Logistics Team Red

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***Abstract*—This report evaluates the feasibility of constructing and operating a lunar station from a logistics standpoint within a three-year timeframe. The logistics of the steady state are also examined to determine the long-term viability of the project. The study concludes that the construction logistics are feasible within the given timeframe. It also finds that using the Lunar Gateway simplifies crew and cargo transportation to the lunar station. A SpaceX Falcon Heavy rocket, launched from Kennedy Space Center, combined with a modernized SpaceX Crew Dragon is deemed suitable for transporting a crew of four people to the Lunar Gateway with a direct transfer trajectory, whereas cargo launches are sent on a weak boundary stability trajectory to increase the mass ability of each launch. The CAVEMAN lander is chosen for transportation between the Lunar Gateway and the lunar surface, and the Astrolab Venturi Flex rovers are selected for their ability to transport varying dimensions of cargo on the lunar surface. Mitigating the consequences of lost cargo shipment in the latter stages of transport is essential due to the length of the shipment, surplus storage of essential cargo, therefore, needs to be maintained on the lunar station. The total number of launches required per year is calculated to be 29, with an estimated annual transportation cost of approximately 4,5 billion USD.**

***Index Terms*—Lunar Station, Logistics, Lunar Gateway, Falcon Heavy**

I. Introduction

This report will cover the Logistics part of the lunar base project for Team Red. The context of the project is as follows: the year is 2037, and we decided to build a lunar research station large enough to house up to 50 people. It has to be operational by 2040 and will be situated on the South Pole of the Moon for research and resource purposes. Building a research station this big requires a lot of logistics to meet the due date and to make sure the project will unfold as expected without any major issues or casualties.

Several assumptions have been made to take into account the innovations and scientific realizations between 2023 and 2037. The Artemis program was successful, a Lunar Gateway is in place and performing launchers and landers already exist.

In section II we will detail the flight logistics, meaning everything related to sending cargo and crew to the Moon. In section III we will present the logistics on the lunar surface. Finally, in section IV, we will study off-nominal scenarios and explain our emergency plans.

II. Flight Logistics

A. Trajectory

First, we are going to launch from the Kennedy space center in Florida. It was decided to have 2 different trajectories to reach the Moon, one for humans and one for cargo, a trajectory for the crew to avoid long radiation exposure, and a longer and fuel-efficient one for cargo.

Through rewriting Tsiolkovsky's rocket equation [1], eq. 1, as a ratio between the final and initial mass of the rocket, the final mass, m_f, was related to the initial mass, m_i through the change in velocity, Δv, and the specific impulse, I_{sp}, of the engine as seen in equation 2. On top of this, a factor of 1,1 was added to the Δv to account for any gravity drag encountered [2].

$$\Delta v = I_{sp} g_e ln \frac{m_f}{m_i} \tag{1}$$

$$\frac{m_f}{m_i} = e^{-\frac{1.1 \Delta v}{I_{sp} g_e}} \tag{2}$$

Knowing how the structural coefficient, ϵ, the final mass, and the initial mass relate [3], an equation for the payload mass, m_*, was written, see equation 3.

$$\epsilon = \frac{m_s}{m_p + m_s}, \;\; m_f = m_* + m_s, \;\; m_i = m_f + m_p$$

$$m_* = \frac{\epsilon}{\epsilon - 1} m_i + (1 + \frac{\epsilon}{1-\epsilon}) \frac{m_f}{m_i} m_i \tag{3}$$

TABLE I
DATA USED CALCULATING PAYLOAD MASS

ϵ	I_{sp} [s]	m_{LEO} [kg]	g_0 $[m/s^2]$
0,4 [3]	348 [4]	63800 [5]	9,81 [6]

1) Crew:

The key driver for the choice of the human trajectory is a short duration to minimize the radiation exposure, maximize their time on the Moon, and for other psychological reasons. So we chose a direct transfer with a free return trajectory. It means that in case of failure of the engine before the lunar orbit insertion, the spacecraft will return back to Earth without any propulsion (see Figure 1). It is not the most efficient trajectory in terms of delta-V but it's the safest and most relevant option.

