IAC-14-E5.1

HUMAN LIFE SUPPORT IN PERMANENT LUNAR BASE ARCHITECTURES

Luca Levrino
Politecnico di Torino, Italy, luca.levrino@polito.it

Giacomo Gatto
Politecnico di Torino, Italy, giacomo.gatto@polito.it
Sherrie Hall
Massachusetts Institute of Technology, United States, shall6@mit.edu
Janelle Wellons
Massachusetts Institute of Technology, United States, jwellons@mit.edu
Eugenio Gargioli
Thales Alenia Space Italia, Italy, eugenio.gargioli@thalesaleniaspace.com
Jeffrey A. Hoffman
Massachusetts Institute of Technology, United States, jhoffma1@mit.edu
Paolo Maggiore
Politecnico di Torino, Italy, paolo.maggiore@polito.it
Nicole Viola
Politecnico di Torino, Italy, nicole.viola@polito.it
Maria Antonietta Viscio
Politecnico di Torino, Italy, maria.viscio@polito.it

The future of human space exploration relies on many different requirements that must be fulfilled to expand human presence beyond Low Earth Orbit (LEO). Indeed, a major factor affecting deep space mission architectures resides in the ability to cope with a hostile environment, which is very different from the one found in LEO. With the ultimate goal of taking humans to Mars, several technological limitations need to be overcome in order to sustain human life in such harsh conditions. In the context of an evolutionary path, which would see the incremental employment, testing, and validation of new elements for future Mars expeditions, a lunar mission can be considered as an inevitable and paramount milestone. Even though several astronauts have already set foot on our natural satellite, it was only for short sorties, whose architectures would need to be radically altered for long stays to be envisioned. The present paper investigates enabling factors related to long permanence on the lunar surface, and proposes solutions to support human life. The main aspects to be tackled include crew size, tasks analysis, outpost location, habitable and laboratory modules, and the feasibility of a lunar greenhouse. The crew is sized starting from the analysis of tasks and activities to be performed, as well as accounting for psychological and social aspects. For the assessment of habitat location and configuration, particular attention has been given to geography and illumination of the site. Moreover, the aim is indeed to respond to the need of a self-sustaining lunar outpost, where most of the consumables necessary for life support, such as oxygen, water and food, are produced in-situ: this is why in-situ resource utilization (ISRU) and greenhouse technologies are at the core of our investigation. Additionally, ISRU is also taken into account for radiation shielding purposes: covering the modules with regolith or burying them is in fact the best way to reduce launch masses from the Earth.

I. INTRODUCTION

In the future of space exploration, the need for a permanent base on the Moon is twofold. On the one hand, it is paramount to develop and test new technologies to lay the groundwork for future missions. On the other, it may be seen as an active support to other missions within the solar system and beyond. A major example is in-situ propellant production: in practice, propellant produced on the Moon can be important not only for sustaining the base itself, but also to refuel spacecraft travelling to further destinations like Mars, Phobos or beyond. Whereas the necessity of a permanent lunar base is not important to fulfill the former aim, for the latter it becomes paramount: in order to extend the human outreach in space, the fact of creating bases other than on the Earth does not have to be overlooked.

Considering the role of a human outpost responding to the above-mentioned goals, it is important that the statement of such a mission be in line with the incremental scenario outlined for the future of space exploration[1]. The most general mission statement can be written as "*To enable Human Exploration of the Moon and to support the utilization of Moon's potential* *mineral resources as an incremental step towards Mars; to account for the creation of a permanent base for scientific activities and technology development and validation*". This implies to have a modular base, which can be upgradable in terms of crew and technologies. The scope of this preliminary study is then to cast light on some of the major factors enabling the realization of such an enterprise.

This paper is structured as follows. In Section II we analyze the issues related to the crew, in particular regarding its size and tasks. Section III discusses some of the enabling factors playing an important role for the feasibility of a permanent lunar base, and which need further investigation and development. Section IV is then devoted to the trade-offs on outpost location and on its configuration; moreover, mass, volume and power budgets are presented. Finally, in Section V we draw the conclusions about the broad variety of topics treated and discuss future work.

II. CREW ESTIMATES

The first step of this preliminary study revolves around the key player of our mission: Man. Even though the outpost is supposed to be upgradeable, the minimum crew size has to be established along with their tasks.

Crew size

Crew estimates are based on literature analysis and simple considerations at first. In order to perform EVAs without major constraints and to have support by at least two crewmembers while others are outside, a minimum of four astronauts shall be assumed for the crew. Moreover, considering return vehicles, the crew shall not exceed their capacity (i.e. 6 for an Orion capsule). To determine precisely the number of crewmembers, psychological considerations are needed[2]. The main aspects to be considered are:

- Social density (volume roughly available for each crewmember)
- Confinement (crew size/expected mission duration)
- Unexpected shortening or lengthening of the mission (especially in first time missions like Moon missions)
- Crew characteristics (gender, cultures of origin, assigned roles, technical skills, command structure, relative experience)
- Physical environment (freedom of movement, subjective perception of habitable volume, atmosphere, time outside the outpost)
- Work/rest (workload, rest and leisure time, tasks variations; perceived relevance of the task strongly influences crew motivation, morale, and relationship with ground)
- Autonomy (must increase for planetary exploration: lower re-supply, reduced communication with ground; need for leadership, on-board control and management of the in flight schedule)
- Communication (connectedness with family and friends, time lag, confidentiality, interpretation and clarity of ground instructions)
- Illness or injuries (account for sick crewmembers and possible anticipated reentry)
- High demand situations due to dangers and contingencies (failure of a vital component, fire, depressurization, SPE, death of a family member on Earth, extreme thermal conditions, sleep shift/loss, low tolerance for errors)

In addition to these aspects, total duration of the mission must be considered. Based on ISS missions, we assumed a minimum lunar stay of 180 days. The maximum permanence on lunar surface is fixed at 240-360 days. Little sensitivity of volume to mission duration for stays of more than six months allows greater duration flexibility, and having partial gravity implies lower physical deconditioning than in microgravity (however, effects of low gravity have not been assessed yet, thus we must not overlook them).

