Celestial Heaven: Overall Coordination

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***Abstract*—This document gives an overview of what a permanent lunar base for 50 people could look like in 2037-2040. The location of the base is a crucial point taking into account a number of considerations such as view to Earth, solar illumination, presence of water ice, landing surface, or topography. The project involves a lot of different actors; contributors such as national space agencies as well as private partners. Assuming that, the budget is evaluated for the development and assembly costs and the yearly running costs once the base is fully operational. Finally, a risk analysis is conducted with potential solutions to mitigate the risks of living on a lunar base.**

***Index Terms*—lunar base, location, risks, budget, timeline**

I. INTRODUCTION

A. Project Background

It has been more than 50 years since humans last set foot on the Moon, until now. The NASA Artemis program has finally begun and humans should be back on the Moon by the end of the decade. With new advancements in technologies by both governments and private companies in space technology, a lunar research base, once long theorized, could finally be a reality. We like to think of space and stars as something completely foreign yet something that humans since the dawn of time have relied upon. As a result, the name of our base – Celestial Heaven – is a name that is fitting for the centuries of reliance on space exploration and that which is to come in the permanent lunar research station.

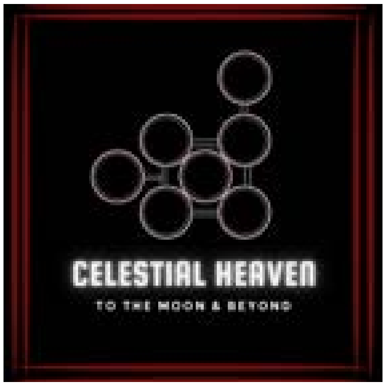


Fig. 1. Red Team Mission Logo and Slogan

B. Mission Overview

The overall mission for our team was coordinating with the teams of Station Design, Operations, Logistics, and Human Aspects, to provide a government-owned, safe, reliable, sustainable and livable environment where human lunar exploration could take place. Our team focused on the project management of the base including but not limited to location, risk analysis, political aspects, and budget analysis.

II. OVERALL MANAGEMENT

On top of deciding upon more general aspects of the lunar base, one particular focus for the overall management was to manage all the other groups. The different groups that made up the team along with overall management are Operations, Station Design, Human Aspects and Logistics. The main objective with the managing part was to ensure that the teams were all on the same page in terms of ambition and assumptions as well as to enable efficient teamwork.

The work of the groups was done both independently and during workshops. The workshops were then utilized for checking in on the different groups verbally, giving input and also getting information. This process was primarily done with one specific person who had extra responsibility of one subgroup, but also in the form of bigger presentations in front of the whole group. On top of the verbal communication, an Excel sheet was created where the groups continuously updated their assumptions as well as inputs and outputs. This continuous flow of information was crucial in order to maintain consistency in our designs and planning.

A lot of the work was dependent on work being done in other groups beforehand. This means that planning ahead is a requirement for the teams to be done with their respective parts in time, and in turn the whole project. To ensure this, a GANTT chart was created that involved the different steps each group should take and at what time it should be done. A copy of the GANTT chart can be seen in Figure 2.

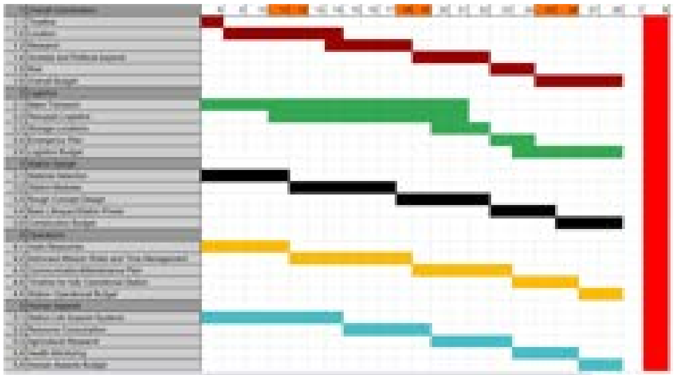


Fig. 2. GANTT chart for the different subgroups

III. LOCATION

A. Locations considered

The criteria that were considered for the determination of the location of the lunar base are:

- constant view to Earth for communications,
- high solar illumination,
- gentle slope for landing and Moon exploration,
- proximity to Permanently Shadowed Regions (PSRs) where the presence of water ice is very likely.