Direct transfer trajectory to the Moon

- 3-day travel
- 6 persons per crewed capsule
- 3-day launch window
- Delta-V 3,44 km/s LEO to TLI
- Payload mass 21,1 tons

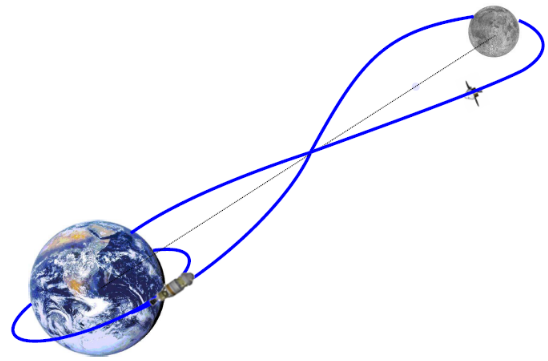

Fig. 1. Free return trajectory

For a Free-return trajectory the characteristic energy, $C3$, at departure from LEO is $-1.7\ km^2/s^2$ [2].

$$E = \frac{v^2}{2} - \frac{\mu_e}{r} = -\frac{2\mu_e}{a} = \frac{1}{2} C3 \tag{4}$$

Solving equation 5, the total specific energy [7], for the velocity, v, two valid equations pop out. One in terms of the semi-major axis, a, and the radius of the s/c to the body,r. and one in terms of C_3 and the radius, see equation 5.

$$v = \sqrt{C3 + \frac{2\mu_e}{r}}, \;\; v = \sqrt{\frac{\mu_e}{r}} \tag{5}$$

These were then used to find the velocity increase needed for a Free-return trajectory, Δv_{TLI}, see equation 6.

$$\Delta v_{TLI} = \sqrt{C3_{Dep.} + \frac{2\mu_e}{r_{LEO}}} - \sqrt{\frac{\mu_e}{r_{LEO}}} = 3.44\ km/s \tag{6}$$

Using equation 2 and 3 together with table I resulted in $m_{*,TLI} = 21.57$ ton

2) Cargo:

Concerning the cargo trajectory, alternative trajectories which are more fuel-efficient can be considered. A 3-month trip is still reasonable considering storage and given the fact that in case of emergency, we still have the direct trajectory. The 21-day launch window is enough to guarantee enough re-supplies throughout the year. That's why we chose this Weak Boundary Stability trajectory, which uses the Lagrange first point to return back to the Moon (see Figure 2). This kind of trajectory has already been used successfully to achieve a more fuel-efficient trajectory.

Weak Stability Boundary trajectory to the Moon

- 3-month travel
- 21-day launch window
- Delta-V 3,56 km/s LEO to NRHO
- Payload mass 20,7 tons

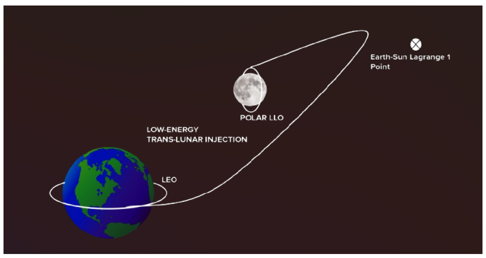

Fig. 2. Weak Stability Boundary trajectory

The cargo has no ability to move on its own, unlike the crew dragon. This meant that the cargo needed to be "dropped off" at the Lunar Gateway something which needed to be taken into account when calculating the useful payload capacity. To this end the trajectory was split into two parts, one being the Trans Lunar Injection TLI and the other being the Near-Rectilinear Halo Orbit Injection NRHOI. Thankfully these separate trajectories had already been calculated. $C3_{TLI} = -0,52km^2/s^2$ [2] which using equation 6 resulted in $\Delta v_{TLI} = 3,50km/s$. NRHOIs using weak stability boundary starting from TLI have been looked into by JAXA for an HTV capable of transferring to the Lunar Gateway and found that dv $60m/s$ dependent on launch time [8]. This resulted in $\Delta v_{WSB} = 3,56km/s$ compared to $3,86km/s$ if adding the Δv expended by the crew dragon to the direct transfer. Using equations 2 and 3 as well as table I resulted in $m_{*,WSB} = 20,74$ ton, 1,56 ton more than if having used the direct transfer discussed earlier.

B. Spaceships

1) Launcher: Falcon Heavy

For the launcher, we chose SpaceX's 70-meter-high Falcon Heavy Rocket [5]. One of the assumptions made was that in 2037, spaceships like Starship[9] with a SuperHeavy launcher would be available. Nonetheless, finding realistic numbers on a SuperHeavy launch was quite difficult, especially budget-wise, since SpaceX's official numbers for this launcher are no longer official and public. Furthermore, using Starship would imply more logistics complications since it needs refueling in orbit. Another possibility was using the SLS launcher [10] with the Orion capsule, as planned for the Artemis program. However, the cost of launch with SLS is tremendous, nearly 2 billion USD, and the construction of the lunar base would thus be extremely expensive considering the huge amount of materials needed.

