# Crowning Olympus Mons
# Blue Team - Project Management Report

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Submitted March 20, 2021

***Abstract*—Earth has an abundance of regions of spectacular geological features, many of which have now been explored and conquered, and humanity is now setting out for our neighbouring planet Mars. The Red Planet inhabits the highest mountain in the Solar System, Olympus Mons, that now waits to be explored. The main objective of this project, named the Hephaestus project, is to perform a mission design such that at least one human reaches the highest point of Mars' Mount Olympus, launching from and returning to Earth. The project work was split up among five groups, covering different aspects needed to satisfy mission objective and constraints. This paper describes a sample 3-year mission design proposal of the Project Management aspect of bringing the first human to the top of Olympus Mons, including an overall mission summary collected across all groups' work, funding, a mission cost estimation and reduction, political and societal aspects, law and space treaties, a risk analysis, as well as an off-nominal scenario. The total mission budget was approximated to be in the order of $17B, which was estimated to be feasible with today's available funding options, as well as through future events on the way to and on Mars. Furthermore, the mission proposal estimated sending an international crew of six astronauts to crown Olympus Mons, achieving the main objective and returning back to Earth. However, the mission would be complimented by research and other tasks to ensure reduction of the cost of the mission and optimizing the time in orbit and the 11-month stay on the surface of Mars.**

***Index Terms*—Interplanetary, Human Spaceflight, Mars, Martian expedition, Olympus Mons**

***Sammanfattning*—Jorden har ett stort antal regioner med spektakulära geologiska särdrag, varav många nu har utforskats och erövrats och mänskligheten blickar nu mot vår grannplanet Mars. Den röda planeten besitter det högsta berget i solsystemet, Olympus Mons, som nu väntar på att utforskas. Huvudmålet med detta projekt, kallat Hephaestus-projektet, är att utföra en uppdragsdesign så att minst en människa når den högsta punkten på Mars' Olympus Mons, genom att börja från och återvända till jorden. Projektarbetet delades upp i fem grupper som täckte olika aspekter som krävdes för att uppfylla uppdragets mål och begränsningar. Denna rapport beskriver ett förslag från projektledningsaspekten på ett 3-årigt uppdrag för att föra den första människan till toppen av Olympus Mons, inklusive en övergripande uppdragsöversikt ihopsamlad från alla gruppers arbete, finansiering, uppskattning och minskning av uppdragets kostnader, politiska och samhälleliga aspekter, lag- och rymdföredrag, en riskanalys samt ett icke-nominellt scenario. Den totala kostnaden för uppdraget uppskattades vara i storleksordningen $17B, vilket tros vara genomförbart med dagens tillgängliga finansieringsalternativ samt genom framtida händelseförlopp på väg till och på ytan av Mars. Vidare togs uppdragsförslaget fram att skicka en internationell besättning om sex astronauter för att bestiga Olympus Mons och därmed uppnå huvudmålet och återvända till jorden. Uppdraget skulle dock kompletteras med forskning och andra uppgifter för att hålla ned kostnader och optimera tiden i omlopp runt Mars och de 11 månader som tillbringas på ytan av planeten.**

## I. Introduction

### A. Mission Denomination

The mission to crown *Olympus Mons* is named Hephaestus, as this was the Greek deity that, among other things, built automatons that walked to *Olympus* Mount, where the Greek gods lived. The designed logotype for this mission is presented in Figure 1.


Fig. 1. Mission Logotype

### B. Project Background

EARTH has an abundance of regions of spectacular geological features, from high mountains to deep oceans, many of which have now been explored and conquered. Humans are now reaching beyond Earth to go further and explore new frontiers where no one has set foot before; among these, humanity is now setting out for our neighbouring planet Mars. The honor and glory of taking the first steps on the Red Planet is of great magnitude, but climbing its highest mountain, *Olympus Mons*, may be even greater.

This volcano on Mars has a height around three times that of Mount Everest, and a volume 100 times greater than of the Earth's largest volcano, Mauna Loa [1]. *Olympus Mons* is thought to have formed by the combination of Mars' low surface gravity and high eruption rates, allowing lava to pile up high into the atmosphere over millions of years [2]. Having earned the title of highest mountain in the Solar System, it now waits to be explored.

### C. Mission Statement and Constraints

The main objective of the Hephaestus project is to perform a mission design such that at least one human reaches the highest point of Mars' *Olympus Mons*. The mission shall launch from and return to Earth. No flying vehicle shall be used at an altitude above 10 km below the peak. Lastly, the last 1000 m altitude climb shall be completed without the aid of vehicles.

For the purpose of this mission it was assumed that, by the selected launch date, a handful of crewed missions to Mars had been completed, though there is no permanent human presence. There are, however, three bases with automated facilities that reliably provide sufficient water and methane to meet the requirements of the mission.

### D. Internal Organization

Due to the complexity of such an endeavour, the work was split into five groups; each was responsible for different aspects of the mission. This section aims to show the division of responsibilities of each group. Since most of these aspects were interrelated and directly influenced each other, most topics required collaboration among groups; the designated responsible group was, however, in charge of the task, its progress, and of maintaining proper communication about the task with other groups as needed.

There were 1-2 team meetings per week, and it was expected that all groups meet at least once more by themselves; an online form allowed for group updates to be relayed to the management group without the need to arrange extraordinary meetings. Slack was used as main channel of communication, and Google Drive was the information hub for the whole team. While some groups set requirements that needed to be met by other groups' work, all decisions were approved by all groups affected, and thoroughly discussed with Management members serving as moderators when an agreement could not be reached. Lastly, a format of presentation slides and final report were provided to each group to promote homogeneity throughout the presentation of the project.

*1) Mission Design:* The Mission Design group's focus was in the higher-level requirements for the mission in terms of timeline, interplanetary transfer orbits, mission profile, and propulsion budget. Mission Design determined the mission schedule, from Earth launch to return, including dates, trajectories, and windows of opportunity.

