Logistics of Mars Expedition

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***Abstract*—The logistics for a deep space mission to Mars are discussed. First, a diagram of the whole mission is shown. It is required in the mission to perform an on-orbit assembly of a transfer vehicle to Mars using the Pythomspace launch vehicle Kang. A crew of two is to travel to Mars and land on the surface, then safely come back to Earth. A schedule of the launches is studied given a list of payloads and duration constraints. An assembly sequence is proposed, and assembly technologies are compared. Communications related issues are studied to propose an adequate communication architecture to minimize black-out periods. The general objective of the mission is to minimize the mass budget as much as possible.**

***Index Terms*—interplanetary transfer, Mars, assembly, communications**

ACRONYM LIST

ATV	Automatic Transfer Vehicle
DOF	Degrees Of Freedom
EM	Earth - Mars (for tanks)
HA	Human Aspects
LEO	Low Earth Orbit
LMO	Low Mars Orbit
LOG	Logistics
LSS	Life Support System
MAV	Mars Ascent Vehicle
MDV	Mars Descent Vehicle
ME	Mars - Earth (for tanks)
MO	Mars Operations
OOA	On Orbit Assembly
SSRMS	Space Station Remote Manipulator System
TV	Transfer Vehicle

I. INTRODUCTION

In recent years the interest in sending humans to Mars has increased drastically. SpaceX is planning to put astronauts on the planet's surface in 2026 and are not alone in planning a manned mission to Mars in the near future. One such planned mission to Mars is by the company PythomSpace, owned by explorer couple Tina and Tom Sjögren. They plan on going to Mars themselves, on a minimal mission with just the two of them. The mission concept is exploration, which translates in reducing as much as possible both monetary and weight costs.

In this report, the logistics aspects of a such mission are discussed.

The layout in this project after the introduction will begin with the presentation of the taken assumptions for the work. Then, the overall mission timeline will be shown. The forth section consists on the presentation of general characteristics to take into account before the assembly (that is, launching site and assembly orbit). The fifth part will be the pre-departure and launch timeline presenting the development period, payload list, launchers trade-off, launching sequence, and timeline of assembly. Following, the next section will focus on the assembly procedure by specifying requirements and technologies trade-off. The seventh section presents the return to Earth from LEO, discussing two possible options; and the eighth section explains the communication throughout the whole mission (requirements and infrastructure). Finally, off-nominal scenarios are discussed; finishing with the sustainability aspects throughout the whole mission. In the appendix, the schemes for the mission timeline, TV assembly timeline, and a table with the whole launching sequence and specific payload are shown.

II. ASSUMPTIONS

In this section, the relevant mission assumptions for logistics aspects are stated:

1) Kang launcher has a 3t capacity to LEO.
2) Kang launcher will be ready by 2024.
3) At the beginning of the mission there are 5 Kang launchers already manufactured.
4) For payloads related to the transfer vehicle and supplies, Kang launcher is preferred.
5) Kang launcher is not able to carry humans, so for human rated vehicles to LEO, the Falcon 9 vehicle with the crew dragon spacecraft will be used.
6) The crew will consist of 2 people.

III. MISSION TIMELINE

The mission will start when the completely assembled transfer vehicle (TV) departs from LEO. It will reach Low

Mars Orbit (LMO) 10 months after, and the descent to Mars together with all the planned operations will be performed. The return will take around 11 months. The total mission duration will be around 3 years. The most important dates of the mission are summarized as follows:

2024 July 15^{th}: First launch with the pressurized TV module
.... Total launching sequence and assembly will take 2 years, 4 months and 16 days (refer to appendix for detailed launching sequence and assembly timeline).
2026 October 31^{st}: Final launch with the crew and remaining payload.
2026 November 1^{st}: Departure from LEO.
2027 September 4^{th}: Arrival to LMO.
2028 August 7^{th}: LMO departure.
2029 July 16^{th}: Arrival back to LEO.
2029 July 16^{th}: Return to Earth of the crew.

Refer to the appendix for the corresponding image of the overall mission timeline with the dates and most important points.

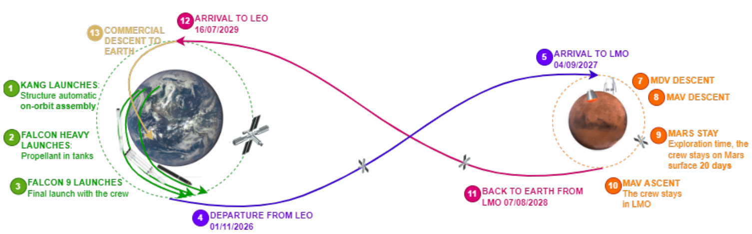


Fig. 1: Mission timeline (refer to appendix for a bigger image)

IV. General before assembly

There are a few aspects that must be taken into account before scheming the whole assembly process. These aspects are the decision for a launching site for the Kang and the orbit for the assembly.

A. Launching site

Several launching sites were compared for the launch of the Kang rocket. The most relevant ones are presented in table I. Note that the latitude of the launching site will correspond to the orbit inclination.

	Country	Latitude	Note
French Guiana	France	∼5º	For equatorial orbit
Cape Canaveral	**USA**	**∼28º**	**SpaceX launching site**
Vandenberg	USA	∼34º	Closer to PythonSpace
Esrange	Sweden	∼67º	To reach polar orbit

TABLE I: Launching sites comparison

Since the *PythomSpace* headquarters are located in California, the chosen launching site will be located in USA. Also, Cape Canaveral is located at a latitude of ∼28º. This angle is the minimum orbit inclination angle that can be achieved from this launching site. As it will be explained in the next section *B. Assembly orbit*, this is the preferred inclination for the assembly orbit. Therefore the **chosen launching site will be Cape Canaveral**.

B. Assembly orbit

This section will be divided in three parts: factors affecting LEO; space debris proposed solution; and finally the characteristics for the assembly orbit.

1) Influencing factors: To choose an assembly orbit, a few factors were taken into account:

– **Space debris**
The spacecraft will be subjected to a considerable collision risk during the assembly. Indeed, during the last few decades, an exponential increase in the space debris volume has occurred, especially in LEO. This exponential increase is due to the impact of the already existing debris against other objects orbiting. As a result of all these impacts, more space debris are created, which means a higher risk of impact, and so on [1].
The maximum debris flux is located at an altitude around 850-900 km [2] (see figure 2). Since the launches are to LEO, the major debris flux could be avoided by choosing an altitude of around 400 km.