We thus chose the Falcon Heavy Rocket, a reliable launcher with realistic numbers for payload that is not too expensive. Indeed, each launch costs between 90 and 150 million USD. The variation depends on how much material is reused for the next launches. For the budget estimations, we used the worst-case scenario cost.

Fig. 3. Falcon Heavy Rocket

a) Cargo: payload capacity

The payload capacity of Falcon Heavy for cargo is roughly 20 tons to the Lunar Gateway.

b) Crew: Crew Dragon

To transport the crew, we considered a human-rated version of Falcon Heavy with a cabin similar to the Crew Dragon capsule [11]. SpaceX was initially going to build such a rocket, so we know it is a realistic assumption, but since they are busy developing Starship they gave up that idea.

The characteristics of the capsule are:

- capsule volume: 9,3m^3

- trunk volume, used for extra fuel and cargo storage: 37m^3
- mass: 13 tons of capsule + 5 tons of propellant needed for re-launch to Earth

Fig. 4. Crew Dragon capsule

2) Lander: In 2018-2019 American Institute of Aeronautics and Astronautics AIAA had a competition for reusable lunar launders. The top three designs CAVEMAN, I-MARS, and JELLY were compared and given comparable lifting performance, 4 crew/ 15 tons [12] [13] of down mass except for I-MARS with 22.5 tons[14], the fuel usage came to be the Achilles heel where CAVEMAN and I-MARS came out neck and neck only needing around 80 tons per flight [12]. But due to the I-MARS needing two launches and crew capacity being the limiting factor for missions per year, CAVEMAN was chosen.

The CAVEMAN is made up of three modules, the landing module LM housing the landing gear, the cargo as well as the engines and fuel used during the Landing/lift-off phase. The second module orbital module OM is used to transfer back and forth from LLO to NRHO and the final module is the HAB which facilitates the crew during transit. Though this system's intended mission profile had it carrying all its fuel the whole mission as it was meant to solely refuel at the Lunar Gateway there is nothing stopping it from using the same refueling system on the surface of the Moon as well using Celestial Heaven's fuel production. Using equation 2 as well as data from table II to get the fuel usage for getting roughly 4 tons of cargo and the 4 crew members down to the surface as well as transporting fuel and the new crew up again. This turned the 80 tons of fuel needed to be shipped to the Lunar Gateway into 22 tons, rounded up, with 28,1 tons needed from the in situ production per flight.

TABLE II
PERFORMANCE DATA CAVEMAN [12]

m_{LM}	12068,74
m_{OM}	6558,1
m_{Hab}	5500
$\Delta v_{L/T}$	2067
$\Delta v_{NRHO-LLO}$	904
$\Delta v_{LLO-NRHO}$	1114
I_{sp}	449,7

C. The Lunar Gateway

The lunar gateway is a space station stationed in a highly-elliptical polar non-rectilinear halo orbit (NRHO) with a 7-day period around the moon [15]. It will be used as a perpetual terminal for incoming and outgoing crew and cargo, a research station for deep-space testing, and a communication centre, for a time no less than until the construction of the lunar base is completed. The gateway's purpose is to accommodate the incoming and outgoing spacecraft, crew or cargo and will be uncrewed at other times.

Fig. 5. Lunar Gateway [15]

The Gateway's NRHO will have its closest approach to the moon, the perilune, within 3000 km of the Lunar North Pole and the farthest distance, the apolune, at 70000 km from the Lunar South Pole.

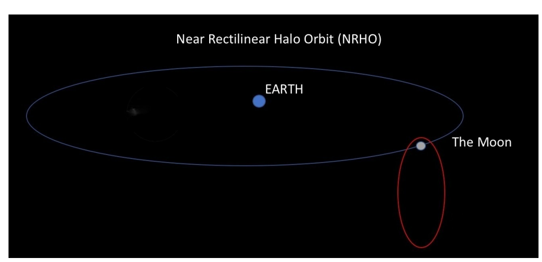

Fig. 6. Lunar Gateway NRHO [16] (perilune = 3000km and apolune = 70000km)

