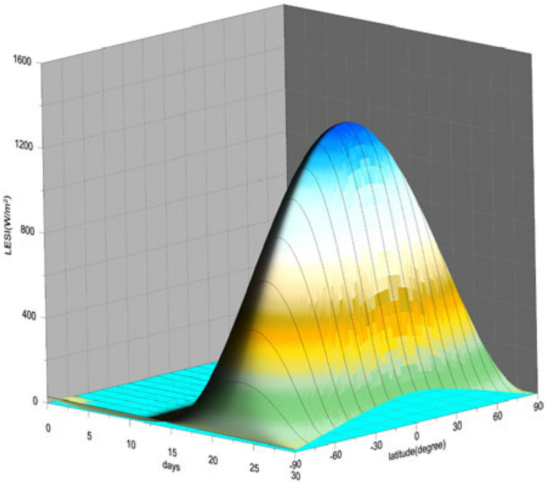


Figure 2.7.
Changes in LESI on the prime meridian with time and latitude over a month [27].

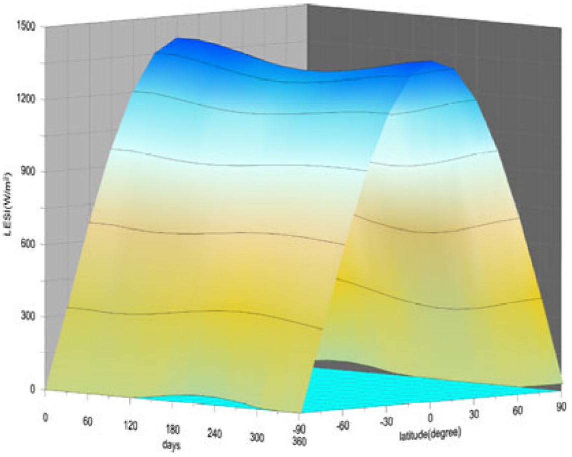


Figure 2.8.
Variations in the maximum monthly LESI on the prime meridian with time and latitude in one year [27].

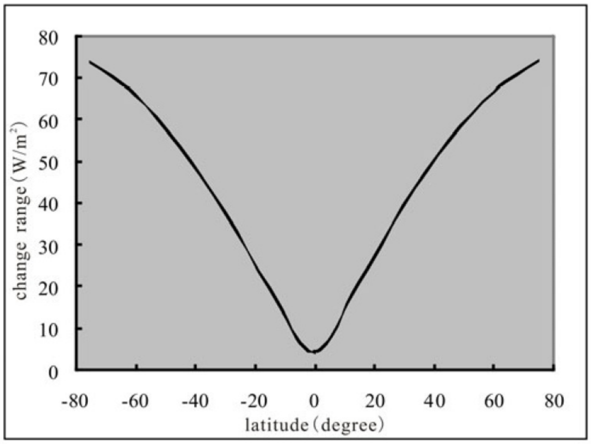


Figure 2.9.
Variations in the maximum annual LESI at different latitude [27].

Longitude also affects LESI values, which reach the same maximum value and have the same tendency at different selenographic longitudes, with only a time delay caused by the rotation of the Moon.

Finally, Li et al. [27] present the global distribution of LESI after having studied the effect of longitude and the latitude, showing that the global distribution of LESI on a given day has a ring-like distribution, decreasing gradually from the centre outwards toward a sub-polar point at 1.18° S and 93.08° W, as depicted in Figure 2.10.

LESI also has a non-zero alternation at the poles over a year, with a non-zero LESI occurring at the lunar south pole in the first 135 and last 50 days of the year south pole, while the opposite happens in the middle 180 days, mainly due to the tilt of the Moon's axis.

Finally, the instantaneous distribution of LESI is a stripe, as depicted in Figure 2.11, with gradual decreases from the lunar equator to the lunar poles.

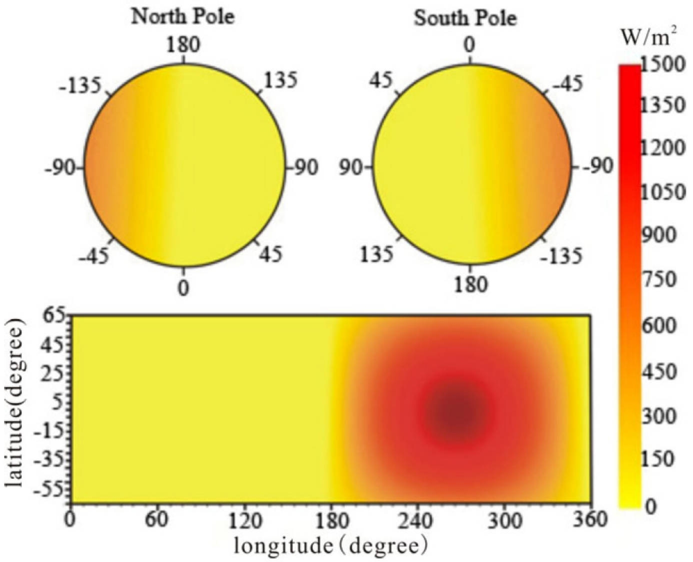


Figure 2.10
Global distribution of LESI on June 1st, 2008 [27].

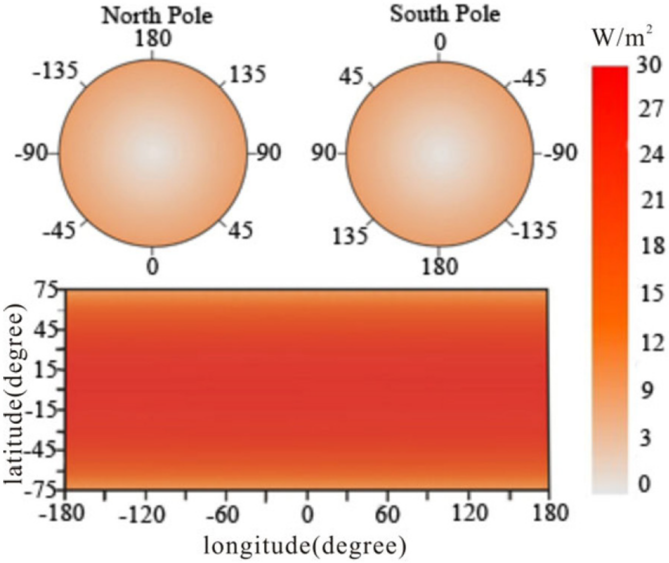


Figure 2.11
Average LESI in an 18.6-year lunar cycle [27].

Other factors such as lunar topography and inclination also have huge effects on the Moon’s solar radiation. Due to topography, some areas may be in shadow and have changes in the incidence angle. For its part, surface inclination causes changes in the solar incidence angle when compared with a flat surface.

2.2.6 Radiation

Space is filled with various kinds of radiation travelling in every direction. This radiation is harmful to humans and to generally every living thing we know. Fortunately, the Earth’s atmosphere and magnetosphere prevent most of it from reaching us at the surface. This is not the case for the Moon. Its negligible atmosphere allows most of the radiation to hit its surface, which can be both a bad and a good thing.

Let us first look at the different types of radiation [4]:

- Solar Wind
  This is a plasma formed by ions and electrons in equal numbers streaming from the Sun’s surface. These plasma rays are embedded in a magnetic field, creating interplanetary magnetic field lines with spiral shapes due to the Sun’s rotation. Their mean energy at a distance of 1 A.U. is ~1 keV at velocities ranging from 300 to 700 km/s and a proton flux of between $1{\cdot}10^8$ and $8{\cdot}10^8$ protons/$cm^2{\cdot}s$.

- Particles Associated with Solar-Flares
  The Sun produces intermittent high fluxes of energetic charged particles called solar cosmic rays. The particles can accelerate in either the Sun’s corona or in space, and they have much greater energy (1 MeV) upon reaching 1 A.U. They move along the field lines.

- Galactic Cosmic Rays
  Formed by particles from outside the solar system, these rays have the greatest energy of all at $\sim10^{20}$J, although some cosmic rays have energy below $\sim10^{15}$J. These particles come from our galaxy and the nuclei take ~7 years to reach the Earth.

Without any protection, this radiation could kill humans or produce fatal cancers in them while on the Moon, thus requiring some means to shield them from such damage. One possibility is the Moon’s regolith. However, not all radiation is bad and we can also use it for our benefit, as electromagnetic radiation can be observed by placing detectors on the Moon’s surface to study its origins, measure the solar winds, and even study the behaviour of Earth’s magnetosphere from the Moon [2].

2.3 Resources

Exploitation of space involves probing a limited region to find a promising solution S. Experimentation involves refining the research vicinity S. Travelling to the Moon and concentrating our efforts will allow us to improve on our knowledge of humanity and the origins of the universe.

In the fifty years since mankind first landed on the Moon, countless projects have been carried out to explore the Moon further. While government space agencies have led the way, the advent of nanosatellites has made it possible for student groups and private companies to explore space and the Moon in parallel with national and international space agencies. Now is the time to take a step further and advance our knowledge of the Moon, the Earth and the universe.

Exploitation, by definition, is the act of using and benefiting from resources. That is exactly what this document aims to encourage. Not only should the Moon's resources be exploited for our survival, but also to reveal fascinating secrets about our universe. This section outlines how the naturally available resources in the lunar environment can be used to support human habitation, and it also highlights the unique quality of some particularly exciting materials.

2.3.1 Light

Section 2.2.5 described the global distribution of solar illumination over the lunar surface. Considering that the Moon's solar illumination conditions can serve as a key resource for returning there, site selection is a crucial parameter. Here, we will study some areas of special interest for exploiting light as a resource.

Although studies have been conducted on the Moon's polar lighting conditions using Clementine image data, they are insufficient for definitively understanding the lunar illumination environment. More data is required. In order to identify all regions of extreme illumination, wide area imaging during the course of an entire year is necessary. Additionally, lighting simulations using high resolution topography could produce quantitative illumination maps [27].

Some theoretical models have been proposed based on the geometrical characteristics of the craters. Some of these models have been used together with the Laser Altimeter data of Chang'e 1 and topography data from Clementine to deduce that a small region exists around the lunar south pole that is permanently illuminated, which has also been reported in previous studies.

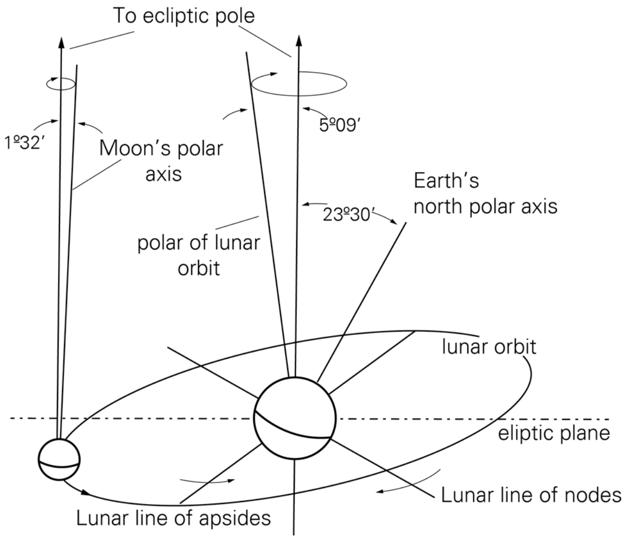
Peaks of Eternal Light

Peaks of Eternal Light (PELs) on the lunar south pole were predicted in the 19th century, and interest in them has been revived by the Clementine and Lunar Prospector Missions, as well as by detailed ground based radar imagery [29].

But what is a Peak of Eternal Light? Why are they interesting? How can we identify them? These are some of the questions that will be considered below.

The Peak of Eternal Light is a spot on the Moon where the Sun never sets. This is possible because, as mentioned above, the Moon's axis is unlike Earth's in that it does not tilt very much but instead runs nearly straight up and down relative to the solar system [30]. This causes both Sun and Earth to appear only very low above the horizon at the lunar poles. The local topography of this geometric condition thus creates regions of permanent shadow, with the tops of mountains rising above shadows close to the pole and remaining lit by the Sun moving low and close to the local horizon. These peaks can be illuminated for periods longer than the typical 14 days that affect the remainder of the lunar surface [29]. Thus, in theory, there might be a hill or crater edge near the north or the south poles of the Moon where the Sun never sets as the Moon spins around on its axis. So, why is this so interesting to us?

Figure 2.12
Angles in the Earth-Moon system [29].



According to [29] and [30], some expected properties of the PELs that make them so interesting are:

- Continuous light for operations and the wellbeing of lunanauts. 14 days of night-time is difficult for human beings to endure.
- Continuous power from solar panels.
- Benign temperature, predicted to be around 260 K and constant.
- Convenient shield against radiation. The bottom of a 20 m diameter crater is sufficiently protected by the crater walls.

- The Aitkin basin is geologically interesting
- Close to suspected water ice and cold traps. The first Lunar Prospector results estimated that the regolith in dark craters contains 0.3–1% water ice. Recent estimates are a bit more sceptical.

Now that we understand why this region is so important and may be perfect for a permanent lunar settlement, let us see how we can detect PELs and how close we are to finding them.

The following steps were undertaken to identify the PELs:

1. **Establishing the geometry of a PEL** The height restrictions for a theoretical PEL on a given meridian are determined by studying the worst possible geometrical case of a lunar altitude (midnight and midday in winter). By doing so, it is possible to determine that the theoretical PEL is expected to be within a radius of 157 km from the pole.

   This condition allows us to state that, although a lot of sites close to the perfect PEL may exist, a true PEL is not possible because it would be a conical mountain 600 meters higher than the mean radius and with a sharp top angle of less than 177°, meaning that the PEL would be infinitesimally small.

   For this reason, a permanently lit surface is only possible through elevation to a certain height (for example, solar panels). Thus, a PEL can be established by certain planetary landers that receive perpetual sunlight [29].

2. **Generating a high precision overlay using Clementine's polar images** Over a two-month period in 1994, Clementine was in a nearly polar orbit, approximately on the plane of the polar axis and Sun. During this time, the Moon rotated underneath its orbit twice, and the polar area was imaged with subsolar longitudes ranging from 0-360 in steps of ~5° [29].

   After rotation, resizing and post-processing (as seen in [31]), the video results turn out to be really useful for fully understanding the elongated winter shadows [29].

3. **Identification of the most lit pixels** After positioning all individual images, the pixel values for each individual image exceeding a certain threshold value were set to one while the rest were assigned zero. After that, a total score was given to each pixel by considering in how many images the corresponding pixel is lit (its value is 1 instead of 0). By doing so, three maxima were found on the rim of the 20 km Shackleton crater (one of which was previously identified by Spudis), on the westward ridge [29].

4. **Identification of slopes and the size of PEL** The MIS (Monthly Illumination Spectrum) is a powerful tool characterising slopes and, thus, locating mountain tops.

   As the PEL itself is a small value and too dark, it cannot be noticed directly and does not necessarily have to be the pixel with the highest cumulative illumination score. However, the MIS allows for possible indirect deduction of its whereabouts. The PEL is expected to exist in the pixel with the lowest maximum refection or slope, which are signs of a flat mountain top. As expected, such pixels are found close to the pixels with the highest cumulative score [29].

5. **DEM development and Lunar Visibility Calculator** Since data from the Clementine were gathered only during wintertime, it is necessary to make some calculations to predict PEL lighting throughout the whole year.

   To do so, both a physical 3D model and a DEM of the lunar south pole were produced.

   This indicated that a shift of 30% in elevation results in ~20% more illumination over a month [29].

The Shackleton Crater

The Shackleton crater lies nearly directly on the Moon's south pole. At its centre, the coordinates are 89.54° S latitude and 0.0° E longitude. The crater is approximately 21 km wide and 4.2 km deep. The interior of the crater has a 30° downward slope that stops at the crater floor. which is about 6.4 km in diameter.

The interior of the crater receives almost no direct sunlight, making it a perennial cold trap. For this reason, the Shackleton crater promises to contain sequestered volatiles. However, previous orbital and Earth-based radar mapping and orbital optical imaging have led to conflicting interpretations about the existence of volatiles [32].

A detailed study of the Shackleton topography would improve our current understanding of what happens in permanently shadowed places and the processes that take place there. Furthermore, the geometry of the crater, its age and state of preservation are relevant for understanding the accumulation and preservation of volatiles and the processes that modify the lunar surface over geologic timescales.

Observations made by the Lunar Orbiter Laser Altimeter on board the Lunar Reconnaissance Orbiter revealed that the Shackleton crater is ancient and unusually well-preserved, with interior walls that are fresher than its floor and rim. This could be due to little floor deposition occurring since the crater was formed more than three billion years ago.

An interesting feature of this crater is that, at some frequencies, the floor of the crater is brighter than the surrounding terrain and interior of other craters, but not as bright as the interior walls.

These combined observations could be explained by the downslope movement of regolith on the walls exposing fresher underlying material.

Although the crater floor could be brighter because of the reduced space weathering due to shadowing, another possible explanation could be a one-micrometre-thick layer containing about 20 per cent superficial ice [32].

The characteristics of the crater are presented in Figure 2.13 and Table 2.1, with the following characteristics depicted in Figure 2.13:

a. Topography in km.
b. Percentage of time illuminated.
c. *10-m baseline slopes in degrees.*
d. *(Surface roughness shown as Root Mean Square (RMS) residual in m.*
e. *Locations of crater counts used to determine relative ages.*
f. *Zero-phase, 1,064-nm reflectance shown as I/F.*

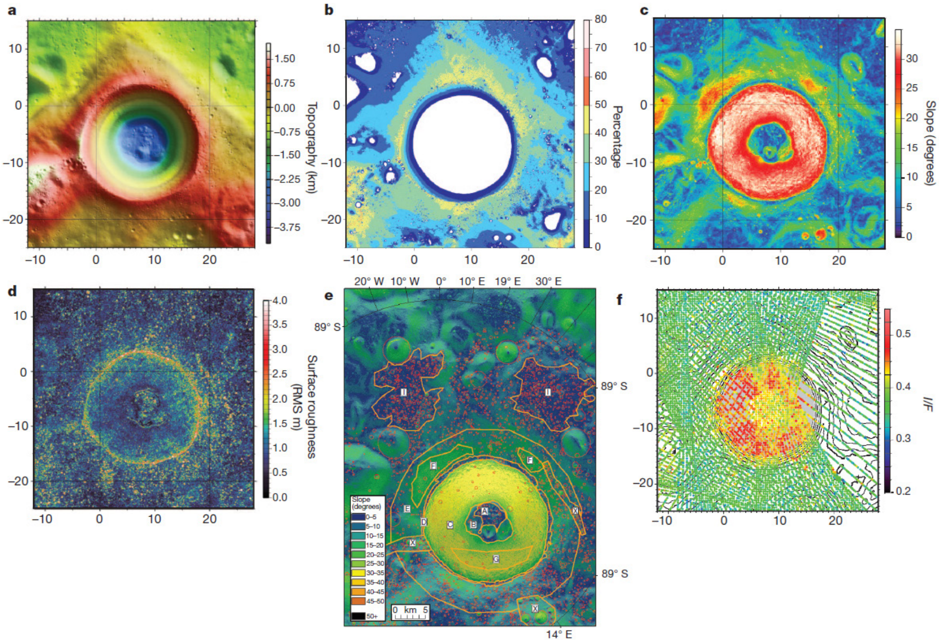


Figure 2.13.
Detailed characterisation of Shackleton crater [32].

In a–d and f of Figure 2.13, the x and y axes indicate the spatial scale, where (0, 0) is the lunar south pole. The colour scales show the magnitude of the plotted quantity. White regions in b correspond to zero illumination. Panel e shows the locations of craters that were counted to estimate the relative age, plotted over

10-m slopes (colour coded as in inset). The crater regions in e correspond to: A, crater floor region; A/B, entire crater floor; C, crater wall; D, crater rim crest; E/F, inner rim annulus (~5.5 km); E, inner rim annulus excluding steep region (F); F, steep rim region within annulus; G, crater wall section; I, Shackleton crater deposits north of rim in flat areas; and X, secondary crater chains and clusters (removed from analysis). In f, reflectance is expressed as a radiance factor (I/F), which is defined as the ratio of the measured radiance I to the radiance F of an ideal diffusive surface in a vacuum with 100%r reflectance under the same illumination. Each dot represents a 0.4× 0.4 km pixel median average of LOLA's spot 3 reflectance. Contours show topography at 0.2 km intervals. The grey annulus shows the 7 km diameter of the steepest portion of the walls and the 7 km diameter of the floor [32].

Table 2.1.
Parameters of the Shackleton crater [32].

Parameter	Value
Areocentric latitude of rim centre (degrees)	-89.655
Areocentric longitude of rim centre (degrees)	129.174
Lunar radius at floor centre (km)	1734.63
Mean crater diameter at rim (km)	21
Mean depth, rim to floor (km)	4.1 ± 0.05
Mean rim height above datum (km)	1.3
Range of floor topography (km)	~0.210
Area of crater at rim (km2)	~346
Area of crater floor (km2)	~38
Estimated fill depth (km)	~0.75
Crater volume (km3)	640 ± 10
Fill volume, including mounds (km3)	12 ± 1
Maximum wall slope (degrees)	35
Average wall slope (degrees)	30.5
RMS roughness within 5-m spots of crater exterior (m)	~1
RMS roughness within 5-m spots of crater walls (m)	< 1
RMS roughness within 5-m spots of crater floor (m)	~1
RMS roughness within 5-m spots of crater rim (m)	~1
I/F of crater exterior	0.32 ± 0.04
I/F of crater walls	0.46 ± 0.03
I/F of crater floor	0.43 ± 0.02
Ratio of average depth/average rim diameter, d=D	0.195 ± 0.025

2.3.2 Regolith

Oxygen Production

Samples of lunar regolith taken by Apollo missions indicate that major oxides make up about 98% of the lunar crust. Table 2.2 shows the breakdown of this composition [33].

Table 2.2 .
Chemical composition of several lunar samples – identified by Apollo mission number (A11 = Apollo 11) [33].

