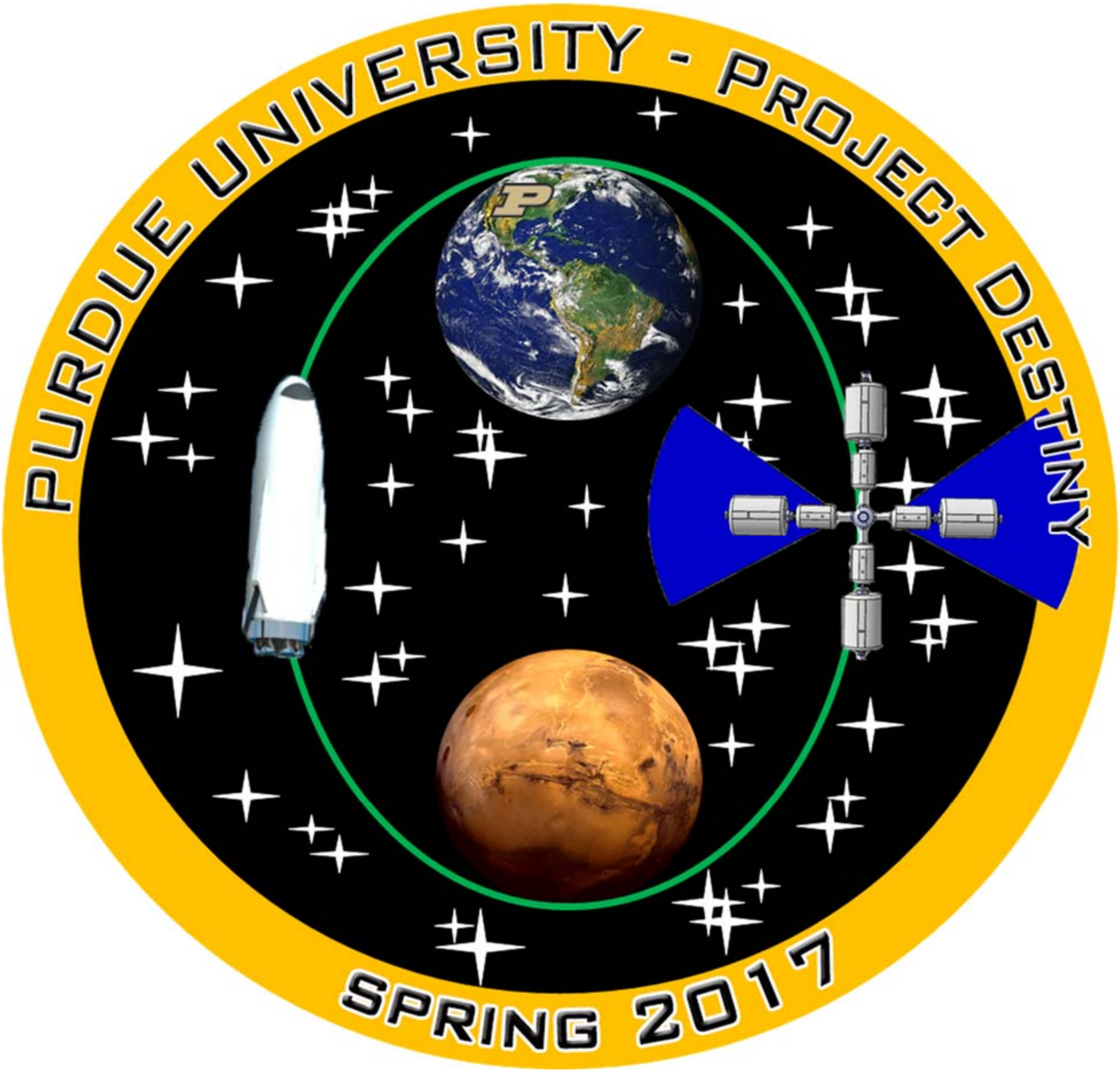
PROJECT DESTINY

AAE 450 | SPRING 2017



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Foreword

This report represents the culmination of an intensive spacecraft design course, AAE 450/EAPS 391, undertaken by seniors during a single semester. The students perform a feasibility study for a specified mission goal, subject to certain constraints.

The entire class works as a single team to achieve this goal. They elect a Project Manager and an Assistant Project Manager and organize into specialized groups to study (in this case) CAD (Computer Aided Design) communication and control, human factors, mission design, power and thermal control, propulsion, science, and structures.

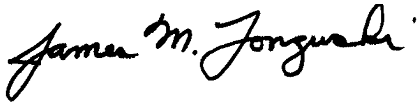
The science group represents a relatively new collaboration between the School of Aeronautics and Astronautics and the Department of Earth, Atmospheric, and Planetary Sciences. This group consists of students in the Planetary Sciences major program. Their successful integration into the team, and their numerous important contributions have proven the value of bringing scientists and engineers together on a space mission design project.

At the end of the semester the students deliver a formal presentation of their results. Besides this report, the class provides an appendix, which contains detailed analyses of their methods and trades studies.

The quality of the work in this report is consistent with the high standards of the aerospace industry. The students who participated in this study have demonstrated that they have mastered the fundamentals of astronautics and planetary science, have learned to work efficiently as a team, and have discovered innovative ways to achieve the goals of this project.

In this project, the students were given a unique opportunity to work with Dr. Buzz Aldrin and his son, Dr. Andy Aldrin. On January 12, 2017 Dr. Buzz Aldrin and Dr. Andy Aldrin visited the class to discuss the final version of the Project Specifications for Project Destiny that the class would be required to achieve in their design. In particular, Project Destiny is taking the challenge of Elon Musk—t o put one million colonists on Mars within the next hundred years at the cost of $200,000 per colonist—and calculating the numbers. Central to the specs for the class is that Dr. Buzz Aldrin's cycling concepts be implemented. In Project Destiny, the two Dr. Aldrins are acting as customers that the students must satisfy. The ultimate question that must be answered is: is the Elon Musk plan feasible? (We will not spoil the answer by giving it here!)

We believe this design team rose to the challenge to produce an important feasibility study. The leadership of the Project Manager and Assistant Project Manager as well as the outstanding cooperation of the team members were key elements in the success of their project. They have every right to feel proud of their accomplishment and we are proud of them.



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1 Introduction

1.1 Background

On September 27th, 2016, Elon Musk gave a presentation to the International Astronautical Congress. In his presentation titled "Making Humans an Interplanetary Species", Musk lays out an architecture using SpaceX hardware that he argues will make Mars more affordable and accessible to anyone who wishes to colonize Mars.

The fundamentals of the presented SpaceX architecture are:

- Fully Reusable Launch System
- LEO refueling
- Propulsive Landings
- Direct
- Hyperbolic Trajectory between Earth and Mars
- Return capability of landing vehicles through fuel production on Mars Surface using a methane/LOX fed propulsion system.

At the cornerstone of this architecture is the use of the proposed Interplanetary Transport System. The Interplanetary Transport System or I.T.S. for short, is a 2 stage, methane liquid oxygen powered rocket and is shown in Fig. 1.3.1.1. Both stages are provided thrust from SpaceX currently in development raptor engines depicted in Fig. 1.3.1.2.

Fig. 1.1.1 Artists rendition of a fully assembled ITS at launch (Credit: K. Jantze)

Fig. 1.1.2 Methane / Liquid oxygen fed Raptor engine (Credit: K. Jantze)

The upper stage consists of raptor engines optimized for use in vacuum and atmospheric landing while the lower stage only consists of engines optimized for sea level launch. The upper stage will be either the I.T.S. spacecraft which will actually carry the crew and cargo or a tanker vehicle which will be used to refuel the I.T.S. in orbit. Both of these upper stages are equipped with heat shields and landing legs to allow pinpoint landing on Mars or back on the earth for reuse. The I.T.S. spacecraft consists of a pressurized habitable section and unpressurized cargo bay. Musk

argues that in order to increase the population of those who would like to go to Mars, the journey needs to be made more enjoyable. To do this, the I.T.S. is designed to have large open spaces and will be equipped with restaurants, game areas, and other luxuries to make the trip more enjoyable.

Musk challenged that using this architecture, SpaceX will be able to eventually reduce the cost of each ticket to below $200,000 per person and that a colony of 1,000,000 could be established on Mars in the time range of 40-100 years.

Fig. 1.1.3 ITS performing an in orbit refueling (Credit: M. Gripe and K. Jantze)

1.2 Project Destiny Objectives / deliverables

The purpose of Project Destiny is to validate the claim that a colony of 1 million inhabitants can be feasibly established on the surface of Mars within 40-100 years using the SpaceX architecture presented. We accomplish this by developing a colony that minimizes cost and the number of launches to build the actual colony. We then will evaluate 3 different methods of delivering this colony based on the SpaceX architecture. These 3 different systems offer unique benefits and draw backs that will emphasize the considerations that should be made while continuing to develop the ITS for Mars colonization.

We present the deliverables as the following:

- **Launch Minimized optimized colony:** A colony designed to minimize the mass delivered from earth per colonist to minimize the number of launches and lost logistics.
- **Transport Model Trade study:** A trade study comparing 3 different models based on the ITS .
    - **SpaceX original Model**: launching people and cargo in a comfortable living environment in the same vehicle on a direct trajectory.
    - **Crew and Cargo on separate direct flights**: we use the full ITS internal volume for just crew or just cargo instead of a partition. These vehicles also take a direct hyperbolic trajectory to Mars.
    - **Cycler and Taxi Vehicle:** we use a vehicle on a solar cycler orbit between earth and Mars that can be launched and deployed from a modified ITS. We then use a taxi designed to rendezvous with the cycler at earth and perfom entry, descent and landing at Mars.
- **Feasibility Analysis:** An analysis of the colony and each transportation model's feasibility in terms of economics, launch infrastructure, and risk management.
- **Overall Conclusions and Recommendations:** Project Destiny's conclusion on the feasibility of Musk's claim and our recommendation on how to improve the feasibility of the architecture.

2 Requirements, Assumptions, and Constraints

2.1 Requirements

While the primary objective is to test the feasibility of achieving a colony of 1 million people within 100 years, we met a set of requirements from our customers regarding the living conditions and safety of the colonists.

Game Rooms: Spaces are for games and other physical activities to insure musculoskeletal health.

Artificial Gravity: For transit between Earth and Mars, an artificial gravity equivalent to 0.165 G

Cycler Concept: We evaluate an Earth-Mars cycling trajectory vehicle in our design.

Continuous Communication: We maintain a continuous line of 2-way HD communication between the colonists and Earth.

Free Spaces and Recreation Rovers: Colonists must be able to leave their living habitats in a shirtsleeve environment either in a recreation rover or artificial green space at least 3 times a week.

Scientific Rovers: We include rover vehicles with advanced scientific capability in our colony architecture.

Radiation Protection: Colonists are from Space Radiation whenever feasible.

Sustainable Colony: Once the colony reaches a population of 1 million, it must be able to sustain itself for 20 years.

2.2 Critical Assumptions

Using these requirements, we needed to apply a set of simplifying assumptions for the entire mission:

SpaceX ITS architecture is valid: Our feasibility study is not to test whether or not SpaceX can build their vehicles, but whether or not vehicles with the provided specifications can develop a million inhabitant colony on Mars surface. As such, we assume the numbers for vehicle performance, lifetime, and scale are 100% accurate.

Mars environment has Earth analogues: When NASA data is insufficient, we assume that earth analogues for geography and topography will be sufficiently accurate for modeling digging and construction operations.

2.3 Additional Constraints

From our requirements and design assumptions, we constrained our design further to narrow the scope of our analysis:

Only SpaceX Launch Vehicles: We will only use SpaceX hardware as launch vehicles for our design.

Limited ITS Modifications: We are giving ourselves the liberty to modify the working space consisting of the cargo bay and pressurized cabin of the presented ITS such that the inert mass is approximately the same. However, we will not be adjusting the tank design, rocket engines, or 1st stage booster for the system. In this way, we open up the different possibilities of how the ITS could be utilized without developing new technology or adjusting performance.

Fixed Vehicle Lifetimes: Due to the lack of comparable data, we assume that the lifetime and performance of the vehicles included in the ITS architecture retain the same lifetimes provided by SpaceX throughout the mission:

- **First Stage Booster:** First Stage Booster Can be launched 1,000 times
- **Tank Vehicle:** Each Tanker vehicle can be launched and docked 100 times before retirement.
- **ITS Ship:** Each ITS can be used 12 times. For our analysis, we assume a use as one launch from earth, one landing on mars, one launch from mars, and one landing back on earth.

Thirty Year Future Technology Only: we restrict our design to reject the use of future technologies that are not likely to be in production within 30 years. Though our mission duration is 100 years, we can learn where our greatest limitations are and how those limitations affects the mission by restricting our focus to present technology.

Table 2.3.1 Raptor engine specifications

Property	Value
Thrust	3.05 MN (sea level)
	3.5 MN (vacuum)
Isp	334 seconds (sea level)
	382 seconds (vacuum)

Table 2.3.2First stage booster specifications

Property	Value
Length	77.5 meters
Diameter	12 meters
Dry Mass	275 Mg
Propellant Mass	6700 Mg
Raptor Engines	42 (sea level)
Sea Level Thrust	128 MN
Vacuum Thrust	138 MN

Table 2.3.3 ITS Spacecraft and Tanker Specifications

Property	Value
Length	49.5 meters
Diameter	17 meters
Vacuum Thrust	31 MN
Dry Mass	150 Mg (Spacecraft) 90 Mg (Tanker)
Cargo to LEO	300 Mg Cargo (Spacecraft) 380 Mg Propellant (Tanker)
Cargo to Mars Surface	300 Mg Cargo
Raptor Engines	3 (sea level) 6 (vacuum)

3 Design Overview

We optimized our design to reduce the number of total launches necessary to build and sustain the colony. Reducing the number of launches simplifies logistics and infrastructure required on earth and reduces the total cost directly. We accomplish this optimization by maximizing the amount of usable materials we can produce on Mars and by minimizing the number of different resources our colony needs to sustain itself.

3.1 Mission Storyboard and Architecture

3.1.1 Deployment of initial interplanetary communication system

The first system we implement is the interplanetary communication system. This system consists of the earth ground stations, earth orbiting communication satellites, solar orbiting relay satellites, mars orbiting satellites and Mars ground stations linked to the colony itself. This system is a prerequisite to the success of many other systems that we control via automation or remote operation. We place the relay satellites in orbits such that there is continuous coverage even in a conjunction or opposition event between earth, Mars and the sun. This system is critical as a risk mitigation tool as it allows a high-speed data downlink to earth in the event of a failure or an emergency. We use Falcon Heavy launch vehicles to launch all satellites for the entire mission duration.

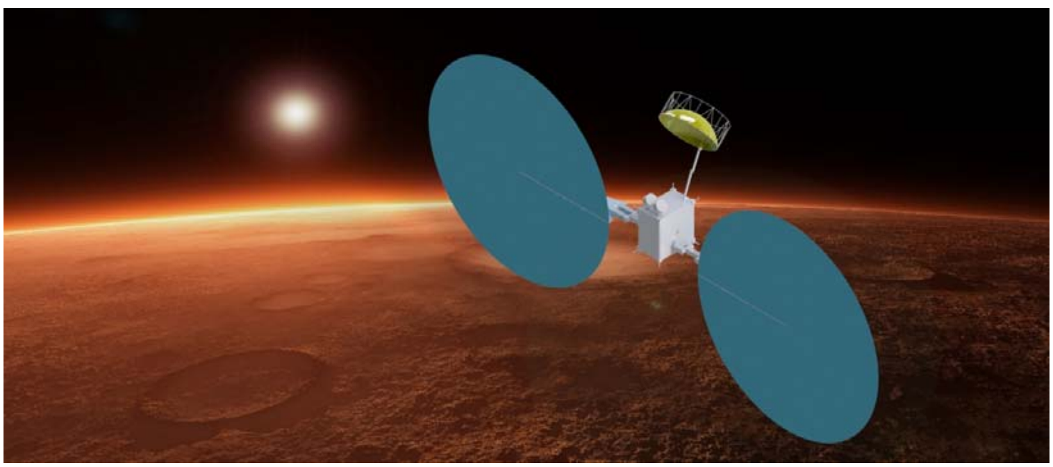

Fig. 3.1.1.1 Artist Rendition of relay satellite positioned above Mars' surface (Credit: John Renaud)

3.1.2 Construction of Cyclers for initial population if applicable

About 1 cycle in advance of the incoming crew, there will be a set of cargo launches that will arrive prior to the first colonist's arrival. These cargo vessels will be a modified version of the ITS that Musk presented except where there is no pressurized habitat inside. Instead, we use the entire vehicles internal volume as unpressurized cargo space. We refer to these models as the ITS-C in the report. This are discussed in depth in chapter 5.1. The ITS-C is equipped with its own crane deployment system that allows heavy cargo to be hoisted from inside of the ITS to the Martian surface.

The initial cargo launches will contain deployable habitats and all supporting infrastructure to keep the first 300 colonists alive and healthy. This includes the following:

- Self-deploying inflatable habitat modules
- Water Stores for 1 synodic cycle
- Food stores for 1 synodic cycle
- Nuclear reactors for power and heat
- Environmental Life Support Systems or ECLSS
- Medical and recreational facilities
- Rovers / Vehicles for personnel and cargo transfer from the ITS to the colony.

It is not sustainable for a 1 million person colonists to bring every piece of equipment and material used by the colony from earth. This is necessary for the initial arriving population, but is not cost effective for long-term development of the colony. Therefore, included in these launches is the equipment necessary to begin building a permanent, self-sustaining habitat capable of housing 25,000 colonists. We will refer to these as "Quarry cities" in the report. They earned this name due from their construction within large surface quarries dug out of the Martina surface then buried under 2 meters of regolith. More information on these quarries is included in chapter 7. The equipment necessary to build these quarry cities are high efficiency digging equipment, earth relocation rovers / vehicles, and In-Situ Resource Utilization (ISRU) equipment capable of producing materials out of the Martian regolith.

Reusability is critical the design ITS. We cannot reuse the vehicles if they cannot launch back to earth. Part of the ISRU equipment are water production facilities, propellant production plants, propellant storage capability. We must establish propellant production plants as soon as possible in the mission or more ITS spacecraft will be manufactured to meet the 1 million colonists in 100-year timeline. This would ultimately drive up costs and launch logistics for the entire mission.

3.1.3 Launch of initial work crew population

The initial 300 colonists consists of a skilled construction crew whose primary objective is to layout and deploy the larger colonies architecture prior to the larger population's arrival. Once the cargo has been confirmed as to have landed on the Mars surface and is awaiting crew arrival, the initial 300 colonists will board either an ITS "Taxi" vehicle or an ITS direct vehicle.

The ITS taxi vehicle or "ITS-T" as we will refer to it in this document is built and optimized to maximize passenger capacity per launch. The interior is similar to that of an airliner with rows of seating and a central pathway through the vehicle. This is not conducive for a flight that would be approximately 150-200 days. We make this design feasible using a cycler vehicle that we propel into a solar cycling orbit between earth and Mars in advance of the colonists' arrival. This cycler will contain the comfortable living space and resources necessary for a comfortable and safe voyage to Mars. The ITS-T performs a carefully timed rendezvous is achieved by entering a hyperbolic intercept orbit from low earth orbit into a cycler trajectory. The cycler's design, assembly, and usage is covered discussed in section 5.2.

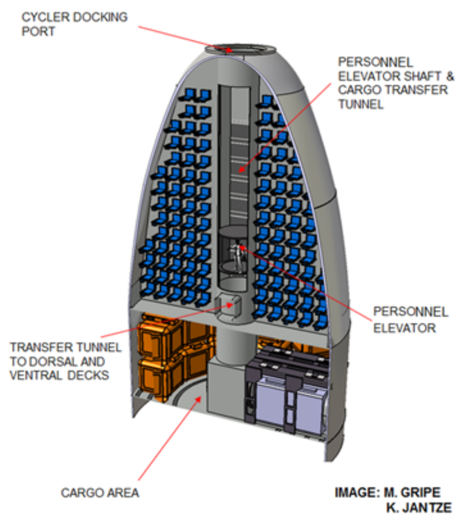

Fig. 3.1.3.1 ITS-T cutaway view
(Credit M. Gripe and K. Jantze)

Once the vehicles rendezvous and docks with cycler, the colonists, and all food and water necessary for the duration of the trip to Mars is brought on board the cycler vehicle. Due to the fluctuations in intercept velocities at earth and mars over varying cycles, there will be various synodic cycles where multiple ITS-T will need to dock to the same cycler before all colonists offload into the cycler vehicles. If the vehicle remains undocked with the cycler, it will have the necessary propellant to perform corrective burns to remain in proximity of the cycler.

When the cycler approaches Mars intercept, the colonists enter the ITS-T and the vehicles perform a burn to slow down in preparation to descend into the atmosphere. The vehicle will perform a propulsive landing on Mars' surface within proximity of the ITS-C vehicles that contain their equipment, habitats and supplies. Prior to their arrival, Mars Personnel, and Cargo Transports or MCPTs will automatically be deployed from their ITS-C and will be prepared to

begin offloading colonists from the vehicle. The crew offload the cargo using the same process.

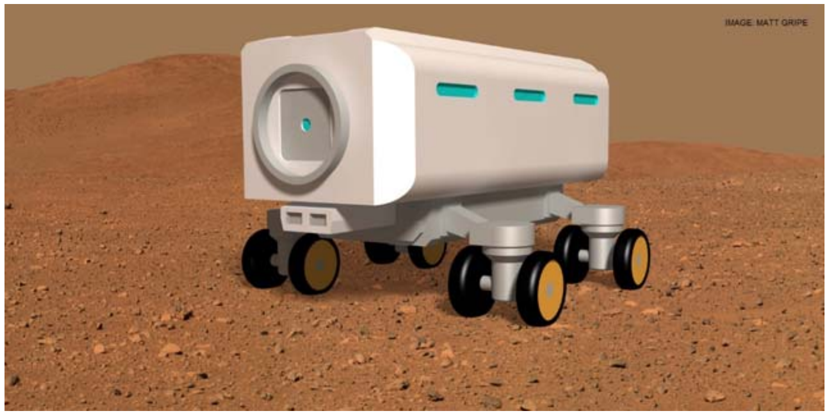

Fig. 3.1.3.2 MPCT transport vehicle used to offload passengers and cargo from ITS (credit: Matt Gripe)

ITS "Direct" flights come in one of two variants: the model presented by SpaceX that contains an unpressurized cargo bay, and one where the entire internal volume is pressurized and used as living space. The first variant with the unpressurized cargo bay included we will refer to as the "ITS-D1" model and the fully pressurized model as the "ITS-D2" in this report. These vehicles utilize the same architecture and framework as the ITS-T model, except that each vehicle has the necessary life support and living space to sustain their passengers on the voyage to Mars. This results in diminished passenger capacity for both of these vehicles. Instead of rendezvousing with a cycler, each vehicle performs a single burn toward Mars and a single burn before entry, descent, and landing.

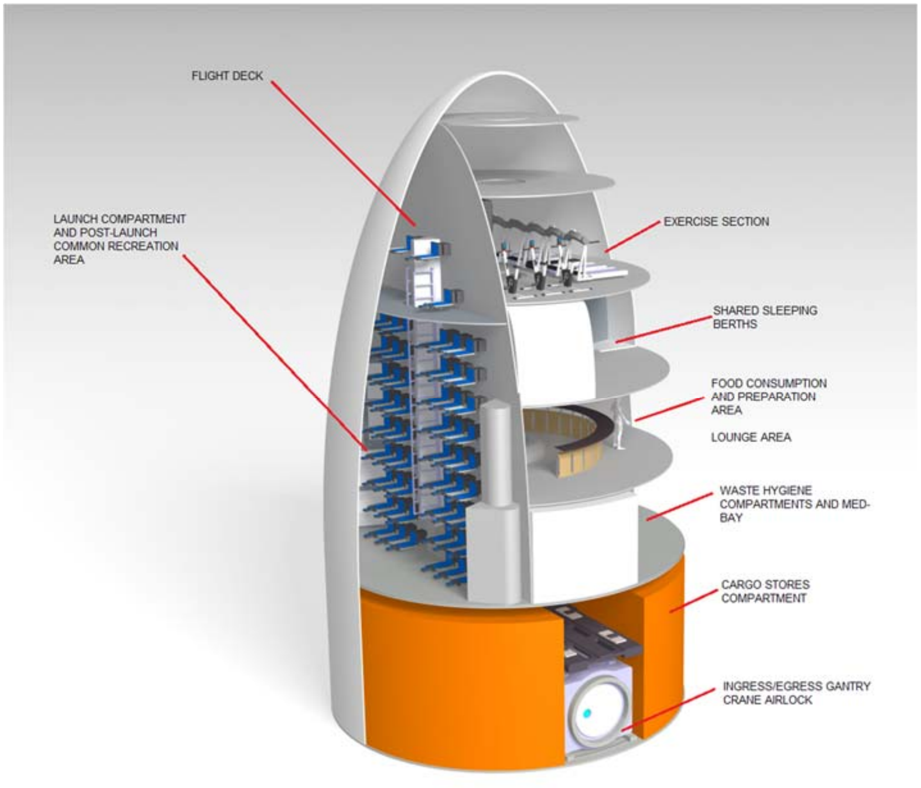

Fig. 3.1.3.3 ITS-D2 Cross Sectional view (Credit Matt Gripe, Bill Muth, Bieber Alexis)

3.1.4 Launch of initial work crew population

Once the colonists offload from the ITS, they will need to have a habitable structure ready for them. The first step in this process is the deployment of the Operations Support Cargo rover or OSCAR. This vehicle is a heavy lift transportation rover that has the capability of relocating bulky and massive items. OSCARs will transport the habitats from the ITS to their deployment location as is shown in Fig. 3.1.4.1.

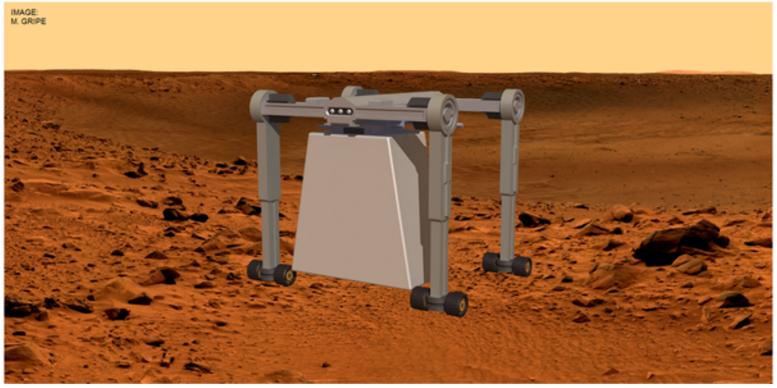

Fig. 3.1.4.1 OSCAR transporting inflatable habitat to the deployment destination (Credit: Matt Gripe)

The OSCARS deploy automatically and do not need colonists to be offloaded from the ITS. However, colonists control the OSCARs either remotely or autonomously. This capability allows the OSCARs to have all Habitats offloaded and positioned prior to the first colonist's arrival. Once the habitats are in position, they can inflate automatically shortly after the colonists land. Fig. 3.1.4.2 depicts this deployment process. This is done for risk mitigation reasons to prevent debris from being projected from the landing exhaust of the ITS and damaging the habitats. Not every component can be deploy automatically and will need colonists to be established. For example, the colonists manually integrate the connecting tunnels between the different modules. Similarly, the colonists connect the nuclear reactors that power the colony to the habitats via steel cable. For this reason, our General-Purpose Recreation Rovers or GPRRs are equipped with robotic arms for completing these detailed tasks and processes. This will reduce the amount of time it takes to get all inhabitants inside the fully assembled settlement by eliminating the need for donning EVA suits.

Fig. 3.1.4.2 Deployment of a single inflatable habitat (Credit J. Kang)

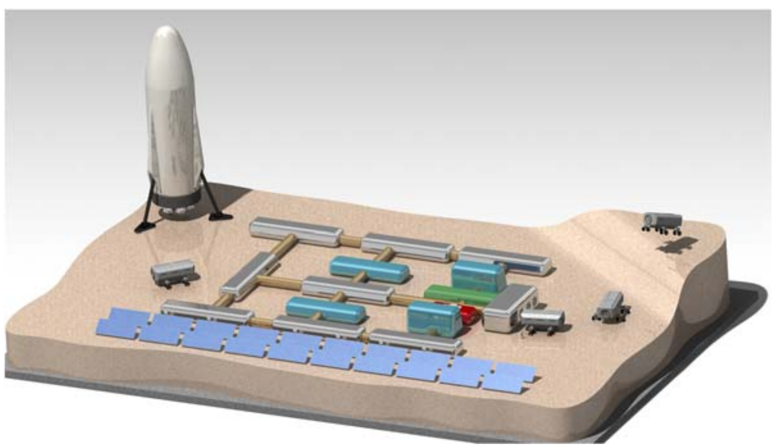

Fig. 3.1.4.3 Fully deployed temporary settlement for 100 inhabitants. ITS is positioned for scale in image. We use three of these settlements for the initial 300 colonists (Credit Matt Gripe and K. Jantze)

3.1.5 Initial increasing arrival rate

We designed the population growth rate so that a majority of the mission operates with a constant arrival rate of colonists. Jumping to a constant arrival rate immediately is very high risk as it requires perfect operation of all hardware to prevent an impact on the mission timeline. Jumping to the constant arrival rate immediately also requires all mission infrastructure to be established immediately which increases the upfront cost and manufacturing load. To mitigate this risk and cost, the arrival rate increases up to 24,700 over ten synodic cycles. Fig. 3.1.5.1shows the colonist arrival rate for the entire mission. Fig. 3.1.5.1 which shows the resulting colonist population over time.

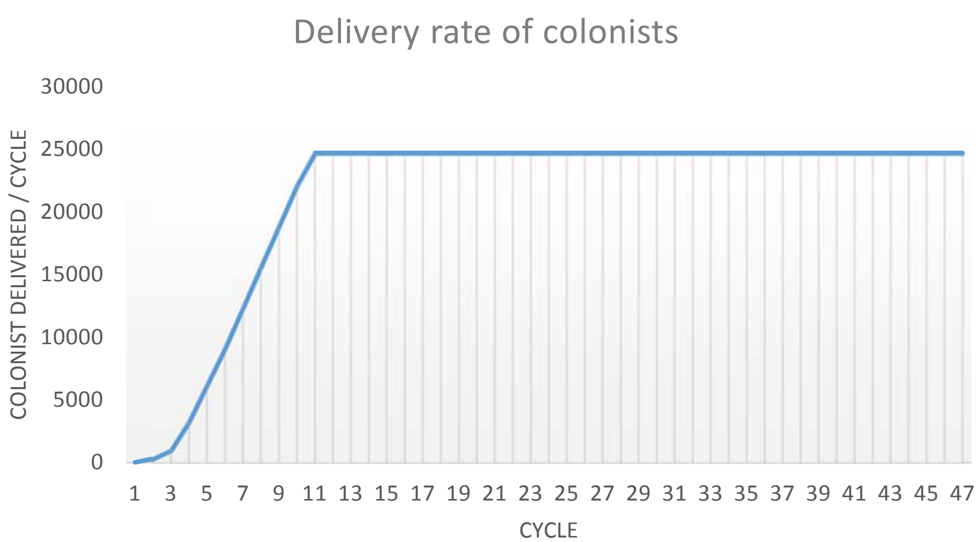

Fig. 3.1.5.1 Delivery rate of colonists by synodic cycle

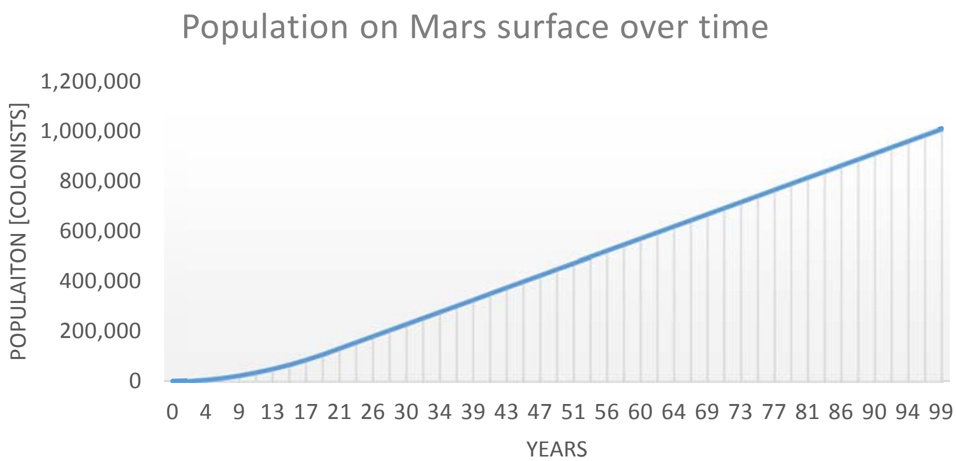

Fig. 3.1.5.2 Colony Population over time

Prior to constructing new habitats for the next round of colonists, the initial 300s priority is to establish the In-Situ Resource Utilization systems critical to longevity of the colony. The metal refining facility is the first system to be established. These metal refineries process Martian regolith into steel. This steel is a critical first resource because just over 20 kilometers away, there is a rich deposit of hydrated minerals. Hydrated minerals is our colonies primary water source. However, we establish the colony away from the hydrated minerals because there is a greater demand for basaltic rock in the construction of our quarry cities. We collect this basaltic rock in the process of digging the quarries. There is more information on this process in section 6.1, 7.2 and 7.3. At the hydrated mineral deposit site, we will establish a water extraction plant with its own set of excavators, dump truck rovers, and nuclear power plants. These pieces of equipment are delivered and deployed autonomously from an ITS-C that lands directly next to the deposits. Landing directly next to the deposits overcomes the range restrictions on the OSCARs and GPRRs needed to transport and assemble the water extraction plant and nuclear reactor. The steel from the metal refineries is used to construct a pipeline that between the water extraction plant and the colony. The nuclear reactor power source at this site also produces sufficient heat that the water travels to the colony as superheated steam to prevent it from freezing as it travels down the pipeline.

This pipeline feeds directly into a water tower at the initial colony location that we established once to satisfy the daily water needs of the eventual 1 million-inhabitant colony. Our system does not have cranes sufficiently tall enough to get the water tower necessary to supply the colony. However, we bury the colony underground in these quarry cities, which require large volumes of regolith to be unearthed. Burying the colony provides sufficient radiation protection from regolith without the development of new radiation resistant materials. The unearthed material that we do not use to bury our fabricated structures forms a mound on which we place the water tower. The initial 300 colonists have sufficient water supplies to survive one synodic cycle, so water must begin filling the water tower before the first synodic cycle is over.

The water produced on Mars has another critical role beyond human consumption: propellant production. In fact, a majority of the water demand will be from propellant production. This is because the Sabatier reaction used in our propellant plant that produces methane requires hydrogen gas and carbon dioxide. Conveniently, carbon dioxide makes up most of the atmosphere on Mars. However, we must extract hydrogen from water through electrolysis. As pipe becomes available, the colonists will place and connect electrolysis driven hydrogen plants to the water supply and the Sabatier reactors. We configured the pipelines such that the outputs of the hydrogen plants feed directly into the Sabatier reactors at the same rate the Sabatier reactor consumes hydrogen gas. We then pipe the outputs of the Sabatier reactors (methane) and hydrogen plants (oxygen) to steel storage tanks manufactured using steel from the metal refineries. After the first synodic cycle, we provide every ITS with a designated landing zone. At each zone, there are two tanks: one for methane and one for oxygen. Both the methane and the oxygen will be stored at high pressures in a gaseous state to prevent the need for electrical power. Both tanks will have sufficient volume and material strength to hold the propellant of a fully fueled ITS vehicle. Since all ITS vehicles variants in our design use the same core design, this will always be 1950 Mg of propellant. The number of water plants, propellant plants, metal refineries, excavators, dump trucks and nuclear power plants were all determined such that we can construct a full 25,000-person quarry, fabricate propellant tanks, and lay the pipeline to hydrated clay deposits within one synodic cycle. There is also sufficient water and power available to generate the fuel to refuel the ITS fleet to return by the next synodic cycle. Due to orbital mechanics, it is not feasible to return the ITS within the same synodic cycle, so there will need to be 2 sets of vehicles: one group of ITS

vehicles en-route to Mars on a cycler trajectory / hyperbolic trajectory (cargo) and a second group that is taking a direct return trajectory to earth.

The structures of quarries themselves also employ In-situ resource utilization processes. We fabricate the structures buried in the quarries out of the basalt material that we extract from the quarries. Due to our population requirements, we ensured that building takes under a synodic cycle. Specifically, it takes us approximately 1 year to dig a quarry out and just over a year to print out all the internal structures of the quarry city. What this means is that after the first year is spent digging out the quarry, the digging equipment can immediately begin digging out the next quarry while structures are being print in the previously dug quarry. Once we finish printing all the facilities in a quarry, we then bury the facilities using the same initial digging equipment while the structures are then being 3D printed in the next quarry. It is in this way that quarry construction is always one synodic cycle ahead of the arrival rate of the next wave of colonists.

Unfortunately, we cannot produce everything on Mars with our current technology. Therefore, we will transport equipment such as ECLSS, farm equipment, replacement rovers, nuclear fuel, etc. from earth with each new habitat. When these systems wear out, we will also send the replacement parts or systems from earth. The equipment and furnishings of each new quarry is always shipped one cycle in advance of the quarries initially construction.

3.1.6 1 million person colony reached and 20 year self-sufficiency

Once we reach our goal of 1 million people, it was a project requirement that the colony can be self-sufficient for 20 years. Due to a lack of data, it was difficult to speculate ways to generate or recover certain resources consumed by the colony. Specifically, nuclear material and nitrogen. Our ECLSS system attempts to recover nitrogen from human waste in the form of urea, but is not perfectly efficiency. More information is provided on these ECLSS systems in section 7.5. This poses a problem for plant growth sufficient in the farms necessary to feed the colonists. The urea is be provided as fertilizer for the farms, but an additional quantity must be either produced on Mars or brought from earth. The only known source of nitrogen on Mars our team could find was the atmosphere where trace amounts of nitrogen is present. Unfortunately, this amount was so trace that if we wished to maintain our nitrogen levels with this system, it is more cost effective for our timeline to deliver the nitrogen lost in the form of plant fertilizer. To meet the project requirement, we deliver enough fertilizer is provided to last the 20 years in synodic cycle 46. We use the same process for nuclear material. In this regard, a fully self-sufficient colony (no earth launches) will not be possible on Mars unless we find a sustainable source of fissile material and nitrogen below Mars surface.

As for equipment failures or other system issues during this time, the overall demand of many resources will drop to near zero, as there will be no longer a specific demand for steel once construction stops. If there are no longer colonists arriving, there is no longer a large fleet of cargo and transport vessels landing, and therefore there will be almost no propellant production. Lower propellant production means less water is excavated. If there are any failures during this 20-year trial period, parts can be salvaged from the no longer necessary rovers and equipment on the surface. The interplanetary communication satellites will be built at the 1 million person mark to last sufficiently long to not need a replacement launched during this time unless there is an unexpected failure.

3.2 Mission Launch Schedule

3.2.1 Departure Launch Windows and Return Flight Propellant Requirements

Fig. 3.2.1.1 shows the launch windows in days as over the length of the mission duration. As one can see, the cycle repeats every 15 years. This launch window is critical as it impacts the minimum number of vehicles that must leave earth per day in order to meet the mission profiles we developed. The launch window for a cycler intercept is a fixed 60 day window inherent the design of the cycler trajectory while the direct launch window varies depending on the positions of earth and mars at each synodic cycle.

Fig. 3.2.1.2 contains the propellant required to return to earth for each synodic cycle. All vehicles return on a direct trajectory no matter what the mission model is. These propellant requirements per cycle were used in conjunction with the dwell times shown in Fig. 3.2.1.3 (how long the vehicle remains on the surface after landing) to determine a worst-case propellant demand and design our refueling facilities for this case. Note that Taxi vehicles must remain on the surface longer allowing for lower propellant production per day to refuel them sufficiently to return to earth.

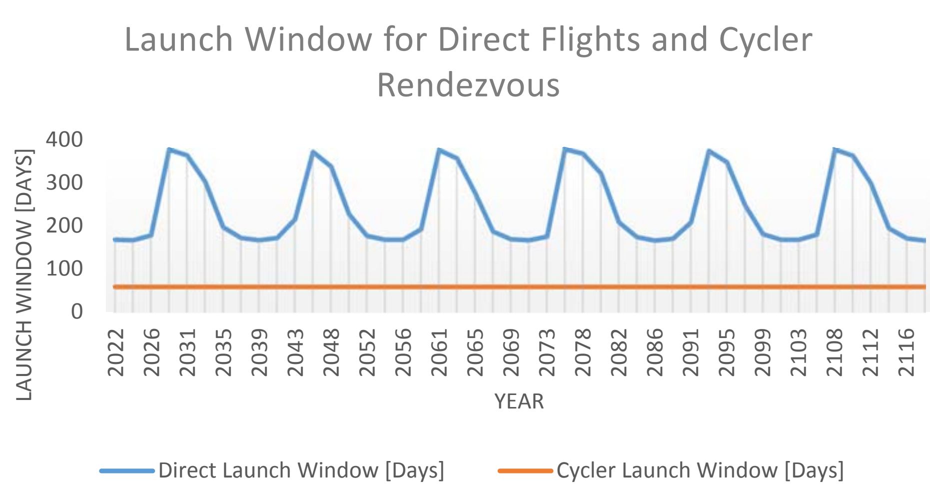

Fig. 3.2.1.1 Launch windows for Direct Flights and Cycler Rendezvous

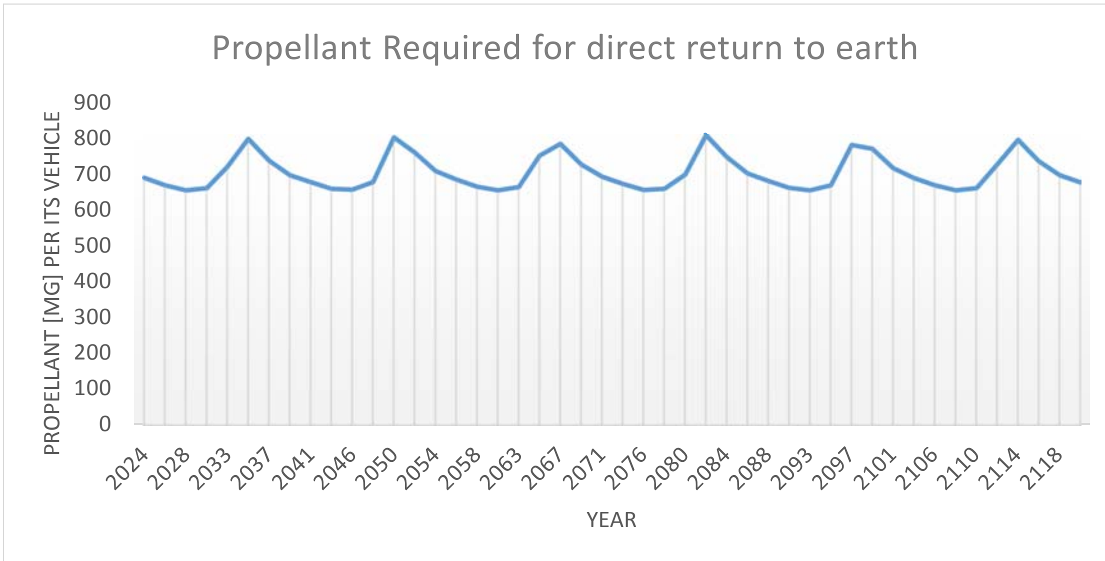

Fig. 3.2.1.2 Propellant required for direct return to earth for each ITS vehicle by year

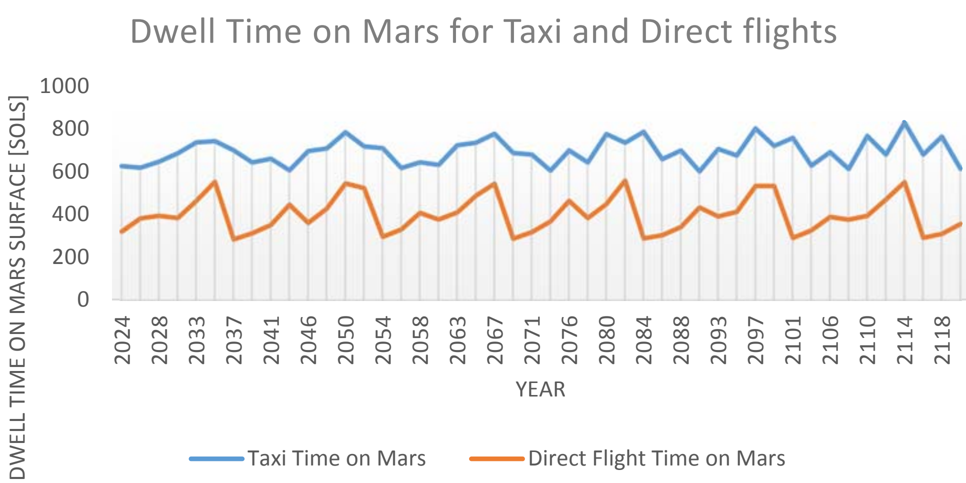

Fig. 3.2.1.3 Dwell time for taxi and direct flight models

3.2.2 Cargo ITS launches

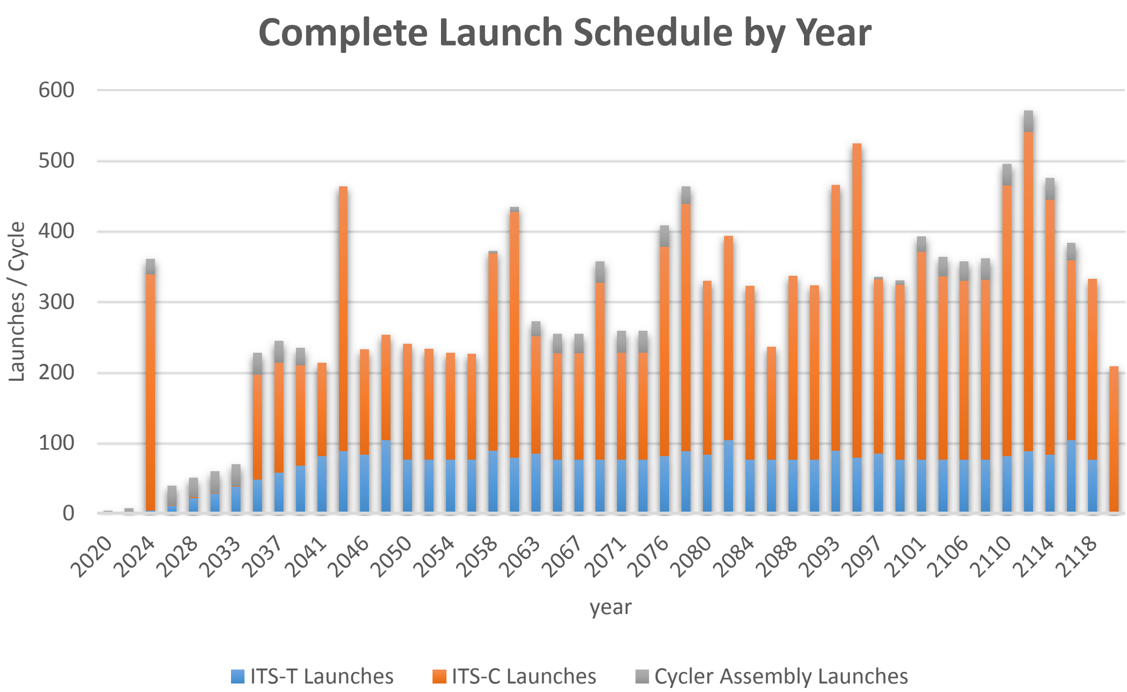

Fig. 3.2.2.1 Full Mission Launch Schedule for Cycler / Taxi model

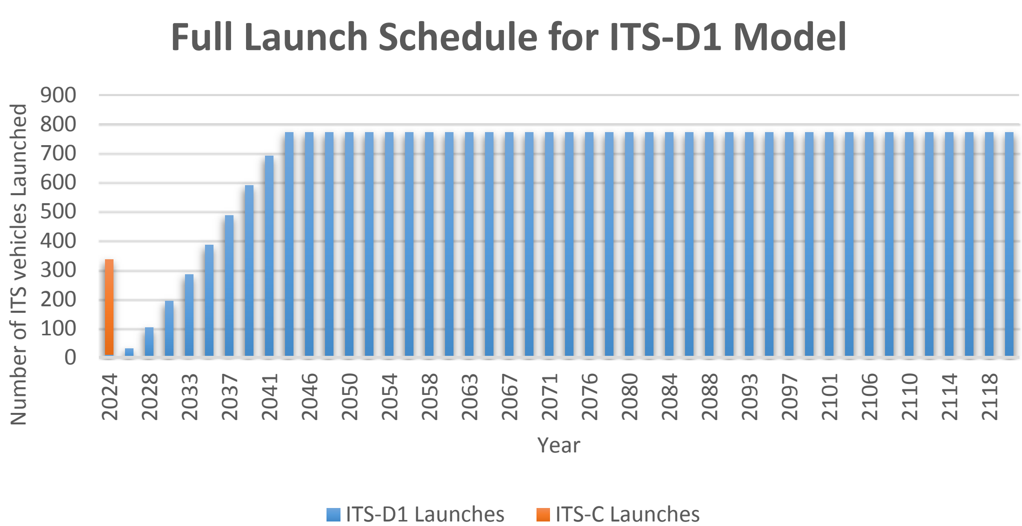

Fig. 3.2.2.2 Full Launch Schedule for ITS-D1 Model

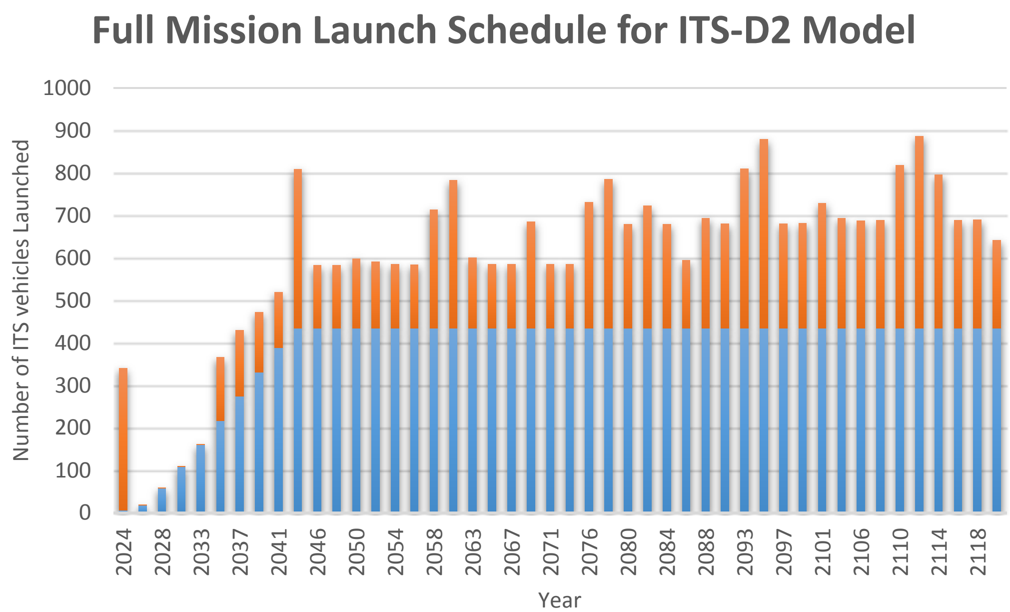

Fig. 3.2.2.3 Full launch schedule for ITS-D2 model

3.3 Mission MPV totals

Table 3.3.1 system totals for the mission. Note that the maximum number shown on the table depicts the peak number in service at any time in the mission while the mass and volume is the total mass and volume delivered from earth to Mars. The mass and volume include all the replacements sent during the mission. The power consumed is based on the peak power consumption in the mission profile.

Table 3.3.1 Mission Mass Power Volume Totals

Component	Maximum Number	Mass [Mg]	Volume [m3]	Power Consumed [Kw]
25,000 Colonist Quarries (Equipment brought from earth)	40	2,332,500	2,152,500	5,504,000
Water Plants (Cycler)	25	400	1,530	650
Steel Refineries	297	541,800	135,450	821,500
Sabatier Reactors	232	13,600	19,450	535,000
Hydrogen Plants	232	20,900	16,100	
OSCARs	10	1,100	5,250	
MCPTs	34	3,100	12,500	
GPRRs	776	29,700	35,600	
Excavators	12	2,300	8,600	
Dump Trucks	6	1,800	1,200	
Nuclear Reactors	26250	26,200	123,400	-6,861,150
Total		**2,973,400**	**2,511,580**	

3.4 1 Million Person Colony Layout and visualization

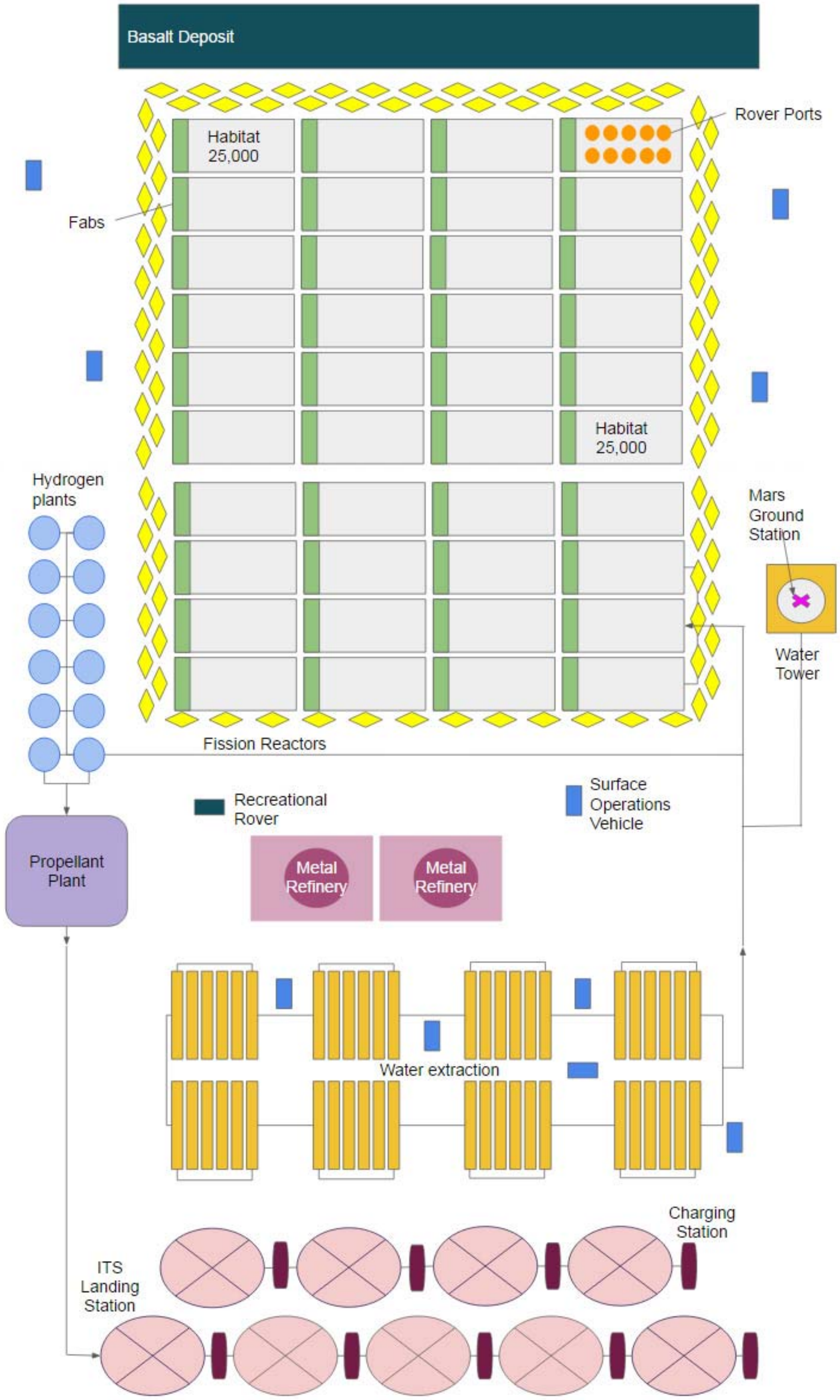

Fig. 3.4.1 A Million-Person Colony Layout (Concept)

Planning a colony for a million people 100 years in advance is difficult as humans are quick to adapt and change their mind. However, we devise a possible solution to ensure efficiency through system integration and access to essential resources. A concept visualization of the colony is shown above (Fig. Note that this diagram is not to scale, but it is produced in order to show the overall concept of the full colony.