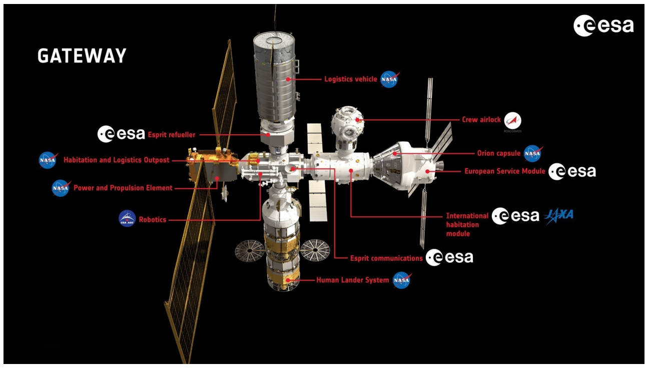

Fig. 7. Lunar Gateway Modules [17]

1) Capabilities and Storage on the Gateway: The Gateway has two habitation modules, US-HAB and I-HAB [18], with life-support capabilities, a U.S. Utilisation module [17], the first habitable module assembled on the Gateway which has the capacity for additional habitation, and the ESPRIT module [19], a logistics and utilization module, for cargo storage with a dedicated docking port for incoming cargo spacecraft.

The Gateway can accommodate up to 6 astronauts for 30 days, but the mission calls for only four astronauts to be occupying the space station for around 3,5 days. In addition to the crew, the cargo capacity of the Gateway is 20 tons at a time, excluding the propellant used for maneuvering the Gateway.

2) Arrival at the Gateway: The Dragon spacecraft launched from the Earth will arrive at the Gateway at its apolune above the lunar South Pole and will dock on the Lunar Gateway. Once docked, all the cargo and equipment on the Dragon spacecraft are transferred to the lunar lander that is docked on the Gateway. Once reaching the perilune position (close to the lunar North Pole) after a 3,5-day wait on the Gateway, the crew and the cargo will depart for the lunar base on the lunar lander and land near the base on the South Pole using a Hohmann transfer approach trajectory.

3) Launch from Base to the Gateway: When departing the Lunar Base and sending the crew and/or any cargo, a similar trajectory is considered for approaching the Gateway. After loading up the Lunar Lander, the Lander is launched off the landing pads near the base at the South Pole for a rendezvous with the Lunar Gateway at the apolune near the North Pole.

D. Flight Timeline

The flight schedule is divided into three launch phases: before the beginning of the construction, the arrival of the first crew during the construction, and steady-state use of the lunar base.

1) Launch Phase 1: before the beginning of the construction

The initial launch phase consists in sending everything that is needed for the construction of the base and the survival of the first crew.

For the construction, this includes the materials needed and the construction and excavation robots. The goal is also to bring the long-term cargo to make sure that the base is operational as soon as possible, meaning the materials for research and communication, the transport rovers, the electrolysis machine and the KRUSTY for nuclear power. Finally, the life support system is also being shipped in this first phase so that the base can host the crew as soon as the first module is built to avoid shipping more cargo for life support.

TABLE III
AMOUNT OF CARGO FOR LAUNCH PHASE 1

Type of cargo	Mass	Volume
Station Design	307 tons	$915m^3$
Operations	18 tons	$50m^3$
Human Aspects	40 tons	$25m^3$
Total	**365 tons**	**$990m^3$**

We therefore need 19 cargo launches for this first launch phase. If we want to use the Weak Stability Boundary trajectory to the Moon in order to save some fuel, we would therefore need to start sending the rockets roughly one year and three months before the beginning of the construction if we launch one rocket at a time. Some parts of the cargo are not necessary for the construction to begin though, so if we are on a tighter schedule we could send the rockets with all the construction materials and robots first, start the construction at once, and then send the rest of the cargo.

2) Launch Phase 2: the arrival of the first crew

40 days after the beginning of the construction, a small crew of four astronauts will land on the lunar