*2) Human Aspects:* The Human Aspects group was responsible for determining the crew size and the subsequent requirements to sustain their mental and physical health throughout the entirety of the mission. This encompassed some aspects and design feasibility of the rovers, orbital and on-the-ground habitats, and *Extravehicular activity* (EVA) suits. These requirements influenced and constrained the design of said vehicles by other groups. Moreover, Human Aspects took upon other requirements for the safe operation of manned activities on Mars, such as communications and optimization of selected location to minimize radiation intake throughout the mission.

*3) Space Vehicles:* The Space Vehicles group's main task was to devise a series of vehicles to allow for the transfer of the crew and other material needed for the mission from Earth's orbit to Mars'. In collaboration with the Mars Operations group, they aided in fusing the requirements of the interplanetary vehicle with that needed to not only land, but possibly "hop" to cover large distances within the planet. This included orbital re-entry methods, vehicle reusability, and coordination with the requirements set by the Mission Design group.

*4) Mars Operations:* The Mars Operations group was in charge of the mission profile after the crew arrives to Martian orbit. This involved the sizing of the rovers, planning for the mounting of *Olympus Mons*, transport from the selected base to the mountain, and the study of habitat designs for the time spent on the surface of Mars.

*5) Project Management:* The Project Management group was responsible for topics of the mission that did not fall directly under the engineering design field, but were still necessary to be considered in a manned, interplanetary mission. This involved a mission cost estimation, main funding options for a multi-billion dollar mission, ways to decrease the overall mission cost, a high-level risk analysis, and the influence of: politics, society, and the present and future legal framework in the development and viability of the mission.

### E. Crew Sizing

A major aspect which played a deciding factor in an extensive amount of choices for this mission was the crew sizing and composition; the team decided that a crew of six was a reasonable size for this mission. The crew would consist of five trained astronauts and one paying customer. The professional crew would be composed by: one electrical engineer, two mechanical engineers, a physician, and one other mission specialist to be determined once the scope of the research and hypothetical secondary missions to be performed in orbit and on Mars were established. The mission specialist could be a biologist, geologist or chemist, for instance.

One mechanical engineer was deemed crucial for managing any problems that may arise throughout the mission, but two were designated as to reduce the risk of mission failure when climbing *Olympus Mons*. The rovers have a high risk of breaking down during the mission, and having two mechanical engineers would decrease the risk of mission failure were one of them not able to join the expedition to the top. Then, a physician would be needed to provide adequate medical care given the risks of the mission and long-term exposure to the space environment; this need has been raised by NASA's own research [3].

Note that all crew members, including the paying customer, shall have completed the necessary astronaut training. While the professional astronauts will more than likely have a more in-depth training, all crew members shall have basic knowledge of medicine and of the hardware critical to the mission such as Life Support Systems, spacecraft operations, EVA suit procedures, etc.

## II. Mission Summary

This section aims to give an overall mission summary of the work by all groups previously described to ease understanding of the entirety of this project.

First, Mission Design devised the trajectories for the mission between Earth and Mars, as well as a general mission architecture. To select the trajectory, 700 000 direct trajectories were evaluated with departure dates between 2038-01-01 and 2042-12-31, travel time and required $\Delta V$. A Venus flyby was considered but ruled out due to the time astronauts would spend in deep space. Furthermore, trajectories where the arrival date on Mars occurred after the departure date were eliminated, for obvious reasons. After considering which criteria would be of the greatest importance for the mission, trajectories with the lowest $\Delta V$ requirements were selected. The chosen trajectories placed the departure date from Earth by 2039-09-19 and the return date by 2042-05-31, providing a total mission duration of 985 days, 339 of which would be spent on the surface of Mars; a timeline of the mission is shown in Figure 2. Moreover, the Mission Design group decided, in collaboration with the Mars Operations and Space Vehicles groups, to use two spaceships for the mission. One for the crew to travel to and from Mars, and one to travel from the landing site at a Martian base to *Olympus Mons*. Regarding communications, the Monarch Project [4] was selected to provide a communications link with Earth through the Deep Space Network.

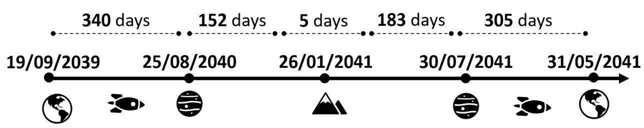


Fig. 2. Overall timeline of the mission

The Human Aspects group determined the appropriate life support systems, basic survival necessities such as food and water, followed by corresponding mass calculations. It was decided that enough water was to be brought along from Earth for the outbound trip to Mars, and supplies would then be replenished at the Martian base. To make this sustainable, water would be recycled from urine and condensation, and the atmospheric regulation would be made with a system based on 3 units of the *Environmental Control and Life Support System* (ECLSS) that is used on the *International Space Station* (ISS) today.

Once on the surface of Mars, the astronauts would need space suits to stay outside their habitat, such as when performing the climb of *Olympus Mons*. Human Aspects selected the “Bio Suit” for the astronauts to use, developed by Massachusetts Institute of Technology, which is a mechanical counter-pressure suit, thus much lighter and mobile than an air pressurized suit.

To keep the astronauts healthy during the mission, extensive workout sessions would be needed, which brought up the necessity of bringing exercise equipment capable of being used in a microgravity environment as well as on land on Mars. Another aspect that the Human Aspects group considered was radiation, and it was calculated that the total received dose from the entire mission for an astronaut would be about 1.2 Sv, just above the current *European Space Agency* (ESA) career limit of 1 Sv, enough to deem it as a reasonable amount. Furthermore, the psychological health of the crew was considered, which was planned to among other things keep the astronauts busy with research during the trip to alleviate boredom, depression, and other possible symptoms of a 3-year interplanetary mission.

Next, Space Vehicles selected SpaceX’s Starship as the basis for the design of the spaceships, as it is being designed with the main purpose of bringing humans to Mars; mainly, these being it’s propulsive capabilities and bearing a methane and liquid oxygen propellant system, make the spacecraft ideal for Mars. The main modification of Starship consisted of reducing the length of the payload system to lower structural mass, as the payload section was larger than required for this mission. The vehicle is designed to use SpaceX’s Raptor engines, which would provide the specific impulse necessary to “hop” from the Martian base to *Olympus Mons*, and back.