Based on the same criteria, NASA identified thirteen candidate landing regions for the Artemis III mission planned for 2025. They are all located within six degrees of latitude of the lunar South Pole. It is then assumed that this region will be very well documented by 2037, even more, because a small temporary lunar base will have been constructed by 2037. Among these thirteen sites, only those with the most sunlight (c.f. Figure 3) were selected. Among these four sites, the one for which the access to PSRs was the easiest, in terms of distance and slope [1], was selected.

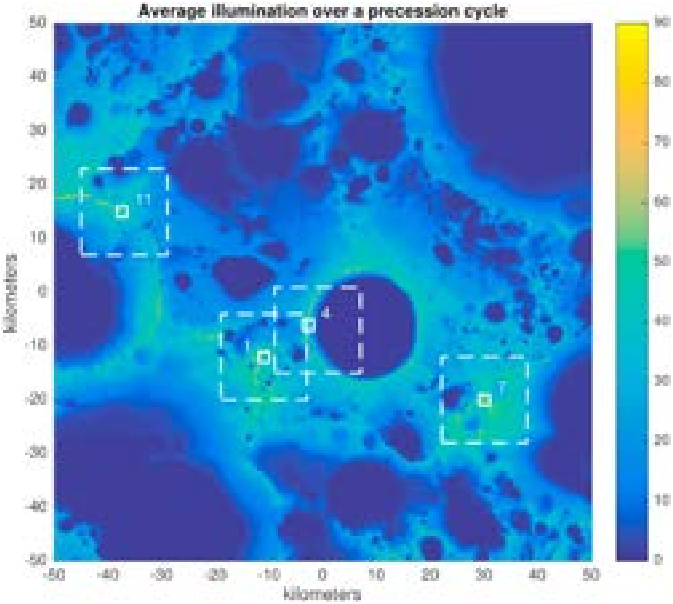


Fig. 3. Average solar illumination at the lunar South pole over an 18.6 years cycle, showing four regions with near-constant sunlight. [1]

B. Chosen location

Finally, site 011 on Figure 3 was chosen. It is located 88.7°S 67.9°W i.e. 40.6 km from the lunar South pole, on the rim of de Gerlache's crater which has a diameter of 32.4 km.

1) Visibility to Earth: The simplest way to communicate with Earth is via "line-of-sight" communication, which requires an unobstructed path between a transmitter on the Moon and a receiver on Earth. However, Figure 4 shows that the Earth is visible only 60% of the time at site 011. Therefore, other means of transmission are needed for Earth-based communications. As explained in the "Operations" team's report, communication will be possible by using the Lunar Gateway as an intermediary (or, when the Lunar Gateway is hidden by the Moon, by using another satellite on the same orbit as the Lunar Gateway but with a different true anomaly).

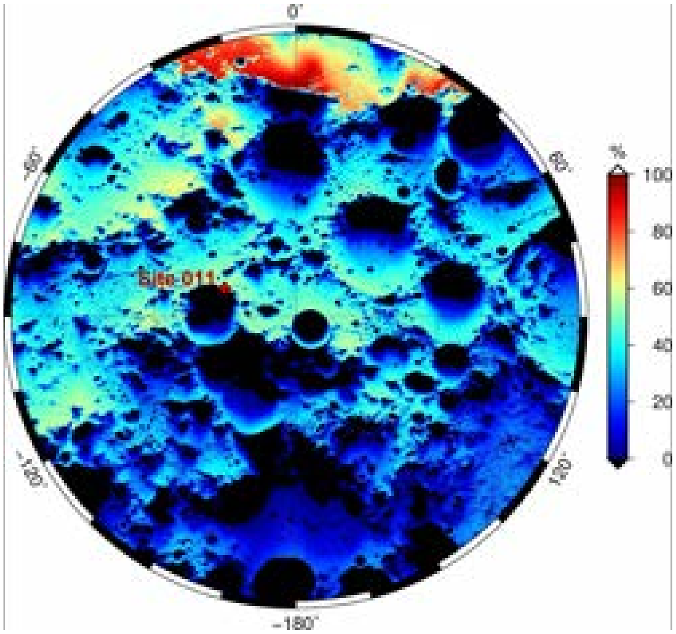


Fig. 4. Average Earth visibility at the lunar South pole over the 18.6 years precession cycle of the plane of the lunar orbit. The location of the base is shown by the red diamond. [2]