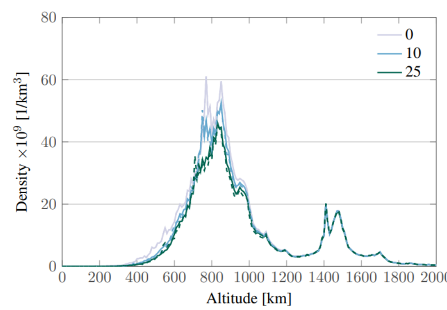


Fig. 2: Debris population evolution over 25 years [3]

– **Solar activity**
The Sun activity increases and then falls in cycles of 11 years. The time for the start of the mission is scheduled to be during a high solar activity period. The flux of particles coming from the Sun increases during periods of high solar activity, and these have a damaging effect on the spacecraft components. The higher the chosen orbit, the more exposed to these effects the vehicle will be during the assembly as the Earth's magnetic field weakens.
It is also important to highlight that this radiation will also have a negative effect on humans. This will be an important note to take into account if any EVAs (Extra Vehicular Activities) have to be performed as an alternative in case the automatic assembly fails up to some extent (more on alternative EVA in section ...).

– **Air drag**
Previous factors tend to point towards choosing an orbit as low as possible. However, a lower orbit means higher air drag, which translates as altitude loss. This effect would have to be counteracted with some kind of propelling mechanism, which would increase the costs in both propellant subsystems mass and monetary terms. Also, it is important to know that as the solar activity increases, the upper layers of the atmosphere are influenced,

and the air drag on satellites increases. In other words, during the assembly time, spacecraft might be specially affected by air drag.

– **Radiation**
  As introduced in the solar activity section, for electronics to not be compromised during the months of the assembly by the radiation, a lower orbit is preferred in order to stay inside magnetic field effect. As both, the inclination of the orbit and the altitude increase, the radiation effect becomes more dominant. Another issue are the radiation (Van Allen) belts. These are zones surrounding the Earth where charged particles are trapped and can endanger any satellite going through it. The inner belt is the one that factors in for the assembly orbit decision, and ranges from about $\sim$ 640 km of altitude [4]. The South Atlantic Anomaly (SAA) need also to be taken into account since it is a region of the belts located at a lower altitude, that is around 200 km. According to this aspect, the chosen assembly orbit should be lower than said altitude.
– **Transfer between orbital planes**
  It is interesting to choose an inclination for the assembly orbit that minimizes the required Δv. The chosen transfer orbit from the assembly orbit takes an angle of 28º with respect to the equatorial plane. In this sense the best option for Δv optimization would be an inclination for the assembly orbit of 28º (more on this information in Mission design report [5]).

2) Proposed solution for space debris: From the factors previously presented, the space debris one is the one that cannot be avoided independently of the chosen altitude. For it a solution must be proposed. There are developed space debris tracking softwares that model the space debris flux. The proposed solution is to use *MASTER* (debris flux model from ESA) [6], to track the bigger debris. In order to account for the smaller debris pieces that cannot be tracked, a shield can be added to protect against the smaller size debris.

3) Assembly orbit characteristics: After careful consideration of the aforementioned factors, the chosen characteristics for the assembly orbit are:

- **Circular orbit**
- Altitude **h = 530 km**: High enough to avoid high atmospheric drag, but also inside magnetic field to protect against radiation. For space debris issue there is a proposed solution.
- **Inclination of 28º**: To optimize the total Δv, and to have and inclination low enough to be shielded against radiation. Also, it corresponds to the latitude of Cape Canaveral (launch site).

This orbit will be used both as the departure orbit and arrival orbit at the end of the mission coming back from Mars.

V. Pre-departure timeline

In this section, the launches are scheduled to bring payload from Earth surface to LEO orbit for assembly. First, the duration of the development period is discussed; then a list of payloads is proposed with the corresponding masses. Third, trade-off between launchers is presented; followed by the launching sequence. Finally, the assembly timeline is presented.

A. Development period

There will be a development period before the beginning of the mission. This period comprises from the development of all the required instruments throughout the whole mission to their manufacturing.

An estimation of the times required for the whole development process for different modules and systems are shown in table II(from largest to shortest required time):

Pressurized module	1.5 y
MAV	1 y
General MO systems	1 y
LSS	0.6 y
MDV	0.5 y
TV modules from Kang	0.2 y
EM tanks	0.2 y

TABLE II: Development periods

Taking into account some of these processes can be performed in parallel, the total preliminary estimated time for the development process is **3 years.**

B. Payloads

A summary of payload masses is proposed as of departure from Earth surface to LEO. The total mass to be launched is 617.2t. From that, the amount of fuel to be brought in LEO was estimated to be 578 t for the whole mission (608 t including margin). That represents about 6% of the total mass of all space objects (9800 t in 2022, see [7]). For a more in detail payload itinerary, refer to the Coordination report [8].

Following pie chart shows the percentages of the dry payload (the whole payload except for the propellant):

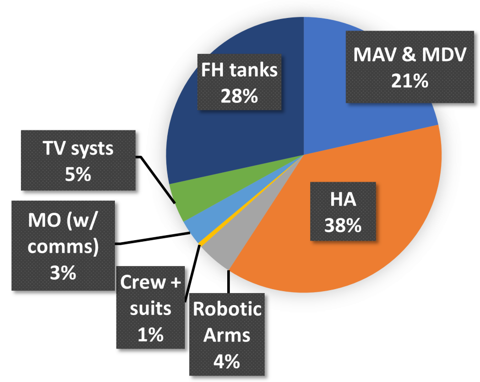


Fig. 3: Payload distribution without the propellant

The 38% of Human Aspects (HA) mass are the supplies (storage comprising food, water at departure) and the machines and modules structure of the Life Support System (LSS).

It should be noted that the propellant tanks in Falcon Heavy count as a payload (28%). However, the second stage of Kang will be used as the EM tanks (with the propellant for Mars-Earth trip back) so they are not in the payload list, see figure 8.

The 3% of the Mars Operations (MO) equipment comprises, ranked in decreasing mass: the water regeneration systems, power systems, temperature control systems, space suits, MOXIE, communication hardware, survival kit and drills. Note that in this pie chart, the communication equipment is accounted together with the MO mass.

For a in depth distribution of the payload among the launches, refer to the final table in the appendix of the launching sequence.

C. Trade-off between launchers

A comparison between different launchers is proposed. The launchers are compared with respect to their maximum payload to LEO, number of launches per year, cost per launch, estimated price per kg to orbit and time to complete the assembly on orbit.

