Lunar Base LOGISTICS

Team Blue

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***Abstract*—It is the year 2037. The Artemis program has been concluded, successfully with all goals met, bringing back people to the Moon after 1972. Reaching Mars is now the next main goal for human space exploration. However, the big scientific potential of the Moon has become more and more apparent over the years and it was recently decided to build a large research station on the Moon. This Lunar Research Station, which needs to be operational from the year 2040, will have a size large enough to house up to 50 people.**

This report focuses on the logistics involved in designing a human base from scratch on the Moon, including cargo and crew transportation via SpaceX's Starship, infrastructure and rover requirements, and in-situ resource utilization, with a particular emphasis on water ice.

The timeline for setting up the operational Moon base is divided into settlement and fully operational phases, requiring at least 11 launches for cargo and crew. This report provides insights into the complexities of establishing a human presence on the Moon and the challenges that must be overcome to achieve this ambitious goal.

***Index Terms*—Moon, Habitat, Starship, Timeline, Rover, ISRU**

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I. Introduction

According to definition, logistics is defined as the management of material and immaterial flows. In this project, it involves the transport between the Earth and the Moon, the transport over Moon surface and the utilization of the resources that can be mined on Moon. Furthermore, a detailed timeline of the mission is provided, split into the settlement and a full operational phase of the human base. Non-nominal scenarios, which are always part of a deep analysis, have also been covered, with also hints on what could be research areas for further developments.

A. Structure of the Report

II. Launch vehicle

A. Launchers comparisons

When it comes to finding suitable space vehicles for a manned mission to the Moon, the choice is rather limited. The main reason is that there are just a handful of rockets at the moment of writing the report that are technically capable of bringing a certain payload, i.e. a manned or cargo-equipped lander, to a low lunar orbit. It could be assumed that in the future other launch vehicles could be capable for the mission but there is little to no information about them for the general public. Because of it only rockets that have outlined development plans or are already in use were compared.

The launch vehicle will be selected between Falcon Heavy by SpaceX, Space Launch System Block 2B Cargo by NASA and the Starship by SpaceX. By the year 2037 the status of each vehicle will be considered operational, consequently the choice will be driven focusing on payload capacity to trans-lunar insertion (TLI), cost per launch and fairing dimensions.

	Payload to TLI	Cost per launch	Fairing dimensions
Falcon Heavy [1]	21 t	97 million $	⌀ 5.2 m h_{max} = 13.1 m
SLS Block 2B [2]	46 t	$\sim$ 2 billion $	⌀ 9.1 m h_{max} = 27.4 m
Starship [3]	100 t	10 million $	⌀ 8 m h_{max} = 22 m

Table I: Launchers comparison

The result of the comparison is reported in Table I. Which shows that Starship is by far the best option in terms of payload capacity and cost per launch which is why is was selected to be the launch vehicle for the mission.

Starship is a two stage rocket which is fully reusable. This means that both stages can return back to the ground using propulsive landing and control surfaces. This is one of the reasons why the cost of one launch could be around 10 million dollars. It is considered that there are two variants for second stage of the rocket - one is for the grew and another for cargo which can be seen in Fig.1. Important technical data about the Starship can be seen below. [3]

- First stage - Super Heavy Booster
  - dry mass = 180 t
  - propellant mass = 3,400 t
  - maximum thrust = 7,590,000 kgf
- Second stage - Spacecraft
  - dry mass = 90 t
  - propellant mass = 1,200 t
  - maximum thrust = 1,500,000 kgf
- Capacity
  - payload to LEO = 150 t
  - payload to lunar surface (orbital refueling) = 100 t
  - payload volume = 1,000 m^3
- Raptor engine
  - specific impulse, vacuum = 363 s
  - specific impulse, sea-level = 327 s
  - propellant LOX/CH4

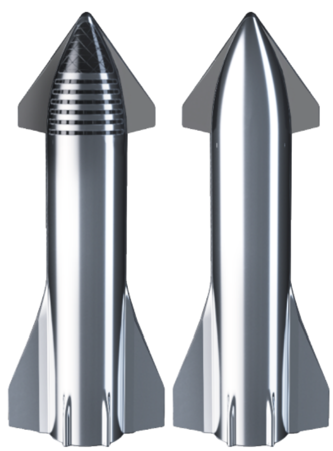

Figure 1: Starship crew (left) and un-crewed (right) configurations [3]

B. Starship's payload capacity analysis to the Moon

For approximating the payload capacity that Starship can bring to the surface of the Moon the rocket equation 1 was used. Where specific impulse (I_{SP}) shows the efficiency of the rocket engines in s, g_0 is the acceleration due to gravity on Earth in m/s^2, m_0 and m_f represent the initial and final mass of the vehicle in kilograms.

$$\Delta V = I_{SP} g_0 \cdot ln \frac{m_0}{m_f} \quad (1)$$

It can be seen that the required ΔV dictates the amount of fuel required based on the weight of the vehicle and the performance of the engine. Finding the required ΔV budget for the mission is critical for analyzing the optimal strategy for getting payload to the surface of the Moon.