The 25,000 person quarries are centralized in order to centralize the colonists to create a metropolitan network. In this configuration, communication, interactions, and access to resources are maximized by allowing the colonists the most living space possible. The concern of cabin fever is high in a civilization devoid of a freely traversable outdoors. By creating a large city of habitats, colonists' sentiments of entrapment and confinement can hopefully be minimized. A section of the quarry is dedicated towards FABs or farm habitats that are designated for growing food. As the quarries are dug, colonists mine for basalt needed in the construction of additional habitats. On top of each of the quarries are rover ports that allow for colonists to enter into vehicles without the need of space suits. These rover ports can also be used for evacuation in the event of an emergency. Fission reactors are placed around the quarry more than 100 meters away in order to minimize the power and heat loss generated from transporting it over a long distance. As more colonists arrive, the more fission reactors are needed. Eventually the fission reactors will cover each side of the quarry network as shown. Surface operations vehicles like construction vehicles, recreational rovers, and science rovers can drive around the colony with relative ease, as the terrain is relatively even in our colony location. Colonists pipe in water in from a separate water extraction location. This water is stored in the water tower and fed to the habitats, the FABs, hydrogen plants, and the propellant plant in order to produce enough fuel to send the ITS back to Earth. Propellant is fed from the propellant plant to the ITS charging stations. The ITS fleet will be placed at a fair distance away from the colony, but in the same area. During the initial ITS testing phase, it will be determined the appropriate distance that the ITS needs to be separated from the colony for safety reasons.

4 Interplanetary Communication System

4.1 Earth System

4.1.1 CAD / System totals

We design the satellites to all have the same overall components so that differences between the different systems are minor and only have to do to scaling different parts, such as the fuel tanks. Below is a view of the Earth side satellite and the internals.

The total mass, power, and volume of the Earth satellite system per satellite and of the 100-year mission can be seen in **Error! Reference source not found.Error! Reference source not found.**. For a further information on the total system breakdown, refer to the Interplanetary Communications appendix..

Table 4.1.1.1 The mass, power, and volume of the Earth Orbiter

Satellite	Mass [Mg]	Power [kW]	Volume [m^3]
Earth Orbiter	3.646	87.01	19.50

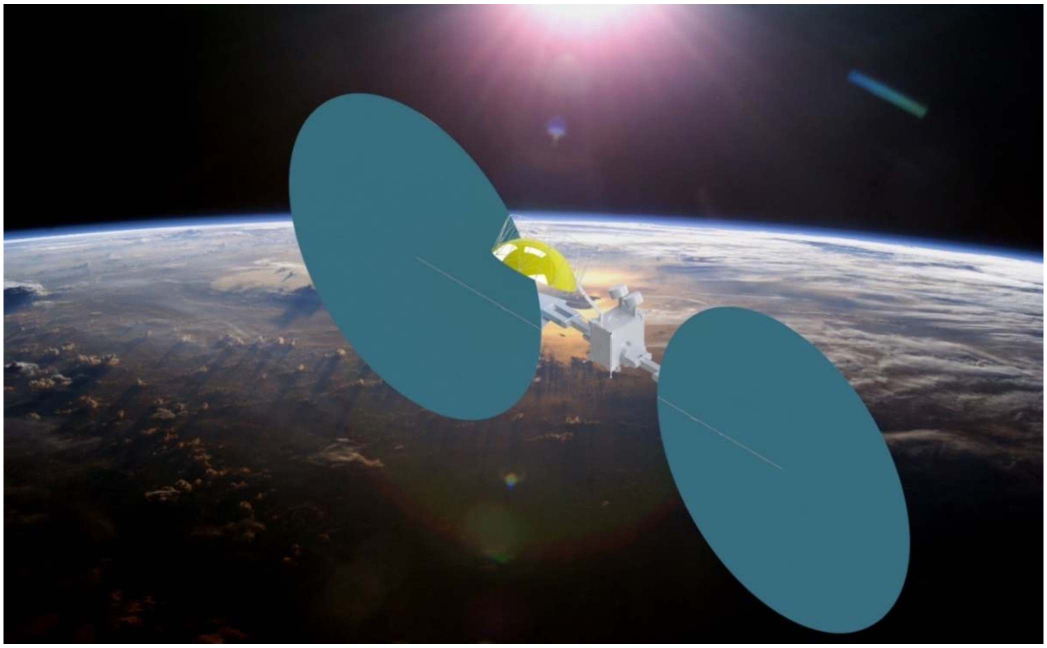

Fig. 4.1.1.1 Earth Satellite by Joe Renaud

4.1.2 System Map

This system is for the Earth side of the communications line. The Earth satellites receive communications signals from either the Mars or Relay satellite. The ground station and satellites are in constant communication on Earth and on Mars.

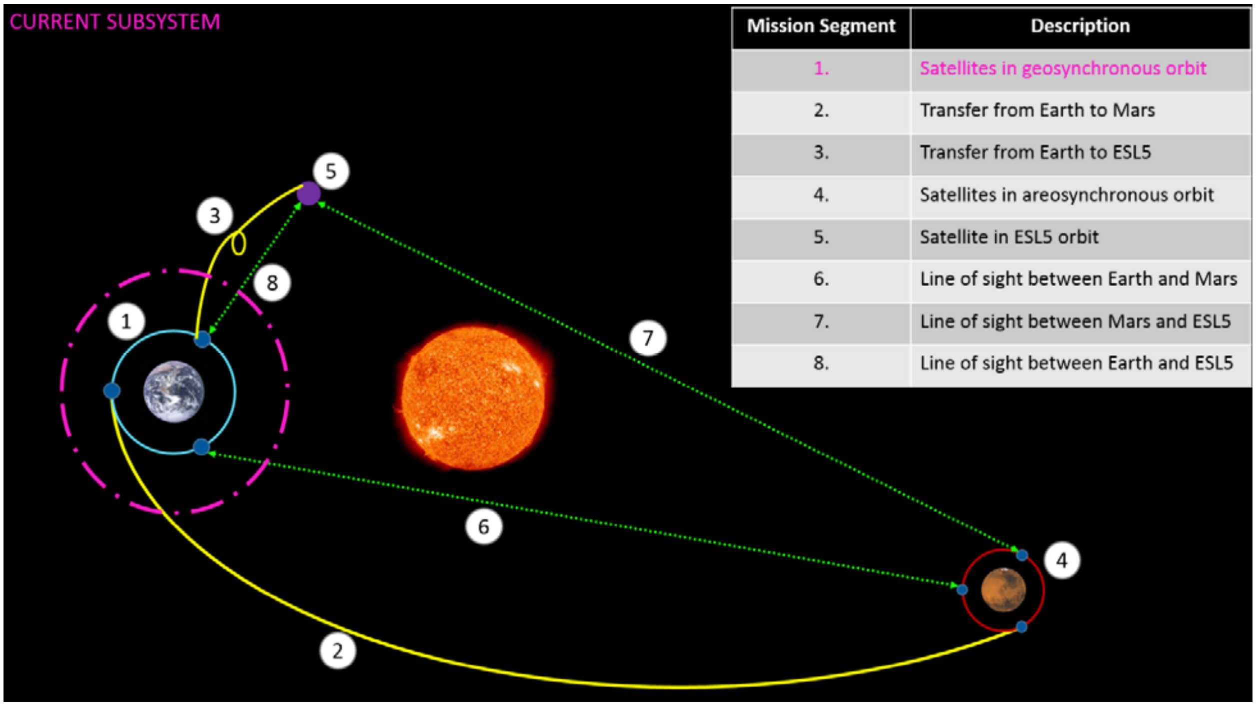

Fig. 4.1.2.1 System Map for Earth Satellites (Credit A. Murali)

Error! Reference source not found. shows the overall system view, with the circled section being the current system.

4.1.3 Deployment / Fabrication

To fabricate the satellites, we hire contractors to create the various parts. The satellite bus will be fabricated by welding aluminum struts together. The thrust cylinder of the satellite is made from a cold formed titanium tube and is welded to the bus.

The propellant and pressurant tanks are made of carbon fiber, similar to SpaceX's new tanks for the ITS. The tanks are fabricated by placing layer of carbon fiber prepreg on hemispherical molds. The carbon fiber is the cured with a UV light to harden it. Two hemispheres are then joined together to complete the tank.

We note that these fabrication methods are shared between the Earth, L5 Relay, and Mars satellites.

The three types of satellites (Earth orbiter, Relay, and Mars orbiter) all share a common component layout and are therefore packed the same.

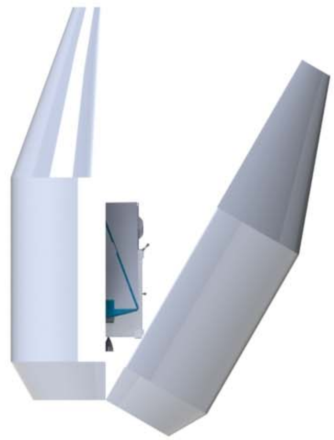

Fig. 4.1.3.1 We pack the satellites into a standard SpaceX Falcon 9 fairing. The satellite is mounted via an adapter to the SpaceX Payload Attach Fitting (PAF). (Credit: J. Renaud)

This fairing is the same for both the Falcon 9 and Falcon Heavy rockets. While all the satellites fit within this fairing, their masses dictate which rocket will be used. Each satellite will be launched with a Falcon Heavy rocket. The difference in the masses of the spacecraft is primarily due to the amount of propellant they carry, which is a function of the ΔV required.

Inside the satellite bus, there is a thrust cylinder that provides structural support on launch. It is designed for up to 8.5 Gs on launch and is made of aluminum. The propellant tanks are mounted inside of this cylinder and the pressurant tanks are mounted to the outside.

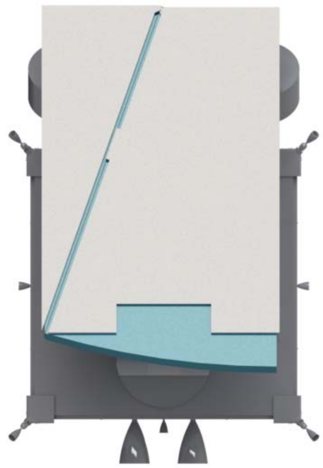

Fig. 4.1.3.2 The solar panels are packed on either side of the bus, which is the main body of the satellite. The panels are packed into a roughly rectangular shape and will unfold into a circular shape, similar to a paper fan. (Credit: J. Renaud)

Fig. 4.1.3.3 Once the launch vehicle has made it to the injection location, the releasing process is started. The fairing is released from the vehicle in such a way as to remove itself from interfering with the ejection system of the satellite. The satellite is deployed from the system via the ejection system built into the launch vehicle payload delivery system. By Joe Renaud

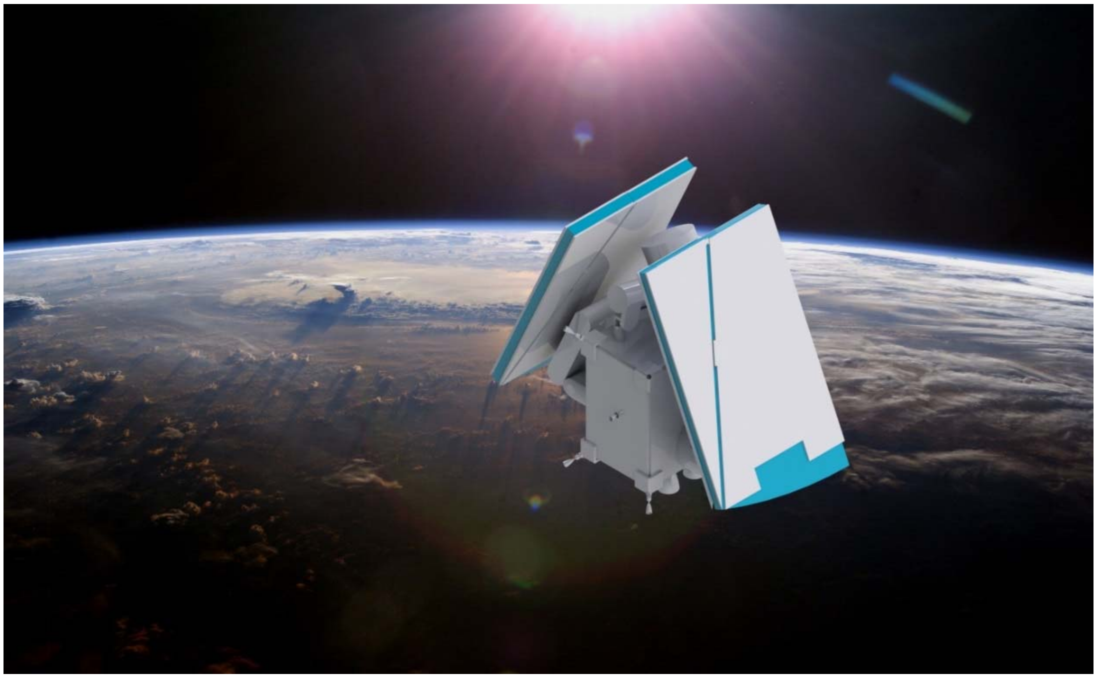

Fig. 4.1.3.4 The relay satellite prepares to deploy its solar panels. Note that this process is identical for the Earth and Mars orbiters. CAD rendering by Joe Renaud.

Fig. 4.1.3.5 The solar panels first fold downwards. CAD rendering by Joe Renaud.

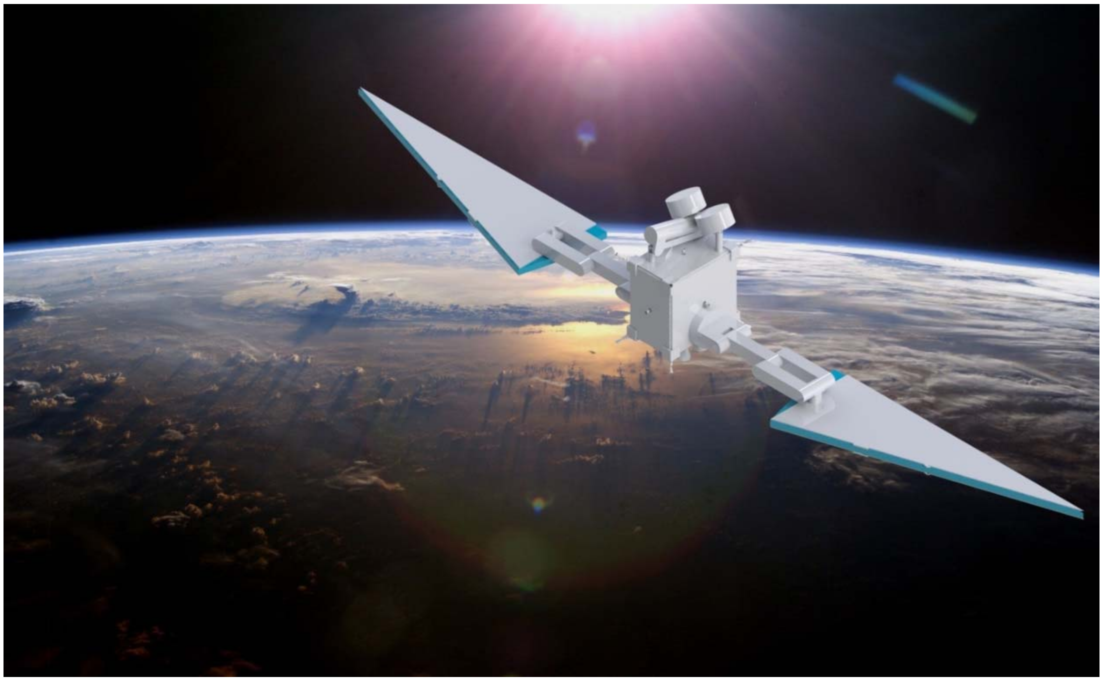

Fig. 4.1.3.6 The folded wedge swings out to form a triangle. CAD rendering by Joe Renaud.

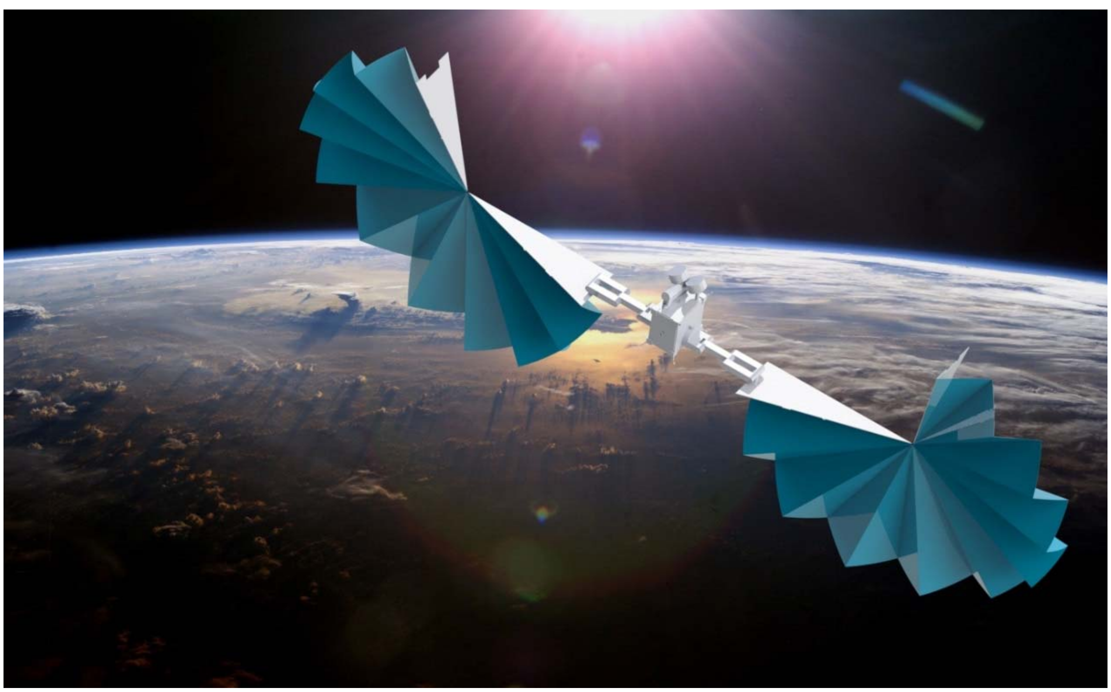

Fig. 4.1.3.7 The solar panel leaves begin to fan out radially. (Credit: J. Renaud)

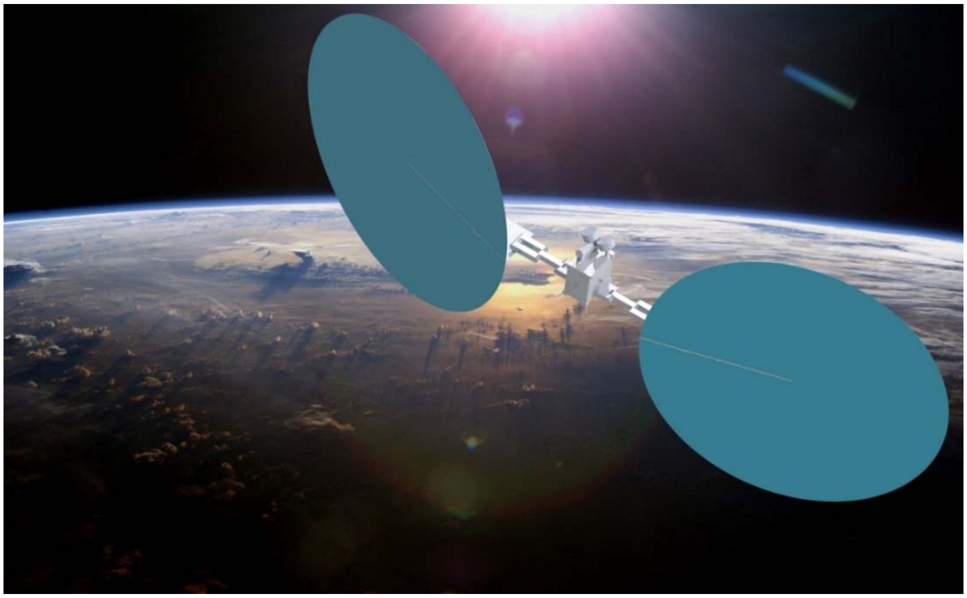

Fig. 4.1.3.8 The solar panel leaves are now completely unfolded into their circular shape. (Credit: J. Renaud)

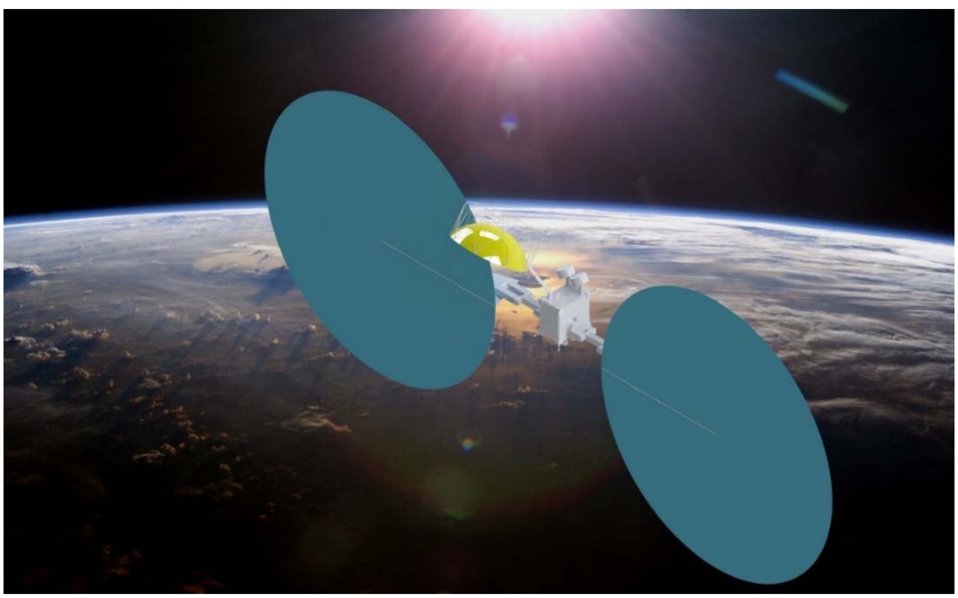

Fig. 4.1.3.9 The antenna is fully deployed and begins communicating with the Earth or Mars ground station. . (Credit: J. Renaud)

When the satellite is ready for retirement, after 15 years due to the decay rate of the solar panels, we burn the engines to perform the disposal maneuver to a retirement trajectory.

4.1.3.1 *Deployment Timeline*

There are two scenarios in which a satellite is deployed: satellites are deployed when the colony population data demand exceed the data transfer capabilities of the satellite network or when a satellite already deployed is retired after its design lifetime expires and needs replaced. We launch satellites the cycle before they are needed by our colony to ensure that they are in position and operating when they are needed. Table 4.1.3.1.1 shows the Mars satellite deployments necessary for each cycle.

Table 4.1.3.1.1 Earth satellite deployments required for every synodic cycle

Cycle	Earth Satellites	Cycle	Earth Satellites	Cycle	Earth Satellites
0	3	**16**	0	**32**	3
1	0	**17**	0	**33**	0
2	0	**18**	3	**34**	0
3	0	**19**	3	**35**	3
4	0	**20**	0	**36**	3
5	0	**21**	0	**37**	3
6	3	**22**	0	**38**	3
7	0	**23**	3	**39**	0
8	0	**24**	3	**40**	0
9	0	**25**	3	**41**	6
10	0	**26**	0	**42**	3
11	0	**27**	0	**43**	3
12	3	**28**	0	**44**	3
13	3	**29**	3	**45**	0
14	0	**30**	3	**46**	0
15	0	**31**	3	**Total**	66

4.1.4 *Operation and Servicing*

4.1.4.1 *Communication*

The Earth satellites uses radio frequency telecommunication systems for transmission of signals through the Earth's atmosphere to a ground station. For our satellites, we design the radio frequency system using a Northrop Grumman Astromesh antenna. The Earth satellites uses optical laser communication to transmit data to the L_5 relay and Mars satellites. Note that for all optical communication, two apertures are required to account for point-ahead angles. The communication characteristics of the Earth satellite are in Table 4.1.4.1.1.

Table 4.1.4.1.1 Earth Satellite Communication System Characteristics

Parameter	Unit	Earth Oriented	Mars Oriented
Frequency	GHz	32	3.00E+05
Maximum Data Rate	Mbps	2.26E+10	2.26E+10
Communication Power	W	47	46953
Antenna Diameter	m	5	-
Aperture Diameter (x2)	m	-	1

4.1.4.2 *Power Source*

In order to meet the power requirements of the satellite, we choose to use the Orbital ATK MegaFlex Solar Array System, which relies on solar cells mounted on a circular structure. We explain this choice of power source. We have to note, however, solar cells do not cover around 10% of the surface. We also note here that the folding method of those arrays allows them to divide their volume by 16 when folded. We explain the determination of the solar cell type.

From the specification of the MegaFlex Orbital ATK [16], the requirements for our satellites (Table 4.1.4.2..1), and the available size of the payload fairing, we are able to size the solar panels. The diameter for each solar panel is 19 meters. Table 4.1.4.2..2 shows the results for each satellite.

Table 4.1.4.2.1 Power requirements for our satellites

Source/Satellite	Communication and Control (kW)	Propulsion (kW)	Thermal (kW)	Others (kW)
Earth Orbiter	47	0.79	0.3	0.1

Table 4.1.4.2.2 Mass, Power, Volume and Area of the solar panels

Source/Satellite	Mass (Mg)	Power (kW)	Volume (m^3)	Area (m^2)
Earth Orbiter	1.271	87.01	6.418	641.7

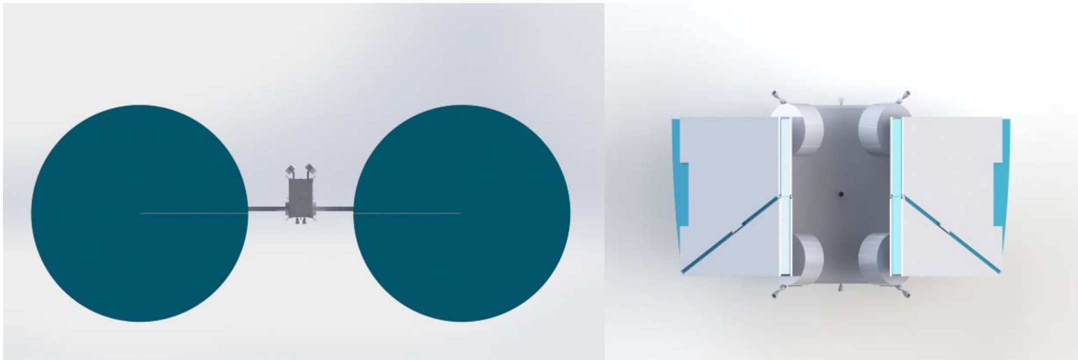

Fig. 4.1.4.2.1 Solar panels of the Earth Orbiter folded (right) and unfolded (left). (Credit: J. Renaud.)

We only show the Earth Orbiter solar panels on the fig. above because there are the same throughout every satellite. We take in account the increase of characteristics of each components of the satellite. To do so, we consider a new "increased" configuration for each new synodic period. Thus, every single launch on the same synodic period will be composed of the same satellite for every type of them. Finally, the length life of each satellite is 10 years.

Finally, from this power generation, we need to store energy. There are many reasons to do it. First, one is to counter an eventual failure mode of the solar panels. We know that if one solar panel is not working, the other one can assure a great part of the requirements from every components, but it cannot generate enough power to meet all the requirements. Having a battery allows to store power, and thus ensure a full and complete active mode for a good portion of the orbit. We thought about doubling the number of batteries to ensure redundancy. Table 4.1.4.2.3 is a summary of the characteristics of the battery onboard.

Table 4.1.4.2.3 Mass, Power and Volume of battery GS-YUASA for the Earth Orbiter

Characteristics	**Value**
Power Capacity (kW/hr)	94
Volume (m^3)	0.2990
Mass (kg)	0.6731

4.1.4.3 *Thermal Systems*

Once we manage all the power requirements from every source, we can deduce, from the efficiencies, the thermal loads from each time. We also know that every single system does have an operation temperature. Therefore, we must manage the thermal flux to ensure that this temperature is met for each of them. Table 4.1.4.3. intends to sum up the temperature requirements for each of our system.

Table 4.1.4.3.1 Temperature required for the satellite's components

Component	Operating Temperature (°C)	Survival Temperature (°C)
Digital electronics	0 - 50	-20 - 70
Analog electronics	0 - 40	-20 - 70
Batteries	10 - 20	0 - 35
Momentum wheels (Control systems)	0 - 50	-20 - 70
Solar panels	-100 - 125	-100 - 125
Fuel (Propulsion)	0 - 450	0 - 450

As a result, the temperature inside the Satellite must be between 10°C and 20°C. From this analysis, we decide to study the thermal exchanges between the satellite and its environment and determine if we need, or not, any additional passive or active thermal control system.

Table 4.1.4.3.2 Summary of the characteristics of the thermal exchange systems for the Earth Orbiter

Component	Characteristics / Value
Multi-Layer Insolation (Thickness)	13.6 mil
Space Radiators (Power)	0.4 kW
Space Radiators (Area)	41.53 m^2
Space Radiators (Mass)	0.207 Mg
Heat Pipes (Power)	0.3 kW

4.1.4.4 *Earth Satellite Propulsion*

We have three main propulsion needs for all the variants of our satellites (Earth, L5 Relay, and Mars), orbital insertion, orbital maintenance, and attitude control. The goal of all these needs is to make sure that the satellites remain useful and preform their function until the end of their lifespan. Each of these needs requires a different type of analysis will allows us to determine the appropriate system to meet all these needs. The propulsion system for all three satellites use the same general layout but are scaled differently due to each satellite requiring a different level of the main propulsion needs. With the base level requirements understood, each satellites propulsion will be designed accordingly.

The mass, power, and volume of the Earth propulsion system as a whole can be seen in the table below:

Table 4.1.4.4.1 Mass, Power, and Volume for Earth Satellite Propulsion

	Mass (Mg)	Volume (m^3)	Power (W)
Earth Satellite Total	0.778	1.004	790

4.1.4.4.1 Propellant

The propellant in use satisfies all three of the main needs of the satellite so that the complexity of the propulsion system is kept as low as possible. We chose a bipropellant system of Monomethyl hydrazine (MMH) and mixed oxides of nitrogen (MON3), specifically Dinitrogen Tetroxide (97%) and Nitrogen Dioxide (3%), to act as our propellant for all these needs due to its high ISP, low freezing point, and low fuel tank weight. This propellant is hypergolic so does not require an ignition source, reducing the complexity of the injector system and leading to a reliable system in terms of generating thrust when desired and avoiding hard starts in the combustion chamber.

The system is pressure fed with tanks of helium compressed to 6000 psi. Both the fuel and oxidizer tanks are connected to the same helium tank system which consists of two small tanks.

This system is sized and pressurized to ensure that the thrusters will always receive their designed pressure conditions until the fuel and oxidizer tanks are completely empty.

For the mission to succeed, the colony and all interplanetary vehicles must be in constant contact with the Earth and Mars based mission control personal. This is a large driving force in the choice of propellants as this system must be as reliable as possible so that mission control has constant control over the behavior of the communications satellites always. We have a propellant system that will provide this reliability at the cost of increased mass and lower ISP with respect to other bipropellant systems. However, this increase in cost is marginal with respect to the communications system and is well worth the increased stability the propellant.

4.1.4.4.2 Engines

The engines that are in use in this design are the Aerojet Rocketdyne R-4D for orbital insertion, R-1E for orbital station keeping, and R-6D for attitude control. These engines were picked for their high ISP, compatibility with the chosen propulsion system, and level of flight-testing to prove design reliability. Below is a table of the MPV breakdown of the engines:

Table 4.1.4.4.2.1: Mass, Power, and Volume of Thrusters

Engine Type	**Mass (Mg)**	**Power (W)**	**Volume (m^3)**	**Number of Units**
R-42	4.53E-03	46	0.0959	4
R-1E	2.00E-03	36	0.006	6
R-6D	4.54E-04	5	2.79E-06	8

To further justify the choice of these engines, the main engine specifications are tabulated, such as thrust and burn time.

Table 4.1.4.4.2.2:Design Characteristics of Thrusters

Engine Type	Thrust (N)	Chamber Pressure (MPa)	Flow Rate (kg/sec)	Max Burn Time (Single Firing) (sec)
R-42	890	0.745	0.3	3940
R-1E	110	0.731	0.041	No Limit
R-6D	22	0.731	0.008	No Limit

4.1.4.4.3 Propellant System Overview

With the propellant and engines selected, the rest of the propulsion system needs to be considered. This includes the valves, tubing, and sensors that are necessary to ensure safe operation of the system. One of the larger concerns with MON3 is that by its' nature of being a potent oxidizer, corrosion problems are considered when any part design for this system is worked on. Stainless steel tubing is chosen to act as the conduit for the fuel and oxidizer to travel through as stainless steel is non-reactive with most chemicals.

Various sensors and valves are used to make sure that the system have an adequate level of redundancy and fail-safes. These systems are vital as interplanetary communication is mission critical and any failure in it could result in loss of life and/or cargo. The figure below details the overall system view including the fail-safe systems.

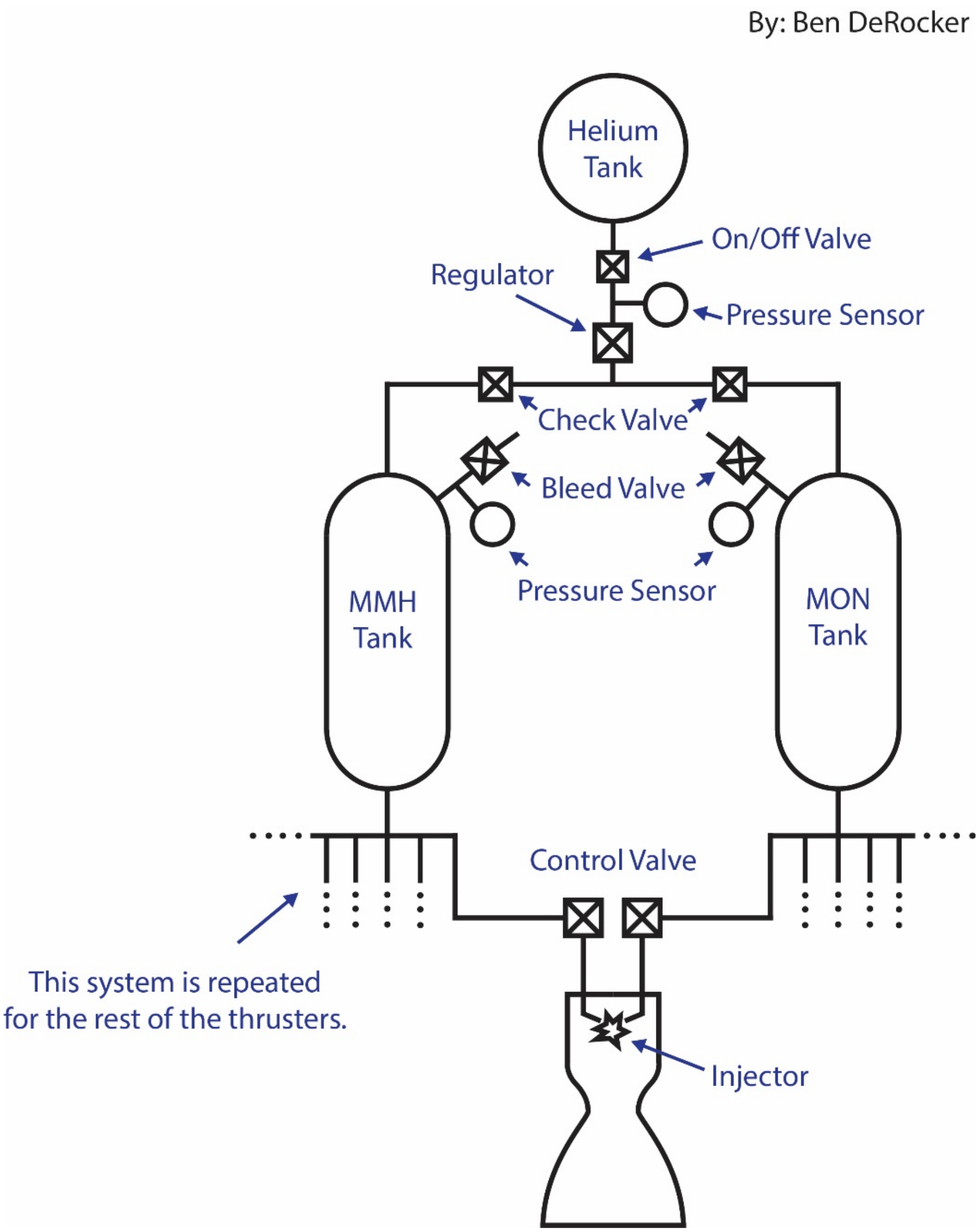

Fig. 4.1.4.4.3.1 Satellite Propulsion System Diagram (Credit B. DeRocker)

4.1.4.4.4 Attitude

While the orbital insertion and station keeping costs are calculated by mission design using a simple Delta V analysis, finding the greatest torque on the system, etc., the attitude control system requires us to find the moment of inertia of the satellites. Once this was calculated, we finalized the attitude thruster layout and the acceptable amount of thrust needed to desaturate the reaction

wheels on the craft. This is an extremely important system on the craft as the allowable pointing error for this mission is very small.

The fuel allocated to the attitude thrusters are seen in the fig. below with the calculations and explanations available in the appendix.

Table 4.1.4.4.4.1 Attitude Fuel Mass for the Earth Satellite

Satellite	Mass (Mg)
Earth	0.030

4.1.4.5 *Attitude Control System*

The Earth satellites maintain pointing accuracy of less than one mili rad because the satellites employ a free space optical communication system. To accomplish this accuracy, we connect the optical transmitter and receiver apertures to the satellite bus using a vibration damping platform. This platform allows the optical apertures to slew independent of the satellite bus's orientation and insulates the apertures from any vibrations in the satellite's structure.

To keep the satellite bus's orientation fixed we employ a three axes stabilization system that consists of three reaction wheels. The reaction wheels spin about three axes, each independent of one another. These wheels spin up and down to cancel out any disturbing torques acting on the satellite. The mass of these wheels is shown in Table 4.1.4.5.1.

Table 4.1.4.5.2 Earth Satellite Reaction Wheels

Momentum Accumulation [N m s]	Wheel Mass [kg]
15.76	18.00

4.1.4.6 *Earth Ground Station*

Earth ground stations are existing university owned ground stations that we separate by approximately 120^{o} around the Earth. Ground station spacing ensures continuous line of site contact with Earth. The Earth ground stations are assumed to be 20 meter dishes and able to be operated at a frequency of 32 GHz. The power requirements for each ground station throughout the mission are minimal and assumed to be available using existing Earth

4.1.5 Retirement, disposal, and replacement

We retire our Earth satellites by performing a two-burn decommission maneuver at the end of each satellites lifetime. Table 4.1.5.1 contains the required ΔVs to accomplish the two-burn decommission maneuver for satellites around Earth.

Table 4.1.5.1 ΔV needed to decommission satellites in geosynchronous orbit.

Transfer Parameter	**Value**
Geosynchronous Deorbit	0.273 km/s

Our Earth satellites will be retired at the end of their design lifetime of 15 years. Table 4.1.5.2 contains the quantity of Earth Satellites retired each cycle due to their lifetime expiring.

Table 4.1.5.2 Earth Satellites Retired each Synodic cycle

Cycle	Earth Satellites	Cycle	Earth Satellites	Cycle	Earth Satellites
0	0	**16**	0	**32**	3
1	0	**17**	0	**33**	0
2	0	**18**	0	**34**	0
3	0	**19**	3	**35**	0
4	0	**20**	3	**36**	3
5	0	**21**	0	**37**	3
6	0	**22**	0	**38**	3
7	3	**23**	0	**39**	3
8	0	**24**	0	**40**	0
9	0	**25**	3	**41**	0
10	0	**26**	3	**42**	3
11	0	**27**	0	**43**	3
12	0	**28**	0	**44**	3
13	3	**29**	0	**45**	3
14	0	**30**	3	**46**	0
15	0	**31**	3		

4.1.6 System Cost

Once we design the satellites and determine the deployment timeline for Interplanetary Communications, we must determine the feasibility of the system. This feasibility is quantified in terms of total cost and risk.

To determine the total cost of the system over 100 years, we must determine the cost of each individual satellite. In order to cost each satellite, we determine the cost of each individual component by either research or size calculations. The main cost drivers of the individual satellites include the optical apertures, the Northrop Grumman Astromesh radio frequency antenna, the many transponders, the control processor, and the Orbital ATK solar panels. Due to unknown manufacturing costs and the unknown costs associated with other systems, we add a 50% cost margin to all satellite components. Additional costs with no margin include cost of operations and launch. The cost of hardware, launch, and operations of each satellite over 15 years is $764 million for Earth. These costs are shown below in Table 4.1.6.1.

Table 4.1.6.1 System Costs for Earth over 100 years

Satellite	Quantity	Cost Per Launch	Total Cost Over Mission
Earth	80	$764M	$61.1B

4.1.7 Risk Analysis

To quantify risk, we determine several probabilities of failure, including the probability of a total communications blackout and the probability of failure of an individual satellite.

First, we determine the probability that one satellite will fail before the end of its lifetime to be 0.1113. We calculate this number using critical failure mechanisms and probabilities of the major satellite subsystems, including batteries, thrusters and fuel, electronics, structures, solar arrays, sensors, telemetry and tracking, pointing control system, and the control processor. This probability of failure is consistent for the Earth, Relay, and Mars satellites. Using a statistical projection, we determine that 7.3458 Earth satellites will fail over the 100 year development, shown below in Table 4.1.7.1.

Table 4.1.7.1 Failure Analysis for Earth over 100 years

Satellite	Probability of Failure Before End-of-Life	Quantity That Will Fail Over 100 Years
Earth	0.1113	7.3458

Next, we determine the probability of a total HD video communications blackout at any time, we use the probabilities of an individual satellite failure given above and the probability of a ground stations failure, which we find to be 0.02. Assuming independence of failure events, we use these probabilities and a system fault tree to calculate the total blackout probability, which is 0.0128.

4.1.8 *Risk Mitigation Strategies*

Not only must we determine mechanisms to mitigate risk, but we must quantify them in terms of the reduced probability of failure and the associated cost. We analyze a few general risk mitigation techniques for all satellites, including backup low-gain antennas for basic communication. The addition of redundant amplifiers and filters, and a backup control processor. In terms of accounting for the number of failed Earth satellites, the cost to replace them is an extra $5.61 billion over 100 years. These results are shown below in Table 4.1.8.14.1.8.1

Table 4.1.8.1 Failure Mitigation Costs for Earth over 100 years

Satellite	Quantity That Will Fail Over 100 Years	Cost Per Launch	Total Cost Associated With Replacement
Earth	7.3458	$764M	$5.61B

4.2 *Relay Satellites*

4.2.1 *CAD / System totals*

As stated in the previous Earth CAD/System section, the satellites are very similar in design. Most of the changes done to the Relay satellite are due to the communication system only needing apertures and no longer requiring an RF antenna. The size also changes due to our calculations that alternated the ΔV required.

Table 4.2.1.1 The mass, power, and volume of the L5 relay

Satellite	Mass [Mg]	Power [kW]	Volume [m^3]
L5 Relay	6.127	111.8	35.49

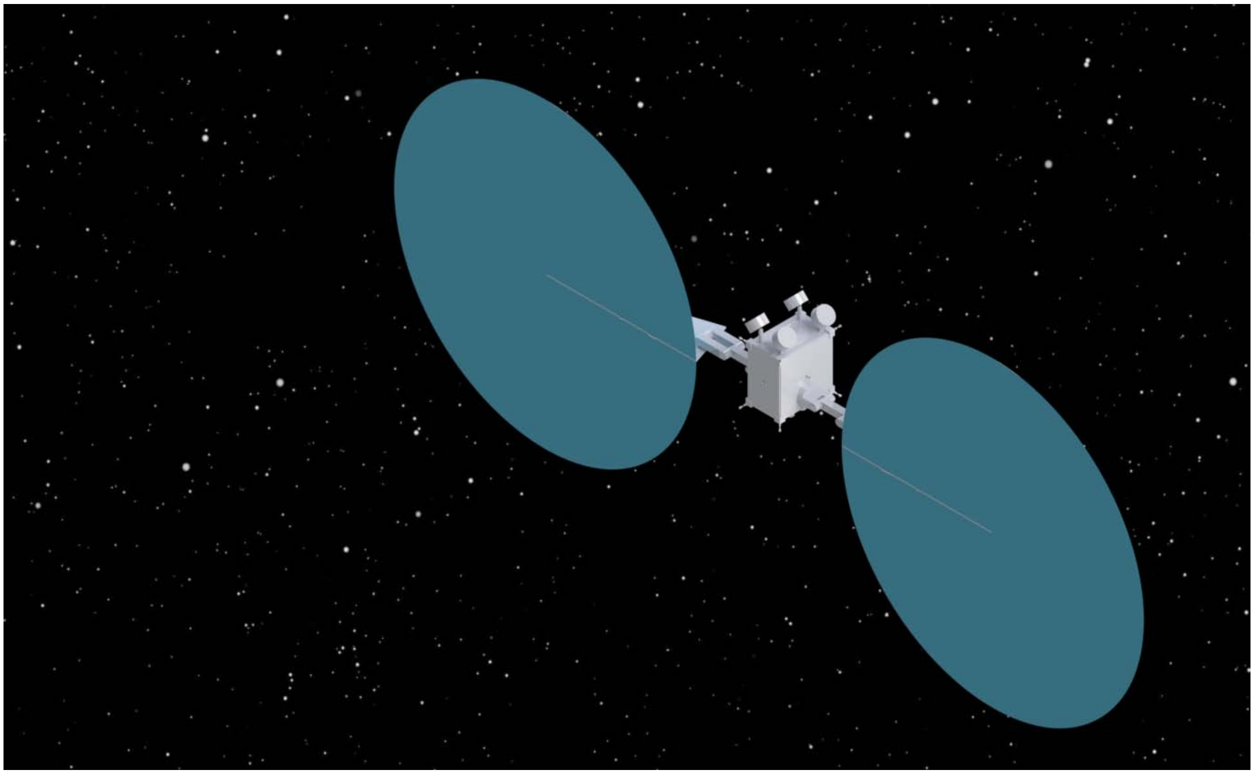

Fig. 4.2.1.1 Relay Satellite by Joe Renaud

4.2.2 System Map

This system is for the Relay side of the communications line. The Relay satellites receive communications signals from both the Mars and Earth satellite during periods of conjunction interference.

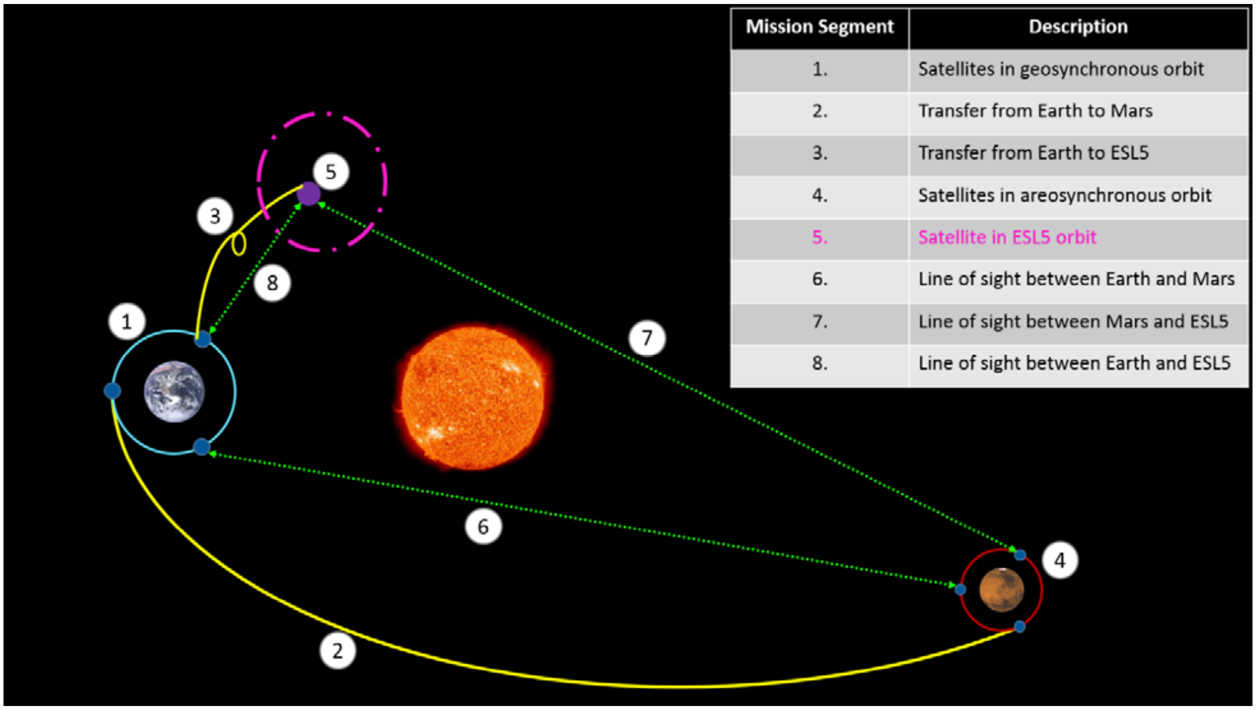

Fig. 4.2.2.1: System Map for Earth Satellites by Abishek Murali.

Fig. 4.2.2.1 shows the overall system view, with the circled section being the current system.

4.2.3 Deployment / Fabrication

Deployment and fabrication is similar to the Earth satellite in scope and structure. Please refer to the Earth satellite section (4.1.3) for further details.

4.2.3.1 *Deployment Timeline*

We recall the scenarios for satellite deployment mentioned in 4.1.3.1 and produce a Relay satellite deployment timeline. Table 4.2.3.1 shows the Relay satellite deployments necessary for each cycle.

Table 4.2.3.1 Relay satellite deployments required for every synodic cycle

Cycle	Relay Satellites	Cycle	Relay Satellites	Cycle	Relay Satellites
0	1	**16**	0	**32**	2
1	0	**17**	1	**33**	0
2	0	**18**	1	**34**	1
3	0	**19**	1	**35**	2
4	0	**20**	1	**36**	2
5	0	**21**	0	**37**	1
6	1	**22**	1	**38**	2
7	0	**23**	1	**39**	1
8	1	**24**	1	**40**	1
9	0	**25**	1	**41**	2
10	0	**26**	2	**42**	2
11	0	**27**	0	**43**	2
12	1	**28**	1	**44**	2
13	1	**29**	1	**45**	0
14	1	**30**	2	**46**	0
15	0	**31**	1	**Total**	41

4.2.4 Operation and Servicing

The Relay satellite transmits data to both the Earth and Mars satellites via optical laser communication. The communication characteristics of the Mars satellite are in Table 4.2.4.1 4.2.4.1.

Table 4.2.4.1 Relay Satellite Communication System Characteristics

Parameter	Unit	Earth Oriented	Mars Oriented
Frequency	GHz	32	3.00E+05
Maximum Data Rate	Mbps	1.07E+10	1.07E+10
Communication Power	W	3400	16600
Antenna Diameter	m	-	-
Aperture Diameter (x2)	m	1	1

4.2.4.1 *Power Source*

Here is the Table 4.2.4.2 of the requirements for the Relay Satellite.

Table 4.2.4.2 Power requirements for the Relay Satellite

Source/Satellite	**Communication and Control (kW)**	**Propulsion (kW)**	**Thermal (kW)**	**Others (kW)**
Relay	60	0.79	0.3	0.1

We also get in the upcoming Table 4.2.4.3 the Mass, Power and Volume for the Relay Satellite

Table 4.2.4.3 Mass, Power, Volume and Area of the solar panels

Source/Satellite	**Mass (Mg)**	**Power (kW)**	**Volume (m^3)**	**Area (m^2)**
Relay	1.291	111.8	6.521	652.1

Finally, here is the Table 4.2.4.4 of the batteries installed on the Relay Satellite.

Table 4.2.4.4 Mass, Power and Volume of battery GS-YUASA for the Relay Satellite

Characteristics	**Value**
Power Capacity (kW/hr)	120
Volume (m^3)	0.3844
Mass (kg)	0.8655

4.2.4.2 *Thermal Systems*

We can see in the following Table 4.2.4.5 the passive and active thermal systems needed on the Relay Satellite.

Note: 1 mil = 25.4 µm.

Table 4.2.4.5 Summary of the characteristics of the thermal exchange systems for the Relay Satellite

Component	**Characteristics / Value**
Multi-Layer Insolation (Thickness)	13.6 mil
Space Radiators (Power)	0.4 kW
Space Radiators (Area)	44.10 m^2
Space Radiators (Mass)	0.220 Mg
Heat Pipes (Power)	0.3 kW

4.2.4.3 *Relay Satellite Propulsion*

The overview of the satellites mass, power and volume can be seen below:

Table 4.2.4.3.1: Mass, Power, and Volume for Relay Satellite Propulsion

	Mass (Mg)	**Volume (m^3)**	**Power (W)**
Relay Satellite Total	2.605	2.642	790

4.2.4.3.1 Propulsion/Engines/System Overview

The propulsion, engine, and system overview of the system are the same as the Earth satellite. Please refer to the Earth Satellite Propulsion section for a breakdown of the results for this section.

4.2.4.3.2 Attitude

The attitude system consists of the same components as the Earth satellite but are scaled to a different level as the needs of the Relay satellite change due to the satellite's different mass and volume. This difference is due to the satellites having different Delta V requirements by the nature of them having different orbit locations and different attitude control requirements. The sums of this system can be seen in the table below:

Table 4.2.4.3.2.1: Attitude Fuel Mass for the Relay Satellite

Satellite	Mass (Mg)
Relay	0.059

4.2.4.4 *Relay Attitude Control System*

Like the Earth satellites, the relay satellites must also maintain pointing accuracy of less than one mili rad due to the free space optical communication system. To accomplish this accuracy, we connect the optical transmitter and receiver apertures to the satellite bus using a vibration damping platform just like that on the Earth Satellite. This platform allows the optical apertures to slew independent of the satellite bus's orientation and insulates the apertures from any vibrations in the satellite's structure.

Again, like the Earth satellite we employ a three axes stabilization system that consists of three reaction wheels. The reaction wheels spin about three axes, each independent of one another. These wheels spin up and down to cancel out any disturbing torques acting on the satellite. Since the relay satellite has twice the transmitting apertures, it requires larger reaction wheels.

Table 4.2.4.4.1 Relay Satellite Reaction Wheels

Momentum Accumulation [N m s]	Wheel Mass [kg]
48.90	24.00

4.2.5 Retirement, disposal, and replacement

We retire our Relay satellites by performing a decommissioning maneuver at the end of each satellites lifetime. Table 4.2.5.1 contains the required ΔV. The exact method of the decommissioning will not be determined at this time as this is highly dependent on specific mission parameters. The goal is to demonstrate the feasibility of performing a maneuver for less than the 0.7 km/s allotted. Two possibilities exist. First, the satellite could be deorbited and reinserted into cis-lunar space or pushed into a heliocentric orbit. Either of these methods are viable for under 0.7 km/s. The goal of this was to determine the feasibility of deorbiting satellite, and so this has been done.

Table 4.2.5.1 ΔV needed to decommission satellites in L_5 orbit.

Transfer Parameter	Value
L_5 Deorbit	<0.7 km/s

Table 4.2.5.2 Relay satellites retired each synodic cycle

Cycle	Relay Satellites	Cycle	Relay Satellites	Cycle	Relay Satellites
0	0	**16**	0	**32**	1
1	0	**17**	0	**33**	2
2	0	**18**	0	**34**	0
3	0	**19**	1	**35**	1
4	0	**20**	1	**36**	1
5	0	**21**	1	**37**	2
6	0	**22**	0	**38**	1
7	1	**23**	0	**39**	2
8	0	**24**	1	**40**	0
9	0	**25**	1	**41**	1
10	0	**26**	1	**42**	2
11	0	**27**	1	**43**	2
12	0	**28**	0	**44**	1
13	1	**29**	1	**45**	2
14	0	**30**	1	**46**	0
15	1	**31**	1		

4.2.6 System Cost

To determine the price of the individual relay satellite, a costing process similar to that of the Earth satellites was used, as described in Section 4.1.6. The major source of price difference between the Relay and Earth satellites is the addition of two 1 meter apertures for transmitting and receiving the crosslink with Mars.

Although the analysis produces a quantity of two Relay satellites, a third is added to significantly decrease the probability of a total communications blackout. We deploy one extra Relay satellite every fifteen years, bringing the total quantity of Relays from 53 to 60. The cost of hardware, launch, and operations of each Relay satellite over its 15 year lifetime is $897 million. The additional 7 redundant Relays add an extra $6 billion to the total cost. The total cost of Relay satellites over the 100 year mission is $53.8 billion. These costs are shown below in Table 4.2.6.1.