Lastly, Mars Operations selected the strategy for the 339 spent on the Martian surface. Once the astronauts have landed on Mars, preparation for the climb of *Olympus Mons* would begin immediately. The astronauts would be weak after the journey in microgravity, and hence in need of exercising in the newfound gravity to regain muscle mass and strength and acclimatize to the Martian environment. This would take about 150 days, providing ample time to get ready for the climb. The ships would then be fueled up to take the astronauts from the base to and altitude of 10 km below the peak of *Olympus Mons*. Once at the mountain, two pressurized rovers would be unloaded, acting as habitats during the climb, while being driven 100 km up the slightly inclined mountain side until an altitude of 1 km below the summit is reached; NASA’s rover concept is shown in 3 From here on, at least one crew member set to proceed the mission objective must walk on foot, though other crew members would be allowed to follow alongside in rovers as backup in case of emergency. Once the summit has been reached, the crew would return to the landing site, load the rovers back in the ships, and ”hop” back to the base. From here on, the astronauts would spend the remainder of the time on Mars performing secondary missions before finally returning to Earth with both spaceships.


Fig. 3. Space Exploration Vehicle Concept by NASA [5]

## III. Funding

### A. Main Sources of Funding

For a mission of this caliber, there are few sources that may be able to provide funding for all or most of the mission. First, one or several space agencies such as NASA, ESA, Roscosmos, et cetera could fund this endeavour; especially if they collaborate. Seeing the course of space missions since the Apollo-Soyuz test project in 1975, specifically the creation of the ISS, it would be safe to assume that space agencies around the world would collaborate to some degree to this mission.

Next, a partnership among private companies with the funds and resources to achieve the goal. This group is smaller; while there are many space companies (big and small) all over the globe, politics and national space law would have an even-heavier influence than in a collaboration among space agencies. A private partnership would most likely be limited to space companies within the same country, which would offer a considerable advantage to the United States.

Lastly, a private sponsor could, in theory, fund the whole mission. Seeing that the total mission budget approximates $17B (an in-depth cost breakdown is presented in chapter IV), and assuming any private sponsor would be as keen as Elon Musk to use half of their wealth towards interplanetary human travel [6], there are over 40 people in the world that could fund this mission [7]. Of these, at least two of them have space companies that are currently working towards bringing humans to Mars, so this funding source should be worth considering.

### B. Research Throughout the Mission

Throughout the mission there would be plenty of things to prepare for prior arriving to Mars. Nonetheless, there would be a significant amount of free time for the astronauts. There lacks literature in the effects of isolation in space combined with the inability of going back home that an interplanetary mission poses. However, it has been theorized by psychological studies of isolation experiments in Antarctica that a busy schedule helps promote a good mental health throughout extensive isolation periods. Admiral Richard Byrd, who spent a winter alone at a meteorological base at the Ross Ice Shelf in the 1930s, expressed that "the brain-cracking loneliness of solitary confinement is the loneliness of a futile routine. I tried to keep my days crowded", and that isolation is survived best by "those who can live profoundly off their intellectual resources" [8].

While the crew would get time off to rest and devote to their individual activities, too much free time could pose a threat to their mental health. Hence, including different kinds of research within the mission's duration could be advantageous not only to the funding of the mission but also to the crew's psychological stability.

*1) General and In-transit Research:* There are several fields of research that could be studied throughout the mission. The approximately 640 days spent in orbit to Mars and back provides a wide time window to perform research or gather data in the fields of human psychology (behavioral evolution of an isolated group of astronauts), human physiology (effects of long-term exposure to microgravity or reduced gravity environments), radiation protection methods, and sustainable life support systems.

Although this mission would likely not be the first to bring humans to Mars, it could be assumed that it takes place in a time where human interplanetary travel is not common; hence, most of the mission's aspects could be studied. This would not directly entail additional weight (if the purpose would be to gather data), as all are things required for the crew in the first place; funding could be secured in order to collect and analyze all the data generated by this mission, or to carry additional materials for experimentation.

*2) On-site Research:* During the 11-month stay on the Martian surface, certain research projects could be tackled with minimum mass additions to the mission:

- Soil sample return: as planned for future Martian missions such as ESA/NASA's Mars Sample Return mission, which is scheduled to bring soil samples to Earth by the end of this decade [9], the larger scale of a crewed mission to Mars would allow for larger and more varied samples of Martian soil to be returned.
- Volcanic research: Olympus Mons was formed by volcanic activity over millions of years. The vast magnitude of this topographical characteristic of Mars has led to deformations in the bedrock, which is believed to be porous and permeable, therefore presenting the possibility that it contains water in the present time [10]. As well, the material pushed onto the surface from the inner layers of the planet offers an opportunity to gather soil samples that may help determine the composition of Mars' mantle and the planet's history.
- Reduced-gravity research: Humans have been able to study everything from Earth gravity to microgravity more in-depth, with limited knowledge of Lunar gravity gathered during the Apollo missions. This mission presents an opportunity to research effects of Martian gravity that has not been able to be studied before, especially those on humans.

### C. Cargo Transportation and Re-supply Services

Limited additions in mass to the mission in order to carry cargo for third-parties would offer a way to partly fund the mission. Since there would be three different bases on Mars that produce methane and water, there may perhaps be a need to resupply or deliver materials. Whether it would potentially be needed for humans placed at these stations, or to perform upgrades or repairs on them, the time spent on Mars' surface would provide an opportunity to perform secondary missions of this kind as a source of income towards the overall funding of the Hephaestus Mission.

### D. Broadcasting to the World

This mission would be groundbreaking, and something people across the globe would like to see as it happens. Broadcasting all the important moments of the missions would therefore be a priority. The constraints for this mission state that it is not the first mission to mars, however an early one, and it would be the first mission to mount *Olympus Mons*. It would then be fair to assume great interest from the public in seeing the events unfold, even if it wouldn't be expected to receive the same amount of attention similar to those of the first lunar landings. This presents opportunities both for public outreach and funding.