Getting to the Moon was divided into 4 distinguishable steps that each have a dedicated ΔV requirement. To start the mission the launch vehicle has to put the spacecraft with the cargo or crew into low Earth orbit (LEO) for orbital refueling. From there the spacecraft can make a trans-lunar insertion to the Moon which will put it into an elliptical orbit towards the Moon. After that the spacecraft needs to get into a circular parking orbit around the Moon called lunar orbit insertion (LOI). Which is needed to initiate the landing sequence that consist of de-orbit burn, power decent and hovering. The mission trajectory to the Moon can be seen in Fig. 2. After the payload is unloaded the spacecraft will launch back to Moon's orbit, from there it will initiate trans-Earth insertion (TEI) burn and return to Earth which is depicted in Fig. 3. [4]

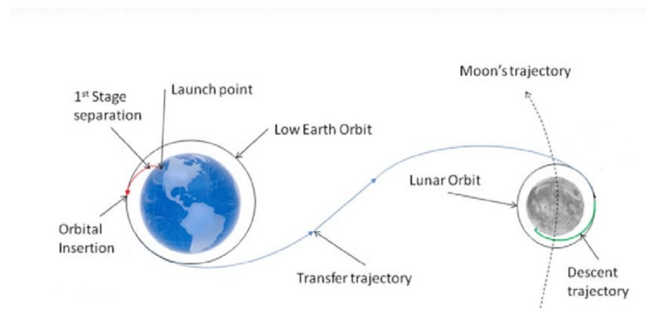

Figure 2: Lunar mission trajectory from Earth to Moon [5]

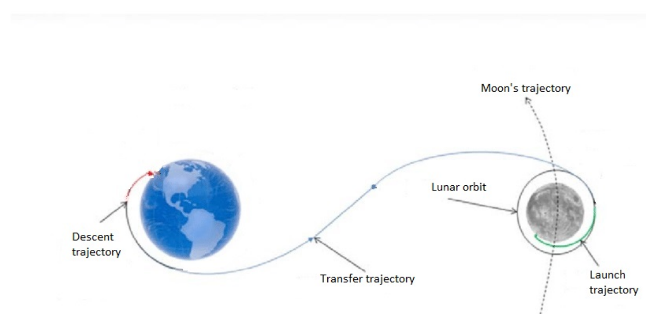

Figure 3: Lunar mission trajectory from Moon to Earth [5]

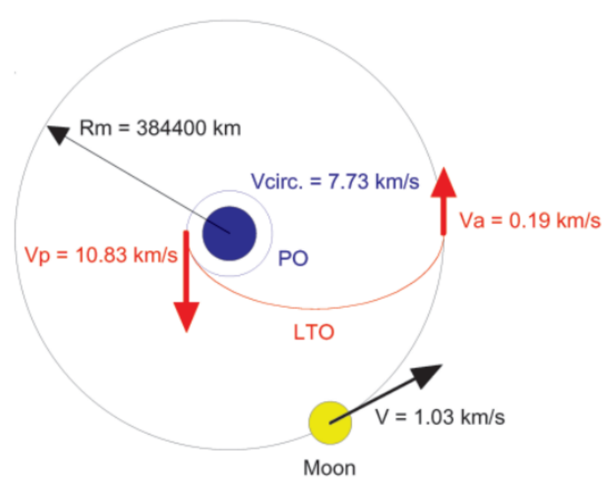

Figure 4: Direct transfer to the Moon [6]

1) Launch to LEO: The Starship with the payload is launched into low earth orbit where orbital refueling is performed. To fully refuel the orbiting cargo Starship it is assumed that 8 additional launches are needed with tankers that have 150 tons of propellant as payload. [3] This is required because the additional propellant can be used to bring 100 tons to the surface of the Moon. This step requires no additional ΔV for the spacecraft due to the fact that the propellant tanks are refilled.

2) Trans-lunar and lunar orbit insertion: After the spacecraft is fueled with 1200 tons of propellant, TLI burn is done to reach the sphere of influence of the Moon. Different approaches can be taken for calculating the required ΔV for this step.