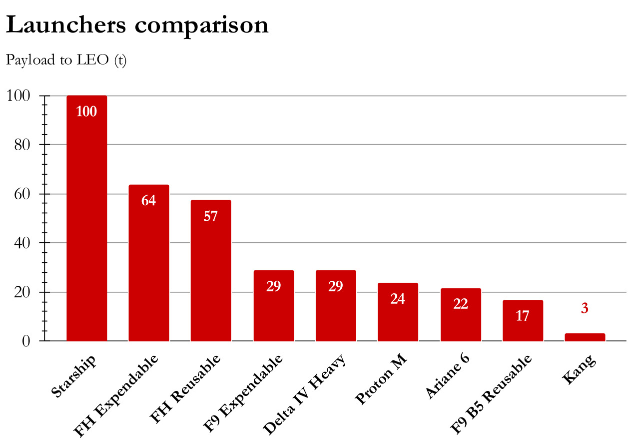


Fig. 4: LEO capabilities (t)

Starship capability is estimated from Elon Musk Starship update of February [9]. It was stated that Starship can carry 100 to 150 t to orbit depending on altitude. The lowest estimation (100 t) was chosen although the capability may be higher for a LEO orbit at 530 km. Fig.4 highlights the gap between Kang capabilities and commercial or state heavy launchers. It should be noted that SLS and Long March 9 are not included in this graph although they have similar payloads. The reason is that it is unlikely they will be available for commercial launches (SLS will be used for the Artemis program and Long March 9 is still in development [10]). Among the launchers included, only Starship, Ariane 6 and Kang are still in development. Falcon Heavy and Falcon 9 are flight proven.

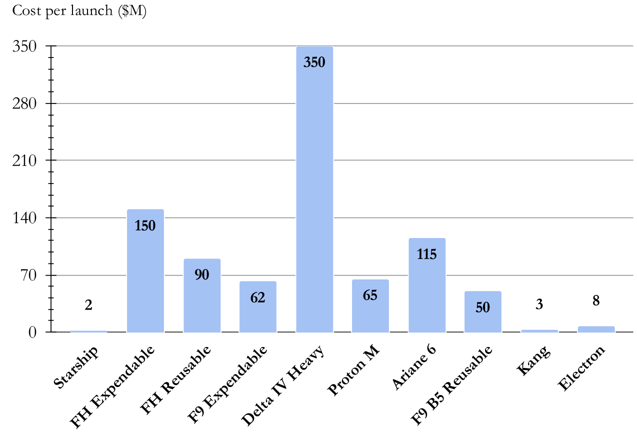


Fig. 5: Cost per launch ($M)

Fig.5 shows the cost per launch in million dollars. The costs for Kang cannot be compared properly with heavy class launchers such as Falcon Heavy. Thus Fig.5 shows the cost for Electron, developed by Rocket Lab, which is capable to launch 0.3 t to orbit. 3 M$ dollars per launch for Kang looks optimistic. It is only 50 % higher than Elon Musk estimation of a Starship launch [11] in a few years.

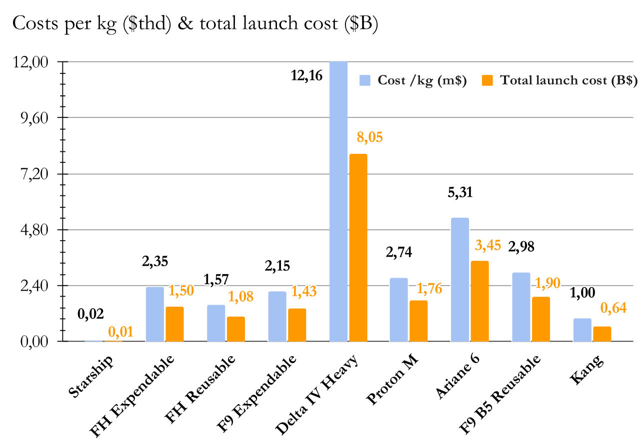


Fig. 6: Cost per kg (thousands $) and total costs ($B)

Tom and Tina have a budget of 500 M $. Fig.7 shows that only Starship meets this requirement (10 M$). The current costs estimations for Kang do not meet the budget requirements (128% of the budget). The cheapest commercial launcher is Falcon Heavy in reusable configuration. The remaining available launchers are Falcon 9 and Falcon Heavy in expendable configuration, and Falcon 9 Block-5 configuration. The launch cost would represent 216 % to 380 % of the allowed budget estimation.

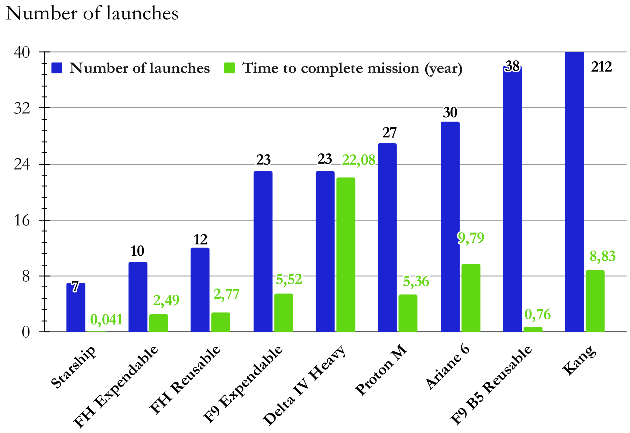


Fig. 7: Cost per kg (thousands $) and total cost of launches

SpaceX aims to launch a Starship 3 times a week at first (retained in this graph), then 3 times a day. For Kang, it was assumed that a minimum of two weeks between two launches of a Kang rocket can be achieved (accounting for flight, landing, recovery and reconditioning). The time to complete the mission (i.e. bringing payload to LEO) was computed considering that only one type of launcher is used, and that every single launch is fully dedicated to Pythomspace. The time between two launches varies from ~ 3 days for Starship, a week for Falcon 9 B5 configuration, to 3 months for Falcon Heay. If the transfer vehicle is to be ready in 2026, i.e. in 4 years as of 2022, only Starship ($\sim$ 16 days), Falcon Heavy and Falcon 9 could be able to meet this requirement. Using only Kang is out of question given the amount of launches. That highlights the necessity to rely on commercial launchers that have a high volume of launches per year.

Fig. 8: Stages of Kang [12]

Kang was chosen to bring low-mass payload ($\leq$ 3t) and parts of the transfer vehicle. For higher payload mass ($\geq$ 3 t, that is the propellant) the Falcon Heavy was chosen given its higher payload capacity. The Crew Dragon capsule was chosen for the crew launch.