2) Solar illumination: Site 011 has 84% solar illumination on average over the 18.6 years precession cycle of the plane of the lunar orbit [1]. Reference [3] states that site 011 enjoys several weeks of continuous sunlight. It experiences only short eclipses (12–24 h) during the 6-month period centered on mid-summer. Finally, site 011 has the shortest maximum single eclipse period of any other location at the South pole: approximately six days. These conditions permit providing solar power and to mitigate the effects of brutal temperature changes.

3) Surface conditions: In the immediate surroundings of site 011, the boulder density (5 boulders per 250,000 m^2) and slope are modest [4]. The total area with slopes inferior to 5° around site 011 stretches over 1.0 km^2. Therefore, the site is able to accommodate the lunar base, as well as a landing pad and launch pad sufficiently distant from the lunar base itself to avoid lunar dust dispersal on the base, as explained more thoroughly in the "Station design" team's report.

4) Access to PSRs: The site is located close to several PSRs [4]. Access to these regions is crucial because they harbor icy regolith deposits that can be used for crew consumables and propellant production. Water ice can be found on the surface or within one meter from the surface, and is likely mixed with dry ice or other volatile constituents. A large PSR of 6.1 km^2 resides within de Gerlache's crater (c.f. Figure 5). From the base, the path to access it reaches 14.9 km and up to 25° slopes. A more accessible PSR of intermediate size resides 5.8 km from the base. The slopes can also reach 25° but if a longer path of 11.5 km is taken, it is possible to limit the steepness to 15°. In any case, a rover is necessary to access these regions.

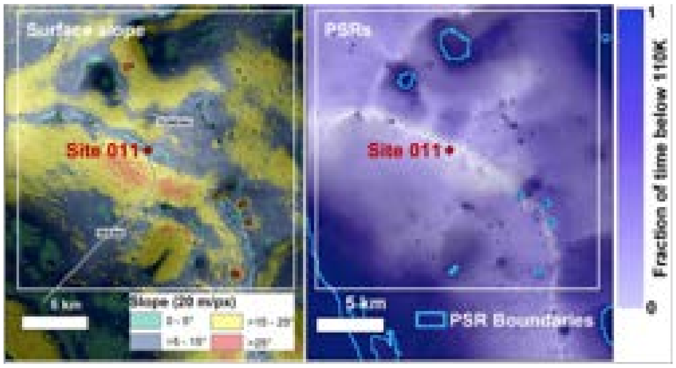


Fig. 5. On the left, slopes around site 011. On the right, the location of PSR around site 011. Two paths are drawn on the left-hand side figure showing access to intermediate-size and large PSRs within limited slope ranges. [4]

5) Geological context: Plains material and crater de Gerlache represent the oldest geologic units in the area. The crater has an estimated age of 3.9 billion years [5]. The site has then been modified by the addition of younger impact ejecta deposits. This context is ideal for research as it will help scientists on the lunar base to know more about lunar history.