Direct transfer such as Hohmann transfer represents the easiest way for getting from Earth to the Moon, Fig. 4. Although this method requires more ΔV than more novel approaches due to the fact that the spacecraft will be in an hyperbolic trajectory when it reaches Moons field of influence. Because of it the spacecraft requires additional deceleration burn for getting into circular low orbit around the Moon. None-the-less this approach was chosen because the time for getting to the Moon is only 5 days compared to months with other approaches such as weak stability boundary transfer. When using the Hohmann transfer the required ΔV is 3100 and 500 m/s for TLI and for LOI respectively from literature. [7]

3) Landing and launching from lunar surface: It was assumed that Starship has the capability of landing propulsively on the surface of the Moon without requiring any additionally propulsion system. Due to the fact that the National Aeronautics and Space Administration (NASA) has picked SpaceX's Starship has one of the human landing systems (HLS) for the Moon. [8]

Because Straship uses liquid oxygen and methane as it propellant it is not possible to refuel it on the Moon due to lack of resources for the production of methane. That is one of the constraints that need to be taken into account for finding an optimal strategy for getting to the Moon and back. Additionally, the required ΔV for landing and launching from the surface of the Moon was based on going straight from lower lunar orbit (LLO) of 100 km to the surface and launching back to the same orbit.

4) Return to Earth: Getting from the lunar low orbit to Earth is not as energy intensive as the other way around due to the fact that Earth's gravity is stronger than Moon's. Additionally, a free-return trajectory can be used when there is a failure with the propulsion system or other mission critical problem after TLI which enables the spacecraft to return to Earth. This trajectory was used for the first three Apollo missions and required no additional correctional maneuvers. [9]

After the required ΔV for each step of the mission was acquired the propellant needed for every phase could be calculated using the Eq.1 based on the payload, dry mass and the amount of propellant left. Using this method it can be seen that in Table II the required propellant for initiating the trans-earth insertion is not possible for a payload of 100 tons. This suggests that it is possible to get 100 tons to the surface of the Moon using one Starship but it will stay in orbit around the Moon. But lowering the payload capacity to 35 tons is sufficient for making a round trip from LEO to the Moon's surface and back to Earth as can be seen in Table III. This is the base case scenario based on the available information and with out taking into account any margin.

Phase	ΔV (m/s)	Propellant left (t)	Duration (days)
Start in LEO	0	1200	0
TLI	3100	392	5
LOI	500	357	~ 0
Landing	1730	121	~ 0
Launching	1730	1	~ 0
TEI	1300	-57	4

Table II: Performance parameters for Starship with dry mass of 90 tons, specific impulse of 363 s, payload mass of 100 tons

Phase	ΔV (m/s)	Propellant left (t)	Duration (days)
Start in LEO	0	1200	0
TLI	3100	430	5
LOI	500	357	~ 0
Landing	1730	172	~ 0
Launching	1730	57	~ 0
TEI	1300	2	4

Table III: Performance parameters for Starship with dry mass of 90 tons, specific impulse of 363 s, payload mass of 35 tons

III. TIMELINE OF THE MISSION

Close collaboration between other sub-teams was done for determining the required mass and volume of different payloads. Once the overall payload that needs to be carried to the Moon's surface is known, a suitable timeline was made: basically, the number and the frequency of launches and the specific payload of each launcher were determined based on two different capabilities of Starship. As stated in subsection II-B, there are two ways for transporting loads to the Moon: for heavy launches (payload > 35 *tons*) Starships will stay in in lunar orbit for later refueling, for light launches (payload < 35 *tons*) computations show that a round trip is possible.

From a temporal perspective, it is natural to split the timeline in two main phases: a first transitory phase where the base and all the needed infrastructures are actually built and a second steady phase where the base is in full regime and pursues the aims for which it was designed. This subdivision is performed in the following subsections, where we refer to a settlement phase followed by a full operativity phase. The former one will contribute to the initial cost of the global mission, the latter to the running cost.

A. Settlement phase

As main constraint we have that the base needs to be operational from 2040, so no more than three years can be covered by the previously defined settlement phase. Its main aspects are the actual building of the base, the realization of the solar power system, the construction of the infrastructures over Moon surface and the establishment of a permanent crew. In this phase not only all the equipment and material needs to be transported but also the human workforce with its necessary resources, workforce that for health reasons (due to radiation) has a maximum permanence of 7 months on Moon's surface.