As for funding, broadcasting live video and recording video content both present significant opportunities. The single largest event of the mission would be the mount of Olympus Mons. This event would have large public interest and be suitable for a live broadcast. Sporting events such as the Olympics and FIFA World Cup have been able to pull in more than 3 billion viewers [11], and the charity concert "Live Aid" had almost 2 billion viewers [12]. By making a realistic assumption that the general public prefer football over space travel, a conservative estimate could be made that 2 billion people would like to watch the mount of *Olympus Mons*.

The Super Bowl, the final of the American National Football League, is a very popular event in the United States, but has flopped internationally for obvious reasons. It is significant however in the success of its monetization. The 2020 edition gained 99.9 million viewers [13] but brought in $450M in revenue [14]. If the mission broadcast would be similarly monetized for the estimated 2 billion viewers, that would net a total of $9B.

The remainder of the mission could be made into a feature length film to be released in cinemas. Again, the viewership can be expected to be high, but perhaps not as high as the record holder "Avengers: Endgame" which brought in $2.8B. Space movies are also on the charts, with "Avatar" bringing in just $7M less than the record holder, and "Star Wars: Episode VII – The Force Awakens" bringing in just over $2B [15]. A conservative estimate of $1B raised by the release of a film about the mission is made.

These two sources alone would then contribute $10B to the mission, and that is just in direct income. They may also provide funding indirectly by creating the strong public image of the mission, which would aid in raising funding from other sources. For example, governments may be more inclined to contribute to a mission if that mission places their contribution in front of billions of people and gain them positive perception with the public.

### *E. Non-essential Personnel*

Another way of profiting from this mission to reduce costs would perhaps be to sell tickets. Space tourism is, still to this day, in its infancy; nonetheless, it's showing signs of significant growth ahead. Recently, the company "Axiom Space" has sold tickets for an eight-day trip titled "AX-1" to the ISS. The AX-1 mission is of course not of the same scope as this mission, but some parallels can still be drawn. AX-1 has no need to bring subject experts in any field of engineering or science, as they will be flying an autonomous space craft to an already operational station close to Earth. This mission, however, mission would be spanning two years of travel in relatively uncharted waters, doing something which has never been done before, further away from home than anyone has ever been. The majority of the crew would nonetheless need to be engineers or scientists, but the sale of a couple of seats should not be impossible. As mentioned in section IIA there are nearly two dozen people in the world who have enough wealth that they could finance the entire mission on their own, with two of them also owning space companies working to send humans to explore the solar system. This means that there exists a greater number of individuals who have the capacity to purchase a ticket to come along on this journey, with the motivation of gaining the trip of a lifetime and the ultimate bragging rights of being on the first expedition to the tallest peak in the solar system.

On AX-1, a ticket is $55M which includes the $35 000 NASA charges per person and day for the stay on board the ISS [16], equating to $280 000 per person for the eight-day mission. Assuming then that the customers would be willing to pay almost $55M just for the launch to space and then $35 000 per day for the voyage, that equates to a ticket price of $80.5M. Scaling this price up five times for the likely more than ten times as difficult mission produces a conservative price estimate of roughly $400M per seat.

While this opportunity would be available to anyone with those kinds of funds there would need to be a selection process, as there is only one spot open. Knowing that this non-essential crew member would need to complete a general astronaut training, it would be more likely that a prepared candidate brought forward by a company or space agency is chosen rather than a private individual.

## IV. Mission Cost Estimation

In order to estimate the cost of the entire mission two main approaches were considered: use the cost of the specific component, if available, or evaluate the price in relation to the mass boarded.

In order to have an estimate of the cost in relation to the mass *m* an exponential law (1), valid mainly for the payload, was used and, since it refers to the dollar of the fiscal year 1994, it was subsequently multiplied by the inflation rate of 2021 from 1994, being 1.77 [17].

$$C(FY94\$) = 0.704 + 0.0235 * m^{1.261} \quad (1)$$

*1) Astronaut Training:* The entirety of the crew would need to have the necessary astronaut training, especially considering the length and the complexity of the mission. Despite choosing the crew in order to have five members that are already professional astronauts and one paying participant, the cost was considered to be the standard price for the complete training of roughly $15M each, giving a total of $90M [18].

*2) Launch Vehicle:* The launch vehicle selected was SpaceX's Starship. This vehicle is still in the testing phase but it was considered reasonably safe to assume that by the start of this mission it would be ready and able to complete its tasks. Moreover, Starship is completely reusable which lowers its projected cost of launch during the next 15 years considerably. Elon Musk's prediction for the cost of Starship is $2M per launch due to its complete reusability [19]. For this mission the launches that need to be considered are both the launches of the main spaceships, the crew and the cargo ones, as well as all the spaceships needed to refuel the first two in orbit around Earth, being seven for each main spaceship, giving a total of 14 launches. However, the current price taking SpaceX's Falcon 9 as a benchmark, is around $62M for a launch which makes it considerably higher than the projection for Starship [19]. Therefore, for the purpose of this estimation, a 100% margin was added to the final result in order to account for the $2M mark not being reached by the start of this mission.

*3) Communication System:* A manned mission to the surface of Mars presents the challenge of maintaining a reliable communication link, as half of each Martian day is spent without line-of-sight to Earth. The Monarch Project [4] is a network of small satellites designed to provide constant communication from any point on the Martian surface back to Earth with minimal delays, reliably, and redundantly. This communications system is a stand-alone mission, so it would be launched independently, and allows for the loss of two of its satellites while maintaining perfect coverage. The total cost of this system would be $259M.

*4) Food and Water:* The overall cost for food and water couldn't be calculated based on the purchase price since this data wasn't available. In order to have an estimate the mean prices currently in place to send food to the ISS were used, in particular $250000 per gallon of water and $4000 per pound of food. Clearly these values are linked to the current cost of launch and therefore could easily decrease in the future, but for the purpose of this study they were deemed realistic and given a safety margin if a lower cost would be reached in the future.