Table 4.2.6.1 System Costs for Relay over 100 years

Satellite	Quantity	Cost Per Launch	Total Cost Over Mission
Relay	60	$897M	$53.8B

4.2.7 Risk Analysis

Using the same analysis described in Section 4.1.7, we determine that 4.5633 Relay satellites will fail over the 100 year development, shown below in Table 4.2.7.1.

Table 4.2.7.1 Failure Analysis for Relay over 100 years

Satellite	Probability of Failure Before End-of-Life	Quantity That Will Fail Over 100 Years
Relay	0.1113	4.5633

4.2.8 Risk Mitigation Strategies

The cost to replace the failed Relay satellites is an extra $5.61 billion over 100 years, shown below in Table 4.2.8.1.

Table 4.2.8.1 Failure Mitigation Costs for Relay over 100 years

Satellite	Quantity That Will Fail Over 100 Years	Cost Per Launch	Total Cost Associated With Replacement
Relay	4.5633	$897M	$4.09B

To reduce the probability of total HD video communications blackout, we analyze the possibility of permanently adding a redundant Relay satellite, mentioned in Section 4.2.6. Calculating the probability of a total communications blackout with three Relay satellites lowers the probability from 0.128 to 0.0018. We add one additional Relay satellite every 15 years, which results in an extra 7 Relay satellites over the 100 year mission. The associated additional cost is $5.98 billion, shown below in Table 4.2.8.2. We choose this risk mitigation technique and add this cost into the total Relay cost in Section 4.2.6.

Table 4.2.8.2 Total Blackout Mitigation Strategy and Cost

Strategy	Probability of Blackout	Total Added Cost Over 100 Years
Add Relay Satellite	0.0018	$5.98B

4.3 *Mars System*

4.3.1 *CAD / System totals*

As stated in the previous Earth CAD/System section, the satellites are very similar in design. Most of the changes done to the Mars satellite are due to our calculations that alternated the ΔV required.

Table 4.3.1.1 The mass, power, and volume for the Mars Orbiter

Satellite	Mass [Mg]	Power [kW]	Volume [m^3]
Mars Orbiter	7.667	36.99	50.78

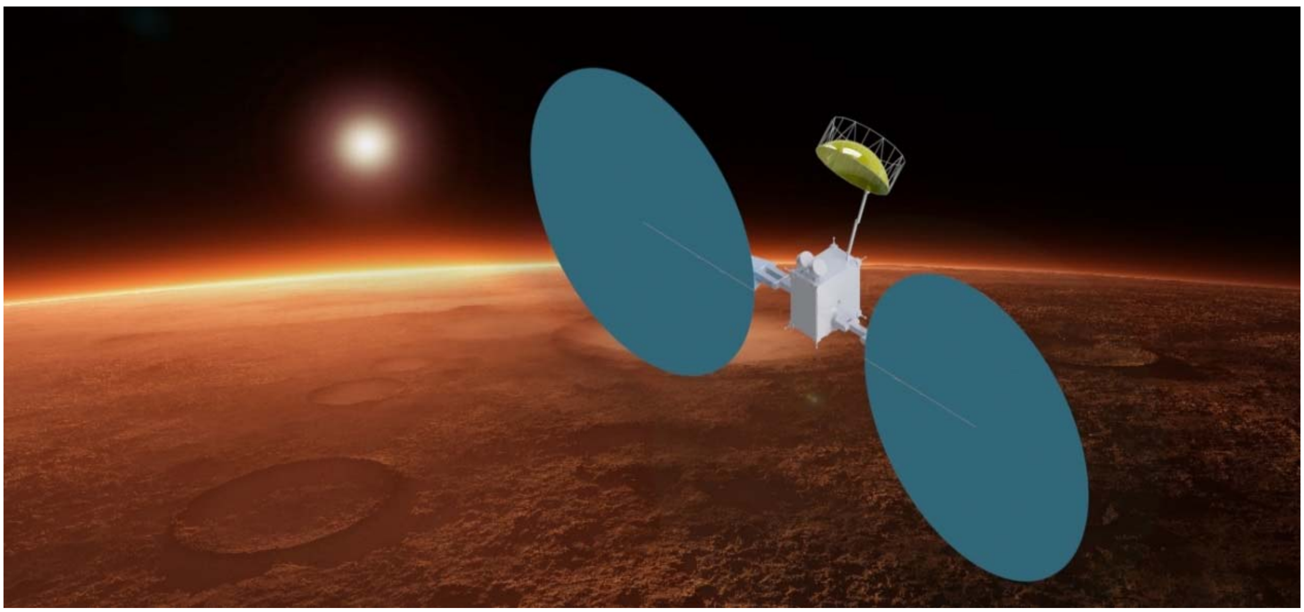

Fig. 4.3.1.1 Relay Satellite by Joe Renaud

4.3.2 System Map

This system is for the Mars side of the communications line. The Mars satellites receive communications signals from either the Earth or Relay satellite. The ground station and satellites are in constant communication on Mars with one satellite always in line of sight of the colony.

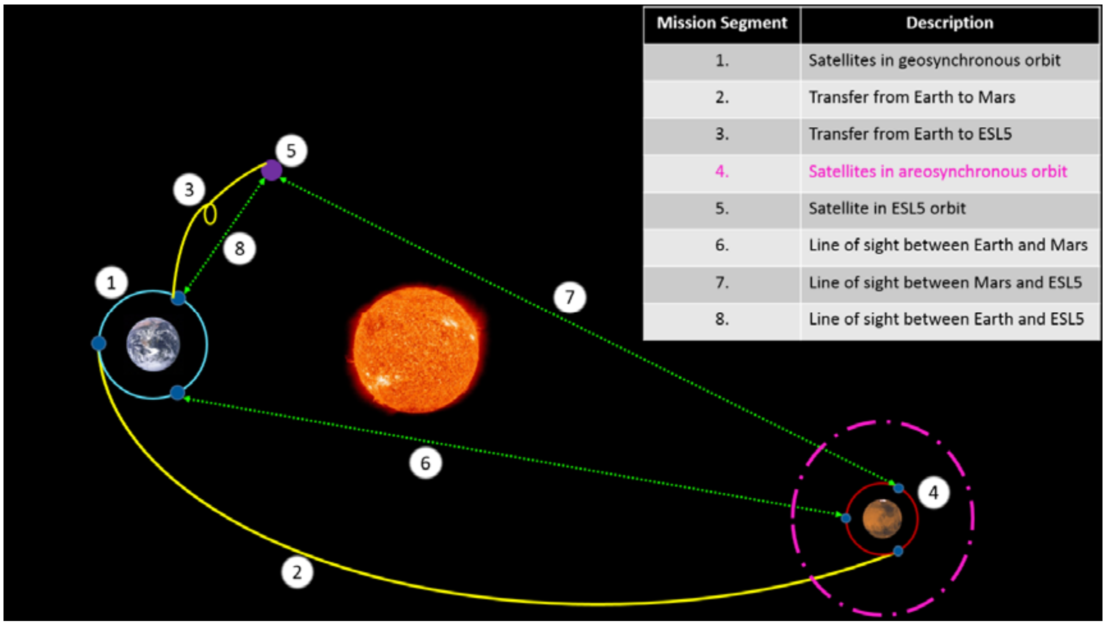

Fig. 4.3.2.1 System Map for Earth Satellites (Credit: A. Murali.)

4.3.3 Deployment / Fabrication

Physical deployment from the Falcon Heavy and fabrication techniques are similar to the Earth satellite in scope and structure. Please refer to the Earth satellite section (4.1.3) for further details.

Based on mission requirements, we know that continuous HD video communication is necessary between the Mars colony and ground stations back at Earth. We can help satisfy this requirement by providing constant line of sight coverage between the Mars colony and satellites orbiting Mars. The satellites that orbit Mars can then send video data either to relay satellites located at L_5 or directly to satellites orbiting Earth and geosynchronous altitudes.

Through trade study analysis described in the previous section of this report, we can conclude that the most feasible solution is to place satellites in areosynchronous orbits around Mars. This

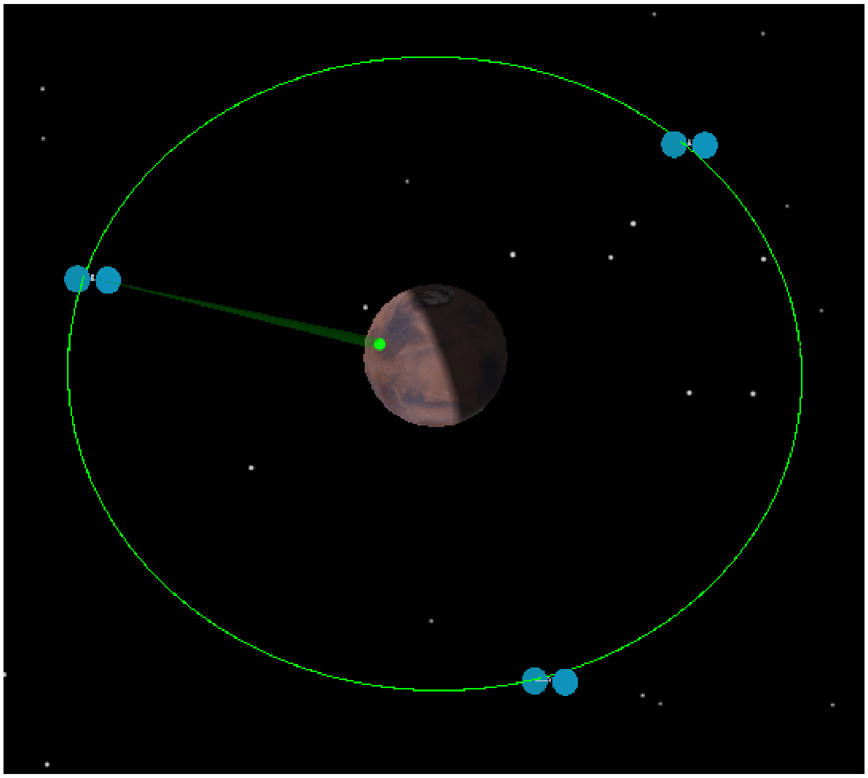

Fig. 4.3.3.1Areosynchronous Walker-Delta constellation used to provide constant line of sight coverage between the colony and Mars orbiting satellites. (Credit: A. Murali)

allows us to minimize the total number of satellites required to maintain constant line of sight coverage and provides the system with strong coverage characteristics. Fig. 4.3.3.1 contains a visual representation of the finalized areosynchronous Walker-Delta constellation designed to satisfy mission requirements. The green conical beam starts from the satellite and points to the green dot on Mars, which is the colony location, showing that line of sight is always maintained.

Table 4.3.3.1 Areosynchronous Walker-Delta constellation used to provide constant line of sight coverage between the colony and Mars orbiting satellites. (Credit: A. Murali)

Transfer Parameter	Value
ΔV to get on transfer orbit	3.6 km/s
Insertion ΔV	1.4 km/s
C3	8.0 km^2/s^2

To get an understanding of the Mars satellites operating conditions, we must determine the altitude time history of the satellite's orbit. Although the Mars satellites occupy areosynchronous orbits, gravitation perturbations can cause argument of perigee rotation and small changes in inclination. This is easily visible when examining Fig. 4.2.4.4.2. Notice how the orbit, over the twelve periods of propagation, has changes in inclination and minute changes in semi-major axis. From the visualization model shown in Fig. 4.2.4.4.2, we obtain the maximum and minimum altitudes that define the Mars satellite operating conditions. This information is used to more accurately size the satellite's power/thermal systems.

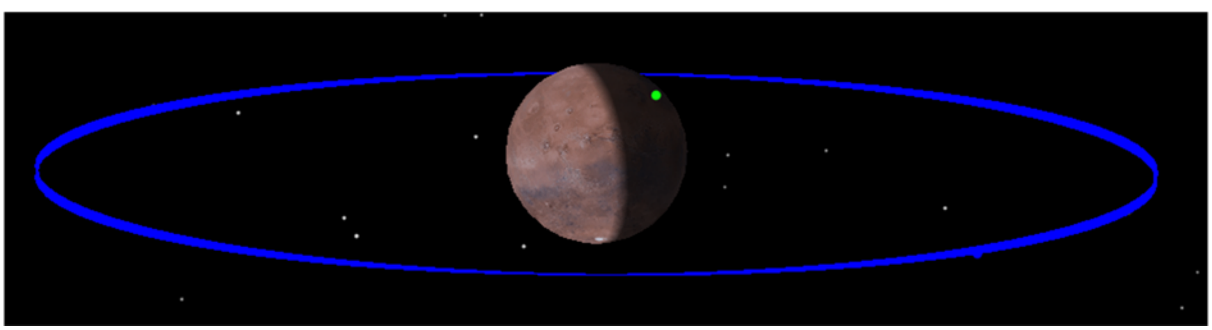

Fig. 4.2.4.4.2: Mars satellite areosynchronous orbit propagated for 12 periods to show impacts of gravitational perturbations. (Credit: A. Murali.)

Table 4.3.3.2: Maximum and minimum orbit altitudes.

Transfer Parameter	Value
Max Altitude	2.31E4 km
Min Altitude	1.80E4 km

We use Lambert arcs to construct a transfer from Earth to Mars using specific state information and inputted time of flight. After constructing our Lambert arc, we then obtain the necessary ΔVs to get on the transfer orbit from Earth and insert into our target orbit around Mars. Table 4.3.3.2 contains the required ΔVs needed to insert into an areosynchronous orbit from a transfer arc as well as the C3 value of the trajectory. We cross-reference the computed C3 value with NASA's launch vehicle performance database. We find that the Falcon Heavy is capable of sending the satellite on the designed transfer.

We use System Toolkit (STK) to get a visual understanding of the transfer arc. The following sequence of images provides an overview of the transfer starting from Earth, Mars, and satellite initial states up until Mars rendezvous. Note that the purple triangle corresponds to the satellite position, the blue orbit corresponds to Earth's orbit, and the red orbit corresponds to Mars' orbit. Initially, the satellite is located in the vicinity of Earth. During the transfer, the satellite is mainly under solar influence until arrival at the Martian system. The final image in the sequence shows successful rendezvous with Mars at the end of the transfer trajectory.

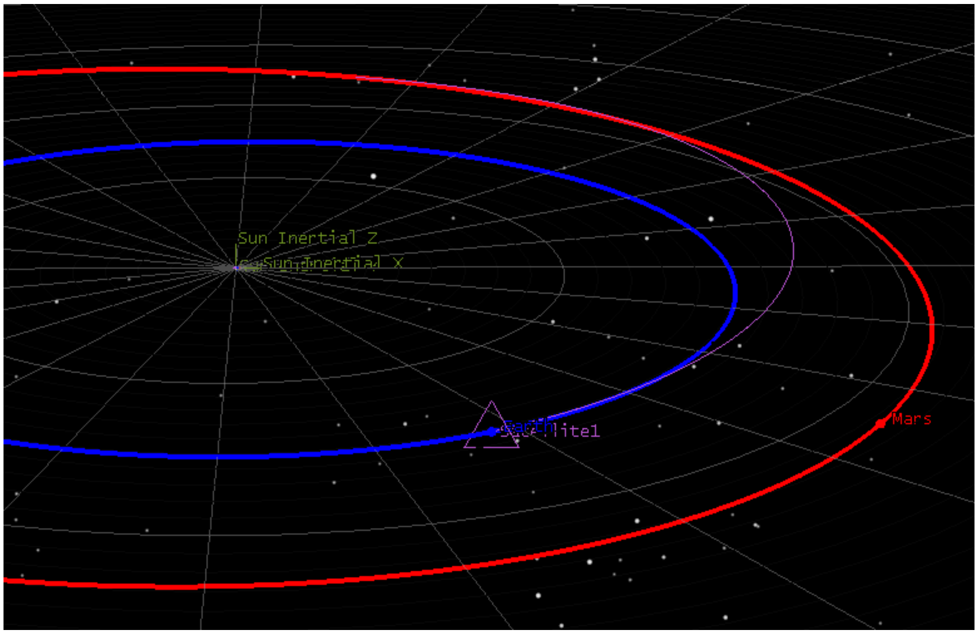

Fig. 4.2.4.4.3: Initial state of Earth, Mars, and satellite. Image credit to Abishek Murali.

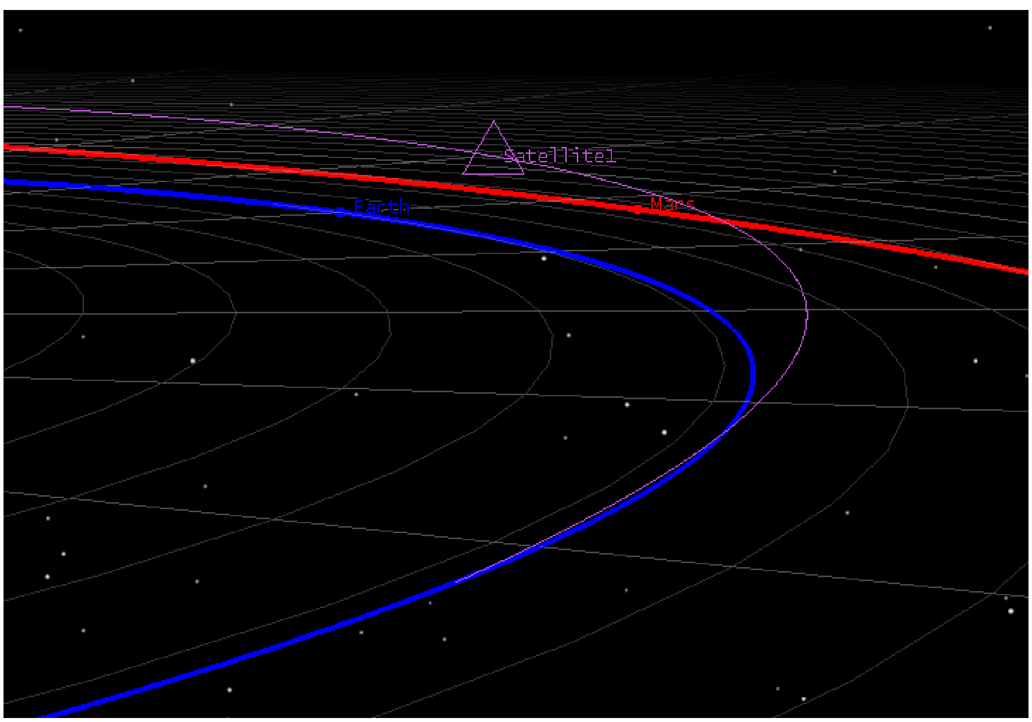

Fig. 4.2.4.4.4: Earth, Mars, and satellite during transfer. (Credit: A. Murali.)

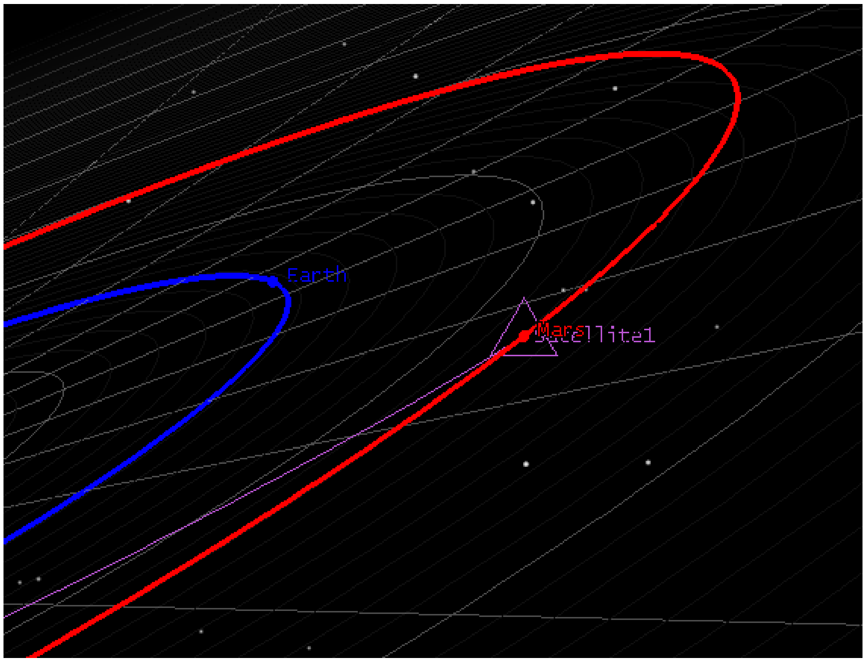

Fig. 4.2.4.4.5: Earth, Mars, and satellite when satellite rendezvous with Mars. (Credit: A. Murali.)

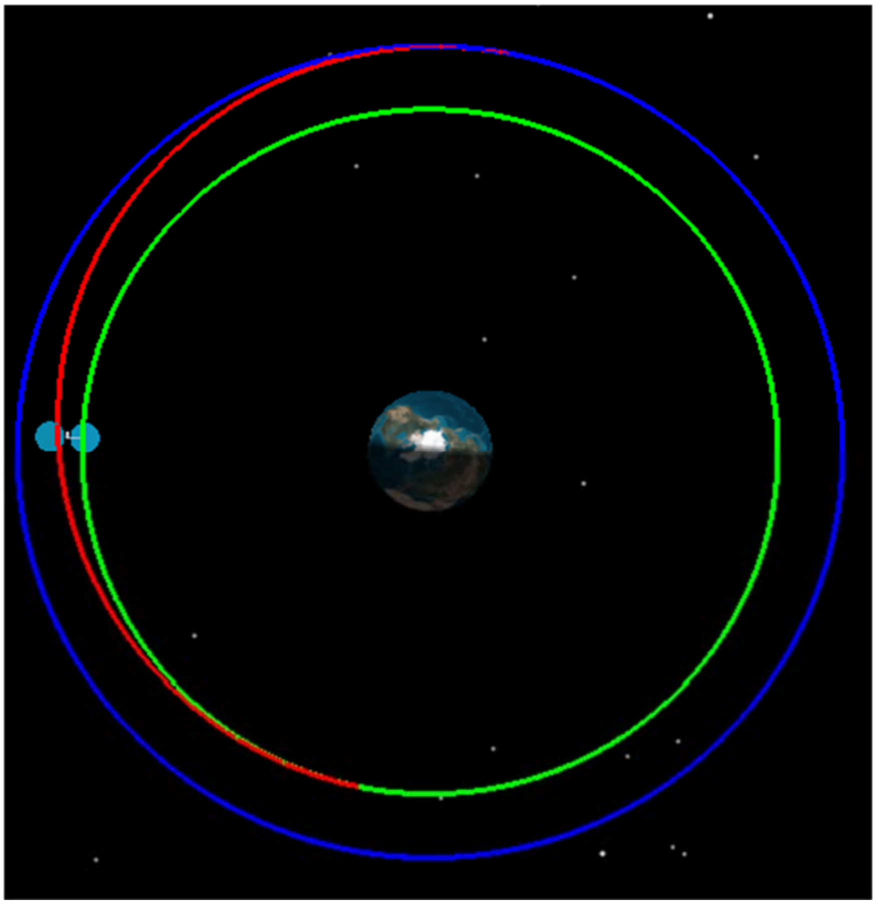

Fig. 4.2.4.4.1: Decommission maneuver performed by satellite at geosynchronous altitudes (Credit: A. Murali.)

4.3.3.1 *Deployment Timeline*

We recall the scenarios for satellite deployment and produce a Mars satellite deployment timeline. **Error! Reference source not found.** shows the Mars satellite deployments necessary for each cycle.

Table 4.3.3.3 Mars satellite deployments required for every synodic cycle

Cycle	Mars Satellites	Cycle	Mars Satellites	Cycle	Mars Satellites
0	3	**16**	0	**32**	0
1	0	**17**	3	**33**	9
2	0	**18**	0	**34**	0
3	0	**19**	3	**35**	9
4	0	**20**	0	**36**	0
5	0	**21**	6	**37**	6
6	3	**22**	0	**38**	0

7	0	**23**	6	**39**	12
8	3	**24**	0	**40**	0
9	0	**25**	3	**41**	9
10	0	**26**	0	**42**	0
11	0	**27**	9	**43**	9
12	6	**28**	0	**44**	0
13	3	**29**	6	**45**	12
14	0	**30**	0	**46**	0
15	0	**31**	6	**Total**	135

4.3.4 Operation and Servicing

4.3.4.1 *Communication*

The Mars satellite uses radio frequency telecommunication systems for transmission of signals through the Earth's atmosphere to a ground station. The Earth Satellite uses optical laser communication to transmit data to the L_5 relay and Mars satellites. The communication characteristics of the Mars satellite are in Table 4.3.4.1.

Table 4.3.4.1 Mars Satellite Communication System Characteristics

Parameter	Unit	Earth Oriented	Mars Oriented
Frequency	GHz	3.00E+05	32
Maximum Data Rate	Mbps	9.63E+09	9.63E+09
Communication Power	W	19940	60
Antenna Diameter	m	-	5
Aperture Diameter (x2)	m	1	-

4.3.4.2 *Power Sources*

Here in Table 4.3.4.2.1 is the power requirement for the Mars Satellite.

Table 4.3.4.2 Power requirements for each of our satellites

Source/Satellite	Communication and Control (kW)	Propulsion (kW)	Thermal (kW)	Others (kW)
Mars Orbiter	20	0.79	0.3	0.1

We also get in the upcoming the Mass, Power and Volume for the Mars Satellite.

Table 4.3.4.3 Mass, Power, Volume and Area of the solar panels

Source/Satellite	Mass (Mg)	Power (kW)	Volume (m^3)	Area (m^2)
Mars Orbiter	1.256	36.99	6.345	634.5

Finally, here is **Error! Reference source not found.** of the batteries installed on the Mars Satellite.

Table 4.3.4.4 Mass, Power and Volume of battery GS-YUASA for the Mars Orbiter

Characteristics	Value
Power Capacity (kW/hr)	40
Volume (m^3)	0.1271
Mass (Mg)	0.2862

4.3.4.3 *Thermal Sources*

We can see in the following table, the passive and active thermal systems needed on the Mars Satellite.

Table 4.3.4.5 Summary of the characteristics of the thermal exchange systems for the Mars Orbiter

Component	Characteristics / Value
Multi-Layer Insolation (Thickness)	13.6 mil
Space Radiators (Power)	0.4kW
Space Radiators (Area)	5.89 m^2
Space Radiators (Mass)	0.295 Mg
Heat Pipes (Power)	0.3 kW

4.3.4.4 *Mars Satellite Propulsion*

The overview of the satellites mass, power and volume can be seen below:

Table 4.3.4.6: Mass, Power, and Volume for Mars Satellite Propulsion

	Mass (Mg)	Volume (m^3)	Power (W)
Mars Satellite Total	3.791	3.746	790

4.3.4.4.1 Propulsion/Engines/System Overview

The propulsion, engine, and system overview of the system are the same as the Earth satellite. Please refer to the Earth Satellite Propulsion section for a breakdown of the results for this section.

4.3.4.4.2 Attitude

The attitude system consists of the same components as the Earth satellite but are scaled to a different level as the needs of the Mars satellite change due to the satellite's different mass and volume. This difference is due to the satellites having different Delta V requirements by the nature of them having different orbit locations and different attitude control requirements. The sums of this system can be seen in the table below:

Table 4.3.4.7 Attitude Fuel Mass for the Mars Satellite

Satellite	Mass (Mg)
Mars	0.040

4.3.4.5 *Mars Satellite Attitude Control System*

Like the Earth and relay satellites, the Mars satellites must also maintain pointing accuracy of less than one mili-rad due to the free space optical communication system. To accomplish this accuracy, we connect the optical transmitter and receiver apertures to the satellite bus using a vibration damping platform just like that on the Earth Satellite. This platform allows the optical apertures to slew independent of the satellite bus's orientation and insulates the apertures from any vibrations in the satellite's structure.

Again, like the Earth and relay satellites, we employ a three axes stabilization system that consists of three reaction wheels. The reaction wheels spin about three axes, each independent of

one another. These wheels spin up and down to cancel out any disturbing torques acting on the satellite. The mass of these wheels is shown in Table 4.3.4.8

Table 4.3.4.8 Mars Satellite Reaction Wheels

Momentum Accumulation [N m s]	Wheel Mass [kg]
18.00	20.00

4.3.5 Retirement, disposal, and replacement

We retire our Earth satellites by performing a two-burn decommission maneuver at the end of each satellites lifetime. Table 4.3.5.1 contains the required ΔVs to accomplish the two-burn decommission maneuver for satellites around Mars

Table 4.3.5.1 ΔV needed to decommission satellites in areosynchronous orbit.

Transfer Parameter	Value
Areosynchronous Deorbit	0.129 km/s

Table 4.3.5.2 Mars Satellites retired each synodic cycle

Cycle	Mars Satellites	Cycle	Mars Satellites	Cycle	Mars Satellites
0	0	**16**	0	**32**	0
1	0	**17**	0	**33**	6
2	0	**18**	0	**34**	0
3	0	**19**	6	**35**	6
4	0	**20**	0	**36**	0
5	0	**21**	3	**37**	9
6	0	**22**	0	**38**	0
7	3	**23**	3	**39**	9
8	0	**24**	0	**40**	0
9	0	**25**	6	**41**	6
10	0	**26**	0	**42**	0
11	0	**27**	6	**43**	12
12	0	**28**	0	**44**	0
13	3	**29**	3	**45**	9
14	0	**30**	0	**46**	0
15	3	**31**	9		

4.3.6 System Cost

To determine the price of the individual relay satellite, a costing process similar to that of the Earth satellites was used, as described in Section 4.1.6. The costs of the Earth and Mars satellites are similar, with the only notable differences resulting from station-keeping due to different orbits.

The cost of hardware, launch, and operations of each Mars satellite over its 15 year lifetime is $765 million. Because we calculated at least double the amount of Mars satellites compared to Earth and Relay, the Mars satellite constellation is the most expensive component of the total system. The total cost of Mars satellites over the 100 year mission is $119 billion. These costs are shown below in Table 4.3.6.1.

Table 4.3.6.1 System Costs for Mars over 100 years

Satellite	Quantity	Cost Per Launch	Total Cost Over Mission
Mars	156	$765M	$119B

4.3.7 Risk Analysis

Using the same analysis described in Section 4.1.7, we determine that 15.0255 Mars satellites will fail over the 100 year development, shown below in Table 4.3.7.1.

Table 4.3.7.1 Failure Analysis for Mars over 100 years

Satellite	Probability of Failure Before End-of-Life	Quantity That Will Fail Over 100 Years
Mars	0.1113	15.0255

4.3.8 Risk Mitigation Strategies

The cost to replace the failed Mars satellites is an extra $11.5 billion over 100 years, shown below in Table 4.3.8.1.

Table 4.3.8.1 Failure Mitigation Costs for Mars over 100 years

Satellite	Quantity That Will Fail Over 100 Years	Cost Per Launch	Total Cost Associated With Replacement
Mars	15.0255	$765M	$11.5B

5 Interplanetary Crew and Cargo Transportation System

5.1 ITS Cargo Vehicle

5.1.1 *System Description and Purpose*

To make the most effective use of Interplanetary Transport System (ITS) Launches, we deem it fitting to make modifications to Elon Musk's initial proposed design for the ITS. Several of these new ITS configurations are designed specifically for transporting cargo to and from Mars or for construction in LEO.

5.1.1.1 *Purpose, Variants, and Capabilities*

5.1.1.1.1 ITS-A

The first iteration of the ITS is what we call the ITS-A, short for Assembly ITS. This variant is tasked with serving as a construction "platform" for the cycler vehicle, which is discussed in detail in Section 5.2. The cycler is a huge vehicle, and, in turn, needs a large vehicle to help in its construction. The ITS-A is different from the initial concept of the ITS since the majority of its non-propellant system volume is cargo area. There is still a flight deck forward of the cargo bay that provides living quarters for the crew and control over the construction and maintenance processes. Employing the forward docking port at the nose of the ITS-A, we can dock with any station, or, in the case of the construction of the cycler, with the central node to begin the construction process. The ITS-A is a full-sized ITS that contains a large robotic arm that we call the Remote Manipulator System (RMS) in addition to a construction vehicle called the Orbital Construction Pod (OCP) inside of its cargo bay. We deploy both components out of the large payload bay doors in the cargo bay. The RMS allows the ITS-A to grapple the Cycler Component Stack, which is discussed in Section 5.2.2, while the OCP works in tandem to connect cycler components to one another. The ITS-A is meant to be a crewed vessel that carries the number of astronauts required to operate the RMS from onboard the ITS-A, pilot the OCP, and perform any necessary spacewalks to aid in the cycler construction process. Please see Fig. 5.1.1.1.1 for a model of the ITS-A. In addition to being used for construction, we also use the ITS-A for cycler refurbishment mission.

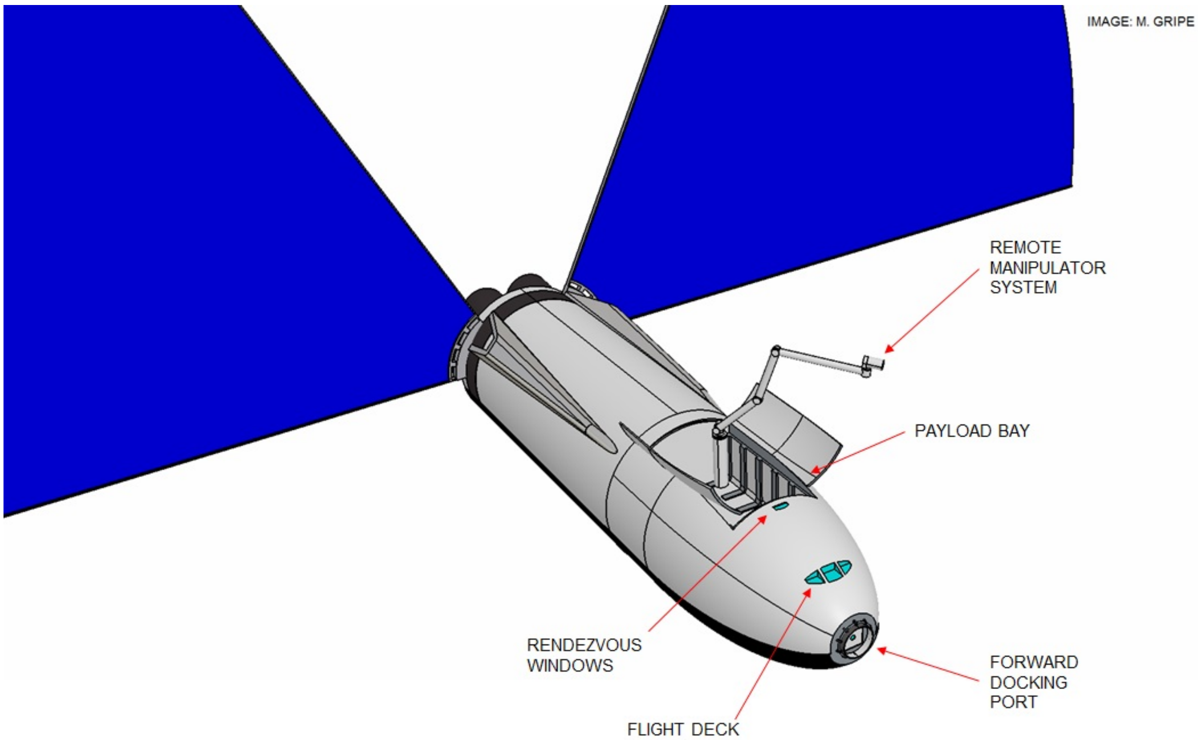

Fig. 5.1.1.1.1 A model of the ITS-A, which will be responsible for cycler construction and maintenance. Credit: M. Gripe and K. Jantze

5.1.1.1.2 ITS-C

Since we are using a cycler for human transport, it is necessary to develop a variant of the ITS that allows for transportation of large amounts of cargo to and from Mars. For this purpose, we develop to different variants of what we call the Cargo ITS, or ITS-C1 and ITS-C2. The Cargo ITS is different from the initial concept of the ITS since all of its interior volume is allocated for cargo. Both vehicles make direct flights to and from Mars carrying essential cargo for sustaining the Martian colony. The difference between the two variants is the type of cargo that they transport. The ITS-C1 is meant for transporting large amounts of small cargo like seed, lights, food, clothing, and other items the colonist need to establish a permanent settlement on Mars. These small cargo items will be packed in standard-sized cargo crates that will be discussed in Section 5.1.1.1.2.2. This configuration provides the ITS-C1 the ability to transport approximately 943 m^3 of cargo not including a crane system and airlock that will be instrumental for loading and unloading purposes. The ITS-C2 is meant for transporting our larger cargo items like temporary habitats, powerplants,

refineries, and other items needed to create a strong infrastructure for our new colony. These items will not be packed in any specific containers and will be carefully attached to the internal structure of the ITS-C2 in such a way that the launch environment and subsequent vibrations do not create an unbalanced payload. This configuration provides the ITS-C2 with approximately 1465 m^3 of cargo space not including a crane system that is used for loading and unloading all the heavy equipment on board. The reason for the difference in cargo capacity between the two variants is attributed to the fact that the ITS-C1 contains an airlock and also has less efficient packing that is inherent with trying to efficiently fit squares inside of a circular cross-section.

5.1.1.1.2.1 Cargo Capacity

To determine how much available volume and mass we have to pack the different variants of the ITS with, an analysis was done of the images SpaceX presented. Table 5.1.1.1.2.1.1 contains the results of this analysis.

Table 5.1.1.1.2.1.1 A breakdown of the dimensions, volume, and mass that the ITS-C's can carry.

Variable/Data of Interest	Value	Units
Total Usable Volume	1479	m^3
Cargo Maximum Length	20.84	m
Cargo Usable Diameter	12	m
Cargo Maximum Mass	300	Mg

The initial design of the ITS calls for a pressurized upper portion of the spacecraft complete with a large window in addition to an unpressurized cargo bay beneath this area. From the initial design, the pressurized volume of the ITS is found to be 877.6 m^3 and the cargo area is found to be 601.7 m^3. These values combined give us our total volume of 1479 m^3, which is the cargo space available to work with aboard the ITS-C1 and ITS-C2. The maximum length of the ITS that makes up this volume was determined by extrapolating the value from a picture of the ITS and its known full height of 49.5 meters [1]. The usable diameter of the cargo area is known since SpaceX has already developed a 12-meter diameter fuel tank that sits flush with the internal walls of the ITS. Lastly, SpaceX provides us with this maximum cargo mass of 300 Mg [1]. Please note that we define cargo as the mass of passengers and cargo, not including the structural or propellant mass of the ITS. For a more in-depth description of how the cargo capacity was determined please refer to Appendix 5.

5.1.1.1.2.2 Cargo Crate layout and Capacity

The ITS-C1 features a large number of crates for the transport of goods to Mars. For this study we designed and used 3 base shipping crates. There is the 1m, the 2m, and the 2m-L. The 1m and 2m are cubic crates that have a length height and width of 1 meter and 2 meters respectively. The 2m-L is a 2m crate whose length has been modified to a length of 3 meters so that it can carry slightly larger items, like the pumps need to maintain water circulation for the crops being harvested in The Hive. The Table 5.1.1.1.2.2.1 shows the capacity of each of the crates.

Table 5.1.1.1.2.2.1: Cargo container breakdown and capacity

Container Variant	2m	1m	2m-L
Length (m)	2	1	3
Mass (kg)	367	92	489
Capacity	2639	660	3959

In order to get an accurate accounting of the total number of crates that would be on the ITS-C1, we create layouts of what a potential loads. There are two variants of these, one that features the 2m-L crate and one that does not. In Fig. 5.1.1.1.2.2.1 and Fig. 5.1.1.1.2.2.2 we see a layout that only features 2m crates. In Fig. 5.1.1.1.2.2.3 and Fig. 5.1.1.1.2.2.4 in contrast, we see a layout that features 2m-L crates. The table below give the number of each variant of the layouts. We can also note that the ITS-C1 does not specifically have to carry one of the two layouts given, and that it can in fact carry any combination of crates of these sizes that is necessary to complete the mission.

Table 5.1.1.1.2.2.2: A breakdown of the number of each type of crate in each of the featured layouts.

Crate Variants	2m-L Featured	2m Featured
1m	468	388
2m	28	68
2m L	20	0

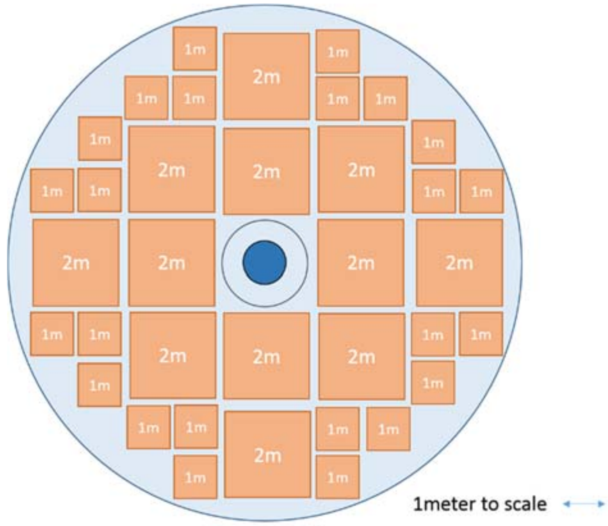

Fig. 5.1.1.1.2.2.1 A top view of an ITS-C layout that features only 2m crates. Credit: S. Fulton

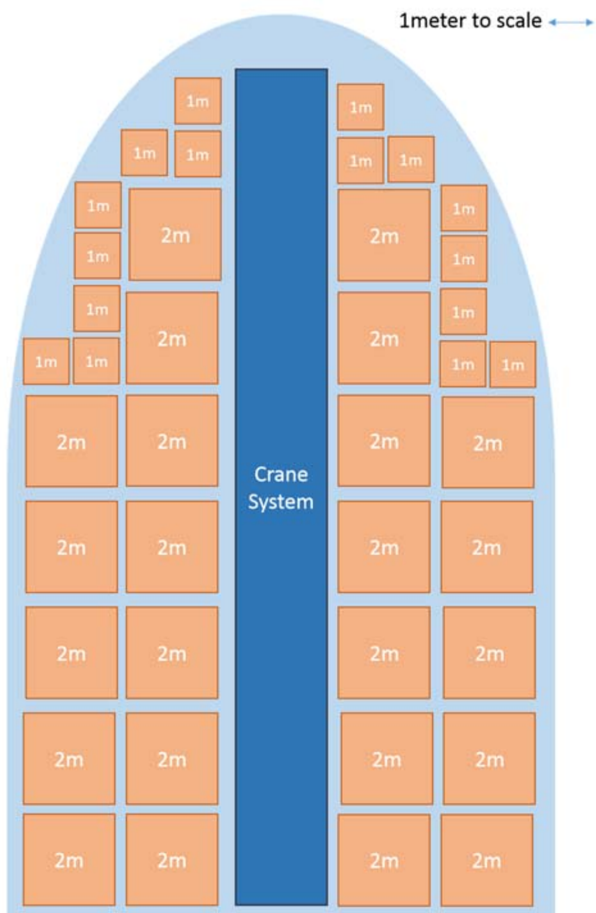

Fig. 5.1.1.1.2.2.2 The side view of a layout for the ITS-C1 that features 2m crates. Credit: S. Fulton

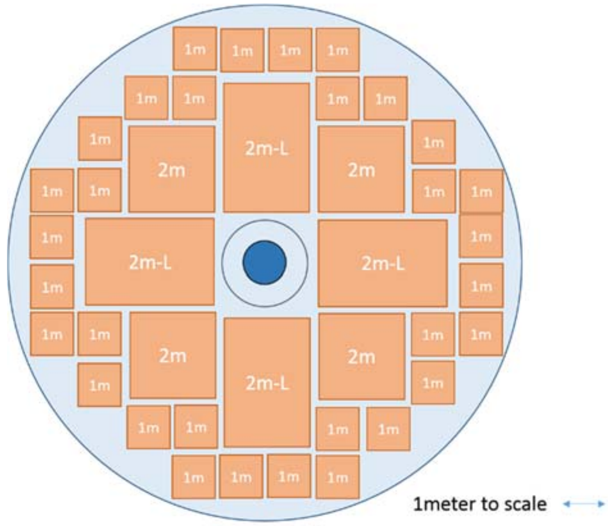

Fig. 5.1.1.1.2.2.3 A top view of a layout for the ITS-C1 that can carry 2m-L crates. Credit: S. Fulton

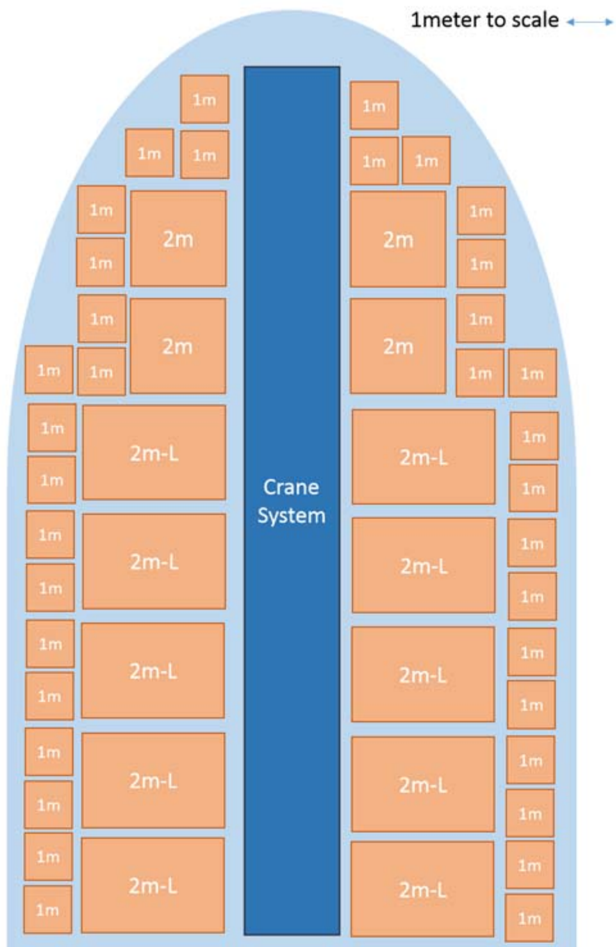

Fig. 5.1.1.1.2.2.4 A side view of a layout for the ITS-C1 that can carry 2m-L crates. Credit: S. Fulton

5.1.1.1.2.3 ITS-C Trajectory Overview

The goal of the cargo missions is to deliver as much payload mass to the Mars surface as possible. Then, the empty cargo vehicle must return to Earth requiring as little propellant as possible in order to minimize the ISRU propellant production. As a result, we choose conjunction-class missions as the primary method to transport cargo since they employ the minimum energy transfers between Earth and Mars.

Conjunction-class missions begin with a mass-optimal direct transfer from Earth to Mars, where it directly enters the Mars atmosphere upon arrival. The vehicle then remains on the surface of Mars until the next launch opportunity to Earth. Finally, the vehicle is refueled and launches into a direct injection into a mass-optimal direct transfer from Mars to Earth, where it directly enters the Earth atmosphere upon arrival. Fig. 5.1.1.1.2.3.1 shows the schematic for conjunction-class missions.

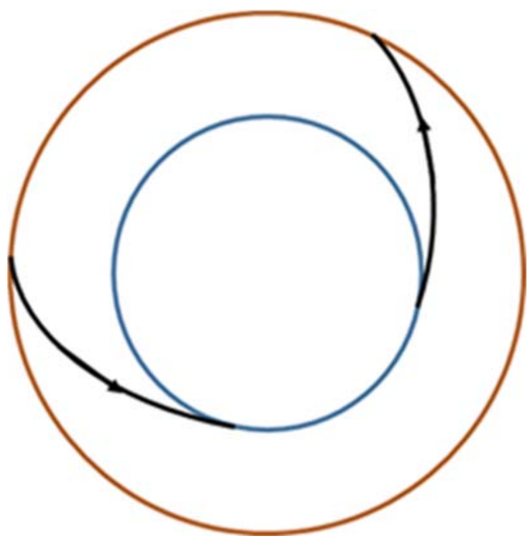

Fig. 5.1.1.1.2.3.1 Conjunction-Class Mission. This is the schematic for the trajectories used in the cargo missions. (Credit: A. Arora.)

The overall mission timeline starts in 2024 and lasts for 100 years. The trajectory information for each cargo mission is tabulated in Appendix 5, provides a summary of this information.

In Table 5.1.1.1.2.3.1, we define the launch window width as the amount of days that are available for sending a cargo vehicle towards Mars per synodic period. Any trajectory within the launch window can deliver at least 300 Mg of payload mass to the Mars surface. The interplanetary TOFs are the spacecraft travel times from when the spacecraft leaves the Earth system to when the spacecraft enters the Mars system. The stay time is the amount of time the spacecraft remains on the surface before launching to return to Earth. Lastly, we define the required ISRU propellant as the amount of propellant that must be produced on the Mars surface to return the spacecraft to Earth with no payload mass.

Table 5.1.1.1.2.3.1 This table provides a summary of cargo mission trajectory data from 2024 to 2124

Parameter	**Value Minimum**	**Value Maximum**
Launch Window Width (days)	167	378
Interplanetary TOF to Mars (days)	193	398
Stay Time on Mars (days)	285	560
Interplanetary TOF to Earth (days)	190	339
Required ISRU Propellant on Mars (Mg)	655	809

We note that there are two major types of direct trajectories contained within this data: type I and type II. Type I trajectories have shorter TOFs and typically deliver lower payload masses, while type II trajectories have longer TOFs and typically deliver higher payload masses. However, there are some launch opportunities in which the faster type I trajectories can deliver higher payload masses than the slower type II trajectories. This difference occurs solely due to the relative alignments of the Earth and Mars around the Sun, and accounts for the large variance in many of the key parameters in the trajectory data. Since a spacecraft with an excessively high entry velocity will not be able to enter a planet's atmosphere safely, we must ensure that any trajectories we select are feasible for entry. In the case of the cargo missions, all the trajectories both to Mars and to Earth fall well below the maximum allowable limits for a safe entry.

5.1.2 System totals

The ITS-C and all its variants are the backbone of our design. They provide the humans traveling to Mars with the massive amounts of equipment, tools and resources necessary to colonize the planet and make it a home. The tables below show give a breakdown of the mass, power, and volume (MPV) that each ITS-C requires for operation, as well as its final cargo capacity. On first glance, it may appear that the ITS-C2 is the most efficient choice to carry cargo, however, for the purposes of this feasibility study, it was important to note that not all items and equipment sent to The Hive would be able to pack with 100% efficiency. In fact, a lot of the items that are needed for the colonist are small and would require special packaging to undergo space flight. This is the ITS-C1 was created to evaluate the feasibility of shipping supplies to with less than perfect packing efficiency.

Table 5.1.2.1: A total MPV breakdown of the ITS-C1.

ITS-C1			
System	**Mass (Mg)**	**Volume (m^3)**	**Power (kW)**
Totals for Cargo	**273.76**	**946.80**	**8.535**
Crane System and Airlock	2.00	14.80	8.535
Cargo Crates	70.56	932.00	-
Cargo Capacity with Shipping Containers	201.20	932.00	-
Totals for Structure	**150**	**3392.92**	**253.22**
Frame, Infrastructure, Tanks, and Solar Arrays	150	3392.92	253.22
Totals for ITS-C1	**423.76**	**4339.72**	**244.69**

Table 5.1.2.2: A total MPV breakdown for the ITS-C2.

ITS-C2			
System	**Mass (Mg)**	**Volume (m^3)**	**Power (kW)**
Totals for Cargo	**300.00**	**14.80**	**8.535**
Crane System	2.00	14.80	8.535
Cargo Capacity of Open Space	298.00	1465.20	-
Totals for Structure	**150**	**3392.92**	**253.22**
Frame, Infrastructure, Tanks, and Solar Arrays	150	3392.92	253.22
Totals for ITS-C2	**450.00**	**3407.72**	**244.69**

In addition to the ITS-C's above, there is a second type of utility vehicle known as the ITS-A. This vehicle is a modified ITS-C that holds a crew of 6 and carries the equipment and small spacecraft necessary for constructing the large Avalon Cyclers in orbit. Located in the table below is the MPV estimate for the ITS-A.

Table 5.1.2.3: A total MPV breakdown for the ITS-A

ITS-A System	Mass (Mg)	Volume (m^3)	Power (kW)
Totals for Cargo	31.46	417.92	29.19
Human Needs	4.00	45.97	-
Food	1.37	3.71	-
Drinking Water	0.08	0.08	-
Utility Water	1.31	1.31	-
Oxygen	0.12	0.46	-
Clothing and Hygiene	1.13	40.41	-
Passengers	5.70	120.00	-
ECLSS	2.00	31.00	15.66
Facilities	13.92	180.05	8.535
Medical	1.00	28.25	-
Command	1.00	137.00	-
Airlocks and Cranes	11.92	14.80	8.535
Cargo and Assembly Kit	5.84	40.90	5.00
Space Assembly Arm	1.64	6.90	1.00
Orbital Construction Pod	4.20	34.00	4.00
Totals for Structure	**150**	**3392.92**	**253.22**
Frame, Infrastructure, Tanks, and Solar Arrays	150	3392.92	253.22
Totals for ITS-T	**181.46**	**3810.84**	**224.03**

5.1.3 Risk Analysis and Fault Tree

ITS-C variants face some many of the same risks that most modern day spacecraft. However, on top of these already extraordinary challenges, the ITS-C's will face some added problems as they transport cargo and supplies to our Martian colony. In the figure below, we examine some of the major risks that could impact this system. One of the notable ones is the failure of the ITS-C's crane. If the crane fails, while the system is on Mars, there may be no way to unload the cargo in the early stages of the mission. It this case, the ITS-C system would fail, as all the valuable cargo would be stranded in the top half of an ITS.

ITS-C:

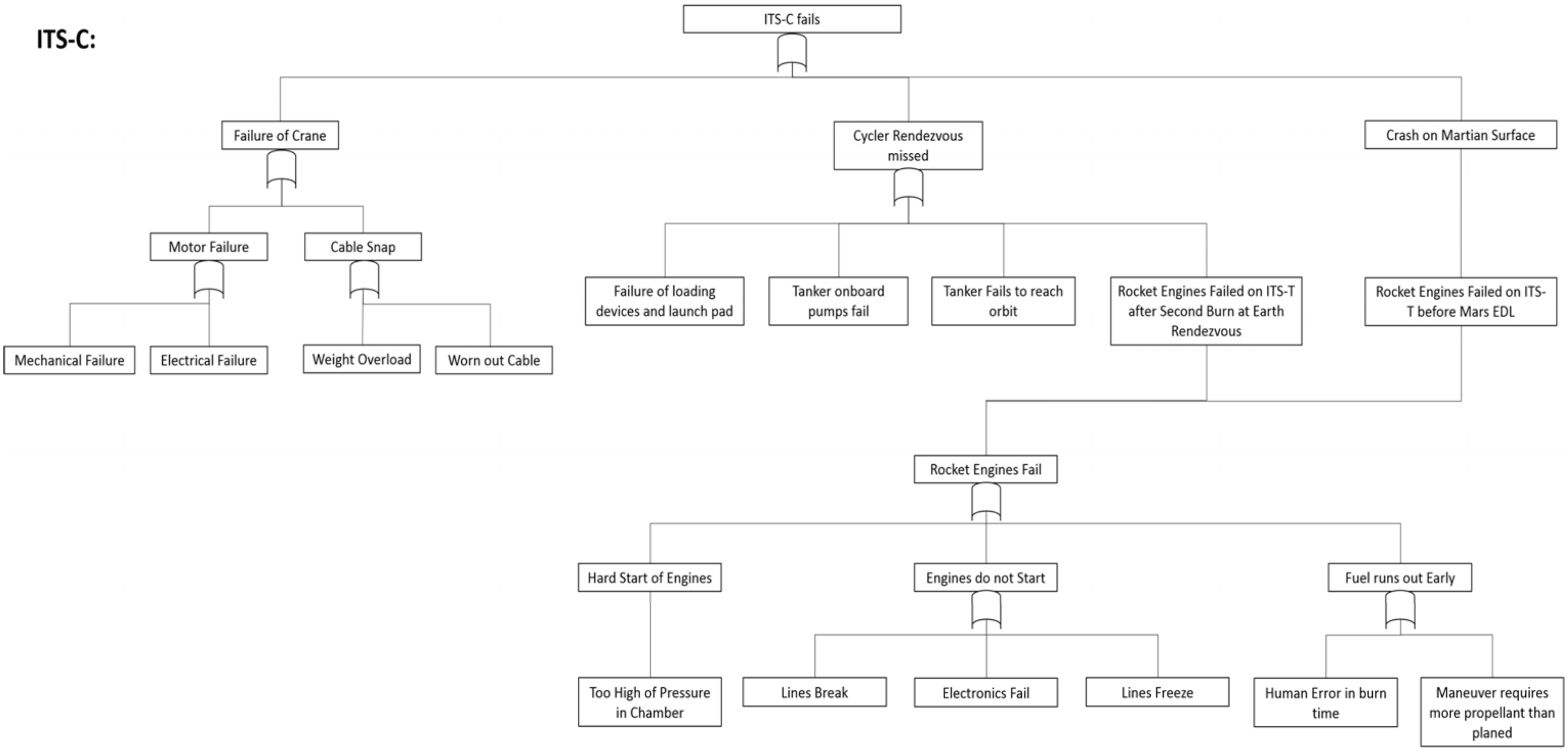

Fig. 5.1.3.1: An initial fault tree for the ITS-C. The ITS-C faces many of the same risks that current ISS resupply mission face. Credit: S. Fulton

5.2 Cycler Vehicle

5.2.1 System Description and Purpose

In an attempt to create the most feasible model, we decide that direct ITS flights transporting our colonists to Mars is not the most efficient method. Rather, we develop a cycler concept that will help to reduce the total cost and launches required over the course of the 100-year mission

5.2.1.1 Purpose and Capabilities

A requirement of our customer is to perform a trade study between Elon Musk's proposed ITS direct model and a cycler. A cycler is a vehicle, normally carrying people that maintains an orbit between two objects over a long period of time. In this case, these two objects are Earth and Mars. The trade study that was performed found that the cycler wins out over the course of the 100-year mission, making for a more feasible model. The purpose of the cycler is to transport a large amount of people to Mars at once using a vehicle with a relatively long lifespan. These factors made a very convincing case for employing a cycler for human transport to and from Mars. Considering existing technologies, concepts, and the maximum population delivered to Mars in one synodic period, we size our cycler to be capable of transporting 325 people at a time. This means that when the maximum number of colonists, 24,700, are on their way to Mars, 76 cyclers will be in transit. The time of flight depends on the orientation of the planets relative to one another and will be discussed in the following section. Table 5.2.1.1 provides an initial breakdown of the components that make up our proposed cycler, named the Bigelow Cycler.