Task Analysis

Task analysis has been performed trying to focus on activities to be done and their workloads, frequency and main stressors. All the activities can be performed by one or more crewmembers on IVA or EVA (both with and without rovers), unmanned teleoperated rovers, unmanned autonomous rovers, mission control and ground support. Cross-training tasks (i.e. tasks that can be performed by more crewmembers since they are not extremely specific) can be found and consequently tasks for only one astronaut can be identified. Cross-training tasks are communication, teleoperation of rovers, EVA, navigation, systems supervision, science, medical backup and maintenance. On the other hand, tasks that are not subject to cross training include piloting, medical qualifications, and geology tasks such as analysis of the samples. These results lead us to confirm a number of crewmembers between four and six. Moreover, since long-range rovers need a crew of three (so that two can safely perform an EVA with support on the rover), the final number of crewmembers adopted is six.

III. ENABLING TECHNOLOGIES

A permanent lunar outpost requires that several technologies be employed to increase and eventually achieve self-sufficiency, i.e. to stop relying on Earth supplies. Two enabling factors will be now discussed: In-Situ Resource Utilization (ISRU), whose importance is probably unquestionable, and a lunar greenhouse, whose feasibility is still under discussion.

In-Situ Resource Utilization (ISRU)

As presented in many papers[3,4], potential lunar resources include H_2 and O_2 for propellants, O_2 and H_2O for life support, and other elements or compounds for chemical and metallurgic production processes. Lunar regolith is the most likely primary feedstock from which we can extract useful resources. Regolith is made up of tiny particles described by log-normal size distributions whose mean diameters range from 45 to 100 μm: regolith mainly contains minerals such as plagioclase, pyroxene, olivine, ilmenite ($FeTiO_3$) and spinel ($MgAl_2O_4$).

ISRU carries many implications on a permanent human lunar settlement[5,6,7]. Several are the benefits that can be traced back to the incorporation of ISRU in the outpost design from the beginning, i.e. involving the phases of outpost deployment until lunar base growth and self-sufficiency.

Considering the production of oxygen, the following benefits emerge:

- Complete closure for oxygen in life support systems (outpost modules and EVA systems)
- Propellant production for robotic and human vehicles (ascent vehicles and hoppers)
- Regeneration of fuel cell consumables

Along with oxygen production, there is also water production, whose benefits result in:

- Complete closure for water in life support systems (outpost modules and EVA systems)
- Radiation protection
- Thermal energy storage

Finally, regolith processing brings about the following benefits:

- Site preparation: roads, pads, berms realized with lunar feedstock
- Structures built with in-situ materials
- In-situ repair and reuse
- Thermal energy storage and use from processed regolith
- Power generation (He-3 for instance, being more abundant on the Moon than on Earth)
- Solar arrays, concentrators, and other equipment fabricated with in-situ materials
- Crew radiation protection

All the above-mentioned aspects additionally result in two important advantages coming from ISRU:

- Mission flexibility due to use of common modular hardware and consumables
- Reduction in launch costs, since the more the elements produced in-situ, the less the mass we have to launch

One process to extract oxygen from lunar soil is hydrogen reduction of ilmenite, which applies particularly to titanium-rich regolith. The primary product is water, which may be electrolyzed to oxygen and hydrogen, with the hydrogen being re-used in further reduction. This process is more suitable to areas where ilmenite is abundant, like lunar maria in near-equatorial regions, and it requires high temperatures (around 1050°C). Therefore, this is not the most efficient technology for a base, especially at the South Pole, but it is more mastered than others. As a consequence, we suggest using it for the beginning while trying to develop and test other more efficient techniques. In this fashion, we have defined several phases (called "campaigns"[8]) for developing the ISRU necessary for lunar base self-sustainment, from robotic teleoperated rovers to big plants processing large quantities of regolith.

Oxygen production

In our study, not only is ISRU included to support the lunar base, but also to produce propellant for missions from Earth to Mars, since the final goal of the present space exploration scenario is the manned exploration of the Red Planet. A thorough analysis of the literature led us to consider the Lagrangian point L1 as a suitable candidate for exchange and storage[9]. A depot in L1 can be maintained in a halo orbit with low station-keeping requirements, has a privileged position for Earth communications, and can be reached easily both from Earth and the Moon. Then, a manned mission to Mars using cryogenic propellants should be launched in LEO, and from there reach L1 where it will find tanks previously sent from the lunar surface with all the oxygen needed for the outbound trip to Mars. At this point, using a gravity assist from Earth, the spacecraft can perform a Trans Mars orbit injection followed by a Mars Orbit Injection, stabilizing its orbit around the planet near all the equipment sent in advance, possibly using electric propulsion. Consequently, estimates suggest that ISRU has to provide 2.3 mT of oxygen per year to the ECLSS with 96% regeneration, 17.4 mT O_2/year for propellant production for Moon-Earth transfers, and 44.2 mT O_2/year for propellant production for Moon-Mars transfers.