An overview of the chosen launchers and their specific characteristics is shown in table III.

	Payload capacity	**⌀ (m)**	**# Launch**	**Launch Freq.**	**Launch cost**	**$/kg**
Kang	3t	2.5	x 4	2 w	3M $	1000
Falcon 9	28.8t	3.7	0 x1crew	2 w	62M $ 55M $/seat	2150
Falcon Heavy	63.8t	3.66	x10	3 m	150M $	2350
TOT.	**678.8t**	-	**x15**	**-**	**1.62B $**	**-**

TABLE III: Launchers characteristics

D. *Launching sequence*

The mission requires to bring a payload mass to LEO higher than the capability of a single launcher. Thus the mission includes several launches to LEO to perform an On-Orbit assembly. The launch timeline and assembly sequence use available commercial launchers, Kang, autonomous docking and robotics.

First an airlock equiped with docking rings is launched with Kang. The rocket second stage is then used as a pressurized module for the transfer vehicle. Then the solar arrays and radiators are automatically deployed. Engines are discarded. It was supposed that a docking system was integrated on the pressurized module. Then the first MDV (Mars descent vehicle) is launched with Kang. It is docked to the airlock. Similarly, Kang's second stage is docked to the pressurized module. It will be used as a propellant tank during the transfer back from Mars to Earth. Again, engines are discarded. The same procedure is repeated for Kang 3, bringing the second descent vehicle. Falcon Heavy n°1 carries a large propellant tank, called EM1, and is used to refuel ME1 and 2 propellant tanks. The robotic arm catches EM1 tank and fixes it to a lightweight truss structure surrounding ME2. In a similar process, 3 Falcon Heavy are launched to LEO with one tank each. Again, Kang second stage is assembled to the transfer vehicle as a tank for the journey back to Mars. One year has elapsed since. 6 Falcon Heavy bring the remaining propellant tanks to the Transfer vehicle. A final Falcon 9 launches to LEO with the remaining amount of propellant required, the remaining dry payload and the crew. **Refer to appendix for a visual representation of the launching sequence.**

E. *Timeline*

The beginning of the mission is scheduled to be October 1^{st} 2024. The main challenge is to bring a large amount of propellant and supplies for the crew in orbit,

The timeline includes departure dates, time between two launches, ports utilization of the transfer vehicle.

Refer to appendix for both assembly timeline and launching sequence.

VI. Assembly

Different on-orbit assembly technologies available today to build the transfer vehicle are discussed. First, the requirements of the mission relevant for OOA are stated, then a comparison between the current technologies is proposed.

A. Requirements for assembly

The crew will have some basic training to perform EVA, but reaching a high level of autonomy for the assembly is required. Indeed, the crew will not be able to perform any assembly operations but might need to perform some maintenance operations of the ship. Another key factor is to minimize the mass of the transfer vehicle. This means the structural mass needed for assembly must be minimized. Fuel tanks will have to be filled therefore some on-orbit refueling systems are necessary.

The complexity of the assembly should remain as low as possible. Element-element mating (like docking modules) or modular structure assembly with standard interface are preferred to complex assemblies (such as engines and propulsion system piping). Welding individual parts together using electron beams is not considered (according to [13], only one attempt of in space welding was conducted on Soyuz 6 by a soviet crew but it was a disaster).

The structure of the transfer vehicle should remain as modular as possible with standard interfaces to maximize reusability, cut down development costs and minimize mission risks (see [14]). The module design should include the use of robotic arms thus the modules must be easy to manipulate.

The size of the transfer vehicle should remain as little as possible. Indeed, robotic arm have a limited range of operations. Power and signal lines must be protected from radiations and leakage everywhere.

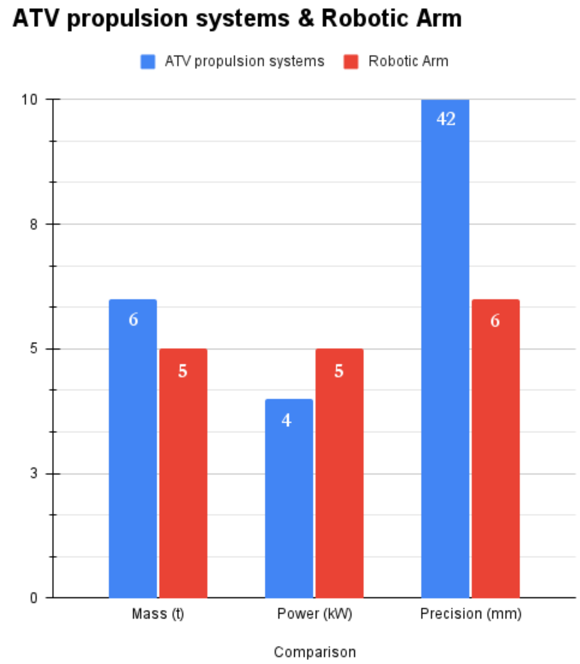
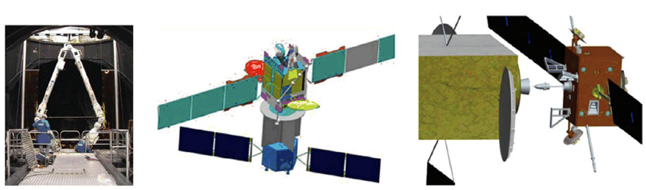


Fig. 10: Comparison of solutions for assembly

B. Trade-off between assembly technologies

Current robust assembly technologies include autonomous docking systems using AOCS [14] and robotics.



(a) ERA (b) CX-OLEV is docking with a client (c) SMART-OLEV is docking with client

Fig. 9: ESA research topics on assembly, picture from [14]

Other missions including assembly are typically refueling of spacecrafts (Notion Mission 4 [14] or robotic maintenance (JEMRMS performs some maintenance on ISS).

Three criteria were chosen to qualify the assembly technologies. The most important one is the mass, then the assembly accuracy is essential to limit failure risk. The power required to perform the assembly is also important. The technology readiness level was also maximized in the final scenario (≥ 6 i.e. technological demonstration) because many solutions are still hot research topics. As highlighted in [14], many technologies are promising in OOA but many of them are still research area where feasibility has not been demonstrated.