C. Research fields

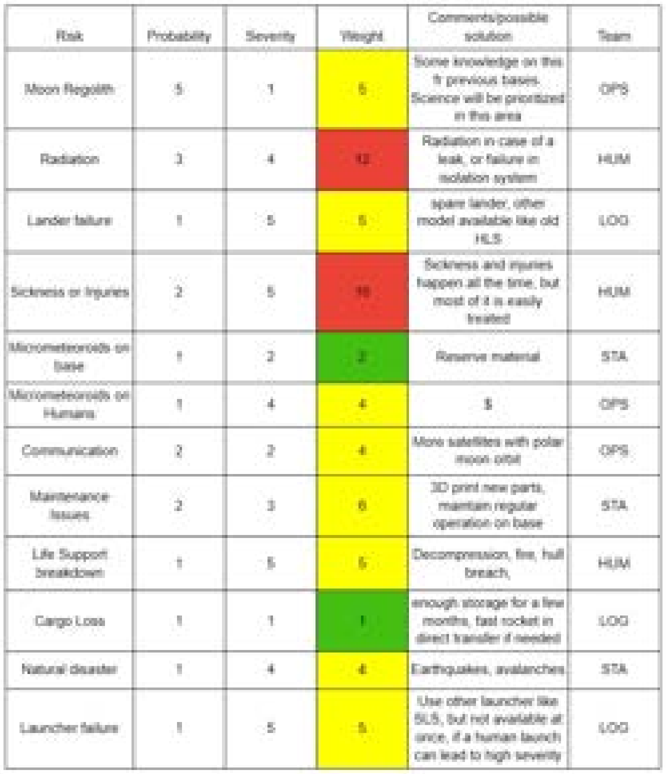
One important research field is linked to the Moon geology and resources around the location. Research on lunar ice will be necessary to determine the concentration of water in the ice, and how to separate it from dry ice in order to use it for water supply and rocket fuel production. Research on lunar geology will help to learn about the Moon's history and investigate the possibility of mining valuable resources. Research on lunar regolith will also help to determine if it can be used as soil to grow plants or as a construction material.

Another important field of research is the way humans adapt to the Moon. The astronauts' health can be studied to assess the physiological effects of deep space radiation or fractional gravity as well as the psychological effects of extended isolation on another celestial body. The lunar base efficiency and autonomy will also be researched. All of this will pave the way for more challenging missions like going to Mars.

Finally, the astronauts will be able to do more precise Moon mapping around the base and push the research on Moon navigation. Some fundamental science will also take place: the Moon is ideal for deep-space astronomy as there is no atmosphere. [6]

IV. RISK ANALYSIS

This project of realizing a lunar station implies sending astronauts for long missions. It is therefore necessary to consider and analyze the different sources of risks to be able to know their **weight** in terms of **probability that harm occurs** and **severity**. The probability and the severity are integers between 1 and 6. Thanks to this analysis, it will then be possible to **anticipate the solutions** to cope with these risks and to prioritize the risks by their weight.



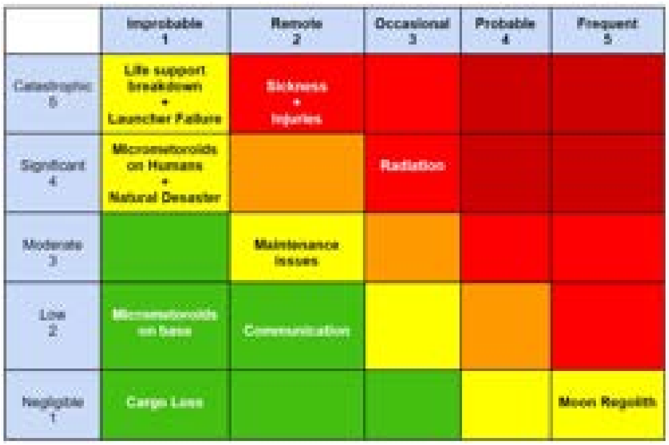
Risk	Probability	Severity	Weight	Comments/possible solution	Team
Moon Regolith	5	1	5	Some knowledge on this fr previous bases. Science will be prioritized in this area	OPS
Radiation	3	4	12	Radiation in case of a leak, or failure in isolation system	HUM
Lander failure	1	5	5	spare lander, other model available like old HLS	LOG
Sickness or Injuries	2	5	10	Sickness and injuries happen all the time, but most of it is easily treated	HUM
Micrometeoroids on base	1	2	2	Reserve material	STA
Micrometeoroids on Humans	1	4	4	$	OPS
Communication	2	2	4	More satellites with polar moon orbit	OPS
Maintenance issues	2	3	6	3D print new parts, maintain regular operation on base	STA
Life Support breakdown	1	5	5	Decompression, fire, hull breach,	HUM
Cargo Loss	1	1	1	enough storage for a few months, fast rocket in direct transfer if needed	LOG
Natural disaster	1	4	4	Earthquakes, avalanches	STA
Launcher failure	1	5	5	Use other launcher like SLS, but not available at once, if a human launch can lead to high severity	LOG

Fig. 6. Analysis of the main risks

A. Classification of the different risks

Figure 6 summarizes the main relevant risks that we have retained after discussion with the different groups.