Taking everything into account, in table IV are listed the launches required for the settlement phase, specifying what each Starship is carrying and what is its payload mass: in total, 11 launches define the settlement phase. As evident the launch order is such that what is carried to the Moon scales with priority; for example, the first launch comprehends the main tube and the construction equipment whereas only in the ninth launch the lab is brought. Furthermore, solar panels (1st energy source) are carried gradually over the phase: having them all since the beginning would have been not necessary. It is worthy to notice in table IV the difference between crew and cargo spacecraft, which will be discussed more in detail in subsection VI-A.

The 11 launches are distributed over time according to table V. 2037 and 2038 follow the same scheme: three launches at the beginning of the year followed by a change of crew (composed by 10 people) after 6 months. From a technical and organizational perspective the launches on January should leave Earth and reach Moon at the same time, but from a logistical point of view they are separated by three days in order not to monitor three trips simultaneously. At the beginning of 2039 we have three other launches and it is planned that everything that makes the base fully operational is completed within 3 other months: consequently, the end of the settlement phase can be set as 2039/04/01. Therefore, the base is planned to be fully operative in 2 years and 3 months. This allows for some delays and margin, very common in the space sector, as will be discussed also in subsection VI-A.

Launch order	Payload mass (t)	Type of spacecraft	Comment
1.	99	Cargo	Inflatable Main Tube, Airlocks (2), Construction rovers, Construction equipment
2.	99	Cargo	Habitat (1), Emergency Module (1), Solar Panels (25%), Nuclear Reactor
3.	27	Crew	10 people, Resources for 10 for 1 year, Hydrogen Fuel Cells, EVA suits, PWB Equipment
4.	28	Crew	10 people, Resources for 10 for 1 year, Pressurized rovers (2)
5.	97	Cargo	Storage, Airlocks (2), Life support, Solar Panels (25%)
6.	92	Cargo	Habitat (1), Emergency Module (1), Solar Panels (25%)
7.	25	Crew	10 people, Resources for 10 for 1 year, Unpressurized rover (1), Extraction rover
8.	24	Crew	10 people, Resources for 10 for 1 year, Unpressurized rover (1)
9.	92	Cargo	Workshop, Lab, Solar Panels (25%)
10.	49	Cargo	Greenhouse, Resources for 50 for 3 months, Unpressurized rover (1)
11.	30	Crew	50 people, Resources for 50 for 3 months

Table IV: Launch order for the settlement phase

Launch order	Date of arrival on the Moon	Comment
1.	2037/01/01	
2.	2037/01/04	
3.	2037/01/07	10 people arriving
4.	2037/07/01	10 people leaving 10 people arriving
5.	2038/01/01	
6.	2038/01/04	
7.	2038/01/07	10 people leaving 10 people arriving
8.	2038/07/01	10 people leaving 10 people arriving
9.	2039/01/01	
10.	2039/01/04	
11.	2039/01/07	10 people leaving 50 people arriving

Table V: Launch frequency for the settlement phase

B. Full operativity phase

The beginning of the full operativity phase coincides with the end of the settlement phase, so we can pick 2039/04/01 as reference date. The most important aspects can be identified in the resupply and in particular in the crew change. Differently from the previous one, we will not determine a specific end for this phase, even if it is possible to take as reference for the following launch frequency an operational window of 10 years.

The scheme adopted in reported in table VI, with people that are scheduled to stay on the Moon for half a year (except for crew A, only for a trimester). Basically, we have a launch every 3 months and each launch carries 25 people (referred as a crew) with resources for 50 people (2 crews) for 3 months. The associated mass payload for each launcher is 28 t.

It is worthy to mention that in table VI (where the year 2039 is considered, but the same pattern is repeated for the following years) different crew names do not imply that all members need to be different, e.g. people of crew A could then belong to crew D, but they can not belong to crew C.

IV. Transportation systems on the Moon's surface

A. Main locations

Depending of their dedicated activity, a lot of buildings will be apart from the lunar base. This section lists the main locations between which transportation has to be considered.

Launch order	Date of arrival on the Moon	Comment
11.	2039/01/07	crew A + crew B
12.	2039/04/01	crew A leaving crew C coming
13.	2039/07/01	crew B leaving crew D coming
14.	2039/10/01	crew C leaving crew E coming
15.	2040/01/01	crew D leaving crew F coming
...	...	...

Table VI: Launch frequency for the full operativity phase

1) Station: The station is the main location of the lunar base. That is where humans will live and researches will be performed. Most of the activities are gathered close to the station.