	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O
A11 Mare Basalt	40.46	10.41	10.08	19.22	7.01	11.54	0.38
A11 Soil and Regolith Breccia	41.99	7.94	12.58	16.40	7.93	11.74	0.47
A12 Mare Basalt	44.88	3.62	8.93	20.48	10.64	9.81	0.25
A12 Soil and Regolith Breccia	46.21	2.61	12.13	17.19	10.42	9.85	0.41
A17 Mare Basalt	39.03	11.94	9.00	18.82	8.54	10.82	0.39
A17 Soil and Regolith Breccia	44.47	2.84	18.93	10.29	9.95	12.29	0.43
Anorthosite	45.57	0.08	33.4	1.00	1.21	19.10	0.40

Based on the samples displayed in Table 2.2, the total abundance of oxygen in lunar rocks and soils is approximated at between 42–45%. Due to the importance of oxygen for potential human habitation on the Moon and other extra-terrestrial bodies, this has motivated research into potential methods for extracting this oxygen from the lunar regolith.

The metal oxides displayed in Table [33] are very stable compounds, and thus a high energetic cost is incurred for extracting pure oxygen. There are a number of methods used on Earth for oxygen extraction, although some are more applicable than others on the Moon.

One example is vacuum pyrolysis. The lunar regolith may be extracted from the Moon's surface and then heated in a vacuum (provided by the Moon's own lack of an atmosphere). The presence of a vacuum reduces the boiling point and prevents adverse reactions taking place [34]. The oxide is vaporized, thus reducing the oxide (which can then be condensed out of the low pressure gas) while simultaneously producing oxygen. The vacuum pyrolysis method has a high potential efficiency and would not require additional imported chemicals. All required resources may be found on the Moon (solar/other energy source, vacuum, and regolith), thus making it an ideal potential candidate for oxygen production from lunar regolith.

Other methods are also available, such as solid gas interaction, molten processes (such as electrolysis), and acid dissolution. All of these could be tested on a lunar base in order to obtain data on the most efficient methods for obtaining oxygen under different scenarios while using the Moon’s unique resources and environment.

One commonality among all these methods is that oxygen extraction on the Moon is more cost efficient than launching supplies from Earth. The cost of transporting oxygen only increases with distance, making it unfeasible to supply other locations in this way (Mars for example). As such, many experts agree that the ex-traction of a commodity as essential as oxygen – which, aside from sustaining life, may be used as a propellant – is a key step in future space exploration [33].

Radiation Shielding

Building settlements on other planets or moons is not an easy task. The amount of radiation and solar winds flowing through the cosmos is immense and harmful to humans. Thus, we need a radiation shield to protect us. Creating such a shield is not easy, as most radiation passes through most materials as if they were nothing. This would also incur sending heavy loads of materials to the Moon in order to create this shield, which would obviously be very expensive. To solve this problem, the lunar regolith has been analysed in order to measure the capability of its materials for creating a natural radiation shield.

Three samples of regolith from different missions to the Moon have been analysed, and the results indicate that the regolith is not homogeneous throughout the surface. These samples are composed mainly of silicate minerals. The first sample is a highlands regolith anorthosite (AN). The other two are different mare basalts from the Apollo 12 and 17 missions. The major element concentrations found in the samples are in the following table:

Table 2.3. Major element concentrations in the three samples[35].

Material	AN	MB1	MB2
SiO_2	45.57	44.88	39.03
TiO_2	0.08	3.62	11.94
Al_2O_3	33.40	8.93	9.00
FeO	1.00	20.48	18.82
MgO	1.21	10.64	8.54
CaO	19.10	9.81	10.82
Na_2O	0.40	0.25	0.39

The analyses conducted on these samples measured the particle fluence of protons and neutrons along the thickness of the samples in order to ascertain whether the regolith could serve as a radiation shield for humans. Both analyses show very small variations along the thickness of the shield (from 10 cm to 1 m), with the number of particles reaching the bottom of the sample being low and 'not fatal' at thicknesses greater than 1 meter.

This phenomenon results from the electromagnetic and nuclear interactions between the charged particles and the regolith. On the one hand, the electromagnetic interaction tends to slow down the ions, causing them to increase ionization. On the other hand, nuclear interactions break the ions of the beam into smaller particles, causing them to decrease their charge and therefore decrease their ionization.

The obtained results are represented in Figure 2.14 and indicate the effective doses (in Sv) that produce fatal cancer in humans as a function of regolith thickness. The lines in the figure represent the maximum doses for women and men, showing the maximum permissible dose that an astronaut can receive throughout his/her career (considered to be 10 years).

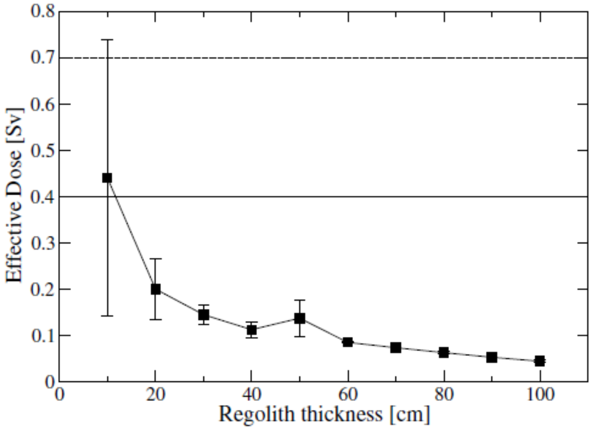


Figure 2.14.
Effective dose in Sv, depending on the thickness of the AN regolith sample. Maximum permissible doses are indicated by the solid line for women and the dotted line for men [35].

In order to characterise the radiation protection properties of the lunar regolith, experiments have been carried out with the Heavy Ion Medical Accelerator in Chiba facility (HIMAC) at the Japanese National Institute of Radiological Science [36].

The tests were carried out on representative samples of different areas of the Moon (mare regions and highland soils, among others) and lunar regolith simulants JSC-1A, MLS-1A and NU-LHT-1 (among other simulants). These simulants were manufactured because of the limited number of lunar regolith samples collected by the Apollo missions for experiments on Earth. The simulants are made by crushing welded volcanic tuff (of a basaltic nature), they are composed of 50% glass, and they have properties similar to the lunar soil samples.

Both tests shared the same set-up seen in Figure 2.15 and underwent similar result analysis that yielded energy deposition (ΔE) spectra. In both cases, a beam of charged particles was passed through the regolith samples, and data was taken at sample output using silicone detectors.

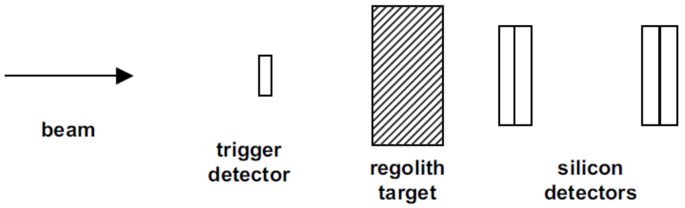


Figure 2.15
Set-up for testing the radiation shielding characteristics of regolith samples [36].

The energy deposition spectra is used to calculate the percent dose reduction per incident beam ion while normalising for the thickness of the sample [37].

In the first test, the soil samples collected by the Apollo missions and the regolith simulants were exposed to an ion beam of 400 Mev/nucleon 10B, showing a result of percent dose reduction per unit area of 0.7–1.0%. These results demonstrate the great radiation protection capacity of the regolith, since they are very similar to those obtained with aluminium and only half those of polyethylene.

In the second test, only the simulant NU-LHT-1 was exposed to an ion beam of 290 M ev/nucleon 10 B, resulting in an energy spectrum of between 7.5–30 $g \cdot cm^{-2}$, depending on the sample thickness. Again, these results are similar to those obtained with aluminium.

Iron

The previous chapter explained that iron in the lunar regolith causes several the particles to contain a mixed variety of different materials. When micro-meteorites impact the Moon's surface, they provoke a small scale melting process in which the iron fuses with the other materials and creates particles of agglutinates that have a glassy iron shell.

Thus, from a resources point of view, extracting iron from lunar regolith requires removing this iron shell from the dust particles.

If the question is whether enough quantity of iron is present to make this worthwhile, the answer is an absolute yes. Figure 2.2 indicates that the concentration of this element in the lunar soil represents around a 14wt% of its total composition in the lunar lowlands, making it the second most abundant solid material in the Moon's regolith [11].

Although the iron quantity is fairly abundant, the glassy shell form that it takes in the lunar regolith makes it very difficult to extract with current technologies.

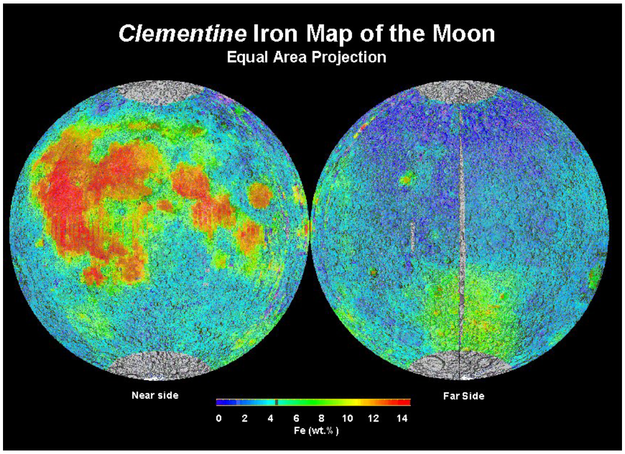


Figure 2.16. Clementine iron map of the Moon [38].

However, if this lunar soil is being treated to extract oxygen, the process for extracting iron may not be as complicated as processes for removing only the iron itself [39].

Despite these difficulties, two alternatives could increase the possibilities for obtaining iron on a lunar base. The first is to extract the iron directly from impacted meteorites, which contain a native iron concentration of 0.3wt%. This is not a negligible value, since it represents 5 kg from 1 m^3 of meteoric regolith. The second alternative is to extract it from nearby lunar asteroids ejected from a past lunar impact. In this case, the lack of gravity and the asteroids' metallic cores could make operations feasible.

Silicon

Silicon constitutes 21% of the lunar regolith by mass. It has many forms and allotropes that mimic carbon [40] and can be used to make semiconductors, since it is the only element found in abundance in the lunar soil. The production of silane from silicon would also be useful, as it can be used for rocket fuel rather than hydrogen [41].

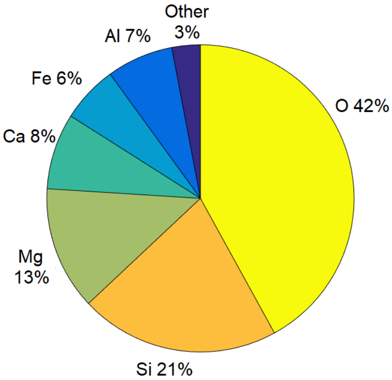


Figure 2.17. Composition of lunar regolith [41]

Helium-3

One particularly captivating resource available on the Moon is helium-3. The idea of harvesting clean and powerful fuel on the Moon has caught fire in fact and fiction over recent decades. Because the Moon has been bombarded by the solar wind, vast quantities of helium-3 have been deposited on the lunar surface. This material could produce safer nuclear energy in fusion reactors, as the process does not produce radioactive waste. The opportunity to exploit the Moon's resources has been a prominent issue for years. Newt Gingrich, seeking to be US President, proposed doing so in his campaign to become the Republican Party nominee in 2012; and private companies are currently pushing toward mining the Moon.

Common helium has two protons and two neutrons, whereas helium-3 has two protons and a single neutron. This has significant effects on the isotope's quantum mechanical properties. Helium-3 was first isolated in 1939 after being theoretically proposed in 1934 by the physicist Mark Oliphant. Helium-3 was thought to be a radioactive isotope until it was found to exist in samples of common helium taken from the terrestrial atmosphere and natural gas wells. Helium-3 is the only known stable element with more protons than neutrons. Much of the helium-3 in Earth's atmosphere is believed to be there as a result of underwater and stratospheric nuclear weapons testing.

It is believed that helium-3 was deposited in the upper regolith of the Moon by the solar wind over billions of years, although it is less abundant on the Moon than in the solar system's gas giants.

In sunlit areas of the Moon, the regolith contains between 1.4 and 15 ppb [42]. The permanently shadowed areas of the Moon may contain up to 50 ppb. With such small concentrations, mining equipment would need to process huge amounts of regolith. As a result, it has often been suggested that any mining operations form part of a larger development plan for the Moon.

Many of the world's superpowers have expressed their desire to mine helium-3 and return it to Earth for power. The chief scientist of the Chinese Lunar Exploration Programme, Ouyang Ziyuan, is a proponent of mining helium-3 and has stated that "each year, three space shuttle missions could bring enough fuel for all human beings across the world." [43]

Some have also proposed mining gas giants for helium-3, as the significantly greater concentration could compensate for the extreme distances. However, such projects remain hypothetical. Issues have plagued helium-3 reactors for years, but progress is being made, particularly in the experiments being carried out at the Massachusetts Institute of Technology [44].

2.3.3 Topography

Topography of the Moon Fifty Years Ago

When the Apollo 11 mission landed in the Sea of Tranquility fifty years ago, very little of the lunar topography was known. Mare Tranquillitatis, as it is officially named, is near the Moon's equator on the side facing Earth. It is a relatively smooth area on the lunar surface and therefore provided the best opportunity for a smooth landing, although Neil Armstrong did have to take control of the lunar lander when he saw the intended landing site was strewn with boulders. The planned landing site was just north-east of a 91-meter crater known as West. Armstrong took semi-autonomous control of the Apollo 11 module and piloted the craft to clear West, as the horizontal velocity of Eagle was too great. A seemingly clear landing site presented itself, but as they came closer, Armstrong spotted another crater in the landing site. During descent, lunar dust obstructed the crew's view and Armstrong focused on large rocks to judge the speed of the lunar module as the remaining propellant dwindled down.

The risk that Neil Armstrong and Buzz Aldrin took with their Moon landing may never happen again, thanks to the extensive understanding of lunar topography that we have today.

Current Topographic Maps

In June 2009, the Lunar Reconnaissance Orbiter (LRO) was launched. The first three years of data were obtained from polar orbit, followed by a more stable elliptical orbit. Its Lunar Orbiter Laser Altimeter (LOLA) was used to make a topographic map of the Moon by measuring the calculated two-way travel time of the laser beam. Basically, the time it takes for the laser pulses to return to the on-board receiver indicates how far it is from the lunar surface. It sent 140 pulses each second to the surface, which was crucial for obtaining a high resolution map. The altitude was measured by over 6 billion points on the Moon's surface, which provided the highest resolution topographic map of any planetary body except for Earth [45].

The figure below is a topographic map of the Moon with the colours representing elevation. The lowest areas are purple to black and the highest are red to white. The map is centred on the Moon's near side at a pixel scale of 300 meters [46].

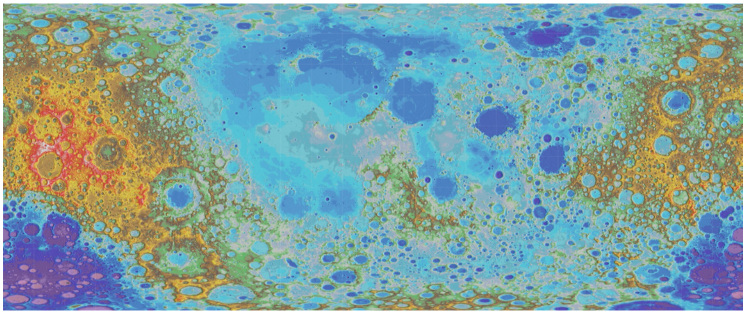


Figure 2.18.
Lunar Topographic Map [46].

Regarding the most plausible landing sites having been determined as the poles, the topographic data from the north and south poles can be observed in Figures 2.19 and 2.20.

The difference between the near and far sides of the Moon is very big at the north pole. The highlands labelled in red and orange dominate the far side, while the lower-lying mare basins labelled in dark and light blue dominate the near side. The South Pole–Aitken basin, the largest and deepest impact feature on the Moon, is labelled in blue [46].

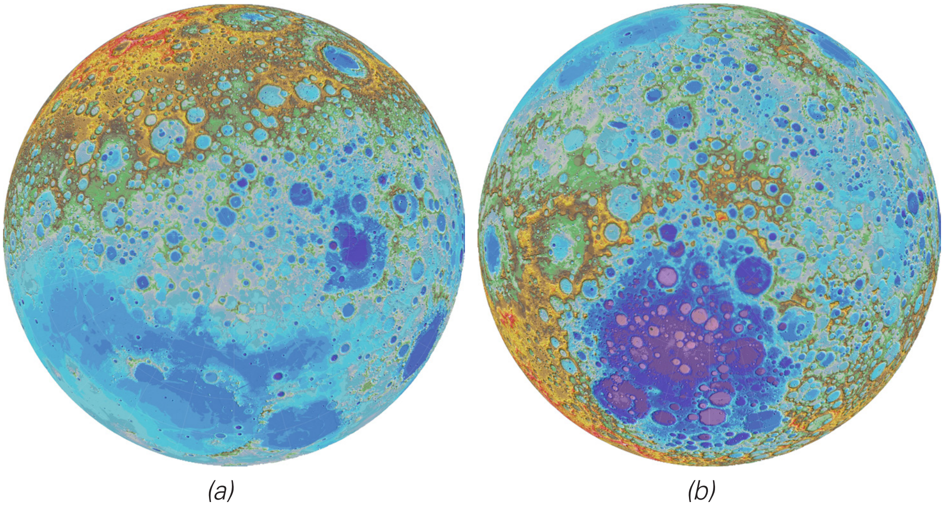

(a) (b)

Figure 2.19
(*a*) North pole topography
(*b*) South pole topography
[46]..

Topographic Maps for Determining Landing Sites

The most important feature of a good landing site is that it be level and free of obstacles, such as large boulders that could potentially damage or unbalance the spacecraft during its landing attempt.

The LRO carries a pair of Narrow Angle Cameras (NACs), which together can take images that reveal details at 0.5 meters of resolution over swaths that are 10 kilometres wide. The Diviner is an instrument for measuring the temperature. It is used for back-up and to verify results. Because temperature changes more quickly with rocky terrain, it can determine which apparently smooth areas are actually unsafe for landing. With this data, future astronauts can identify safe landing zones and be able to avoid unwanted surprises like the one that happened on the Apollo 11 mission [47].

2.3.4 Water

It is a generally unknown fact that water is present on the Moon's surface, although it cannot exist there in either liquid or vapour form but, rather, as ice.

It has long been presumed that this water can be found only on the very cold parts of the Moon's surface, and the coldest parts of the Moon are those always covered in shadows, which is precisely what occurs at the bottom of craters in the Moon's polar regions. This was actually proven by the Indian spacecraft Chandrayaan-1 in 2009, using a spectrometer that detected absorption lines of around 2.8–3.0 μm [48]. That test is typical for ascertaining the presence of hydroxyl groups or water in silicate rocks.

Prior to Chandrayaan-1, other evidence for the presence of water and hydrogen on the Moon's surface had been found using impactors, radar experiments like those on the Clementine Mission (1994), and the neutron spectrometer on the Lunar Prospector Mission (1998). This last one measured the abundance of hydrogen in the Moon regolith and detected a larger concentration of it near the Moon's poles. Although this indicated the presence of ice water there, it could also be due to hydroxyl radicals (OH^-). After processing the data from both Clementine and the Lunar Prospector, scientists estimated that the total amount of potentially present water ice could be on the order of 1-3 km^3.

More recent studies like the Lunar Reconnaissance Orbiter, launched on June 2009, conducted some experiments to find water on the Moon's surface. During the mission, the upper stage of its Atlas V carrier rocket was impacted into the Cabeus crater. After that, the LCROSS probe was flown into the ejected plume generated by the impact. In November 2009, NASA confirmed that the presence of a water signature although, again, what was detected was the hydroxyl group, which could also be due to hydrates.

All this data points to the high probability of finding ice water the Moon's poles, but further research and measurements are required. Despite that, the interesting conclusions of this study are that: if there is water on the Moon and we want to use it for human exploration, watering plants, and extracting pure hydrogen and oxygen, then we will need to build mining facilities near the lunar poles.

This could be a problem, given that the poles are the worst areas for producing electricity. Thus, it is essential to find a solution for mining that water and transporting it to other lunar settlements, knowing that the distance from the pole to the Moon's equator is around 2700 km. This is crucial to any discussions on the best places for fixed settlements on the Moon, and a trade-off should be found

generating power by solar irradiation and proximity to the poles for exploiting this water supply.

→ 3

Energy generation

3.1 Energy Requirements on the Moon

Section 2.3 discusses a number of the Moon’s natural resources, many of which are related to energy production, particularly light and helium-3. However, before jumping to the methods for this, we must properly understand the amount of energy required to create a lunar base. To assess such an unknown quantity, this section will analyse a number of different aspects in order to understand the energy needed per person and per facility.

3.1.1 Human Energy Requirements

Human biological needs have not changed for millennia, and they have evolved for adaptation to the planet Earth’s environment. As with ventures in past centuries, generations of explorers will need to transport nourishment and materials with them. They will need to have a certain amount of energy input through food and for maintaining normal temperatures through either cooling or heating [3].

In order to calculate the energy required, Habold et al. [49] conducted some tests, taking into account RMR (resting metabolic rate) and a coefficient proportional to individual physical activity. Results were gathered on both space and Earth, indicating that “on average, energy needs in space are about 7.5 MJ per day and 8.5 MJ per day for a 55 kg woman and a 70 kg man, respectively.” For EVA operations, the energy requirements reach higher:

“an additional 2.2 and 2.9 MJ per day therefore need to be added to the normal needs for 55 kg women and 70 kg men, respectively, assuming 6 h of EVA per day.” In total, the energy needs would be 9.7 MJ per day for a woman and 11.4 MJ per day for a man.

NASA has estimated that an astronaut on the ISS consumes about 0.83 kilograms of food per meal each day. About 0.12 kilograms of this weight is packaging material. Long-duration missions such as to the Moon or Mars will require carrying more food on board. For example, the predicted food load for a four-person Mars mission of a three-year duration would be over 10,886 kilograms [50].

3.1.2 Life Support Systems

The Environmental Control and Life Support System (ECLSS) provides and controls the atmospheric pressure on the ISS. The ECLSS' atmospheric pressure monitoring also detects and suppresses fires while controlling oxygen levels, waste management and the spacecraft's water supply. Gases produced by the human metabolism, such as methane and ammonia, are removed from the ISS by activated charcoal filters. Life support systems are discussed further in Chapter 4.