The majority of the risks come from the *environment*.
Some are very probable – because ineluctable – but with a low severity such as from the **Moon regoliths**. Moon regoliths are composed of jagged, microscopic shards of rock, and Moon dust which is abrasive and irritating powder. Thus, they can be harmful to the astronauts and the machines in getting into the tiny parts.
The other risks caused by the particular environment (**radiation, micrometeoroids, natural disasters**) have a fairly low probability (between 1 and 3). The low probability of occurrence is explained either by the fact that several solutions have been put into place to minimize the risks (life support system) or by the fact that naturally, the risk has little chance of occurring, like natural disasters. Nonetheless, they can have some consequences in the long term hence the severity going from 2 to 4.



	Improbable 1	Remote 2	Occasional 3	Probable 4	Frequent 5
Catastrophic 5	Life support breakdown + Launcher Failure	Sickness + Injuries			
Significant 4	Micrometeoroids on Humans + Natural Desaster		Radiation		
Moderate 3		Maintenance issues			
Low 2	Micrometeoroids on Base	Communication			
Negligible 1	Cargo Loss				Moon Regolith

Fig. 7. Risks matrix

Another part of the risks come from *technical problems*: **communication, maintenance issues, life support breakdown**. The probability of occurrence is directly linked to the security and reliability of the systems and the severity is linked to the alternative solution setup. The probability of occurrence of these risks is therefore low but the severity can be high, especially in the case of a life support breakdown.

The final part corresponds to uncontrollable hazards with a very low probability of occurrence (between 1 and 2): **lander failure, launcher failure, sickness or injuries, cargo loss**. Except for the cargo loss for which a replacement with a new one is easy, the other ones have extremely high impacts.

B. Calculation of the weight and risk matrix

Fig. 7 corresponds to the final risk matrix.
To do it, we calculate the weight of each risk according to this formula:

$$\text{weight} = \text{probability} \times \text{severity}$$

Doing this matrix allows to hierarchize the risks according to their weights and to assist management decision making.
We can see that the risks to which we must pay the most attention are those coming from **sickness and injuries**, and from **radiation**.

V. LEGAL ASPECTS

As with any cooperative mission, there are bound to be disagreements between the parties involved, especially with a project of this size involving many different country agencies and possibly private parties. To mitigate the effects of such disagreements and to ensure all parties involved are on the same page, a set of rules were presented surrounding the lunar base and its operations.

A. Background on legal aspects

Before unveiling the legal policies that were believed to be optimal for the mission, some background information will be presented. The main inspiration was taken from existing treaties for spatial and lunar activity. Examples of those are the Artemis Accords, the Moon Treaty, and the Outer Space Treaty. All of the treaties utilized have a varying amount of signatories and therefore approval as shown in the Figures 8 to 10.

Fig. 8. Parties and signatories of the Moon Treaty (1979) [7]

Fig. 9. Parties and signatories of the Outer Space Treaty (1967) [8]

Fig. 10. Parties involved in the Artemis Accords (2020) [9]

A list of the most likely participating agencies and companies along with their percentage contributions was then brought about. This allowed for a comparison between the accords/treaties with the expected parties to create an applicable set of legal regulations. The expected parties and their contributions can be seen in Figure 11.

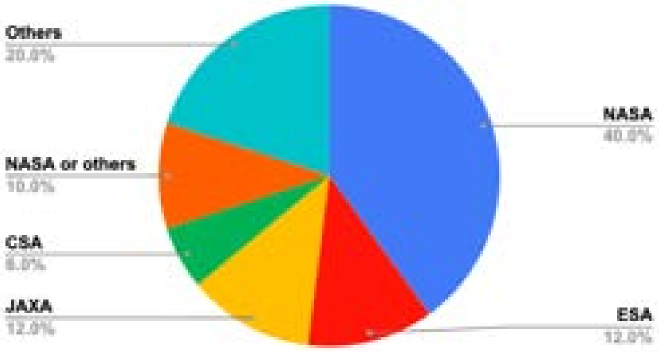


Fig. 11. Cost contributions of potential parties involved

B. Rules of the Lunar Space stations

With that being said the following set of rules was then assembled:

- Assume Artemis Accords have been signed by all space dominant nations and the lunar research station's contributors are only the governments which have signed the Artemis Accords (i.e. NASA (main contributor), CSA, ESA, JAXA)
- Governments involved will be able to rent out their own research space to private companies on the Lunar Research Station as long as they comply with Outer Space Treaty set by the United Nations, the U.S. Commercial Space Launch Competitiveness Act of 2015 (if applicable regarding nation), and the Artemis Accords.
- Research, discoveries and new technologies done by private companies must be public knowledge, however, discoveries and emerging technologies from such research belong solely to the private companies (patents).
- Countries wishing to participate in Lunar Research Station in the future must abide by the same rules and regulations and should provide materials to add their section on the base.
- The base in and of itself is "international" with certain parts of the research stations belonging to different countries. The nationality of each person on the lunar base will be fairly distributed but also representative of the amount of contribution towards the base.

VI. TIMELINE

The lunar base project is divided into two independent phases: the **Construction** and then, the **Expansion** (see fig. 5).

- **Construction**: It is the first phase which lasts between 134 and 250 days (about 4-8 months). This phase includes the delivery of the initial modules (materials for constructions), the arrival of the first crew, first cargo and first power source and the beginning of the exploration of a PSR and research for water ice. During this phase, vital needs are implemented and allow the crew to live on the short term.

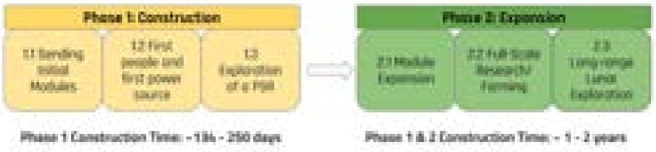


Fig. 12. Timelines of the lunar station

- **Expansion**: It is the second phase which is the development of the base in the long term. The base is expanded, and research becomes large-scale both to find resources and to develop new technologies. Farming is then being developed to allow the crew to limit the supply of food.

VII. BUDGET ANALYSIS

A. Government Budget Projections

As government funding appears to be the most likely way a lunar research station could appear by the year 2037, an analysis involving NASA's 2023 [10] and ESA's 2023-2026 [11] budget was made. NASA has a very structured distribution for its budget allocations, so by using the current budget allocations for the International Space Station (ISS), Lunar Research, and other research, a realistic budget of what would be applied if the lunar base was to be constructed in 2023 was made using NASA's budget. Since ESA's budget allocations were not as clear, to the best of the team's knowledge and resources available, a similar breakdown was made to that of NASA's.

Our team used the estimated budget of both NASA and ESA for 2023 and then did an estimated projection regarding an increase in budget for each of the agencies in increments of 1% and 5% each year.

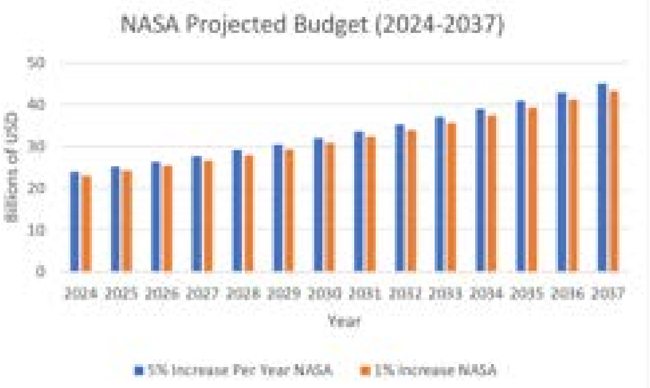


Fig. 13. NASA yearly increase projected budget with a 1% and 5% increase until the year 2037