Cold traps

The Apollo and Luna missions brought back over 382 kg of lunar samples, but since most of them were collected from the equatorial regions, which are unrepresentative of the lunar surface, more sampling needs to be performed. Data on Polar Regions are only known from remote sensing surveys thanks to the satellites orbited around the Moon by space-faring nations. From observations like these, the presence of water ice in permanently shadowed craters near the poles has been suggested for long: water is thought to be enclosed in these "cold traps" where the temperature is below 40 K (coming from the Diviner instrument on

Lunar Reconnaissance Orbiter[10]). The removal of water from regolith pores is a physical process requiring far less energy than oxygen extraction through hydrogen reduction of lunar ilmenite. Of course, a campaign to locate and validate accessible water ice resources must be carried out beforehand: were this campaign successful, then an affordable human long-term presence on the Moon would be enabled. Recent studies have suggested that cold trap water ice could be present in Craters Cabeus and Shackleton (see results from LCROSS, Lunar Crater Observation and Sensing Satellite), but also in Aitken basin[11]. Icy materials in smalls craters appear as small grains (approximately less or equal than 10 cm in size) mixed with regolith, or as a thin coating of ice on rock. These measurements are in urgent need of verification: in fact, the source of hydrogen may be accumulation of solar wind hydrogen, and not to the presence of water[12]. However, accessing cold traps, identifying the presence of ice, and exploiting them, are activities that pose major technical challenges, and are therefore beyond the scope of near-term missions. Fortunately, robotic assets to operate in cold traps have already been proposed; for example, Carnegie Mellon University's Scarab robot[13] mounts the so-called RESOLVE payload, Regolith and Environment Science & Oxygen and Lunar Volatile Extraction.

Besides, other technologies to produce oxygen in situ are currently under study. Indeed, they could represent alternative techniques to sustain LOX production and answer the requirements. In particular, some of the most promising technologies are[4]:

- Reduction with methane (1600 °C, max yield 50%)
- Vapor phase pyrolysis (2000 °C, max yield 50%)
- Sulphuric acid reduction (low yield)
- Electrolysis of molten lunar regolith (1600 °C, max yield 50%, most straightforward approach)
- Electrolysis of solid lunar regolith (900°C, max yield 50%)

<u>Lunar Greenhouse</u>

A lunar greenhouse on the Moon presents a new and complex system that would need to be researched thoroughly before its implementation. For this reason, a feasibility study and investigation into the best areas for research conduction have been explored in attempts to make the first steps towards its application.

The greenhouse is at first examined at a baseline level with multiple constraints to allow for a model that contains the most advanced and versatile sub-systems to make Equivalent System Mass (ESM) estimates. The crew size, diet and plant selections remain constraints in this study while the initial sub-systems are meant to be variable to allow for the consideration of future technologies that could bolster the greenhouse design further.

The greenhouse would be fit for a crew of six members. The diet, scaled to fit their needs, would consist of the crops outlined in Finetto *et al.*, 2010[14] that coincide with the Energy diet. This chosen diet can provide the crew with 67% of their dietary needs, and has the long-term benefit of having a low ESM compared to the other proposed diets. It would require a total area of 162 m^2 and 236.6 kW of power, a costly but necessary amount.

The baseline sub-systems were chosen considering a couple of key factors: complexity, ISRU implications, density/mass, maintenance, potential for future technological growth, and resource management. Each of these factors were weighted equally with the exception of the density/mass and ISRU implications and this was done for the research's heavy involvement in furthering ISRU research and the great cost associated with each systems impact on the total ESM. The sub-systems that were considered were the external structures, nutrient delivery system, crop handling system, and illumination system. The need for spares was also noted and considered as an auxiliary and dependent sub-system. From each category, choices were proposed and eventually narrowed down to fit the baseline model. A cylindrical rigid structure was chosen over inflatable and hybrid structures for its simplicity of design and familiar reliability. LEDs powered with a photovoltaic power source were chosen for the illumination system because of their long life cycle, flexibility to change wavelengths, and promising growth for the near future. A hydroponic nutrient delivery system won out over aeroponics and zeoponics on account of its high harvest index, toleration to malfunctions and high efficiency among other things. Zeoponics originally tied with the hydroponic system however the dependence on soil-like substrates and lacking research in the area made hydroponics the more favorable choice. The crop handling system was chosen to be partially autonomous, a balance between a greenhouse completely run by the crew and one run completely by an automated system. While the degree of this balance is not specifically specified, it highlights the need for both human and computer interaction for such a system.

Using these sub-systems for the baseline the Equivalent System Mass (ESM) could be calculated using equation [1] whose variables are highlighted in Table 1. This equation takes into account all the factors suggested by Levri *et al.*, 2003[15], except the crew time, which was disregarded for this study's purposes.

$$ESM = \sum_{i=1}^{n} \left[\left(M_i \times M_{eq} \right) + \left(V_i \times V_{eq} \right) + \left(P_i \times P_{eq} \right) + \left(C_i \times C_{eq} \right) \right] \quad [1]$$

Variable	Definition
M_i	total mass of the system
M_{eq}	mass equivalency
V_i	total pressurized volume of the system
V_{eq}	volume equivalency factor
P_i	total power requirement of the system
P_{eq}	power equivalency factor
C_i	total cooling requirement of the system
C_{eq}	cooling equivalency factor

Table 1: Variables and definitions of ESM equation.