3.1.3 Power Requirements for the First Lunar Outpost

In 1993, NASA calculated the power requirements for a scientific outpost on the lunar surface, dividing these requirements into four critical sections, which will be explained here briefly.

Space Transportation System

The possibilities for a space transportation system are described in the chapters on cislunar transport and evacuation procedures. Table 3.1 presents the requirements calculated by NASA.

Keeping propellants at their ideal operating temperatures constitutes one of the most important factors for being able to return the crew back to Earth. The temperature of a variety of other systems should also be maintained at operational requirements. The total nominal energy needed for a piloted vehicle is 1639 kWe-h, and for a cargo vehicle it is 236 kWe-h.

Table 3.1. Transportation system power requirements [51].

Mission Phase	Duration (hours)	Power (kW)
Lunar Orbit to Lunar Surface	1.92	2.52 to 2.59
On Lunar Surface (Day)	672	0.48 to 2.66
On Lunar Surface (Night)	408	2.10
Lunar Surface to Lunar Orbit	3.23	2.51
Lunar Orbit to Earth Orbit	96.7	1.83 to 2.51

A crew transportation vehicle will use much more energy and will require greater power storage and supply systems. In order to eliminate unnecessary mass, the lunar outpost should be able to provide power for cargo mission. In addition, 'the power system must be able to supply power during lunar transfer and descent to the surface as well as keep alive power for the habitat.' [51]

Habitat

Here, the term habitat will refer to the living and working quarters. The estimates made in this section are for a crew of four people, and the habitat design is a scaled-down version of the Space Station Freedom HAB Module (10 m in length and 4.5 m in diameter).

Table 3.2 shows the power requirements for the habitat, which includes an airlock chamber for safe access and egress, may serve as a safe zone in the event of habitat breach.

Table 3.2.
Habitation activity power requirements [51].

Procedure	Daytime Power (kW)	Nighttime Power (kW)
Out-bound	0.5	N/A
Deployment	2	N/A
On-surface crewed	10	9
Crewed Rover Recharge	1.4	1.4
Robotic Rover Recharge	0.1	0.8

The rovers mentioned in the table have baseline charging times of 14 hours. Peak power requirements are roughly 12 kW during the day and 11 kW at night [51].

Surface Transportation System

Compared to the 1 km radius during the Apollo 11–14 missions, the Apollo 15–17 missions had the capacity to explore within a 9 km radius thanks to the lunar rover.

In analysing a system that can carry 1 to 4 crewmen wearing EVA suits, we set the range to a total of 50 km, 20 km outbound, 10 km traversing and 20 km inbound. For the single rover scenario, the speed is set to 2.5 km/h and the nominal power required is set to 1.6 kW with peak values at 2.2 kW.

A second rover is included for having rescue capabilities with a greater outbound range of 30 km. For functionality during a worst case scenario, its nominal power is also set to 1.6 kW, peaking at 2.2 kW. Figure 3.1 details the power requirements of the lunar rover.

Table 3.3.
Lunar transport power requirements [51].

TYPE OF SORTIE	FUNCTION	POWER (kWs)
CREWED ROVER	Mobility	1.35
	Housekeeping (Mobile)	0.30
	EMU/PLSS	0.50
	Science	0.50
	NOMINAL	1.52
	MAXIMUM	2.15
RESCUE ROVER	Mobility	1.35
	Housekeeping (Mobile)	0.30
	EMU/PLSS	0.50
	Science	0.00
	NOMINAL	2.03
	MAXIMUM	2.45
TELEROBOTIC ROVER	Mobility	0.10
	Housekeeping (Mobile)	0.10
	Telerobotics	0.30
	Science (Mobile)	0.10
	Science (Stationary)	0.50
	NOMINAL	0.54
	MAXIMUM	1.00

Scientific Payload

The science payloads researched here consist of a set of astronomical instruments, a laboratory contained within the habitat, a physics experiment payload for studying the solar system, and a package for monitoring geophysical conditions.

Included in the astronomy payload are three strawman telescopes: a Lunar Transit Telescope; a Small Solar Telescope; and another Small Research Telescope. These telescopes would remain at least 10 km from the outpost. The solar telescope would be used to capture detailed images of the Sun and thus be used only during periods of natural light. The suite of equipment would be remotely operated and function as a standalone scientific station.

Each of the stationary payloads could be located close to each other and thus benefit from a shared power source. The sum of the stationary payloads' power requirements is 930 W (Table 3.4).

Table 3.4.
Power requirements of stationary science payloads on the Moon [51].

Instrument	Power (W)
Lunar Telescope	100
Small Telescope	500
Solar Telescope	50
Solar System Physics	190
Geophysical Monitoring	90

As shown in Table 3.5, the total assessed power budget for mobile science payloads is 600 W.

Instrument	Power (W)
Traverse Geophysical	100
Geological Drill	500

Table 3.5.
Power requirements of mobile science payloads on the Moon [51].

3.2 Fission

Nuclear fission is a process in which the nucleus of an atom splits into two or more smaller nuclei, thus generating great amounts of nuclear energy in the form of gamma rays and kinetic energy. The chemical element isotopes that can sustain a fission chain reaction are called nuclear fuels, and they are referred to as fissile. The most common nuclear fuels are heavy elements such as U^{235} (the uranium isotope with an atomic mass of 235, which is used in nuclear reactors) and Pu^{239} (the plutonium isotope with an atomic mass of 239). Due to their odd atomic numbers, they produce thermal reactions (slow or low energy reactions). However, elements with odd atomic numbers can also produce thermal reactions if hit by +1MeV neutrons. The problem with high-mass nuclear fuels such as these is that they are very dangerous. Their radiation levels from emitting alpha rays are not directly a great threat, but inhaling them will result in fatal cancer of the lungs and bones, among others [52]. Inhaling less than 500 g of plutonium oxide has been calculated to produce cancer to over 2 million people. So, why use such a dangerous process? To understand the importance of fission, we will provide a brief explanation of the whole process.

3.2.1 Nuclear Structure

Most elements in the periodic table have more than one structure, and they are called isotopes. Depending on the composition of the nucleus, each isotope is different. For example, uranium-235, -236 and -238 are distinct, but because we can use different atoms with the same number of nucleons, their different characteristics (due to differences in the number of electrons), make their decay chain different and, hence, they produce different levels of energy.

The stability of an atom strongly depends on the balance between protons and neutrons. Generally speaking, nuclei with an even number of these tend to be more stable. When we have an isotope, these numbers may differ, thus generating an instability that the atom will try to fix by decaying into other atoms. For example:

$$ {}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{0}_{2}He \qquad (3.1)$$

where an alpha particle is released (that is, a helium-4 nucleus) and generates energy.

Then, the thorium produced is also radioactive, and it in turn decays into:

$$ {}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e + \bar{\nu} \tag{3.2} $$

thus releasing a beta particle (electron) and an antineutrino. This chain of processes is what we call a "decay chain", and it is used to generate energy.

The process we have seen in the equations above is called "transmutation of elements". All conservation laws obey the processes described in these equations, including those of nucleons, charge, momentum and total energy. When this transmutation takes place in the case of an unstable element, it will decay into another atom and release energy in the process, as we saw in the chemical equations above. This energy can be in the form of alpha or beta particles, as well as photons or electrons [53].

3.2.2 The Fission Process

The absorption of a neutron by most isotopes involves radiative capture, with the excitation energy appearing as a gamma ray. When this absorption occurs, the atom splits into two smaller atoms by a process called fission. The whole process of fission consists of four stages. In the case of uranium-235, it would be: Stage 1, the neutron hits the U^{235} nucleus; stage 2, an excited nucleus is formed, U^{236}; stage 3, the excess energy is released; stage 4, the nucleus oscillates and electrostatic repulsion causes it to split into two smaller atoms. This whole fission process takes only 10^{-15} s.

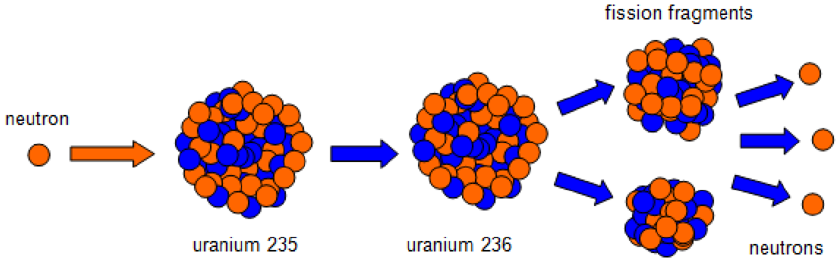
When fission occurs, many neutrons are released and generate a chain reaction. The number of neutrons released depends on the atom, which has two different types of neutrons: those that are released instantly due to fission and those generated through the decay process. The greater the number of neutrons released, the greater the chain reaction is going to be, and the more energy we get from the process [53].

A typical nuclear reaction would be:

$$ {}^{235}_{92}U + {}^{0}_{1}n \rightarrow {}^{A_1}_{Z_1}F_1 + {}^{A_2}_{Z_2}F_2 + \mu\,{}^{0}_{1}n + Energy \tag{3.3} $$

Graphically represented:

Figure 3.1. Graphic representation of a U^{235} fission process .



Where F1 and F2 indicate different possibilities, for example.

$$n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3n + 177\ MeV \tag{3.4}$$

The total energy released by the fission of a nucleus into smaller parts is given by:

$$\lambda E = \left(M_0 - \sum M_i\right)c^2 \tag{3.5}$$

where M0 is the mass of the original atom and Mi are the masses of the resultant particles. We therefore can see that the difference in mass translates into the amount of energy we have obtained. The resulting energy obeys the laws of relativity, since these particles move at very high velocities [54].

3.2.3 Hazards

The isotopes used for fission are radioisotopes, meaning they radiate harmful particles that can change the molecular structure of other materials. These changes can result in many types of fatal cancer in humans. As we have seen in the previous section, when both uranium and plutonium decay or split into smaller atoms, they emit gamma rays as well as beta and alpha particles. These particles are highly ionizing forms of radiation, and external exposure to them is not a high risk due to their low penetration, meaning that skin will stop them. The problem occurs when these particles are ingested, which gives them access to cells that they modify and thus produce cancer. The most dangerous of these particles is the alpha particle, which is up to 1000 times more dangerous than the other two. Plutonium emits mainly alpha particles, and that is why it is more dangerous than uranium, though the energy production is much higher [55].

Building nuclear plants on the Moon would not be a “difficult” task, and the main problem would lie in transporting enriched plutonium and uranium to the Moon. The radiation is very toxic for astronauts, and it can also interact with radiation from space, thus generating much more radioactivity. What is more, if some kind of failure were to occur, we would have radioactive material orbiting the Earth or Moon, leading to a great increase of global cancer due to radiation.

3.3 Solar Energy

An alternative to the high power generation of nuclear systems is photovoltaic cells. These systems have been widely used for space applications (e.g., satellites, ISS, etc.), and they have also been tested on the Moon’s surface.

These systems can generate energy from an abundant and unlimited resource on the Moon, namely solar radiation. In order to better understand these systems, we shall briefly describe the solar radiation in the Moon environment. Due to the Moon's minimal atmosphere, there is no radiation attenuation, with the estimated radiation there reaching almost eight times that on the Earth's surface [26]. Even so, it should be taken into account that these types of systems do not generate energy during periods of darkness (i.e., eclipses and at night). Lunar eclipses occur when the Earth is interposed between the Moon and the Sun. On the other hand, lunar nights result from the Moon spinning about its rotation axis once every revolution around the Earth (about 354 hours).

3.3.1 Energy storage

Due to these periods of darkness, the solar electric generation systems must be complemented with energy storage units. It should be noted that this increases the complexity and cost of the overall system. For energy storage, conventional options such as batteries can be used. These have a storage capacity of 25 W hr/kg. Other technologies such as flywheels or fuel cells can be used, the latter being the most suitable solution due to its high storage capacity with respect to other current technologies (300 W hr/kg). Fuel cells have been used by NASA for different spacecraft missions and have been shown to have high efficiency (60–70%) and long lifetimes ranging from 1000 to 50000 hours.

3.3.2 Photovoltaic cells

Solar cells, also known as photovoltaic cells because of their photovoltaic effect, are devices that can generate electrical energy directly from light energy. The photovoltaic effect generates electric potential from the excitation of an electron absorbing light (see Figure 3.2).

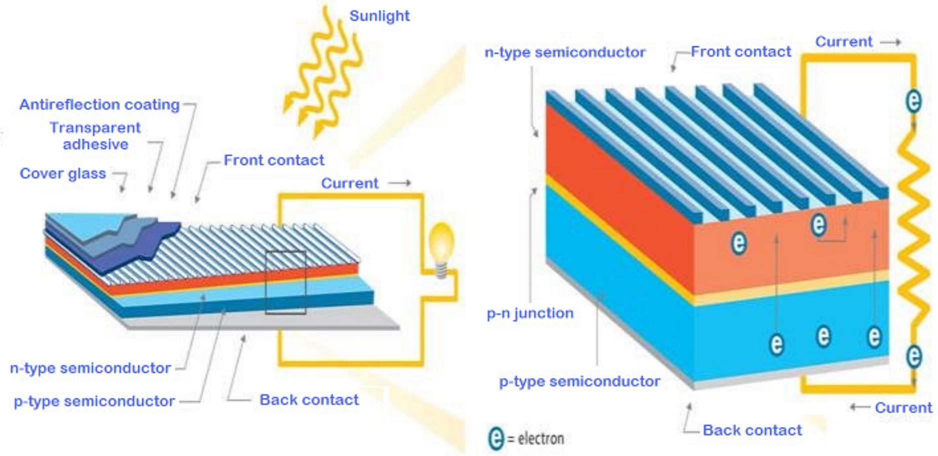


Figure 3.2. Representation of photovoltaic effect [56].

Specifically, protons are absorbed by the semiconducting materials (e.g., silicon) and they excite the electrons. Therefore, electrons move until they reach the electrode, thus creating an electrical potential. The efficiency of this process is related to how much energy is produced from the incident light. The current technologies of solar cells for space applications have achieved efficiencies of around 15% [57], although some experiments using multi-junction cells have achieved an efficiency of 38.3%.

Different solutions have been proposed for the construction of a solar generation system with photovoltaic cells on the Moon. Some of them simply consider the placement of solar cells directly on the surface. Due to the possibility of lunar dust deposition over the photovoltaic cells, which will decrease the energy production, the cells should be equipped with mechanisms for dust removal. Other methods consider the construction of power systems on opposite sides of the Moon in order to ensure sunlight conditions for at least one of the bases [26].

Furthermore, because an abundance of construction materials can be obtained from the lunar regolith, some proposals suggest manufacturing solar cells with in-situ lunar materials. The lunar regolith contains all the materials used for making photovoltaic cells (i.e., silicon, iron, titanium oxide, calcium and aluminium) and, even though their efficiency will be very low (~5%), this will make it possible to construct fields of large solar cells for harvesting the Sun's energy. This idea has also fuelled proposals for roving robots that can manufacture and set up solar cells on the Moon's surface [26].

3.4 Satisfying Needs

From the information presented in this section, one might be under the impression that the energy needs on the Moon are not as demanding as might have been previously imagined. While it is true that the amount of energy required for a lunar base is not massive, relative to the energy production capacity, it is huge. Upon analysis of the requirements and potential of solar and nuclear energy on the Moon, it seems that a hybrid power source is optimal for setting up a lunar base.

Solar energy does not present a sufficient potential for satisfying the energy needs. Even if there was enough solar energy generated on the Moon, the cost would be outlandish for tested PV cell technology. Due to the high cost, redundancy would be minimal, and this could lead to an otherwise avoidable situation of having to evacuate the base in the event of a failure in the power generation system.

The ideal situation would be to generate solar power on the Moon with large solar panels with redundancy provided by nuclear power. This solution would not be a permanent one, but would instead be used only during base construction and in its infancy. It is anticipated that a helium-3 reactor will eventually generate clean nuclear power and that the other issues surrounding it (described in Section 2.3.2.5) can be overcome.

→ 4

Life support systems

4.1 Life Support Systems

A life support system is generally an artificial environment that replicates the Earth's natural environment at sea level for aerospace travellers and settlers. Commercial jets also maintain certain natural conditions for easy travel. However, supporting life in a hostile environment like space is a challenge itself.

4.2 Subsystems

The subsystems contributing to life support on the ISS are:

- The Electrical Power System
- The Thermal Control System
- The Flight Crew System

Flight crew system The flight crew system mainly provides the daily life requirements for the inhabitants, namely a safe environment and basic necessities:

1. Restraints and mobility
2. Portable emergency provisions
3. Housekeeping and trash management systems
4. The crew health care system
5. Lighting
6. Personal hygiene equipment
7. Wardroom
8. Crew privacy

The most complex of these is CHeCS, which is comprised of the Health Maintenance System (HMS), the Counter Measure System (CMS) and the Environmental Health System (EHS).

HMS provides in-flight preventive medicine, diagnostic and therapeutic care.It is also charged with transport between vehicles and stabilisation during emergencies.

CMS. The CMS evaluates crew fitness and measures cardiovascular and musculoskeletal deterioration.

EHS manages the internal environment of the station mainly by focusing on microbiology, toxicology, and radiation while also conducting acoustic monitoring.

CHeCS interfaces with the C&DH (Command and Data Handling) system and provides on-board display and data transmission to ground control.

4.2.1 Environmental Control and Life Support System

The ECLSS provides a perfect environment for the inhabitants of the station by maintaining oxygen levels at 24.1% and station pressure at 14.2–14.9 psi).

- Most of the water, including urine, is recycled into drinkable water and even for flushing toilets and generating oxygen.
- Carbon dioxide is removed from the cabin air.
- Cabin air is filtered and removed of any microorganisms.
- Volatile organism traces are removed.
- Cabin air is monitored for nitrogen, oxygen, carbon dioxide, methane, hydrogen and water vapour. Cabin air pressure is controlled.
- Humidity levels are maintained.
- Ventilation is provided to all station modules.

4.2.2 Water Management

Water is essential for any manned mission, especially a permanent settlement. In addition, water is not only necessary for Controlled Ecological Life-Support Systems (CELSS), but also for many other experiments and operations related to human survival, like agricultural programs [27].

As seen in Section 2.3.4, a huge amount of water is predicted to be available on the Moon, and this is one of the key factors for determining the best spot for settlement. However, a number of other questions must be considered when it comes to water. Is it easy to obtain? How does it have to be processed in order to be suitable for drinking? Is it possible to use systems similar to those currently available on the ISS? How much water does a human need? How long would lunar reserves last in the case of re-using them?

First of all, a human needs more or less 3.50 kg of water per day for both drinking and food preparation. Then, most of this water (up to 3 kg) is expelled in urine, sweat, respiration and faeces [58]. If most of this expelled water could be recycled, it is possible to reduce the external amount of water required, which is in fact currently being done on the ISS.

How does the ISS' Water Recovery and Management (WRM) System work? First of all, let us consider that the ideal system would obey a very simple law: input/output. However, it is impossible to obtain this balance in the real world, since the input is a function of the onboard crew, namely their metabolic rates and Sabatier reactions; while the output depends on how much the crew drinks, OGA (Oxygen Generation Assembly) production and payload usage. Although this balance can largely vary from day to day, it is more stable over long-term operations, thus making it easier for logistics operations. In addition to this, it is also important to consider that the WRM on board the ISS is a real system, which means that it is not perfect and other phenomena like clogging or leaking may occur. For instance, the ISS systems tend to clog due to biofilm growing in tanks containing condensate of precipitants when removing water, thus affecting valves, pumps, lines, etc. In addition, leaks commonly occur in seals and during quick disconnects. Seal leaks are usually terminal to the ORU and need to be replaced with proper seals [59]. In summary, the main goal of water management onboard the ISS is to obtain something similar to a closed loop while always considering leaks and other phenomena that make this impossible.

Bearing this in mind, it is time to give an overview of the ISS WRM System and see how it could be transferred to a hypothetical lunar settlement. First of all, it is important to say that the WRM System must ensure that

potable water is available for the crew to drink, their hygiene, oxygen generation, treating urine and other waste, and payloads, as required [60]. To do this, the waste water is collected in the form of condensation, urine, and Sabatier product water and is processed by the Water Recovery System (WRS) [59] to subsequently distribute potable water via the potable bus.

The waste water comes mainly from the Common Cabin Air Assemblies (CCAAs) and the Carbon Dioxide Reduction System, which uses Sabatier technology to produce water from carbon dioxide by means of the Carbon Dioxide Removal Assembly (CDRA). Hydrogen is collected from the electrolysis process of the Oxygen Generation System. In addition, crew urine is collected in the Waste and Hygiene Compartment, then treated with chemicals and water before being delivered to the Urine Processor Assembly (UPA) Here, it is processed and urine distillate is produced, which is then pumped directly to the WPA Waste Water Tank and combined with the previously mentioned sources of waste water. Subsequently, this mixture is processed by the WPA [60].

Once processed by the WRS, potable water is delivered to the potable bus, which is maintained at a pressure of around 230 to 280 kPa. The main systems using the potable bus are the OGS (Oxygen Generation System), WHC (Waste and Hygiene Compartment) and the PWD (Potable Water Dispenser) [59]. A general overview of the WRM architecture is depicted in Figure 4.1, while Figure 4.2 shows the layout of the two WRS racks.

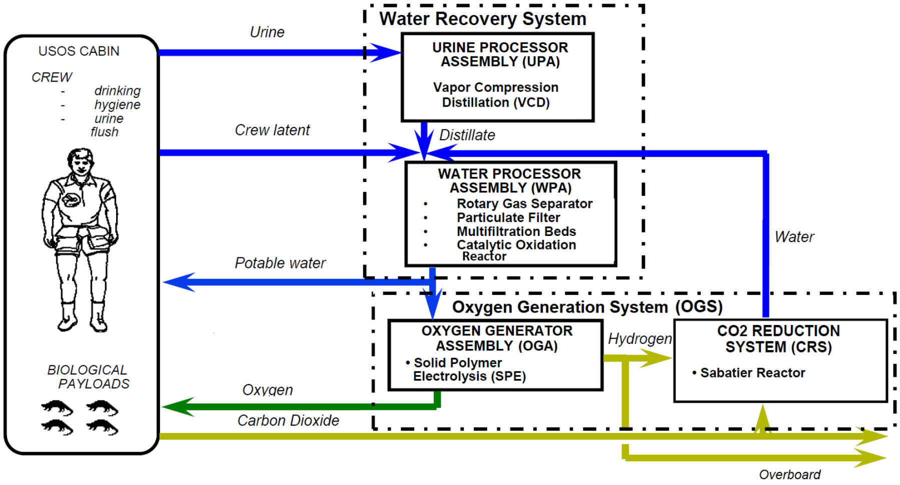


Figure 4.1.
Water Recovery and Management Architecture for the ISS US Segment [60].