Table 5.2.1.1: Quantity of Modules for ITS

Component	Quantity
BA-330	4
Bigelow XL	4
Central Module	1
Power Module	1
Propulsion Module	1

The components that are responsible for holding passengers during their trip to Mars are the BA-330 modules and Bigelow XL modules. The BA-330 is an inflatable habitat in development by Bigelow that provides 330 m^3 of habitable volume. The Bigelow XL is a scaled-up version of the BA-330 that provides a habitable volume equal to that of the ITS, 1479 m^3. To

see the in-depth logic behind this design, please refer to the trade study in Appendix 5 An in-depth discussion of the system totals of these components can be found in Section 5.2.3. Please see Fig. 5.2.1.1.1 for a visual representation of our cycler.

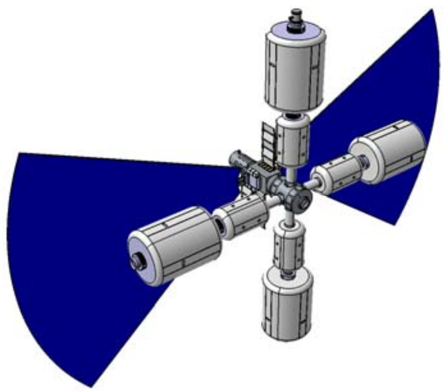

Fig. 5.2.1.1.1 The Bigelow Cycler with all assembled components. Credit: M. Gripe

5.2.1.2 *Cycler Mission Trajectory*

We choose the S1L1 cycler trajectory for this mission. This is a two synodic-period cycler orbit that encounters Earth twice and Mars once every cycle. The order of these encounters is Earth-1, Mars-2, Earth-3, Earth-4, with Earth-4 being the same encounter as Earth-1. The designation S1L1 refers to the nature of the cycler trajectory, with S1 standing for the short period solution over 1 to 2 revolutions around the sun. S1 is first because it refers to the Earth-1, Mars-2, Earth-3 portion of the cycle. L1 stands for the long period solution over one to two revolutions around the sun and refers to the second half of the cycle. For a certain number of revolutions, cycler orbits can have a unique solution, or a short and long period solution, with period referring to the orbital period of the trajectory. So, this cycler is a combination of the short and long period solution for 1 to 2 revolutions [3].

Earth-1 and Earth-4 (note again E-4 is E-1 for the next cycle) are both what we will refer to as an Earth Rendezvous. These are the encounters that will be used to pick up future Martians and take them to their final destination. E-3 is a gravity assist from Earth and will be used only minimally for any mission operations, mostly for cycler maintenance and retirement. Any Mars

encounter is a rendezvous since we will be dropping off colonists every time the cycler passes Mars.

The S1L1 orbit is a not a single orbit, but instead a family of orbits, and so we have chosen two specific S1L1 orbits. These two orbits are staggered by one synodic period so that a cycler group will rendezvous with Earth every synodic period. This allows for the best use of the S1L1 orbit. Critical orbital characteristics for these two trajectories are outlined in Table 5.2.1.2 and Table 5.2.1.3below. Note these tables only refer to Earth and Mars Rendezvous, and ignore any data from the E-3 encounter. The time of flight for Earth rendezvous refers to the time passed since the last Mars rendezvous (or the time passed between M-2 and E-4), and vice-versa for the Mars time of flight.

Table 5.2.1.2: Selected S1L1 Orbital Characteristics for Outbound Trajectory #1

Rendezvous	V_∞ (km/s)	Closest Approach (km)	ToF (days)
Max Value at Earth	7.09	41520	1466
Average Value at Earth	5.38	26104	1393
Min Value at Earth	4.01	2756	1335
Max Value at Mars	7.85	17710	223
Average Value at Mars	5.34	9789	162
Min Value at Mars	2.77	1770	115

Table 5.2.1.3: Selected S1L1 Orbital Characteristics for Outbound Trajectory #2.

Rendezvous	V_∞ (km/s)	Closest Approach (km)	ToF (days)
Max Value at Earth	7.06	41310	1462
Average Value at Earth	5.36	24456	1399
Min Value at Earth	3.98	617	1330
Max Value at Mars	7.87	16700	231
Average Value at Mars	5.59	9057	160
Min Value at Mars	3	1454	111

One of the advantages of the S1L1 orbit is that it does not require significant ΔV maintenance because the E-3 encounter supplies the necessary ΔV to maintain the orbit. We have calculated the deterministic ΔV necessary to maintain the orbit throughout its cycle to be 114m/s over two cycles, as can be seen in Fig. 5.2.1.2.1.

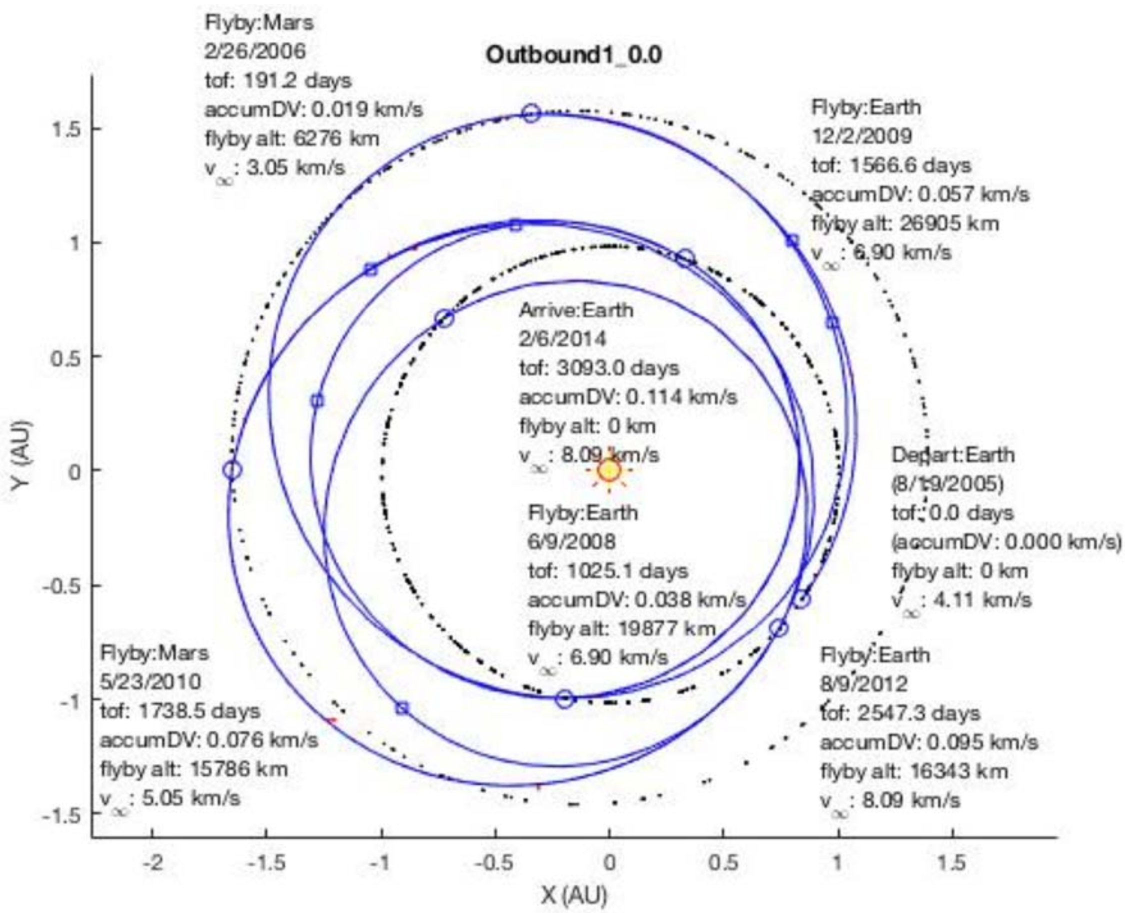

Fig. 5.2.1.2.1: This is a propagation of outbound trajectory #1 over two cycles, or 4 synodic periods, beginning on 8/19/2005, and ending on 2/6/2014. It shows that after two cycles, the accumulated deterministic ΔV required to maintain the orbit is only 114 m/s. Credit: A. Arora

To put our cycler into this S1L1 orbit from LEO, we will use the standard value of 4.208km/s. This is a standard value given for all S1L1 orbits, so this will act as an accurate enough of an estimate for the ΔV required to put each cycler into orbit. We have calculated that the launch window for the cyclers is 60 days about the optimum launch date. Each cycler launches into the cycler orbit from a parking orbit of 300km. An ITS tanker which has been refueled by two other ITS tankers puts each cycler into orbit with a propellant mass of approximately 1000Mg. The

tanker remains docked with the cycler until it reaches the E-3 encounter, at which it deorbits and reenters Earth's atmosphere.

5.2.1.3 *Propulsion Systems*

The cycler design has three propulsion requirements. The first requirement is the propulsion systems and fuel to push the cycler from its Low Earth Orbit into its hyperbolic trajectory. Pushing the cycler into its hyperbolic orbit is a one-time maneuver and will not need to be completed every cycle. The second requirement is the orbit maintenance system that will make trajectory corrections while the cycler is in transit to Mars. This system is expected to be used every single cycle of the cycler. The orbit maintenance system needs to be refueled every time the cycler returns to earth. The third propulsion system aboard the cycler is the spin up system. The cycler needs to be spun at a rate of three revolutions per minute in order to achieve lunar gravity at the outer compartments of the cycler. This system also only requires a one-time burn and will not need to be refilled. There will need to be slight maintenance done to the angular velocity of the cycler throughout its lifetime, but the fuel requirement is small enough that the spin up modules are able to carry a lifetime supply of fuel for spin up maintenance.

The first system to run will be the spin up module. Immediately after construction of the cycler, the propulsion modules located on the top and bottom Bigelow modules. These propulsion modules are made with one S5.79 engine per module. We choose this engine due to its relatively low thrust at 3.09 kN. This allows for a gradual spin up of the cycler that will not place too much stress on the Bigelow habitat modules and the internal structure of the cycler. We decide to spin up the cycler without the ITS on board in order to reduce the moment of inertia and lower the amount of fuel that is required for spin up.

Each propulsion module will hold 5.434 Mg of fuel. The fuel that the S5.79 runs on is unsymmetrical dimethylhydrazine (UDMH) and dinitrogen tetroxide (N_2O_4). The engine runs at an O/F ratio of 1.85. Each module is 6.28 m^3. Based on the flow rate and thrust of the two S5.79 engines, the burn time for the spin up module will be 202.75 seconds.

The next propulsion module that will be fired is the main engines on the ITS tanker variant to propel the cycler into orbit. These engines are fueled by liquid methane and liquid oxygen. There

are 6 raptor engines sized for optimum efficiency in vacuum and 3 thrusters sized for optimum efficiency at SL. These sizing differences allow for optimal performance in all conditions.

The main propulsion module will be fueled with 2880 Mg of fuel at an O/F ratio of 3.8. It will contain the fuel necessary to propel the cycler into its hyperbolic orbit. The tanker will stay with the cycler and return to Earth.

The final propulsion module is the orbital maintenance module. This module is used for station keeping of the cycler throughout its orbit. We choose the S5.79 engine again for this module due to the amount of station keeping we require and its thrust values. It also simplifies the design of the cycler since we use the same engine and fuel types for the spin up module and orbit maintenance module. We only require two of the S5.79 engines for the orbit maintenance module due to the spinning of the cycler. One engine will be aligned perpendicular to the axis of symmetry of the cycler. For attitude corrections, this engine will be fired when it is pointed in the necessary direction. The other S5.79 will be aligned with the axis of symmetry of the cycler, and it is used for forward propulsion of the cycler.

The orbital maintenance module must provide 113 m/s of deltaV each journey of the cycler. Therefore, we refill the module each time the cycler returns to Earth. The module requires 47 Mg per cycler at the same O/F ratio as the spin up module of 1.85. The S5.79 is rated for 70 restarts, so if that number is exceeded, we need to replace that engine. Due to the low mass of the S5.79, any replacements can easily be carried to the cycler on the ITS-T variant and replaced.

Table 5.2.1.4 This table shows the mass and volume components of the S5.79 engines.

Part of S5.79 Engine	Mass (Mg)	Volume (m^3)
S5.79 engine	0.0385	0.2
Spin up UDMH	2.08	2.623
Spin up N_2O_4	3.263	2.266
Orbit maintenance UDMH	11.7	14.754
Orbit maintenance N_2O_4	18.461	12.945

5.2.1.4 *Power Systems*

5.2.1.4.1 Cycler Power System

We employ the NASA Advanced Life Support Sizing Analysis Tool (ALSSAT) to determine the following set of electrical power requirements for the Cycler Vehicle. By using the mission specifications for a 'Mars Transit Vehicle using Advanced Technology' as input for ALSSAT [5], we estimate the total power needs of the cycler vehicle to be approximately 844kW. A per system breakdown of power requirements can be found in the appendix. A 15% safety margin is assumed to yield a total system power requirement of 969.77 kW_e; approximately 2.98 kW_e per passenger.

5.2.1.4.2 Cycler Primary Power Supply System

We choose to deploy a multi-mode solar and nuclear fission power system onboard the Cycler to meet the power requirements outlined in Section **Error! Reference source not found.**. Power Generation is accomplished by 3 SAFE-800 fission reactors [6] and an ATK Megaflex Solar Array [7]. Each of the three SAFE-800 reactors produces 240kWe and the remaining 253.22kWe is produced by the solar array on the ITS-T vehicle. Specifications for these two systems are given in Table 5.2.1.5.

Table 5.2.1.5: The Cycler uses a multimode power system to improve redundancy.

System	Type	Quantity	Power (kWe)	Mass (Mg)	Volume (m^3)
ATK Megaflex (40%)	Solar	3718 m^2	253.22	18.5	37.19
SAFE-800 Reactor & Conversion	Fission	3	720	10.82	36.18

5.2.1.4.3 Power System Architecture and Redundancy

Since the fission reactor is more mass and volume efficient, 3 reactors are installed on each Cycler to supply 74.2% (720 kW_e) of the total power requirement. The vehicle generates the remaining 25.8% (259.77 kW_e) using a set of ATK Mega-Flex panels, which are assumed to be a part of the ITS-T which docks to the Cycler. In this arrangement, we have both applied a 15% safety margin and distributed the power generation almost equally across 4 sources. Using 4 sources increases reliability to the point where if any one of them failed (either a single reactor or the solar array), the vehicle would still retain 86.2% of the total required power generation. In other words, the Cycler can complete its mission even if one of the reactors has to be taken offline.

Fig. 5.2.1.4.3.1 and Fig. 5.2.1.4.4 show the arrangement of all three reactors, and the required Brayton conversion engines packed into a single shielded module. This Cycle EPS housing contains all necessary electronics and cooling apparatuses. An aluminum housing with a thickness ranging from 0.1m to 0.3m provides sufficient shielding to ensure a protection factor of 40. This estimate comes from an International Associate of Energy Economics report on the use of aluminum in gamma ray shielding. Three coolant loop radiators are mounted on the exterior of the power module to provide 1680 kWt of heat expulsion. Finally we provide sufficient power storage to replace losses associated with up to 12 hours of reactor downtime. Power Storage is accomplished by including 10 batteries with 288 kWh each.

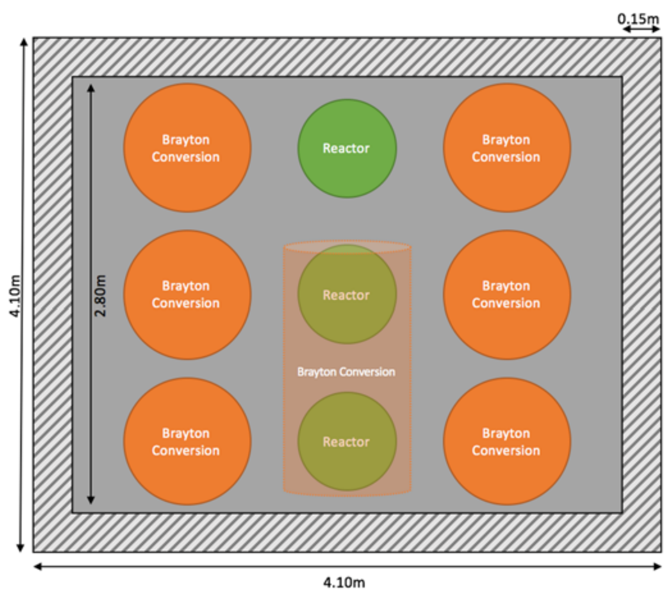

Fig 5.2.1.4.1. The Cycler Power system packs three SAFE-800 fission reactors and seven Brayton conversion engines into a single shielded module. Axial View. (Credit: B. Merrel)

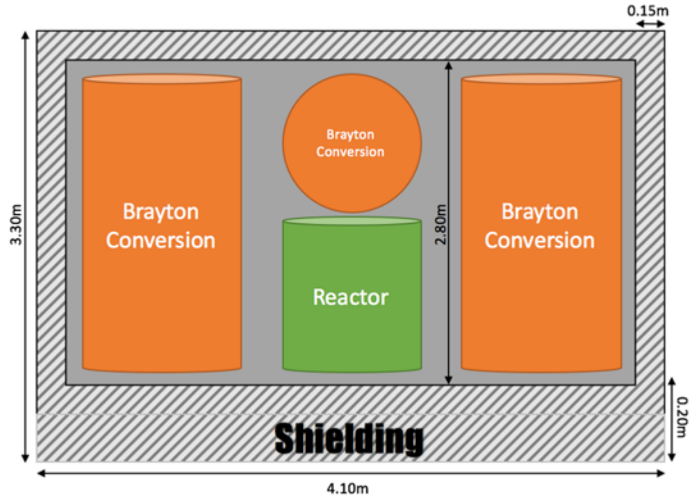

Fig. 5.2.1.4.2 The Cycler Power Shields all external systems and passengers from harmful radiation using 0.15 to 0.20m of aluminum shielding. (Credit: B. Merrel)

5.2.1.4.4 Cycler MPV Summary

Table 5.2.1.6: Cycler Power system mass and volume values.

System	Mass [Mg]	Volume [m^3]
TOTAL	**82.24**	**73.50**
Reactors & Power Conversion	18.50	36.18
Thermal Regulation	0.71	13.20
Batteries	20.45	9.08
Shielding	42.58	15.04

5.2.2 Deployment and use of system

In order to construct the Bigelow Cycler, a significant number of components need to be transferred from Earth to LEO. Using the ITS-C2, this would require 4 launches minimum just to get all the needed components for construction into LEO. To avoid the tracking of multiple cycler

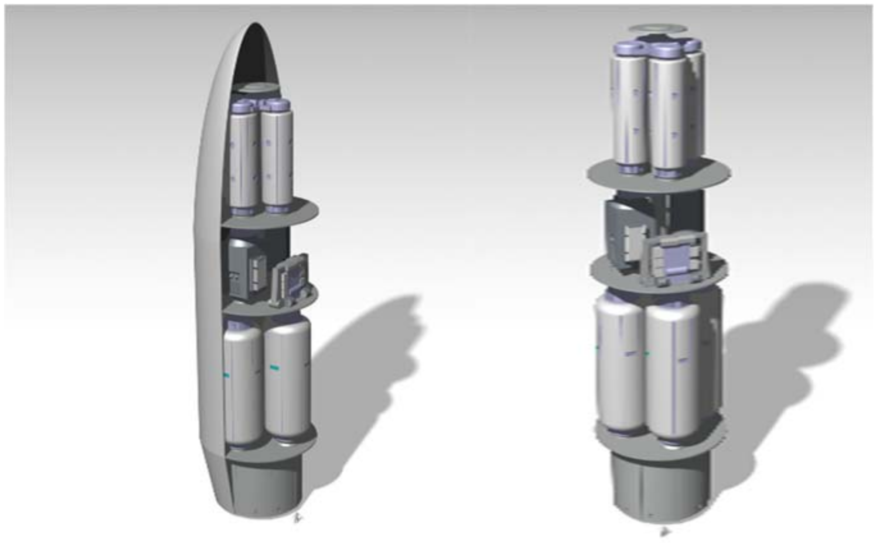

Fig. 5.2.1.4.1: A sectioned and side-on view of the Bigelow Cycler Component Stack in the Payload Fairing. (Credit: M. Gripe)

elements with individual cycler component launches, we develop a single payload fairing structure that is launched aboard the first stage booster of the ITS and capable of carrying all of the Bigelow Cycler's components. Please see Fig. 5.2.1.4.1 for a sectioned view and side-on view of the Bigelow Cycler Component Stack in the payload fairing.

The payload fairing itself is approximately 1.33 times the size of the ITS. However, the first stage is able to launch our payload fairing to Low Earth Orbit (LEO) because it weighs less than the ITS since it does not have any propellant mass. Once the payload fairing reaches LEO, it detaches from the booster, separates, and releases the Bigelow Cycler Component Stack seen above. The first stage booster returns to Earth shortly after launch, where it is loaded with an ITS-A, the construction variant of the ITS. Once the ITS-A is launched and separates from the first stage booster, it performs a rendezvous with the Bigelow Cycler Component Stack that is orbiting in LEO. The construction process is initiated when the ITS-A docks with the central docking node in the base of the stack and retrieves it. This allows the ITS-A to serve as a relatively stable

construction platform throughout the remainder of the construction. Please see Fig. 5.2.1.4.2 for a visual representation of the extraction of the central node from the stack.

Once the ITS-A has secured a connection with the central node, the crewed Orbital Construction Pod (OCP) and Remote Manipulator System (RMS) deploy from the ITS-A payload bay to assist with construction.

Fig. 5.2.1.4.2: The extraction of the central node from the stack. Credit: (M. Gripe and K. Jantze)

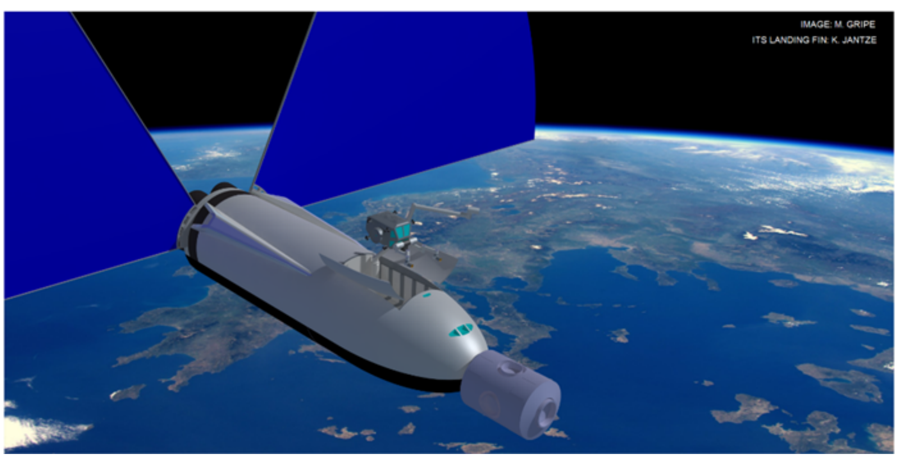

Fig. 5.2.1.4.3: The OCP and RMS deploy from the payload bay of the ITS-A.
(Credit: M. Gripe and K. Jantze)

Once operational, the RMS, controlled from the flight deck of the ITS-A, grapples the Bigelow Cycler Component Stack while the OCP retrieves individual components and docks them together.

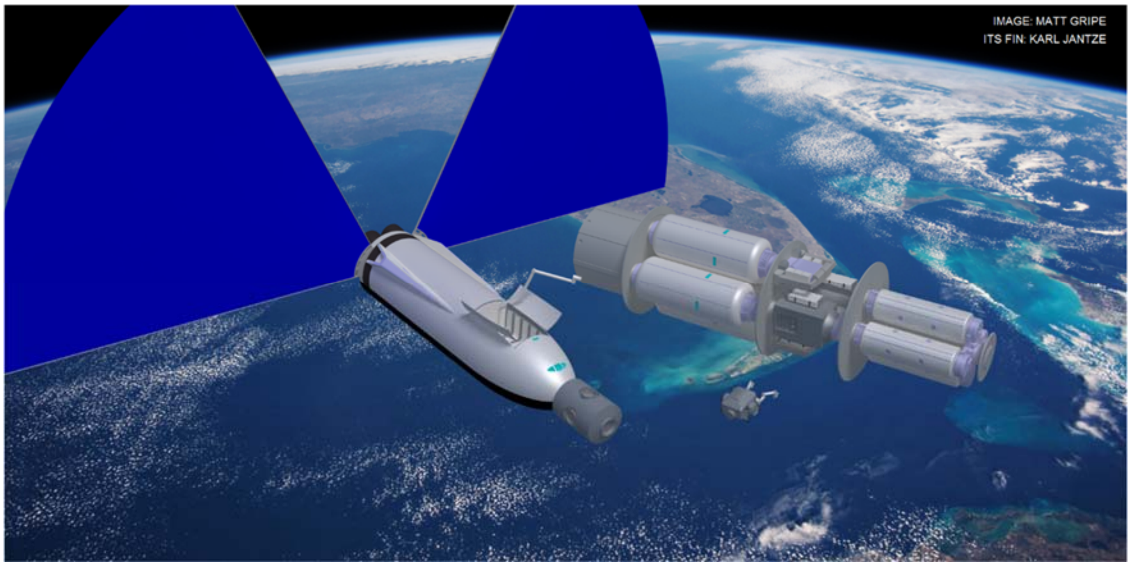

Fig. 5.2.1.4.4: The RMS maintains a hold on the component stack while the OCP retrieves components and assembles them. Credit: M. Gripe and K. Jantze

The OCP first attaches the power module to the central module, followed by the propulsion module. Next, the B330s are attached beginning with the upper B330 in a clockwise manner. The same order is repeated for the Bigelow XLs. Upon completion of cycler construction, the expandable Bigelow modules begin to inflate. We expect this process to take approximately 4 weeks. This inflation time is estimated by scaling the time it took Bigelow's Expandable Activity Module to inflate and accounting for improved methods [2]. When every expandable module is inflated, the ITS tanker variant provides the fuel needed to get the cycler into the S1L1 trajectory. Two tankers are required to refuel the third tanker prior to final orbital insertion. Spin up of the cycler to create artificial gravity occurs before the ITS docks and establishes the cycler orbit in an effort to reduce mass when the DeltaV burn occurs.

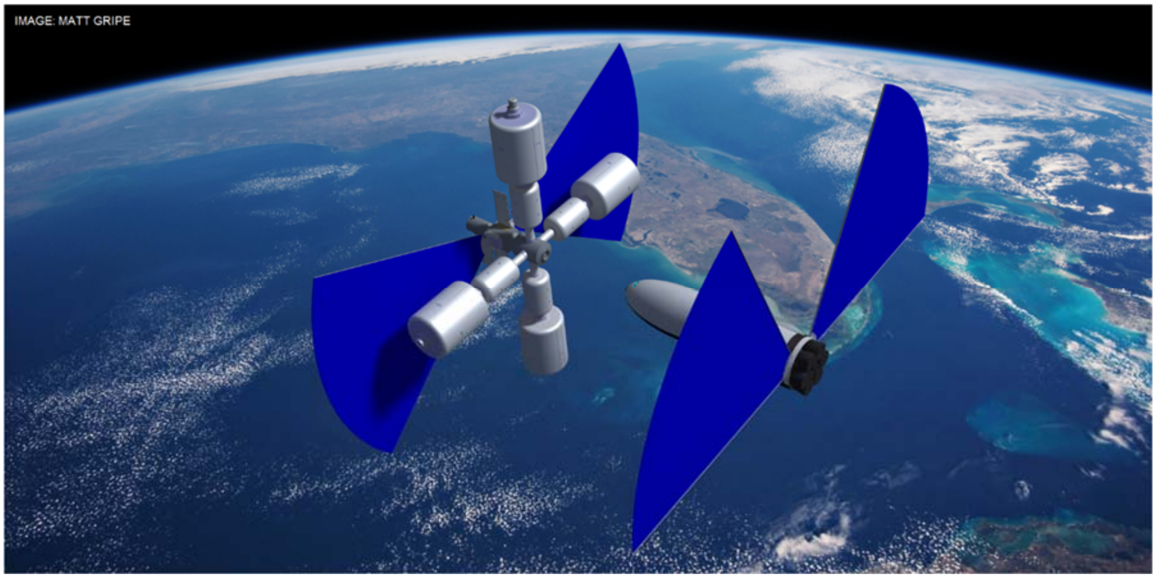

Fig. 5.2.1.4.6: The ITS Tanker prepares to dock with the Bigelow Cycler prior to orbital insertion. (Credit: M.Gripe and K. Jantze)

Once the cycler reaches its correct orbit, it is ready to be transport humans to Mars. During the launch window, an ITS-T launches into a circular orbit of a predetermined altitude depending upon the mission requirements. The ITS-T will be refueled using the ITS tanker anywhere from 3 to 5 times depending on the trip to Mars.

Fig. 5.2.1.4.5: The ITS tanker refuels the ITS-T prior to departure for Mars. (Credit: M. Gripe and K. Jantze)

Once the refueling is complete, the ITS-T executes a propulsive maneuver and is sent out of its parking orbit and onto a predetermined hyperbolic escape trajectory that intersects with the cycler orbit.

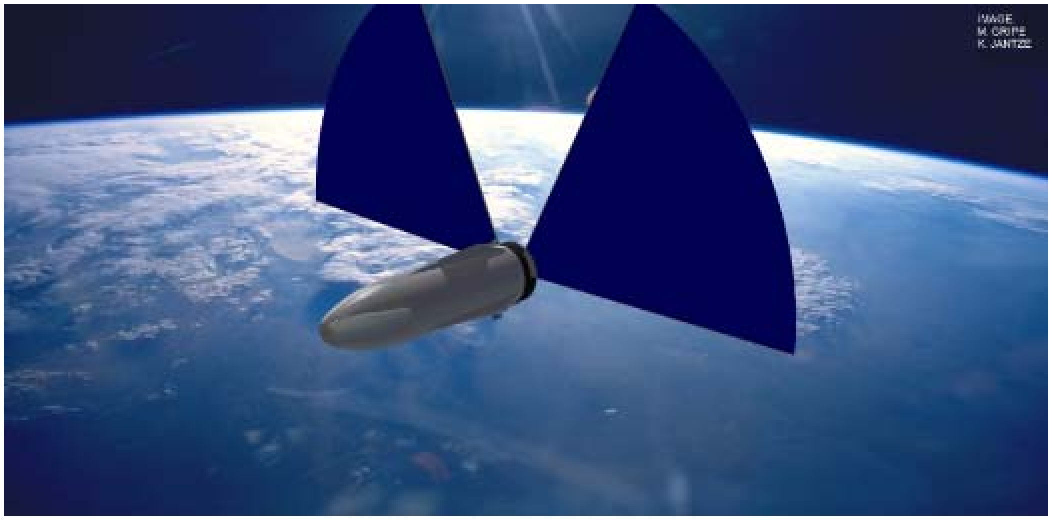

Fig. 5.2.1.4.7: The ITS-T departs Earth and begins to make its way towards the cycler. (Credit: M.Gripe and K. Jantze)

Once on the cycler intercept trajectory, the ITS-T rendezvous with the cycler after an amount of time dependent on the launch. The ITS-T approaches the cycler docking port and executes a small burn to initiate a spin that matches the rate of rotation of the cycler vehicle, which is approximately 3 rotations per minute. Once the docking completes and the vehicles are

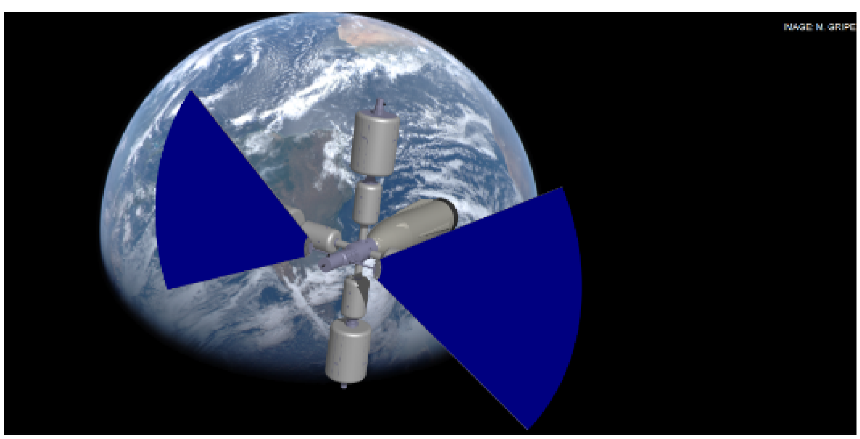

Fig. 5.2.1.4.8: The ITS-T docks with the cycler and begins the trip towards Mars.

(Credit: M. Gripe and K.Jantze)

stabilized, the 325 passengers aboard the ITS-T can get out of their seats and enter the habitable volume of the cycler vehicle to prepare for their journey to Mars.

Once the cycler enters the Martian vicinity, the passengers re-board the ITS-T and it detaches from the cycler. The ITS-T adjusts its course for Mars and the cycler continues its heliocentric trajectory.

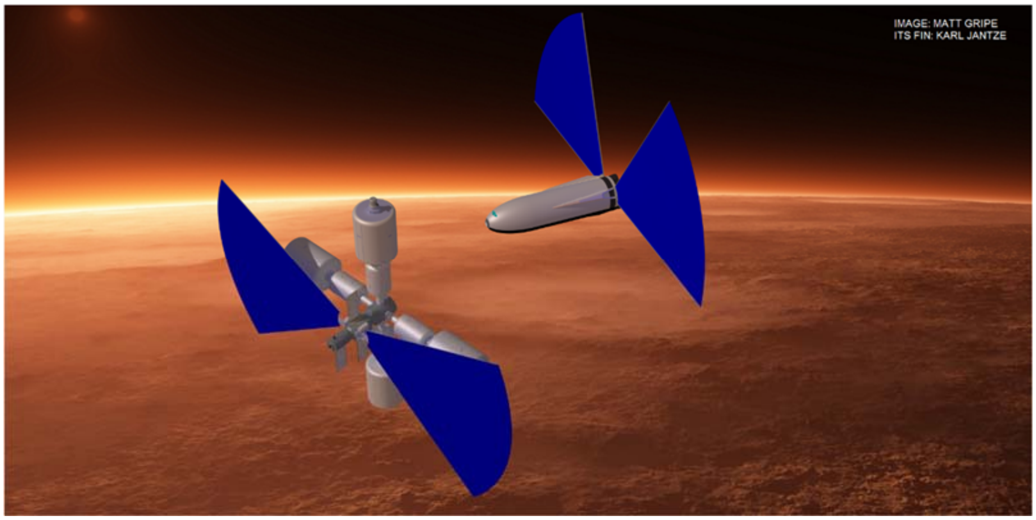

Fig. 5.2.1.4.9: The ITS-T detaches from the cycler and begins the descent to Mars. (Credit: M. Gripe and K. Jantze)

The ITS-T then lands on Mars near the Martian colony and the Bigelow Cycler begins the long trip back to the intersection with Earth's orbit.

5.2.3 System totals

The Avalon Cycler is a complex and integral part of this feasibility study. It is larger and more massive than anything currently deployed to outer space. It is also one of the single craft in the entire project. The Avalon Cycler is made up of several modules, including larger variants of the Bigelow B330's. In the table below you can see a mass, power, and volume (MPV) breakdown of the cycler. The largest modules are the expanded Bieglow XL's while the most massive individual module is the power system.

Table 5.2.3.1: MPV breakdown of an Avalon Cycler

System	Cycler		
	Mass (Mg)	**Volume (m^3)**	**Power (kW)**
Total Power Module	**93.05**	**86.45**	**1243.22**
ATF Megaflex Solar Array	18.5	37.19	523.22
SAFE-800 Reactors and Converters and Structure	53.4	36.18	720
Radiators	0.71	4	-
Batteries	20.44	9.08	-
Total Propulsion Module	**72.343**	**79.14**	**-**
Structure	20	79.14	-
Spin Up Modules	5.34	6.28	-
Maintenance Module	47	65.55	-
Total Central Module	**44.31**	**216**	**846.28**
ECLSS	14	177	846.28
Human Day Water Needs	10.31	10.31	-
Structure	20	216	-
Total Habitual Structures	**297**	**7236**	**-**
Bigelow B330 Module	20	330	-
Bigelow XL	54.25	1479	-
Total for Cycler	**506.70**	**7538.45**	**396.94**
Total with ITS-T	**954.72**	**12206.95**	**396.94**

5.2.4 Cost of System

Although we are using the SpaceX's cost model for the all the ITS variants, it is necessary for us to analyze the cost of the new Avalon Cycler. In the table below we can see that there are two costs that need to be accounted for. There is the initial cost, and then there is the maintenance cost. The most dominate cost is clearly initial construction and assembly costs. However, the cyclers will complete 10 cycles in a standard lifetime of 40 years, adding an additional $6 billion. Eventually, with mass production the cost per cycler may decline, but that was not examined in the feasibility study.

Table 5.2.4.1: Initial Cost breakdown of the Avalon Cycler.

System	Cost (initial)	Cost (per cycle)
Power Module	$ 4,054,000.00	$ 610,500.00
Safe-800 Systems	$ 4,054,000.00	
Fission Power Refueling		$ 322,500.00
Battery System		$ 288,000.00
ECLSS	$ 9,934,166,666.67	$ -
Structures	$ 2,240,000,000.00	$ -
Payload Fairing	$ 266,000,000.00	
BA-330	$ 125,000,000.00	
Bigelow-XL	$ 368,500,000.00	
Central Module	$ 448,340,000.00	
Propulsion Module	$ 3,298,892.73	$ 8,583,259.87
Unsymmetrical Dimethylhydrazine for spin up	$ 40,077.20	
Dinitrogen Tetroxide for spin up	$ 84,015.53	
Unsymmetrical Dimethylhydrazine for orbit maintenance		$ 2,772,052.85
Dinitrogen Tetroxide for orbit maintenance		$ 5,811,207.02
Methane for Tanker push to orbit	$ 364,800.00	
LOX for Tanker push to orbit	$ 810,000.00	
4 S5.79 rocket engines	$ 2,000,000.00	
Assembly of Cycler	$ 362,628,000.00	$ -
Cost of second stage	$ 361,453,200.00	
Fuel to push into orbit	$ 1,174,800.00	
Totals	$ 12,544,147,559.40	$ 9,193,759.87
	$ 18,954,127,737.15	Per Cycler

5.2.5 *Risk Analysis and Fault Tree*

Early examination of the risks for the Avalon Cycler reveal that it faces similar challenges at those currently faced by the ISS. The most important system that could fail is still the environmental control and life support systems (ECLSS). This system will be larger than any other space ECLSS system built, and as such will be both more prone to failure and need to be more robust. A recommend mitigation strategy for the ECLSS system is carrying extra parts to on the cycler so that it can be repaired by its inhabitants in the event of an emergency.

Cycler:

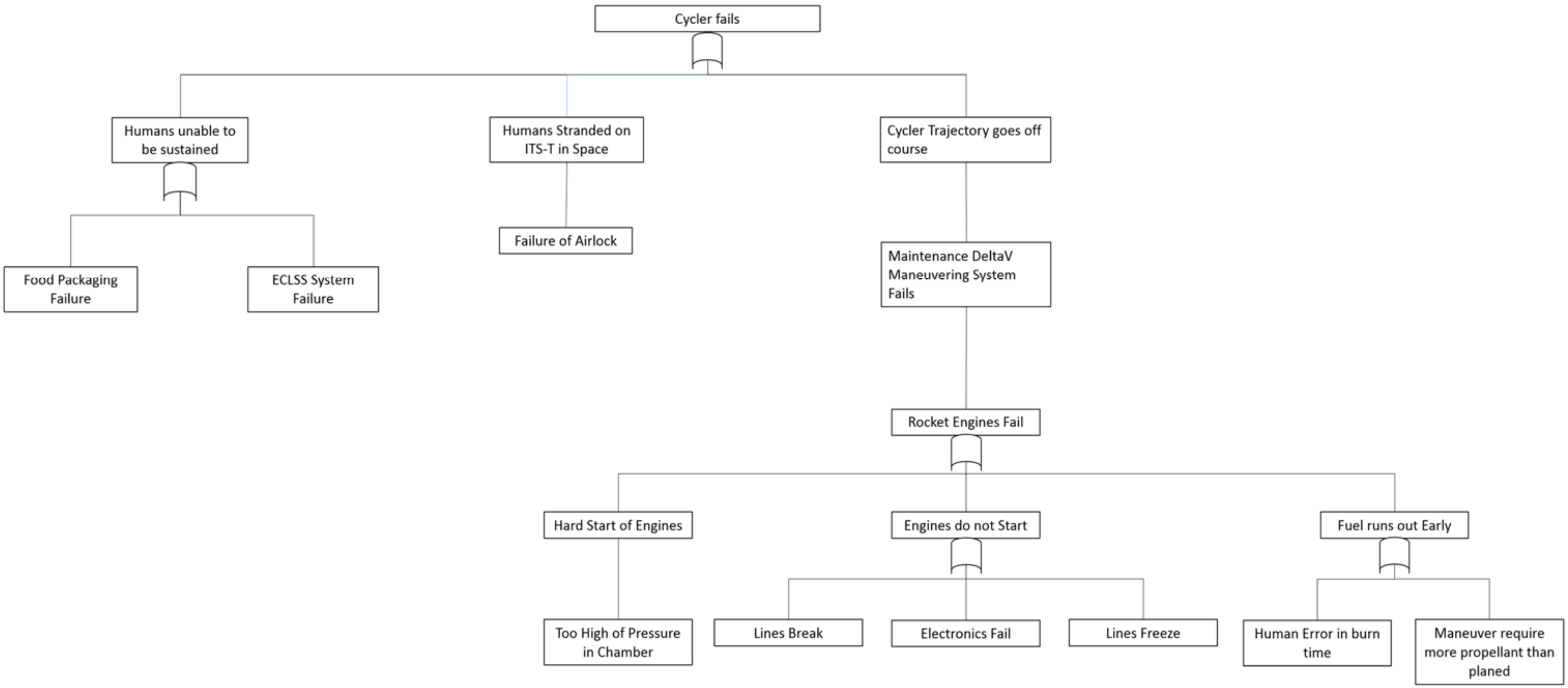

Fig. 5.2.1.4.1: An initial fault tree for the Avalon Cycler. The Avalon will face similar risks to the ISS, however, its systems will be much larger and robust to survive the journey to Mars.

5.3 ITS Taxi Vehicle

5.3.1 System Description and Purpose

5.3.1.1 *Purpose and Capabilities*

The ITS-Taxi (ITS-T) is a unique and special spacecraft that was developed for this mission. It moves the masses of people from Earth to the Avalon Cycler, and then from the Cycler to the Martian Colony. After a duration being refueled by The Hive, the ITS-T will depart Mars and return to Earth to carry its next load of passengers to the final frontier. The ITS-T carries close to 325 people and the food, water, and oxygen necessary to sustain them, at any stage in the mission. It is able to achieve this by departing from conventional human spacecraft and more closely approximating a commercial aircraft that we would think of today. The ITS-T features closely packed passenger seats, and a moderate cargo bay for holding the necessary resources for sustain the crew on their entire voyage.

5.3.1.2 *ITS-T Trajectory Overview*

The ITS-Taxi (ITS-T) is designed to carry a large number of passengers, in a small volume to the longer term living areas on the cycler. Because of this the ITS-T trajectory is designed to be as short and efficient as possible. That being said, this trajectory still requires multiple steps, and requires the assistance of multiple other vehicles.

First the ITS-T will launch into a 300 km parking orbit. A reusable rocket booster will assist in the initial launch of the ITS-T. The rocket booster will account for a significant portion of the required thrust to inject the ITS-T into orbit before dethatching, and returning to Earth where it can be refueled and used again. The additional thrust required to get into the parking orbit is provided by the fully fueled ITS-T. At the same time that the ITS-T is launched, tanker vehicles, specifically designed to transport propellant to the orbiting ITS, are launched using the rocket boosters. The tanker vehicles can hold a maximum of 380 Mg of propellant, so if the ITS-T is to be fully re-fueled, 5 tanker vehicles must launch to complete the refueling mission. The tanker vehicle also must provide additional thrust in order to inject into the parking orbit, where it meets the ITS-T. These launches are staggered such that the tankers are able to approach the ITS and begin refueling as soon as it has checked out and all systems are ready to begin the refueling procedure. This is important, as the refueling process should be completed as quickly as possible. When the tanker vehicles have finished, and delivered all of the propellant they have, they will

begin re-entry and land safely at the pad that they launched from. All of the tanker vehicles are reusable for future launches.

Once refueled, the ITS-Taxi (ITS-T) departs from the 300 km parking orbit to rendezvous with the cycler, along a predefined Lambert Arc. We optimize this trajectory to minimize the Delta V and propellant requirement. However, given that the passengers are packed into and confined within the cramped environment of the ITS-T, a limit is placed on the time of flight (TOF) to rendezvous. The TOF ranges from one to two days, depending on the synodic period of departure. We allot 50 m/s of Delta V for trajectory correction maneuvers. Two burns are performed for the rendezvous maneuver. The first burn places the taxi vehicle on an outbound transfer arc towards the rendezvous location. Once the ITS-T encounters the cycler, the second burn inserts the ITS-T onto the cycler trajectory to facilitate the rendezvous.

After mating with the Cycler, the Taxi-Cycler system transits for 100-200 days, until it reaches Mars. At this point, the ITS-T then separates from the Cycler and heads to the surface. Again, the point of separation and the trajectory to the surface is optimized to reduce the Delta V requirement. The time of flight varies from 6-12 hours, depending on the synodic period. Only a single burn is required for the maneuver, which places the ITS-T on a direct trajectory into the atmosphere. We place a constraint on the entry velocity; to protect the vehicle and allow the vehicle to slow down, we set this value to 8.5 km/s. It is assumed that the retropropulsion system functions properly and that EDL analysis has been completed. Based on Spacex's ITS presentation, approximately 0.96 km/s of Delta V is reserved for EDL.

5.3.1.3 *ITS-T Rendezvous Abort System*

To mitigate the risk of loss of crew and cargo in the event of some sort of systems failure during the cycler rendezvous event, some basic contingency schemes have been devised to ensure rendezvous or Earth return. The first and most simple contingency is to allot additional propellant mass to trajectory correction maneuvers (TCM's) along the hyperbolic cycler intercept trajectory. This requires that we know the location of both the ITS-T and the cycler throughout the approach and can course correct using low-thrust maneuvers. This has been implemented in many missions up until this point and is a safe and viable option.

The worse of the two options is to have to return the ITS-T to Earth in the event of some large systems failure that would make cycler rendezvous impossible. This will mean an overall failure for the mission, but will guard against the loss of crew and cargo. One option, called the "full reverse option", is to completely pull the cycler back using a large maneuver near the cycler rendezvous point. This is impractical in all cases that it is not impossible. When the ITS-T is as far out as the cycler rendezvous point, it is impossible to deliver a large enough propulsive maneuver to return the vehicle to an Earth orbit with the remaining propellant on board. If the abort protocol is initiated earlier, it is still not possible for the vast majority of intercept courses. This would only leave highly inefficient trajectories that would allow for some expensive safety maneuver but would increase the cost of rendezvous, and ultimately make some rendezvous impossible, which is not an option. A better option to mitigate this risk is to break up the initial propulsive maneuver for rendezvous into two separate burns conducted close together in time. This would allow for the first burn to bring the ITS-T into an elliptical orbit for a few seconds using the first burn and then delivering a second so that it is on its hyperbolic intercept trajectory. This redundancy will make it so that we do not place all of our propellant allocated to rendezvous in one burn that could ultimately have large errors.

5.3.2 System totals

The ITS-T is a unique craft for human spaceflight. As you can see in the MPV breakdown in the table below, the ITS-T carries systems similar to ISS, like ECLSS, but they are far more massive. In comparison, the ITS-T is fairly small compared to the Avalon Cycler, but still sizable in comparison. A distinction between the ITS-T and the Cycler is the fact that the ITS-T most carry all the food, water, and oxygen necessary to sustain the crew for the entire voyage. That alone makes up over 55 % of the ITS-T dry mass.

Table 5.3.2.1: The MPV breakdown of the ITS-T.

ITS-T System	Mass (Mg)	Volume (m^3)	Power (kW)
Totals for Cargo	298.02	1275.58	219.94
Human Needs	243.22	524.03	-
Food	123.34	334.59	-
Drinking Water	6.04	6.04	-
Utility Water	102.20	102.20	-
Oxygen	10.51	40.79	-
Clothing and Hygiene	1.13	40.41	-
Passengers	30.88	422.50	-
ECLSS	10.00	149.00	211.41
Facilities	13.92	180.05	8.54
Medical	1.00	28.25	-
Command	1.00	137.00	-
Airlocks and Cranes	11.92	14.80	8.54
Totals for Structure	**150**	**3392.92**	**253.22**
Frame, Infrastructure, Tanks, and Solar Arrays	150	3392.92	253.22
Totals for ITS-T	**448.02**	**4668.50**	**33.28**

5.3.3 Risk Analysis and Fault Tree

The ITS-T also shares very similar risks to the Avalon Cycler. However, the ITS-T most also land on the surface, which produces its own unique challenges. One big risk will be the loss of the airlock or airlock crane while the ITS-T is on the surface. In such an event, the crew on board the ITS-T would be stranded aboard their ITS-T until repair crews could be sent to fix the craft. One way that we can mitigate this is by adding a second smaller airlock, with access to a ladder so that the crew can climb down the ITS-T if necessary.

ITS-T:

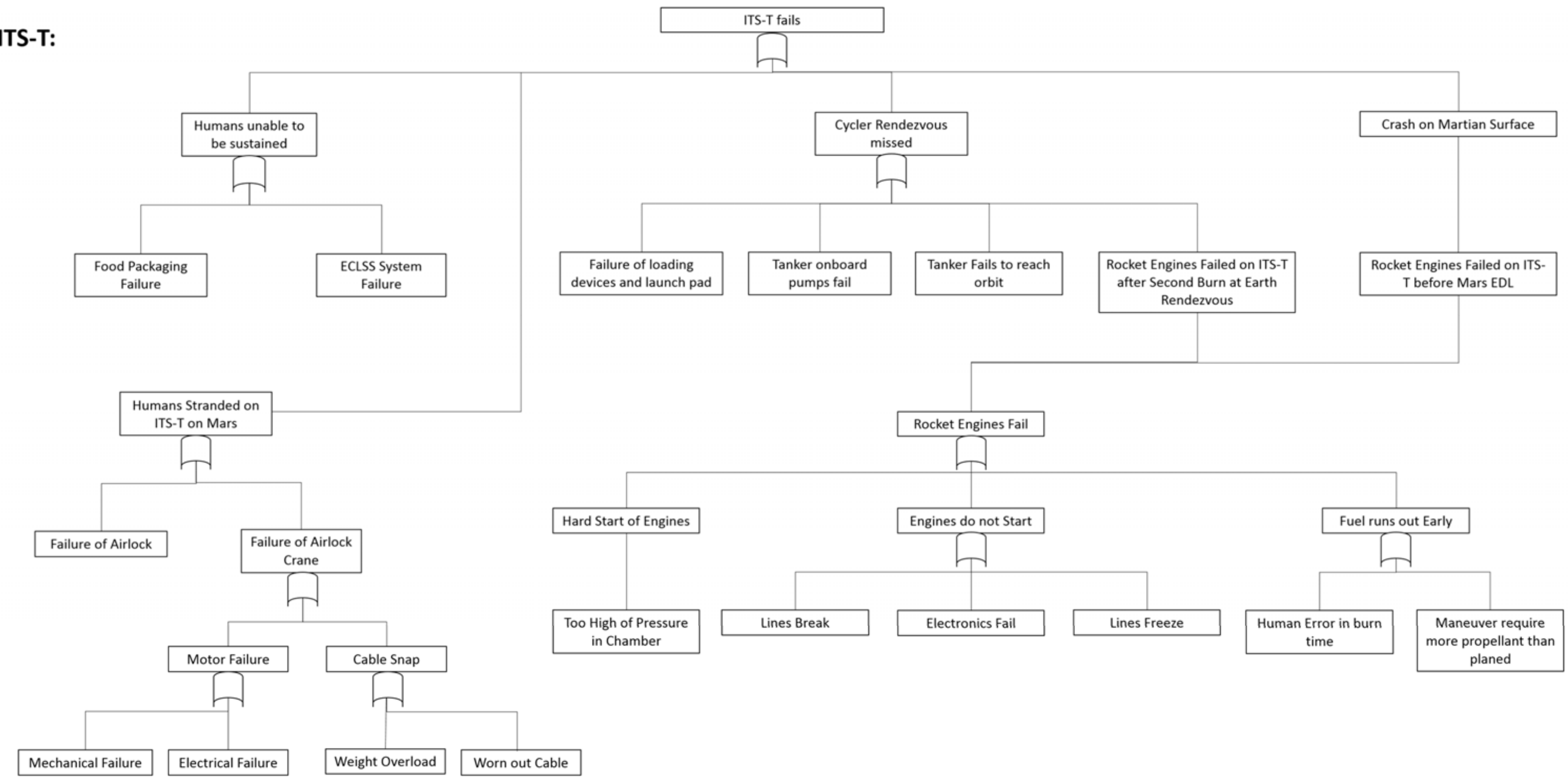

Fig. 5.3.1.3.1: An initial fault tree for the ITS-T. The ITS-T will have higher risks because of its repeated landings and launches.

5.4 ITS Direct Vehicle

5.4.1 Purpose and Variants

The ITS Direct (ITS-D) is a vehicle that is very similar to that referred to in Elon Musk's. These vehicles travel on the same trajectory that the ITS-C's use, but carry people instead. The amount of people is based on the weather or not the variant carries cargo in addition to its crew. The ITS-D1 has a crew capacity of 32 people and also carries roughly 252 Mg of cargo in its hold. The ITS-D2 is a similar model except the areas that would normally carry cargo are converted to hold additional passengers. The table below summarizes the capacities of the ITS variants.

Table 5.4.1.1: A breakdown of the capacities of the ITS-D variants.

Variant	Capacity		
	Mass (Mg)	Volume (m^3)	Passengers
ITS-D1	252	562	32
ITS-D2	-	-	57

Like the ITS-T these vehicles also carry all the food, water and oxygen need to survive the journey to Mars. The ITS-D variants have such a limited capacity of passengers because the crew onboard have to live in the same space for the entire mission duration. Each person will require living quarters, bathrooms, eating areas, and other assorted facilities in order to survive, both physically and mentally. This is the same volume that is provided in the Avalon Cycler.

5.4.2 System Totals

The ITS-D's use very similar layouts for achieving human delivery to Mars. As a result the mass, power, and volume (MPV) breakdowns are comparable. The main difference is the cargo bay featured in the ITS-D, which carries an impressive 252 Mg. You can also see that the amount of space required for the passengers is far larger than that in the ITS-T breakdown.

Table 5.4.2.1: A MPV Breakdown of the ITS-D1.

ITS-D1 System	Mass (Mg)	Volume (m^3)	Power (kW)
Totals for Cargo	296.57	1480.81	24.19
Human Needs	25.60	75.76	-
Food	12.14	32.94	-
Drinking Water	0.65	0.65	-
Utility Water	11.02	11.02	-
Oxygen	1.03	4.02	-
Clothing and Hygiene	0.76	27.13	-
Passengers	3.04	640.00	-
ECLSS	2.00	23.00	15.66
Facilities	13.92	180.05	8.535
Medical	1.00	28.25	-
Command	1.00	137.00	-
Airlocks and Cranes	11.92	14.80	8.535
Capacity of Cargo Bay	252.00	562.00	-
Totals for Structure	**150**	**3392.92**	**253.22**
Frame, Infrastructure, Tanks, and Solar Arrays	150	3392.92	253.22
Totals for ITS-D1	**446.57**	**4873.73**	**229.03**

Table 5.4.2.2: A MPV Breakdown of the ITS-D2.