The ESM was then calculated using volume, mass, power, and cooling as parameters with each having a different associated factor that put all data in terms of mass. These factors were acquired from literature with similar mission circumstances[16]: M_{eq}=1 kg/kg, V_{eq}=66.66 kg/m^3, P_{eq}=476 kg/kW, C_{eq}=163.9 kg/kW. As a result the baseline ESM was calculated and broken down by sub-system, as seen in Table 2, to make for a total of about 320 mT. Of this, 49% of this ESM was contributed by the external structure while another 48% was contributed by the illumination system, making each the largest contributors and therefore most fruitful areas of research concerning the baseline lunar greenhouse. Research in both areas would make the greatest impact in reducing the overall cost of a lunar greenhouse system while the nutrient delivery and crop handling systems would not have the same effects.

After analysing the baseline ESM it is clear to see that improvements and advancements in technology must occur before a viable lunar greenhouse can be created. Two other models can be used in comparison with the baseline to show how improvements can affect the ESM and overall feasibility of the system. The first model can be described as the credibly improved model and it focuses on technologies that are already undergoing promising research that should confidently be able to aid in the greenhouse modelling. The second model is more far-reaching and crafts a greenhouse that is based on technology that is currently under speculation or has only currently undergone discrete or isolated testing. While the first model can be quantitatively compared to the baseline the second can offer insight into another alternative that may work in the future.

The credibly improved advancements considered, but not limited to, are the changes that could be made in launching costs, 3D printing, inflatable structures, LEDs and spares. 3D printing technology allows for the creation of bigger space structures, on-demand manufacturing, and optimization of parts for space[17]. Inflatable structures are less massive, have better deployment reliability than their rigid counterparts, and can reduce the volume equivalency factor through new packaging possibilities. LEDs are predicted to have exponential growth in efficiency for the near future opening up many avenues for improvements in the illumination system. Spares would subsequently be reduced through improvements in these possible areas. All of these would lead to a new ESM calculation as shown in Table 3, and when compared directly as seen in Figure 1 the areas of greatest impact can be seen to come from the massive reductions in power consumption and volume from the illumination and external structure systems. In this second case, all the equivalency factors remain unchanged, except for V_{eq} that has now become 32.37 kg/m^3, because of the use of inflatable structures.

Sub-Systems	Parameters				
	Volume (m^3)	Mass (kg)	Power (kW)	Cooling (kW)	Total (kg)
Illumination	1.60	2174	236.6	236.6	153708
External Structure	1965	24000	0	0	154987
Nutrient Delivery System	9.94	5386	2.55	2.55	7680
Crop Handling System	0.5	270	2	2	1583

Table 2: Baseline ESM, the combined systems yielded an approximate total of 317 mT

Sub-systems	Parameters				
	Volume (m^3)	Mass (kg)	Power (kW)	Cooling (kW)	Total (kg)
Illumination	1.58	2129	94.7	94.7	62752
External Structure	489	3600	0	0	19429
Nutrient Delivery System	9.94	5386	2.55	2.55	7340
Crop Handling System	0.5	270	2	2	1566

Table 3: Credibly Improved ESM, the new systems prove to drastically reduce the ESM from the baseline's 317 mT to 91mT

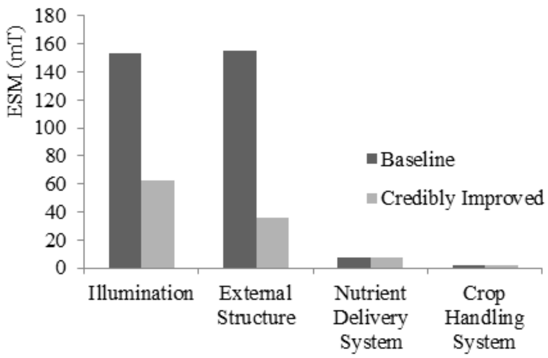

Fig. 1: Baseline vs Credibly Improved ESM Breakdown, the y-axis is the ESM while the x-axis lists the sub-systems

Breakthrough improvements can further aid in ESM reduction. With help from virtual reality (see next section), illumination can be set up in the most optimal areas of the lunar surface saving on energy usage. Or nuclear power could be used as a substitute source altogether. Minerals and metals could be obtained and processed in-situ to reduce or even eliminate costs in structures, spares, and nutrients, while LEDs could become specialized to increase crop yield and reduce disease in particular crops. Despite these technologies being in their early stages, if they have even been realized that far, they could have a huge impact on the feasibility of the lunar greenhouse, and this opens up the possibilities of future lunar exploration and ISRU[18] in a major way.

IV. OUTPOST CONFIGURATION

After sizing the crew and discussing enabling technologies, to establish a preliminary architecture for a lunar outpost it is also important to consider the location in which it will be built.

Outpost Location

A trade-off analysis on the place where the outpost can be placed allows identification of two important regions, the Equator and the South Pole. At the Equator, there could be more resources (e.g. Helium-3) to process than the ones present at the South Pole. Furthermore, at the Equator there are three different possible locations:

- On the near side: direct communication link with Earth but more problems for deep space observation (Earth electromagnetic disturbance)
- On the far side: good deep space observation but no direct communication link with Earth
- On the border between the two sides: compromise between the previous possibilities.

On the other hand, the South Polar Region has two factors that greatly favor human exploration: nearly constant sunlight, which favors power generation, and the likelihood of water. In fact, the nearby regions remain in constant darkness and could possibly contain water ice. In addition, the temperature at the suggested sites remains at a relatively constant -64°C, due to the steady light that the sites receive. A steady temperature would be much easier for a base to work with, as opposed to the extreme temperature swings that are common on most of the Moon's surface. Finally, low delta-Vs are required to reach the South Pole and launch windows are more frequent.