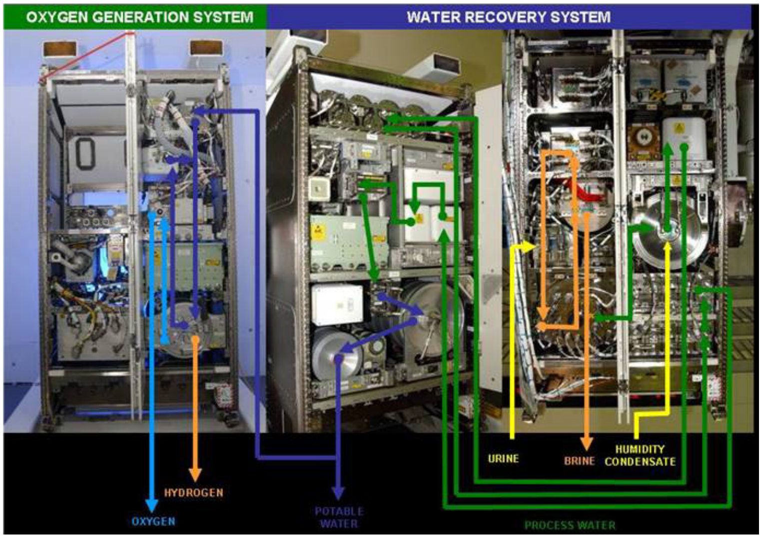


Figure 4.2.
International Space Station Regenerative ECLSS Racks [60].

The functioning of the Water Processor Assembly is as follows. The wastewater coming from the Temperature and Humidity Control System, the UPA and Sabatier product water is temporarily stored in the Waste Water Tank ORU, which is maintained at a pressure of approximately 5.2–15.5 kPa. Then, water is pushed into the Mostly Liquid Separator (MLS), where the gas is removed from the wastewater. After that, water is pumped through the Particle Filter ORU and two Multi-Filtration Beds (MF beds), where inorganic and non-volatile organic contaminants are removed. Following the MF Beds, the processed water goes to the Catalyst Reactor ORU, where any low molecular weight organics not removed by the adsorption process are oxidized by oxygen, elevated temperature, and a catalyst. Finally, the products dissolved by oxidation are removed by the Ion Exchange Bed ORU, which also adds iodine for residual microbial control. Then, the water is stored in the Water Storage Tank and delivered to the potable water bus [60]. The entire process is schematized in Figure 4.3.

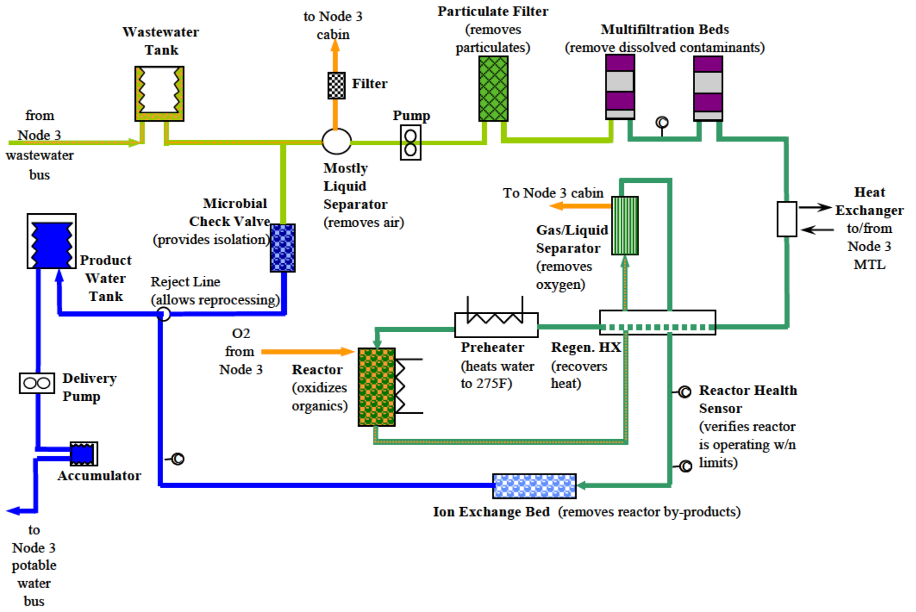


Figure 4.3.
WPA Simplified Schematic [60].

Over years of operations, several lessons have been learned from this system, which is capable of recovering up to 85% of the water on ISS [60]. For instance, the necessity of storing excess water for eventual system failures, water imbalances or the redundancy of critical systems has proven to be a key factor in the design. Universality also plays a role, since the current ECLSS has countlessly different QD sizes and keying that require adapters and hoses for contingency interfaces, and this makes leakages more likely to occur. Finally, system interfaces have proven to be helpful in making it easier for the different systems to interact, and spreadsheets help to predict and manage water systems [59].

How can this all be used on the Moon? To properly answer this question, it is first of all important to consider the similarities and differences between these two environments. In both cases, we are talking about nearly-closed environments requiring an ECLSS, since they are unsuitable for human life. As it is close to Earth, ISS has the advantage of being easier to deliver supplies there. However, being an artificial satellite, its main disadvantage is that it is not possible to build big structures or mine any resources. On the other hand, the Moon is way farther away than the ISS (a 3-day journey, which is still much shorter than a trip to Mars). So, delivering resources there would be more difficult and expensive, but it offers the huge advantage of having its own water supply. The future for long space travel is closely related to the capability of creating a closed loop for water, in which the input equals the output (or, at least, comes close to it). For this reason, any settlement on the Moon must rely on the experience, expertise and knowledge gained from the ISS, since water on the Moon is not an unlimited resource and can be used for other purposes such as rocket fuel. However, its substantial availability allows us to think bigger and start considering other activities like agriculture. In summary, it will be essential to both mine water from the Moon and improve on the reuse of it in order to establish a lunar settlement, because neither bringing it from Earth nor consuming what is already there without reuse are possible.

4.2.3 Atmospheric Control

As explained in Section 2.2.2, the Moon's atmosphere is very different from that of Earth. For this reason, maintaining tight control of an artificial atmosphere is mandatory, since oxygen must be supplied, pressure kept and CO_2 processed.

The Current Atmosphere Management System onboard the ISS handles circulation, air-conditioning, emergency services, monitoring and air pressure.

The circulation segment includes fans (cabin and intermodule), valves, ducting, mufflers and filters. Its main task is to filter impurities from the air and distribute it throughout the whole system. The main challenge for this system is to obtain high-capacity, low-maintenance and quiet fans. However, when considering a lunar settlement, it is mandatory that the filtration and circulation system be able to deal with surface dust.

The air-conditioning segment's tasks are to remove the CO_2 produced by, among other things, astronauts breathing, as well as to remove humidity, help control temperature and recover and supply O_2. The current systems can recover around 50% of O_2 from CO_2 using the Sabatier process. However, efforts are being made to improve this process and increase the amount of oxygen recovered. With respect to the O_2 supply, the system on the ISS uses stored gas, expendable perchlorate candles and electrolysis conducted on H_2O. Using this system on a hypothetical lunar settlement would require some changes. First of all, it would be impossible to evaluate the state of the pre-mounted high pressure tanks, thus work is still being done to facilitate monitoring their pressure while on the truss. This is a necessary modification, since bringing new supplies to the Moon would be more difficult than delivering them to the ISS. In addition, the OGA functioning also presents some issues. The first OGAs failed, and the recently developed Nitrogen/Oxygen Resupply System (NORS) currently in use is coming to the end of its expected lifetime. This is because of the system's complexity, which directly affects its duration and reliability. For this reason, a permanent settlement would be aided by improving this system and making it more reliable and simpler while also giving it the capacity to carry out high pressure electrolysis (over 3600 psia) and scavenging from cabin air, which would optimise the process. It is important to note, however, that the dimensions of a settlement would be much larger than those of the ISS, making redundancy and eventual equipment repairs much easier.

Regarding emergency services, their main purposes concern fires and spills, since the applied technology and human activity make this phenomena very likely to happen. The emergency services on the ISS are capable of detecting fire and suppressing it with inert gases (CO_2 and N_2), then recovering these gases (emergency return, followed by scrubbing and venting the cabin). Finally, these systems also provide a medical response in case of toxic spillage by providing the crew with respirators and O_2 masks. Although this is a very complete system that has worked perfectly for years on the ISS, several improvements could be made. For instance, the fire detection system, which is currently optical, could be improved by introducing some acid or CO_2 detection devices. Long-duration fires and vacuum exposure should also be considered, since it is possible to have other failures occurring simultaneously with the fire. Furthermore, the fire suppression and oxygen recovery processes need to be improved before implementation at the supposed settlement. Recovery should employ smoke eaters, while some procedures and mechanisms for cleaning and recovery should be considered in cases of spillage rather than segmentation and isolation, as this would make reuse of the affected areas possible much sooner.

For all this to work while ensuring that the atmosphere remains in proper conditions, good monitoring is fundamental. Monitoring on the ISS is currently done using a mass spectrometer on the major constituents, while the scientific samples themselves are used for analysing the trace constituents in the different modules. Although this would be basically the same on the Moon, the complexity of the installations would require a more reliable device for the major constituents, since some issues surround the use of a simple mass spectrometer. In addition, it is advisable to prepare the trace constituents of H_2O samples on board using miniaturized front-end equipment, which would obviate the need to rely on scientific samples from different modules. Finally, because the objective is to maintain life on the settlement for periods much greater than six months, extensive and detailed atmospheric microbial control would be essential.

Now that we have covered filtration, oxygen, emergencies and monitoring, the final task of this segment is to detail the proper atmospheric pressure on the ISS, which is kept constant at the same as sea level on Earth. Apart from eventual leakages, some air is always lost when performing an EVA, because the vacuum that is applied before opening the door cannot remove every bit of air. For this reason, regular resupply missions are required to replenish the tanks [58][61][62][63].

After this brief study of atmospheric control on the ISS, we can conclude that it is very similar to what will be needed for a lunar settlement, as it will share some primary features. As already mentioned above, the main differences are the dimensions and distance from Earth, which will greatly hamper resupply and other external missions. On the other hand, because it will be a permanent structure with available nearby resources, a certain degree of maintenance is possible – which is not the case on the ISS. It remains clear, however, that improvements on the current technologies are needed, both on the ISS and for constructing a lunar settlement, especially in regard to the reuse of water and oxygen. This is key for sustainable long-term manned missions.

4.2.4 Radiation

The ISS travels within a Low Earth Orbit (LEO), meaning that it resides within the Van Allen Belt made possible by the Earth's magnetic field. Thus, it is shielded against the majority of harmful radiation from the Sun, galactic cosmic rays, or other sources. Whatever energetic particles do reach the spacecraft, a few millimetres of material such as aluminium in the hull can sufficiently block them further. The levels are low enough that further protection is currently unnecessary, as astronauts are maintained within a safe limit as radiation levels are constantly monitored aboard the station. For safety, mission durations aboard the ISS are kept (fairly) short – typically not extending past a limit of 6 months.

The case of the Moon, however, is different. The Earth's magnetosphere does not extend that far and therefore cannot provide its protective layer to any lunar space station or its occupants. The greater distance also hinders short mission times. Although the Moon is close enough to limit missions to around the six-month mark, this will not be possible when human space exploration ventures outward to other destinations – such as Mars. Due to the lack of any natural layer for protection and increased time in which humans will be exposed to the effects of radiation, proper shielding on any Moon base is a top priority. Any major radiation event – such as a solar flare – could therefore prove fatal to any humans who are not suitably protected [64][65].

If the current solution for radiation shielding on the ISS is not possible (e.g., relying on the magnetosphere and the spacecraft's thin hull), what methods can be used on the Moon? The research is ongoing, but one simple if inelegant solution is to use higher mass structures in the base's hull design. Radiation is blocked by mass, so more mass will block and absorb the energetic particles from reaching humans, instruments, and other sensitive targets inside the structure [66]. While this solution is simple, it is a more expensive option, as all that mass would need to be initially launched into space.

A more efficient radiation protection solution may be found by focusing on how to block the primary particles making up the radiation – protons and neutrons. Hydrogen, due to its similar size, is extremely effective at blocking these particles. Water can therefore be used as a radiation shield because of its high hydrogen content. Thus, keeping any Moon base's reserves of water stored in a layer between the hull and the occupants within could serve to absorb dangerous energetic particles. Other materials incorporating hydrogen have been specifically designed for the purpose of radiation shielding. One such example is HBNN (Hydrogenated Boron Nitrate Nanotubes) which is a strong and stable material.

The hydrogen in it can block neutrons and protons, while the boron is also useful for blocking secondary neutrons. HBNN could be incorporated throughout the lunar base's hull and other structures to form a layer of radiation shielding, and it could even be used in the astronauts' space suits [66].

As previously mentioned, radiation shielding is needed on a lunar base due to the Moon's lack of a natural magnetosphere. However, it is in fact possible to generate a man-made and localised magnetosphere to act as a force field for deflecting and absorbing harmful energetic particles. This approach is still in need of development, due to the current requisite power being prohibitive. Nevertheless, it could certainly prove effective in the future [66].

Finally, the geography of the Moon itself may be utilised as a radiation shield. An analysis of lunar regolith and regolith simulant reveals that the soil's radiation shielding properties are similar to those of aluminium [67]. It also has the benefit of already being present on the Moon and thus not requiring transport from Earth. The regolith can be built up over any Moon base to a significant extent. Alternatively, the base could potentially be built within a crater, using the natural landscape as a shield to reduce the necessary labour requirements. Modest amounts of regolith packed over any base would offer significant protection against Galactic Cosmic Radiation (GCR)– which threatens the long-term health of any potential astronaut. Solar radiation is another significant source of radiation that poses a threat on the Moon. It can be significantly more dangerous, as high energy protons are ejected during major Solar Particle Events (SPE). 5 cm of regolith is capable of stopping protons with energies approaching 100 MeV, while 18 cm of regolith can stop 200 MeV protons [67]. Regolith therefore provides a highly viable option for radiation shielding.

The most likely effective solution for radiation protection of life support systems aboard a lunar base would be to incorporate all of the various protection methods described here. Water shielding may be used throughout the base while HBNN is woven into a large number of structures. It may be inefficient to make the entire hull of the base large in mass, but a radiation "storm shelter" could be constructed: a small section of the base for astronauts or other vital equipment to shelter in during a major SPE. It is also possible to use local resources when creating the mass of the base instead of transporting construction materials, namely by using the lunar regolith as an additional packed layer over the base hull. Localised force fields could also be turned on in the case of such a radiation event.

4.2.5 Waste Management

Trash disposal, recycling and waste management on Earth is currently a major issue; but in space it becomes even more vital. While on Earth we currently have plenty of areas for dumping our rubbish once we are done with it, this is not an infinite resource. No such area is available on a space station, and unwanted materials have to go somewhere.

When it comes to dealing with waste aboard the ISS, the astronauts sort the dry and wet rubbish and package it. When a space vehicle comes to resupply the station, the supplies are switched out for the waste and it is burned up upon re-entry into Earth's atmosphere [68]. While this method serves its purpose, ideally all rubbish would be repurposed in a space environment due to the difficulty in and expense of supplying new materials. The research is ongoing in regard to recycling and repurposing materials. New developments could be incorporated into the current system aboard the ISS, as well as into future exploration missions – such as to the Moon.

One current waste management project under development is the Heat Melt Compactor (HMC), which recovers usable water from compacted waste while converting it into dry, sterilised plastic encapsulated tiles [68]. These tiles could be used as radiation protection or as a building material. This method is beneficial in that the dry waste component is converted into something useful that is as compact as possible (due to the water extraction), as space is finite in a space station environment. Also crucial is the production of water, and this would mean a reduced need for further resupply to the space station as a result of this recycling.

Other methods for waste management being looked into involve converting waste into methane gas, which could potentially be used for propellant or as an energy source. One such example is a Steam Reformer, which utilises steam and oxygen to create a chemical reaction with waste. The by-products of the reaction are hydrogen, carbon dioxide, water and methane. All of these products could then be used in other processes aboard a space station (hydrogen to produce more water, methane as a propellant, etc.) Another technology for creating methane is a Catalytic Wet Air Oxidation Unit, which uses a catalyst in order to decompose polymers [68]. The by-products from this reaction are primarily hydrogen and carbon dioxide, which can also be used for other processes.

While the current process and new developments discussed here are currently intended for the ISS, they are also possible on a lunar base. The HMC can be used in the Moon environment, and it works suitably in the presence of gravity. It also provides the additional benefit of producing tiles for shielding against radiation, which is essential to a lunar base due to the previously mentioned lack of a magnetosphere. This could be combined with the methane-producing methods for creating by-products that are important to the numerous processes necessary on any base. Finally, when repurposing is not an option, a Moon mission can also employ the classic solution that is currently used for waste disposal aboard the ISS. While the Moon is at a greater distance, resupply runs from Earth will still be necessary, and thus waste may still be switched out for burning up upon re-entry.

→ 5

Robotic vs. Human activity

This chapter analyses some of the tasks that should be performed on a lunar base, and it discusses using automated agents that may or may not need some human support. Some of the activities done by robots would need some human input or control. In most of the cases, it is preferable to not rely on direct human oversight, as this would be more expensive and complicated, given the need to have people on site. In other cases, it could also be dangerous for the astronauts.

5.1 Exterior Base Maintenance Tasks

One of the most important tasks on a lunar base is maintenance of the exterior areas and facilities, because these are exposed to the most adverse conditions. Being outside means being subjected to large variations in temperatures, impacts from micro-meteoroids, and dust, all of which could damage some of the electronic devices and mechanical structures exterior to the base.

These tasks would be best accomplished robotically for two main reasons. The first is that the area they cover may be quite large. The second is that the exterior environment is hostile to humans, who would require expensive vessels and suits to survive outside the base. The time spent by an astronaut on EVA represents cost in terms of oxygen and water. Plus, their time is limited, as they would be required to periodically return to the base to refill their tanks and recuperate from their exterior activities.

This would not be so with robots, as they could survive for longer periods without any need for vital supplies like water. Also, they could work continuously and cover greater distances. One example is the task of monitoring the proper functioning of a solar panel farm, which could be quite considerable. Robots could do this without interruption as they continuously scan the panel surfaces in search of damage. They could also clean them of dust and small stones, thus increasing their efficiency.

The same applies to other exterior infrastructures such as antennas and rooves. A robot could patrol the facilities and take pictures for processing by computers and human eyes.

Of course, more serious problems that cannot be handled by a specialised robot would require a human team to visit the site and repair the damage. One intermediate option is using a robot controlled by humans inside the base, which would allow some risky operations to be performed with more intelligence than that of an autonomous robot while minimising the risk to human life. Such could be the case when repairing a fuel tank or something else that could explode.

5.2 Interior Base Maintenance Tasks

The maintenance activities of the base's interior facilities may be quite similar to those performed in scientific environments. However, they also have to take into account several factors of the Moon's environment, all of which could affect the installations and other necessities on a lunar base.

Some of the most significant maintenance tasks that distinguish a lunar base from other research centres are the regular monitoring of various human needs, such as electrical systems, thermal control and running water. Above all, the oxygen supply is a top priority.

Such an infrastructure must be regularly monitored and controlled by equipment whose functionality in case of system failure has been thoroughly checked to within a certain tiny margin of error. The current software that already controls such machinery is able to function 24/7, so it is obviously a better option than humans.

Continuously checking the infrastructure simultaneously allows for regular daily maintenance. However, even if this first-level monitoring can be easily done by automated systems, more thorough maintenance is required on a weekly and monthly basis, and this must be conducted by a small group of people who will also control and maintain the automated equipment in order to ensure their proper functioning.

5.3 Exploration and the Search for Resources

One primary activity necessary to every planetary settlement is the search for new resources. This is crucial for sustaining the base over the long term and/or expanding it. In addition to finding new sources of materials, it is also important to search for new places where facilities can be built, such as new modules, buildings and launch pads.

This activity could be performed autonomously in most cases, as it would initially not require much human control. Because exploration may not always provide relevant information, autonomous robotic vehicles could continuously move through the settlement's surroundings in search of possible materials, energy and natural formations for constructing new buildings, facilities, and mines. These robots would send the gathered information to a central node or back to Earth. After computational analysis, any potentially interesting results could alert human agents for further, more detailed study.

Another reason why this task would be best performed robotically is the expense in resources consumed by humans conducting activities outside the main settlements, as well as the greater danger. Without knowing the characteristics of the area, exploring new environments pose a risk to the physical integrity of the astronauts. Furthermore, using renewable energies like solar panels to fuel autonomous robotic vehicles would allow them to cover great distances without any need to refuel, whereas a human-driven vehicle would require oxygen, water and food for each trip, thus limiting the radius of their activities.

Obviously, when robotic exploration yields positive results, a human would need to travel to the site for visual inspection and a more exhaustive in-situ analysis of the area.

5.4 Extraction of Resources

After having established a good site for a mine or farm, the resources need to be extracted. For that, some sort of facilities will always be needed for generating power and transporting the material from the mine to the base or a processing factory.

For the same reasons explained in the previous subsection, the actual extraction of raw materials should be performed by robots and automated machines. Also, these tasks may require power that cannot be provided by human efforts. For example, drilling a mine can be done by an automated machine, similarly to some excavations on Earth.

As usual, these tasks should be periodically monitored by a human team. Being exterior to the base, the same concerns apply as in Section 5.1.

In some cases, the resource extraction site may be located far from the main base or where the resources are needed. The transport of these materials could be done by robotic vehicles following predefined routes.