*5) Rovers:* The rovers selected for this mission were NASA's *Space Exploration Vehicle* (SEV) which is still in development, consequently their cost was calculated as the price for the development program, being $153M as if it was their purchase cost and then the total was corrected with the inflation rate of 1.20.

*6) Exercise Equipment:* The exercise equipment needed was composed of a "Colbert" treadmill, a Fergo bike and an *Advanced Resistive Exercise Device* (ARED). The treadmill had a price of $5M in 2009 [20], which was corrected with an inflation rate of 1.22. The bike had a purchase price of $500 000 in 2020, which was adjusted with an inflation rate of 1.01, and the cost of the ARED was calculated with the exponential approximation (1).

*7) Life Support Systems:* The life support systems selected for this mission were the *Oxygen generation system* (OGS), the *$CO_2$ removal assembly* (CDRA) and the $CO_2$ reduction systems. Each system would be boarded in both the crew ship and cargo ship, and moreover three spares for each subsystem would be boarded in both ships. In this instance the cost was calculated based on the mass using the exponential approximation (1).

*8) Overhead:* The main factors of a mission's budget that are left to be accounted for are all the costs related to what can be defined as "civil service and institutional costs" [21], i.e. salaries, mission control, international agreements, bureaucracy. NASA estimates this overhead to be equal to 25% of the cost of the payload. This percentage was made considering the mean value of the percentages of the budgets assigned to the operational costs of NASA's previous missions.

A detailed cost breakdown of all the components considered for the cost estimation and their respective prices is presented in Table I.

TABLE I
COST BREAKDOWN

| **Component** | **Cost (Million $)** |
|---|---|
| Astronauts | 90 |
| Starship launches | 96 |
| Communication system | 259 |
| Food and water | 154.3 |
| Rovers | 367 |
| Exercise equipment | 97.8 |
| Life Support Systems | 2471.8 |
| Water and waste management system | 3923 |
| EVA suits | 72 |
| Crew and personal items | 101 |
| Power system | 113.1 |
| Airlock, crane system, interior furnishing | 1605.3 |
| Aeroponics garden | 15.1 |
| Propellant | 10.4 |
| Thermal Protection System [22] | 35 |
| Radiation shield | 5768.3 |
| Total with overhead | 17410 |

## V. MISSION COST REDUCTION

### A. Use of Widely Available Technologies

The mission is being developed bearing in mind technologies that are currently in use or in the late stages of development. It could be safely assumed that the cost estimation performed for this project would be an overestimation of the cost of these technologies in 20 years. Not only should the technology have matured, but it should be either cheaper than it is at the moment or obsolete, and having given way to cheaper, more efficient, and more reliable technologies.

### B. Operating Within an Exclusive Market Segment

Developing human interplanetary travel is no easy feat; it takes years or decades to develop and this knowledge is easily lost, as exemplified by the dawn of the Apollo space program. The thought of sending another human to the Moon in the immediate future is, while tempting, unlikely; it will still take NASA more than 7 years to gain the ability to send humans to the Moon, with the 2024 deadline being "really, really remote" [23]; this has been expressed by some members of the NASA Advisory Council's Human Exploration and Operations Committee. This provides a chance for any other space program attempting to bring humans to another celestial body to compete with the traditional space agencies, and reach the ability to carry humans through deep space before others. This would offer a unique situation on the market, which offers the possibility to significantly profit by carrying non-essential crew and cargo to Mars.

### C. *In-house Development and Manufacturing*

As shown by small space companies such as Pythomspace[1], having a team specialized in manufacturing to build in-house would not only reduce the cost, but significantly reduce the time required for manufacturing and delivery. Additionally, the use of in-house methods - where possible -, on top of overall reducing the use of contractors and third-parties, would reduce the influence of external factors in the development of the mission. Lastly, it would also highly increase the experience and ability of engineers within the mission, which would directly influence the quality of designs and manufacturing methods.

## VI. Political & Societal Aspects

### A. *Public Relations*

For any mission of this scale, good public relations are vital. As previously mentioned, funding can for some sources depend entirely on the public image of the mission. No politician would want to be associated with a mission that is hated by the public, neither would the potential ticket buyer-billionaire. Any movie made about said mission would flop, and its live broadcasts would not be viewed by billions of people all over the world. Those people and those achievements all go hand in hand with a mission the public loves; the mission intended to be created with this project.

The first way to do this is through the selection of the crew. Crew sizing and professions covered in section IE will not be mentioned again here, as the selection considered in this instance is from within the subsets of qualified individuals previously described. Many qualities which are not strictly important for a candidate to possess to perform well in a given engineering job on the mission are vital to a public figure, which these astronauts will become. One such quality is their public speaking ability and general charisma. The objective is to transform these individuals into rock stars, the type of people kids will have a poster of on their bedroom wall. For this to be at all possible the chosen astronauts will have to be well-spoken individuals with no fear for crowds. This will help when they do interviews, speaking engagements and just interact with the public in general.

A second quality deemed desirable is relatability. Do they share a fun hobby such as playing a sport with the public? Do they have a family? Do they have cute videos their mother took of them when they were a child talking about wanting to be an astronaut one day? Are they kind and smile a lot? These are all points where regular people can bond with the astronauts and feel as if the astronauts are one of them. If the astronauts instead are snobby, private, no-fun individuals, the effect will be the opposite. Regular people will see the astronauts as elitist aristocrats without anything in common with them, which makes them despised instead of loved, reflecting poorly on the mission as a whole.

Moving on from the crew, the public outreach campaign needs to be discussed. These wonderful astronauts that have now been recruited, will be the face of it and speak favorably about the mission at a variety of locations and to various media outlets. The goal is to make people feel inspired by the mission and feel that they either contributed to it or that one day they might accomplish such great things themselves. Inspiration is a powerful emotion and people who feel inspired by the mission will favor it. The ability to inspire ties back into the previously mentioned qualities an astronaut should possess. A well-spoken, friendly, relatable individual doing an interview on a talk show about how they came to be an astronaut headed for *Olympus Mons* can be very inspirational for anyone watching. They would speak about how they came to be interested in space as a child, how they would lay on the football field after an evening practice and gaze at the stars, how they met their loving spouse in a class at university, and how torn they are between going on this fantastic mission and getting to see their kid at their first football practice. A very important topic they would have to tackle in parallel to all of this is discussed in subsection B.