System	ITS-D2 Mass (Mg)	Volume (m^3)	Power (kW)
Totals for Cargo	66.95	1486.01	24.19
Human Needs	45.61	134.96	-
Food	21.63	58.68	-
Drinking Water	1.16	1.16	-
Utility Water	19.63	19.63	-
Oxygen	1.84	7.16	-
Clothing and Hygiene	1.35	48.32	-
Passengers	5.42	1140.00	-
ECLSS	2.00	31.00	15.66
Facilities	13.92	180.05	8.535
Medical	1.00	28.25	-
Command	1.00	137.00	-
Airlocks and Cranes	11.92	14.80	8.535
Totals for Structure	**150**	**3392.92**	**253.22**
Frame, Infrastructure, Tanks, and Solar Arrays	150	3392.92	253.22
Totals for ITS-D2	**216.95**	**4878.93**	**229.03**

5.5 *Loading and Unloading the Spacecraft*

Once the ITS-T and ITS-C variants land on the surface of Mars, the colonists and cargo will need to be unloaded. To solve this problem, we add a crane to the ITS that is able to service both colonists and cargo. The crane deploys on the outside of the ITS on the side with each set of bay doors. The crane has attachments for unloading both colonists and cargo from the ITS. The crane operates on a power usage of 8.54 kW. The power for the crane is supplied directly from the electricity storage on board the ITS.

Table 5.4.2.1: This table shows the MPV for the crane and airlock system

Module	Mass	Power	Volume
Crane and Airlock	11.92 Mg	8.54 kW	14.8 m^3

We choose colonists to be unloaded first from the ITS before cargo. Colonists being unloaded first will allow them to assist transporting the cargo from the ITS to the colony once it is unloaded and mitigate risk. If there is a system failure of the unloading system during unloading of cargo, the colonists are already safely on the Martian surface. To unload the colonists, an airlock is attached to the crane. The airlock has a volume of 12.4 m^3. This volume allows for ten colonists to be lowered to the surface at a time.

Once the colonists reach the Martian surface, the airlock connects to a transportation vehicle that will take the colonists to their final colony destination. We choose to transport the colonists in this manner due to the colonists never having to wear EVA suits during the transportation process from the ITS to the colony. This reduces the number of EVA suits that are required for the colony.

After all of the colonists have been unloaded from the ITS, the airlock will be pulled inside of the ITS and the crane will lower to the cargo bay doors in order to begin unloading cargo. Inside the cargo bay of the ITS we need to have a method of moving the crates of cargo onto the crane. We choose to have an internal rotating hydraulic system that is capable of grabbing each crate of cargo and relocating it onto the crane. Once the crates are loaded onto the crane they will be lowered onto a different type of rover than the colonist transporter and will be carried to the colony.

5.6 Spacecraft Retirement and Disposal

5.6.1 ITS Variants

In order to get the most amount of reusability of our ITS variants, it was decided that every ITS variant that has the capability to got to Mars will retire on Mars. The ITS vehicle can then be striped of any remaining parts. Virtually every part of the ITS can be used by the Martians living in The Hive. Even the engines can be melted down with the on planet ISRU and reused to make structures or replacement parts for rovers. In some cases this may require that an ITS retire a little earlier than expected. This is currently not accounted for and further cost and risk analysis will have to be performed to determine the marginal benefits of Martian retirement.

Another option is returning the ITS vehicles to SpaceX so that they can be refurbished and retrofitted. This would require that ITS vehicles be return to Earth instead, and my help drive down both the production rate of ITS need in later cycle and the cost of each craft.

5.6.2 The Cycler

The retirement and disposal of spacecraft the size of a Cycler as presented in this report is a task space missions have yet had to grapple with. To safely retire a vehicle weighing over 300 tonnes, deorbit into the Martian or Earth's atmosphere is not an option. Leaving the vehicles in the orbit of either planet is not an option either, as this would lead to significant orbit cluttering. Therefore, any cyclers that must be retired are accelerated so that their orbits remain beyond Mars' orbit.

Due to the time constraints on getting one million people to Mars, we must ensure that the moment a cycler is no longer suitable for human space travel, that it is removed from its orbital position so that a new cycler can take its place. So we send ITS tanker at the end of its usable life on a direct flight to Mars ahead of the cycler, which is on its last usable run to Mars. The ITS tanker is then filled up with enough propellant to rendezvous with the cycler, which will vary depending on where in the launch window and on what cycle number the cycler that is being retired is on. Then the ITS tanker docks with the Cycler, and prepares for a final burn. At the orbit's aphelion, which is beyond Mars' orbital radius, the tanker spends the rest of its fuel creating a stable orbit beyond Mars. This orbit should be large enough that there is little to no risk of the retired and nonretired cyclers colliding at this shared aphelion. This maneuver also prevents the

cycler from making any future Earth encounters or unpredictably interacting with the asteroid belt or other inner solar system planets. It also allows for the total recovery of the cycler infrastructure at a later date, whatever the reason for doing so may be. The ITS tanker remains with the cycler, but since it was no longer able to fly new missions anyways, the loss is negligible.

To maximize recycling of Cycler hardware and safety of Cycler retirement, crew on the Cycler's last Mars departure ware trained to prepare the Cycler for retirement. This will include stripping the Cycler of any reusable hardware that would not cripple the Cycler while it is still carrying passengers. This crew's most critical job will be to ensure the reactor is nonfunctional once everyone is off board the Cycler and ready to rendezvous with Mars on ITS-T. This ensures that, if there are any issues with Cycler retirement, the failure will not end in a nuclear explosion.

5.7 Ground Transportation from Landing Site to Colony

As the ITS landings sites are some distance away from the colony site for safety, we require a system to transport cargo and personnel from the ITS to the colony. This is accomplished by two vehicles: The Operations Support and Cargo Autonomous Rover (OSCAR) and the Martian Cargo & Personnel Transport Rover (MPCT)

5.7.1 Operations Support and Cargo Autonomous Rover

5.7.1.1 *System Description*

We based the OSCAR on mobile boat cranes found on Earth, but with the ability to compress for shipping. It transports most payload from the ITS landing sites to the colony. Additionally, the OSCAR supports construction operations and ITS refueling. Like many of our other vehicles, this system is designed to operate autonomously. As such, the design includes a suite of instruments necessary for unmanned operation.

5.7.1.2 *CAD / System totals*

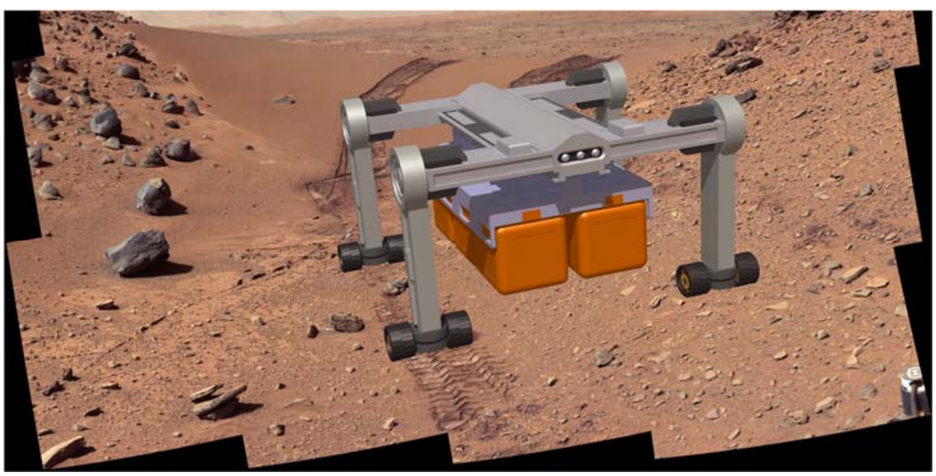

Fig. 5.7.1.1.1: The OSCAR Transports six standard cargo cubes across the Martian landscape.

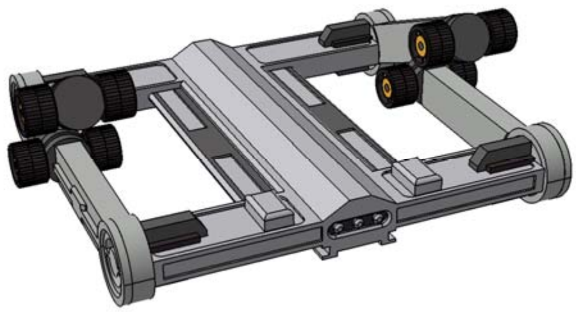

Fig. 5.7.1.2.2.2: OSCAR in its stowed configuration. Note that the extensible legs have been retracted, and the rotary joints engaged so that OSCAR's volume is diminished for transport in the ITS. (Credit: M. Gripe)

Table 5.7.1.2.5.7.1.1: OSCAR Mass, Power, Volume

	Per vehicle
Mass	29.84 Mg
Nominal Power	90.66 kW
Volume	164.3 m^3 (undeployed) 616.4 m^3 (deployed)

Table 5.7.1.2.2: OSCAR Capability Metrics

OSCAR- Capabilities	
Cargo Capacity	198 Mg
Speed (max)	9.875 km/hr
Range	30 km
Lifetime	30 years

5.7.1.3 *System Map*

The OSCAR interfaces with nearly all colony systems, but three are central to its operation: ITS vehicles, Rover charging ports, and colony locations. Except for other vehicles, passengers, and special cargo that is not pressurized in cargo containers, all ITS payload moves to its destination through the OSCAR.

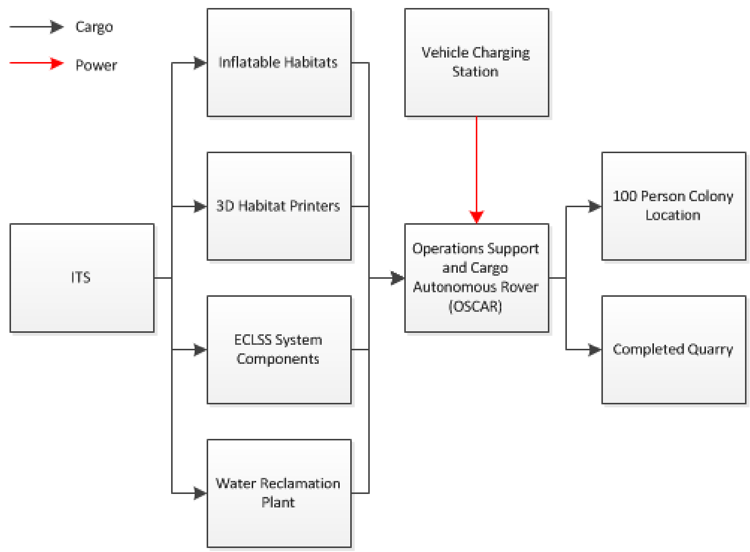

Fig. 5.7.1.3.1 The OSCAR is the a mission-critical system, as demonstrated by this system map.

5.7.1.4 *Deployment / Fabrication*

Due to the complexity and versatility of the Operations Support and Cargo Autonomous Rover, these vehicles will be produced on Earth and flown to Mars via ITS. Once landed on the surface, the ITS will deploy the OSCAR using the integrated cargo crane (See Section 6.5).

5.7.1.5 *Operation and Servicing*

No vehicle like the OSCAR has been fielded in space before, thus our outline of operation and servicing procedures are educated speculation using the Earth-equivalent vehicle as a model. We estimate the lifetime of this vehicle with be 30 years, and 10% of its operational life is dedicated to maintenance and other necessary downtime

The OSCAR vehicles will operate mostly autonomously, but we intend that they may also be directly remote controlled. Due to the repetitive routes and relatively smooth terrain of Chryse Planitia, we do not expect difficulty is operating the OSCAR in this capacity. The vehicles may

find their paths via radar beacons or similar landmarks, but the exact control mechanism is outside the scope of the report.

Service intervals were approximated from heavy construction equipment. We claim that the OSCAR can operate continuously for 30 years with 90% uptime, provided the colonists conduct daily inspections of each vehicle and each vehicle is held for maintenance for three days of every year. Major maintenance will be conducted inside the Rover Ports situated above the habitats. However, because the majority of tasks the OSCAR must complete are tied to ITS arrival and refueling, this magnitude of operation will not be required.

5.7.1.6 *Retirement, disposal, and replacement*

Little of the Operations Support and Cargo Autonomous Rover would be useful for repairing other systems. However. At the end of its useful life, any still useful parts are saved for possible repair of future vehicles. Remains are moved via other OSCAR vehicles to a location out if the way of colony operations. Replacement vehicles are brought from Earth via ITS as necessary.

5.7.1.7 *System Cost*

Table 5.7.1.7.1 OSCAR Cost Estimates

Component	Cost	Margin
Base (Traverlift 75 BFM II)	$1,600,000	
Autonomous Control System	$150,000	
Space Hardening Factor	10X	
Total	$6,000,000	50%

5.7.1.8 *Risk Analysis & Mitigation*

Table 5.7.1.8.1 OSCAR Risk Estimates and Mitigation Strategies

Risk being mitigated	Probability of failure/ MTTF	Cost of mitigation strategy in $/MPV	Improved
Cabin Pressure Loss	5%	Maintenance of pressure systems and life support for passengers- Oxygen masks/8 people cost = $2200	4%
Tire Degradation	10%	Maintenance cost $450/10000 km	3%
Battery power runs out	9%	Battery change before degradation of 40%	6%
Vehicle Breakdown	10% - 13%	Maintenance and storage of extra spare parts, Costs $100 – 1000 per part	5% - 7%

5.7.2 Martian Cargo and Personnel Transportation Rover

5.7.2.1 *System Description*

The Martian Cargo and Personnel Transportation Rover is designed to transport passengers to the colony from the ITS upon arrival, as well accomplish any other long distance human trips. It also supports cargo operations when not fulfilling its primary use. The MCPT is also designed with detachable cabin and chassis modules for ease of packing and deployment.

5.7.2.2 *CAD / System totals*

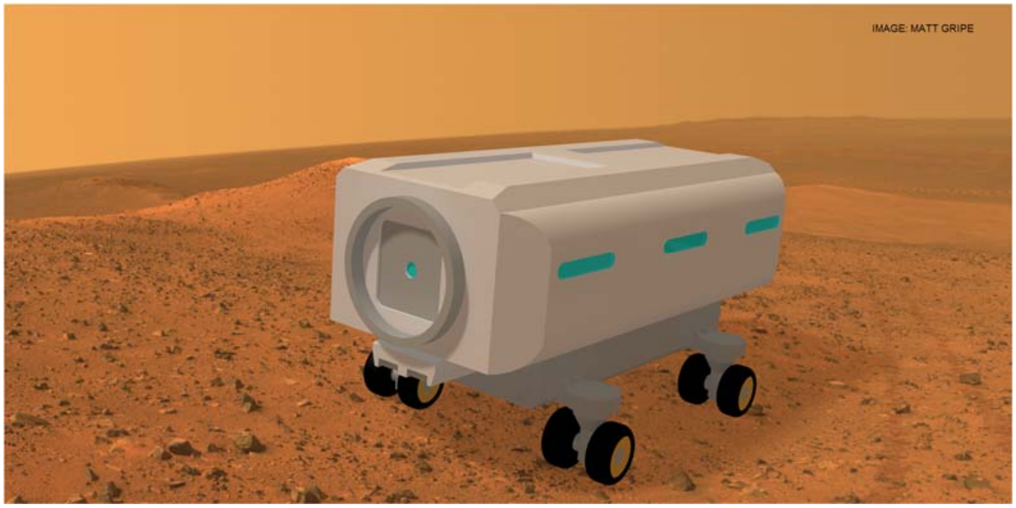

Fig. 5.7.2.2.1:The MCPT ferries passengers and light cargo across the Martian Surface

Table 5.7.2.1: MCPT Mass, Power, Volume

	Per vehicle
Mass	8.53 Mg
Nominal Power	217 kW
Volume	34.84 m^3

Table 5.7.2.2: MCPT Capability Metrics

MCPT- Capabilities	
Passenger Capacity	25 passengers
Cargo Capacity	11.26 Mg
Speed (max)	20 km/hr
Range	40 km
Lifetime	11.4 years

5.7.2.3 *System Map*

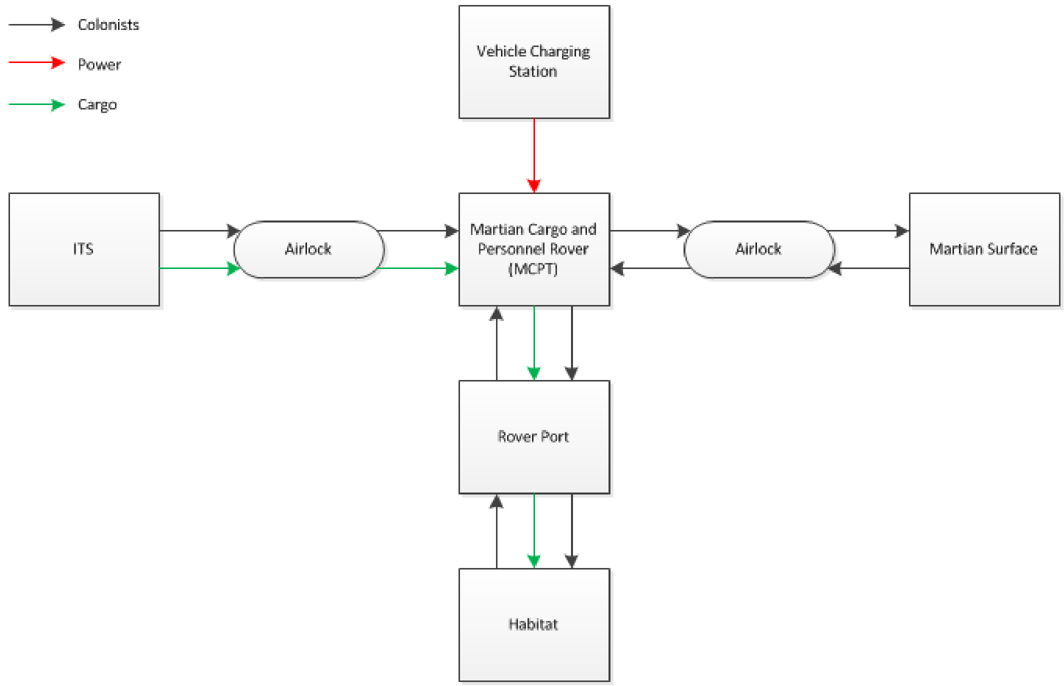

Fig. 5.7.2.3.1: The MCPT's primary task is moving colonists to the Habitat Rover Port from the ITS landing seeds

5.7.2.4 *Deployment / Fabrication*

All the MCPT vehicles are brought to Mars aboard ITS vehicles. Like many of our vehicles, the MCPT is deployed to the surface via the integrated ITS crane (Fig. 5.7.2.4.1).

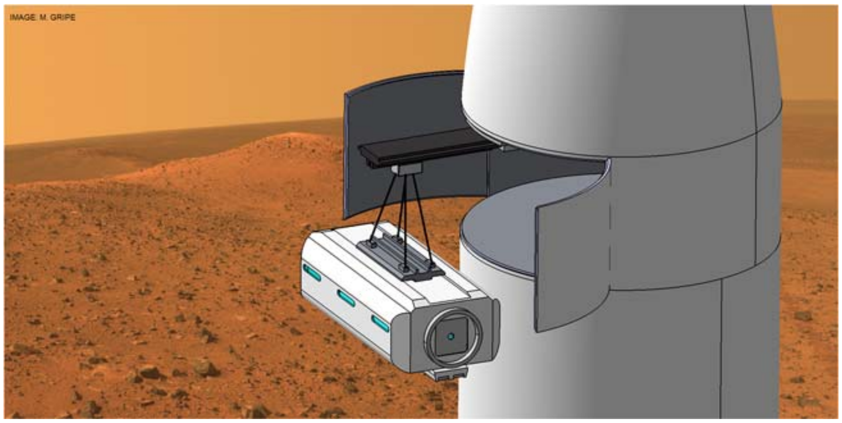

Fig. 5.7.2.4.1. The MCPT cabin is lowered to the Martian surface via the integrated ITS crane. Note that some of our largo cargo requires a modified ITS with large bay doors. (Credit: Matt Gripe)

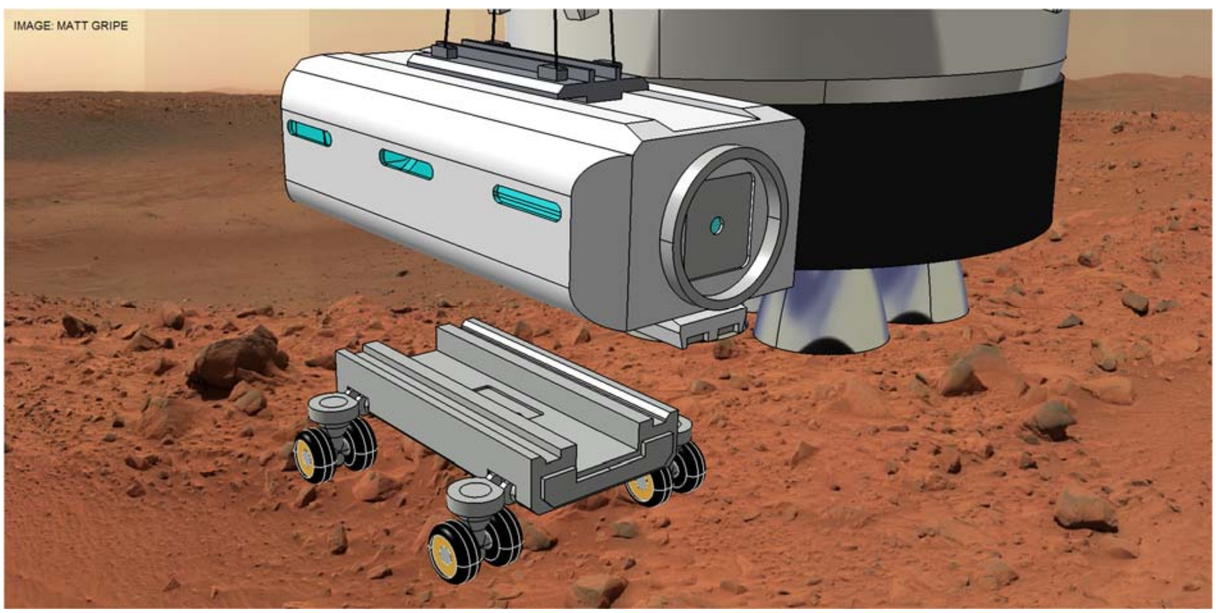

Fig. 5.7.2.4.2. The already deployed chassis positions underneath the lowered MCPT cabin .(Credit: Matt Gripe)

5.7.2.5 *Operation and Servicing*

The MCPT is intended to include both manual and autonomous control systems. The MCPT usually includes passengers, and thus is normally operated manually. However, the inclusion of

the autonomous control system allows the vehicle to transfer cargo or attempt rescue missions without a pilot.

The surface rover ports are used to service the MPCT at major maintenance intervals. We determine that these vehicles should be inspected daily and should undergo regular maintenance three times per year.

5.7.2.6 *Retirement, disposal, and replacement*

We estimate the lifetime of the MCPT will be 11.4 years. After their useful lifetime, the cabins may be used for a variety of purposes, such as surface storage units or emergency evacuation shelters. Useful parts are salvaged from non-operational rovers for the remainder of the fleet. Replacement vehicles are brought from Earth via ITS as necessary.

5.7.2.7 *System Cost*

Table 5.7.2.7.1: MPCT Cost Estimate

Component	Cost	Margin
Base (Dulles Airport Mobile Lounge)	$1,600,000	
Autonomous Control System	$425,000	
ECLSS System	$352,000	
Space Hardening Factor	2.5X	
Total	$ 5,942,500.00	50%

5.7.2.8 *Risk Analysis & Mitigation Strategies*

Table 5.7.2.8.1: MPCT Risk Estimates and Mitigation Strategies.

Risk being mitigated	Probability of failure/ MTTF	Cost of mitigation strategy in $/MPV	Improved
Cabin Pressure Loss	5%	Maintenance of pressure systems and life support for passengers- Oxygen masks/8 people cost = $2200	4%
Tire Degradation	10%	Maintenance cost $450/10000 km	3%
Battery power runs out	9%	Battery change before degradation of 40%	6%
Vehicle Breakdown	10% - 13%	Maintenance and storage of extra spare parts, Costs $100 – 1000 per part	5% - 7%

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6 Mars In-Situ Resource Utilization

6.1 Water Extraction Plants

6.1.1 CAD / System Totals

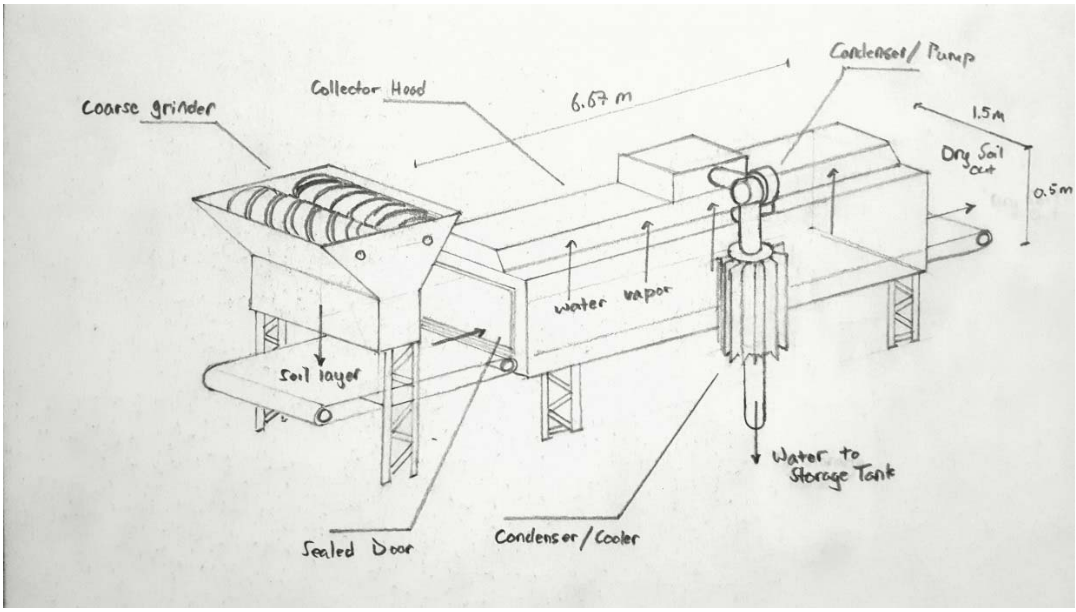

Fig 5.7.2.8.1 A fully assembled Water Extraction Plant (WEP), including dimensions and labeled components. (Credit: A. Judson)

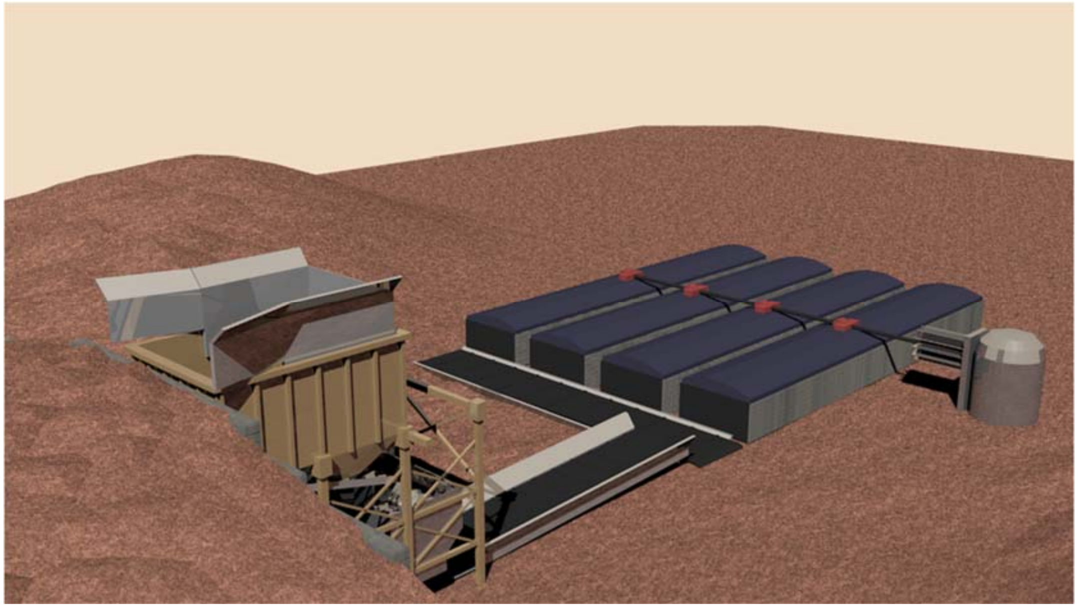

Fig 5.7.2.8.2 Four WEPs placed side by side with regolith collection hopper. (Credit: A. Judson)

We design the water extraction plant (WEP) to produce water for the colony. Water extracted by the plant is transferred to other systems within the colony, or stored for later use. Fig. 6.1.1.1 displays a single plant with labeled components and dimensions, while Fig. 6.1.1.2 depicts a system of several WEPs. Each individual water extraction plant has a mass of 2.16 Mg, a volume of 5.0 m^3, and requires a power input of 25.92 kW. Sixteen water extraction plants are required to fulfill the colony's water needs throughout the mission timeline. The system's mass, power, and volume are listed in Table 6.1.1.1. To meet the needs of the colony's water-reliant systems, the WEPs require an input of 116 m^3 of Martian clay per hour. Such an input produces 37.8 m^3 of water per hour.

Table 6.1.1.1 Water Extraction Plant MPV Breakdown

System	Mass (Mg)	Power (kW)	Volume (m^3)
Single Unit	2.16	25.92	5.0
Total System	34.56	414.72	80.0

6.1.2 System Map

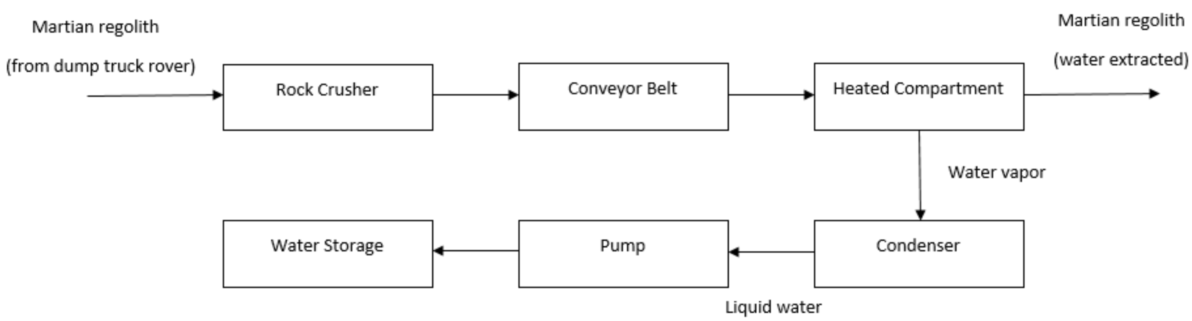

Fig 5.7.2.8.1 System map of the Water Extraction Plant. Liquid water is extracted from Martian regolith that is put into the system. (Credit: C. Lindberg)

A single water extraction plant system map is given in Fig 6.1.2.1. Each plant consists of a rock crusher, or grinder, where chunks of excavated regolith are deposited. This grinder breaks the regolith down to uniform pieces, and deposits the pieces onto a conveyor belt. The conveyor belt carries the ground-down regolith into the main body of the plant. Once inside the main body, a door on each end of the plant closes, forming a seal with the conveyor belt and plant walls. Magnetrons within the WEP then produce microwaves, heating the regolith within the plant to 600 degrees Celsius. At this temperature, water frozen within the regolith enters a gaseous state, and rises out of the regolith as water vapor. The water vapor is collected in a collection hood at the top of the plant, and is transferred to a condenser. The condenser cools the water vapor into a liquid state, at which point it is pumped to the colony's water storage system.

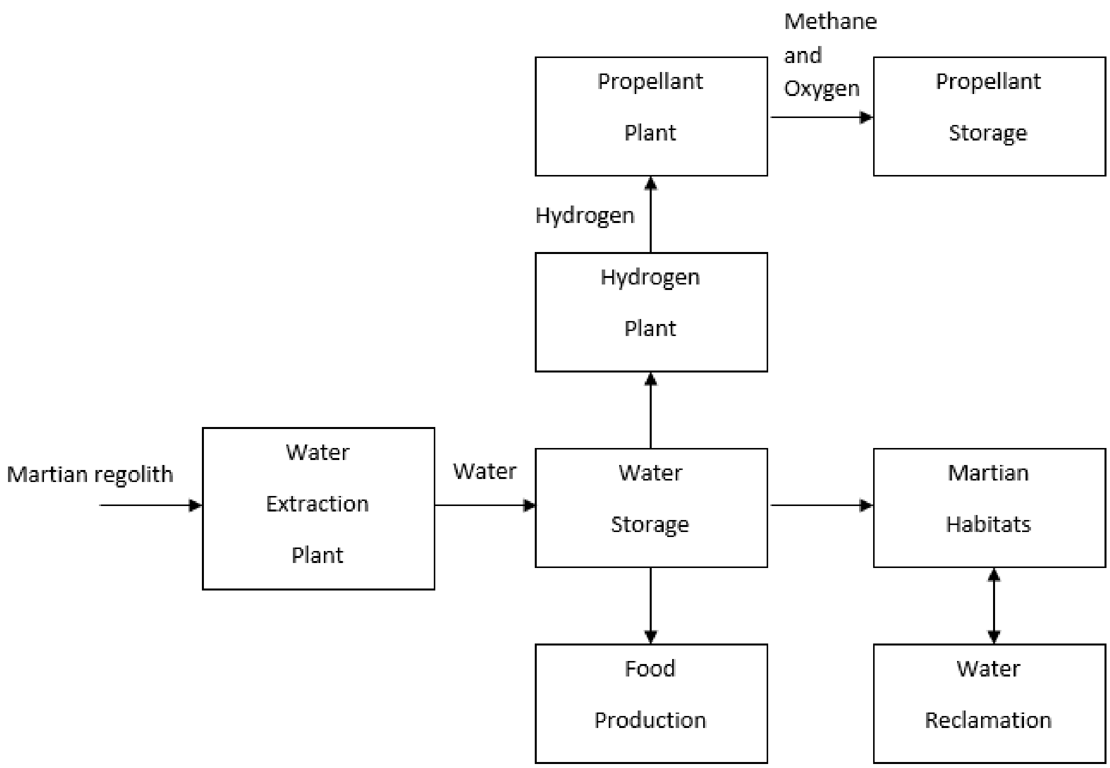

Fig 5.7.2.8.2 System map of water throughout the colony from its initial production to its final destinations. (Credit: C. Lindberg)

A system map of water flow throughout the entire colony is given in Fig. 6.1.2.2 After water is extracted from the Martian regolith, it is moved to other systems throughout the colony. Most of our colony's water needs come from propellant production. Water used for this purpose is sent to hydrogen plants, where it undergoes electrolysis. The remaining water is used to provide for the colonists' basic human needs. Most of this water is used for food production, as the Martian farms employ a hydroponics system for food growth. The rest is sent to the colonists' habitats, where a water reclamation system reclaims over 90% of the water used.

6.1.3 Deployment / Fabrication

Deployment and assembly of the water extraction plant on Mars takes place in several steps. The plant as a whole is fairly modular; individual components can be packed aboard a cargo ITS and put together when deployed on Mars. For packing purposes, the plant components are broken down into several sections. We pack the plant in this way to minimize the volume consumed on the ITS-C. Each packed water extraction plant takes up only 5 m^3 of volume within the spacecraft.

Upon reaching Mars, we offload the water extraction plant components from the ITS. These components are then loaded onto a rover and transported to the water extraction site. This site is located about 20 km away from the main colony. The discrepancy in locations is due to the locations of critical resources. The colony is built on a deposit of basalt rock for habitat construction purposes, while water extraction takes place at an off-site location where water-rich clay is abundant.

The water extraction plant components are unloaded from the rovers and put together at the water extraction site. Due to the modularity of the system, new plants can be quickly put together upon reaching this destination. First, the body of the plant is bolted together. The conveyor belt is then assembled and run through the plant. Next, the rock crusher is assembled and placed at the front end of the conveyor belt. After assembly, the system is connected to its power supply, and the plant's water pump is connected to the colony's water pipeline. This pipeline carries water from the extraction site to the water storage facility, where it is then distributed throughout the colony. The piping will be manufactured on Mars, and will be laid during the first few synodic cycles. The pipeline must be fully operational during the constant delivery stage of the mission, when water extraction operations reach their peak. Once the system is assembled and connected to the power and water lines, it can begin operations immediately.

6.1.4 Operation and Servicing

The colony's water extraction operations are largely autonomous. Our water extraction process begins with excavating water-rich clay from the Martian surface. This process is conducted by autonomous excavation and dump truck rovers. After the clay is collected, the dump truck rovers transport it to the water extraction plant site. To aid in the offloading of regolith, we elevate the space where the dump truck rovers deposit their payload. Elevating this space allows gravity to assist with transporting regolith from the dump truck rover to the collection hopper, allowing the process to remain autonomous; colonists are not required to manually move clay from the rover to the hopper. The deposit zone is elevated by piling excess regolith into a mound, and adding supporting structures to one side. Such support structures are able to be manufactured on Mars, and are either made of steel or are 3-D printed from basalt rock. The regolith deposit zone is pictured in Fig. 6.1.4.1

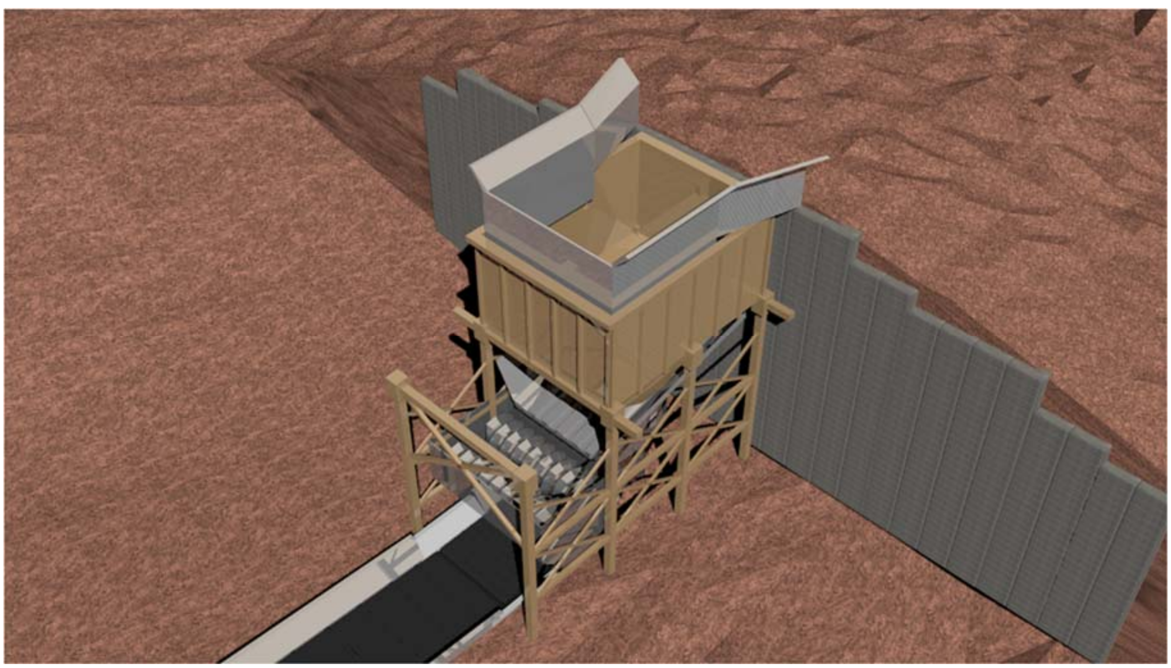

Fig 5.7.2.8.1 The elevated regolith collection hopper receives clay from dump truck rovers. The regolith is then fed to the rock grinder, where it is broken down. (Credit: A. Judson)

Once regolith is provided to the system, the water extraction plant processes the clay and extracts water autonomously. At the beginning of a water extraction cycle, the door on each end of the extraction plant will slide open. At this time, water-rich clay is deposited into the rock crusher, where it is ground down. A layer of fine regolith is dropped onto the conveyor belt, which

moves while the plant doors are open. As the conveyor belt carries the water-rich regolith into the system, leftover regolith from the previous water extraction cycle is deposited onto the ground at the opposite end of the plant. The system operates in this fashion until the main, heated body of the water extraction plant is filled with water-rich clay. Upon reaching maximum capacity, the doors at each end of the extraction plant close, and the water extraction process as described in Section 6.1.2 takes place. Once the process is completed, the doors open, and the cycle repeats. Power is provided to the water extraction plants by the colony's central power system.

While we design the system to perform its duties autonomously, some servicing and maintenance is still required. As the system operates, dried-out regolith is deposited at the end of the conveyor belt. Regolith builds up over time at this location, and must be removed to prevent a stoppage in water production. This dry regolith is still valuable to our colony; while water-deprived, the soil still contains metals that will be processed in the metal refinery. Additionally, due to the working environment around the water extraction plant, rocks and soil may build up around the water extraction plant's moving parts. Pieces of regolith caught in the moving parts of the rock crusher or conveyor belt may prevent the extraction plant from working properly. During operation cycles, the rock crusher and conveyor belt components will remain stationary. At this time, any potential hazards to operation can be addressed by colonists. While the system as a whole is mostly autonomous, its operation should still be monitored, as water production is a critical component to the success and survival of the entire colony.

6.1.5 Retirement, Disposal, and Replacement

We estimate the lifetime of the water extraction plant to be 15 years. The system achieves this relatively long lifetime because it is made up of components regularly used in industries on Earth that mirror the harsh working conditions on Mars. A further analysis of the system's lifetime is explained in sections 6.1.7 and 6.1.8.

Upon reaching retirement, we strip the WEP of any remaining functional parts. These parts are particularly valuable due to the importance of water to the colony. If one component of a water plant fails, it can be replaced by a recycled component from an old water plant. Additionally, spare parts will be on hand to immediately replace the parts of the plants that are most prone to failure. Maintaining constant operation of the water extraction plants is of extreme importance to the colony, and all working parts of retired plants should be saved for later use. In the event that these parts are not needed to serve as replacement parts on future water plants, they may be melted down at the metal refinery and repurposed to meet other colony needs. Retiring systems on Mars requires us to think like Martians; specialized parts are difficult to manufacture on Mars, and cannot be thrown aside carelessly when a piece of machinery reaches the end of its usable lifetime. Cost benefits are also achieved when recycling parts. Magnetrons account for over 25% of the cost of each water extraction plant, and have a relatively low lifetime of 9 years. We assume that the magnetrons in each water extraction plant are replaced once during the system's lifetime, as discussed in section 6.1.8. As a result, the magnetrons in each water extraction plant should still have 3 years of useful life remaining when a water plant is retired. These parts are expensive with respect to the rest of the system, and are critical to the system's operation. The magnetrons should be kept and recycled until the parts cease to function properly.

The water extraction plant replacement process resembles the deployment and fabrication process discussed in section 6.1.3. We retire our WEPs as new plants arrive from Earth. The individual plants are disassembled and checked for recyclable parts when the new plants arrive. The new plants are then fabricated on site, and begin operation.

6.1.6 System Cost

When estimating the cost of the water extraction plant, we consider the plant as a system made up of several components that are comparable to existing systems on Earth. Some components, such as the grinder that accepts extracted regolith and the conveyor belt that runs through the body of the plant, are directly paralleled by existing Earth systems. Other components are similar to, but not exactly the same as existing systems on Earth. For example, the body of the water extraction plant resembles a scaled-up microwave oven. Additionally, the condenser and pump that collect and transport liquid water can be modeled as an industrial HVAC system.

Table 6.1.6.1 Water Extraction Plant Cost Breakdown

Component	Cost ($)
Rock Crusher	60,000
Conveyor Belt	13,500
Door	0
Door Seals	40
Magnetron	85,000
Condenser	5,000
Pump	700
Structure/Fabrication	164,240
Total	328,480

We use existing data for these Earth systems to estimate the cost of our Martian system. Existing rock crushers are scaled to resemble the size of the crusher used in our system, and equipment prices are extrapolated. The rock crusher component of the water extraction plant has an estimated cost of $60,000 [6-1]. The water extraction plant employs a 10 meter-long, 1.5-meter-wide conveyor belt to move ground-down regolith through the system. Existing data on conveyor belt prices is used to calculate the cost of the conveyor belt for our system. The average price for a 1 meter-long by 0.67-meter-wide section of conveyor belt is approximately $600, resulting in a total conveyor belt cost of $13,500 [6-2]. The doors on each end of the water extraction plant can be made from steel on Mars, and are not included in this cost analysis. However, the door seals must be brought from Earth, as our colony cannot produce rubbers and other sealant materials.

Based on Earth systems that use door seals, we estimate the cost of one of these seals to be about $20 [6-3]. This cost is negligible compared to other system component costs. The cost of the magnetrons used to heat the water out of the regolith is calculated by scaling the cost of magnetrons used in average microwave ovens. Magnetrons cost between $90 and $150, and heat a volume of about 0.0425 m3 [6-3]. The average cost of $120 is scaled to meet the volume and temperature requirements of the water extraction plant, resulting in a total cost of $85,000. While this is a fairly rough estimate, it is difficult to estimate the price of magnetrons used to heat large volumes similar to that being heated in the water extraction plant, as information on these large magnetrons is not readily available. Finally, water vapor is converted to liquid form and transported to other systems by a condenser and a pump, similar to those found in conventional industrial HVAC systems. The price for these components is estimated at $5,000 and $700, respectively [6-5, 6-6]. A complete cost breakdown for the water extraction plant is given in Table 6.1.6.1 above.

Similar to the cost of the magnetrons, the structural and fabrication costs for the water extraction plants are difficult to estimate. The function of the plant is similar to that of an industrial oven or kiln. However, fabrication cost information on ovens and kilns of this size is also unavailable. As a result, the structure and fabrication costs of the system are estimated at about the same cost as the total costs of the other components. This system is required to operate constantly in the harsh Martian environment, with little room for failure. The plant will require specialized manufacturing to sustain consistent operation on Mars, and as with other space systems, the fabrication costs will be substantial. The water extraction plant, as a whole, has an estimate cost of $328,480. Over the lifetime of the colony, sixteen water extraction plants will be required, resulting in a total cost of $5,255,680. Due to the rough nature of these cost estimates, a 50% margin is assigned to the cost of the system.

6.1.7 Risk Analysis

Table 6.1.7.1 Water Extraction Plant Cost Breakdown

Description of Failure	Effects of Failure on the System	Risk Mitigation	Probability of Failure	Mean Time To Failure
Rock Crusher Failure	WEP cannot grind regolith down to small, uniform pieces.	Perform regular servicing and maintenance	Low	25 Years
Conveyor Belt Failure	Ground-down regolith cannot move through the plant, and water cannot be produced.	Perform regular servicing and maintenance	Low	35 Years
Door Failure	Regolith cannot enter or exit the heated section of the plant.	Perform regular servicing and maintenance, manufacture extra doors	Low	30 Years
Seal Failure	The door on either end of the plant cannot create a seal, leading to heat loss within the system and water loss.	Bring extra seals	Medium	2 Years
Magnetron Failure	The system can no longer heat water out of the regolith.	Bring extra magnetrons	Medium	9 Years
Condenser Failure	Extracted water vapor cannot be cooled to a liquid state.	Perform regular servicing and maintenance	Low	15 Years
Pump Failure	Collected water cannot be pumped to storage facilities	Perform regular servicing and maintenance	Low	15 Years

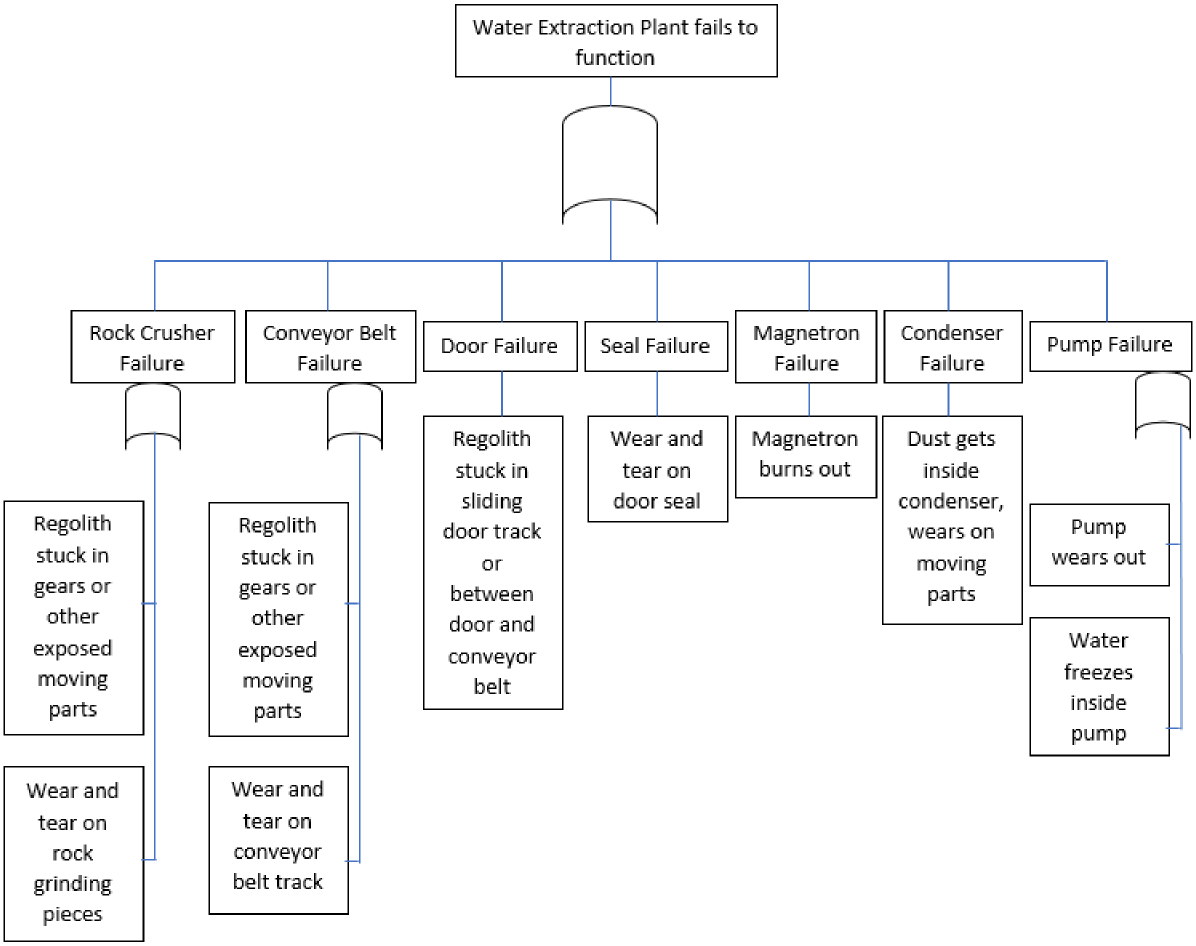

Fig. 5.7.2.8.1 A fault tree diagram for the water extraction plant. Credit: C. Lindberg

Each component of the water extraction plant possesses its own failure rate. The large components of the plant, such as the rock crusher and conveyor belt systems, have long component lifetimes, and large mean times to failure. For example, the rock crusher is built to withstand heavy use under industrial conditions, and possesses a mean time to failure of about 25 years [6-7]. Conveyor belts are designed to run constantly and sustain heavy use in factories, and possess a mean time to failure of 35 years [6-8]. The doors used in our system are based on standard garage doors, which are operated regularly in various environmental conditions around the world. These doors have an estimated mean time to failure of 30 years [6-9]. The smaller components, such as seals on the steel doors and magnetrons, have shorter lifetimes. For example, when used heavily, weather seals on doors typically wear out after only 2 years [6-10]. Additionally, magnetrons tend

to burn out after approximately 9 years [6-11]. These small components, however, can be replaced as needed during the lifetime of the plant. The condenser and water pump are more difficult to replace, and each has a mean time to failure of 15 years [6-12]. Due to these components, the lifetime of the water extraction plant is estimated to be 15 years. A full FMECA analysis of the water extraction plant is given in Table 6.1.7.1.

6.1.8 Risk Mitigation Strategies

Table 6.1.8.1 Water Extraction Plant Risk Mitigation Strategies

Description of Failure	**Risk Mitigation**	**Cost of Strategy ($ per Plant)**	**Improved Mean Time to Failure**
Rock Crusher	Servicing/Maintenance	0	N/A
Conveyor Belt	Servicing/Maintenance	0	N/A
Door	Servicing/Maintenance	0	N/A
Seal	Bring extra seals	300	15 Years
Magnetron	Bring extra magnetrons	85,000	18 Years
Condenser	Servicing/Maintenance	0	N/A
Pump	Servicing/Maintenance	0	N/A

The lifetimes of the door seals and magnetrons can be extended through risk mitigation strategies. The door seals have the lowest usable life of any component within the system, but also cost the least (excluding the steel doors, which are produced on Mars). The seals on the doors can be replaced as they fail for a cost of only $300 per plant, and can be shipped from Earth for a negligible mass and volume cost. The magnetrons have the second-lowest lifetime within the plant, and are also replaceable upon reaching failure. These components, however, carry a significant cost. Shipping spare magnetrons for each water plant costs $85,000, but extends the lifetime of the system by up to 9 years. Due to the lifetimes of other, irreplaceable parts, the water extraction plant only serves another 6 years of use after the replacement of the magnetrons; however, bringing replacement magnetrons still increases the lifetime of the plant by 40%. These risk mitigation

strategies and their costs are given in Table 6.1.8.1 Other system components are maintainable through regular maintenance service, including tasks such as cleaning debris from the conveyor belts and other moving parts, at no extra cost to the colony. We assume that these servicing and maintenance procedures do not improve the mean time to failure of these components. The Earth systems that these components are based on are large, industrial systems that undergo regular maintenance. It is implied that regular maintenance is required to achieve the mean times to failure given in Table 6.1.8.1. The door seals and magnetrons, however, are paralleled by much smaller systems on Earth that typically do not receive regular maintenance throughout their lifetimes. After we employ these risk mitigation strategies, the water extraction plant has a probability of failure of only 1.5% throughout its 15-year lifetime.

6.2 Water Storage and Transport

6.2.1 CAD / System totals

Once the water has been extracted, it needs to be stored. It will be stored inside a water tank, which will lay on top of a hill. This system will serve three purposes: storing the water, keeping it warm and regulating the pressure. The next figure shows the design of the system.

Fig. 5.7.2.8.1 The water tank lays on top of a hill. The central pipe goes through the hill until it reaches ground level. (Credit: A. Cocheril)

The water tank is made out of steel and needs a certain amount of power for pumping the water to the top and keeping it warm.

Table 6.2.1.1 This table summarizes the characteristics of the water tank.

System	Pumping Power	Heating Power	Volume	Mass
Water Storage	1.986 kW	61 782 kW	497 m^3	3827 Mg

The colony also needs two different types of pipes. A main pipe will bring the water from the water plant to the water tank. Smaller pipes will go from the water tank to each habitat and facility that requires water.

Table 6.2.1.2 Each type of pipe has different dimensions.