5.5 Manufacturing

After establishing a base on the Moon and extracting resources, post-processing will be required to obtain useful materials.

Tools and machinery will be needed for this task, as well as to perform maintenance and create items for the structure or for experiments. Manufacturing would also be key to reducing payloads from Earth to the Moon and, instead, these could be dedicated to scientific cargo, for example.

For these reasons, having a production plant might be worthwhile on the Moon. Such a plant should be as automated as possible, leaving only quality controls for humans to perform. This should be studied during the first stages of the settlement, as the most repetitive and simple tasks would be the first to automate. In time, with more advanced robots and technology, the more complex tasks would also be automated.

It is possible that many of the instruments used on Earth will be useful on the Moon, making a fully automated plant easier on the Moon.

5.6 Moon base science experiments

Some experiments on the lunar base should be carried out to gain some knowledge of the lunar environment and study some phenomenology in Moon conditions. These activities should be done in a specialised laboratory and, in most cases, cannot be automated. Human interaction with certain experiments is crucial, because they need human intelligence to set up the experiment and obtain certain results.

In the same way as on Earth, some tasks can be automated using electronic devices that eliminate the need for scientists to be in charge of all experiments, as in the case of long-term tests.

5.7 Food Processing

One of the most important tasks on the Moon will be to grow and process food, thus making the base autonomous and not as reliant food shipments from Earth. This will also free up payloads for other items.

Food processing on the Moon would consist of growing vegetables, fruits and other plants to process them for food. This is already viable, as agricultural technology has advanced greatly in recent years. From vertical vegetable gardens to plague surveillance with drones, agriculture could be automated on the Moon just as it is done on Earth.

In the first stages of implementation, the vegetable gardens would be small and probably need a lot of monitoring in order to study and assess the most optimal ways to produce food. Once the procedures are established, they can be automated for robots to perform all the gardening.

Processing these foods would consist of cleaning and cooking the vegetables before providing them to the crew ready to eat. Cooking bots are already common in most homes. More automated versions of them could achieve full robotisation of the process.

Livestock farming could be conducted if the settlement is big enough, as it requires more space for animals and processing of the meat, which is more complicated than vegetables because it requires more time, energy and resources. Such an option should be considered only for long-term habitation.

5.8 Health

Keeping track of the crew's health and being able to react in case of a medical emergency on the Moon would be one of the most important tasks for human survival. Despite having information gathered on the ISS, the Moon environment would affect the human body differently and it will be necessary to track and study these changes. The most critical health issues on the station would be nutrition, physical maintenance and emergencies.

For nutrition, each crew member should have a specified diet in order to keep track of the nutrients, vitamins and minerals ingested according to each person's requirements. This task must be coordinated with the production of food on the base. Preparing meals could be performed by a robot that is programmed to know the needs of each person and able to update their status information in concert with the base's food stocks.

No human interaction would be required for physical maintenance either. Nowadays, most gym facilities on Earth provide full tracking of heart rate during exercise. Doing so on the Moon would not be any more difficult.

Finally, a clinic will be necessary, but there would be no need for medical experts in the settlement, as current medical technology is advanced enough to keep track of the crew's health status and provide feedback for instant action, if required. The Moon crew should be trained in basic medical care and be able to perform minor surgeries for quick response in case of emergency.

In all cases, all the gathered data must still be sent to Earth for experts to evaluate and maintain close control in order to ensure that all automated functions are working correctly.

5.9 Housekeeping

This section focuses on the activities for avoiding emergencies and, if one should unfortunately occur, the required infrastructure for solving it. Furthermore, it also studies the activities required for maintaining the base as an operational scientific facility without any issues arising that affect the daily lives of the people working there.

A wide variety of causes for a possible emergency exist, but the most probable on a lunar base would be the malfunction of some systems such as electricity or the oxygen supply. Other problems could involving them breaking down, causing a fire or even exploding, in the worst cases.

To avoid these emergencies, the same automatic equipment that performs the daily maintenance tasks must be able to detect any malfunctioning or irregularity in any of the systems. Moreover, it must be able to communicate this situation immediately to a group of people in charge of the emergency, depending on its type.

If a specific system malfunctions, the incident is automatically communicated to the engineering department the person responsible for coordinating the lunar base occupants, who would then follow the required, pre-established procedures.

Furthermore, in the event of an unfortunate fire or explosion, a specified group of people prepared for these situations would be in charge of the firefighting operations. Robotic equipment and a fire suppression system must be installed throughout the facilities to ease the work of these emergency crews.

In addition to emergencies, housekeeping must also perform other tasks such as residue management. These labours can be performed perfectly by robotic systems specifically programmed for these operations in concert with the regular maintenance carried out by groups of human workers.

5.10 Transport

The dimensions of the base may not be large enough to require an internal transport system. But various settlements that are far apart from each other will need this.

Currently on Earth, a number of self-driving systems are in operation, such as autopiloted Tesla cars and Barcelona's Metro lines L9 and L10. On the Moon, there would be no GPS system guide self-driving cars, but a network of remotely controlled or fully automated trains would be a highly convenient transport solution.

The only drawback to these systems is the infrastructure cost in terms of both money and time, as well as the possible maintenance requirements should they be exposed to the Moon's environment.

Bearing this in mind, the most optimal solution is human driven rovers during the first stages of the Moon base mission. When the settlement is fully operating and the most common routes between modules are established, then the first trains could be implemented. Finally, when their efficiency is proven, they could be fully automated.

5.11 Base Management

As the lunar base a scientific facility where employees work and live together, tasks must be coordinated and delegated in order to ensure proper base operations. This will require a management team.

Although the base's robotic equipment will provide continuous support, the management team would be comprised of the most respected and well-prepared people on the base. They would be responsible for establishing what tasks must be performed, manage possible work and even cohabitation conflicts and, finally, handle most of the delicate decisions taken on the base, such as emergency protocols.

Although this team would be in charge of these base management tasks, its members would also work in their corresponding fields, just as the other workers.

→ 6

Cislunar Travelling

6.1 Going to the Moon

In order to operate the Moon base, a safe, reliable and efficient means of transfer between Earth and Moon should be available for human travel.

From the 1950s up to now, 109 missions to the Moon have been performed, some with success and others not [69]. Six of these missions were able to put humans on the Moon. Therefore, there is no reason why our current capabilities cannot repeat these missions based on all the new knowledge gained in the last fifty years.

6.1.1 Past Missions: The Apollo Program

NASA's Apollo Program was carried out between 1969 and 1972 with the aim of performing manned lunar landings. Apollo 11 was the first to accomplish this mission.

In order to reach the Moon, the Apollo missions used high-thrust rockets to perform a Hohmann Transfer. This is when the spaceship is first put into a parking orbit around the Earth, then a Translunar Injection is performed to enter a Translunar Orbit for getting closer to the Moon. Finally, another velocity injection is required for entering a parking orbit around the Moon [70].

This allowed for a quick transfer to the Moon (3–4 days), but was a very expensive option, as a large part of the spacecraft's mass was dedicated to the propellant needed for the velocity injections.

6.1.2 Future Missions in Development

Some programmes are currently in development for taking humans back to the Moon:

- NASA's EM-1, EM-2 (2022-2022): These missions will perform a fly-by of the Moon to demonstrate the capabilities of the Space Launch System (SLS) and Orion. The first Exploration Mission (EM-1) will serve as testing for Orion and SLS. This uncrewed mission will perform a Distant Retrograde Orbit (DRO). EM-2 will have a crew on board and perform a hybrid free return trajectory [71].

- SpaceX's #DearMoon project (2023): Their goal is to reach the Moon (fly-by) using a reusable launch vehicle "Starship". As a private company, their focus is more commercial and aesthetic than scientific.

- Roscosmos' Federation spacecraft (2025): Their spacecraft will be able to carry up to 4 cosmonauts and cargo to the Moon for autonomous operations over a period of up to 30 days [72].

These missions are planned over the next decade and will be the first modern efforts by humans to return to the Moon. With the exception of Roscosmos, they are fly-bys for testing new technologies to prove that going to the Moon is still viable.

6.1.3 Travelling between the Earth and the Moon Base

After studying past trips to the Moon and future plans for the same, the fastest means to get there is through a Hohmann Transfer. Low-thrust orbits take too much time to travel that distance, and this would cut into useful working time on the Moon base.

Another important aspect is the use of a lander and leaving the main ship orbiting around the Moon, as in the Apollo missions. This makes ship design easier, as different requirements are fulfilled for the journey and the landing. We cover these aspects in the section Returning From the Moon.

6.2 Survival

The Moon is one of the harshest environments humanity has ever encountered. All of the traditional risks that need be considered in hostile conditions on Earth must be considered: access to food and water; shelter from the elements; first aid; and many others. However, all of these risks are taken to their extremes while in space, and additional factors must also be considered.

Water is the most basic of needs associated with maintaining life. Astronauts aboard the ISS drink on average 1.62 litres of water per day [73]. Over the course of a 6-month mission on a lunar base, this equates to approximately 290 litres – or 290kg – of water. Carrying this amount of water from Earth to the Moon for each individual to drink is not feasible, and would be very expensive. Thus, rationing and recycling is key for any lunar mission. Similar methods for water recycling on the ISS may be utilised on the Moon: reclaiming waste water from the fuel cells; from hygiene and washing; from urine; and from condensed humidity in the air [74]. While reclamation is not completely efficient, it allows for minimal loss, and thus water transport to any lunar base can be minimised while maintaining reserves for emergencies.

The food requirements on a Moon base would be fairly similar to those on the ISS, and thus may be addressed in the same way. The volume of food will be minimised via dehydration, and should average about 1.77 kg per day – with 0.8 kg of water being necessary for re-hydration [75]. This value will vary fairly significantly, depending on the individual, but it can be adjusted for specific persons. Food must also be stored correctly, as refrigeration is not currently available in space. One significant way in which food consumption varies on the Moon compared to the ISS is that the Moon has a somewhat significant gravity. There should therefore be no issues with food particulates (salt, pepper, etc.) floating away and clogging air filters or other apparatus [76].

Perhaps the most obvious human need on a lunar base is a breathable atmosphere. Oxygen is a key element that will need to be produced and contained in any living area of the Moon base. Cryogenic tanks may be used to store and transport oxygen to the Moon, although further generation will be required. Oxygen generation can be accomplished via electrolysis – combining water and electrical power to produce hydrogen and oxygen [75]. This is used on the ISS and may also be used on the Moon. The hydrogen by-product from electrolysis is currently expelled from the ISS due to its flammability. On the Moon, however, the Sabatier reaction can be used to combine carbon dioxide and hydrogen to produce water for further use [77]. In this case the by-product of the reaction is methane, which may be expelled or used to generate more energy. The Sabatier reaction is key for long-term space travel, as it both removes carbon dioxide and produces water. However it is not currently in use and, thus, it would also be beneficial to have traditional carbon dioxide scrubbing on the station to avoid dangerous levels.

The air aboard the station can be filtered through zeolite that traps the carbon dioxide (and also water) for later removal. Heat and exposure to the vacuum of space allows reusing the zeolite for further scrubbing. After oxygen is produced by electrolysis, carbon dioxide removed by the Sabatier process and scrubbing, and the removal of dangerous by-products, one additional key aspect remains for increasing the base's atmospheric pressure to that of Earth. Inert nitrogen gas can do this safely. The only concern in this case is removing nitrogen from the bloodstream when doing external activities in order to avoid the bends [3]. Finally, a base on the Moon must face the issue of lunar dust – which may be brought into the Crew Exploration Vehicle and potentially be electrostatically charged. This dust will need to be filtered to ensure that it does not clog up filtration systems, such as those used for carbon dioxide scrubbing. Otherwise, they could cause a short-circuit.

The lunar environment varies widely according to location and with the day/night cycle, which spans 28 days. During the day, temperatures can reach 374K while at night it may drop to as little as 120K [78]. Due to this vast temperature swing – and the duration across which it spans – temperature control is vital for any base to survive. Not only is it impossible for humans to deal with such temperatures, but current sensors and space habitats are also limited to a range of 270K–297K. The precise location of any Moon base would have significant impacts on the exact conditions that must be faced. The greatest variations occur at the Moon's equator – where the base's thermal control would need to maintain temperatures as much as 100K lower than the outside environment. This could be done through conceptual technology such as heat pumps [78] that expel excess heat. During the night cycle, temperatures would need to be up to 150K higher than the exterior environment and heat generation would be necessary. This would be possible using fuel cells that utilise hydrogen and oxygen to produce water and electricity [75]. An additional method for generating power on a Moon base is through solar panels. These could generate power during the long day cycle, stored in batteries, and then used when the base requires additional heating. The final key ingredient for thermal control on a lunar base is effective insulation. For instance, aerogel has very low thermal conductivity and would be ideal for use on the Moon. Multi-layer insulation is also possible, as it is extremely effective for thermal insulation in a vacuum environment and thus suitable for the Moon's extremely thin atmosphere [79].

Without radiation shielding, it would not be possible for humans to survive long-term spaceflight and occupation of the Moon. Although the Van Allen belt around the Earth protects the ISS astronauts from the barrage of high energy solar radiation and galactic cosmic rays, this belt does not extend to the Moon and humans would therefore be at extreme risk – especially if a major solar radiation event occurs during their mission [64][65]. Research into methods for radiation protection is currently ongoing. One less elegant solution is to simply use high-mass structures in the Moon base design. This means more mass for the high energy radiation particles to interact with before they would be able to reach astronauts [66]. However this is inelegant and expensive, as it would initially require launching all the high-mass structures from Earth into space. Protons and neutrons are the particles that cause a large portion of radiation damage, and the most effective way to block them is with an element of a similar size: hydrogen. Water may therefore be used as a radiation shield due to its high hydrogen content, as well as other specifically designed materials such as polyethylene (high in hydrogen) or Hydrogenated Boron Nitrate Nanotubes (HBNN). HBNN is newly developed as well as strong and stable even at high temperatures – meaning it is ideal for structures. Boron also works to block secondary neutrons, and this material has even been woven into space suit fabrics [66]. This therefore represents a feasible solution for surviving radiation exposure on the Moon. In addition to physical protection, force fields are an additional potential method. A relatively small localised electric or magnetic field would provide the base with the same protection from radiation that we experience on Earth. However this technology currently requires large amounts of energy to perform effectively, so it is likely something for future consideration [66].

One final consideration regarding survival on a lunar base concerns medical emergencies. Doctors and hospitals may not be readily available if astronauts become sick while on 6-month missions to the Moon, which is why first aid capabilities must be factored in. Much of the extensive first aid technology aboard the ISS may be re-purposed to function on a Moon base, with a few slight differences that need to be accounted for. The Moon does have some gravity – 1/6 that of Earth – which makes some things easier, such as work-out facilities for astronauts to preserve muscle mass [80]. However, the higher radiation levels on the Moon may degrade pills, which may also simply expire and need to be replaced [80]. All these considerations for astronaut well-being take into account the vastly different environment on the Moon due to low gravity and higher radiation, and this means that the duration of missions should be limited in order to minimise long-term impacts such as bone mass depletion and the multiple negative effects of radiation exposure. A final factor to take into account is that astronaut physical health is not the sole concern. Mental well-being will also need to be constantly monitored by psychologists, as humans are not readily adapted to spending months in a confined space with few people to interact with [81]. If there should arise any medical issues that were beyond the lunar base's capabilities, a means for rapid return to Earth is essential. This will be explored further in the section on Emergency Procedures.

6.3 Returning from the Moon

The Moon is an extreme environment where humans currently cannot stay for long periods of time. In the same way that short stays on the ISS are advisable for astronauts, lunar astronauts should limit their exposure to the Moon's environment. However, given the cost of traveling to the Moon and that certain conditions like gravity are in some ways more similar to Earth than they are on the ISS, astronauts may live there longer than on the ISS.

Nevertheless, a safe system for returning to Earth must be designed and include regular journeys. Return journeys from the Moon could take two different approaches.

The first uses a single spacecraft launched from the Moon's surface to land on Earth in a single journey. Another option uses different spaceships during different phases of the journey.

The first one seems simpler in that it has no intermediate infra-structures and there is no need for astronauts to transfer from one spaceship to another. But the spacecraft for such a journey would be highly complex. This spacecraft should be able to launch from a lunar spaceport, perform manoeuvres to escape Moon orbit and transfer to Earth, then perform the even more difficult procedure of re-entering the Earth's atmosphere and landing safely on the surface.

Given that, a better option might be a two-phase journey using smaller and simpler spacecraft. This method is what we will call the Double-Spaceship method.

This Double-Spaceship method consists of employing a large spaceship called an E2M vehicle (Earth to Moon) to cover the journeys from Earth to Moon and Moon to Earth. A smaller ship called MooTrans (Moon Transport) will transport the astronauts and cargo from E2M to the Moon's surface. MooTrans will land and stay at a lunarport next to the settlement until it is launched again.

This technique also provides two options for the intermediate step between the two vehicles. An orbiting Moon station could be used for docking and transferring the human cargo from one to the other; or, instead, a simpler docking procedure could be performed between E2M and MooTrans while in low orbit around the Moon.

The second approach seems easier in that there is no need to build and maintain an orbital space station around the Moon. But it also imposes some requirements on both spacecraft. For example, both will need to be ready at the time of transfer. In the case of returning from the Moon, the E2M should be ready and orbiting the Moon when MooTrans launches from the lunar surface. This means that, if there is any problem during the E2M Moon orbital insertion or some other difficulty impeding humans from boarding E2M, this would mean a delay in the launch, which could be a serious problem in an emergency.

In this particular, a Moon-orbiting station with the ability to maintain humans for at least some weeks would be a better option. This is because MooTrans could launch to that station and dock with the E2M vehicle during nominal conditions, thus allowing the astronauts to transfer from one vehicle to another and return to Earth.

6.3.1 Lunarport

In order to land and launch a spaceship on the Moon's surface, a lunarport is required.

The requirements of this lunarport are the following:

- The lunarport terrain must be stable and secure in order to ensure the stability and safety of the spacecraft.
- The lunarport must have a means for attaching the spacecraft to the landing pad.

- The lunarport must include a flame trench. This would be smaller than one on Earth because the Moon's lower gravity eliminates the need for a powerful rocket engine.

- The ground material of the lunarport must be thick enough to ensure thermal, chemical and mechanical resistance.

- The lunarport must include ground markers and beacons.

- The lunarport must be painted with radar reflective paint in order to improve landing precision.

- The lunarport must include restricted safety areas.

- The lunarport must have road access to the base.

- The lunarport infrastructure must facilitate regulated safety procedures during launch and landing.

- The lunarport must provide or be easily accessed by the necessary safety services such as firefighters and remote-controlled pressurised water cannons.

- The lunarport must provide Foreign Objects Debris (FOD) prevention protections like walls and procedures for avoiding this, such as being able to clean the landing site. FOD could damage the lunarport infrastructure or the spacecraft itself.

- The lunarport must provide a power source on the ground that can supply the spacecraft with electricity at the right frequency.

- The lunarport must be equipped with cameras, sensors and radar to monitor the spacecraft while it lands. The readings from this equipment must also be shared with the spacecraft cabin to ensure proper coordination during launch and landing procedures.

- The lunarport must provide the required communications equipment to guarantee coordination between the spacecraft cabin and the lunarport.

- The lunarport must be equipped with a Command and Control Center in charge of monitoring and communication during launch and landing operations.

- The lunarport must provide all necessary spacecraft services such as handling, maintenance and refuelling.

- The lunarport must provide the required passenger services such as handling, as well as medical and psychological attention.

6.4 Safety Plan

Emergency evacuation procedures would be essential on the Moon, as the safety of the lunar astronaut inhabitants is the number one priority. This section will discuss the aspects of a lunar laboratory evacuation procedure, with some reference to similar, existing procedures aboard the ISS.

6.4.1 ISS Evacuation Procedures Overview

Vehicle

The vehicle currently used for evacuation on the ISS is a Soyuz spacecraft, which is used in rotation every 6 months. Other proposals for a CRV (Crew Return Vehicle) have been put forth, such as NASA's Station Crew Return Alternative Module (SCRAM), HL-20 PLS, and X-38, as well as some other European proposals. In the end, the Soyuz was the cheapest and most reliable vehicle, which led to its choice as an evacuation vehicle. It can carry three astronauts on board at a time [82].

Emergency Procedures and Checklists

Emergency procedures are put in place to avoid evacuation of the space station, which has been considered only a few times: after the space shuttle Columbia crashed (2003); after 3 consistent resupply mission failures (CRS Orb-3 2014, ISS-59P 2015, and CRS SpX-7)[83]; and after a Soyuz launch failure (2018). The only other procedure for crew evacuation is during imminent danger from space debris, in which the crew stands by in the Soyuz capsule until the danger has passed. Evacuation is considered as a last resort.

The procedure list is published under the title *International Space Station Complex Operations Emergency Procedures: All Expedition Flights and International Space Station Emergency Operations*. Here, all procedures are described in checklists for each observable malfunction. After an alarm sounds, the crew follows the checklist to solve specific emergencies. The checklists are divided into system and subsystem groups, with each alarm indicating the priorities regarding the severity of emergency. These procedures are put in place to resolve such situations and avoid evacuation [84] [85].

If an evacuation order is issued, the crew proceeds to the Soyuz spacecraft and prepares for flight to Earth just as they do for a regular flight.

6.4.2 Moon Evacuation Procedures

Vehicle

The ISS evacuation solution (Soyuz) is not suitable for the Moon, which will require a differently designed vehicle. One possible emergency escape vehicle for the Moon would be similar to the lunar ascent modules used in the Apollo missions. In the case of ascending, a secondary concern will be lunar dust surface contamination or possible damage to engines, while the primary concern is successful evacuation of the crew. It must be decided whether to use a secondary spacecraft only for evacuation or the same spacecraft that runs the resupply missions (similarly to how Soyuz is used on the ISS). The best solution will always be to have two vehicles ready for flight.

The main decision will be based on three concepts:

1. Moon surface – Moon orbit vehicle
2. Moon surface – Earth orbit vehicle
3. Moon surface – Earth surface vehicle

The safest procedure would employ one vehicle to quickly ascend to lunar orbit and dock with a gateway station. For safety during the laboratory and habitation construction phases, the vehicle should be locked in orbit before commencing construction on the lunar surface. Another vehicle able to return to the Earth's surface should be docked with the gateway module and ready to transport the crew back to Earth.