### B. *Investing on Space vs. on Earth*

In between all the talk about themselves and space in general, the astronauts would of course have to speak about the mission more directly. They will inevitably face the question "why don't you spend that money on things we need here on Earth instead?" There are many counter arguments to this which enforce the belief that we go to space for all of humanity back on Earth. For these arguments to aid in the public image however, they must be disseminated to the public. Information campaigns prior to and during the mission will spread the message of the good space travel has provided Earth to those who are skeptical of the program. Convincing them is not as important as it was to the Apollo missions as they relied 100% on funding from NASA and thus the American public, but still important. Several of the previously discussed sources of funding are still intertwined with public opinion, placing it as a priority for the mission to occur.

One important argument to disseminate is the list of important technologies that everyone benefits from which originate in space research [24]. The one of these with the largest impact are likely the integrated circuit. The integrated circuit was not originally invented for space research but was quickly picked up by the industry which was then responsible for the majority of development in the sector before it made it to consumer devices. The impact of this technology is so huge that the value it has provided humanity is immeasurable. Other technologies the have resulted from space programs are GPS, fireproof materials, fly-by-wire, and freeze-dried food.

### C. *Mission Command*

One question to consider for a long duration space mission is: who's in charge during interplanetary travel and the mounting of Olympus Mons? Since this mission is significantly longer than any deep space mission performed today, it was considered whether the commander role should be rotated between the crew or not.

[1]No reference available, information obtained during a live lecture from the company's founders

On the ISS there is always one active commander in charge of a six (or seven) manned crew, usually during one expedition which lasts for around 6 months [25] before handing over the role to the next expedition commander. This rotation of the commander is, of course, from one expedition to another and can be seen as different missions, or in other words: one mission equals one commander.

Apart from the strategy used on the ISS, shifting the commander role between the crew during the mission might affect interpersonal relationships with power struggles and create conflicts and so on. The conclusion was therefore drawn that for this mission there should be no rotations between the crew members having the commander role, i.e., one commander of the six manned crew for the entire mission from start to finish.

## VII. Law & Space Treaties

The main legal aspects of the mission at hand pertain human interplanetary travel, the responsibilities and duties of the entity managing the mission, planetary contamination, in-situ resource utilization, and the applicable law to a potentially international crew in outer space. This section aims to present the current status of international space law and the expected direction of it over the following decades, as well as present the legal framework that would condition the design, operation, and international collaboration of this mission.

Although the main five treaties that rule over the use of space are several decades old, they are still relevant to this day. These treaties are legally-binding, and most have been adopted by a majority of the countries that form the United Nations. The main piece of legislation relevant to this mission, the *Outer Space Treaty*, was opened for signature in 1967, and to this day 111 countries have signed and ratified it; this includes all space-fairing States[2].

It must be noted that this series of treaties are children of their time; they were formed in the midst of the Cold War and, as such, they remain generic and, in some cases, ambiguous. Nonetheless, they present a main framework for each State's duties, rights, and responsibilities when operating in outer space and celestial bodies. These treaties present the foundation of international space law.

### A. Outer Space Treaty (1967)

This treaty pertains the peaceful use of, weaponry limitations in, and a general code of conduct in outer space and celestial bodies. [26]

Articles I, II, and III establish that all use of outer space "shall be carried out for the benefit and in the interests of all countries", that no territory or region in outer space shall be subject to national appropriation, and that all activities performed in outer space shall be in accordance with international law, including the Charter of the United Nations.

Articles V establishes that international collaboration is crucial to the peaceful use to space. Astronauts shall be seen as "envoys of mankind in outer space", and in their activities in outer space "the astronauts of one State Party shall render all possible assistance to the astronauts of other States Parties". This presents and legally requires an international crew to work together throughout the mission, as well as with any other possible crew present on Mars or in orbit during the period of the mission.

Article IX reinforces this aim of cooperation, declaring that "States Parties to the Treaty shall be guided by the principle of co-operation and mutual assistance and shall conduct all their activities in outer space, including the moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty".

The remainder articles within the *Outer Space Treaty* do not pertain the mission directly, but rather policies and prohibitions regarding the presence of weapons of mass destruction in Earth orbit (Art. IV), the jurisdiction of each State Party to the Treaty over its own space activities (Art. V), the responsibility and liability of any State Party to the Treaty that launches or procures the launch of any space object for the actions performed by said space object (Art. VII), the establishment of jurisdiction and control of any State Party to the Treaty over a space object launched by it (Art. VIII), and the supervision of activities in outer space by other States Parties to the Treaty (Art. X), and the required transparency in space activities and their findings by each State Party to the Treaty, to both the United Nations (Art. XI), and other States Parties to the Treaty (Art. XII).

### B. Rescue and Return Agreement (1968)

The *Rescue and Return Agreement* [27] establishes the duties of States to report any danger to the personnel of a spacecraft (Art. I), and each State Party to the Treaty's duty to rescue and safely return any personnel to their State, were a crewed spacecraft to land in foreign territory or the high seas if in position to do so, always in close collaboration to the launching State (Art. II, III and IV). Lastly, Article V established the procedure for the recovery and return of space object that re-entered Earth's atmosphere and landed in a territory under the jurisdiction of a State Party to the Treaty that is not the launching State. The remainder articles present clarifications and general declarations of a Treaty.

### C. Liability Convention (1972) & Registration Convention (1975)

The *Liability Convention* elaborates on each State Party to the Treaty's responsibilities and jurisdiction over any space object launched by it. The *Registration Convention* introduces the mechanism for proper registration, identification, and cataloguing of space objects, and clarifies some aspects of previous treaties.

Note that, while not as many countries ratified these treaties when comparing to the ratification of the *Outer Space Treaty* [28], they are still commonly accepted as protocol and guidelines, and were ratified by all major space-fairing States.