2) Launch/landing pads: The launch/landing pads will be located at least 1km away from the the lunar base [10]. They will regularly take spacecrafts carrying supplies (from cargo) or humans (from crewed vehicles). Moreover, according to the mission's timeline, there might be up to three spacecraft on the surface during the same period (Table V), thus three or four pads will be constructed.

3) Extracting sites: Extracting sites will depend on the precise localisation of resources areas. Concerning regolith, the resource is abundant and can be mine almost everywhere around the station. For water, its concentration and location are quite rough but ice is expected to be located in PSRs (Permanently Shadowed Regions). Such areas exists close to the base and allow the extraction of water [12]. For more precision, missions with dedicated rovers such as VIPER aim to detect water and map its concentration at the South Pole before the launch of this project [15].

B. Transports

There will be three different types of flows representing what need to be moved on the Moon's surface. One can notice: the resources, the supplies and the humans. This part is an overview of the chosen transports to operate the lunar base.

1) Resources: For water transportation, the Masten's rover will be used (Figure 10). It can carry up to 1000kg of water and will be mainly use between the extraction sites and the station. More description about the utilization of this rover is explained in part V-B. As for regolith, the resource will be mined and carried with a lot of RASSOR 2 (Regolith Advanced Surface Systems Operations Robot 2) rovers. They will be mainly used for the construction of the station. More information about this technology can be found in the Station Design report.

2) Equipment/Supplies: A lot of equipment or supplies will need to be moved on the lunar surface from the beginning of the station construction with modules, devices, solar panels to the regular resupplying with food, maintenance materials, *et cetera*. To do so, the ATHLETE (All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer) rover will be employed (Figure 5). More details about this rover are provided in the Station Design report.

Figure 5: ATHLETE rover carrying habitation modules

3) Humans: Transportation of humans on the lunar ground will depend on the type of EVA. One can identify three different configurations:

- Small and punctual leaps around the station: performed with the LTV (Lunar Terrain Vehicle).
- Long and distant trips: executed with the Lunar Cruiser.
- Short and regular journeys: operated with an adapted version of the ATHLETE rover. Several seats equipment from NASA's LANCE rover could be assembled on the rover (Figure 6).

See the report from Operation team for more description of these rovers.

Figure 6: Seat equipment from NASA's LANCE rover

C. Constraints

Two major constraints can be identified regarding transportation on the lunar surface: the lunar dust and the amount of time outside the base while humans transportation.

Figure 7: Lunar Terrain Vehicle from Northrop Grumman for NASA

Figure 8: Lunar Cruiser from Toyota

1) Lunar dust issue: One of the major issues affecting all movement on Moon's surface is the lunar dust. This disturbing dust has been highlighted since the several Apollo missions (where the biggest contribution to dust generation was the lift-off and landing of lunar modules) and remains today a significant problem. Half of the regolith rock is like fine sand and one fifth is less than $0.02mm$. These fine dust can lead to many mechanical issues (incorrect instrument measures, clogging, abrasion, failures, *et cetera*) but also harm the human's health (inhalation could cause important damages in the lungs). Furthermore, in the same way as the low gravity (one sixth of Earth's gravity), the lunar soil pose a problem regarding the traction of wheeled vehicles.

2) Duration and number of EVAs: Humans outside the station will have less protection regarding the harsh space environment. They have to spend as less time as possible outside the station in order to reduce their received radiation dose. All issues concerning ionizing radiation are explained in Part V in the Human Aspects report. Moreover, the dedicated time for EVAs to move between two locations is as much time unused for other important researches on the Moon.

D. Infrastructures

In order to handle the constraints explained in the previous section, it is required to consider and build some infrastructures on the ground: lunar roads and landing pads.

1) Lunar Roads:

a) Concept: One solution taken on are lunar roads. Such infrastructures would link and improve the exchanged flows between the important locations mentioned in part IV-A. They consist in a flattened track which can be optionally covered with regolith pavers or raised above the ground depending on the need. The roads are derived from the landing pads technology performed with the PICES rover [18]. In order to save money and mass carried on the lunar surface, the technology will be adapted to the ATHLETE rover already present on the ground.

b) Construction: The construction of the lunar roads consists in three steps:

- Leveling of the ground: realized with blade and roller tools.
- Sintering of regolith to form the pavers: created with the sintering device used for the construction of the station.
- Transport, drop-off and sticking of the pavers: performed with ATHLETE rover and a robotic arm.

Transposed to the ATHLETE rover, the technology would allow to build $3.3m^2$ per hour per rover. Considering the availability of 2 ATHLETE rovers, one kilometer of a 6-width road can be constructed in 2 weeks.