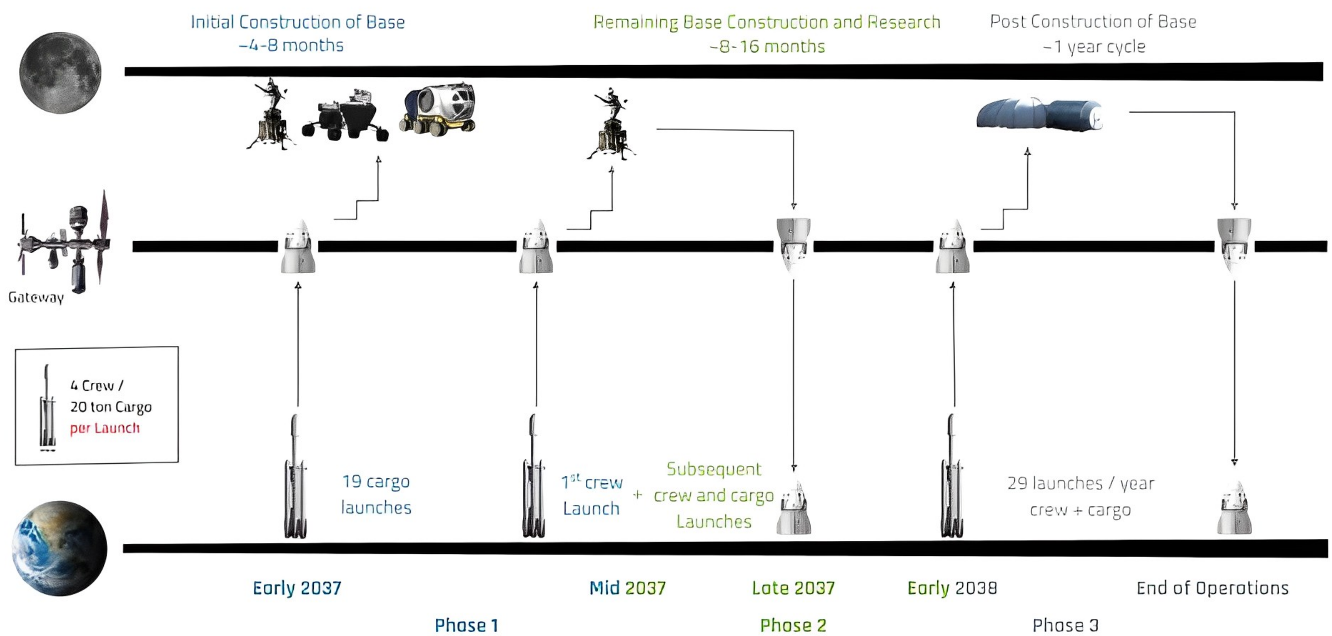

Fig. 8. Flight Logistics Timeline

surface to oversee the construction. Since water and food production will not be operational at first, they will need enough consumables to survive until the base is ready to support their needs. We decided to send supplies for roughly a year of survival since the first module should be ready by then. Of course, if there is some delay in the construction, other launches would be organized to ensure that the crew survives. For this phase, there would therefore be one crew launch and one cargo launch.

3) Launch Phase 3: steady state

The last launch phase begins when the construction of the base is finished and the steady-state utilization of the lunar base begins.

To avoid too much exposure to radiation, the astronauts will stay one year on the Moon. We decided to rotate the crew by a team of four people, which means that there will be 12,5 crew launches per year on average to complete this rotation. Furthermore, since the crops grown on the Moon will not be enough for the crew, there will be a cargo resupply of dry food. The crew will also need spare parts to repair broken rovers or for other maintenance issues. Finally, the landers will need to be refueled at the Gateway since they cannot take all the fuel needed for landing in the ascent.

TABLE IV
AMOUNT OF LAUNCHES FOR LAUNCH PHASE 3

Crew or type of cargo	Mass
Crew rotations	12,5 launches per year
Food and maintenance	2 launches per year
Fuel for landers	14,5 launches per year
Total	**29 launches per year**

In the steady state, there will therefore be on average 29 launches per year. Extra launches might be needed occasionally to completely renew machines and rovers.

III. On-site Logistics

A. Transport

For safety reasons, the landing sites are situated one kilometer away from the lunar base. A means of transportation is thus needed in order to get the crew and cargo to the base after landing, especially since the amount of cargo is significant, as each rocket brings 20 tons of material.

In the steady state phase, we chose to use 5 Flex rovers[20]. The Flex rovers were designed by Astrolab Venturi precisely for crew transport and small-distance cargo transport, with the purpose of being easily deployed from the Moon landers. Each rover can carry 2 crew members and up to 1 ton of cargo, and the dimensions of the cargo containers can be adapted to the cargo itself, with different standard sizes.

Fig. 9. Flex rover

B. Maintenance

Our strategy to avoid shipping new rovers and machines every year consists of regular maintenance to keep our systems in good condition. This implies monthly check-ups of the rovers and machines to identify the eventual faults, and, if needed, the occasional shipping of spare parts to increase their lifespan. The spare parts weigh much less than the global system and can extend the use of the machines and rovers by a few years.