[2] A space-fairing nation is a nation with the capability of accessing space using exclusively its own indigenous systems

### *D. Moon Agreement (1979)*

The *Moon Agreement* [29] elaborates on the general guidelines presented in the *Outer Space Treaty*, making an emphasis on the peaceful purpose of any space activity, and declaring that, once the utilization of resources on the Moon and other celestial bodies becomes possible, an international organism shall be created to control the exploitation of resources.

Article 1 specifies that, in the absence of legislation pertaining any other specific celestial body, the *Moon Agreement* shall also apply to it; for instance, Mars. Hence, and although only 18 countries have ratified this treaty to date, it shall be used as a guideline for any interplanetary mission; especially for those characterized by international cooperation, as some of the participating countries may have signed the Agreement. As well, Article 2 establishes the reign of international law, including the Charter of the United Nations, on the Moon and other celestial bodies.

The remainder articles expand the prohibition of weapons of mass destruction to orbit around the Moon and other celestial bodies (Art. 3), reiterate the aim of cooperation in space among States (Art. 5), in-situ resource utilization (Art. 6), planetary protection (Art. 7), allow for States to operate on the Moon and other celestial bodies and to avoid interference in the operations of other States (Art. 8), the establishment of stations on the surface (Art. 9), the establishment of an international regime to regulate space mining (Art. 11 and 18), jurisdictional matters (Art. 12 and 14), the required transparency in space activities and their findings (Art. 13 and 15) and, throughout most articles, an emphasis on the responsible, collaborative, and safe use of the resources and locations present on the Moon and other celestial bodies.

### *E. The Future of Space Law*

Humanity is entering the fourth era of space exploration, after the early study of astronomy, the rise of space-fairing nations, and the ISS-era of peaceful international cooperation. This fourth era is characterized by the globalization of space. Space exploration is no longer driven by governmental efforts, and there are ways of space travel and exploration (such as space tourism, CubeSats, and the growing challenge of space debris) that are not reflected in the treaties mentioned above.

The aim of space exploration, the amount of players on the field, and the rate of development have changed significantly over the last 50 years. Over the next decades, it would be expected that there will be an overhaul of the fundamental treaties signed to better reflect the current heading of the space industry and space exploration. While some States, such as the United States of America, have taken the initiative by proposing their own Agreements, legislation written by one nation is unlikely to reach global consensus. This agreement does not aim to achieve a common understanding among nations, but a bilateral one between the United States of America and other States. While this may work, since a majority of States are not space-fairing, facing a future where space is even more widely accessible, a global consensus would be required. This legislation would come in the form of a new space treaty to be formed within the Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space of the United Nations.

Given that no international space legislation has been written in over four decades, and seeing the evolution of the space industry over the last ten years alone, a reformation of the space treaties adopted by the United Nations Office for Outer Space Affairs is expected to happen over the next decades.

### *F. Artemis Accords (2020)*

The *Artemis Accords* [30] are a bilateral agreement signed between the United States of America and seven other States to establish a code of conduct to guarantee peaceful and friendly operations and collaboration of nations once NASA's Artemis program lands humans on the Moon for the first time since 1972.

Similarly to the Moon Agreement, Section 1 of the Accords establishes the validity of the Agreements to any celestial object and region of outer space, and specifies that they also apply to both the surface and the subsurface of said celestial objects.

Moreover, Sections 3, 4, and 5 reiterate the peaceful, transparent, and cooperative nature that space exploration shall have, with a specific note to the use of standardized methods in manufacture ans operations; this would enable for different missions and hardware from different States to easily and successfully interact. Sections 6 directly references the *Rescue and Return Agreement* and the obligation to follow it. Section 7 references the *Registration Convention*, but allows for dialogue with a non-Party to the treaty to ”determine the appropriate means of registration”.

Unlike the *Moon Agreement*, Section 8 allows for the optional release of information regarding space activities to the public, although it expresses the commitment to the ”open sharing of scientific data”. Section 9 references the preservation of the Moon environment, although it only refers to ”historically significant [...] sites [...]”. Section 10 paves the way for in-situ resource utilization and space mining within the limitations of the *Outer Space Treaty*. Section 11 establish a strong link to the *Outer Space Treaty* and lays the groundwork for the designation of areas to possible bases on or under the surface of the Moon or other celestial bodies. Lastly, and adding on the principles presented by the treaties, Section 12 establishes a framework for the management of orbital debris to be generated throughout missions to other celestial bodies.

Overall, while the *Artemis Accords* present the beginning of the needed evolution of current space law to better monitor and regulate the new era of spaceflight, it is seen by many countries as vague and generic, and as an attempt to form non-enforceable guidelines (also known as soft law) outside the umbrella of the Charter of the United Nations.

### *G. Planetary Contamination*

As the search for life beyond Earth in the solar system is in progress, protecting other bodies from contamination by Earth life, as well as protecting Earth from possible extraterrestrial life that may be returned, must be practiced as per NASA's

Planetary Protection policies [31] and per Article 7 of the Moon Agreement [29].

To prevent forward contamination, in the event that a spacecraft were to be abandoned in orbit or on the Martian surface, and in the certainty that the rovers would be left on Mars, the vehicle would be sterilized to reduce or eliminate any microbiological presence leftover by the crew to comply with the present planetary protection policies. This could be done by substituting or mixing the atmosphere in the vehicle with ozone ($O_3$) [32].

## VIII. Risk Analysis

A brief risk analysis was performed for this mission, covering some of the most relevant events possible throughout the mission timeline. This includes events such as a failure of launch from Earth or of the cruise vehicle, astronaut injuries or deaths, post-mission crew health issues etc, as presented in Table II. It should be noted that this analysis was not based off collecting data from past missions but merely the groups' own ideas.