Fig.10 compares the mass, accuracy and power of two solutions for assembly. The first one uses AOCS thrusters installed on each module, in a similar way to the ATV (4 main thrusters and 28 attitude control thrusters as seen on Fig. 11). The second solution includes the use of a main robotic arm to grasp the largest payloads from the fairing of the launcher and connect them to the rest of the spacecraft. A smaller arm, similar to Dextre on ISS (see Fig.12) is used to perform smaller operations such as joining trusses or storing payloads inside the airlock and pressurized module. The main arm would move on a mobile station which travels on a rail .Both arms would be controlled from the ground.

Fig. 11: ATV Propulsion system

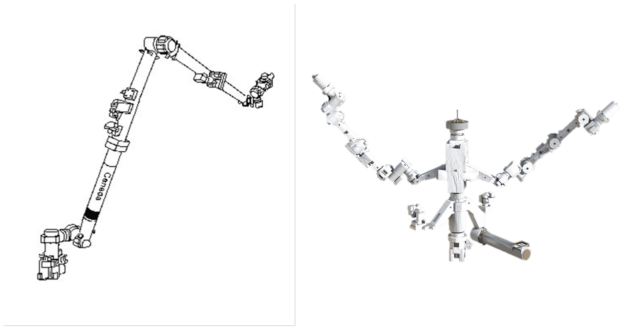


Fig. 12: Robotic arms on ISS (SSRMS and Dextre)

Fig.10 shows that the robotic arm has several advantages over the AOCS systems. In terms of mass, according to [15] the ATV uses about 5.5t of propellant, and the thrusters mass is negligible. On the ISS, the total mass of SSRMS, Dextre and the mobile platform is about 4.8 t (see [16]). The robotic arm looks more advantageous in terms of payload to bring to LEO. However the key factor is the mass of the transfer vehicle. From this point of view the robotic arm is dead weight compared to the attitude control thrusters which weighs almost nothing.

In terms of power, the ATV needs 3.8 kW and the robotic arms plus the mobile station need a total of 4.8 kW (according to [16]). Only some fraction of the ATV power is used for attitude control so the power consumption is lower for the guidance system.

Eventually, precision is much greater for the robotic arm than for the guidance system (42 mm is the greatest precision of the target position according to [17]).

The choice was made to bring two arms and a mobile platform (downscaled to 1.6t for the transfer vehicle) and to equip all the modules with AOCS thrusters. To maximize autonomy, the solar panels and the radiators will be deployed automatically.

VII. Return LEO-Earth

Once the transfer vehicle reaches Earth's sphere of influence, it is necessary to decide how the re-entry to Earth will be performed. There are two possible solutions: Vehicle reentry and commercial reentry.

A. Vehicle reentry

This option consists on capturing the transfer vehicle into LEO and descending by means of an Earth descent vehicle that is carried in the transfer vehicle.

The main advantage by applying this option is optimization of the total Δv (for more information about this point, refer to Mission Design report [5]).

Nevertheless it would be necessary to design a vehicle for solely this purpose. One possibility would be to design a vehicle whose only purpose were Earth descent. This would mean to carry during the whole mission extra weight. The other possibility would be to use MAV, modified to withstand the reentry on Earth's atmosphere. However, this would require a very high complexity vehicle design. Also, the risks would increase since MAV would have already withstood significant high forces and might be damaged after the descent and ascent form Mars. This option is disregarded.

B. Commercial reentry

The other option would be to descent to Earth by means of a commercial spacecraft from a private company. As for today, there are few available human rated vehicle options that have been completely developed (although most probably at the return of the mission in 2029 there will be more and cheaper options available):

– Government agencies: probably not possible as Pythomspace is a private company and their proposed mission relies on only exploration.
– SpaceX: a crew dragon that docks and returns to the Earth splashing into the ocean.

Final decision for reentry*:*

1) Transfer vehicle reaches Earth sphere of influence and gets captured.
2) The chosen orbit is the same as the one used for the assembly of the vehicle at the beginning of the mission: 530km of altitude, circular, and 28º inclination.
3) Commercial reentry, by making use of Crew Dragon.

VIII. Communications

Communication is an important requirement for such mission. From private conversations to keep mental health or experiment data transfer, one must not neglect communication without increasing the risk of the mission. Furthermore, Mars communication presents challenges never encountered before and which are so much more complex than those ever encountered in any space missions.

First, the distance between earth and Mars varying from 56 to 400 millions km makes live feed impossible. Even at speed of light, the radio wave would take 3 to 22 minutes to go from Mars to Earth. In this situation, the crew must be prepared to fix emergencies on its own.

In addition, both communication devices on Mars and on Earth need to face each other. Thus, communication black-outs will occur during the Mars-Sun-Earth conjunction and when the communication device will be in the opposite side of Mars with respect to Earth. The former lasts 2 weeks [18] and the duration of the latter depends on the communication system and network.

A. Communication requirements

During the entire mission, the crew need to have the ability to communicate with Earth. However temporary blackouts could be accepted if the duration is not unreasonably long and the cost of removing the blackouts is to large. The communication hardware should be capable of transmitting and receiving video messages in decent quality. This is so that the crew can get efficient help from experts in times of crisis as well as being able to communicate with friends and relatives on Earth on a good level.

We ranked three level of communication useful for a human mission:

- Video transmission
- Audio transmission
- Data transmission

Each of these levels require a specific amount of bit rate in order to be acceptable i.e not to add to much delay to the already existing distance latency. These bit rates are specified in IV. Note that the Mars reconnaissance orbiter data transmission rate in this table is not the maximum data rate but the necessary one for current rover missions.

Level	Data rate
Video transmission (1080p)	4.5 Mbit/s
Audio transmission (medium quality)	200 kbit/s
Effective data transmission (MRO)	0.5-4Mbit/s

TABLE IV: Bit rate necessary for different level of communication [19]

With this numbers, it is possible to establish the communication data rate needs of the crew. Knowing that the full speed video transmission will only be needed for emergency and that only few experiments will be conducted, the need is approximately around **6 to 10 Mbit/s**.

B. Communications infrastructure on Mars

The overall strategy for communicating with Mars will be centered around having only some smaller antennas on the Mars base while larger communication hardware are kept in orbit, which will act as a relay between the Mars base and Earth. Bringing down a larger parabolic antenna on Mars would be a challenge due to the martian atmosphere and the transfer vehicle are going to need some form of communication hardware anyway that is used during transit. Instead the base on Mars will utilize similar communication technology as a starlink antenna and the the Perseverance rover, which consists of three different antennas. Firstly there will be a starlink antenna which is capable of achieving bit rates of 10 megabits per second [20] which communicates through the infrastructure in Mars orbit to Earth. Then there is the X-band High Gain Antenna which is steerable so it can focus its radio beam in a specific direction. It can communicate/receive directly with Earth at a bit rate of 160/500 bits per second to/from the Deep Space Network's 34 meter-diameter antennas or 800/3000 bits per second to/from the Deep Space Network's 70 meter-diameter antennas. Lastly there is the X-band Low Gain Antenna which can send and receive data in every direction which provides some redundancy. However it can only communicate at around 10/30 bits per second with the 35/70 meter Deep Space Network antennas [21].