Evacuation Procedure

The evacuation procedure should be as follows:

1. The crew must put on their pressurized flight suits.
2. The crew must immediately proceed to the emergency lunarport.
3. The crew must have constant communication with their supervisors and with each other via the emergency communications channel.
4. In case of medical injury or problem, the crew member must report to the flight surgeon and continue on to the evacuation vehicle. The medical problem will be addressed after successful evacuation.
5. In case of serious injury to a crew member (such as loss of consciousness), the crew commander should decide whether to continue evacuation or help the crew member.
6. It should be decided whether to use the evacuation vehicle (to lunar orbit) or the normal vehicle (to the Earth's surface), then proceed to that vehicle.
7. The flight should follow the emergency flight procedures within the shortest time possible.

6.4.3 Reasons for Evacuation

Critical situations which may force an immediate evacuation:

1. An incoming meteorite may collide with the Moon. A foreign object surveillance station must take responsibility for this risk.

2. Constant solar radiation bursts from the Sun expose the Moon but can be mitigated by protective measures. However, these bursts are unpredictable and cause unforeseen problems.

3. Leakage and depressurisation in the settlement may result in an uninhabitable environment.

4. Sparks or leakage of combustible substances leading to uncontrollable fire.

5. Severe medical condition (life threatening), which cannot be dealt with during a catastrophic event.

6. Failure of a routine resupply mission to the Moon resulting in dangerously low stocks of necessities.

7. Events leading to the damage of life support systems in the settlement.

8. Irregular maintenance and lack of attention to the internal structure of the settlement, resulting in non-reparable structure failure.

9. Leakage of poisonous gases.

10. Other unpredictable reasons.

→ 7

A Lunar Base

The initial phase of establishing a base on the Moon will involve short missions of no more than one week. A lunar infrastructure will be established during these short missions, capable of supporting increasingly longer missions. Basic operations such as construction, life support activities and communications system development are crucial to the project's success.

7.1 Structure of the Base

Concepts for habitation modules have been in development for decades, some of which consider using the inhospitable lunar environment's resources that can help sustain human life on the Moon. Engineers designing these habitations seek to harness the Moon's natural resources.

Locating the proposed lunar base is a very important part of the design process. A vast number of factors must be considered, such as geography, geology, temperature, atmosphere, radiation, meteoroids, lunar dust, seismic activities and many more. All of these indicate that the ideal location for such a base would be on either of the Moon's poles. There are six main reasons for locating a habitable base at the lunar poles, in particular the south pole:

- There is an abundance of sunlight the poles, thus reducing the need for huge energy storage devices [86].
- Temperature varies significantly less at the poles compared to the equator. At the poles, the temperature may vary by 50° C in a year; whereas the equatorial temperature may vary by 250° C per year [86].

- Evidence of hydrogen has been found at the south pole of the Moon. Of course, hydrogen is an important component in most current propulsion systems [86].

- The poles are inherently interesting for scientific experiments, due to their geological complexity [86].

- Transporting humans and equipment to the south pole is cheaper, as less fuel is required [86].

- Lastly, the region of the south pole in shadow is much larger than the shadowed region at the north pole. The south pole is interesting to scientists because sunlight does not reach the bottom of the craters. Water ice has been found to occur in permanently shadowed regions around the south pole. In addition, there are volatile compounds that could serve as extremely valuable resources for future explorations [87].

The Shackleton Crater at the Moon's south pole has long been a contender for hosting a lunar outpost. It is roughly 19 km wide, 4.2 km deep, and illuminated by sunlight for a substantial part of the day. Thus, solar panels would be sufficient for meeting the outpost's electricity supply demands [86].

Unmanned cargo missions to the Shackleton Crater could land large habitats before human arrival in order to reduce the "set-up" times. To reduce structural stress on launch vehicles, a number of habitats would be preferable to a single, extremely large habitat. The four main criteria for habitat design are: habitable volume; radiation protection; weight; and shell thickness. A trade-off study of the design criteria found the optimal habitation to have a "tunnel, hatch area, cylinder, end dome", with 158 m^3 total volume and 92.1 m^3 of habitable volume [88].

7.2 Experiments Carried Out on the International Space Station (ISS)

This section discusses the construction of a base on the Moon's surface. Regarding its scientific relevance, one may ask: Can we perform the same experiments already done on the ISS and add more to those results? Or could the money and resources be better spent on another orbital laboratory?

A scientific base on the Moon would provide the opportunity to study the Moon itself in greater detail than before, hopefully giving insights into the formation of the universe, and it would also allow for far more experiments to be conducted simultaneously. However, in this section we are going to focus on the differences between a lunar laboratory and the ISS.

First, we discuss the pros and cons of every experiment that has been performed on the ISS [89] in order to assess the feasibility of repeating them on a lunar base. Due to the vast number of experiments, they have been divided into 6 categories: Biology and Biotechnology; Earth and Space Science; Education and Cultural Activities; Human Research; Physical Science; and Technology Development and Demonstration.

7.2.1 Astrobiology

Astrobiology: Extremophiles, Cell biology and Microbiology

The main goal of this section is to identify how the environment on the Moon affects life. Since the Moon is located outside the Van Allen belt, its radiation profile is different from that of the ISS. Our focus centres on: the radiation profile of the Moon; extremophile bacteria from the Earth that has actually survived on the Moon; and cellular response to radiation, especially the effects of radiation on DNA. Finally, we provide an overview of tardigrades and their importance for a lunar settlement.

Extremophiles

First, it is necessary to define what an extremophile is. Extremophiles are a group of microorganisms that belong to all three domains of life (Archaea, Bacteria and Eukarya). They are found on Earth in habitats considered extreme from an anthropocentric point of view, which are characterised by harsh conditions of temperature, pH, salinity, pressure and radiation [90].

Although surviving in space without any technological help is impossible for humans, some kinds of microbes have developed an incredible toolkit of survival tricks over billions of years evolving on Earth. From them, we may be able to extrapolate tricks for overcoming the harshness of space travel. A good example could be the lesser known passenger of the Apollo missions, a common bacteria known as *Streptococcus mitis*. This was the only known survivor of unprotected space travel [91] until tardigrades were experimented on in 2007. This microbe survived for nearly three years without nutrients while exposed to radiation and harsh space conditions. For several years, it was not possible to understand how a creature like this managed to counteract vacuum, boiling temperatures, burning radiation, and crushing pressures, at least not with the technology of the time. However, the recent biological revolution may change our understanding of the bacteria genome, which has advanced dramatically since 1995 [92].

In November 1969, the Surveyor 3 spacecraft's microorganisms were recovered from inside the camera that the Apollo 12 crew brought back to Earth under sterile conditions. The 50–100 organisms survived launch, space vacuum, three years of radiation exposure, deep-freezing at an average temperature of only 20 degrees above absolute zero, and no nutrients, water or energy source (The United States landed 5 Surveyors on the Moon; Surveyor 3 was the only one visited by any of the six Apollo landings. No other life forms were found in the soil samples retrieved by the Apollo missions or by two Soviet unmanned sampling missions, although amino acids – not necessarily of biological origin – were found in soil retrieved by the Apollo astronauts [91]). How this happened still partially remains a mystery, since it was not until 1998 that the first entire microbial genome was deciphered. Since then, scientific advances in these fields have occurred rapidly, and this could especially have implications in medicine [92].

The best way to understand how bacteria may have this surprisingly amazing capacity for adaptation is to consider the conditions of our own planet when bacteria first colonised it: scarce oxygen and an ozone layer still in formation. In some ways, they were already space travellers, by our current standards, since the conditions on Earth were much different than nowadays. And these conditions still exist here in some ways: bacteria have been recovered from significant depths in the Earth's crust (high pressures); from deep-sea hydrothermal vents and oil reservoirs a mile underground (heat); and even from the interior of operational nuclear reactors (radiation) [93]. This kind of microbe is capable of living in extreme conditions and taking its capacity for survival to the edge of all known possibilities, which is why these life forms are called extremophiles, and they constitute our main hope for understanding life in space.

Thus, the next logical question: Is there any way to find similar forms of life on other planets? The answer is yes. The presence of polycyclic aromatic hydrocarbon (PAH) is considered to be an indication of the presence of life, and the search for this kind of material and its evolution in different space conditions is one of NASA's main biology research goals [89].

Finally, it should also be said that – although the official version of microbes on the Moon is the one explained above – some theories posit that these bacteria were just contamination from the Apollo 12 crew and a matter of poor space probe hygiene [94].

However, if it is true that a colony of *Streptococcus mitis* survived on the Moon, how can it be useful for space exploration and human survival? What is on the agenda and what has already been done? What advantages would a laboratory on the Moon have that aboard the ISS does not? How has the study of the genome changed the way we understand bacteria? These are some of the questions that will be answered below.

Although most of studies have focused on Mars, the obtained data can be easily applied to the Moon. Some experiments like the one carried out in [90] have shown that not all extremophilic strains present the same behaviour under the same conditions. For instance, while all the tested specimens indicated good resistance to temperature variations in space, irradiation with UV at 254 nm slightly affected the growth of some of them (*Sulfolobus solfataricus, Haloterrigena hispanica and Geobacillus thermantarcticus*). Finally, exposure to simulated Mars conditions showed that only *Haloterrigena hispanica* and *Geobacillus thermantarcticus* were resistant to desiccation and low pressure.

With a more detailed breakdown of the results obtained in [90], some interesting conclusions may be drawn in regard to a hypothetical lunar laboratory and future settlement. Of particular interest are those about the effects of radiation.

The experiment described in [90] clearly shows that UVC radiation is lethal for the microbial growth of extremophiles. For the majority of tested species, growth decreased to about the 50% in a matter of hours. Also, desiccation and low pressure also have large effects. Although it has been proven that extremophiles may survive in space conditions, it is also true that not all of them are capable of doing so, and the family to which they belong may play a significant role. Therefore, it is crucial to further study the genome of the bacteria to better understand the mechanisms that ensure their survival and why some specimens adapt better than others. In addition, because it is really difficult to recreate the exact same lunar conditions on Earth and on the ISS (full radiation spectrum, low pressure and temperature changes, all at the same time), this could be interesting research conducted on the Moon.

Although in [90] it was proven that the three domains of life (*Archaea*, *Bacteria* and *Eukarya*) to which extremophiles belong were suitable candidates for testing the survival of microorganisms in space, some further research has been conducted on eukaryotic extremophiles, in this case the *Circinaria gyrosa*. Following the trend of Mars, [95] present a study that tests the survival capacity of a eukaryotic extremophile. This experiment in Madrid's "Planetary Atmospheres and Surfaces Chamber" is also interesting because it aims to create a model test that is applicable to other microorganisms. This type of lichen was chosen because of its proven capacity for colonising the most extreme weathers on Earth (both cold and hot deserts). In addition, previous experiments were conducted in spaceflight – Biopan-5 (FotonM2, 2005) and Biopan-6 (FotonM3,2007) – and on the ISS in the LIFE mission on Expose-E. Ground-based experiments have also shown that lichens, bacterial colonies, meristematic black fungi and endolithic communities are able to survive and reactivate their metabolism after exposure to space. Post-flight analysis has also found a rapid recovery of biological activity [95].

In the experiment done in [95], which aimed to cross-check the data from previous experiments, the researchers tested combinations of Martian atmosphere and surface UV climate conditions as well as LEO vacuum conditions on lichens. A significant decrease in lichen activity was found after exposures of 120 h. The most important result was that: in spite of having no protection, these extremophiles were not affected by unfiltered solar UV radiation, which is the most deleterious radiation in space because it is directly absorbed by DNA.

This data, when taken together with other experiments finding no significant decrease in the vitality of tested organisms after exposures of 22 days under Mars-like conditions, leads researchers to think it is possibly the more general adaptation of lichens (aspoikilohydrous organisms) that allows them to survive unsuitable environmental conditions. Their ability to enter an ametabolic state is referred to as anabiosis, cryptobiosis or, more specifically, anhydrobiosis. As unfavourable environmental conditions (high insulation levels, temperature extremes) are often correlated to drought, anhydrobiosis might be interpreted as a stress-avoiding desiccation strategy. A combination of both anhydrobiosis and morphological–anatomical adaptations might explain why C. gyrosa resists simulated Mars and space conditions.

In summary, the general results obtained by different studies reinforce the plausibility of the hypothesis of Lithopanspermia. At the same time, they suggest that extremophiles may be perfect candidates not for finding life in space, but also for carrying life outside of the Earth. However, the available data from experiments is not sufficient for making any general assumptions, due to the fact that the timescale used is not comparable. Therefore, long-term studies are needed to demonstrate that both Lithopanspermia and possible Earth microorganisms can survive outside of Earth conditions. One may ask, then: Is it necessary to build a permanent settlement on the Moon to prove this? Or are facilities like EXPOSE-E enough to obtain irrefutable proof?

Current research on extremophiles on the ISS, according to [89], focuses mainly on a unique microbial biotype. The station has been continuously inhabited for over 15 years, with the particularity that it has not been influenced by any other surrounding biological environment, only by the arrival and exit of crew members, supplies and technical items. Adding this to the environmental conditions (high radiation impact, low nutrient levels, and microgravity), the investigations conducted aboard the ISS seek to better understand the contributions of Archaea and bacteria to microflora aboard the ISS.

More specifically, the experimental goals and detailed objectives of the extremophile investigations on the ISS are [96]:

- Presence and distribution: isolation and characterisation of Archaea and extremophile bacteria by sampling from selected locations inside the ISS;

- Adaptation and evolution: assess changes in Archaea and extremophile bacteria over a period of at least one ISS double increment (6 months).

- Similarities and differences: compare the populations of Archaea and extremophile bacteria on the ISS with those of spacecraft clean rooms and visiting vehicles.

With these experiments, scientists aim to understand how the interior environments of space vehicles evolve over time in order to properly plan long-term space travel. Therefore, because microbes play a critical role in nutrient cycling and may pose health risks, a better understanding of microbial communities aboard space stations will help identify the risks and potential benefits of these microscopic agents.

These experiments (done by analysing 8–12-year-old dust samples from the Russian ISS) have used next-generation sequencing (NGS) and focused on the long-term surviving portion of the microbial community. After analysing the extreme tolerance of these cultivable microbial samples to desiccation, heat-shock, and clinically relevant antibiotics, the obtained data may then be compared with that available from the US American ISS dust microbiome [97].

This study has revealed that most of the isolated species exhibited robust resistance against heat-shock and clinically relevant antibiotics. Targeting Next Generation Sequencing on the microbial 16S rRNA and archaeal 16S rRNA genes showed signatures of human-associated microorganisms (*Corynebacterium*, *Staphylococcus*, *Coprococcus* etc.) and specifically adapted extremotolerant microorganisms. Aside from the bacteria, the archaeal signatures detected in high abundance were striking [97].

This information, together with the already known fact that some microorganisms have profound resistance to the presence of Archaea on board, led to scientists being shocked to find that the microbial community on the Russian segment dust samples was different from the recently reported US American ISS microbiotia. This finding means that small differences in the environment may cause the microbiotia to evolve differently or, at least, may affect which specimens survive and which do not.

The scientists conducting this study tried to find out why this happened. They also wanted to gather information on which genes might be essential for adaption to this extreme environment. Although scientists did not follow a metagenomics approach to assess the entire set of functional genes, they obtained 6558 predicted single genes and 281 pathways (KEGG3 level). They then focused on which predicted genes and pathways were responsible for antibiotic synthesis/resistance, transporters in general, resistance in general (e.g., resistance against metals and their ability to sporulate), after which they compared the individual relative abundances throughout all samples.

In general, genes encoded for resistance and adaption were predicted to be equally distributed throughout all samples. Those in silicon-based predictions do not necessarily reflect the actual gene pool and need to be verified experimentally in future work.

This study revealed different strategies among different specimens surviving for 8–12 years aboard the ISS. Desiccation resistance was achieved by means of spore-forming or optimised DNA repair mechanisms. However, the origin of the bacterial isolates remains unknown, but many of them have already been detected on the ISS, in spacecraft clean rooms, or are typical human-associated microorganisms; so they were probably introduced by humans.

The origin of the halophile isolate *Salinibacillus* is very unclear. It has not been detected on board the ISS or in spacecraft assembly clean rooms before; nor is it a typical human-associated bacterium. However, it has recently been detected in human stool, although the authors suspect it may be erroneously classified [97].

Another conclusion drawn from the experiments carried out onboard the ISS is that all spore-forming isolates can survive heat-shock, while most of the non-spore-forming cannot. Also, all the isolates were extremely resistant to antibiotics. However, despite the fact that elevated virulence and antimicrobial resistance has been found among some of these microorganisms, antibiotics have been tested on them and found to be useful in treating infections onboard. For this reason, the authors state that the ISS is and has always been a safe workspace. Although the results need to be reconfirmed with novel microbial isolates, they are a good starting point for planning future habitats on the Moon [97].

Two other sets of extremophile experiments currently being carried out on the ISS are the "EXPOSE-R2-BIOlogy and Mars EXperiment" and the "STaARS-iFUNGUS". The first one measures the extent to which terrestrial organisms can survive in extreme environments like Martian or lunar conditions. It also analyses the interaction between extremophiles and selected materials (including varieties of Moon and Mars analogues). The BIOMEX results are being used to build a database of biological markers to help in the search for existing or extinct life on future space missions to Mars or elsewhere. They will also provide information on the chances for survival during a "natural" trip in space (according to the panspermia theory) [98].

The second one, "STaARS-iFUNGUS", cultures a rare type of fungus in the microgravity environment of space in order to search for new antibiotics. The fungus Penicillium chrysogenum differs from other fungi because it comes from deep in the Earth's subsurface and shows potential as a source for new antibacterial compounds. The STaARS-iFUNGUS experiment transports frozen samples of fungal spores to the ISS, grows the fungus in different nutrient mixtures over different intervals, refreezes the samples and then returns them to Earth, where scientists examine how they grew and what chemicals they produced [99]. This experiment is much more focused on the use of microgravity and the creation of new materials and products rather than the study of the evolution of life and resistance to radiation. So, although a similar experiment could be carried out on the Moon, its results would be complementary and, despite being related, would constitute two different fields of investigation.

In conclusion, investigations on extremophiles and their capacity to adapt to extreme conditions have two goals: deeper understanding and decoding of microbial DNA on Earth in order to identify how these adaptations occur; and conducting Mars-like or lunar-like simulations on Earth to obtain extra data points.

With all this information it should be possible to predict which ways of life would survive on the Moon and which would not, as well as possible threats to human health. However, as the idea is to create a permanent settlement, there is always some level of uncertainty and – as new discoveries were made when ISS' dust was analysed – no doubt studies on the Moon will add extra knowledge.

Tardigrades

Apart from extremophiles, the phylum tardigrade is another interesting organism being studied on the ISS and that is a key factor for future lunar settlements.

The tardigrade (water bear) is the model organism for studying biological survival under the most extreme environmental stress conditions on Earth and in space. The project is called "Using Water Bears to Identify Biological Countermeasures to Stress During Multi-generational" (Cell Science-04), and its objective is to characterise the molecular biology of short-term and multi-generational survival in the space environment by identifying the genes for adaptation and survival in high-stress environments. The findings from this study can be applied to understanding the stress factors and their countermeasures for humans in the space environment [100].

As this field of investigation is closely related to human survival in space, it is needed for filling in knowledge gaps on the impact of space-induced stress on health and performance. It will identify the genes involved in the stress response and the mechanisms that govern or modulate it. It informs us how individual tissues are affected, how the tissue's response interacts with other physiological systems in the body and, finally, effective countermeasures for controlling stress.

The three aims of these experiments are: identify changes in water bear gene expression across multiple generations under conditions experienced on the ISS; distinguish changes in gene expression induced by spaceflight from those that are general responses to stress; and perform functional experiments to test the necessity of candidate genes in mediating tolerance of long-term spaceflight [100].

While these experiments help us understand how tardigrades (and thus humans) behave and evolve during long-term spaceflights, the data collected – although useful – will not be sufficient for predicting their evolution on the Moon, since only lunar exposure can give this information.

Regarding current investigations on Earth and their possible future applications for space exploration, the scientists in [101] demonstrated that a DNA-associating protein unique to the tardigrade may suppress X-ray-induced DNA damage by ~40% and improve radiotolerance. These findings indicate that tardigrade-unique proteins to tolerance could prove to be a bountiful source of new protection genes and mechanisms.

Lunar Greenhouse

To establish human settlements, such as on the Moon, for human exploration beyond the Earth, it is necessary to develop structures that allow plants to grow.

In this way, fresh food can be produced without continuous resupply missions from Earth, which will be very expensive and, in addition, not allow for shipment of perishable food (i.e., fruit, vegetables, etc.).

Structures will be necessary for sheltering vegetable systems from extreme lunar conditions, such as the high radiation, extreme temperatures, and unfavourable light. Greenhouse structures allow for precise control of certain climatic parameters that are key for plant growth. They can increase the module's interior temperature by retaining the incident solar radiation or by controlling the ventilation, lighting and air composition. These properties make the greenhouses indispensable tools for a long-term human settlement.

The environmental differences between the Earth and lunar surfaces are clear: different gravity, absence of water, extreme temperatures, exposure to radiation and different lighting conditions. These would affect the development, growth and metabolism of plants. These effects have been studied for years onboard the ISS by growing vegetables in microgravity in the ADVanced AStroCulture (ADVASC) plant growth unit [102], the Veggie Plant growth system [103], and the Closed Ecological Life-Support System [104], among others. These experiments have found hypoxia problems caused by the lack of convection in space, which has a direct impact on the protein growth of seeds [102].

Based on these studies, greenhouse prototypes have been developed, such as the Lunar Greenhouse LGH prototype built at the University of Arizona [105]. This prototype is based on hydroponic crop production in a lightweight membrane, as defined by Giacomelli [106]. Furthermore, as in the conventional greenhouse modules, the prototype incorporates an air control system (for re-circulating air and controlling humidity and temperature), a lighting system (for providing artificial light to complement the solar incident radiation) and a temperature control system. This unit also includes an automatic nutrition system using a nutrient water solution, pumps and distribution plumbing.