Considering the higher importance of water with respect to Helium-3, the chance of continuous communication with Earth, and the nearly constant temperature and lighting, the lunar South Pole appears to be a more suitable location for a permanent outpost. The precise location must then be sought near the South Pole. In particular, our trade-off is restricted to two sites: Mount Malapert and the rim of Shackleton Crater. The figures of merit (FoMs) chosen for the trade-off are lighting, continuous communication with Earth, cold traps access, and availability of a landing site. The result of this trade-off is shown in Table 4. Mount Malapert has the advantage to be permanently in line of sight with Earth and to be sunlit for long periods (around 90% of the year), but its high slopes (15°-30°) are indeed a disadvantage both for finding a proper landing site and for the setup of the modules. On the other hand, the rim of Shackleton crater has very low slopes (0°-5°), and it is closer to cold traps than Mount Malapert (around 4 km against 10 km). However, the rim of Shackleton crater sees shorter light periods (80-85%), and it is not permanently in line of sight with Earth. The latter problem can be resolved by noticing that Shackleton crater is always view of Mount Malapert: for this reason, if permanent communication with Earth is envisioned, a lunar communication terminal installed on Mount Malapert could guarantee the required link. For the purposes of this preliminary study, Shackleton crater seems the best location to build an outpost.

FoMs	Weight	Malapert	Shackleton
Lighting	0.30	5	4
Landing Site	0.25	2	5
Earth visibility	0.25	5	3
Cold trap access	0.20	3	5
Weighted total		3.85	4.20

Table 4: Trade-off analysis for choosing outpost location at lunar South Pole.

<u>Illumination</u>

The goal of analyzing system architecture for a lunar base near Shackleton Crater is a complex problem with many research elements. Considering asset placement, power availability, science interest in shadowed regions, or feasibility for inclusion of a lunar greenhouse and crops, all require an initial understanding of lighting conditions in the region. By modeling the region around Shackleton Crater in virtual reality (using the software VERITAS[19]), "real time" shadow projection can be used to track the locations of shadows over different sun positions using actual ephemerides data throughout a lunar day. A simulation such as this allows complete visualization of how illumination and shadows change over time. The graphics engine of VERITAS controls all shadowing placement, based on the specified location of a light source (the Sun). In order for the model to be useful, pre-defined realistic sun angles must be used in the system. Sun angles are general specified by an elevation angle and azimuth. However, azimuth is conventionally defined with zero as the north direction of the planetary body in question. At the Lunar South Pole, "north" is no longer a relevant or easily defined reference point, so an azimuth angle referenced from the zero meridian becomes a more meaningful method of defining solar direction. The following images in Figure 2 show shadows produced by the graphics engine with a 3D model of the Lunar South Pole, taken at varying sun orientations throughout a lunar day starting with the sun at 0°, or the lunar line of zero longitude, and a 1.5° sun elevation angle.

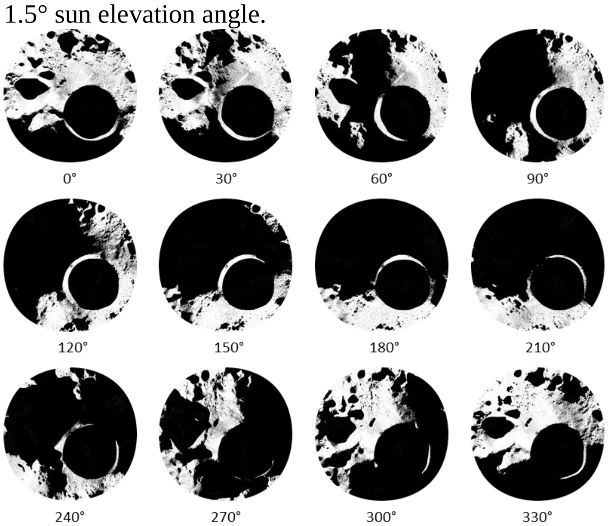

Fig. 2: Shadows at the Lunar South Pole and Shackleton Crater at 1.5° sun elevation and varying solar orientation angles throughout the lunar day.

Furthermore, the shadows rendered in a layer of the simulation are faded and merged over all of sun orientation cases, creating a clear, qualitative illumination map of the region for the time investigated. For example, merging the shadow layers from four sun angles (0°, 90°, 180°, and 270°) produces a layered image in which overlapping shadows create four shades of gray that indicate increasing time spent in shadow with increasing darkness, and vice-versa (Figure 3).

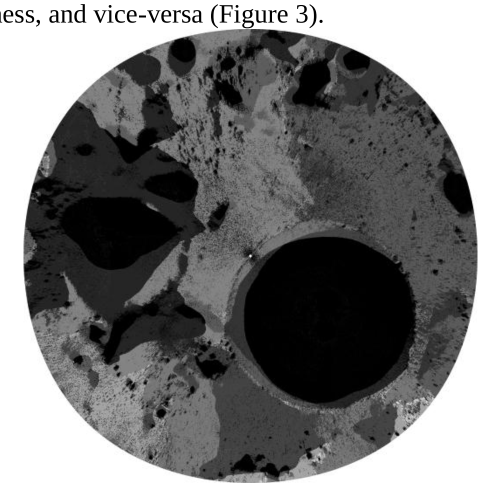

Fig. 3: Merged shadow layers over the terrain model for sun orientations at 0°, 90°, 180°, and 270°.