IV. Emergency plans: What if ...?

We considered three off-nominal scenarios (and three variations of one of the scenarios) which would impact the flight logistics. A breakdown of these can be found in Table V.

A. Launcher failure

Fig. 10. The space shuttles Atlantis (foreground) and Endeavour (background). Endeavour was the backup in "[...] the unlikely event that a rescue mission [...]" was needed for the STS-125 mission. [21]

The first problem that could impact flight logistics is a launcher failure.

First, if this occurs for a crew flight, the crew should be able to successfully escape thanks to the Abort Launch System of the Crew Dragon capsule[11], so there would hopefully be no casualties. Nonetheless, to keep the rotation of the crew running, the new crew needs to be launched as soon as possible, which on average means 3 days after the initial launch date considering the launch window for the direct transfer. In the case of a normal cargo flight, we have a bit more time to prepare since the launch window for the long transfer is once every 21 days. However, if this cargo is urgent, for instance, if there is another emergency, it would need to be sent in direct transfer as well.

Even though SpaceX is known for the company's ability to build Falcon Heavy rockets extremely fast, in just a few weeks, the time needed to get a new rocket and set up the launch would be too long. Several rockets should therefore be built in advance and kept in storage to serve as a backup if the launch fails.

Keeping a launcher ready is not a new strategy, as can be seen in Figure 10.

B. Lander failure

A second issue that could arise is lander failure. Depending on the situation, this could have dramatic consequences.

TABLE V
OVERVIEW OF POTENTIAL LOGISTICS EMERGENCY SCENARIOS.

Scenario	**Solution**	**Consequences**
Launcher failure (crew)	Re-launch crew on a reserve launcher within 3 days.	Slight delay in the crew rotation.
Launcher failure (non-critical cargo)	Obtain new cargo and launch during the next available time slot.	Eventual rescheduling and delays of other non-critical cargo.
Launcher failure (critical cargo)	Launch readily available backup cargo on a backup launcher.	Eventual rescheduling and delays of other launches, including critical ones.
Lander failure	Spare landers are available on the lunar surface at all times.	A new lander needs to be transported to the LGW.
Cargo loss	Critical resources such as food is stored with a surplus to account for failed deliveries.	Upon loss of critical cargo, a period of increased re-supply will follow.

Indeed, if the failure occurs while taking a crew to the Moon or back to the Gateway, this could lead to a deadly accident. If it is during a cargo flight, the consequences would be less dramatic, unless, of course, the cargo in itself was extremely important and urgent.

Besides the direct consequences of such a failure, one major issue would be that the crew would have no way to get off the Moon in case of an emergency. This is why there will always be one spare human lander on the lunar surface.

C. *Cargo loss*

The third scenario we considered was cargo loss, due to an explosion or a launcher or lander failure, as described in the previous subsections. In a nominal scenario, this cargo loss would not have such a big impact on the life of the crew members, since the only thing they need that is not fully available on the Moon is food, and only two launches per year are required to send the amount of food the entire crew needs. In these conditions, and considering that dry and vacuumed food takes very little storage room, it is possible to stock enough essential items such as food and wait for another resupply. In the case of an emergency, for instance, if the crew has to live in the shelter and does not have access to the crops produced on the Moon or to food storage, there is always the possibility to send emergency cargo via direct transfer.

V. SUMMARY

Starting from the Kennedy Space Center, using the SpaceX Falcon Heavy for the launches, the crew will be sent in a SpaceX Crew Dragon on a direct transfer trajectory while most of the cargo would be sent on a weak stability boundary trajectory. Upon reaching the moon crew and cargo alike will rendezvous with the Lunar Gateway. Upon arrival at the gateway crew and cargo will be transferred to the CAVEMAN lander for transportation to the lunar station. At the lunar surface, a small fleet of Flex Rover will handle any transportation needs of both crew and cargo.

To maintain a crew of 50 people that can stay on the lunar station for no longer than one year each, a total of 29 launches will be required per year. This would cost approximately 4,5 billion USD.

The analysis of potential off-nominals found that the biggest risk (besides the obvious risk of the crew during the transport) was the loss of essential cargo in the latter stages of delivery due to its long-duration transport and its infrequent deliveries. The only way to mitigate this was found to be by maintaining a constant cargo surplus on the lunar station for anything that is deemed essential.

The construction of the lunar station within the given timeframe will require continuous shipments throughout Phase 1 and Phase 2, albeit not as frequently as for the requirements of the aforementioned steady-state phase.

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