Pipe Type	Diameter (m)	Thickness (mm)
Main Pipe	0.2032	8.18
Habitat Pipe	0.0508	3.91

6.2.2 System Map

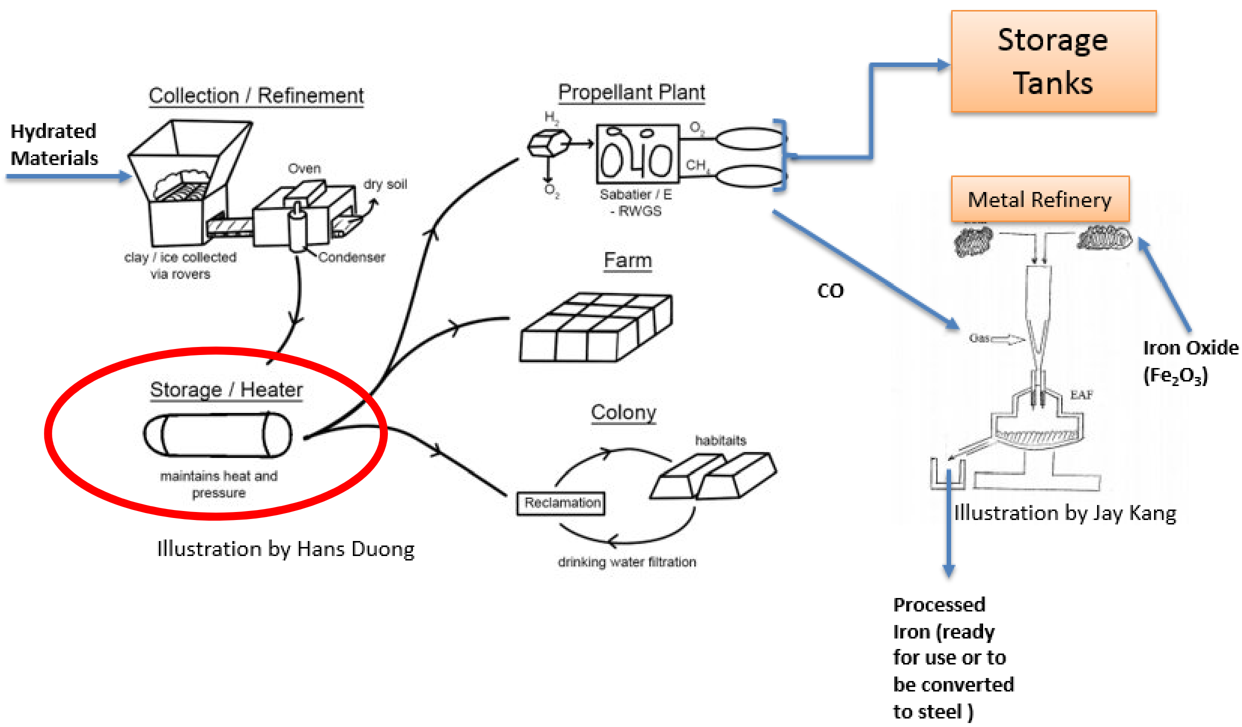

Fig. 5.7.2.8.1 The water storage as it relates to the entire Resource Utilization system

6.2.3 Deployment/Fabrication

The colony will need a water storage system as soon as possible. We cannot wait for the metal production plant to be operational, and then build the system. Therefore, the components of the water tank will be built on Earth and then assembled on Mars. To deliver a sufficient pressure to the colony, the water tank needs to be 55.7m above it. To minimize construction constraints, we will place the tank on top of a hill this high, instead of building an actual water tower.

We don't know for sure that there will be a hill near the colony, but since we're going to extract a very large amount of soil to build the different quarries, we can use this soil to "build" a hill.

The main pipe and the piping for the first quarry will also be shipped from Earth. The rest of the pipeline will be built progressively on Mars, as colonist will keep arriving.

6.2.4 Operation and Servicing

Once the water is extracted, it will go through a main pipe until it reaches the water tank's location. There, it will be pumped through the central pipe to get to the water tank. The pump is located at the bottom of the pipe and will push the water until it reaches the tank. The power needed to pump water 55.7 m high is 1.986 kW. The water doesn't require any pumping to go from the water tank to the colony, because the tank is high enough to deliver sufficient pressure.

We also need to install a heating system inside the water tank to keep it above freezing temperature at all time. The goal is for the water to be at least 1°C. Since the average temperature on Mars is -63°C, we'll have to heat up the water by 64°C.

The power needed to heat 380 m3 of water by 64°C is 61 782 kW.

The water will leave the water tank and be distributed to each quarry. The pipeline will also need to be heated to prevent the water from freezing. The main pipe needs to receive 17,551 W/km and the quarry pipes need to receive 4,468 W/km.

The reactors used in the colony produce excess heat that can be used to warm the water. The heat will be transported through another steel pipeline, surrounding the already existing water pipeline.

6.2.5 Retirement, disposal, and replacement

Both the water tank and the pipeline are expected to live for at least 30 years. Once they have reached the limits of their capacities, we can recycle the steel to make spare parts for any other system of the colony. When the time arrives that we have to replace the components system, the metal production plant will be fully operational. We'll be able to build a new water tank or a pipeline entirely on Mars.

6.2.6 System Cost

The water tower is made out of steel. It will be shipped from Earth, because this system needs to be operational as soon as possible. The cost of steel being $395/Mg, it will cost $6,743 to build a 17.072 Mg heavy water tower. We also need to bring the pump from Earth. The average cost for a pump fulfilling these capacities is about $500.

Both the water pipeline and the heating system pipeline are also made out of steel. We'll be able to produce this material on Mars on the long term. However, we still need to ship a certain amount from Earth for the first colonist, since the metal production plant won't be ready yet, and they will need the pipelines right away.

We will have to ship 1059.99 Mg of steel for the pipeline, which will cost $ 418,696. Since the heating system will make a loop (back and forth to the reactors), we make the assumption that we will need twice as much steel than for the water pipeline. The cost for the heating system pipeline is $ 837,392.

Table 6.2.6.1 The pump and the structure need to be shipped from Earth.

Components	Cost ($)	Margin for cost (%)
Structure	6 743	10
Pump	500	20
Pipeline	418 696	10
Heating System	837 392	10
Total	1 263 331	10

6.2.7 Risk Analysis

Table 6.2.7.1 This FMECA Table summarizes different failure modes for the water tower.

Description of failure	Effects of failure on the system	Risk mitigation	Probability of failure relative to deployment	Mean time to failure
Power Failure	Pump stops working. Colony is left with one day worth of water.	Backup power generator.	7.5×10^{-3}	60 years
Leak [7]	Loss of water for colony, or water freezes if pipe is from heating system.	Maintenance	1.2×10^{-2}	20 years
Overpressure [8]	Pipes leak. Pump can explode.	Regulation system.	1×10^{-5}	20 years
Overheating [8]	Pump can explode.	Shut the pump down and wait for it to cool down.	1.3×10^{-5}	20 years
Structure Failure [9]	Tower collapses. Pipes breaks, water can't be delivered to colony anymore.	Structural analysis.	1×10^{-5}	30 years

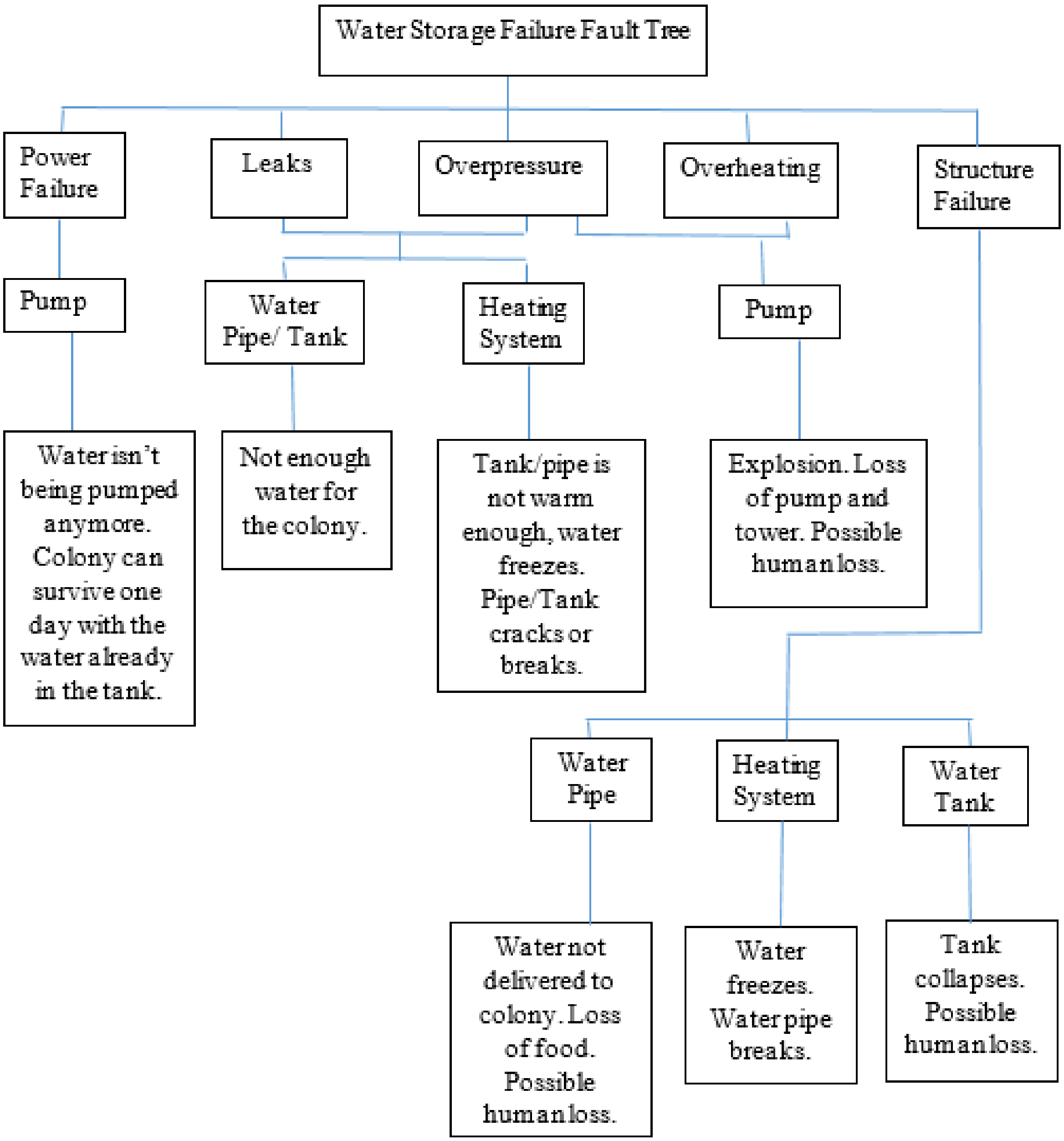

Fig. 5.7.2.8.1 The system fault tree summarizes the different event that can cause a failure and their consequences. (Credit: A. Cocheril)

6.2.8 Risk Mitigation Strategies

Table 6.2.8.1 There is a solution for each possible failure.

Description of failure	Risk mitigation	Cost of strategy	Improved probability of failure	Improved mean time to failure
Power Failure	We use a backup power generator that will take over whenever there's a power failure.	$400	7.5×10^{-5}	60 years
Leaks	Maintenance: prevent corrosion by regularly putting on an epoxy coating [10].	$70/L	7.7×10^{-3}	20 years
Overpressure	Install a pressure relief valve.	$15	4.9×10^{-6}	20 years
Overheating	Have continuously water flowing through the pump. If pump does overheat, shut it down and wait for it to cool down [11].	$0	1.3×10^{-5}	20 years
Structure Failure	Structural analysis on design. Good maintenance.	$0	1×10^{-5}	50 years

6.3 Hydrogen Production Plant

6.3.1 CAD / System totals

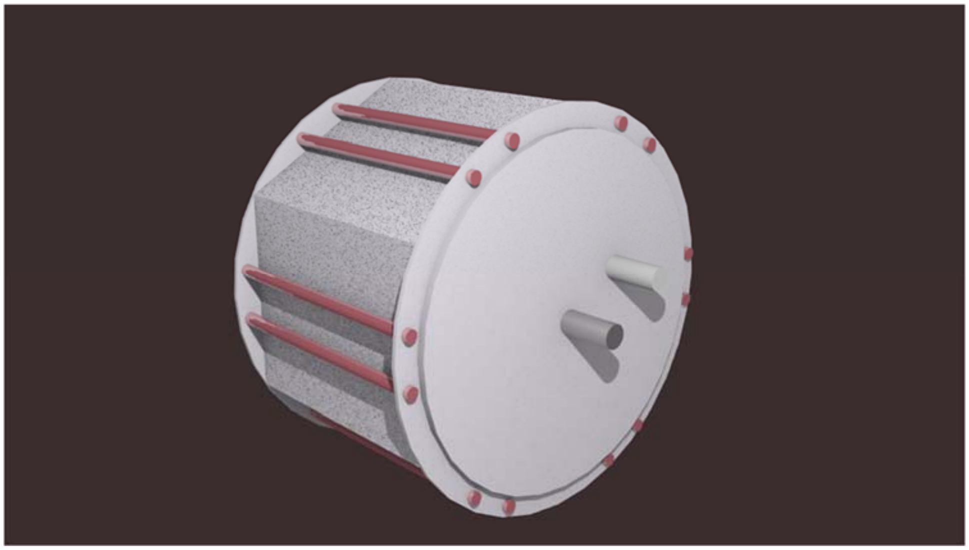

Fig. 5.7.2.8.1 Hydrogen plant. (Credit: Alex Judson.)

We design the hydrogen plant to produce enough hydrogen to run a single propellant plant. Each unit produces enough hydrogen to create 800 Mg of propellant for one ITS in 500 sols. **Error! Reference source not found.** depicts what our hydrogen plant might look like. The plant consists of 29 electrolyzer cells that separate the water into hydrogen and oxygen. Table 6.3.1.1 describes the required throughput of each unit and the total system once we reach a steady state delivery of 76 ITS-Ts per synodic cycle.

Table 6.3.1.1 Hydrogen plant throughput

Hydrogen Plants	Input: H_2O (Mg/day)	Output: H_2 (Mg/day)	Output: O_2 (Mg/day)
Single Unit	1.083	0.0842	0.6683
Total System	82.31	6.399	50.79

The hydrogen plant is 2.4 m in diameter and about 0.63 m tall. Table 6.3.1. shows the total system MPV breakdown based on number of plants delivered over the 100-year period.

Table 6.3.1.2 Hydrogen plant MPV

Hydrogen Plants	Mass (Mg)	Power (kW)	Volume (m^3)
Single Unit	4.62	167.8	3.55
Total System over 100 Years	351.1	12,750	270

6.3.2 System Map

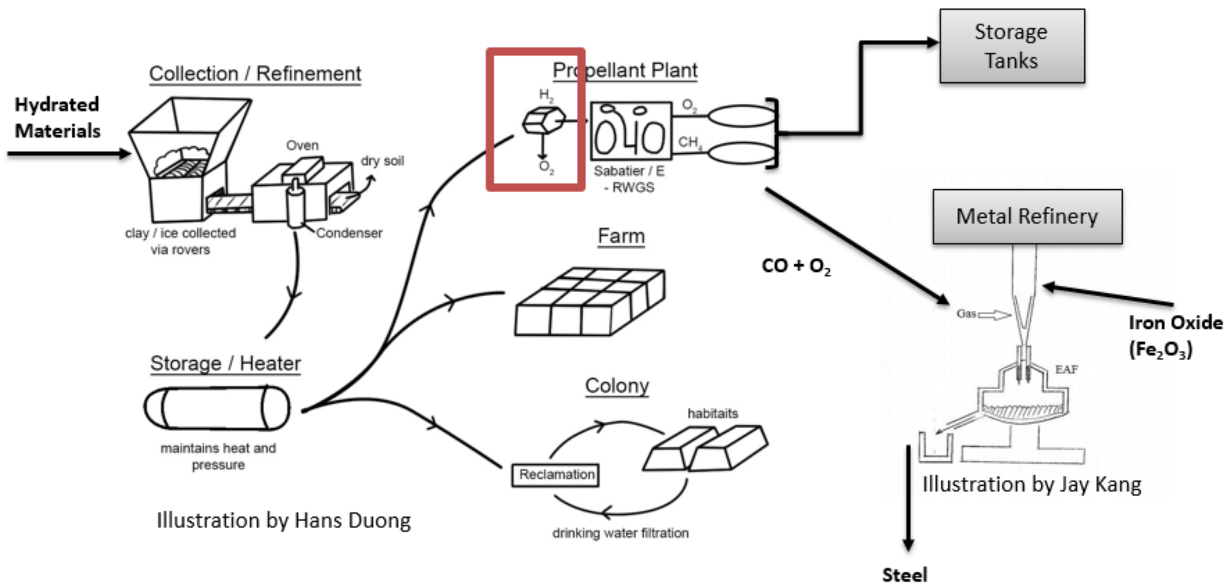

Fig. 6.3.2.1 Mars resource management system map. Hydrogen plant location.

Fig. 6.3.2.1 shows the flow of material through the electrolyzer. The oxygen is pumped to the oxygen storage, habitat and metal refinery. Unless we produce excess oxygen at which point it is vented into the atmosphere. We pump the hydrogen to the propellant plant.

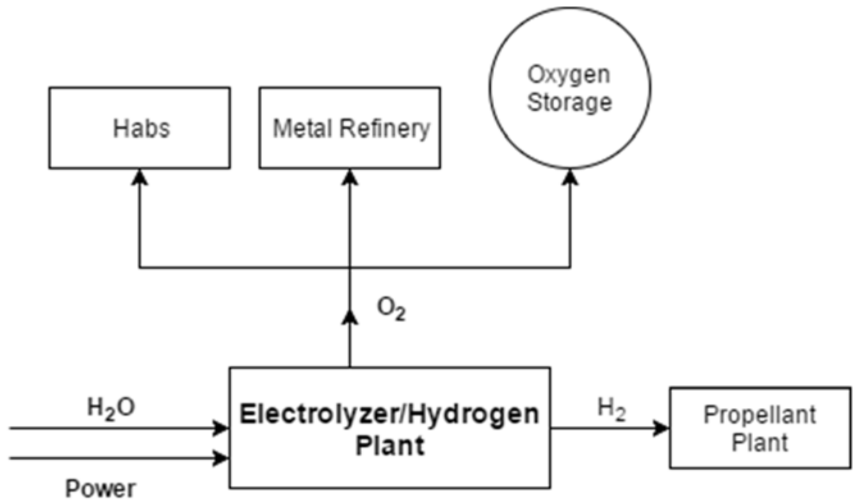

Fig. 6.3.2.2 Detailed system map of hydrogen plant and its outputs

6.3.3 Deployment / Fabrication

Due to the complexity of the system we fabricate the hydrogen plant on Earth. The completed plant is sent to Mars and unloaded one unit at a time from the ITS-C onto a rover. The rovers move the system to the desired location. Once placed at the colony location the plants connect to the propellant plant and other systems via piping. The colonists will also need to connect the power to each plant.

6.3.4 Operation and Servicing

Once turned on we run the system continually for at least 500 sols. The system will only be turned off for maintenance, inspection, and in case of emergencies. Some colonists should be chosen to monitor the hydrogen production process. It is unlikely the colonists can replace the major components inside the plant but minor fixes to piping.

6.3.5 Retirement, disposal, and replacement

We estimate the lifetime of the hydrogen plant around 15 years. A new unit is delivered when an old hydrogen plant needs to be replaced. The old unit is stripped for any useful

components that can be used as temporary spares. Parts made from iron/steel can be recycled using the metal refinery. The rest of the plant is disposed of.

6.3.6 System Cost

We determine the hydrogen plant system cost based on the expected costs of a typical electrolyzer on Earth. Starting from a base value we also added a correction factor for potential cost associated with a system built for Mars. For our plant the unit cost is based on the hydrogen production capacity for one ITS and can be seen in Table 6.3.6.1. The total system cost based on ITS-T refueling and does not include the cargo vehicles that need to be refueled. Lifetime is also accounted for in the total system cost.

Table 6.3.6.1 Cost breakdown for hydrogen plant.

Unit Cost	Cost Margin	Total System Cost
$ 67,370	100%	$ 29,710,000

6.3.7 Risk Analysis

Table 6.3.7.1 provides the potential failures that occur during the operation of the hydrogen plants. Many of the failures result in reduced output but do not cause critical failure. Fig. 6.3.7.1 also shows the approximate fault tree derived for the system. From the fault tree, we see that there are few redundancies in the system, but the risks of individual component failure is low during the lifetime of the plant.

Table 6.3.7.1 Hydrogen plant FMECA

Description of Failure	Effects of failure on the system	Risk Mitigation	Probability of Failure on Delivery	Mean Time to Failure
Plant goes offline	Loss of 1 propellant plant	Excess H_2 Production and multi-plant system	3 %	15 years
Oxygen leak	Reduced O_2 output to metal refinery	Backup O_2 production	Low	
Pump failure	Damage to cells, interruption in production	Maintenance, spare components	Low	20 years
Control failure	Cell damage and potential leaks	Maintenance, spare components	Low	
Hydrogen leak	Potential fire/explosion that can damage other systems	Inspection and separation between units	Medium	
Water leak	Loss in output, potential cell damage	Monitor input and output levels, maintenance	Low	
Gas separation failure	Contaminated output/damage to other systems/explosions	Strict output monitoring, automatic emergency shutdown	Low	
Hydrogen embrittlement	Cell damage	Maintaining hydrogen flow	Low	
Catalyst voltage decay	Reduced output	Maintaining good operational conditions	Medium	15 years

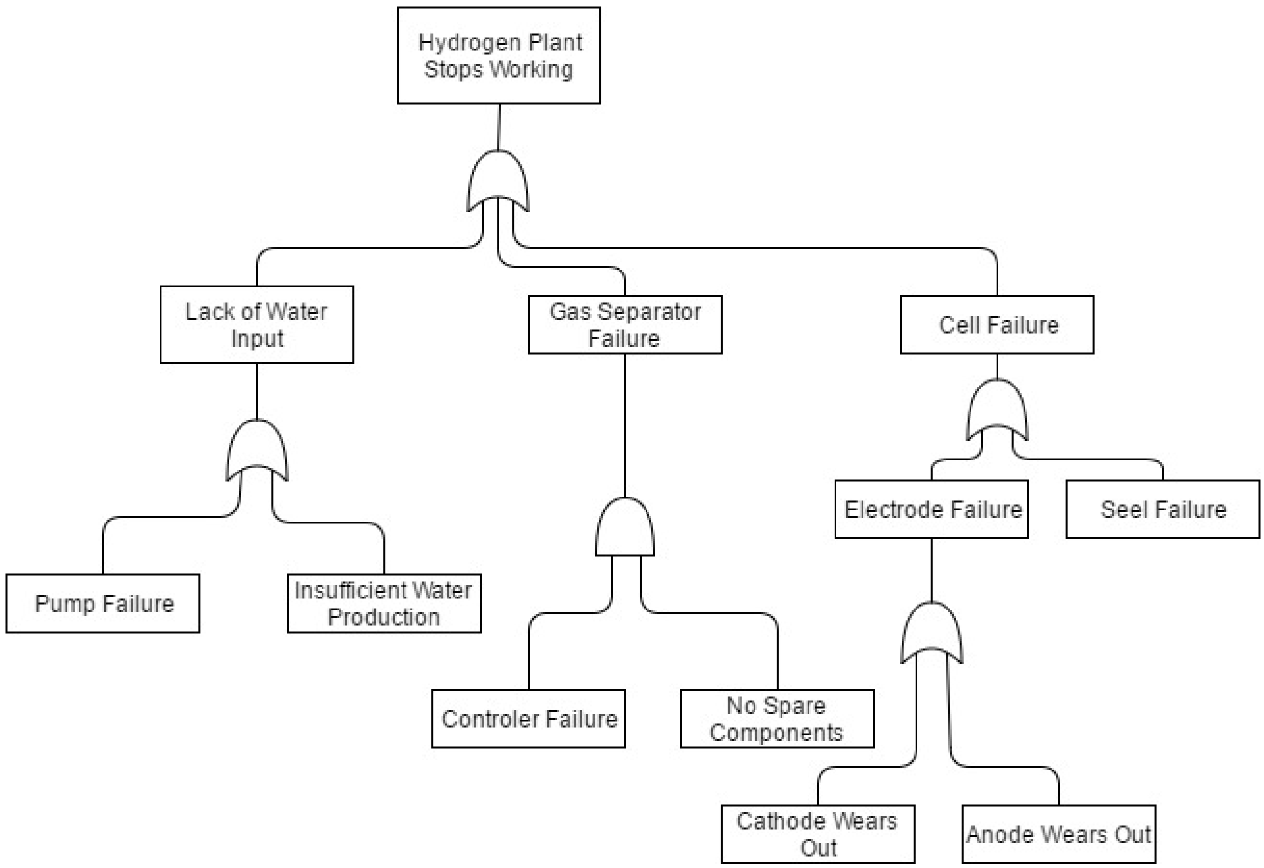

Fig. 6.3.7.1 Hydrogen plant fault tree.

6.3.8 Risk Mitigation Strategies

To reduce the risk of failure the hydrogen plant should be tested before being sent to Mars. This will diminish early life failure. Once on Mars someone should be responsible for monitoring the operation of the plant. Also, routine physical checks and basic maintenance should be performed. Sending some spare components that are likely to malfunction or break can help reduce the risk of full system failure.

A hydrogen plant is not critical to the survival of the colony; however, multiple plant failures can cause major delays in the return of the spacecraft. To mitigate the risk, we can send extra plants as backups. Also since each plant produces the required fuel in only 500 sols we have at least 200 extra sols for the other functioning plants to produce the required hydrogen.

6.4 Sabatier Reactors/Propellant Plants

6.4.1 CAD / System totals

Fig 6.4.1.1 Propellant plant. (Credit: J. Kang.)

We design the propellant plant to handle the production of 800 Mg of propellant in 500 sols, seen in Fig 6.4.1.1. Each ITS vehicle that needs to be refueled on Mars will require one propellant plant. The propellant plant produces Methane and Oxygen which are pumped to their respective storage tanks. We synthesize the propellant at an O/F of 3.8. The throughput of the system is shown in Table 6.3.1.1 As with the hydrogen plant the total system values are for a steady state of 76 ITS-T refueling, and does not include the potential cargo launches. The plants also produce carbon monoxide, this is a byproduct of the reactions, but it can be used in the production of steel.

Table 6.4.1.1 Propellant throughput breakdown

Propellant Plants	Input: H_2 (Mg/day)	Output: O_2 (Mg/day)	Output: CH_4 (Mg/day)	Output: CO (Mg/day)
Single Unit	1.083	1.267	0.3333	1.179
Total System	6.399	96.29	25.33	89.60

The propellant plants are slightly smaller than the hydrogen plants at about 1.5 m wide 1.5 m long and 2 m tall. Table 6.4.1.1 shows the total system MPV breakdown based on number of plants delivered over the 100-year period.

Table 6.4.1.1 Propellant plant MPV totals

Propellant Plants	Mass (Mg)	Power (kW)	Volume (m^3)
Single Unit	3.04	900.6	4.42
Total System over 100 Years	231	68,450	336

6.4.2 System Map

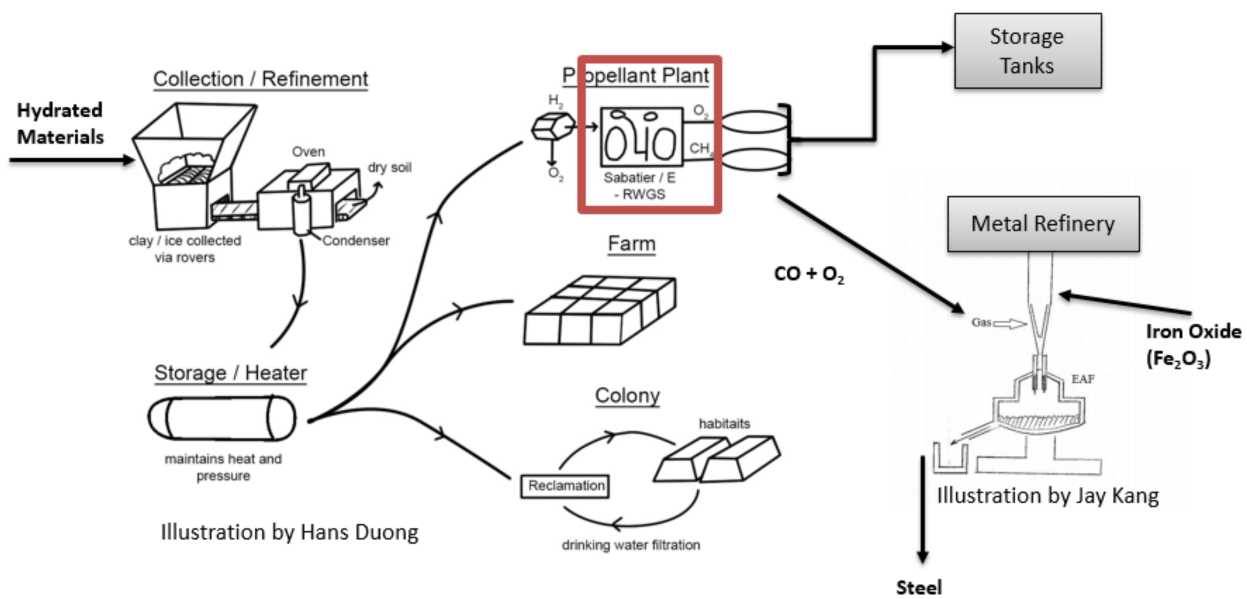

Fig 6.4.2.1 Mars resource management system map. Propellant plant location.

The propellant plant takes in carbon dioxide from the atmosphere and hydrogen from both the recycling process and the external hydrogen plants. Inside the Sabatier reactor we produce methane and water which goes through the gas separator to extract the methane into a storage system. From the gas separator, the water is stored until it is used in the electrolysis reactor, which produces oxygen and more hydrogen. We then transfer the hydrogen into a temporary storage from where it is used by the Sabatier reactor and the reverse water gas shift reactor (RWGS). The RWGS reactor reduces hydrogen consumption and makes the system very efficient. The RWGS reactor also creates carbon monoxide as a byproduct.

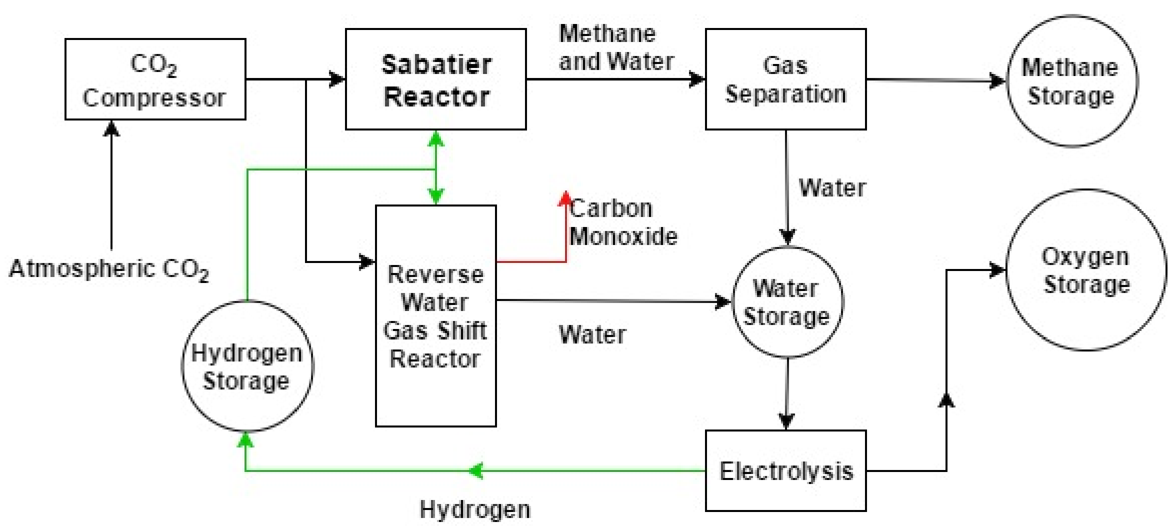

Fig 6.4.2.2 Propellant plant system map.

6.4.3 Deployment / Fabrication

Just like the hydrogen plants, we fabricate the propellant plants in advance on Earth before sending them to Mars. The plants are unloaded one unit at a time from the ITS-C onto a rover, which moves them to a suitable location. The colonists then should connect the piping from the hydrogen plant and storage tanks. A power source is also connected to the plant.

6.4.4 Operation and Servicing

Once turned on we run the system continually for at least 500 sols. The system will only be turned off for maintenance, inspection, and in case of emergencies. Some colonists should be chosen to monitor the propellant production process to ensure safe operation. Major components of the plant, such as Sabatier reactor, electrolyzer, RWGS reactor and CO_2 compressor can be replaced with spares. Minor fixes and replacements to piping and valves can also be done.

6.4.5 Retirement, disposal, and replacement

We estimate the lifetime of the propellant plant around 15 years, about the same as the hydrogen plant. A new unit is delivered when an old hydrogen plant needs to be replaced. The old unit is stripped for any useful components that can be used as temporary spares. Parts made from iron/steel can be recycled using the metal refinery. The rest of the plant is disposed of.

6.4.6 System Cost

The Sabatier reactors are more difficult to estimate the cost of since we did not design them to the component level and only small prototype systems exist. However, we can use typical capital costs for other methane and oxygen production facilities on Earth to estimate the potential cost of a Mars Sabatier reactor. In Table 6.4.6.1 is the cost breakdown based on the Earth plants we use to calculate the final costs. The estimated cost margin is around 50%.

Table 6.4.6.1 Sabatier reactor cost breakdown.

System	**Unit Cost**	**Adjusted Unit Cost**	**Total Cost**
Coal Based	$ 209,900	$ 611,300	N/A
Natural Gas	$ 109,000	$ 317,500	N/A
Mars Sabatier	$ 159,400	$ 464,300	$ 204,700,000

6.4.7 Risk Analysis

Table 6.4.7.1 provides the potential failures that occur during the operation of the hydrogen plants. Many of the failures result in reduced output but do not cause critical failure. Figure 6.4.7.1 also shows the approximate fault tree derived for the system. From the fault tree, we see that there are few redundancies in the system, but the risks of individual component failure are low during the lifetime of the plant. The main redundancy is in the CO_2 compressor.

Table 6.4.7.1 Sabatier reactor FMECA.

Description of Failure	Effects of failure on the system	Risk Mitigation	Probability of Failure	Mean Time to Failure
Plant goes offline	Loss of 1 propellant plant	Backup plants and or excess propellant production	5 %	15 years
CO_2 compressor breaks/faulty	Reduced propellant production	Multiple smaller compressors, redundancy	Medium	15 years
Hydrogen leak	Fire/explosion, reduced production	Inspection and separation between units	Medium	
Gas separation failure	Contaminated output/damage to other systems/explosions	Strict output monitoring, automatic emergency shutdown	Medium	15 years
Methane leak	Fire, reduced output	Output monitoring, maintenance	Low	
Oxygen leak	Reduced output	Output monitoring, maintenance	Low	
RWGS Reactor failure	Loss of hydrogen, increased strain on	Monitoring of water production, maintenance	Low	20 years

	hydrogen plant, water backup			
Electrolysis failure	Reduced efficiency	Maintenance	Low	15 years
Hydrogen embrittlement	Damage to hydrogen tank	Inspection and maintenance of tank	Low	

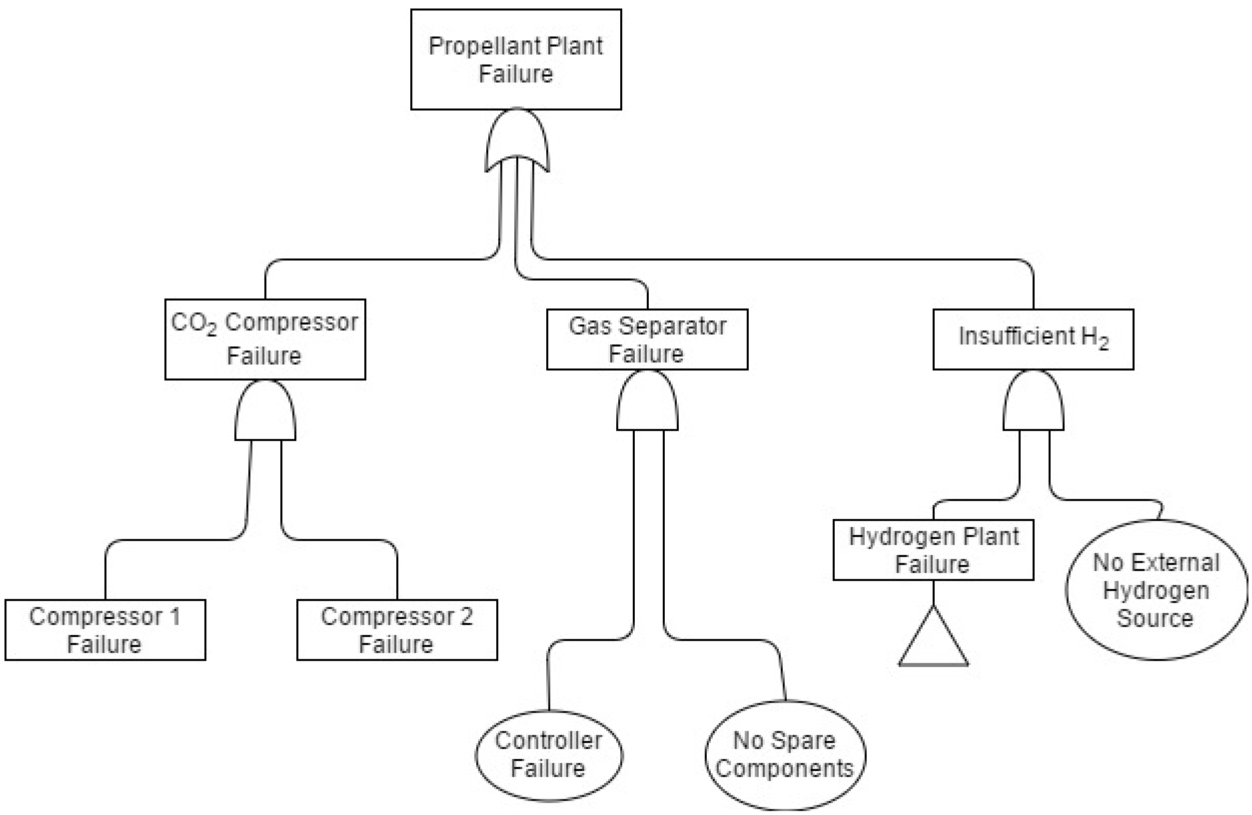

Fig 6.4.7.1 Propellant plant fault tree.

6.4.8 Risk Mitigation Strategies

To reduce the risk of failure the hydrogen plant should be tested before being sent to Mars. This will diminish early life failure. Once on Mars someone should be responsible for monitoring the operation of the plant. Also, routine physical checks and basic maintenance should be performed. Sending spare components that are likely to malfunction or break can help reduce the risk of full system failure. Specifically, replacements for the carbon dioxide compressors and common valves. A high temperature sealing material would be essential for temporary fixes on Mars, as leaks can cause major losses in propellant production.

As with the hydrogen plants the propellant plants are not critical to colony survival. Having backup plants will reduce the chance of mission delays and increases to the fleet size.

6.5 Propellant Storage

6.5.1 System Totals

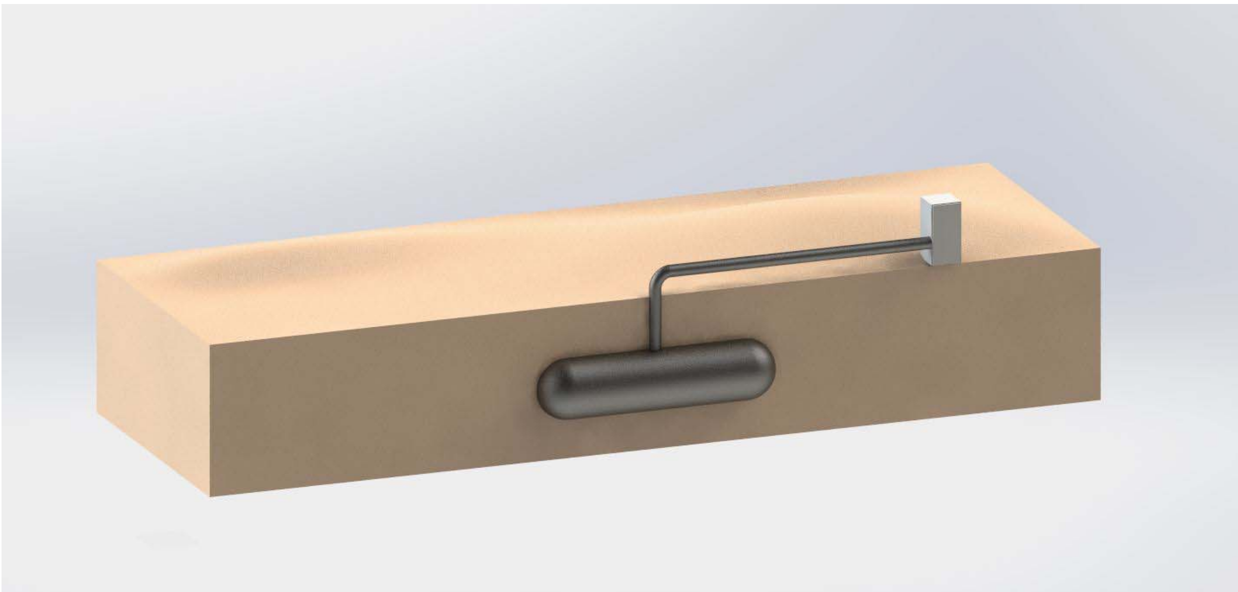

Fig 6.5.1.1 Subterranean storage tank with passive cooling pipe and refrigerator. (Credit: J. Kang.)

Error! Reference source not found. shows the finalized storage tank concept. Each ITS will require two tanks: one for oxidizer and one for fuel—together, they will be referred to as propellant tanks, and they will house the propellants. The apparatus shown in Fig. 6.5.1.1 depicts a subterranean non-cryogenic storage tank, an above ground passive cooling pipe, and a refrigerator. The requirements met by each of these components is discussed at length in subsequent sections. Preliminary analysis showed that for our initial estimate for optimum storage pressures and temperatures, we would need 160 tanks per ITS at a storage pressure of 1.5 atmospheres (atm) and average temperature of -187 Fahrenheit. Seeing as each tank weighs around fourteen tons, this is unrealistic even when considering in-situ manufacturing and fabrication. Both the old and new (finalized) system totals are tabulated as shown in Table 6.5.1.1. Each two tank system is capable of refueling an ITS in one hour.

Table 6.5.1.1 System Requirements for Storage Tanks

Data	Power [kw]	Mass [Mg]	Volume [m^3]
Old (1.5 atm)	31600	16.4	2500
Finalized (220 atm)	148	14.3	1788

6.5.2 System Map

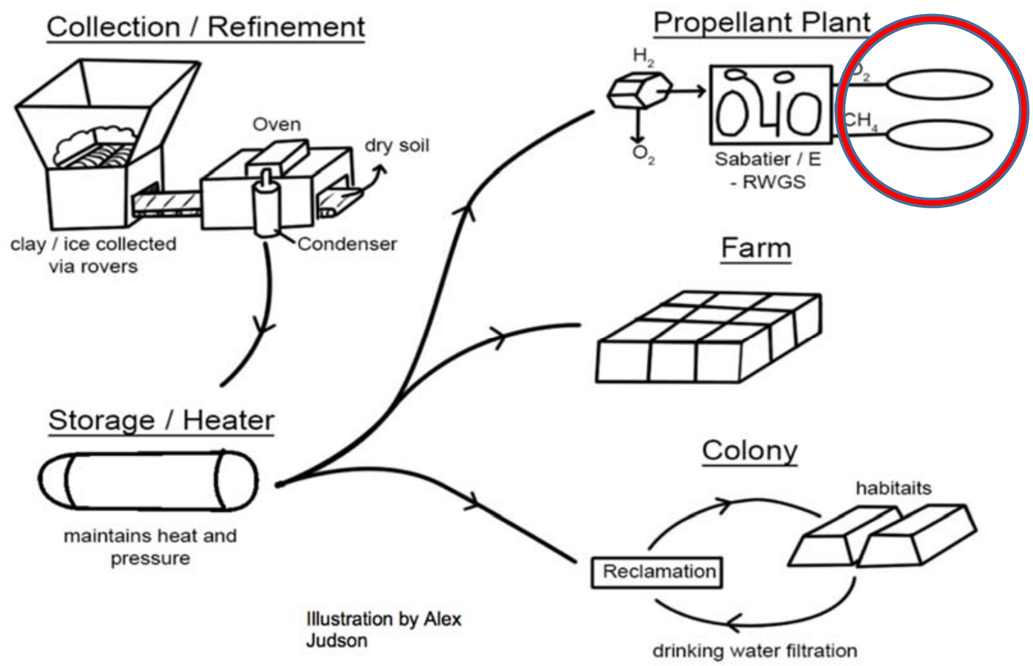

Fig. 6.5.2.1 System Map showing the propellant storage tanks

6.5.3 Deployment / Fabrication

As shown previously in this report, the Martian environment is much more hostile than that of Earth—the atmosphere is much thinner, made up of a much different composition, and thus the radiation levels experienced on the surface are much different than that of Earth. Because of the radiation differences experienced by the Martian surface, we need to rethink how we store materials. On Earth, we can simply store pressurized gasses in large tanks and refrigerate them if there are cryogenic requirements; however, this is both logistically and fiscally irresponsible for our mars mission. We should store the propellants as we do on Earth, as it would both increase the power requirements by several orders of magnitude and cause the complexity of the problem at hand to reach insurmountable heights.

We begin by analyzing how propellant plants are fabricated and deployed on Earth. We know that we will need tanks to store propellant. As for the general shape of the tanks, we know that any corners or sharp angles will drastically reduce the pressure rating for each containment vessel. With that said, we are left with two options: cylindrical tanks with spherical endcaps, or totally spherical tanks. If we assume that methane and oxygen that we are storing are ideal, the analysis below shows that a cylindrical tank is more efficient in terms of storage capacity to mass ratio due to the increase in volume being proportional to the increase in length of the cylinder and the cube of the radius of the cylinder. We will use cylindrical tanks. The tanks will be made out of stainless steel due to its ease of in-situ fabrication and its structural and thermal properties.

One very important aspect for fueling the tanks is timing—the temperature of the Martian surface varies significantly throughout each day, and we know we will be using metallic piping which likely has a high thermal conductivity to transfer the propellants from the tanks to the ITS. This means that, should we fuel the ITS during the day, we will need to extract much more heat than if we do it at night. The average Martian surface temperature at night is roughly -40 C, which is much closer to the cryogenic average target of -187 C than the daytime temperatures. By using tanks made out of stainless steel, we take advantage of both the thermal conductivity for night time cooling/heat transfer as well as the structural properties that will aid in containing the gasses when they expand during the daytime.

The ITS utilizes cryogenic propellants, so logically it follows that they should be in a cryogenic state at the time that they're loaded onto the ship. We did explore the possibility of

loading the propellants first and then bringing them to cryogenic temperatures, but that would require special tanks to be installed on the ITS in addition to a refrigerator. The refrigerator would only be used prior to takeoff, and thus it would be dead weight at all other points in time, and thus the propellants must be in a cryogenic state at the point in time which they are loaded. We are then left with two options for storage: cryogenic and non-cryogenic. Should we store the propellants at cryogenic temperatures, we would need to both reduce the temperature from the reaction temperatures specified by the specific Sabatier reactors selected and maintain that temperature for storage.

The radiation experienced by the surface of the red planet poses a massive problem for cryogenic storage, especially since we will use stainless steel storage tanks for their structural characteristics and reliability. To mitigate this, we can store the propellants underground to provide some radiation shielding, store them at non-cryogenic temperatures, or both. We are unsure how prolonged radiation exposure would change the chemical properties of the propellants if at all, so we have begun to explore the possibility of subterranean storage options. The last storage option to explore is the question of cryogenic versus non-cryogenic storage—from what we can see right now, there is no significant benefit from storing the propellants at cryogenic temperatures. In fact, doing so would only drain more power, and quite a lot; the Martian soil, while it is a mediocre insulator material, it is not near perfect and several kilojoules of heat would be lost every hour. Storing the propellants at cryogenic temperature would require much more additional power, as much as an order of magnitude.

To meet our maximum requirement of producing 1950 mega grams of propellant each day, we will need to have each tank at maximum capacity. Safe storage pressures for methane tanks here on Earth are roughly 220 atm [6-13]. Due to the Martian environment, that pressure would require exceptionally thick tanks should we choose above-ground storage; however, by choosing subterranean storage, we can use tanks of a minimal thickness and utilize the internal pressure as a significant source of structural support. After speaking with the structures team, we calculated that for stainless steel tanks of minimal thickness, the top of each would need to be roughly ten meters below ground in order for the soil above to allow the tanks to be so highly pressurized whilst maintaining structural integrity.

The fabrication of the tanks will happen on mars. It is possible to make them on Earth and ship them in a shell-like fashion to the surface of the red planet, but this will cost roughly fourteen tons of payload mass allotment for each flight to be devoted to each tank in addition to large volume requirements. Fiscally, it is much more responsible and much easier to manufacture the tanks on mars. The tanks will be manufactured from stainless steel by welding two semi spheres to either side of a cylindrical section. A hole will be cut on the top, a pump installed, and then the passive cooling pipe will be welded on and then installed to a refrigerator. All components will be manufactured on mars possibly except for the piping. We did explore the possibility of utilizing detachable piping and simply switching it from tank to tank depending on which was fueling, but this proved to require too much time and power.

Once manufactured, the tanks will be transported via rover to their final installation location. Rovers equipped with digging equipment will dig troughs that are 44 meters long, 20 meters deep, and ten meters wide. The tank will be lowered in by two rovers, one on each side, and the hold for the pump will be facing upwards. After the pump and piping is installed, a rover equipped with a bulldozer-like attachment will push the soil back on top of the tank until it is level with the surrounding ground again.

6.5.4 Operation and Servicing

The tanks and subsequent piping will utilize passive cooling to cool the propellants to cryogenic temperatures. The propellants, at the time of fueling, will flow out of the tank, past the pump, through the above ground piping where they will begin to exchange heat with the environment, through the refrigerator where they will be cooled to the final cryogenic temperatures, and then into the ITS.

Luckily, due to the lack of power required to maintain the temperature of the propellant in storage, the tanks themselves are simple—they require little to no machinery for maintenance other than propellant loading and unloading, both of which will be above ground. Emptying the propellant tanks will be done by relying primarily on the internal pressure pushing the contents out. There will be two pumps—one to supplement this process, and one the pump the propellants in. The pump to move the propellants into the tank will be located in the propellant production

plant, and thus are not directly part of this system. The tanks are mad of stainless steel, and thus will not experience any oxidation whatsoever. So long as the soil composition is as we expect it to be and the tanks are located sufficiently deep in the soil to avoid prolonged radiation exposure, they will not likely need any resurfacing and will require little maintenance.

Operation of these tanks is simple, and will be performed by the same staff that operates the electrolysis and propellant production plants. Operators need only calculate by how much to open the pump to force the new propellant into the tanks. This can be done on a continuous basis or in intervals. There will need to be staff (most likely separate staff due to the requirements of the previously mentioned operators) that will unload propellants from the tanks via the pumps, allow flow through the passive cooling pipes into the refrigerator, operate the refrigerator, and fuel the ITS. As mentioned above, the propellants will be cooled cryogenically, and fueling will take place in sync with the Martian solar cycles to ensure maximum passive cooling efficiency—fueling at night allows the most heat transfer from the propellants to the environment, thus drastically reducing the power required to run the refrigerator.

All components on Earth have a maximum usable lifetime, and just like any tank on Earth, so will the tanks on Mars. We decided to model the maximum usable lifetime and servicing requirements and protocol for these propellant storage tanks in a manner similar to that of the tanks on Earth. Because the tanks will be stored underground, physically reaching them will be difficult. According to most storage tank manufactures that we researched for this problem, the maximum usable lifetime for a tank like this is seventeen years. Each ITS will require both of its propellant storage tanks to be dug up, replaced, and buried at least roughly once every two decades. This is not accounting for any other failures that can occur. Because of the miniscule thickness of these tanks (3 millimeters), digging with machinery will be sufficient only for the first nine and a half meters—should a user make an error when digging, machinery could possibly puncture one of the tanks and cause a catastrophic evacuation of gasses due to the high pressures that could result in loss of life, damage to surrounding materials/environments, or both.

6.5.5 Retirement, Disposal, and Replacement

The lifetime of each tank is expected to be seventeen years. The estimated lifetime is nineteen years (plus or minus two years), but to account for any possible manufacturing error, we define their serviceable lifetime as seventeen years. The tanks are made out of stainless steel which protects them from oxidation. In the best case scenario, they will be dirty and scratched by the end of their serviceable lifetime. This means that they can be melted down, purged of any impurities, and refabricated into new tanks. We currently have no estimate for how much time or power this process will require or if it will be either cheaper or easier to simply make new tanks from scratch. Preliminary estimations conclude that it will be economically more viable simply to verify the tanks' condition at the end of its service life to determine whether or not to integrate it into other functions of the Martian society.

At the end of each tank's service life, it will be dug up. One end cap will be cut off cleanly without destroying its edge. The inside will be inspected, and if both the inside and the outside of the tank are deemed to be in near new condition, the end cap will be welded back on, the tank will be reburied, and it will begin its service life again. If this is not the case, however, various steps will be taken to determine what part in the Martian society the retired tank can serve. Scientists and engineers will test the surface on the inside and outside of the tank for impurities. If there are any cracks, fractures, or outright holes, the tank will be cut into either square or rectangular sections and used for various applications such as flooring, support for regolith mounds and radiation shielding, or even inter-habitat conveniences such as tunnel walls or cargo cart rails. Some other possible uses for slightly worn tanks include but are not limited to: rover parts/components, replacement parts for habitat fixtures such as doors or wall panels, tables, ceilings, underground wall reinforcements, replacement components for any other plant such as the water reclamation or hydrogen production plants. The possible uses for good stainless steel are endless, and thus the pieces will be used where they are most needed. We can expect to harvest roughly 8400 tons of steel each year beginning in year seventeen from retired tanks, assuming no critical failures such as explosions or blowouts.

In the event of a tank blowout, the surrounding equipment including but not limited to the passive cooling pipeline and refrigerator would need to be checked for damages. Any and all damages to other subcomponents would need to be assessed independently. The soil above the

tank would be removed via rover, and the tank would be lifted from its cavity. The damage on the tank would be assessed, and if the damaged section is small enough, it would be cut out and the rest of the tank would be recycled as specified above. In the event that the tank is either totally destroyed or has reached the absolute end of its useful life to the point where it can no longer be recycled, it would either be melted down and reformed or taken to an off-site junkyard area—whichever is more economically viable.

The pipelines will follow the same retirement procedure as the tank components specified above. The refrigerators, however, will not. At the end of their serviceable lifetime, they will be stripped of their housing, their parts will be harvested, and the remains will be transported via rover to an off-site junkyard.

Installation of new systems and replacement of old systems are synonymous except the troughs will already be dug. To reiterate, rovers will bring the new tanks to the troughs and lower them in. A hole will be cut in the top of the tank for the pump. Once the pump is attached, the passive cooling pipe will be welded. It will then be attached to the refrigerator on the other end, and its serviceable lifetime will begin at the point when it is initially filled with propellant.

6.5.6 System Cost

Similar systems on Earth can be very costly; however, the requirements here are very different. Stainless steel can be bought on Earth for $1.05 per kg [6-17]. If we could mirror that cost, the tanks required to fuel one ITS over the course of seventeen years would cost us $1501.5—we cannot necessarily do this though, because both the Martian economy and manufacturing processes will be different. On Earth, we factor the price of materials, the labor cost, and the factory energy expenditure into that cost. This is done because we are living in a society that is based on capitalistic principles. The Martian society will most likely function more like a commune initially until there are enough members to sustain a functioning economy—each person will have certain tasks to complete and will most likely not receive monetary compensation for their completion. We can thus strike those costs and factor in only the energy requirements into the cost.

We base the cost estimate for this system solely off its energy requirements. Unfortunately, nearly all Earth-based data is given by a for-profit basis. While the SpaceX expedition to mars is

definitively for-profit, the steel fabrication plant and refinery is not. There are virtually no companies on Earth that sell energy at a negative profit, and very few, if any, that give it away for free. We thus base our cost estimates on the cheapest energy available on Earth. Cheap energy typically comes from government sources in first world countries. Currently, the cheapest available energy is prices at $50/MWh, or $1.4E-2/kJ [6-15]. This is exceptionally cheap, and when we take into account the total power requirements for both storing and loading the fuel, the cost of energy will be roughly $400 per ITS, or $40,000 total ($42,300 to be exact) for all 100 ITSs on a per synodic cycle basis. This is not including the cost of shipping any propellant storage materials to mars. If we ship refrigerators, piping, and/or tank shells etc, we can estimate that this will run at NASA's estimated $27,000 per lb [6-16]. This will obviously drive prices up exponentially. To keep costs down, we need to manufacture as much as possible on mars and focus on having humans being the main cargo.

6.5.7 Risk Analysis

Table 6.5.7.1 shows a risk analysis of the propellant storage system. Due to its simplicity, failure is not likely. There are ten foreseeable modes of failure, each of which is outlined below. The system is extremely simple except for the refrigerator and the pumps, so naturally those components carry with them the highest risk.

Table 6.5.7.1 Storage Facility Failure Analysis

Failure Mode	Probability [%] (Estimated based on Earth Data)	Severity	Repair Cost [$] (Estimated based on Earth Data)
Tank Rupture	1.0	Extreme	1501.1
Tank Fracture	0.5	Medium	Up to 1501.1
Pump Burnout	2.0	Low	400
Pump Failure	1.5	Low	400
Pipe Rupture	0.2	Medium	850
Pipe Fracture	1.0	Low	850
Refrigerator Failure	3.5	High	1000

Power Outage	4.0	High	Up to cost of Power Plant repairs
Sealant Failure	1.0	Medium	200
Weld Failure	0.5	Extreme	200

Should the tank rupture, fracture, or otherwise fail (including seals and/or welds), the results could be catastrophic—the most expected result is to lose most if not all of the stored propellant; however, this failure could also involve loss of life should there be colony inhabitants near enough to the tank. This could also damage other equipment in the surrounding area. The repair cost for tank failure does not take this into account. Rather, each repair cost listed below is for that individual component; if a tank fails and damages the pipe, add those two repair costs together.