Astrobiology Experiments on the ISS

- Cell Biology
    - PROS: All the experiments carried out aboard the ISS can be done on the Moon. However, when it comes to cellular growth and tumour evolution, data collected at a settlement site may be more useful since it would be closer to practical applications. In addition, some experiments like those on fullerenes and other organic matter may help us better understand the evolution of life in the universe because they will be more realistic when done on an actual planetary body.
    - CONS: Since science already knows the effects of microgravity, some experiments (e.g., on cartilage and muscular cell growth) would not offer new information but only provide commercial and industrial appli-

cations. This is especially true for cartilage, as it may be that low gravity does not allow it to grow the same as on Earth.

- Microbiology
  - PROS: Humans always carry microorganisms with them, so knowledge of their behaviour in different environments is needed, especially those where humans will live for a long time. Therefore, it is necessary to evaluate whether the following phenomena occur in a lunar environment: symbiotic relationships between plants and certain bacteria that allow both to grow; if oxygen-producing cyanobacteria living in terrestrial water can also autonomously produce oxygen while living on the Moon; and how bacteria living in human digestive tracts vary their behaviour after a long time on the Moon. Although some data has been gathered from Earth and the ISS, more is needed for creating bio-regenerative life support systems and ensuring the appropriate microbial equilibrium, both of which will contribute to the success of a long-term space mission.
  - CONS: None. For the success of a human settlement on another planetary body, it is essential to conduct microbiology experiments on the Moon.
- Vaccines
  - PROS: Because microgravity conditions have been proven to affect vaccine performance, more knowledge is needed if humans are on the Moon for any extended period of time (or even their whole lives, some day). It may be necessary to adjust their components and possibly improve their performance.
  - CONS: If there are no intentions for humans to take vaccines on the Moon, data collected on the ISS is enough for a scientific understanding of how outer space affects vaccines.

7.2.2 Biology Experiments on the ISS

No permanent settlement living outside our planet can survive without understanding how biological systems behave beyond Earth. Several ISS experiments have been conducted over recent years on reproduction, cell growth and macromolecular crystal growth. This section presents the main features of these experiments and a brief summary of how they would be different on the Moon.

- Animal Biology
  - PROS: Research on animal biology helps us understand the effects of spaceflight and long stays in extra-terrestrial conditions (low gravi-

ty, high radiation exposure, etc.), particularly in terms of the development, metabolism and reproduction of vertebrates and invertebrate. Experiments on radiation exposure are also possible on the Moon. Furthermore, Moon surface settlements can be studied for the amount of protection they offer when comparing the results from the same experiments on the ISS.

- CONS: Some investigations focus on microgravity's effects on muscle, bone, and tissue regeneration, as well as on the degradation of vascular, lymphatic and immune systems. Since gravity on the Moon is noticeably greater than it is on the ISS, the results obtained will differ. Although they will provide more information, it will be outside the framework of microgravity conditions.

– Plant Biology

- PROS: Researches on plant biology studies how spaceflight affects the ability of plants to grow and thrive. The Moon environment also offers low gravity and radiation exposure, which will allow further study of plant–microbe interactions in these conditions and provide a source of fresh food for human settlements.

- CONS: None. The investigation of plants and their development in a space environment is crucial for any human settlement on an extraterrestrial body such as the Moon, Mars, or other. As mentioned above, the gravity conditions differ from those on the ISS.

– Reproduction and Development

- PROS: If we are to colonise other planets, it is necessary to know how reproduction occurs in space. We currently do not know how differently males and females are affected, nor whether there is any difference between a birth on Earth or in space. Human births in outer space and how different generations will affected is the next logical step in this direction.

- CONS: Though several tests have already been done, the first mammal birth in space has not yet occurred. Such experiments are controversial for sociological, ethical, and political reasons .

7.2.3 Space Science

The workings of space have been a subject of intrigue for centuries: how stars produce energy; how black holes work; and how galaxies are created, just to name a few. After studying these issues from Earth, scientists took the research to orbit aboard the ISS as soon as the chance presented itself, hoping to find different answers. Even more and a greater variety of results can be obtained from the Moon, where there is no interference from the magnetosphere and gravity is much lower, although it is not the microgravity conditions found on the ISS.

One may wonder which of the common space science research areas like astrophysics, heliophysics and Earth remote sensing can be carried out on the Moon.

Regarding the latter, it would be of no use due to a lack of accuracy. The distance to Earth would prevent remote sensing research on seismic waves and weather.

However, astrophysics and heliophysics studies would flourish, as the lack of atmosphere and magnetosphere would allow obtaining better data on cosmic rays, solar winds, particle samples and solar radiation. Although this radiation can be harmful to experimental devices and reduce their life time, it is worth it for the much better data samples and enormous advances for science.

7.2.4 Education and Cultural Activities

Even though we generally think of pure scientific experiments on the ISS, many of them are meant to be educational for showing young enthusiasts the beauty of space. Some others have been conceived by students. Such experiments on the Moon may not be feasible, because the distance and launch costs might make student experiments cost prohibitive.

The student experiments are promoted so that they can learn about space empirically, not by studying theory. And though they are expensive, sending them to the ISS is cheaper than to the Moon. Even so, data from these experiments on the Moon could be very useful, as we now know how they work in microgravity but have very little idea how things work in low gravity. If such educational experiments were opened up to student competitions, they would be of great interest not only to students, but also to major researchers seeking new and cheaper methods for getting to the Moon.

The experiments developed by young enthusiasts for the ISS can also be done on the Moon, but under different and unstudied conditions, which can be of great interest to all. What is more, these experiments intended for the Moon can also be performed during the trip and ultimately obtain data from both microgravity and low gravity.

Carrying out these kinds of activities on the Moon would be commercially problematic, not only because of the increased cost but because of the difficulty in performing them. Nevertheless, it would be remarkable to see some demonstrations from the Moon's surface.

While conducting these experiments on the Moon rather than the ISS may be an economic problem educationally and commercially, new companies popping up in the space industry should overcome these difficulties and have no problem with performing educational experiments. A Moon base will allow larger experiments.

7.2.5 Human Research

Understanding how the human body reacts to prolonged spaceflight, low gravity and microgravity is crucial for human space travel. This section examines a number of key areas related to previous and potentially future areas of research on human behaviour and the feasibility of extended stays on a lunar base.

- Bone and Muscle Physiology
    - PROS: On the Moon, these experiments could be conducted over a much longer period than on the ISS.
    - CONS: The Moon's gravity is much greater than microgravity. Thus, the studies will not be able to examine the same extreme conditions.
- Cardiovascular and Respiratory Systems
    - PROS: A base on the Moon would provide more space for exercise and exercise equipment. It is crucial to understand how muscle degradation will progress in low-gravity satellite/planetary habitats intended for future exploration [26].
    - CONS: The more extreme microgravity allows for accelerated experiments.
- Crew Healthcare Systems
    - PROS: A lunar base allows for the potential development of a dedicated medical centre. In addition to providing care for astronauts, such a centre could research how diseases develop in the habitat environment, which is crucial for the future of human exploration.
    - CONS: None.
- Cross-Disciplinary
    - PROS: None.
    - CONS: Microgravity provides an environment for a more extreme battery of tests that measure the subject's cognitive functions under varied conditions. For example: after waking up; before sleep; after a fall.
- Dental Health

- PROS: Long-term tests could be carried out on a permanent Moon base. Tests over such a long time-span would provide valuable information about the normally slow deterioration of human teeth [107].

- CONS: None.

– Habitability and Human Factors

- PROS: Previous experiments have focused on human reactions to spaceflights and the long-term effects on human mood, stress and food consumption. These experiments could be extended to give a better understanding of the effects.

- CONS: None.

– Human Behaviour and Performance

To date, studies on human behaviour and performance have focused on the environmental effects on sleep, cognition and cultural adaptation to the subject's environment. Both the ISS and the Moon present equally interesting test facilities.

- PROS: None.

- CONS: None.

– Human Microbiome

- PROS: Building on previous studies in a different environment with a different atmosphere will give researchers a more comprehensive understanding of the human microbiome.

- CONS: A more extreme environment on the ISS provides an understanding of the gut and human microbiome.

– Immune System

- PROS: Different viruses would behave differently in the lunar laboratory environment than on the ISS. It is important to understand how viruses would behave in human habitations on other planets/satellites.

- CONS: None.

– Integrated Physiology and Nutrition

- PROS: None.

    - CONS: As this studies the physiology of muscles, bones, tissues and organs, all working together, it is better to perform them on the ISS because of the more extreme microgravity environment.

- Nervous System
    - PROS: Prolonged exposure to hostile conditions is important for understanding how the nervous system reacts to living off of Earth.
    - CONS: More extreme conditions, greater stress on the nervous system, and more extreme reactions.
- Radiation Impact on Humans
    - PROS: The Moon is naturally exposed to higher radiation [108], enabling further research.
    - CONS: None.
- Vision
    - PROS: On the Moon, we have a new atmosphere with a different amount of radiation than on the Earth or ISS, so vision experiments could offer some interesting insights.
    - CONS: None.

7.2.6 Physical Science

The ISS has conducted numerous experiments on the production and behaviour of physics, particularly in terms of materials and processes. This section groups those experiments into five categories, then analyses these categories.

- Combustion science
    - PROS: Combustion experiments on the Moon would give us a better understanding of flammable substances and how they interact with the environment of space. Fire safety issues can also be discussed in relation to these experiments, and the use of combustible components can be standardised. Standard fire and safety rules can be established during the settlement process.
    - CONS: None.
- Complex fluids

  - PROS: Polymer fluids experience stress and strain when stretched out. Experiment on the Moon will expand our knowledge of complex fluids with long chains of polymer molecules. Measuring these on the Moon could give better insights into flexible polymers.

  - CONS: Wet foams cannot be stabilised on Earth, so better results would be obtained from experiments in microgravity.

- Fluid Dynamics

  - PROS: Fluid dynamics experiments can be conducted on the Moon. As the fluids behave like solids under stress, this increases our understanding of particles and helps civil engineers plan for potential earthquakes.

  - CONS: A simpler test on the diffusion of glucose transport in the ISS microgravity environment will improve accuracy and mainly benefit the diabetic community.

- Fundamental Physics

  - PRO: One of the first issues to emerge when space research began was that spacecraft fuel behaved like water. Bubbles in the fuel posed one of the first challenges to engineers and this remains an extensive object of study. Fluid dynamics are difficult to analyse in microgravity rather than on the Moon, where, even though they could not be manipulated as easily as on Earth, the weak gravitational force could benefit fluid experiments.

  - PRO: A more complex research topic is the study of plasma. As with fluids, many ISS experiments focus on plasma. The main reason for this is that the Earth's magnetic field has greater effects on the surface than on the ISS. The magnetic field's reduced influence and minimized variations make plasma easier to confine. A logical next step to these plasma studies study is to take these experiments to the Moon, which is not influenced by the Earth's magnetic field, and its own is much weaker than the Earth's is on the ISS.

  - CONS: None.

- Macromolecular Crystal Growth

  - PROS: Macromolecular crystals grown in microgravity consist mostly of proteins, of which there are more than 100,000 in the human body. To understand how proteins work (structure maintenance, tissue regulation, catalysing chemical reactions, immune responses, etc.), their structure and the effects of space on them must be studied in order to preserve human life for long periods beyond Earth.

- CONS: As in some of the abovementioned cases, the Moon's gravity differs from the conditions on the ISS. Therefore, despite the unique results, they cannot be classified as microgravity experiments.

– Material Science

- PRO: The Moon's low gravity can provide stability to experiments materials.
- PRO: Regarding experiments on the solidification of materials in processes like crystallisation, the microgravity could cause imperfections such as bubbles. These experiments on the Moon's surface would largely eliminate such imperfections.
- PRO: The Moon's nearly negligible magnetic field eliminates the solidification issues that result from great variations in the Earth's magnetic field.
- CONS: Since it is mostly solid materials whose properties are experimented on, microgravity provides an advantage due to the lack of forces subject to gravity. This allows experiments on the ISS to focus more on other forces such as external, atomic, electric, or magnetic.

7.2.7 Technology Development and Demonstration

Technological development is a key goal of ISS experiments and activities. Understanding how technology may function in zero-g conditions and how such environments can benefit humanity is vital to future space exploration. The Moon presents a different environment for such testing, and below are a set of technological subsections detailing more pros and cons of lunar versus current ISS testing.

– Air, Water and Surface Monitoring

- PROS: A different environment for testing the effectiveness of such technology.
- CONS: Distance is significantly increased, leading to a likely drop in accuracy and precision. It is likely no specific improvements to the tests done on board the ISS.

– Avionics and Software

- PROS: Less protection from the Earth's magneto-sphere exposes the Moon to greater solar and cosmic radiation. Testing radiation protection for computer hardware is vital for further space exploration.

  - CONS: Sending computer equipment to the Moon is more expensive than putting it in orbit.

- Experiment Hardware
  - PROS: Development of new hardware for experiments and 3D printers that use Moon dust for construction.
  - CONS: Hardware that can be tested off the surface or in higher radiation is cheaper to do on the ISS.

- Commercial Demonstrations
  - PROS: Commercialising the Moon will make it more accessible to the public and businesses. “Moon tested” marketing or similar could be appealing.
  - CONS: The technologically is too complex and expensive to be cost-effective for current entrepreneurs and private businesses.

- Communications and Navigation
  - PROS: The possibility of developing the relay communications needed for exploring the dark side of the Moon, as well as specialised Moon navigation systems. This new testing environment would benefit future Mars missions and beyond.
  - CONS: Again, compared to the ISS, any specialised mission equipment will be expensive to transport to the Moon (or Mars) for testing.

- EVA Systems
  - PROS: Development of suits that can function under new hazards, such as Moon dust, and to test them in an environment likely to be more similar to other planets.
  - CONS: Aside from certain new considerations for the Moon environment, EVA systems can already be tested on the ISS.

- Fire Suppression and Detection
  - PROS: Different environments need different fire systems. How will lunar dust in the air content potentially affect the system? What is the effect of lower gravity? This needs to be developed specially for Moon missions, and the findings may be applicable to future Mars missions.
  - CONS: Expensive. Almost all tests could be done on the ISS.

- Food and Clothing Systems
  - PROS: Testing of clothing for space habitats. The Moon is a similar environment to other planets like Mars (dust content, lower than Earth gravity, low atmosphere).
  - CONS: A significant number of tests can already be done on the ISS.
- Imaging Technology
  - PROS: Certain imaging is improved from farther outside the Earth's magnetosphere, which can disturb radiation.
  - CONS: Imaging for Earth observation is less effective on the Moon than on the ISS, due to the increased distance.
- Life Support Systems and Habitation
  - PROS: Habitation needs to be developed specifically for the Moon mission and tested in that environment. Considerations include higher solar and cosmic radiation levels, higher dust content levels, prolonged variations in temperature due to the lunar night and day cycle.
  - CONS: Testing life support in zero-g is not possible (although low-g is). For example, maintaining muscle tissue and bone strength under microgravity conditions.
- Microbial Populations in Spacecraft
  - PROS: None.
  - CONS: ISS presents a more realistic long-term spacecraft environment, as it is currently orbiting a planetary body under microgravity conditions.
- Microgravity Environment Measurement
  - PROS: None.
  - CONS: The Moon is low gravity and not zero-g like the ISS. Thus, it is less relevant for microgravity testing, as its gravity is roughly 1/6 that of Earth's.
- Power Generation/Distribution Systems
  - PROS: Solar radiation presents a new environmental hazard for testing power systems. Lunar dust must also be factored in for generation

methods, such as solar panels. How will the problem of dust be overcome?

  - CONS: Some testing is not possible on the Moon, such as the zero-g battery charger.

- Radiation Measurements and Shielding

  - PROS: Galactic cosmic rays and solar energetic particles can be measured without interference from the Earth's magnetosphere, and this can help in planning and developing shielding for future settlements.

  - CONS: Other radiation measurements (such as from Earth) can be done on the ISS – often with greater accuracy.

- Repair and Fabrication Technologies

  - PROS: Applying repair and fabrication technology to new environments more suited to future settlements.

  - CONS: A number of fabrication tests in microgravity are better suited to the ISS. For example: zero-g soldering and zero-g 3D printing.

- Small Satellites and Control Technologies

  - PROS: A new Moon base could potentially serve as a launching station for lunar orbiting satellites. It would be easier and cheaper to launch than from Earth, due to the lower gravity.

  - CONS: The ISS is better for testing, as it is already in orbit and can launch devices like CubeSats).

- Space Structures

  - PROS: Experimenting with an environment, –such as large and prolonged temperature shifts, increased radiation levels, and dust particles. Materials taken from the Moon itself can also be used.

  - CONS: Certain experiments are better suited to the ISS, such as testing re-entry into Earth's atmosphere.

- Spacecraft Materials

  - PROS: None.

  - CONS: All of the spacecraft materials can be tested on the ISS.

- Spacecraft and Orbital Environments
    - PROS: None.
    - CONS: The ISS is already in orbit, and is thus a better environment for many tests. Re-entry tests and detecting space debris are best suited to an Earth orbit.
- Thermal Management Systems
    - PROS: Specific tests of an environment with higher maximum and minimum temperatures over longer periods of time (lunar day and night).
    - CONS: Cheaper to test on the ISS. Microgravity experiments better suited to the ISS.

Conclusions

In this document, we have seen the main aspects related to the viability of the proposed lunar laboratory. This proposition is timely, given the quickly approaching fiftieth anniversary of Neil Armstrong's first steps on the Moon. Though the International Space Station has served as an orbiting laboratory conducting valuable experiments since the turn of the century, its lifetime is limited and retirement is looming for this colossal human endeavour. One may legitimately wonder what the next step will be for human space exploration. Fifty years ago, after watching Armstrong and Aldrin walk on the Moon, people's minds whirred with the possibilities that had opened up to humanity, as life would clearly never be the same again. Unfortunately, all the hope for human spaceflight that was inspired by Apollo 11 has dissipated. Now is the time to reignite those dreams, and what better way than to construct the most fruitful laboratory in human history on the Moon's surface?

Keeping humans alive on the Moon is a hard task, not only because fundamental needs like water are lacking there, but also because the Moon has no atmosphere to protect us from radiation. We know that the cheapest source of protection is the lunar regolith, since it is a natural resource; but how can we use it? The easiest and currently most viable method is to hide in a crater where we can be protected by roughly the volume of a hemisphere, $2\pi/3r^3$. The Moon is covered with craters, and choosing the correct one depends on many factors, such as the temperature and amount of light. After studying the topographic map, the Shackleton Crater is so far the best option for building a lunar base. Located at the south pole of the Moon, its relatively abundant sunlight and stable temperatures make it the most suitable candidate. What is more, due to the presence of water and other chemical elements, as well as the crater's size being suitable for research facilities and infrastructures for obtaining energy, this site is the most ideal option.

The infrastructures for obtaining energy are very important for developing a lunar base, as we need energy for life support systems to function. Our two primary options for obtaining energy are fission and solar. While fission is our best option, it is dangerous and we have no experience with it outside Earth. Its danger lies not only in the breaking of atomic nuclei but also in the need for certain radioactive atoms that can produce decent amounts of energy, which would require transport from Earth. This poses a threat to astronauts as well as the Earth's atmosphere should any malfunction occur, resulting in an epidemic of cancer on both Earth and Moon. While the risks of fission are notable, solar energy also has its problems. The efficiency of photovoltaic panels remains very low and thousands of them may be needed for a minimal amount of energy. Though the expansive Moon surface mitigates this problem, it will still be very expensive. Lunar dust is also a hindrance to these panels, as it would deposit itself on surfaces and impede energy production. Nevertheless, because solar energy is the safest, it should be used in the early stages of Moon colonisation; then, when we have gained enough knowledge and confidence in fission or even fusion, we can add nuclear infrastructures.

Understanding future energy generation on the Moon first requires knowing the amount of energy needed. Of course, the vast number of variables makes it impossible to accurately quantify the exact amount of required energy, but the estimates outlined in this document for NASA's proposed Moon base are a good starting point. In short, given our knowledge of solar and nuclear energy, it is clear that a combination of these two will be needed to satisfy the lunar base's energy needs.

Of course, life support systems are crucial to the success of any settlement on the lunar surface. However, it is also an important opportunity to investigate and test new life-support options for future missions beyond the Moon. Certain parts of the ISS's life support systems, like the water recycling system and atmospheric control, can be put to use in a future settlement. Although these systems can be used in principle, advancements will have to be made. For example, it is unrealistic to plan for resupply missions of water from Earth, which is the current practice for the ISS. The necessity for new procedures will encourage the creation of new life support systems, which in turn will better equip us for travel beyond our own planet's sphere of influence.

The Moon's environment, although hostile, provides a number of naturally available resources. Taking advantage of the extremely low vacuum boiling point, the Moon's abundant oxide can be boiled to create oxygen. The lunar regolith has been found to have the same radiation shielding qualities as aluminium. And though iron is prevalent in this regolith, currently no methods have been developed for extracting it, due to this particular iron's highly brittle nature. Silicon and helium-3 generate great excitement among planners of lunar settlements – for good reason: helium-3 has the potential to generate massive amounts of clean energy, and silicon can be treated for use in hydrogen rocket fuel. Another highly exciting resource on the Moon is water ice, which could be mined to extract hydrogen and oxygen at the poles, where it is most common.

This document has also outlined the types of activities to be carried out on the proposed lunar settlement, as well as the human interventions that will be needed at critical moments. Members of the public often ask why sending humans to the Moon is a popular idea, believing that robots can do all the necessary work. However, robots cannot conduct all the scientific experiments that will enhance the quality of human life, neither on Earth nor on the Moon. When the sanctity of a single human life is involved, humans raise their minimum level of commitment. Robots are not capable of doing so, nor can they provide the necessary expertise in medicine and management.

Since the 1950s, 109 missions have been launched to the Moon, six of which landed humans on the lunar surface. While Hohmann transfers are the method of choice because of their speed, they are particularly expensive for travelling to the Moon. In addition to surviving the hostile environment there, astronauts will need reliable methods for returning home – at least until the Moon can be considered "home". Two of the most popular methods for cislunar travel are laid out in this document, one of which is a type of orbiting platform where astronauts can embark on and disembark from different vehicles.