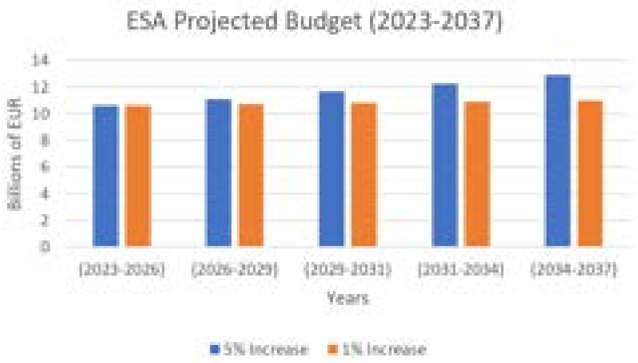


Fig. 14. ESA 3-year increase projected budget with a 1% and 5% increase until the year 2037

B. Preliminary Overall Budget

1) Overall Coordination: As the team responsible for the overall budget, our team evaluated a reasonable budget of what it would cost to build a lunar research base, based on the overall construction and operation costs of the ISS. Based on long-term costs surrounding the ISS, we thought a reasonable budget to be \$150 Billion ∼ €140 Billion (based on March 2023 currency conversion) for the successful construction of a lunar research station. The team then expected each sub-team to provide their own estimates based on the materials used, personnel required, and other factors each sub-team considers to be a necessity for the success of the overall project.

C. Budget Allocations by sub-teams

1) Station Design: Station Design's overall budget can be shown in Table I below. Many of the materials they require have been calculated using rough estimates. The group was tasked with calculating the necessary cost for the materials it would need to build the station, however, upon reviewing the materials the sub-team requires, it is clear that they must have underestimated as they could have forgotten to account for processing costs, such as the aluminum, and they could have forgotten to account for infrastructure costs and potential challenges of assembling such materials on the Moon. The team should be able to further explain their budget calculations, as such our team can only assume miscalculations on other unaccounted aspects pertaining to the material.

Product/Material	Estimated Cost (USD)
Facilities	280 000
Nuclear Reactor	4 400 000
Fuel Cells	15 000
Electrolyzer	5 000
Aluminum	3 600 000
Airlocks	24 000 000
Launch Pads	13 000 000
Antenna	50 000
Total Budget	**45 535 000**

TABLE I
STATION DESIGN'S BUDGET AND ALLOCATIONS

2) Operations: Operations' overall budget (c.f. Table II) seems to be realistic, based on ISS's yearly operation costs, however, it does forget to account for first-year costs, as they should be higher than the overall running costs. The main reason why first-year costs could have been neglected by the sub-team could be due to maintenance and operational issues that mainly occur when first building something new could have been forgotten, or assumed a robust system. The sub-team should be able to explain any miscalculations or misconceptions.

Product/Material	Estimated Cost (USD)
Rover: Rassor & Hippo	1 500 000 000
Communication	800 000 000
Maintenance	100 000 000
Water Storage	30 000
Aluminum	240 000
Total Budget	**2 400 270 000**

TABLE II
OPERATIONS BUDGET AND ALLOCATIONS

3) Logistics: The Logistics sub-team provided a neatly structured budget accounting for both first-year expenses (c.f. Table III) as well as each year thereafter (c.f. Table IV). The calculations made by the Logistics sub-team appear to be reasonable based on the cost per launch in the future and the type of vehicle they expect to use.

Product/Material	Estimated Cost (USD)
20 Launches (1 crew & 1 cargo)	3 000 000 000
Cargo Lander & Crew Lander & Spare Crew Lander	1 800 000 000
Total Budget	**4 800 000 000**

TABLE III
LOGISTICS BUDGET AND ALLOCATIONS (FIRST YEAR)

Product/Material	Estimated Cost (USD)
9 Crew Launches + 2 Cargo Launches per year	1 650 000 000
Crew Lander: Change every 10 years	60 000 000
Human Lander: Change every 2 years	300 000 000
Rover Maintenance: Change every 5 years (overestimate)	30 000 000
Total Budget	**2 040 000 000**

TABLE IV
LOGISTICS BUDGET AND ALLOCATIONS (PER YEAR AFTER YEAR 1)

4) Human Aspects: The Human Aspects team had an extensive list of potential expenses on their budget (c.f. Table V), their list accounts for all the aspects pertaining to the mission, however, some of the numbers could be underestimated as such products would have to be made specifically for the Moon. Overall, the budget seems reasonable in providing a rough estimate, however, there are likely to be more running costs in the future if such items were to increase in price or other factors. As for yearly running costs, the team estimated an amount of $300 000, making it a negligible amount realistically for the overall budget.