C. Communication infrastructure above Mars

There are many ways to reduce black-outs in Mars, but the more efficient the solution, the more satellite it will need. Knowing that sending a telecommunication satellite around mars is really expensive, a trade-off has to be made to find the most suitable solution. Here is a description of suitable solution with emphasis on the selected one.

Solution 1: The first option is to only use the orbiting transfer vehicle as a relay between the Mars base and Earth. This would be the most simple solution and the cost would also be the lowest. However the drawback would be that the windows of communication would be quite short and there would also be a two week blackout when the Sun, Earth and Mars align and the planets are on opposite sides of the Sun. In order to reduce that drawback, the transfer vehicle must be close to an equatorial orbit so that the communication between the vehicle and the surface can be achieved at each orbit. Indeed, Candor Chaos is close to the equator, at an inclination of -7.25°. This would not be possible if the orbit is not close to equatorial because of mars rotation: orbits by orbits, the transfer vehicle would appear lower and lower in the sky and disappear for several orbits letting the crew unable to communicate with it.

The inclination of the transfer vehicle orbit has been set by the ascent and descent course of the MAV and MDV which require an inclination of -7.25°. As an approximation, considering an equatorial orbit at an altitude of 230km, the transfer vehicle completes 13 orbits a day and spends 12 minutes 36 seconds in reach of the base for each orbit. This brings a total close to 2.5 hours of possible communication.
The communication hardware that would be incorporated in the transfer vehicle would be the 3 meter in diameter high gain antenna from the Mars Reconnaissance Orbiter. It was capable of achieving a bit rate of up to 0.5-4 Mbit/s [19]. However as this satellite was launched back in 2005, upgrades could surely be made to boost the bit rate up to around 6-7 Mbit/s with modern technology which would cover the requirements for the mission.

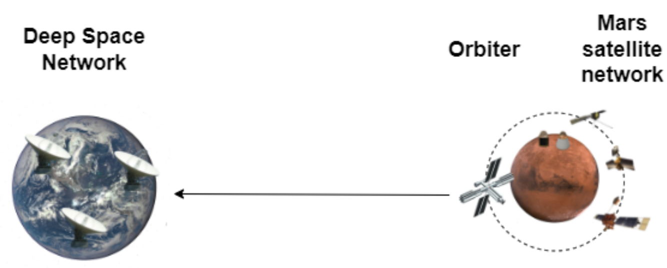


Fig. 13: Communication solution 1

Solution 2: The second option is to instead use a separate satellite placed in areosynchronous orbit above the base on Mars. This would provide a continuous window of communication with a single blackout every sol when Mars obscures the satellite. The satellite would be very similar to the Mars Reconnaissance Orbiter and utilize the communication hardware that was discussed in Solution 1. However this would add to the cost and complexity of the mission. Indeed, the cost of launch and development of the Mars Reconnaissance Orbiter is $416.6 millions for the latter and $90 millions for the former [22]. One can imagine that the development cost includes instruments development that is not useful for this expedition but the order of magnitude is still in the hundreds of millions which compared to the overall cost of the mission of around $72 billion is not a large addition, at least compared to the vast improvement in reducing blackout time.

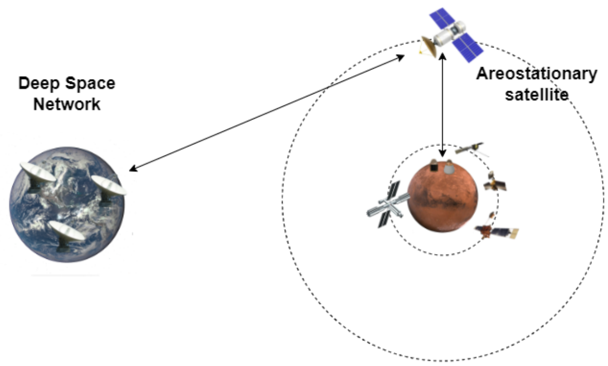


Fig. 14: Communication solution 3

Solution 3: The third solution further builds upon the second solution. The idea here is to both have the aerostatinary satellite around Mars and in addition, another satellite would be put in the same orbit of Mars but either in front of, or behind Mars in the orbit. The purpose here is to make sure that there is always a stable link between the Earth and Mars which, would remove the problem of the two week blackout during a solar conjunction. Having this solution would most likely be required before establishing a permanent base on Mars. However it might not be feasible for this particular mission due to the vast increase in complexity and total cost.

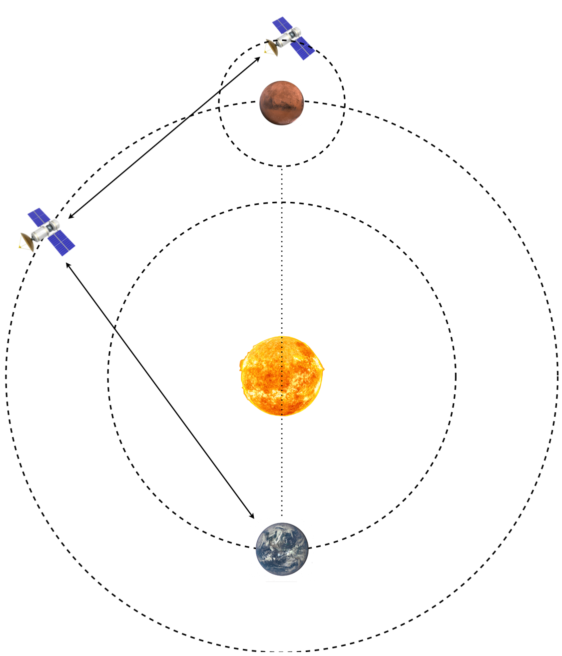


Fig. 15: Communication solution 3

D. Trade-off between the options

Here we include a short trade-off between the different options. The third option can be ruled out due to its price and the low improvements compared to solution 2. Indeed, during the two weeks black-out the crew will not perform any exploration task or risky tasks that can lead to life threatening issues. The first option does not allow a suitable communication time, the total communication time per sol is 2:30 distributed among 13 orbits. Moreover, the latency due to the distance being most of the time superior to 12 minutes, the crew on Mars will have to wait the next transfer vehicle orbit to receive an answer which increases he latency time to more than two hours. All these issues that can become life threatening in case of emergencies requiring an expertise such as engineering issues thus, the second solution which represents an in-between was selected.