2) Landing pads: Landing pads will be constructed with the same technology as lunar road construction is derived from [18]. Effectively, pavers will ensure the exhausted gas from the rocket engines during the launch/landing not to melt the ground. Also, it will mitigate the lifting of dust in the surroundings and so, protect the facilities.

Figure 9: Experimental sample of a pavered area realised by PICES rover

E. Application

The transportation system has to be efficient enough and quickly set up.

1) Between the station and the pads: The way between the launch pad and the station will be one of the main way taken. A lot of goods will route through that track. That is why a **raised pavered road** will be considered between the station and the launch/landing pads. One can foresee around 15 round-trips per spacecraft arrival/departure (and even more during the construction phase of the station).

2) Between the station and the extraction areas: These ways between the station and the extraction areas will be little crossed, only punctually by extraction rovers. Furthermore, they might change depending on the exploration rate of the surroundings. Thus, it will be considered a **simple flattened track**.

3) Near sensitive areas: Some areas can be highly sensitive to lunar dust and need to be protected such as the station, the solar array fields, the maintenance hangar, antennas. Close to these sites, it will be necessary to construct **raised pavered roads** to protect the installations.

V. In-situ resource utilization

In-situ resource utilization and resource exploitation are critical components for the mission. More specifically, water is a key resource that need to be harvested for the base. It is also a stepping-stone for future human mission and space industry as it opens the door to new possibilities and perspectives for future missions, including those to Mars and beyond. [11]

A. Water usages

The location on site 001 close to the Shackleton Crater is located near several craters suspected to contain ice [12]. Harvesting water directly on the moon offers many advantages, including:

- Resupply of water: the total consumption of water on the base is estimated to be around 2 tons/day. If the water recycling rate is (optimistically) 95%, then the resupply need is around 100kg/day. If we consider a more realistic rate (90%, similar to the ISS), then the water resupply is around 200kg/day. Importing all this water would represents a huge logistics challenge and an additional cost (around 100 000$/year).
- Power Backup: water can be split into oxygen and hydrogen through an electrolysis process $2\,H_2O \longrightarrow 2\,H_2 + O_2$. Hydrogen and oxygen can then be stored in the *Regenerative Fuel Cell System* which can secure the electricity supply of the base.
- Fuel source: hydrogen can be used as a fuel source for rockets. Although Starships don't work with hydrogen fuel, the possibility of fuel production on the moon is very promising. For instance, the moon could be a refuel pad for rockets going for long missions such as Mars [13].
- Other uses: agriculture watering, research utilities, oxygen source for the crew (the leaks of oxygen are estimated to be 1.3kg/day according to Human Aspect), fuel for rovers, cooling liquid, etc.

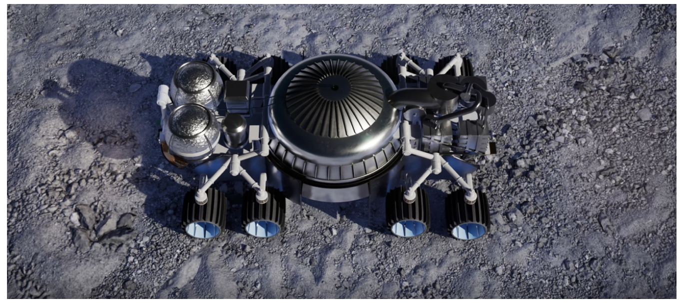

Figure 10: Masten's roover used to extract ice from the regolith

B. Water mining and storage

This section discusses about the technological solutions to collect and use the water on the moon. During the transitory phase of the base establishment, i.e. before 2040, we do not use water as a rocket fuel. Therefore, the estimated water needs are around 350kg/day, and could reach up to 700kg/day in the worst case scenario (during an long eclipse). Therefore, the water extraction solution must be able to collect at least 700kg/day. We consider here the Masten's rover [14] as showed in figure 10.
The concept of this rover involves using an ignition to excavate a predetermined area with water. After excavating the lunar soil, the rover collects various elements and applies a series of different processes to extract water from the mixture. This rover is supposed to collect up to 1.2 tons of water per day. To obtain this number, we made the following assumptions:

1. We know where the water is located. This is a reasonable assumption since missions will be launched by 2024 to map the water areas on the south pole of the moon [15]
2. The water ice concentration in high-concentration areas is 10% at a depth of less than 1 meter and 4% on average between 0.2 and 1 meter deep as shown in figure 11.
3. The rover dig a hole of 2 meters deep and with a $1m^2$ section. The efficiency $\varepsilon = \frac{water\_collected}{water\_available} = 0.75$.
4. The rover can operate up to 12 times a day. It needs to be charged by a power station every 3 holes.