Product/Material	Estimated Cost (USD)
Atmosphere Management	1 300 000
Temperature Control	1 350 000
Water Recycling	1 000 000
Emergency System	250 000
Critical Danger Equipment	45 000
Medical Material	100 000
Light Treatment	25 000
Kitchen Devices	260 000
Sport Machines	80 000
Clothes	35 000
Leisure	25 000
Total Budget	**4 470 000**

TABLE V
HUMAN ASPECTS BUDGET AND ALLOCATIONS

D. New Overall Budget Accounting for Inflation and Miscellaneous Costs

Due to some calculation errors and unaccounted aspects in each sub-team, our team believes a more realistic budget for the first year should be adjusted by adding $10 billion to the current overall budget for the first year to account for our sub-teams' unaccounted materials/products.

1) Adjusted Overall Cost for First Year: The overall cost of all the teams for the first year, including the $10 Billion adjustment to account for other sub-teams' materials/products unaccounted for previously. Figure 15 then accounts for inflation adjustment based on the new overall budget. In Figure 15 an estimated $36 Billion will cost to set up the lunar base station for the first year.

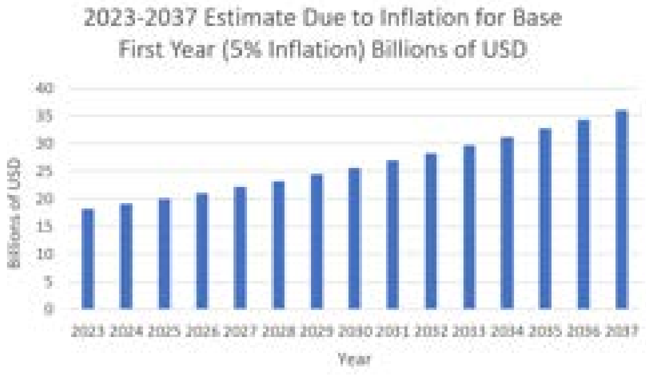


Fig. 15. Adjusted budget increase per year until the year 2037 based on a 5% increase in inflation and accounting for sub-teams unaccounted materials/products for the potential cost of the first phase of the overall lunar base

2) Adjusted Overall Cost After First Year: The overall cost of running the station using team's yearly estimates of running the station; accounting for inflation using a 5% increase until the year 2037. In Figure 16 an estimated $9.8 Billion to operate the station per year after the first year.

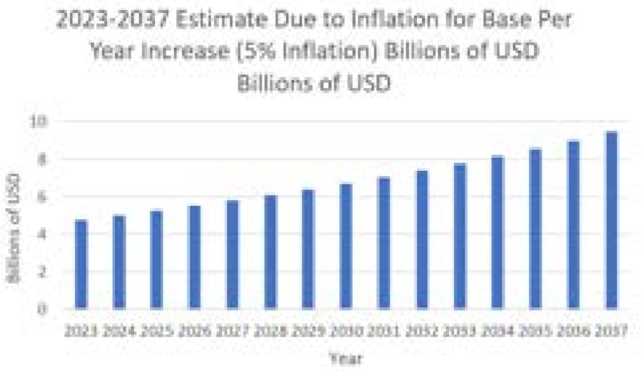


Fig. 16. Adjusted budget increase per year until the year 2037 based on a 5% increase in inflation

VIII. CONCLUSION

The team has been able to efficiently coordinate the other teams in their dedicated tasks while determining some important aspects of the mission, such as visual identity, location, budget and risks analysis, legal aspects, and estimated timeline. The base lies at a strategic point of the lunar South pole, almost always illuminated yet close to several PSRs harboring water ice. A legal framework has been proposed for this base, based on existing accords. The risks associated with the mission have been assessed and solutions anticipated. Finally, a timeline for the main phases of construction has been proposed, as well as a detailed estimation of initial and running costs.

IX. DIVISION OF WORK

The table below shows the division of work for the report. As for the information gathered for each section, each group member contributed equally.

	Eya	Luis	Hugo	Nils
Location			×	
Societal & political aspects				×
Risks	×			
Budget		×		

ACKNOWLEDGMENT

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