Sol.	Hardware	Black-out time	Price
1	Antenna on TV	Except 12 mins/orbit 13 orbits/sol	$10k-$100k
2	Areostationary satellite	2 w. black-out	$320M
3	Areostationary satellite Heliocentric satellite	Almost no black-out	$720M

TABLE V: Communication solutions comparison

E. Communication during transfer

Now the communications between Earth and Mars has been laid out, however the crew must also be able to communicate with Earth from the transfer vehicle during transit. Here the same communication system that is used on the relay satellite between Earth and Mars, that was described in Solution 2, will be used on the transfer vehicle.

IX. Off-nominal scenarios

In this sections a few off-nominal scenarios will be proposed and possible solutions discussed.

A. Communication black-outs

The communication solution allows for a large communication time but in case of a unplanned black-out, the crew must change its planning for its safety. There are two different levels of failure that would create a blackout: an areostationary satellite failure and a failure of the communication hardware on the surface.

In case of the areostationary satellite failure, the communication time would be reduced to the one of the communication solution 1 i.e 12 minutes per orbit of the transfer vehicle for a total of 13 orbits per sol. In this case a communication link would still exist but only partially and there will not be any way of fixing the problem. This scenario would not jeopardize the goal of the mission as the crew is already trained to operate autonomously but any operation that would require immediate fixing would be canceled.

In case of a failure in the communication hardware on the surface, the crew on the surface would not be able to communicate with Earth other than through high gain and low gain antennas which have a very small bit rate. Then, two scenarios can follow: if the fault can be fixed without help the consequences would be minor otherwise, the crew will have to stop operations and come back to the transfer vehicle as the danger would be too high.

B. Launch failure during assembly

Perhaps the most critical part of the mission is the assembly of the transfer vehicle. Indeed, the departure time precision affects the overall ΔV of the mission (as seen in the porkchop plots of in the mission design report [5]) and thus a consequent delay is not acceptable. One event that might delay the departure to Mars is a failure of a launch vehicle lifting a critical module such as the airlock. Indeed, the airlock is a unique and complex module that would require a long time to re-build. In the other hand, the other modules are less complex and easy to re-manufacture and in particular the tanks that are build in several units.

In the worst case i.e a failure of the first Kang launch that contains the airlock, the docking rings, the pressurized module and solar arrays, the whole mission would be delayed. These modules are the core of the transfer vehicle which means that all the following launches can not happen. A failure of this type would delay the mission to the next Mars departure window two years later. A solution would be to manufacture a second unit of these parts but the budget target would not be met and one can expect a Kang success launch rate above 96%.

X. Sustainability Aspects

The main motto of the mission is that the objective is solely to explore. That means that an important requirement is to make the mission as sustainable as possible.

One aspect in which the mission aims to be as sustainable as possible is with regards to what is left on Mars and in the orbits of Earth and Mars. Nothing will be left out on the surface on Mars. Everything that can not be brought back to Earth will stay inside the base as to not contaminate the planet (see MO report [23] for a more detailed description). The Falcon Heavy upper stage is left in LEO after assembly, as well as the tanks from FH launches 8-10 as they are not used for the TV structure. At the end of the mission the vehicle is left in LEO and able to reuse for possible future missions.

To make the many launches required for the assembly as sustainable as possible partially reusable launch vehicles are used.

XI. Conclusion

This report has laid out and discussed some important logistical aspects that would be relevant for a manned mission to Mars. Some basic assumptions for the mission is presented as well as an overall timeline. The main part of this report is focused on how a transfer vehicle, that will take the crew to Mars, should be assembled in orbit. The launch site for the different parts was set to Cape Canaveral and after considering different factors such as space debris, solar activity, air drag and radiation an altitude of 530 km was set for the assembly orbit. Furthermore an inclination of $28\,\mathrm{deg}$ was chosen for the assembly orbit.

The total payload mass to be launched is 617.2t and it would have been unreasonable to only use the proposed Kang launcher which had a payload capacity to LEO of 3t. So other launchers also had to be considered and the most promising ones to use together with the Kang was the Falcon 9 and the Falcon Heavy from SpaceX. This combination would result in a required 15 launches in total. The launching sequence was discussed as well as different technologies that could be used for assembling the transfer vehicle in orbit. Here it was decided to bring robotic arms that could be controlled from Earth, as well as having the different modules being able to dock autonomously with each other.

The plans on how to get the crew back on Earth is also described briefly, here it was decided to do a commercial reentry by using the Crew Dragon.

Communications was also looked at due to its importance especially for a human mission. Some basic requirements gave a minimum bit rate of at least 6 to 10 Mbt/s of communication. Then a few technologies that would be able to provide this requirement was discussed, this included the antenna form the Mars Reconnaissance orbiter, the Starlink antenna as well as antennas from the perseverance rover, where the later would provide some redundancy. One problem when communicating between Earth and Mars was the blackout time that occurs when line of sight is interrupted. A solution where an aerostationary satellite would be placed on top of the Mars base was selected since this reduced blackout time by a lot while not increasing the budget by an unreasonable amount in a relative manner.

Further research would have to look at adapting the starlink antenna to the Mars environment since its not designed to work in those temperatures. A more thorough look at the already existing communication infrastructure around Mars could also be done. If the bit rate and coverage that could be provided is great enough a modified solution 1 might be a better choice for the communications.