TABLE II
Main Risk Factors

| Event | Abbreviation |
|---|---|
| Launch failure | L |
| Take-off explosion | T |
| Failed refuelling | R |
| Cruise vehicle failure | V |
| Astronaut death | A |
| Mars landing failure | M |
| Missed launch window | LW |
| Funding sources fail to sustain mission | F |
| Significant injury or incapacitation | I |
| Post-mission crew health issues | H |

TABLE III
Risk Matrix

| | | Severity | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| Likelihood | 5 | | | | | |
| | 4 | H | | I | A | |
| | 3 | | | | | M |
| | 2 | | | | | V |
| | 1 | L | R | | LW, F | T |

Table III presents the distribution of the main risk factors to the mission. Most of them relate to technical issues, or would more than likely be caused by technical issues on mission hardware. This table only presents higher level risks, as this project does not go in-depth enough to assess more specific topics such as the reliability of life support systems or the accuracy of the expected income from funding sources. Note that the likelihood and severity of an event is ranked with numbers from 1 to 5, where a value of 1 represents an event having the least likelihood to occur as well as not having a sever impact on the mission objective, and a value of 5 represents having the most likelihood to occur as well as being the most sever, ending in mission failure. Moreover, some risks could not be assessed regardless, as they heavily depend on the progress made on new technologies such as SpaceX's Starship, in-orbit refueling, etc.

## IX. Off-nominal Scenario

### A. *In the Event of a Deadly Accident*

Since the late sixties the landscape of space missions has significantly changed. The most evident novelty is the aim of increasing the number of manned missions, especially towards celestial bodies such as Mars and the Moon. However, this choice raises new moral and legal problems regarding the possibility of accidents that could be harmful or deadly to one or more crew members, not just during launch and re-entry, but more specifically in outer space.

Despite the existence of a treaty that explains the procedures to be followed if an astronaut is harmed during launch and re-entry, the Rescue Treaty [27], there is no protocol to comply with if an astronaut dies in outer space. This could raise issues, for example, on a legal perspective but also on how to deal with the body or how to share the news with the family and the public [33].

The first practical problem that would be encountered in such a situation is how to deal with the dead body in outer space or on the surface of another planet. Different solutions were considered depending on the place of a fatal accident [33] [34]:

- One possible solution could be to leave the body in outer space but it's unclear if the UN guidelines on space debris [35], which state that, if avoidable, a mission shouldn't leave litter in space, include human bodies. Other than the damages caused by having a body collide with other spacecraft or objects in space, this suggestion could raise a moral debate on the appropriateness of not giving what could be considered a respectful burial or not bringing the body back to the family.
- If a fatal accident was to happen on the surface of Mars, in particular on a mission of exploration, a burial in Martian soil could be considered, but at the early stages of Mars exploration interfere with scientific studies on microbial life.
- Another solution could be to keep the body on board the spaceship, however, without innovative proposals this approach wouldn't be feasible. One approach that NASA has been taking into consideration since 2005 called "Body Back" [34] requires a vibrating Gore-Tex sleeping bag for the body, provided by Promessa, a company specialized in organic burials. The body would be put inside the airtight bag and left exposed to the space temperature to freeze in the airlock. After retrieving the bag, the body would be vibrated to shutter it, making its transport back to the family easier.

### B. *Commander Succession*

For a mission of this length and complexity there exists a need to reflect over what would happen if the key crew member, the commander, dies. Who would then take over the role, and how this change to the set dynamic in the crew threaten the mission?

As per standard of space missions, there shall be a co-pilot ready to take over the mission entirely should the commander not be fit to fulfill the role for some given reason. This line of succession is dependent on the composition of the crew and the assessment of the crew members prior to departure from Earth.

### *C. Announcing Deaths to the Public*

In the event of one or several astronauts found dead on the mission there should be a speech ready to be broadcast to the public, similar to the one prepared for Richard Nixon for the Apollo 11 mission [36]. The speech includes honoring of the astronauts and their sacrifices made for the human race, as well as hoping for the recovery of their bodies.

As the mission is to be broadcast during the most important moments, such as the mount of *Olympus Mons*, it would not be of interest to include any possible deaths of astronauts, with respect to their families. To solve this the broadcast system could be linked to the health of the astronauts, and in the case of a critical situation the signal could then be automatically terminated until further notice to decrease the risk of broadcasting any deaths to the public. Another mitigation strategy would be to transmit all broadcasts with some delay to allow for any developing situation to be assessed by the group responsible prior to being broadcast.

## X. Conclusions

The Hephaestus Project is a mission design proposal to bring the first human to the top of *Olympus Mons*, the largest mountain in the solar system. This proposal estimated sending an international crew of six astronauts to the Red Planet to crown *Olympus Mons* and return to Earth over a 3-year period. While this mission is based around its main goal, it would be complimented by research and other tasks to ensure reduction of the cost of the mission and optimizing the time usage of the crew throughout their time in orbit and the 11 months spent on the surface of Mars.

This project has shown the existence of a design space and the readiness of current and future technology, assuming a progress in line with that seen over the last decades. Ultimately, both the final mass required for this mission and its estimated cost, including redundant systems and factors of safety, could be met within the current technological and societal context.

## XI. Workload Breakdown

### *A. Sergio Bernabeu Peñalba*

Sections written: IA, ID, IE, IIE, IIIA, IIIB, IIIC, IIIE, IV, VA, VB, VC, VIIA through VIIG, VIII, X

Main topics written: Internal organization of the project, Crew Sizing, Mission summary, Funding, Mission Cost Estimation, Mission Cost Reduction, Law & Space Treaties, Risk Analysis, Conclusion

### *B. Anton Lager*

Sections written: Abstract, Sammanfattning, IB, IC, IE, VIC, VIIG, VIII, IXA, IXB, IXC

Main topics written: Project Background, Mission Statement & Constraints, Crew Sizing, Political & Societal Aspects, Planetary Contamination, Risk Analysis, Off-nominal Scenario

### *C. Alexander Stevens*

Sections written: IE, II, IIID, IIIE, VIA, VIB.

Main topics written: Funding, Mission Summary, Political & Societal Aspects.

### *D. Laura Venturini*

Sections written: IV, VIII, IXA, IXB, IXC

Main topics written: Mission cost Estimation, Risk Analysis, Off-nominal Scenario

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