To produce a useful image indicating areas of highest potential sunlight, a set of thirty-six renderings of the model were used, each with a different sun orientation. Sun angle has been adjusted by 10° for each model image, and each uses a sun elevation angle of 1.5° - this is the maximum elevation angle the sun may ever reach about the Lunar South Pole[20], providing the maximum (or upper limit) potential sunlight. Merging shadow layers from all thirty-six sun angles results in a more detailed, more accurate illumination map (Figure 4a) in which black regions may be easily recognized as areas which see near-constant shadow. Normalizing the merged image (Figure 4b), the areas with greatest potential sunlight appear white and regions of longest extended shadow appear black, making areas of maximum potential light easier to see. The model used here employs digital elevation model data with a resolution of just over 230 m/pixel. The lighting conditions displayed by the illumination map in Figure 4 show areas of maximum potential sunlight at the upper-left rim of Shackleton Crater.

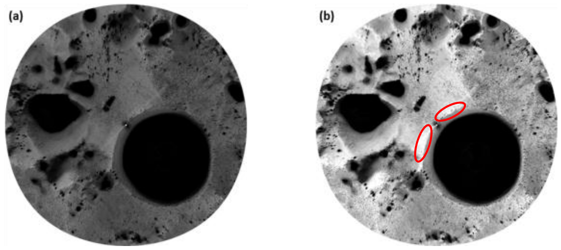

Fig. 4: Complete illumination map from merging shadow layers at all 36 sun orientations (a) and modified map with shadow color normalized from white to black (b).

This illumination map is consistent with previous studies[21] using lower resolution data (roughly 600 m/pixel), and provides greater detail. As is, the information from these images can help determine which areas of the Shackleton Crater region are most suitable for various lunar surface assets or components to a lunar base, such as solar panel and lunar greenhouse placement. Specifically, the relatively shallow section of the crater rim, shown at the upper left of the crater by two ovals in Figure 4b, presents a potentially ideal location for greenhouse and base-element placement. This area receives high potential maximum sunlight, while also a convenient place for initiating exploration of the crater interior. Increasing model resolution (which could be done for small, specified areas at resolutions up to 5 m/pixel) would provide information for more detailed decisions, such as asset specific placement based on lighting and local obstacles, or small areas of near constant shadow that could be interesting for the study of water-ice presence on the Moon.

Outpost elements

Thanks to a high-level functional analysis, it is possible to identify the elements composing the outpost, which is the first step to take before further proceeding in the definition of each module and of its subsystems. Ideally, a permanent lunar base should include the following modules:

1. Lunar surface habitat
2. Airlocks
3. Lunar Science Module
4. ISRU Plant
    a. Lunar Processing Plant
    b. ISRU Utility Carts
    c. Plant Power Source
5. Manned rovers
    a. Short range rovers (for outpost growth/maintenance)
    b. Long range exploration rovers
6. Unmanned rovers
    a. Rovers for outpost growth
    b. Rovers for outpost maintenance
    c. Rovers for exploration
7. Lunar spaceport
8. Lunar greenhouse
9. Storage module
10. Power plant
11. Lunar communication terminal

Other elements may exist, which are related to the well-functioning of the lunar base: for instance there is the ascent/descent vehicle, and possibly also a cis-lunar station supporting robotic teleoperations (before assembling the outpost modules) or hosting the crews on their way to/from the Moon. All these elements give rise to the study of a broad set of enabling technologies that are fundamental to the development of a lunar base. Some of them were analyzed in Section III.

To end this section, we discuss a possible architecture of a lunar base including the elements listed above. Proposing such an architecture is no easy task, since the functions of this outpost are so many that managing all the resulting constraints may be overwhelming. In order to generate some architectures starting from the modules that have already been defined, we begin by making some design considerations about modules disposition and interfaces. For instance, the lunar surface habitat needs to be in a central position so that its relationship with all the other modules is made easier. Protection from radiation and micrometeoroids is paramount; if lava tubes exist, we may consider burying this module in one or more of them. Then, the number of airlocks has to account for the number of crewmembers simultaneously on EVA. Considering also one backup airlock, we suggest to have four airlocks. The lunar science module needs to be accessed from the crew quarters; additionally, experiments (especially geological ones) can be also performed in situ by means of manned or unmanned rovers. Plants dedicated to in-situ resource utilization (production of oxygen and water from regolith, see section III) are dust generating activities, and so need to be far from the habitation modules. Nonetheless, they need to be close to the lunar spaceport for refueling purposes. The lunar spaceport requires a hardened area, for example a bermed or paved platform to reduce blast debris. Moreover, in order to reduce damages to other modules it needs to be 1 to 5 km far from them. If a lunar greenhouse is envisioned, it should be placed close to the habitat to provide food to the crew, and close to the science module to run experiments on plants. The storage module should be in a central position (i.e. close to the habitat module) since all the modules should benefit from the contents of this module, and it may include a vehicle maintenance facility since spare parts are stored inside it. The power plant has to be far from the launch/landing site to avoid contamination with exhaust. For solar generators, it is important to install them away from dust-generating modules, whereas a nuclear plant has to be placed far enough to keep radiation levels near human quarters as low as reasonably achievable. For energy storage and distribution, line losses can be minimized by placing storage devices close to the consumers: however, considerations about a power plant depend on the technologies chosen, and are discussed below.

Crew Accommodations

Once crewmembers are fixed to six and time of stay is between 180 and 360 days, some estimates for crew accommodations can be made. Even though 360 days might be too many and will have to be confirmed after a radiation impact study, our estimates are based on that number to take into consideration the worst case scenario, i.e. 6 crew times 360 days equals 2160 person days.