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APPENDIX

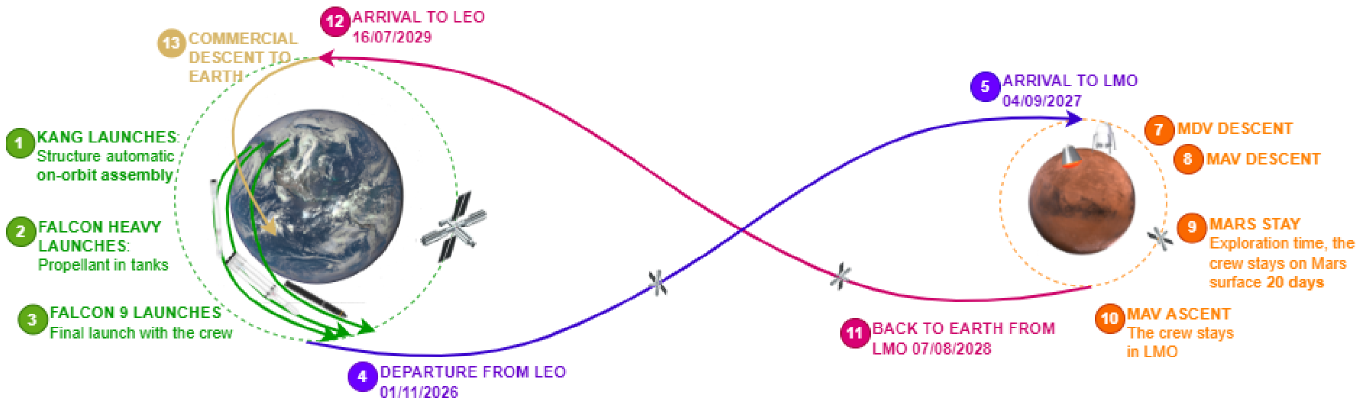

Fig.: Mission timeline

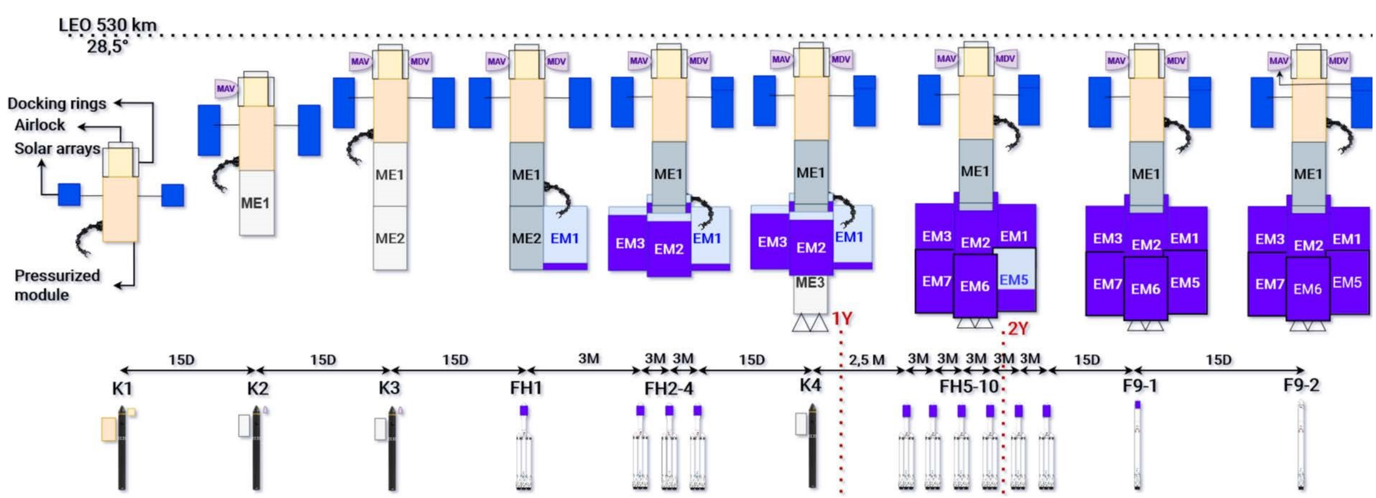

Fig.: Assembly timeline using Falcon Heavy, Falcon 9 and Kang

Launch	Launch Code	Launch date	Elapsed Time (months)	Payload type	Specific payload	Payload Mass (t)
1	K1	2024/06/15	0	**TV structure** Pressurized module	Robotic arms: 1.6t Airlock: 1t Power system: 0.33t Solar arrays: 0.05t	**2.98t**
2	K2	2024/06/30	0.5m	**TV structure** Tank ME1	MAV: 1.12t Whole MO equipment: 1.04t Gyroscopes (x4): 0.4t Hygiene system: 0.29t Communications: 0.11t	**2.95t**
3	K3	2024/07/15	1m	**TV structure** Tank ME2	MDV: 1.12t Sport equipment: 0.93t Food 1st batch: 0.85t Medical equipment: 0.05t	**2.95t**
4	FH1	2024/07/30	1.5m	**Fuel** **TV structure** Tank EM1	Tank: 1.36t Fuel: 62.44t	**63.8t**
5	FH2	2024/10/30	4.5m	**Fuel** **TV structure** Tank EM2	Tank: 1.36t Fuel: 62.44t	**63.8t**
6	FH3	2025/01/30	7.5m	**Fuel** **TV structure** Tank EM3	Tank: 1.36t Fuel: 62.44t	**63.8t**
7	FH4	2025/04/30	10.5m	**Fuel** **TV structure** Tank EM4	Tank: 1.36t Fuel: 62.44t	**63.8t**
8	K4	2025/05/30	11.5m	**TV structure** Tank ME3	Food 2nd batch: 2.8t Safety equipment: 0.16t Psychological equipment: 0.01t	**2.97t**
9	FH5	2025/07/30	1y 1.5m	**Fuel** **TV structure** Tank EM5	Tank: 1.36t Fuel: 62.44t	**63.8t**
10	FH6	2025/10/30	1y 4.5m	**Fuel** **TV structure** Tank EM6	Tank: 1.36t Fuel: 62.44t	**63.8t**
11	FH7	2026/01/30	1y 7.5m	**Fuel** **TV structure** Tank EM7	Tank: 1.36t Fuel: 62.44t	**63.8t**
12	FH8	2026/04/30	1y 10.5m	**Fuel** **TV structure** Tank EM8	Tank: 1.36t Fuel: 62.44t	**63.8t**
13	FH9	2026/07/30	2y 1.5m	**Fuel**	Tank: 1.36t Fuel: 62.44t	**63.8t**
14	FH10	2026/10/30	2y 4.5m	**Fuel**	Tank: 1.36t Fuel: 45.84t	**47.2t**
15	F92	2026/10/31	2y 4.5m 1d	**Fuel**	Air & Water regenerator systems: 3.53t Water: 2.35t Oxygen: 2t Food 3rd batch: 1.47t **CREW + SUITS**: **0.21t**	**9.56t**

TABLE: Launching sequence and payload distribution

COLOR CODE:

Kang (x4)	K_
Falcon Heavy (x10)	FH_
Falcon 9 (x2)	F9_

TV	**HA**
LOG	**MO**