Perhaps the most important point to consider for returning to the Moon is the viability of constructing a Moon base for developing new technologies and conducting ground-breaking experiments. The critical issues to overcome are the life support systems. Can we ensure the survival of astronauts on the Moon? While most of the systems that work well on the ISS can be used for brief periods on the Moon – such as water and waste management, atmospheric control, and radiation shielding – they would be insufficient for long-term survival; so improvements on these systems are essential. The presence of lunar water and the possibility of extracting oxygen from it will support the water and atmospheric systems, thus extending their operational lifetimes. Waste management may be harder to deal with, despite the abundant surface area for depositing all the rubbish and other residue: we do not want to begin destroying the Moon from day one, so perhaps launching it into the Sun would be a suitable method for waste disposal. Radiation could be the greatest problem on the Moon, due to its lack of atmosphere and natural protection from a magnetosphere; thus exposure there is greater than on Earth and the ISS. Radiation can kill humans rapidly and cause fatal cancers, so protection against this is critical.

For this reason, we need to develop different methods for radiation shielding, such as thicker structures or water and regolith shielding.

Following on from the experiments conducted aboard the ISS, astrobiology experiments on the survival of extremophiles and tardigrades can advance further and build on past results and observations. Many ISS experiments rely on simulated microgravity conditions. Continuing these experiments on the Moon would provide a third data point that could potentially lead to fruitful discoveries.

The International Space Station has laid the groundwork for an international lunar laboratory. However, the Moon poses some complications that have not been encountered in developing and maintaining the ISS, and these must be overcome before we can begin exploiting the abundant lunar resources for profit. As discussed, national space agencies and private organisations are racing to extract helium-3 for financial gain, and lunar ice is also being considered as an opportunity. The Moon Treaty attempted to subject the governance of celestial bodies to international adjudication, but in practice it has failed because no major space-faring nations have signed the treaty. Thus, it is perhaps naïve and idealistic to believe that a collaborative laboratory on the Moon is possible, given that so much can be gained independently through colonisation.

Bibliography

1. The Institute of Physics, The Royal Society of Chemistry, and the Parliamentary Space Committee. Space: Exploration and exploitation in a modern society. *Institute of Physics*, May 2009. Accessed on 07-05-2019.

2. David Schrunk, Burton L. Sharpe, Bonnie L. Cooper, and Madhu Thangavelu. *The Moon: Resources, Future Developments and Settlements*. Springer, second edition, 2008.

3. NASA. Earth's Moon. https://solarsystem.nasa.gov/Moons/earths-Moon/in-depth/, April 2019. Accessed on 13-05-2019.

4. Grant H. Heiken, David T. Vaniman, and Bevan M. French. *Lunar Sourcebook: a user's guide to the Moon*. Press Sindicate of the University of Cambridge, first edition, 1991.

5. C. Hirt and W. E. Featherstone. A 1.5 km-resolution gravity field model of the Moon. *Earth and Planetary Science Letters*, 329-330:22-30, 2012.

6. P. M. Muller and W. L. Sjogren. Mascons: Lunar mass concentrations. *Science*, 161(3842):680-684, 1968.

7. Lunar atmosphere and dust environment explorer (ladee) launch. https://www.nasa.gov/sites/default/files/files/LADEE-Press-Kit-08292013.pdf, August 2013. Accessed on 13-05-2019.

8. Ladee project science update. https://www.nasa.gov/ames/ladee/ladee-project-scientist-update-december-2014/, December 2014. Accessed on 13-05-2019.

9. G. T. Delory J. S. Salute S. Noble A. Colaprete M. Horanyi P. Ma-ha y and the LADEE Science Team R. C. Elphic, B. Hine. The lunar atmosphere and dust environment explorer (ladee): Initial science results, March 2014. Accessed on 13-05-2019.

10. J. M. Carroll F. S. Johnson. Vacuum measurements on the lunar surface. *Vacuum Science and Technology*, 450, 1972.

11. Stuart R. Taylor. *Lunar Science: a Post-Apollo View*. Oxford, 1975.

12. Stubbs, T.J. et al A dynamic fountain model for lunar dust. A*dvances in Space Research*, April 2005.

13. Dauna Coulter. Moondust in the wind. https://science.nasa.gov/ science-news/science-at-nasa/2008/10apr_Moondustinthewind, April 2008. Accessed on 20-05-2019.

14. Lawrence Taylor, Harrison Schmitt, W Carrier, and Masami Nakagawa. Lunar Dust Problem: From Liability to Asset. In *1st Space Exploration Conference: Continuing the Voyage of Discovery,* Reston, Virigina, jan 2005. American Institute of Aeronautics and Astronautics.

15. Timothy J Stubbs, Richard R Vondrak, and William M Farrell. Impact of dust on lunar exploration. *Transport*, 2005(September 2005):239-243, 2005.

16. Chiu-wing Lam, Robert R. Scully, Ye Zhang, Roger A. Renne, Robert L. Hunter, Richard A. McCluskey, Bean T. Chen, Vincent Castranova, Kevin E. Driscoll, Donald E. Gardner, Roger O. McClellan, Bonnie L. Cooper, David S. McKay, Linda Marshall, and John T. James. Toxicity of lunar dust assessed in inhalation-exposed rats. *Inhalation Toxicology*, 25(12):661-678, oct 2013.

17. John R. Cain. Lunar dust: The Hazard and Astronaut Exposure Risks. *Earth, Moon, and Planets*, 107(1):107-125, dec 2010.

18. NASA Sandra A. Wagner, Johnson Space Center. The apollo experience les-sons learned for constellation lunar dust management. https://www.hq.nasa. gov/alsj/TP-2006-213726.pdf, September 2006. Accessed on 13-05-2019.

19. Harrison & David Carrier W & Nakagawa Masami A. Taylor, Lawrence & Schmitt. The lunar dust problem: From liability to asset. https://www.researchgate.net/publication/252187719_TheLunar_Dust_Problem_From_Liability_to_Asset, 2005. Accessed on 13-05-2019.

20. Sarah K. Noble Mary Ann Meador Joseph J. Kosmo J. Anneliese Lawrence Lynn Brosto -Amanda Young Terry McCue Roy Christoffersen, John F.

Lindsay. Lunar dust effects on space suit systems: Insights from the apollo space suits. https://pdfs.semanticscholar.org/26fd/ 6058dd8c202f9edc9f8a7d860ed296e0ff80.pdf, April 2009. Accessed on 13-05-2019.

21. Farmer Je rey T. Simonson Lisa S., DeBarro Marc J. Conceptual design of a lunar base thermal control system. https://space.nss.org/media/ Lunar-Bases-conference-2-701-Thermal-Control-System.pdf. Accessed on 13-05-2019.

22. Sefton-Nash Elliot. Surface and near-surface thermal environment of the Moon. https://link.springer.com/referenceworkentry/10.1007 2F978-3-319-05546-6_14-1, December 2014. Accessed on 13-05-2019.

23. Sharp Tim. Atmosphere of the Moon. https://www.space.com/ 18067-Moon-atmosphere.html, October 2017. Accessed on 13-05-2019.

24. Miatello Alberto. Why lunar heating/cooling is so important to disprove the greenhouse effect theory on Earth. http://tech-know-group.com/papers/ Lunar_cooling_disproves_earth_greenhouse_effect.pdf, July 2014. Accessed on 13-05-2019.

25. Szondy David. Esa turns to soil to keep lunar missions warm at night. https: //newatlas.com/esa-lunar-soil-heat/48597/, March 2017. Accessed on 13-05-2019.

26. David Schrunk et al. *The Moon: Resources, Future Development, and Settle-ment*. Praxis Publishing Ltd, Chichester, UK, second edition, 2008.

27. Xiongyao Li et al. *Moon: Prospective Energy and Material Resources – Condi-tion of Solar Radiation on the Moon*. Praxis Publishing Ltd, Chichester, UK, first edition, 2012.

28. I. G. Mitrofanov et al. Hydrogen mapping of the lunar south pole using the lro neutron detector experiment lend. *Science*, 330(6003):483-486, October 2010.

29. Michiel Kruij. The peaks of eternal light on the lunar south pole: How they were found and what they look like. *In Fourth International Conference on Exploration and Utilisation of the Moon: ICEUM* 4, July 2000.

30. Luke Gilkerson. The peak of eternal light: Where the Sun never sets on the Moon. https://experienceastronomy.com/the-peak-of-eternal-light-where-the-sun-never-sets-on-the-Moon/, Juner 2018. Accessed on 12-05-2019.

31. ESA European Space Agency. The peak of eternal light. https://www. youtube.com/watch?v=dXr2auGOxus, December 2012. Accessed on 12-05-2019.

32. Maria T. Zuber et al. Constraints on the volatile distribution within shackleton crater at the lunar south pole. *Nature*, 486:378-381, June 2012.

33. NASA Larson William. Oxygen from regolith. https://isru.nasa.gov/ OxygenfromRegolith.html. Accessed on 20-05-2019.

34. F.Piccolo F.Piccolo - D'Appolonia Appolonia S.p.A. Exploitation exploita-tion of lunar resources resources: Isru and isru and oxygen production. sci. esa. int/science-e/www/object/doc.cfm?fobjectid=42074. Accessed on 20-05-2019.

35. J. Bernabeu and I. Casanova. Moon surface radiation environment analysis for february 1956 solar event conditions. *Science Direct*, ELSEVIER, 2007.

36. J. Miller, L. Taylor, C. Zeitlin, L. Heilbronn, S. Guetersloh, M. DiGiuseppe, Y. Iwata, and T. Murakami. Lunar soil as shielding against space radiation. *Radiation Measurements*, 44(2):163-167, 2009.

37. Cary Zeitlin, Stephen B Guetersloh, Lawrence H Heilbronn, C Zeitlin, S B Guetersloh, L H Heilbronn, and J Miller. Measurements of materials shielding properties with 1 GeV/nuc 56Fe. Nucl. Instrum. Methods. *Lawrence Berkeley National Laboratory*, 2006.

38. Lunar and Planetary Institute. The clementine mission. https://www.lpi. usra.edu/lunar/missions/clementine/images/. Accessed on 20-05-2019.

39. Ian A. Crawford. Lunar resources: A review. *Progress in Physical Geography*, October 2014.

40. Dr. William A. Good Gary J. Rodriguez. Siliocn Moon thefoundationn of a cislunar economy. AIAA, 1(2001-4662):1-1, August 2001.

41. Geoffrey A. Landis. Materials re ning on the Moon. https://www. sciencedirect.com/science/article/pii/S0094576506004085, December 2006. Accessed on 22-05-2019.

42. E. N. Slyuta et al. The estimation of helium-3 probablr reserves in lunar regolith. *Lunar and Planetary Science*, 2007.

43. China Daily. He asked for the Moon-and got it. http://www.chinadaily. com. cn/cndy/2006-07/26/content_649325.htm, July 2006.

44. Jay Bennett. Mit achieves breakthrough in nuclear fusion. https://www.popularmechanics.com/science/energy/a27961/mit-nuclear-fusion-experiment-increases-efficiency/, August 2017.

45. National Oceanic and Atmospheric Administration. Moon: Topography. https://sos.noaa.gov/datasets/Moon-topography/. Accessed on 22-05-2019.

46. National Air and Space Museum. Lunar topography. https://airandspace.si.edu/exhibitions/lroc/online/topography.cfm. Accessed on 22-05-2019.

47. NASA Helen-Nicole Kostis. How lro will find safe landing sites on the Moon – stereoscopic version. https://svs.gsfc.nasa.gov/3567. Accessed on 22-05-2019.

48. C. M. et al. Pieters. Character and spatial distribution of oh/h2o on the surface of the Moon seen by m3 on chandrayaan-1. *Science*, 326(5952):568-572, 2009.

49. Caroline Habold, Veronique Coxam, Donal O'Gorman & Stephane Blanc Audrey Bergouignan, T Peter Stein. Towards human exploration of space: The theseus review series on nutrition and metabolism research priorities. *US National Library of Medicine National Institutes of Health*, 2, 2019-06-03.

50. NASA. Human needs: Sustaining life during exploration. https://www.nasa.gov/vision/earth/everydaylife/jamestown-needs-fs.html, April 2007.

51. A Cataldo R Bozek J. Power requirements for the first lunar outpost. NASA *Technical Memorandum 105925*, January 1993.

52. Ian Hore Lacy. Nuclear Energy in the *21st Century*. World Nuclear University Press, 2007.

53. Raymond L. Murray and Keith E. Holbert. *An Introduction to the Concepts, Systems, and Applications of Nuclear Processes*. Elsevier, seventh edition, 2015.

54. N. Bohr and J.A. Wheeler. The mechanisms of nuclear fission. *Physics Review*, 56:428, 1939.

55. Enzo De Sanctis, Stefano Monti, and Marco Ripani. *Energy from Nuclear Fission: An Introduction*. Springer, 2016.

56. Gino Adrian Alvarado and Carlos Bosquez. Prototype of a "sun ower" solar panel for increasing efficiency photovoltaic, 2017.

57. Geoffrey A Landis, Sheila G Bailey, David J Brinker, and Dennis J Flood. Photovoltaic power for a lunar base. *Acta Astronautica*, 22:197-203, 1990.

58. Robyn Carrasquillo. Iss environmental control and life support system (eclss) future development for exploration. In *2nd Annual ISS Research and Devel-opment Conference*, July 2013.

59. Jesse A. Bazley. Iss regenerative life support: Challenges and success in the quest for long-term habitability in space. In *62nd International Aeronautical Congress*, October 2011.

60. Christopher Brown Layne Carter and Nicole Orozco. Status of iss water man-agement and recovery. In *43rd International Conference on Environmental Systems (ICES)*, July 2014.

61. Gregory J. Gentry and John Cover. International space station (iss) environmental control and life support (ecls) system overview of events: 2010 – 2014. In *45th International Conference on Environmental Systems*, July 2015.

62. Robyn Gatens. Environmental control & life support systems for human spaceflight. In *Exploration Systems Interface with Biological and Physical Sciences Symposium*, March 2017.

63. Gabriel Weinberg. How does pressurizing work in the iss? https://www.quora.com/How-does-pressurizing-work-in-the-ISS, March 2016.

64. Tariq Malik. Lunar shields: Radiation protection for Moon-based astronauts. https://www.space.com/658-lunar-shields-radiation-protection-Moon-based-astronauts.html, 2005. Accessed on 07-05-2019.

65. ARC Education Specialist Wenonah Vercoutere Ph.D. NASA ARC Subject Matter Expert Al Krause MSFC Education Specialist BJ Navarro NASA ARC Project Manager Jon Rask, M.S. *The radiation challenge. Radiation Educators Guide*, Module 3:36, 2008.

66. Sarah Frazier. Real martians: How to protect astronauts from space radiation on mars. https://www.nasa.gov/feature/goddard/ real-martians-how-to-protect-astronauts-from-space-radiation-on-mars, 2015. Accessed on 07-05-2019.

67. M. DiGiuseppe L.H. Heilbronn G. Sanders C.J. Zeitlin J Miller, L.A. Taylor. Radiation shielding properties of lunar regolith and regolith simulant. *NLSI Lunar Science Conference* (2008), 2008.

68. NASA.Repurposing space station trash for power and water. https://www.nasa.gov/content/repurposing-space-station-trash-for-power-and-water/,November 2013.

69. Moon Missions | Exploration - Moon: NASA Science.

70. R Biesbroek and G Janin. Ways to the Moon?, 2000.

71. NASA updates Lunar Gateway plans - NASASpaceFlight.com.

72. Russia may select first crew for its federation spacecraft next year – spaceflight insider.

73. Edward Tchobanoglous, George Schroeder. *Water quality: characteristics, modeling, modification*. Adisson-Wesley, 1985.

74. Tony Patrick L, Barry Dr Phillips. Water on the space station. https://science.nasa.gov/science-news/science-at-nasa/2000/ast02nov_1, 2000. Accessed on 07-05-2019.

75. Living in space. https://www.nasa.gov/pdf/146558 main_RecyclingEDA(final)4_10_06.pdf. Accessed on 07-05-2019.

76. Flint Wild. Eating in space. https://www.nasa.gov/audience/ foreducators/stem-on-station/ditl_eating, 2018. Accessed on 07-05-2019.

77. NASA Content Administrator. The sabatier system: Producing water on the space station. https://www.nasa.gov/mission_pages/station/research/news/sabatier.html, 2017. Accessed on 07-05-2019.

78. J Simonsen, C Debarro. Conceptual design of a lunar thermal control system n93-14003.

79. Tibor S. et al Balint. Extreme environment technologies for in-situ lunar exploration, 2007.

80. Kaleigh Rogers. What goes in our rst-aid kit for the mission to mars? https://www.vice.com/en_us/article/5387w5/what-goes-in-our-first-aid-kit-for-the-mission-to-mars, 2017.Accessed on 07-05-2019.

81. Thomas J. Beven Gary Vander Ark Steve Bollweg, Laura Dr Williams. Behavioural health. https://www.nasa.gov/content/behavioral-health, 2015. Accessed on 07-05-2019.

82. Wikipedia. Crew return vehicle. https://en.wikipedia.org/wiki/Crew_ Return_Vehicle. Accessed on 07-05-2019.

83. Wikipedia. Uncrewed spaceflights to the international space sta-tion. https://en.wikipedia.org/wiki/Uncrewed_spaceflights_to_the_International_Space_Station. Accessed on 07-05-2019.

84. Mission Operations Directorate Operations Division. International space sta-tion complex operations emergency procedures, all expedition flights. http:// www.spaceref.com/iss/ops/emergency.procedures.pdf, August 16 2000. Accessed on 07-05-2019.

85. Mission Operations Directorate Operations Division. International space station emergency operations. http://www.spaceref.com/iss/ops/ emergency.procedures.pdf, 2000. Accessed on 07-05-2019.

86. Erik Seedhouse. Lunar Outpost: *The Challenges of Establishing a Human Settlement on the Moon*. Springer, first edition, 2009.

87. NASA. Lunar south pole. https://www.nasa.gov/mission_pages/LRO/ multimedia/lroimages/lroc-20100927_southpole.html, September 2010. Accessed on 07-05-2019.

88. Bocam K.J. Bodkin D.K., Escalera P. A human lunar surface base and infrastructure solution. Space, 2006.

89. NASA. Space station research experiments. https://www.nasa.gov/ mission_pages/station/research/experiments_category.html, 2019. Accessed on 29-04-2019.

90. V. Mastascusa et al. Extremophiles survival to simulated space conditions: An astrobiology model study. *Origins of Life and Evolution of Biospheres*, 44:231-237, 2015.

91. NASA. Earth microbes on the Moon. https://science.nasa.gov/ science-news/science-at-nasa/1998/ast01sep98_1, September 1998. Ac-cessed on 06-05-2019.

92. Miriam Land et al. Insights from 20 years of bacterial genome sequencing. *Functional and Integrative Genomics*, 15:141-161, 2015.

93. NASA. Extremophiles: Life on the edge. https://science.nasa.gov/ science-news/science-at-nasa/1998/ast01sep98_1, September 1998. Ac-cessed on 06-05-2019.

94. David L. Moon microbe mystery finally solved. https://www.space.com/ 11536-Moon-microbe-mystery-solved-apollo-12.html, May 2011. Accessed on 06-05-2019.

95. F. J. Sanchet et al. The resistance of th elichen circinaria gyrosa (nom. pro-vis.)towards simulated mars conditions|a model test for the survival capacity of an eukaryotic extremophile. *Planetary and Space Science*, 72:102-110, 2012.

96. NASA. Extremophiles. https://www.nasa.gov/mission_pages/station/ research/experiments/explorer/Investigation.html?#id=7370, 2019. Accessed on 06-05-2019.

97. Mora M. et al. Resilient microorganisms in dust samples of the international space station|survival of the adaptation specialists. *Microbiome*, 4(65):141- 161, 2016.

98. NASA. Expose-r2-biology and mars experiment. https://www. nasa. gov/mission_pages/station/research/experiments/explorer/Investigation. html?#id=7467, 2019. Accessed on 07-05-2019.

99. NASA. Intraterrestrial fungus. https://www.nasa.gov/mission_pages/ station/research/experiments/explorer/Investigation.html?#id= 7474, 2019. Accessed on 07-05-2019.

100. NASA. Using water bears to identify biological countermeasures to stress during multigenerational spaceflight. https://www.nasa.gov/mission_ pages/station/research/experiments/explorer/Investigation.html?#id=7672, 2019. Accessed on 07-05-2019.

101. Hashimoto T. et al. Extremotolerant tardigrade genome and improved radiotolerance of human cultured cells by tardigrade-unique protein. *NFature Communications*, 7, 2016.

102. Bruce M. Link, James S. Busse, and Bratislav Stankovic. Seed-to-Seed-to-Seed Growth and Development of Arabidopsis in Microgravity . *Astrobiology*, 14(10):866-875, 2014.

103. Robert C Morrow, Howard G Levine, Gioia D Massa, and Raymond M Wheeler. Growth chambers on the International Space Station for large plants. *Acta Horticulturae*, 1134:215-222, 2016.

104. Michael Rycroft. Grrenhouse: A Strategic Element to Support Humans in Space. In *Beyond the International Space Station: The Future of Human Spaceflight*, pages 119 - 126. Springer Science+Business Media Dordrecht, Strasbourg, France, 2002.

105. Zeidler C. et al. Greenhouse Module for Space System: A Lunar Greenhouse Design. *Open Agriculture*, 2(1):116-132, 2017.

106. G. Boscheri, M. Kacira, L. Patterson, G. Giacomelli, P. Sadler, R. Furfaro, C. Lobascio, M. Lamantea, and L. Grizza . Modified energy cascade model adapted for a multicrop Lunar greenhouse prototype. *Advances in Space Re-search*, 50(7):941-951, oct 2012.

107. Scientific American. How does spending prolonged time in microgravity affect the bodies of astronauts? https://www.scientificamerican.com/article/ how-does-spending-prolong/, October 2003. Accessed on 27-04-2019.

108. Patrick L. Barry. Radioactive Moon. https://science.nasa.gov/ science-news/science-at-nasa/2005/08sep_radioactiveMoon, Septem-ber 2005. Accessed on 27-04-2019.