We need to consider[22]:

- Galley, food systems and wardroom
- Waste collection system
- Personal hygiene
- Clothing
- Recreational equipment
- Housekeeping material
- Operational supplies and restraints
- Maintenance equipment
- Photography
- Sleep accommodations
- Crew health care

For each one of these macro-areas, we can identify components and their mass, volume and power. Depending on the type, components' masses and volumes can either be fixed or vary with number of crewmember or person-days. Moreover, average required power and duty cycle have been considered for each component in order to determine the amount of energy needed in total from the power system.

Our estimates led to an average power need of 1.73 kW for a total energy of 15 MWh for a 360 days mission. The total mass of crew quarters is nearly 13 tons and the volume is of 115 m^3, without considering habitable volume, which is around 25 m^3 per person[23]. Moreover, pressurized volume shall be taken into account too and a low-gravity environment means that only part of the module can be accessed, but, for psychological reasons, ceilings should be high enough, thus the estimates for pressurized volume are around 100 m^3 per person. Thus, on 600 m^3 of pressurized volume, roughly one fifth is filled with crew accommodations.

Overall budgets

In this section, we present preliminary budgets of the lunar base outlined above. Regarding power, the baseline power of the outpost excluding the greenhouse and the ISRU plants is 30 kW; the peaking power, defined as the power required for 50% of the time, is of 40 kW. Power required by ISRU plants utilizing hydrogen reduction of lunar ilmenite is about 290 kW. The greenhouse power demands are very high and vary according to the crop selection. For the greenhouse sizing, peak power during lunar day is 260 kW, and during lunar night, the maintenance power is 12 kW. Recall that a lunar day lasts 708 hours, and on the rim of Shackleton only 13% of the day is dark.

A trade-off on the power system of this lunar outpost led to adopt nuclear only for ISRU, and photovoltaic for the rest of the outpost. Solar arrays area amounts to about 2100 m^2 for a peaking power of about 350 kW. They are supposed to be solar tracking: being at the South Pole, they require only one degree of freedom. As for energy storage, regenerative fuel cells are the preferred solution. An advantage of using regenerative fuel cells at the lunar South Pole is the presence of permanently shadowed craters at 40 K, which can enable the cryogenic storage of oxygen and hydrogen[24]. Normally, we would have to account for the liquefier mass: however, we can take advantage of the outpost location and place LOX and LH2 tanks in permanently shadowed areas (Shackleton crater in this case).

For some of the modules it was also possible to establish mass and volume budgets, which are presented in Table 5. These results were determined from preliminary analysis and will be refined in future work. Notice that in the mass of the ISRU plant, we also include the mass of the nuclear power source, so that the power plant mass includes only photovoltaic and regenerative fuel cells.

Base element	**Mass (mT)**	**Volume (m^3)**
Habitat	60	600
Laboratory	60	120
Airlocks	60	40
ISRU Plant	80	
Lunar Farm	60	1900
Storage Module	120	30
Power Plant	10	

Table 5: Mass and volume budget for some of the lunar outpost elements.

V. CONCLUSIONS

The journey to establish human presence outside the Earth in a permanent way has just started. In order to make it possible, one of the best ways is to proceed on an incremental path with relevant intermediate targets. Advances in technology will surely help achieve them, as many stimuli will arise thanks to the ambitious goals of humanity. The aim of the present paper was to investigate some of the enabling technologies on which research will have to be carried out in the future. Feasibility studies are the best way to guide future research, since they look at the problem from an overall point of view of the system.

As for future developments, several are the fields that need to be further explored. For instance, in view of the establishment of a permanent human lunar base, it is paramount to account for efficient EVAs to allow mainly outpost maintenance and lunar exploration activities. Gas-pressurized suits are indeed effective as a life support system, but they happen to be highly fatiguing to the wearer and a severe hindrance to normal mobility, since they are rigid, heavy, bulky, other than costly, leaky, and requiring high maintenance[25]. For Lunar and Martian exploration, aside from safety, flexibility and mobility are probably the most important design criteria to follow. In order to accommodate these requirements, it might be necessary to re-think spacesuit design, essentially overturning its *modus operandi*. A Mechanical Counter Pressure (MCP) suit could be the solution answering most of the requirements identified so far.

Another issue to be investigated is the chronic exposure to highly ionizing ions in the Galactic Cosmic Rays (GCRs) and sporadic acute exposures to Solar Particle Events (SPEs). Radiation shielding is then one of the most important topics to be tackled, since the lunar base architecture previously described accounts for stays lasting 6 months to one year. The most obvious solution to shielding can be found in the utilization of lunar regolith, whose supply on the lunar surface is essentially unlimited, and there is of course no need to transport it form Earth. Lunar regolith is also a great material to provide protection against meteorite impact, and diurnal cycle temperature buffering[26]. While on the Moon, the radiation quantities to consider are approximately half that of deep space, thanks to the presence of the soil: however, the presence of secondaries (mostly neutrons coming from radiation interaction with the ground) must not be overlooked. Unfortunately, the scientific community has not agreed on definitive estimates on radiation shielding on the Moon and radiation effects and the effectiveness of shielding is still uncertain, so most authors still rely upon experimental data and numerical simulations. The following considerations could be the starting point when considering radiation shielding of a permanent lunar base.

- 3D printers could be used to process lunar regolith and produce a compact shield to place on the outside of lunar modules
- The existence of lava tubes may simplify the shielding from radiations a lot: thus, we need to find evidence for them, starting from precursor robotic missions
- Precursor robotic missions may also contribute to measure radiation exposure and absorption
- The base modules could be partially buried in lunar ground. The regolith removed from the ground to accommodate the module could be then utilized to realize a radiation shield
- An architecture for these radiation shields made of regolith has to be devised (where to process regolith, how to install the shield, etc.)
- Layers of water or hydrogen, polyethylene or of other materials should be considered when making trade-offs regarding radiation shielding.