These assumptions are mainly coming from Masten [14]. A video showing the functionning of the roover is available *here*.

C. Mining of other resources

This section discusses about the possibility of mining other resources than water on the moon for ISRU on the long term or economical purposes. However, it does not include research on lunar soil and the use of regolith for construction. These points are discussed in the Station Design and Human Aspects reports.
As shown in figure 12, the lunar soil mainly compound of oxygen-made elements that are not interesting for ISRU or industrial mining. However, some Helium 3 is present in the lunar soil in very small quantities: $3-4\ \mu g/g$ collectable according to the Lunar Sourcebook [20]. Helium 3 is interesting

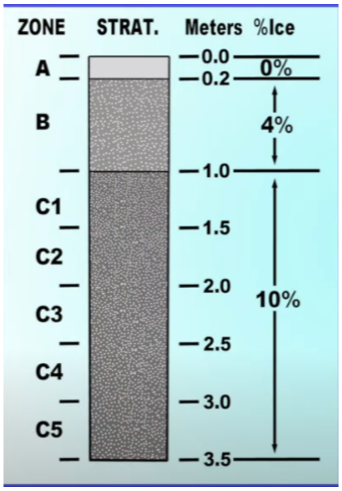

Figure 11: Water concentration expected near the Skeleton Crater [14]

for the use of nuclear fusion: the cleanest and most effective nuclear fusion reaction is

$$^{3}\mathrm{He} + {}^{2}\mathrm{H} \longrightarrow {}^{1}\mathrm{H} + {}^{4}\mathrm{He}$$

Unfortunately, there is almost no helium 3 on earth, and that's why mining it on the moon is a solution. However, Helium 3 is very, very, very low concentrated and huge amount of technology and materiel would be required to collect a reasonable amount of helium 3. Therefore, mining helium 3 would take time and investments, this is why we do not consider it during the establishment of the base. Our idea is to propose an open challenge, entitled the "BLISS challenge for Helium 3". This challenge will bring together researchers, students, and businesses to develop a strategy and rovers capable of efficiently mining helium 3 according to the specifications outlined in table VII. The different phase of this challenge are shown in table VIII. The challenge could lead to a intelligent solution that could be deployed before 2045. This would mark the inaugural "Space Mining" endeavor for the Earth, representing a significant milestone for the burgeoning industry of the future [16].

Table VII: Specification and information about mining Helium 3 on the moon

^{3}He Concentration	3-4ng/g on average, up to 20$\mu g/g$
How much regolith	Around 30 000 tons of regolith for 100kg
Rate of mining	Around 1kg/s
Criterias to win the prize	Autonomy, productivity and longevity

Table VIII: BLISS challenge for Helium 3

Objective	100$kg/year/rover$
Deadline phase 1	2040
Prize phase 1	1M $ for ten teams
Deadline phase 2	2042
Prize phase 2	10M $ for the winning team

Compound	Concentration (%)
SiO_2	42-48
TiO_2	1-7
Al_2O_3	12-27
FeO	4-18
MgO	4-11
CaO	10-17
Na_2O	0.4-0.7
K_2O	0.1-0.6
MnO	0.1-0.2
Cr_2O_3	0.2-0.4

Figure 12: Composition of the lunar soil BIBLIOGRAPHY

VI. Discussion

A. Non-nominal cases

As first non-nominal case we can consider the eventuality of construction works to require more time than planned. As discussed in subsection III-A, the settlement phase is scheduled to last only 2 years and 3 months, while the base is required to be operational 3 years after works have started. We have consequently a margin of 9 months that can be used to cover eventual delays and fulfill in any case our main temporal constraint.

Other off nominal scenarios are linked with eventual issues related to launches. As discussed in subsection II-B4, with a payload mass lower than 35 tons we are able to make a round trip from LEO to the Moon's surface and back to Earth. For this reason the subdivision between cargo and crew Starship is performed in table IV of subsection III-A: each crew Starship (both belonging to settlement and full operativity phase) carries from 25 to 30 tons in order to have the possibility to return safely to Earth if necessary. In table III we notice that with a payload of 35 tons we have 2 tons of propellant left, lower payloads will be associated to higher amounts of propellant left, which is never an issue to be solved.

From a human perspective, in case of some launch delays the time of permanence on Moon could be longer that 6 months, but still there is a month of margin with respect to the health constraint due to exposition to radiation. Furthermore, in the settlement phase the quantity of resources carried is always doubled with respect to the strictly necessary amount, forming gradually a stock to be exploited whenever required. If not touched, this surplus will consist at the end of the settlement phase in approximately resources for 50 people for 7 months. This amount will be kept as a backup and not modified (even if it is constantly renewed with resources more recently carried, adopting a FIFO logic).