The pump will be equipped with electronic shut off valves as it will be underground and impossible to reach during operation. Should one of those valves fail, there are two possibilities: it will have failed while open, or it will have failed while closed. If it failed while open, the worst thing that could happen would be that the pipe would fill with propellant. There is another valve located between the refrigerator and the piping, so that would be sufficient to cease all flow given an expenditure pump/valve failure.

Pipe failure severity could range from trivial to medium depending on the type and location of the failure. Should the failure occur underground during fueling, the surrounding compacted soil could possibly become saturated with flammable methane. In that case, an evacuation of the local site would be necessary. Should the above ground section fail, the methane/oxygen gas would leak into the environment and disperse without any damage to the surrounding inhabitants or machinery.

The refrigerator is the most complex part of this component system, thus it follows that it carries the highest risk of failure. Failure of the refrigerator could include coolant leaks, oxidation of subcomponents, improper seals, etc. In the worst case scenario of a total failure during fueling, the valves need only be shut off and the local area evacuated until on site personnel can evaluate the environment for leaks.

In the event of a total power outage, the severity would depend on the state of the valves. Should the power outage be caused by something like a surge during fueling of an ITS, the valves would be unable to close, and fuel would continue to pour into the ITS at an unrestrained, immeasurable rate; however, if this outage occurs while the tank sits dormant with all valves close, there is no issue—we need only wait until the power system is repaired. The last option if for the power outage to occur during the initial stages of repair. In that scenario, on-site protocol will list valve closure as one of the initial steps, so this would not be too severe.

6.5.8 Risk Mitigation Strategies

Because this system is so simple, the mitigation strategies will be, for the most part, simple.In the event of a tank failure or rupture, total replacement will be necessary. On-site personnel will begin the procedure by shutting off the refrigerator, closing the tank evacuation valve, and evacuating the pipe and filling it with atmospheric CO_2 at atmospheric pressure. They will then proceed to bring in rovers to commence digging until the seal between the evacuation pump and the tank are visible. They will then remove the pump and subsequent piping from the top of the tank, keeping it nearby. The tank will be lifted from the ground and set aside. Workers will then evaluate the state of the tank as described in Section 6.5.5. A new tank will be installed, if necessary, and the process will reverse.

In the event of a pump failure during refueling, immediate evacuation of the local area is required until on-site personnel can evaluate the danger. The failed pump would be rendered useless, so the other pump would need to be shut off and all valves closed. Once all valves are closed, the same procedure as listed above would be followed with exception to removing the tank. Instead, once workers reached the pump, they would remove and replace it. They would then take the old pump and evaluate its usefulness and viability for scrap parts.

Should the pipe fail, both valves would need to be shut off immediately. If the failure occurred underground, immediate evacuation of the local area would be required due to the possibility of subterranean methane saturation. If methane leaked into the soil, there is a possibility of combustion. Should that happen, it is highly likely that the nearby equipment would need to be replaced. If the failure occurs above ground, both valves would still need to be shut off, but any

escaped gasses would simply leak into the surrounding atmosphere and disperse. The refrigerator would be disconnected, and rovers would dig up the buried portion of the pipe. Workers would disconnect it from the tank, remove it, and replace it. They would bury the new pipe, and operations would resume as normal. The old pipe would be taken to a facility where it would be evaluated for future use. Workers would determine if they could repair it or if it could only be used for scrap metal.

In the event of a refrigerator failure, the pump would be shut off and both valves would be closed. The refrigerator is the most complex aspect of this component system, so it would be highly efficient and cost effective if we can leave it connected and simply repair it. Removing it and transporting it elsewhere leaves room for further damage. Workers will assess the damage on-site and determine the cause of the failure—if the cause is simply the need for replacement fluids or a minor servicing, worker will perform that, then open the valves and turn on the pumps to resume normal operations. If the failure involves a more serious issue that the workers cannot repair on-site, they will remove it as necessary, transport it to a separate facility, and attempt to perform repairs there. If they are unable to perform repairs, they will disassemble the refrigerator and harvest all of the working parts to be used in future repairs. They will dispose of the remaining subcomponents and attach a new refrigerator to the pipeline.

The last foreseeable mode of failure would be a total power outage. In the event of a total power outage, on-site workers would need to determine if it was local or if it came from a higher up system. If the outage occurred during fueling, the workers would need to evacuate the local area in the case that fuel could be leaking. Once on-site workers determine that there is no leak or that it is safe to approach the system, they would attempt to find and fix the source of the outage. If they were unable to do so, they would have to call in teams from other component systems to try and identify from what system the source is from and repair it.

6.6 Propellant Transport

6.6.1 CAD / System Totals

One of the most important yet easily overlooked aspects of this project is propellant transport—the majority of our efforts so far have been aimed at propellant production, habitat management, communications, food, etc; however, we haven't spent much time until recently investigating propellant transportation. Section 6.5 outlines how the propellant will be stored and all of the risks and procedures associated with that. This section will outline how we will move the propellant from the tanks to the ITS. Shown below, in Fig. 6.6.1.1

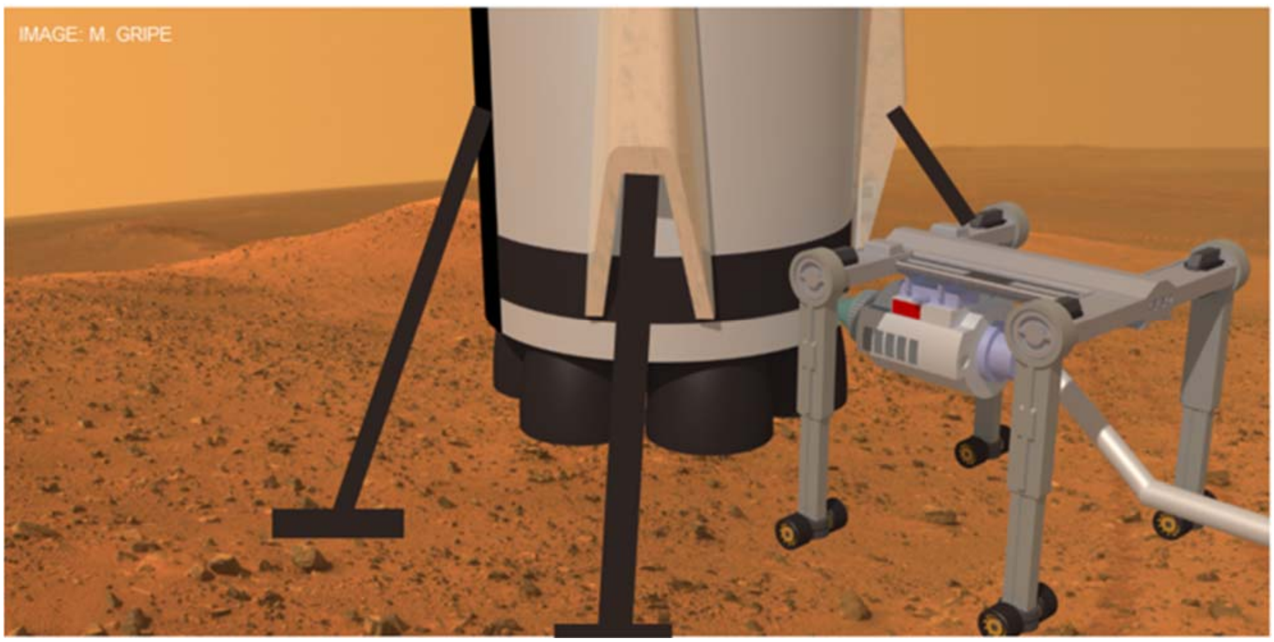

Fig. 6.6.1.1 Rendering of Oscar, the refueling rover. (Credit: M. Gripe)

This rover is a slight variation of the ones that will be used for other aspects of the project. The rover itself will require slightly less power to operate than the storage facility itself. The number of rovers needed is largely dependent on how quickly we want to refuel each ITS and how far apart they can land/will be stationed—If we can improve the landing accuracy of the ITS, we may need as little as one rover per three ITSs for rapid deployment if we can group them close enough. The estimated system totals for the fueling rover are shown below in Table 6.6.1.1

Table 6.6.1.1 OSCAR MPV

Rover Name	Power [kw]	Mass [Mg]	Speed [m/s]	Capacity [Mg]
Oscar	129	1.6	2.8	392.4

Each ITS is capable of carrying up to 1950 Mg of propellant, so at the current capacity, a single rover used for refueling would need to make five trips to and from the refrigerator site. This is, however, to fuel the ITS at max capacity. For most missions, the rover would need to make at most three trips or possibly less should we assign two or more rovers per ITS. These figures help illustrate how important the landing accuracy of the ITS is; if the ITS can land within a reasonable distance of the refrigerators, the rover will have much less distance to travel.

6.6.2 System Map

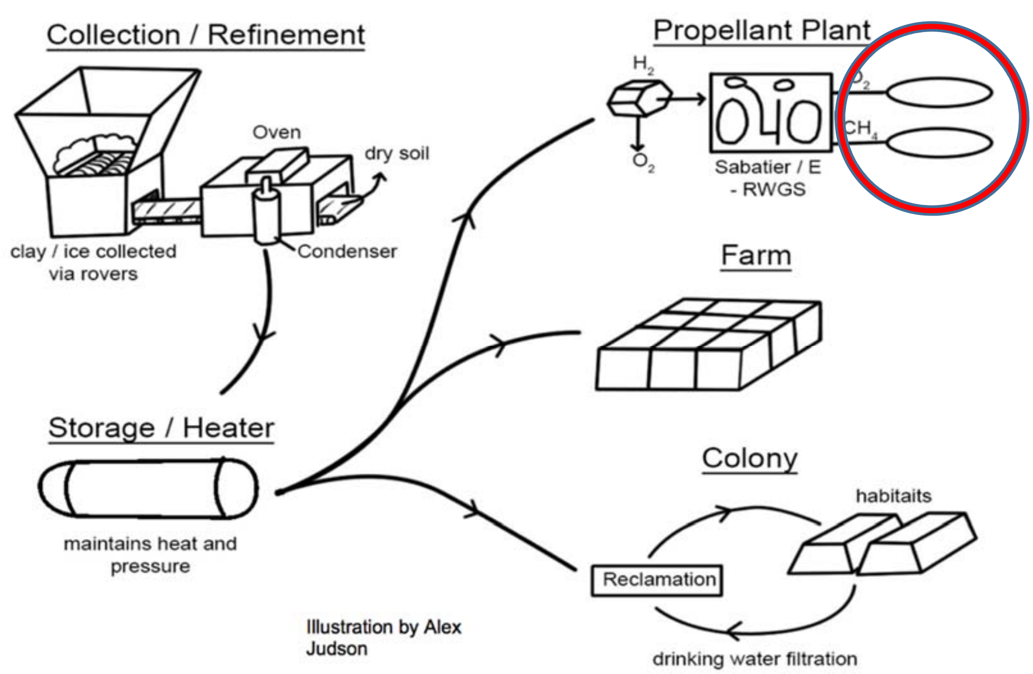

Fig. 6.6.2.1 System Map showing the propellant storage tanks

6.6.3 Deployment / Fabrication

Rovers are heavy—shipping them up is extremely expensive, but this isn't like the storage tanks mentioned in Section 6.5; those are relatively simple pieces of equipment that can be shipped up without paying much attention to onboard vibrations during liftoff, initial flight, and descent. The rovers will be chock-full of sensitive instrumentation and machinery. NASA spends millions sending their rovers up, and we do not want to spend that kind of cash if we don't have to. Thus, we look to in-situ fabrication, again.

As previously stated, rovers are full of sensitive, advanced instrumentation. Unfortunately, the soil composition and readily available mineral and resource supply on Mars are lacking, especially when compared to that of Earth. The rovers have some larger, simpler components such as housings, containers, and covering—these are most likely the components that will be made on the red planet. Unless we can find more materials and develop advanced manufacturing facilities, we will not be able to manufacture them completely on mars.

It is possible to send rovers up already assembled in the cargo bays of the human-transport ITSs, however, this would take up precious cargo space. This would allow an opportunity for the rovers to be built here on Earth, which subsequently would lead to a higher build quality over their lifetime. It would also allow them to be fitted with more precisely built/machined parts. Any fabrication that happens on mars may be sufficient, but it simply will not match the quality of fabrication on Earth. So these rovers will either be built on Earth entirely, or have their main components built on Earth and then larger, simpler components built on Mars and assembled there.

Should the rovers be built on Mars, the sensitive machinery will be delivered with an ITS and must be transported to an environment safe from dust until they are ready to be assembled. The housings and covers for the rover exterior including many of the rails and other components of the legs and wheels will come from a metal refinery located on Mars. The rovers will be assembled by on-site workers and tested before they are added to the fleet. Once the rovers are deployed, they will be stationed at the refrigerators of the propellant storage plants so that they are ready for fueling at all times.

6.6.4 Operation and Servicing

Because the rovers are so much more advanced than the propellant storage plants, they will most likely need servicing more often. The rovers that NASA sent up to Mars had, in some cases, lifetimes of several decades. While we do not estimate that this will be the case, they will undergo regular maintenance. We recommend that each rover undergo at least one hour of maintenance for each Sol it is active. Servicing each rover will include general inspection, but may also in some cases include major repairs.

Repairs to each rover will be carried out by skilled technicians. Due to their large size, we will need a large facility to repair and maintain the rovers. Each facility will have full time staff working to repair and service the machines. In the early days of the colony, it is likely that some rovers will need repair to parts that were manufactured on Earth. It is highly possible that those parts will not be available for manufacturing on Mars, so we must send the first few ITSs complete with some spare parts that can only be made on Earth.

Operation of each rover will be done from a remote location. Each rover will only be responsible for two tasks: loading and unloading fuel. We explored the possibility of onboard piloting; however, due to the simplicity of the tasks, this has proved unnecessary.

The service life of each rover will be twenty years. This figure was determined by taking the average service life of NASA rovers [6-18] and applying an appropriate factor of safety to account for the extremely rough conditions that the rovers will be operating in when compared to previous rovers. The Oscar rovers will not only be operating constantly, but they will not have to experience the typical 22 minute delay that the NASA rovers experience. The rovers currently on the red planet are given very short command at a maximum frequency of once every 22 minutes. Oscar will, at its most frequent usage, receive several far more complicated commands instantly. It's very possible that Oscar will not stop travelling until its service period during the current Sol.

6.6.5 Retirement, Disposal, and Replacement

As mentioned earlier, these rovers are extremely complex, especially when compared to the storage tanks already in place. Fortunately for us, they are also rather large due to their large

propellant volume requirements. This means that upon their retirement, they will be able to serve many more purposes than most other components in the colony.

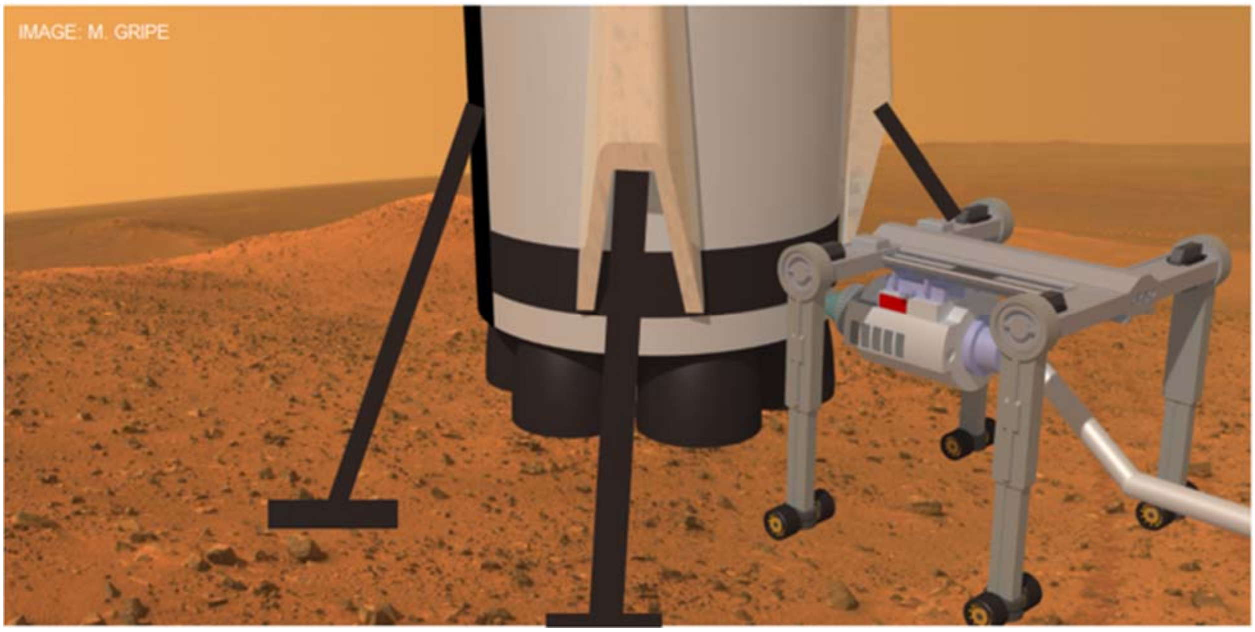

Fig. 6.6.1.1 Rendering of Oscar, the refueling rover. (Credit: M. Gripe

Each rover will be equipped with a storage tank, four legs, "spine" (structural rail), two pumps to aid with propellant loading and unloading—one pump will be used to help the storage tank evacuation pumps load propellant into the rover, and the other will be used to pump the propellant into the ITS—and eight wheel assemblies. Upon retirement, each rover will undergo an inspection.

The inspection will determine exactly what parts of the rover can and cannot be used. On-site workers will begin the inspection by transporting the rover to a facility separate of the storage tank areas. There, they will remove the power supply. They will then test the power supply to see if it is still functional. If it is, they will store it so it can be used as a backup power supply in the event of future rover power failure. Then, they will begin disassembly by fastening the legs so that the rover will not fall. A worker will board the top of the rover and begin disassembling pieces manually. All internal computers and systems, if functional, will be stored for future use. After any and all sensitive internal components are removed, the workers will then move on to the storage tank.

The storage tank is much smaller than that of the propellant storage tanks used by the propellant production plant for long term storage, so using them as a backup or replacement would

be futile and implausible. Once the storage tank is removed, workers will test its current durability and usefulness as a pressure vessel. If it proves useful, it will be stored as a backup tank for future rovers. If not e.g. it is ruptured or corroded beyond repair, the workers will harvest the good portions of the tank and dispose of the useless portions. The useable portions will be treated in a similar fashion to the used storage tanks outlined in Section 6.5.5—they will be cut up into squares or strips and used in various portions in the colony including but not limited to floor tile replacements and fixture repairs. The sections can also be stored for future use. An alternate yet undesirable option would be to melt the metal down and cast it into whatever shape necessary. While this may be a useful alternative in the future, the energy produced by the colony in its early days will be scarce, and this will require power that would otherwise be used for possibly lifesaving functions.

Storing these components allows us to cease most of the back up part shipments from Earth, and will ultimately save us hundreds of thousands, if not millions of dollars in shipments. Disposal will follow the same protocol as outlined in Section 6.5.5—any parts that are beyond their useable lifetime where the workers on hand are unable to harvest any subcomponent for current or future use will be transported to an off-site junk yard. All other parts will be either stored or immediately recycled.

6.6.6 System Cost

Each rover will be very expensive, and modeling that expense is very difficult when launch costs are taken into account. NASA rovers can cost anywhere between $87 million and $2.5 billion [6-14] when the launch costs are taken into account. We don't have that kind of money to spend on such a small component of a subsystem. The following section bases all costs on the prices of the raw materials required and assumes—as mentioned in previous sections—that all in-situ labor does not cost any USD as there will be none circulating in the Martian "economy". As for construction of the rovers, the majority of the body and inner components of each will be made from steel. We can safely assume that they are each 90% steel by mass. This allows for 10% of the mass to be devoted to control systems such as small computers and sealant systems. Using the price of steel as listed in section 1.1.6, we can estimate the cost of the steel required for the rover to be roughly $1,680. Assuming that we have one rover per ITS, that is $84,000 per every

serviceable lifetime. We estimate that about %30 of the cost will stem from computer systems and other subsystems. We can thus estimate that the total cost of each rover per serviceable lifetime, excluding maintenance and repair due to the supply of spare parts, will be $2,184 which will work out to $109,200 for all rovers per serviceable lifetime. This, again, is assuming that one rover can fuel two ITSs.

6.6.7 Risk Analysis

Because the rovers are so complex, there are an incredible number of ways that they can fail especially when we take the computer systems into account. For this analysis, all failures that the computer and control systems can experience will be lumped into the "Computer Failure" section. Table 6.6.7.1 shows the different failure modes and probabilities.

Table 6.6.7.1 The estimated failures risks and costs for propellant storage

Failure Mode	Probability [%] (Estimated based on Earth Data)	Severity	Repair Cost [$] (Estimated based on Earth Data)
Tank Rupture	1.0	Extreme	1501.1
Tank Fracture	0.5	Medium	Up to 1501.1
Pump Burnout	2.0	Low	400
Pump Failure	1.5	Low	400
Computer Failure	0.2	Medium	850
Power Outage	4.0	High	Up to cost of new rover
Sealant Failure	1.0	Medium	200
Weld Failure	0.5	Extreme	200
Structural Failure	1.0	High	2184

Should the tank rupture, fracture, or otherwise fail (including seals and/or welds), the results could be catastrophic—the most expected result is to lose most if not all the stored propellant; however, this failure could also involve loss of life should there be colony inhabitants near enough to the tank. This could also damage other equipment in the surrounding area. The

repair cost for tank failure does not take this into account. Rather, each repair cost listed is for that individual component; if a tank fails and damages the pump, add those two repair costs together.

Should the pump fail, the damage would be minimal at most. There would still be propellants in the lines, but a simple purge and valve closure would remedy this. The rover would then be submitted for repair. This, however, would be very different than a computer failure. A computer failure could mean many different things ranging from failure to start pumps to failure to report accurate flowrate data. The former would also cause minimal damage, while the latter could over pressurize the tanks on the ITS. We would, at that point, need to rely on onboard sensors to verify the pressure.

In the event of a power outage, there may be no damage at all, or there may be catastrophic damage depending on what state the rover is in. A power outage may prevent the control systems from maintaining the rover in a balanced, upright position which could ultimately result in spillage of propellants. In that case, the area would need to be evacuated until a clean-up crew arrives.

6.6.8 Risk Mitigation Strategies

In the event of a sealant/weld/tank failure, the protocol is nearly the same—all systems would be shut down and on-site teams would survey the area to verify that there is no leakage. If there is leakage, workers would verify that all pumps are shut off and evacuate the surrounding area so that no personnel are injured. Once the leak stops and all gasses disperse into the environment, the workers will go out and asses the state of the tank/containment vessels and replace/repair them accordingly.

Should the pump fail, the workers will simply shut off the connecting valves remotely. The rover will then disconnect from the storage tank and the ITS while a worker inspects the pump. Should the pump need replacement the worker will remove it and install a backup while taking the original to a facility where they can assess the damage and determine if the pump can be recommissioned or if it needs to be recycled.

In the event of a power outage or computer failure, there are several different routes the workers can take. If the rover is stable and upright, they can verify that there is no leakage and then inspect it visually, run computer diagnostics, and replace the computer or power supply if

need be. If the rover has fallen over, they would have to verify that all valves are closed and that there are no leaks before they begin the repair processes. They would disassemble the rover if necessary and repair the required components.

6.7 Metal Refinery

6.7.1 CAD / System totals

Fig. 6.7.1.1 Metal refinery CAD model. Credit: Jay Kang

The metal refinery show in Fig. 6.7.1.1 produces steel and or iron from the Martian regolith. The refinery is comprised of a direct reduction furnace and an electric arc furnace. The direct reduction furnace smelts iron oxide into hot direct reduced iron. The reduced iron than goes into the arc furnace to be refined into steel. Table 6.7.1.1 shows the throughput of the system, assuming high iron oxide concentration. We design the metal refinery for ten metric tons of capacity per cycle, with the assumption that five cycles can be completed in a day.

Table 6.7.1.1 Metal refinery throughput.

System	Input: Regolith (Mg/day)	Output: Steel (Mg/day)
Metal Refinery	305.6	50

Metal refineries are large and heavy compared to other systems; however, due to the amount of steel required for colony infrastructure metal refineries significantly reduce the number of ITS cargo launches required. With a lifetime of 20 years and assuming only one refinery is

needed during that time we require 5 refineries over the course of 100 years. Table 6.7.1.2 Metal refinery MPV. shows the breakdown of the mass, power and volume for these systems.

Table 6.7.1.2 Metal refinery MPV.

Metal Refineries	Mass (Mg)	Power (kW)	Volume (m^3)
Single Unit	175	5763	70
Total System over 100 Years	875	5763	350

6.7.2 System Map

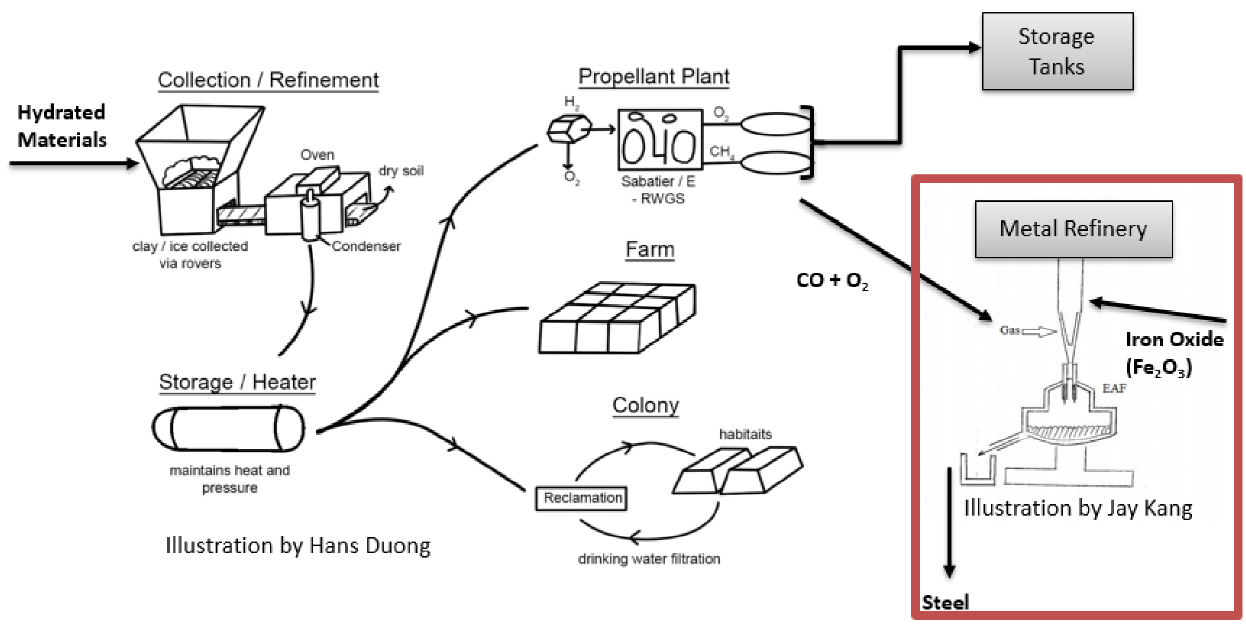

Fig. 6.7.2.1 Mars resource management system map. Metal refinery location.

The system flow of the refinery is shown in Fig. 6.7.2.1 Mars resource management system map. Metal refinery location.. Our metal refinery takes in regolith with high iron oxide concentration and carbon monoxide from the propellant plant. The materials are combined in a direct reduction shaft furnace and heated to reduce the iron oxide into hot iron metal. The iron is

transferred to an electric arc furnace where it is burned with oxygen to create molten steel. The steel is converted to usable form either by a rolling or casting process.

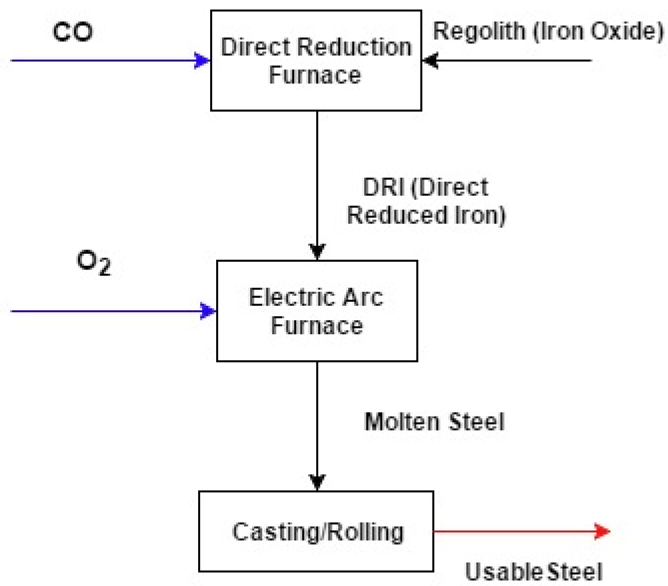

Fig 6.7.2.2 Metal refinery system map

6.7.3 Deployment / Fabrication

We fabricate the metal refineries on Earth, but unlike the hydrogen and propellant plants the refinery is broken up into components. Such as the direct reduction furnace, electric arc furnace, supports, graphite electrodes. Once on Mars the components are offloaded and with the help of machinery the colonists can construct the system at the appropriate location.

6.7.4 Operation and Servicing

Unlike many of the other systems the refinery is not operating constantly, unless there is demand. Since the steel has to be made in batches the required iron oxide needs to be gathered beforehand. Once we have the required materials the iron reduction process is started. After which the hot iron has to be dispensed into the electric arc furnace. The colonists then tilt the arc furnace using the hydraulics to pour out the molten steel and roll it into shape.

During the process of making steel the graphite electrodes are used up and will need to be periodically maintained or replaced. The extra electrodes will need to be shipped from Earth.

6.7.5 Retirement, disposal, and replacement

We estimate the lifespan of the metal refinery to be around 20 years. Some of the components such as the electric arc furnace crucible can last longer so the colonist can just replace the other components, to reduce on the mass being shipped to Mars. However, if this is not possible many of the parts are made of steel which can be recycled in the next refinery to produce higher quality steel. The other parts that are not used up will be discarded.

6.7.6 System Cost

For the metal refinery cost analysis, we use the typical prices for Earth systems and components with the same capacity we require. The major components include the EAF, DRI furnace and the graphite electrodes. The graphite electrodes will need to be replaced due to wear, therefore are a recurring cost. However, for 2 kg of graphite the system produces a metric ton of steel. As we can see in Table 6.7.6.1, the total system cost is minor compared to the other systems, however it is hard to predict the actual cost of modifications required to make these systems Mars worthy. The unit cost of a graphite electrode is per metric ton.

Table 6.7.6.1 Metal refinery cost breakdown.

Component	**Unit Cost**	**Cost Margin**	**Total System Cost**
EAF	$ 250,000	20 %	$ 1,250,000
DRI Furnace	$ 200,000	40 %	$ 1,000,000
Graphite Electrodes	$ 2,650	5 %	$ 26,500
Total	$ 452,700	30 %	$ 2,276,500

6.7.7 Risk Analysis

Table 6.7.7.1 provides the potential failures that occur during the operation of the metal refinery. Many of the failures are very unlikely to occur, except for some mechanical failures that

can be fixed. **Error! Reference source not found.** also shows the approximate fault tree derived for the system with major failures. From the fault tree, we see that there are few redundancies in the system, but the risks of individual component failure are low during the lifetime of the plant. The main redundancy is in the hydraulic system that positions the electrodes and pours out the metals.

Table 6.7.7.1 Metal refinery FMECA.

Description of Failure	Effects of failure on the system	Risk Mitigation	Probability of Failure	Mean Time to Failure
Plant goes offline	Cannot produce more steel	Backup plants or ship steel from Earth	1%	20 years
DRI furnace failure	No more iron or steel production	Backup furnace or recycled steel used instead	Low	20 years
EAF failure	No more steel production	Backup furnace	Low	20 years
Hydraulic failure	Steel cannot be poured out, potential	Use crane/excavator rover as temporary replacement	Medium	20 years
Overheating	Damage to furnace structure, fire.	Automatic emergency shutdown and cooling system.	Medium	
Cracking in EAF shell	Reduced output and potential failure of system	Maintenance and safe operation	Low	40 years
Loss of power	Hardening of steel/iron, damage to furnaces	Backup power supply for emergencies	Low	

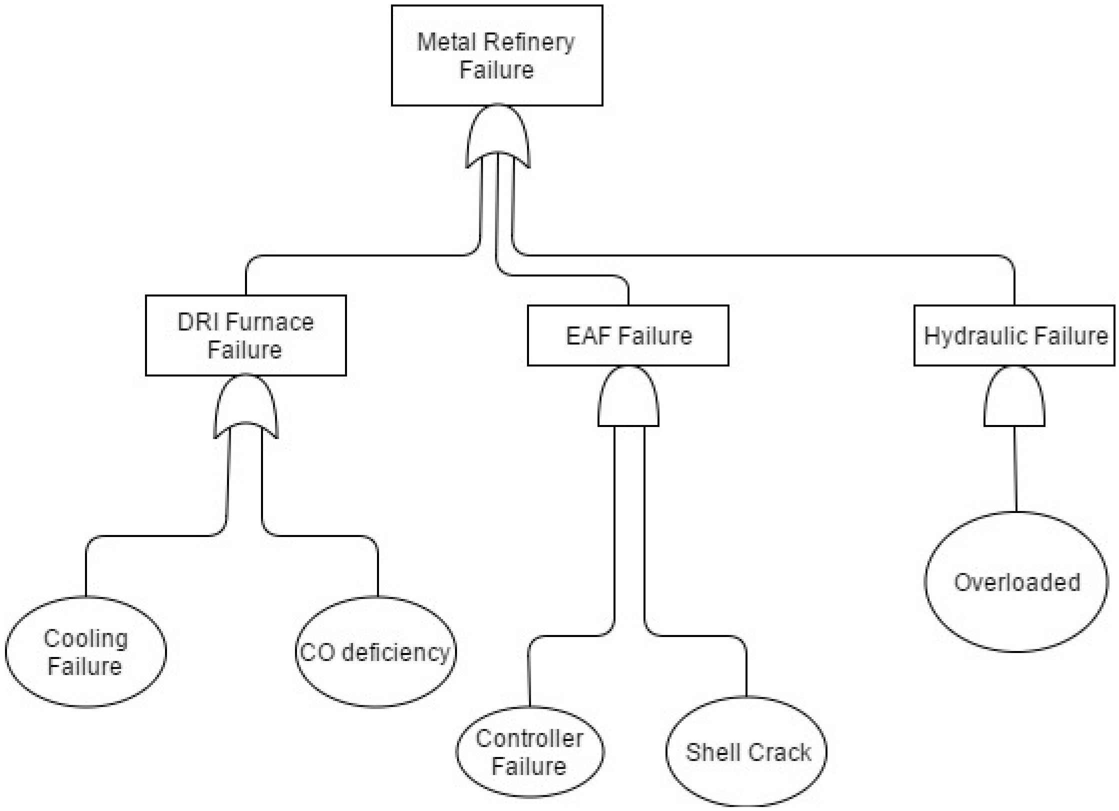

Fig. 6.7.7.1 Metal refinery fault tree.

6.7.8 Risk Mitigation Strategies

The main way to mitigate failure for the metal refinery is constant supervision by a qualified operator that can shut down or adjust refinery operation. In the event of power loss the unfinished steel can also just be poured out manually. Overheating is the biggest issue for the metal refinery which will only occur if there are issues with cooling. In the event of this the refinery should be shut down and the steel poured out to reduce damage to the system. Removing the steel from the furnace should be enough to cool it. As such a dedicated refinery operator position is must.

6.8 References

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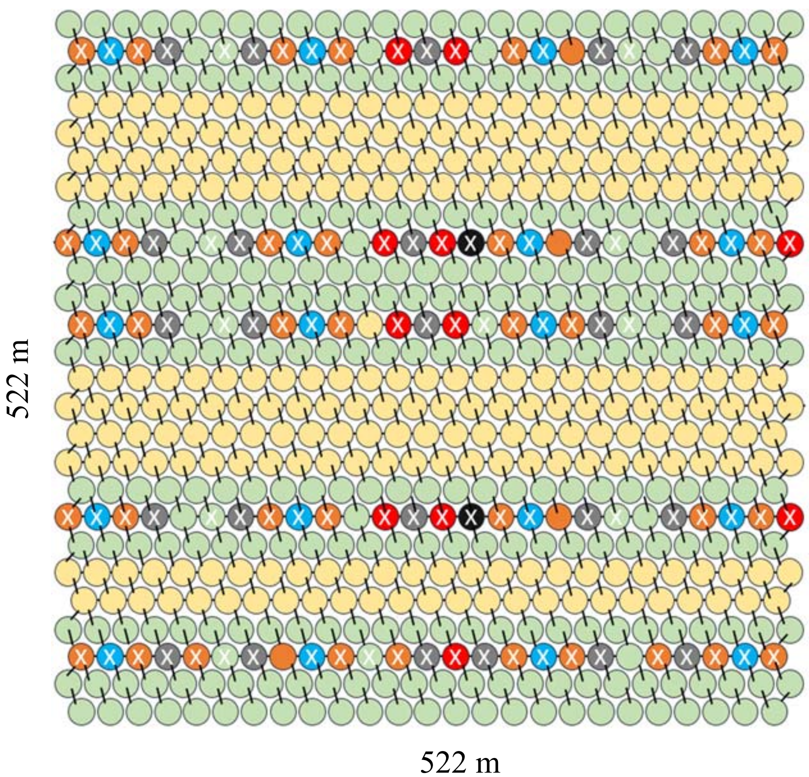
7 25,000 Inhabitant Quarry City

7.1 Layout and Infrastructure

In order to build permanent structures on Mars, the materials that are on the planet's surface must be employed. To gather materials needed for construction, Martian regolith is excavated. Since there will already be large holes in the ground due to material mining and water extraction, we decide that the permanent structures will be built inside of these holes as quarry cities. The peak number of colonists that arrive to Mars in any one synodic period is 24,700. From this number, we set the size of the quarries such that they can hold 25,000 people. This means that a total of 40 quarries are needed to house 1 million people. The top-down view of the underground portion one of these quarries can be seen below in Fig. 7.1.1.



Mint Green – Living/Bathing (305)

Gold – Farms and Food Storage (256)

Orange – Recreation (43)

Light Blue – Wallyball Court (20)

Grey – Common Eating/Meeting (26)

Red – Science (11)

Black – Medical (2)

Fig. 7.1.1 A top-down view of the underground quarry city. (Credit: K. Ziesig)

The dimensions of the quarry shown above are 522 meters wide, 522 meters long, and 22 meters deep. The circles in the figure are 3D printed cylindrical structures made of volcanic basalt. There are 663 of these cylindrical structures below ground. Each cylinder has an internal diameter of 18

meters and internal height of 18 meters. This allows for 6 floors of living space in the structures where that is necessary. In addition to the underground portion of the quarry cities, there is an above ground component that can be seen in Fig. 7.1.2 below.

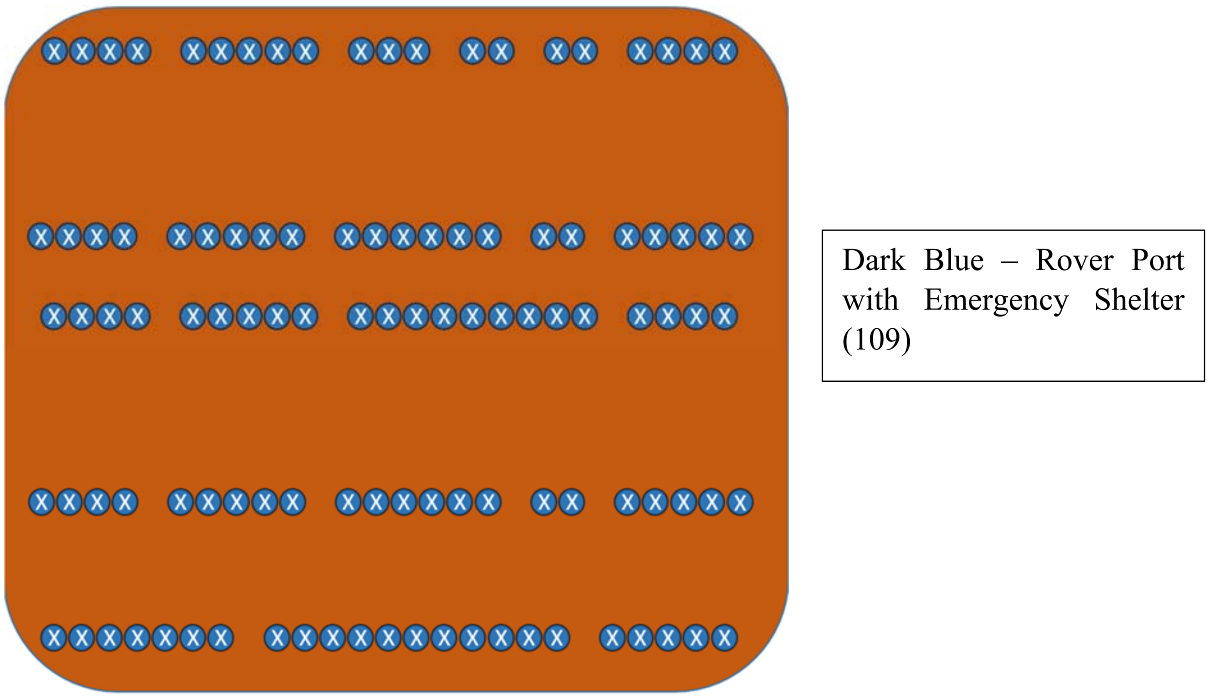


Fig. 7.1.2 A top-down view of the above ground portion of the quarry city. Credit: K. Ziesig

There are 109 rover ports above ground that act as garages to recreation rovers and construction rovers as well as cargo transport and maintenance areas. In the event of depressurization or some other form of structural failure in the underground quarry, each rover port also acts as an emergency shelter for the Martian colonists. Each rover port has an internal diameter of 18 meters and internal height of 9 meters, providing two floors of space. To see an in-depth discussion of quarry and individual structure size, as well as volume requirements for the different quarry components, please refer to Section 7.

7.2 Quarry Digging Process

The colony quarries are excavated using a combination of hydraulic excavators and dump trucks. These vehicles are automated to facilitate operation around the clock, which increases the amount of material that can be mined in a synodic cycle.

Excavation rate are determined by the arrival rate of colonists. By the time a set of colonists arrive, the quarry must be excavated, and the structures inside must be constructed. It is also desirable to finish covering the quarry in the protective regolith layer and constructing the surface rover ports. We determined that our system should meet its target excavation goal for each synodic cycle within one year of the beginning of that cycle. This permits the internal structures to be completed in time for the arrival of the inhabitants in the next synodic cycle.

For the first three synodic cycles, our excavation system must clear one-third of a complete 25,000 inhabitant quarry, which is 1,998,216 m^3 of regolith, per cycle. After those first three cycles, the excavation rate becomes constant: one complete quarry per cycle (Fig. 7.2.1).

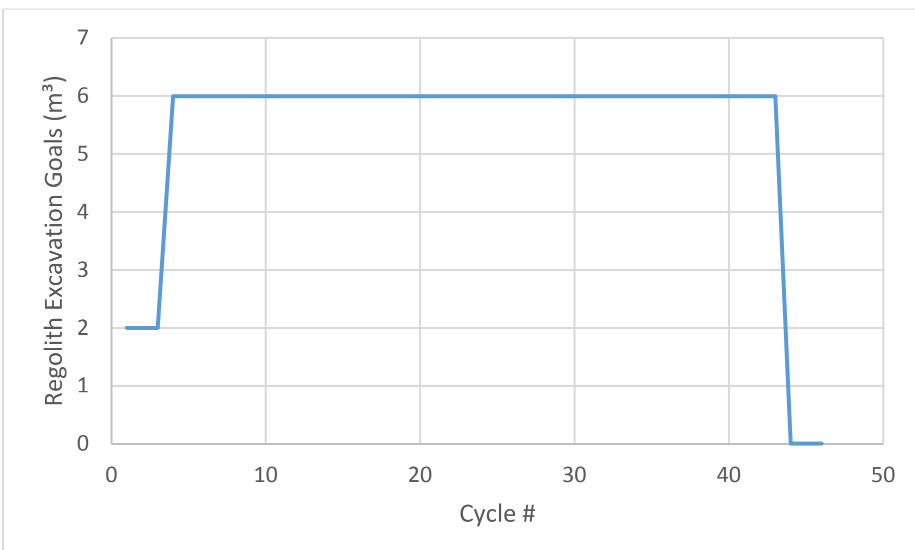


Fig. 7.2.1: Habitat Quarry *Excavation quickly reaches a steady rate, and completes by cycle 43. (Credit: J. Reband)*

In order to match this constant rate, our excavation period for each goal will be spread over one synodic cycle in length. However, excavation will begin early enough to meet the deadline at the one year mark into each cycle.

7.2.1 Excavation Rovers

7.2.1.1 *System Description*

Our excavation vehicle accomplishes the movement of Martian regolith and minerals for the purposes of construction and resource collection. This vehicle takes a form similar to a hydraulic excavator found on Earth, allowing it to dig downward and break up tough rock layers. The vehicle is built on the same modular chassis as the Martian Cargo & Personnel Transport System.

7.2.1.2 *CAD / System totals*

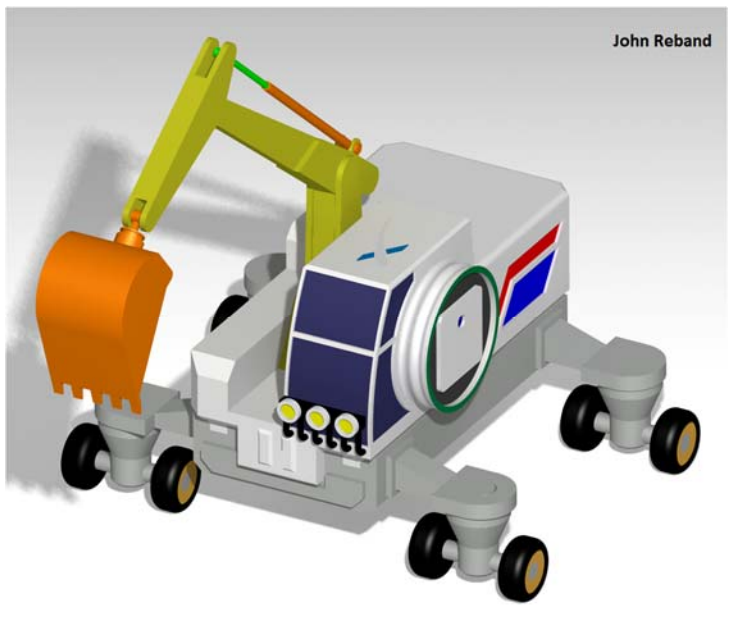


Fig. 7.2.1.1.1: The Excavation Rover Uses hydraulic pistons to excavate large quantities of regolith. (Credit: J. Reband)

Table 7.2.1.1: Excavator Mass, Power, Volume

	Per vehicle
Mass	19.7 Mg
Nominal Power	126 kW
Volume	72.6 m^3

Table 7.2.1.2: Excavator capability Metrics

Excavator- Capabilities	
Excavation Rate	1451.88 m^3
Lifetime	30 years

7.2.1.3 *System Map*

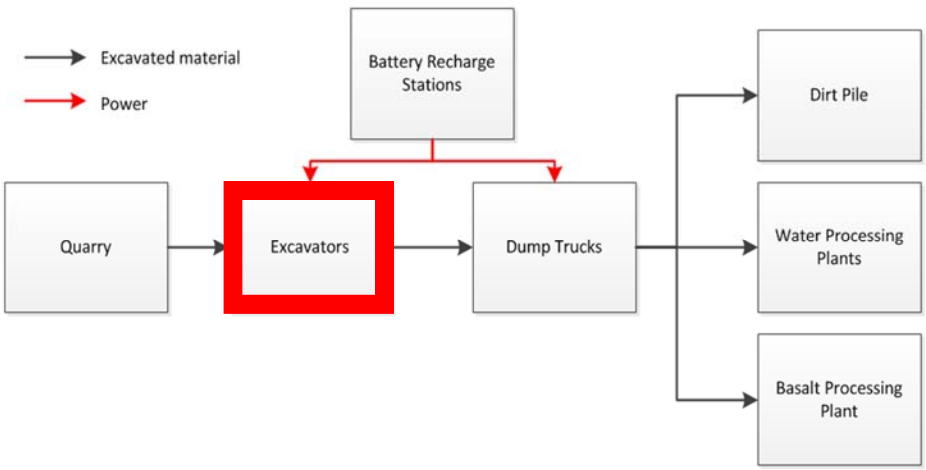


Fig. 7.2.1.3.1: The Excavator is a critical link in the colony's resource production systems (Credit: Jon Tucker).

7.2.1.4 *Deployment / Fabrication*

Like all our surface vehicles, all vehicles are transported to Mars as ITS cargo and deployed to the ITS surface via the integrated ITS crane (See Section 6.5).

7.2.1.5 *Operation and Servicing*

The excavator includes a suite of instruments to facilitate autonomous operation, but also can operated remotely or manually aboard the vehicle. The autonomous capability allows us to reduce total number of vehicles brought by operating around the clock, therefore reducing the amount of vehicles needed to achieve the excavation goals. We determine the vehicle can operate for 30 years with 90% uptime, if daily inspections are performed and maintenance occurs three times per year. The pressurized rover port is used for major repairs. Following these stipulations, we expect the excavators to have a useful life of 30 years.

It is also notable that the excavator relies on hydraulic fluid to operate, and currently no hydraulic fluid exists that remains liquid at the coldest Mars surface temperatures. Monitoring and maintaining hydraulic fluid levels is a servicing challenge of the excavator.

7.2.1.6 *Retirement, disposal, and replacement*

At the end of useful life, any working components of the excavators are salvaged to help maintain the rest of the fleet. Replacement vehicles are brought from Earth via ITS as necessary.

7.2.1.7 *System Cost*

Table 7.2.1.7.1: Excavator Cost Estimation:

Component	Cost	Margin
Base (CAT M318F)	$250,000	
Autonomous Control System	$425,000	
Space Hardening Factor	2.5X	
Total	$1,687,500	50%

7.2.1.8 *Risk Analysis & Mitigation Strategies*

Table 7.2.1.8.1Excavator Risk Analysis & Mitigation Strategies

Risk being mitigated	Probability of failure	Cost of mitigation strategy in $/MPV	Improved
Hydraulic Fluid Leak/ freeze	5%	Advanced hydraulic fluid, fluid heaters, Costs $1000-5000 per vehicle.	2%
Tire Degradation	10%	Maintenance cost $450/10000 km	3%
Battery power runs out	9%	Battery change before degradation of 40%	6%
Vehicle Breakdown	10% - 13%	Maintenance and storage of extra spare parts, Costs $100 – 1000 per part	5% - 7%

7.2.2 Regolith Transportation Rovers (Dump Trucks)

7.2.2.1 *System Description*

The dump trucks accomplish the transportation of regolith from excavation sites to resource plants and other construction sites. Systems that require this regolith include water production, steel manufacturing, propellant production, and the water tower, which is constructed atop a mound of surplus regolith.

7.2.2.2 *CAD / System totals*

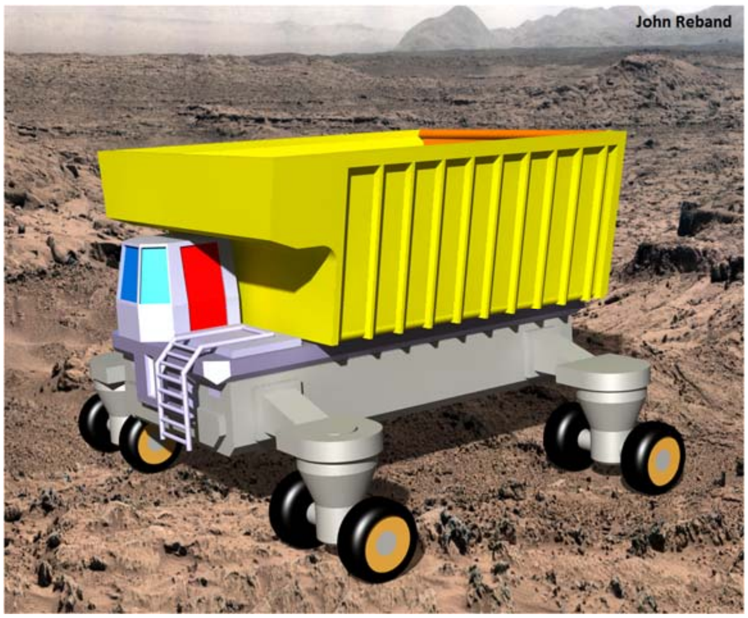


Fig. 7.2.2.1.1: The Dump Truck accomplishes all regolith transport for the colony.

(Credit: John Reband)

Table 7.2.2.1: Dump Truck Mass, Power, Volume

	Per vehicle
Mass	22.51 Mg
Nominal Power	205 kW
Volume	$14.91m^3$

Table 7.2.2.2: Dump Truck Capability Metrics

Dump Truck-Capabilities	
Excavation Rate	2947.272 m^3/sol
Operating Speed	10 km/hr
Capacity per Trip	52 Mg
Lifetime	20 years

7.2.2.3 *System Map*

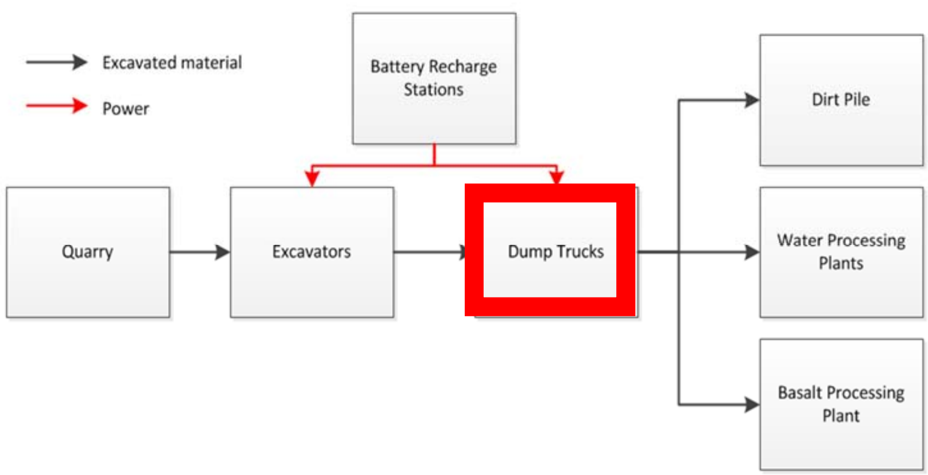


Fig. 0.1: The Dump Truck links the resource plants to the excavator that gathers regolith. (Credit: Jon Tucker).

7.2.2.4 *Deployment / Fabrication*

All the Dump Trucks vehicles are transported to Mars via the ITS vehicles and deployed with the integrated crane (See Section 6.5)

7.2.2.5 *Operation and Servicing*

Like the excavators, the dump trucks are equipped with a suite of instruments to enable autonomous operation. This permits us to lower the number of vehicles brought to Mars by running the vehicles automatically at all hours. We expect the dump truck can operate at 90% uptime provided the servicing guidelines are followed.

The Dump Truck require daily inspection and major servicing 3 times per year. Major repairs will be conducted inside the pressurized rover port. With these measures, we expect a useful vehicle lifetime of 20 years.

7.2.2.6 *Retirement, disposal, and replacement*

At the end of useful life, any working parts from the dump trucks are salvaged to support the operational fleet. Replacement vehicles are brought from Earth via ITS as necessary.