In conclusion, among the numerous factors that have to be taken into account in the realization of such a big enterprise, systems engineering has to act as the binding agent to manage multidisciplinary, complexity and favor creativity.

---

[1] “The Global Exploration Roadmap,” International Space Exploration Coordination Group, August 2013.

[2] W. J. Larson and L. K. Pranke, Human Spaceflight: Mission Analysis and Design, McGraw-Hill, 1999.

[3] M. Anand, I. Crawford, M. Balat-Pichelin, S. Abanades, W. van Westrenen, G. Péraudeau, R. Jaumann and W. Seboldt, "A brief review of chemical and mineralogical resources on the Moon and likely initial in situ resource utilization (ISRU) applications," *Planetay and Space Science*, vol. 74, pp. 42-48, 2012.

[4] C. Schwandt, J. A. Hamilton, D. J. Fray and I. A. Crawford, "The Production Of Oxygen And Metal From Lunar Regolith," *Planetary and Space Science*, vol. 74, pp. 49-56, 2012.

[5] NASA, "NASA In-Situ Resource Utilization (ISRU) Capability Roadmap, Final Report," NASA, 2005.

[6] G. B. Sanders, W. E. Larson, K. R. Sacksteder, C. Mclemore and K. Johnson, "NASA In-Situ Resource Utilization (ISRU) Technology and Development Project Overview," in *Space Technology and Applications International Forum*, Albuquerque, NM, 2008.

[7] G. B. Sanders, W. C. Carey, J.-C. Piedboeuf and A. Lorenzoni, "Lunar In-Situ Resource Utilization In The ISECG Human Lunar Exploration Reference Architecture," in *61st International Astronautical Congress*, Prague, CZ, 2011.

[8] G. Gatto, L. Levrino, S. Hall, J. Wellons, E. Gargioli, J.A. Hoffman, P. Maggiore, N. Viola, and M. A. Viscio, "Incremental Architectures for a Permanent Human Lunar Outpost with Focus on ISRU Technologies," *65th International Astronautical Congress*, Toronto, Canada, 2014.

[9] M. Baine, G. Grush and E. Hurlbert, "An open exploration architecture using an L-1 space propellant depot," in *Proceeding of the Space Ops 2010 Conference*, Huntsville, AL, 2010.

[10] D. Paige and et al., "Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region," *Science*, vol. 330, pp. 479-482, 2010.

[11] M. Deans, S. Moorehead, B. Shamah, K. Shillcutt and W. R. Whittaker, "A Concept for Robotic Lunar South Pole Exploration," 1998.

[12] P. Tompkins and A. Stroupe, "Icebreaker: An Exploration of the Lunar South Pole," in *Proceedings of the 14th SSI Conference on Space Manufacturing*, 1999.

[13] P. W. Bartlett, D. Wettergreen and W. Whittaker, "Design of the Scarab rover for mobility and drilling in the lunar cold traps," in *International Symposium on Artificial Intelligence, Robotics and Automation in Space*, 2008.

[14] C. Finetto, C. Lobascio and A. Rapisarda, "Concept of a Lunar FARM: Food and revitalization module," *Acta Astronautica*, vol. 66, pp. 1329-1340, 2010.

[15] J.A. Levri *et al.*, "Advanced Life Support Equivalent System Mass Guidelines Document," National Aeronautics and Space Administration, 2003.

[16] E. Janssen, T. Tse, X. Vanrobaeys, D. Hagenbeek, et al., "Design of an On Ground Experimental Growth Unit (OGEGU) for Space Applications," SAE Technical Paper 2005-01-2871, 2005, doi:10.4271/2005-01-2871.

[17] "Additive Manufacturing in Space." Made in Space. NASA Ames Research Park, n.d. Web. 18

[18] A. C. Charania and D. De Pasquale, "Economic Analysis of a Lunar In-Situ Resource Utilization (ISRU) Propellant Services Market," in *58th International Astronautical Congress*, Hyderabad, India, 2007.

[19] L. Rocci, V. Basso, "VERITAS Software User Manual", Thales Alenia Space, Issue 7, 2013.

[20] S. Bryant, "Lunar pole illumination and communications maps computed from GSSR elevation data," *Aerospace conference*, IEEE, 2009.

[21] B. Vanoutryve, et al., "An analysis of illumination and communication conditions near lunar south pole based on Kaguya Data," *Proceedings of the International Planetary Probe Workshop*, 2010.

[22] W. J. Larson and J. R. Wertz, Space Mission Analysis and Design, Space Technology Library, Microcosm Press and Kluwer Academic Publishers, 1999.

[23] M. Simon, A. Whitmire, C. Otto and D. Neubek, "Factors Impacting Habitable Volume Requirements: Results from the 2011 Habitable Volume Workshop," NASA/TM-2011-217352, Houston, Texas, 2011.

[24] L. Kohout, "Cryogenic Reactant Storage for Lunar Base Regenerative Fuel Cells," IAF-ICOSP89-3-8. NASA Technical Memorandum 101980, Washington, DC, 1989.

[25] J. M. Waldie, "Mechanical Counter Pressure Space Suits: Advantages, Limitations and Concepts for Martian Exploration," in *Mars Society Conference*, 2005.

[26] I. Schneider, A. Daga, P. de Leon and G. Harris, "Interim Report for the Human Exploration of the Moon and Mars: Space radiation protection and mitigation strategies for a long term duration lunar base (a NASA funded study)".