B. Research areas

1) Electro-magnetic launcher: Transporting resources and cargo from the surface of the Moon to its orbit will be more frequent as research and mining on the Moon increases. But using conventional chemical propulsion is expensive due to the fact that not all propellant can be made on the Moon. Luckily going from the surface of the Moon requires 4 times less energy than on Earth do to the fact that there is no atmosphere to induce drag and that the gravity is 16% of Earth's. This gives the opportunity of using novel solutions for launching goods into low orbit around the Moon.

One of the proposed methods that could be researched on the Moon is electro-magnetic launchers, aka mass drives. The proposed launcher would use "push and pull" inductance coil-gun that can operate many cycles and is suitable for high speed applications. The mass drive could be situated in a crater that will give it the optimal angle of launch without needing additional supports. Additionally, being close to the south pole of the Moon where solar illumination is the highest gives an opportunity to use solar panels for creating the electrical power needed to accelerate the payload to the required speeds. Due to the fact that each launch is powered by the sun many launches can be made annually. Starting from the payload mass of 5 kg up to 500 kg as proposed in the following paper [17].

2) FLOAT: Flexible Levitation On A Track: Once this first permanent base will be establish, one can imagine an increase in lunar resources exploitation. For research or commercial purposes, other resources than water or regolith could be mined (Section V-C). However, Moon's constraints are still there and innovations regarding transportation will be needed facing the increase of resources extraction flows.

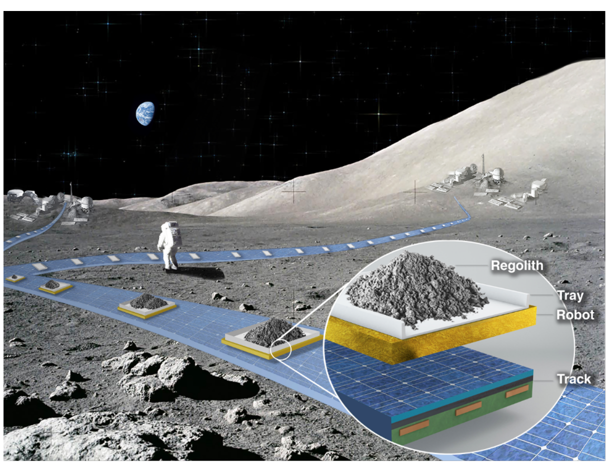

Figure 13: Unrolled FLOAT technology moving regolith on lunar ground [19]

Various researches are led in this domain and the FLOAT (Flexible Levitation On A Track) concept could tackle the several issues encountered on the lunar surface. This project is now supported by NASA Innovative Advanced Concepts and would allow to transport resources, consumables or even modules between different sites. It consists in a unpowered magnetic robot levitating above a flexible track made of graphite, flex-circuits (generating electromagnetic thrust to propel the robots) and an extra solar panel to power the system. Track could be directly unrolled on the ground and moved depending on the wanted site. Each robot could carry up to 33 kg/m^2 at a speed of 0.5 m/s. A large-scale utilisation of this transportation would allow to move hundred of tons on few kilometers per day [19].

VII. Conclusion

The establishment of a permanent station on the Moon will require precise logistics in its construction phase as much as in its running phase.

To do so, a comparison study has led to the choice of the SpaceX's Starship to carry payload and crew between Earth and the Moon. Furthermore, the launcher will perform a direct transfer trajectory. Regarding these first choices, two timelines have been introduced to meet the requirements of the settlement phase and then, the full operational phase. Once payload and crew have been carried on the lunar ground, it has been considered the transportation needed regarding their movement on the surface. In this way, lunar roads will be constructed and many different rovers will be used. Moreover, a study has been led to assess the possibility of ISRU. Locations and extraction means have there been described. Finally, off-nominal cases have been presented and research ares discussed in the last part of this report.

VIII. Division of Work

All members participated actively during the workshops, with a common sense of responsibility for the progress of work and a constant dialogue with all the subgroups of the Blue Team. The tasks of researching and writing of the report were divided as following:

- Matthias Rahu: *launch vehicle selection and Starship payload analysis to the Moon.*
- Riccardo Guglielmi: *design of timeline mission and non-nominal scenarios.*
- Robin Bernard: *transportation on the Moon's surface.*
- Xavier Fiat: *in-situ resources utilization.*

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