7.2.2.7 *System Cost*

Table 7.2.2.7.1: Dump Truck Cost Estimation

Component	Cost	Margin
Base (CAT 785D)	$1,356,293	
Autonomous Control System	$150,000	
Space Hardening Factor	2.5X	
Total	$37,657,334	50%

7.2.2.8 *Risk Analysis & Mitigation*

Table 7.2.2.8.1: Dump Truck Risk Analysis & Mitigation

Risk being mitigated	Probability of failure	Cost of mitigation strategy in $/MPV	Improved
Communication lost	5%	Allow for large margin in link budget analysis $0/truck	2%
Flat/punctured tire	5%	Replace tire, $1000/1 tire on truck	3%
Automated navigation software bug	5%	Extensive software testing, $0/truck (price included in software development)	2%
Automated navigation hardware malfunction	15%	Hardware redundancy, $2000/truck	5%
Battery fails to charge/hold power	9%	Extra battery	6%
Truck tips over	5%	Careful planning of truck path, $0/truck	2%
Truck capacity exceeded	5%	Monitoring of truck capacity with sensors already in place, $0/truck	2%
Hydraulics fail	25%	Maintenance of hydraulic system $500-$1000/truck	12%

7.3 3D printing and Structure Fabrication

7.3.1 CAD / System totals

To construct a single quarry, 663 structures must be built underground, not including the tunnels that connect the habitats, and 109 structures are built on the Martian surface. These structures are cylindrical with an internal diameter of 18 meters and internal height of 18 meters. For a more in-depth discussion of how the structural shape, size, and building material was determined, please see Appendix 13.4. Our goal is to have the ability to print all 663 underground structures in addition to the 109 rover ports on the surface in a year's time. Table 7.3.1.1 provides a breakdown of system totals for each structural component of the quarry. Note that the time to print is based on our printer that has the capability to print 45.70 m^3 of basalt per day. For an explanation of how this printer capability was determined please refer to Appendix 7.4.2.4.

Table 7.3.1.1 Construction Parameters for Each Module

Module	Basalt Printed for 1 [m^3]	Structural Mass of 1 [Mg]	Time for 1 Printer to Print (Days)	Quantity
Living/Bathing	674.2	$2.023*10^3$	14.75	305
Farm/Food Storage	500.4	$1.501*10^3$	10.95	256
Rover Port	517.4	$1.552*10^3$	11.32	109
Recreation	562.2	$1.687*10^3$	12.30	43
Eating/Meeting	562.2	$1.687*10^3$	12.30	26
Wallyball	537.5	$1.613*10^3$	11.76	20
Science	562.2	$1.687*10^3$	12.30	11
Medical	594.3	$1.783*10^3$	13	2
2 Meter Tunnels	1.4	4.2	0.0317	1451

Now that we have determined the individual component properties, we can determine the system properties for each type of structure within the quarry. Table gives a breakdown of quarry totals for each module type described above.

Table 7.3.1.2 Construction Parameters for Entire Quarry

Module	Total Basalt Printed [m^3]	Total Structural Mass [Mg]	Time for 1 Printer to Print (Days)
Living/Bathing	$2.056*10^5$	$6.170*10^5$	4499
Farm/Food Storage	$1.281*10^5$	$3.843*10^5$	2803
Rover Port	$5.640*10^4$	$1.692*10^5$	1234
Recreation	$2.420*10^4$	$7.253*10^4$	529
Eating/Meeting	$1.462*10^4$	$4.385*10^4$	319.8
Wallyball	$1.075*10^4$	$3.225*10^4$	225.2
Science	$6.185*10^3$	$1.855*10^4$	135.3
Medical	$1.189*10^3$	$3.556*10^3$	26.01
2 Meter Tunnels	$2.101*10^3$	$6.306*10^3$	46

Table 7.3.1.3 gives the system totals for an entire quarry, assuming that one printer is tasked with the construction of every component.

Table 7.3.1.3 Basalt and Regolith Extraction for Single Printer

Basalt Printed [m^3]	Construction Time [days]	Internal Volume [m^3]	Structural Mass [Mg]	Volume of Regolith Extracted [m^3]
452,100	9,891	$3.263*10^6$	$1.352*10^6$	$5.995*10^6$

The quarry dimensions that lead to the volume of regolith extracted are stated in section 7.1 and are 522 meters wide by 522 meters long by 22 meters deep. Since we want the construction of all the quarry structures completed in one year's time, there needs to be more than one 3D printer working to build the habitats. Accounting for equipment malfunction, maintenance, and printer transportation, we determine that 42 printers are needed to construct a quarry city in one year.

7.3.2 Thermal Analysis

We preformed thermal analysis for the entire quarry to determine how much thermal power is needed to maintain the internal temperature of the colony. With an internal temperature of 20°C for the buildings within the quarry and the structures being underground, conductive heat transfer through the walls of the quarry and the Martian soil is calculated. This calculation operates under the assumption that the quarry is one, large structure of dimensions 522m by 522m by 22m. Using this assumption, the individual heat loss between each individual building is neglected, but instead the buildings in the quarry are viewed as one system. With this, the heat lost from the system is determined, and is shown in Table 7.3.2.1.

Table 7.3.2.1 Thermal Power needed to maintain an Internal Temperature inside the Quarry/Quarries (Habitats and Fabs both included) at 20°C

Colony Size	Thermal Power needed to Maintain Quarry/Quarries Internal Temperature (MW)
25,000 Person Colony	34
1,000,000 Person Colony	1365

This thermal loss is then cancelled out by heat added by the Central Power team, as they run heating pipes through the colony. These heat pipes design makes it possible to add as much heat to the quarry system as is lost. By doing this, the quarry (and more specifically, the buildings inside the quarry) are maintained at a constant temperature, where all the heat leaving the system through conduction from the building walls, is then re-added to the system through the heat pipes.

7.3.3 System Map

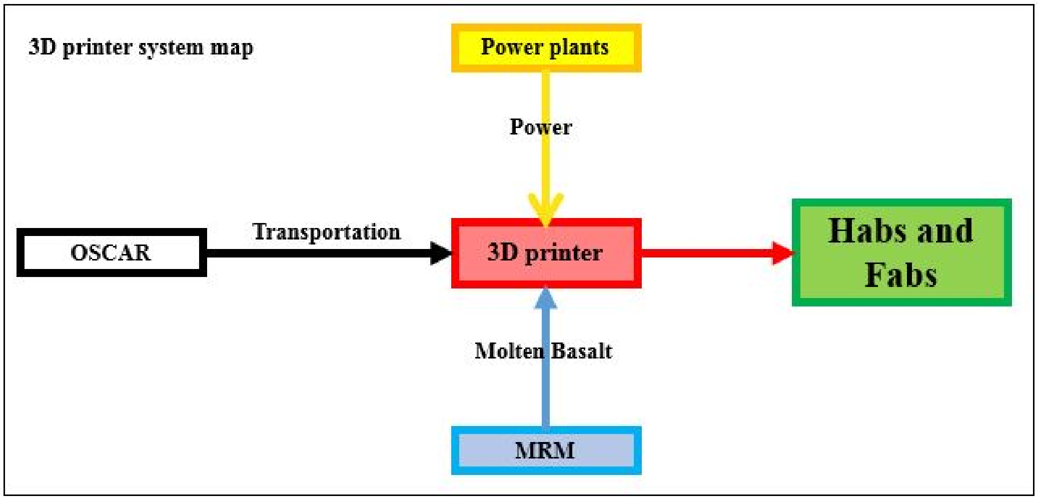


Fig. 7.3.2 3D printer system map showing inputs and outputs. (Credit: Billy Muth)

Shown above is the system map for our 3D printer. All inputs to the system point towards the block labeled 3D printer and the output points outward from the same block. The inputs include transportation via OSCAR, power from our nuclear reactor power plants, and molten basalt from Mars Resource Management. The only output is cylindrical habitats and farms.

7.3.4 Deployment / Fabrication

For the first couple of cycles, our colonists arrive in smaller groups (100 – 200 people) and live in the inflatable habitats presented with our 100 person colony. For these first cycles, all of those habitats are brought from earth and account for the vast majority of habitat cargo mass. From earlier, we know that 3 cargo ITS launches are capable of delivering all of the habitat modules for the 100 person colony.

Once the populations start increasing greatly per cycle, colonists will move away from these inflatable habitats and begin constructing habitats strictly out of material that is found on mars. Using large scale 3D printers and basalt that is abundant on the surface of mars, the habitats for the colony will be created. For the remaining cycles, only the interior components of the habitats and the actual printers are transported from earth as the rest of the material is made on

mars. The printers can be taken apart and then reconstructed on mars. 6 of these printers are able to construct the habs for one quarry (25,000 people) in one synodic cycle. Because they can be taken apart, all 6 of these printers, when broken down to individual components fit into one cargo ITS.

The 3D printers are unloaded (disassembled) from the ITS via the cargo gantry where they are picked up with OSCAR. OSCAR delivers the disassembled 3D printer parts to the construction quarry and we assemble the printers there.

Fig. 7.2.2.8.1 OSCAR transporting the 3D printer's main base arms to the construction site.

(Credit: M. Gripe, B. Muth)

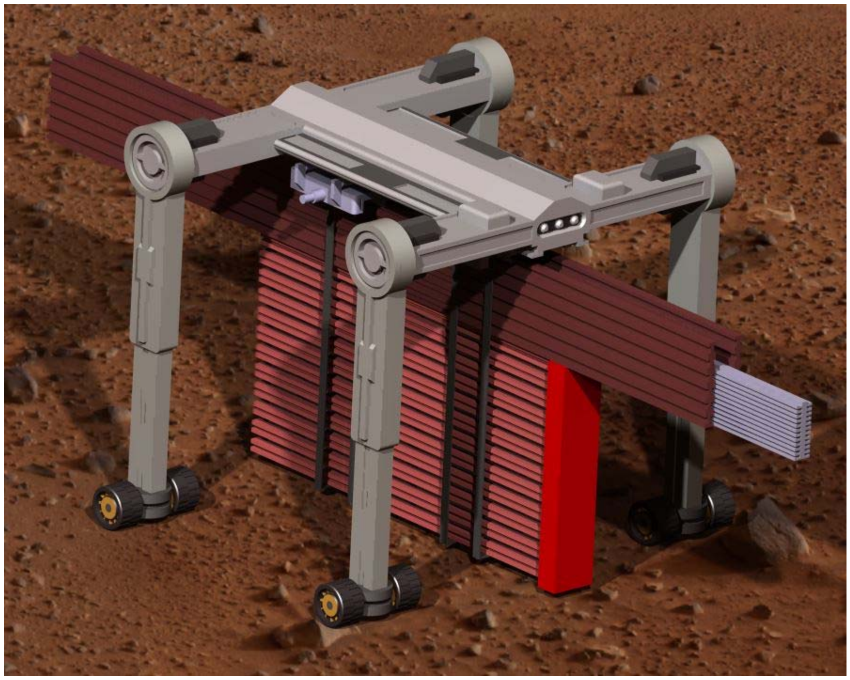


Fig. 7.2.2.8.2 OSCAR transporting the 3d printer's arm extensions, track pieces, and cross-supports to the construction site. (Credit: M. Gripe, B. Muth)

Once an area of the quarry is dugout, we assemble the 3D printers, layout the printer tracks around the area where a building is to be printed, and begin printing our new habitats. Once a cylinder habitat is completed, the tracks are moved to the next construction area, and the next cylinder begins to be constructed. This process continues until all of the habitats for one quarry are completed. At this point, the printers are moved to the next quarry, the buildings are covered in regolith, and we will begin to inhabit these new buildings.

7.3.5 Operation and Servicing

The 3D printers being used to build the habitats are autonomous. They can print the specified structure in a time dependent on the amount of basalt needed for that object. The printers build by moving back and forth on steel railways that are placed by construction rovers along the bottom of the quarry to guide the printer as it moves from cylinder location to cylinder location along a given row. These cylinder rows can be seen above in Fig. 7.2.2.8.1, which contains the quarry city layout. A pipe containing molten basalt feeds each 3D printer during the building process. Fig. 7.3.1 contains an image of what the 3D printer may look like as it constructs the cylinders within the quarry.

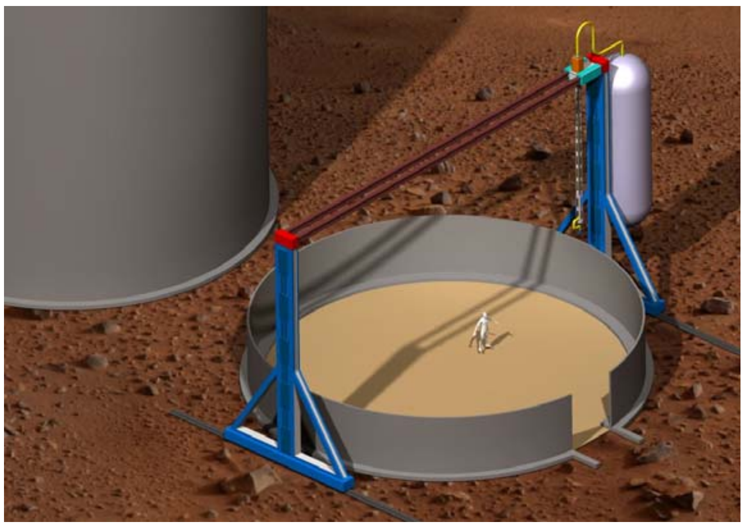


Fig. 7.3.5.1 A view of the 3D printer during the construction process. (Credit: B. Muth)

Of the 24 hours in a day, each printer must operate for at least 16 hours. The 8 hours that they are not in service can be used for minor maintenance as well as movement across the quarry if a certain section is completed.

7.3.6 Retirement, disposal, and replacement

Each printer has a lifetime of 3 synodic periods. However, the entire printer is not replaced after this period. The major structure, or chassis of the printers, does not need to be replaced since it is metal and will not be subjected to fatigue or corrosion since it is a stationary part and not subject to high loads. That said, we determine it is still necessary to account for possible structural failure of the printer as well as construction mishaps. See section 7.3.8 for how we plan to mitigate these possible failures. We determine that 5 printer components need to be replaced every 3 synodic periods. These parts and their associated masses and volumes can be seen in Table 7.3.6.1 below.

Table 7.3.6.1 Mass and Volume of Replacement 3D Printer Parts

Parts to be Replaced Every 3 Synodic Periods	Volume [m^3]	Mass [Mg]
Base Wheels (12)	0.45	0.8
Nozzle Assembly	0.05	0.2
Molten Basalt Tubing	0.15	0.5
Cross-Support Motor	0.7	4
Vertical Motor	0.3	1.7
Total	**1.65**	**7.2**

The printers are deployed in groups of 14 over the course of the first three synodic cycles. This means that at some point at the beginning of synodic cycle 4, the first 14 printers will have the 5 parts listed in the table above replaced. This replacement takes place every cycle for 14 printers up until the end of the quarry construction. This means that over the course of the mission, a total of 574 component replacements take place across the 42 printers. The components, depending on their material, are melted down and recycled for later use, or scrapped as trash.

7.3.7 System Cost

We estimate the cost of a single printer by scaling up existing large-scale printing technology to obtain a single printer cost of $4,759,000 [1]. To maintain the condition of the printers, certain parts, outlined above, are updated every 3 synodic periods [2]. Construction of the quarries requires 42 printers and 574 part replacements over the length of the mission. Based on the dimensions of the ITS-C2, it is determined that 8 printers can fit inside of a single ITS-C2. This value is determined by taking the cross-sectional width of the printer base and figuring out how many of those components can fit inside the 12-meter diameter cargo bay. This means that a total of 6 ITS-C2 launches are needed to transport the 42 printers. The total number of ITS-C2 launches needed for the replacement parts is constrained by mass. The total mass of replacement parts is 4132.8 Mg, which corresponds to 14 ITS-C2 launches, using the 300 Mg of cargo constraint. The cost of the replacement parts is conservatively estimated as 33% of the cost of a single printer. The total system costs are broken down in Tables 7.3.7.1, 7.3.7.2, and 7.3.7.3

Table 7.3.7.1 Cost of 3D Basalt Printer

	Single Printer	**42 Printers**
Cost [dollars]	**4,759,000**	**199,900,000**

Table 7.3.7.2 Cost of Replacement Parts for 3D Basalt Printer

	Single Printer Parts	**Mission Span**
Cost of Replacement Parts [dollars]	1,571,000	901,500,000

Table 7.3.7.3 Launch Requirements

	Cost [Dollars]	**ITS-C2 Launches**
42 Printers	199,900,000	6
Replacement Parts	901,500,000	14
Total	**1,101,000,000**	**20**

7.3.8 Risk Analysis

When performing risk analysis of our 3D printer, it is important to realize that we are only considering internal system failures when constructing our failure modes probability. Even though external modes of failure are considered in the fault tree, shown in Fig. 7.3.2, since they do have an impact on 3D printer success, we do not consider them when developing a FMECA for the 3D printer system. The fault tree below gives some insight into what the different failure modes of the printer system are, and how they affect the system.

There are three main modes of failure for the 3D printer. There are 5 key components to the printer that have less than a 5% probability of failure over the course of their lifetime of 3 synodic periods [3,4]. The mass and volumes of these parts, which will be replaced every 3 synodic periods, are in Table 7.3.4 above. The next failure mode is a failure of one of the cylindrical structures inside of our quarry city and is modeled with a 1% probability [5]. This could occur due to depressurization, buckling, fatigue, etc. If no such failure of this system were to occur, the lifetime of the habitats are approximately 150 years. This lifetime significantly exceeds the mission span. The final failure mode is a structural breakdown of the printer itself. Being on Mars, it is not expected that the printer chassis will break down since corrosion is not an issue and the printer is not a heavy load-bearing structure. The probability of failure is set at 1% to account for any mishaps that may occur when moving the printer throughout the quarries or during a cave in.

7.3.9 Risk Mitigation Strategies

To develop risk mitigation strategies, we saw it fitting to construct a FMECA for the 3D printer. This can be seen below in Table 7.3.9.1.

Table 7.3.9.1 Risk Mitigation for 3D Printer

Description of Failure	Effects of Failure on the System	Risk Mitigation	Probability to Failure Relative to Deployment	Mean time to Failure [Years]
Machine Parts Failure	Delays construction process and takes a printer out of commission	Bring replacement parts and 3D print temporary replacement parts	<5%	6.429
Structure Failure	Loss of living area until repaired. Potential loss of life	Print extra living volume inside of each	1%	150

Printer Structural Failure	Fall behind construction schedule	quarry. Pressurize each structure separately. Print replacement chassis components and bring extra printers	1%	150

To mitigate the failure of machine parts, our plan is to bring enough of these replacement parts to change all 5 components on all 42 printers every 3 synodic periods. In the case of excessive and unexpected part failures, the 3D printers we bring will also be print temporary replacement components to reduce overall cost and number of launches required from Earth. To help reduce the effects of a structural failure on the system, the printers will construct eight extra cylinders per quarry in comparison to what is required for living space. This means that if multiple structures fail, the 25,000-person city will still have enough living space per person. To ensure that a structural failure of a single structure does not lead to a catastrophic depressurization chain in the quarry, each structure is pressurized separately and separated by a tunnel that acts as an airlock. To mitigate the effects of a structural failure of the printer chassis, a factor of safety of 1.5 has been applied to the total number of printers being brought. Hypothetically, 28 printers can complete the construction of a one-million-person colony. However, to be safe we decide on 42 printers to make up the steady state printing fleet.

[1] "Welcome to ErectorBot Store," *ErectorBot Store* Available: http://www.erectorbot.com/store/ [Retrieved 26 January 2017].

[2] "The Economics of 3D Printing at Home," *NovoEd Blog* Available: http://blog.novoed.com/index.php/474/the-economics-of-3d-printing-at-home/ [Retrieved 23 January 2017].

[3] "RELIABILITY OF SYSTEMS WITH VARIOUS ELEMENT CONFIGURATIONS." [Retrieved 28 March 2017].

[4] Penrose, H. W., "Time to Failure Estimation™ Using Motor Circuit Analysis." [Retrieved 28 March 2017].

[5] Fajfar, P., and Dolšek, M., "A practice-oriented estimation of the failure probability of building structures," *Earthquake Engineering & Structural Dynamics*, vol. 41, 2012, pp. 531–547. [Retrieved 28 March 2017]

7.4 Internal Structures

The 25,000 person habitat consists of three main structures: The living space, the medical facilities, and the recreational facilities. Each of these structures is built using the 3D printer habitat cylinders. An exploded view of the cylinder can be seen in Fig. 7.3.9.1. These structures are buried into the ground to protect the colonists from radiation

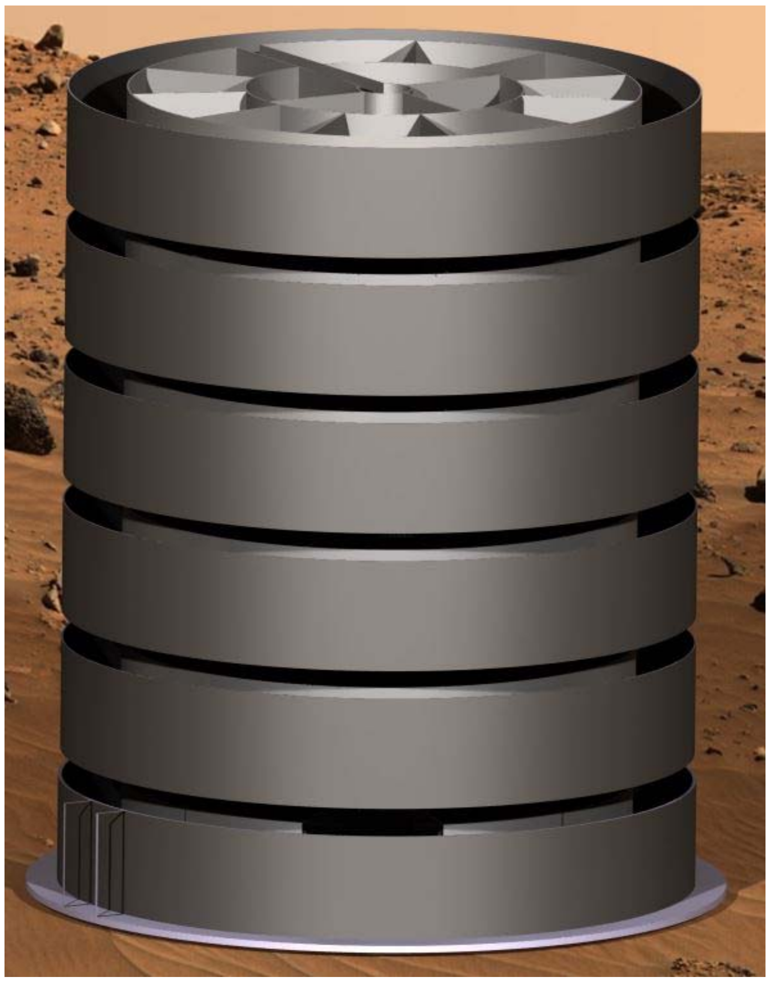


Fig. 7.3.9.1 Exploded view of habitat cylinder. (Credit: W. Muth)

Table 7.3.9.1 Shows the allotted habitat space for each designated activity.

Table 7.3.9.1 Space Allotted for Internal Living Structures per Quarry

Designation	Area Allocated (m^2)	Volume Allocated (m^3)
Living Space	250,000	750,000
Common/Eating Space	35,000	105,000
Medical Facilities	2,125	6,375
Recreation Space	82,500	247,500
Bathing Facilities	13,500	40,500
Science Facilities	17,550	52,650
Total	400,675	1,202,025
Total Including Factor of Safety	560,945	1,682,835

7.4.1 Living Space

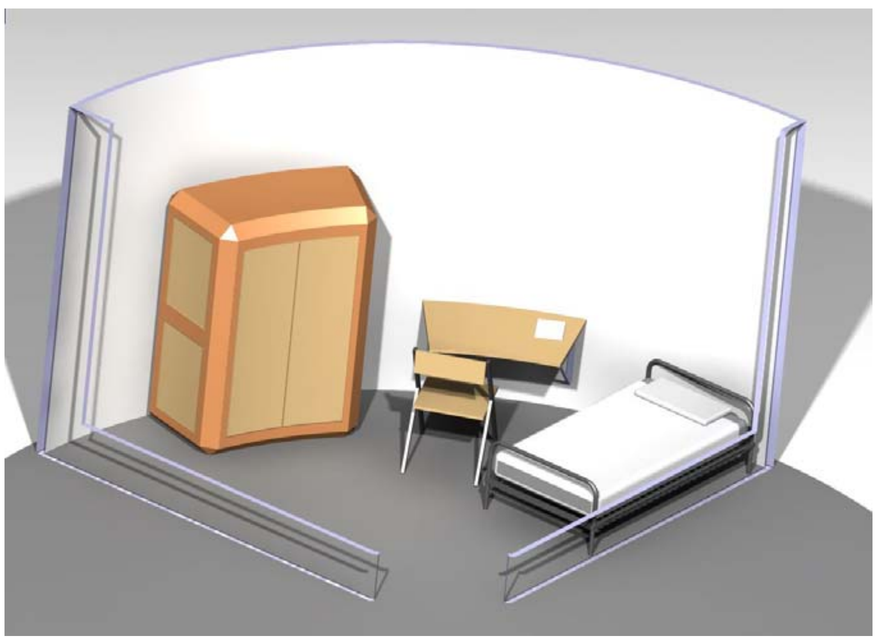


Fig. 7.4.1.1 Close up of the individual living space of the colonists. (Credit W. Muth)

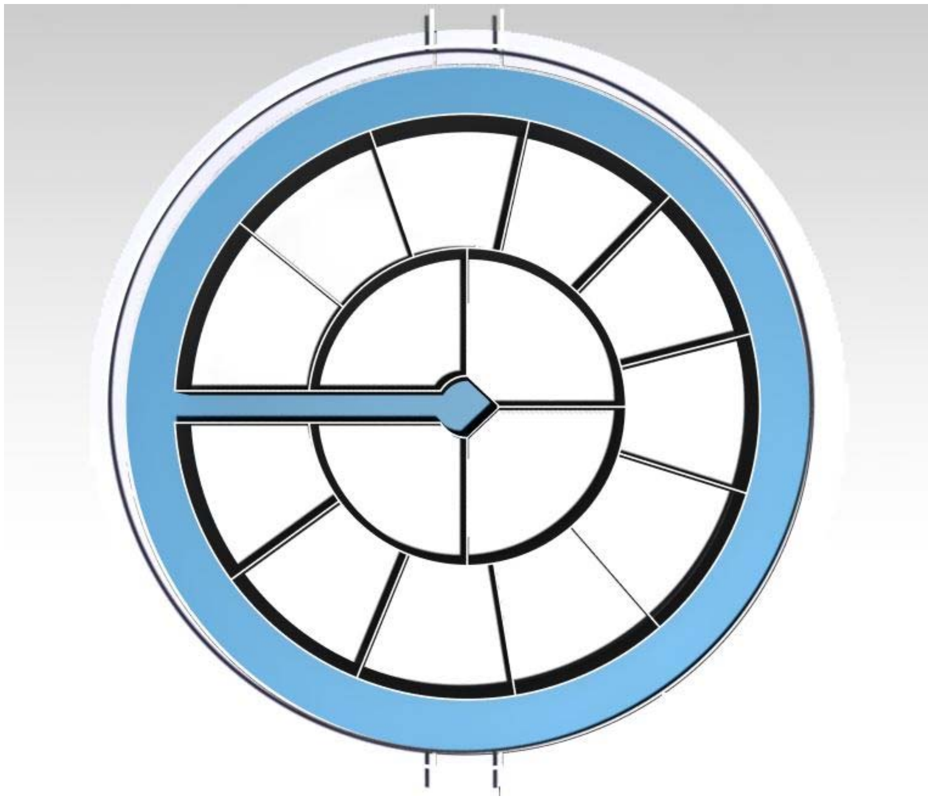


Fig. 7.4.1.2 Top view of a floor of the living habitat. White areas are rooms, and blue areas are walkways. (Credit: W. Muth)

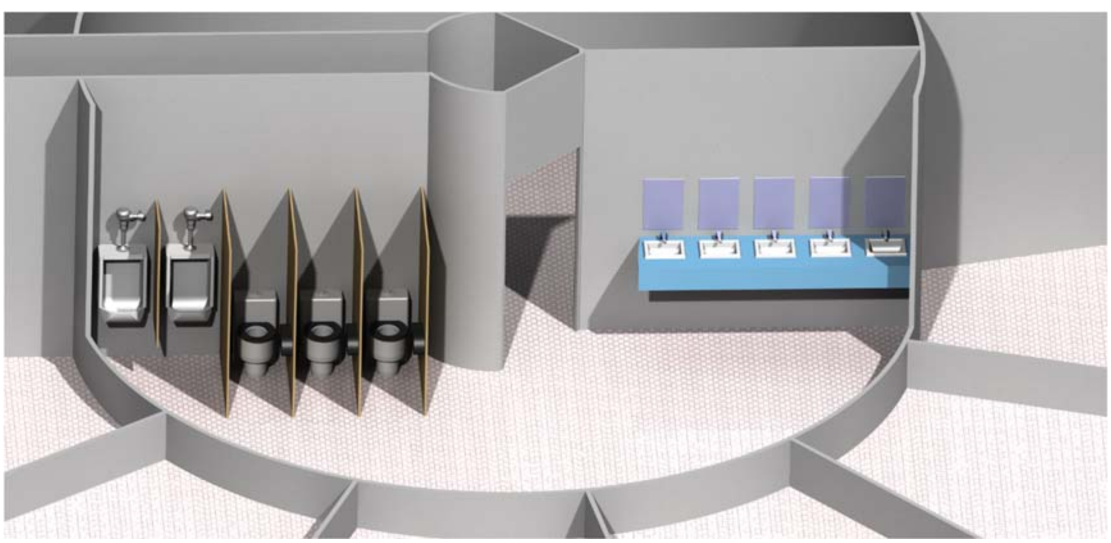


Fig. 7.4.1.3 Restroom inside living space habitat. (Credit: W. Muth)

As you can see in Fig. 7.4.1.1, each colonists gets a bed, desk and dresser. The personal living space of each colonist is 11 m^2. As you can see from Fig. 7.4.1.2, there are fourteen rooms on each of the floors of the living habitat, except for the floor that has restrooms on it. The living

habitat has a total of six levels. The restrooms take up about one fourth of a floor. You can see a close up of the bathroom in Fig. 7.4.1.3.

7.4.2 Medical Facilities

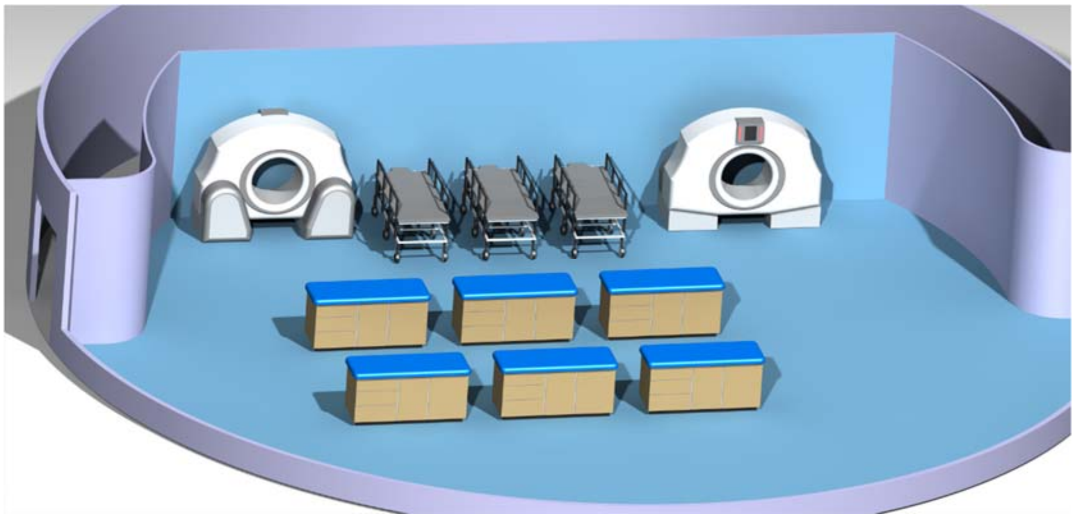


Fig. 7.4.2.1 Close up of the medical facilities, note the two large imaging devices on either side. (Credit W. Muth.)

There are two medical cylinders located inside one 25,000 person habitat. We position these medical facilities in the center of the habitat to minimize the distance needed to travel to reach them. These facilities take up entire cylinders to provide necessary care to the colonists. You can see a close up of a floor of the medical facility in Fig. 7.4.2.1. Here you can see space for large diagnostic equipment.

7.4.3 Recreational Facilities

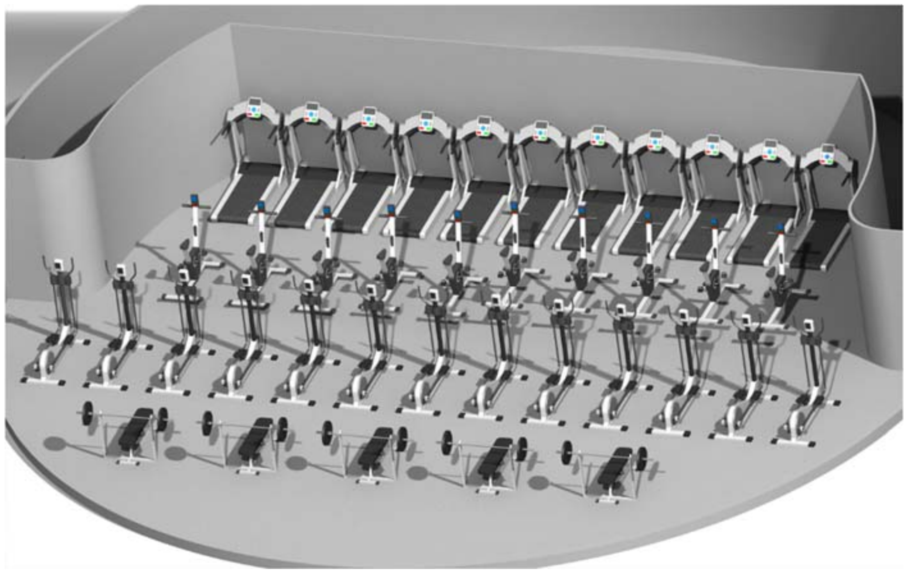


Fig. 7.4.3.1 Cloes up view of the recreational habitat. (Credit W. Muth)

The recreational facilities provide the colonists with a place to exercise and have some fun, physical activities. We allot plenty of space for cardo so that our colonists are able to run, even in the confines of the habitat. In addition to cardio we also place weights to ensure our colonists are able to strength train Fig. 7.4.3.1 shows the cardo level of one of the recreational habitats. The recreational facilities also include courts for sports such as racquetball or Wally ball.

7.4.4 Radiation Protection

Structure and location for the 25,000-person habitat is designed to minimize radiation accumulation for all colonists. We set a daily radiation limit of 0.137 milliSieverts (mSv) per day per colonist, which was based off of a radiation worker's maximum yearly allowance of radiation of 50 mSv.

We will be using the half-value layer method of determining radiation protection for the mission. In layman's terms, each type of material has a thickness that reduces radiation exposure by 50%. This thickness is termed a half-value layer (HVL). Adding another HVL would reduce radiation exposure by another 50%, reducing total radiation exposure to 25%. This pattern continues on endlessly. For example, Martian regolith has a half-value layer of 25 cm.

For the 25,000 person colony in each quarry, radiation protection is greatly increased. This is to be expected, as one of the key reasons for moving the habitat underground is radiation protection. Instead of piling on 50 cm of regolith, each cylindrical enclosure will be under 1 m of regolith. This doubles the radiation protection of the regolith from 2.00 HVL to 4.00 HVL. This alone blocks 93.75% of radiation. However, depending on the level of the cylinder any given colonist lives on, this number increases still. Using basalt cement as an information substitute for our 3-D printed basalt mixture, one HVL is equivalent to 3.96 cm. assuming a floor thickness of 4/9 of wall thickness (which is 0.1 m), each floor has a thickness of 4.44 cm, or 1.12 HVL. Data below is given on radiation shielding depending on the level of each cylinder a given colonist lives on.

Table 7.4.4.1 Radiation Shielding Depending on Level in Cylinder

Levels down	Half Value Layers	Incoming Radiation Shielded
1	5.12	97.1%
2	6.24	98.7%
3	7.37	99.4%
4	8.49	99.7%
5	9.61	99.9%
6	10.73	99.9%

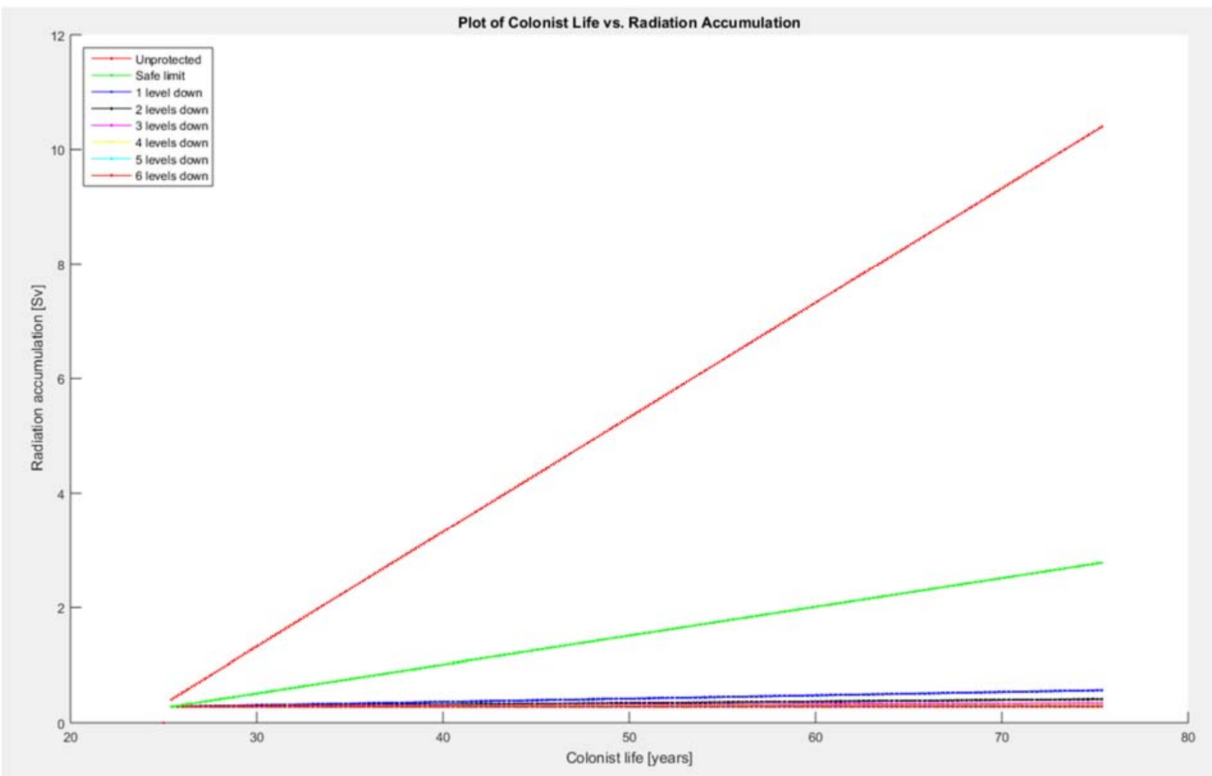


Fig. 7.4.4.1 Plot of radiation accumulation over colonist's life from birth on Earth to landing on Mars at 25 years old to 75 years of age.

Plot of radiation exposure over the colonists' lives up to 75 years is given below

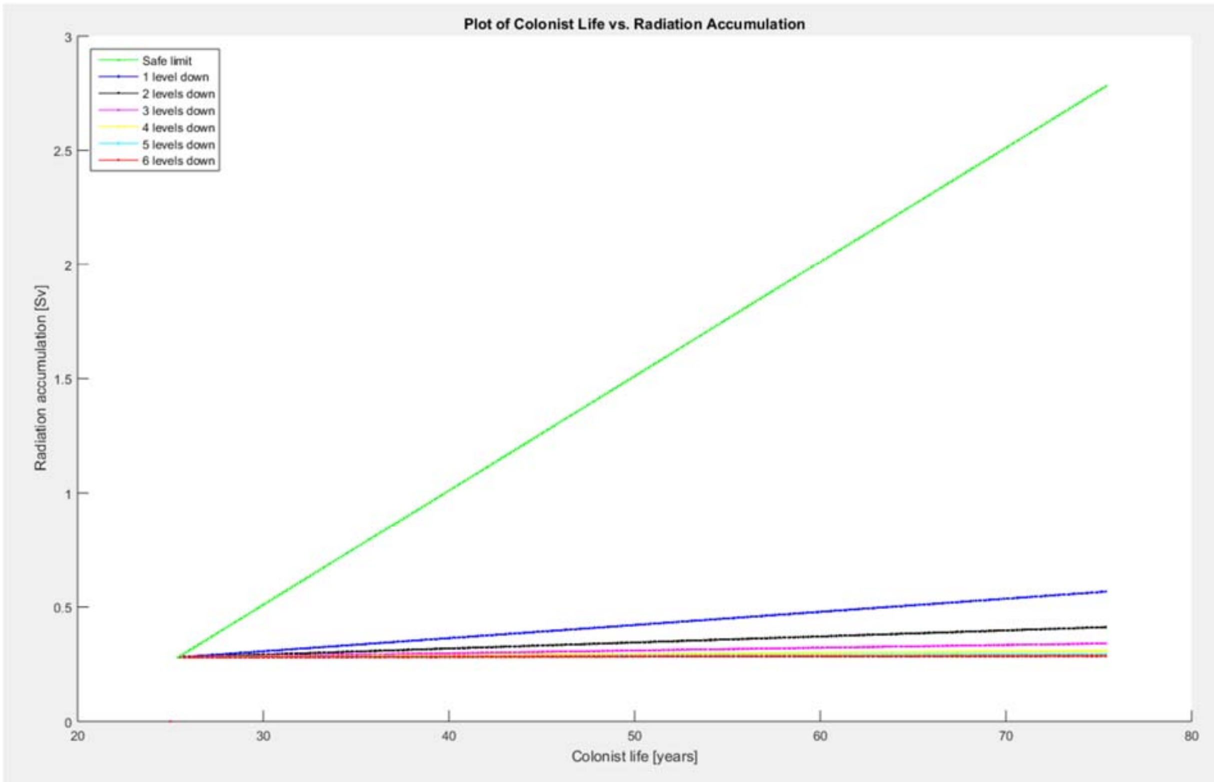


Fig. 7.4.4.2 Plot of radiation accumulating over colonist's life from landing on Mars at 25 years old to

The radiation exposure over this time span is given below in

.

Table 7.4.4.2 Cumulative Radiation Exposure Depending on Level of Cylinder

Location in habitat cylinder	Cumulative radiation exposure at Mars landing [mSv]	Cumulative radiation exposure 50 years after Mars landing [mSv]	% increase in cumulative radiation exposure after 50 years
Safe limit	280	3771	1246.79
1 level down	280	567.12	102.50
2 levels down	280	411.91	47.11
3 levels down	280	340.61	21.65
4 levels down	280	307.85	9.95
5 levels down	280	292.80	4.57
6 levels down	280	285.88	2.10

It can be seen from the above table that the radiation protection increases with the depth below the surface in the habitat. After fifty years on Earth between the ages of 25 and 75 years old, cumulative radiation exposure raises from 155 mSv to 465 mSv, an increase of 200%. At any position in the cylinder, radiation exposure is less than this. The main benefit of this is increased time in surface ops activity. If it is assumed that when in the recreation rover or performing other EVA / surface operations there is no radiation protection, 0.0228 mSv of radiation is consumed per hour. This would allow any prospective colonist to stay on the surface around 5 hours per day, receiving 0.114 mSv of radiation on the surface. Adding this to the radiation they are exposed to while in the habitat under radiation protection, the colonist is still under the daily radiation allowance of 0.137 mSv.

The colony also has enough radiation shielding to protect during solar minima and maxima. During solar minimum, there are an above-average number of sunspots that correspond to a 33% higher radiation exposure than average. During solar maximum, it is the opposite, with 33% lower radiation exposure than average. That data is given below.

Table 7.4.4.3 Radiation Exposure during Solar Minimum and Maximum

Location	Radiation Exposure during Solar Minimum [mSv/day]	Radiation Exposure during Solar Maximum [mSv/day]
Surface	0.7195	0.3598
1 level down	0.0207	0.0104
2 levels down	0.0095	0.0048
3 levels down	0.0044	0.0022
4 levels down	0.0020	0.0010
5 levels down	0.0009	0.0005
6 levels down	0.0004	0.0002

As can be seen from the above table, at the most dangerous point in the eleven-year solar cycle (solar minimum), even the least radiation-protected area (only one level down) is still safely six times under the daily radiation allotment.

Solar particle events are one-time events that occur via coronal mass ejections, solar flares, etc. during solar minimum. These storms are infrequent but have the capability of being very hazardous and dangerous. Still, we have protected the habitat enough in order to safely mitigate these risks. There would have to be a one-time solar particle event of 232.3 mSv in order for the colonists to reach their daily radiation allotment. Putting this into perspective, this is around 424 times larger than the average daily exposure at Chryse Planitia. There would need to be a solar event larger than 169580 mSv in order for the colonists to potentially suddenly develop cancer. Similarly, there would need to be a solar event larger than 1695800 mSv in order for the colonists to develop radiation sickness. Finally, there would need to be a solar particle event of larger than 8478800 mSv in order to cause death in all colonists. This would be larger than any other solar particle event recorded in history.

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7.5 ECLSS System

7.5.1 CAD / System totals

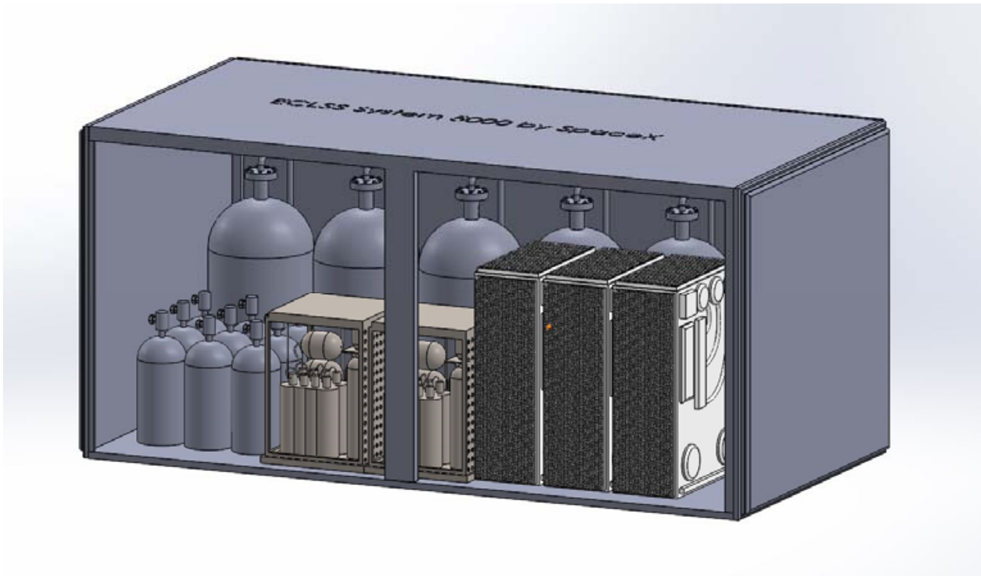

Fig. 7.5.1.1 ECLSS System Credit Jungwoon Kang

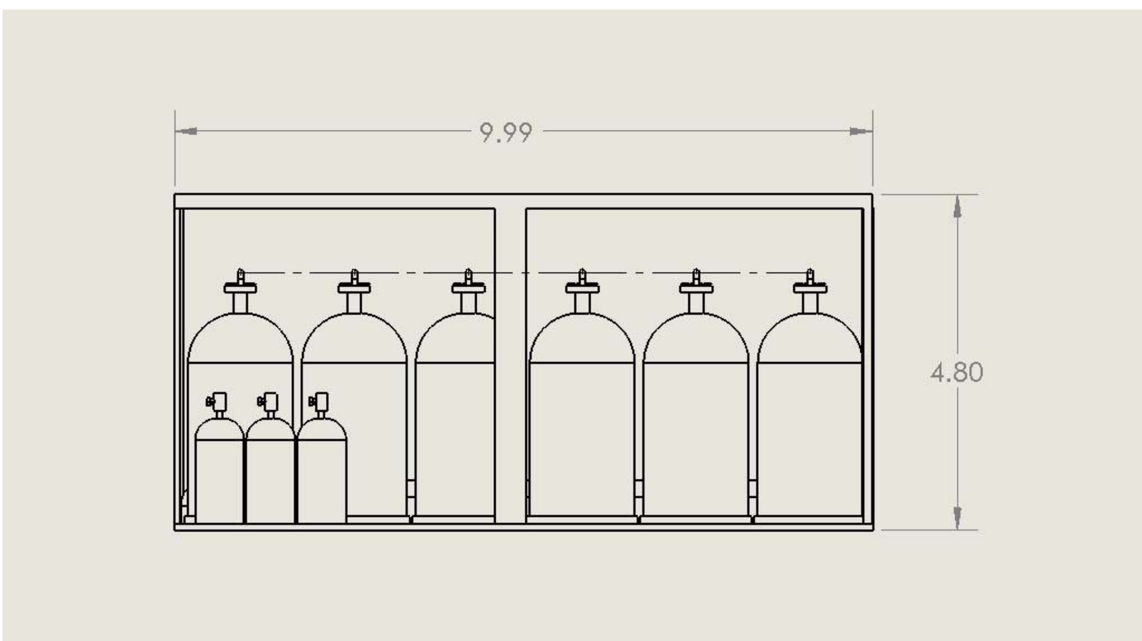

Fig. 7.5.1.2 The Front view Sketch of ECLSS system. [meters] (Credit: J. Kang)

Fig. 7.5.1.3 Water Reclimation 3D view. (Credit: J. Kang)

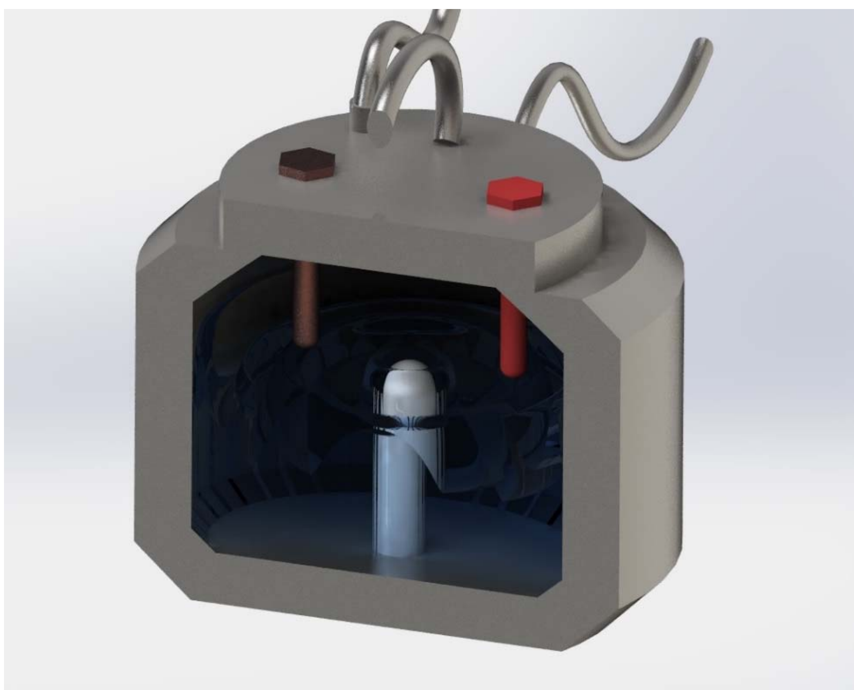

Fig. 7.5.1.4 Water Reclamation Section View. (Credit: J. Kang)

The Environmental Control and Life Support Systems (ECLSS) comprise all operations vital to the continued well-being of the colonists. For the sake of the feasibility study, we choose to hone ECLSS in on a few key components. Inside of the habitats, ECLSS filters and scrubs

contaminants, waste gasses, and humidity from waste gasses and other potential hazardous gas sources. This captured air is processed, oxygenated, and passed back to the habitat to provide clean breathing air for colonists. ECLSS also regulates the pressure and temperature of the ambient environment within the habitable space of the habitats. Furthermore, we choose to design ECLSS for water reclamation. Water is an extremely scarce resource on Mars and happens to be very resource intensive to ship from Earth. By creating a closed loop water cycle on Mars—to the greatest extent possible—we prove to reduce launches from Earth and decrease dependence on hydrated minerals and polar ice. Therefore, we employ a Water Reclamation System that is capable of taking wastewater from bathing, food, farm runoff, or any other source of water, and purifying it for reuse by colonists. However, a purely purification system fails to take advantage of potential key resources available in wastewater. Urine contains urea, a potential fertilization resource for Martian farms. Therefore, a Urine Reclamation System is adapted for Martian surface use. This brings the ECLSS into waste treatment and process. Along these lines, we provide for each quarry a Solid Waste Processing Plant. This plant, placed underneath the main quarry alongside the Urine and Water Reclamation Systems, receives solid human waste and processes it for available energy and resources. These key functionalities are the primary studied functions of ECLSS for feasibility. The mass, power, and volume of the combination of such systems for deployment in a 25,000 person quarry habitat are shown below.

Table 7.5.1.1 ECLSS Mass, Power, Volume

System	Mass (Mg)	Power (kW)	Volume (m^3)
Solid Waste Processing	14.67	-48.45	132.82
Urine Treatment	1,625	5,891	4,584
Water Reclamation	0.4743	1.492	8.611
Air Scrubbing	177	91,228	88
Air Filtration	222	1,875	2,216
System Total	**1845**	**100,857**	**5,019**
Spare Parts	627.3	34,291	1,706
Total per 25,000	**2,472**	**135,148**	**6,725**
Total per 1,000,000	**98,892**	**5,405,935**	**269,018**

It is important to note that when discussing the interior habitat volume with reference to ECLSS, we are referencing only the livable space of the habitat. By doing so, we assume that the above described ECLSS system and its associated MPV values are not regulating the farm habitats. This comes from the very different requirements for environmental conditions set by farms compared to the requirements for colonists' living space. Therefore, ECLSS as described here is responsible for living habitats, common eating and meeting spaces, recreation habitats, court habitats, rover ports, bathing spaces, science habitats, and medical facilities. For continued growth of the ECLSS system, refer to the Appendices.

7.5.2 System Map

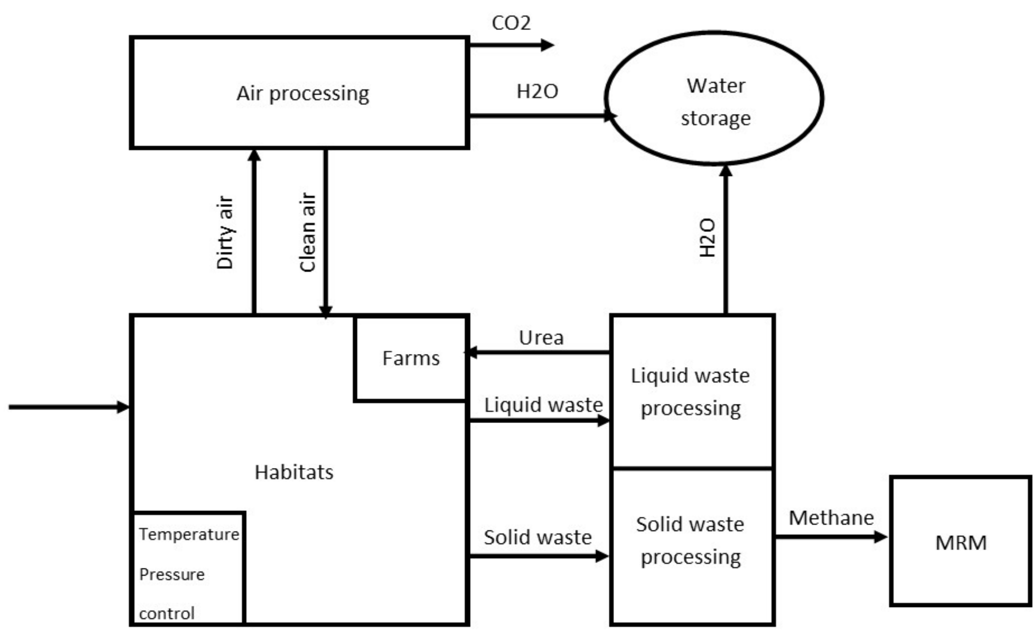

Fig. 7.2.2.8.1 System map of ECLSS showing flow of resources. (Credit: S. Shatto)

Shown here is a system map of the Environmental Control and Life Support System. We choose these systems largely for their control of resource flow. The Air Processing Unit, as

mentioned above, obtains “dirty air,” or air contaminated with carbon dioxide, particulates, humidity, and other non-desirables, filters and scrubs the air, and passes back to the habitats clean air. A benefit of this system is how clean water is passed out to water storage tanks. The Air Water Generation system filters humidity out of the air and makes it available as usable liquid water. The Water Reclamation System (WRS) is responsible for receiving liquid waste. Here, liquid waste refers to any source of non-potable water: bathing, farm run-off, food prep waste, post-urine reclaimed water, post-filtered water from humidity, etc. The only liquid that does not go straight to the Water Reclamation System is urine. Urine passes first to the Urine Reclamation System (URS) to remove urea. Resource management passes urea collected by the Urine Reclamation System to the farm habitats. This urea proves vital as a nitrogen source for crop growth. The Water Reclamation System, while able to pull contaminants from water, possesses no method by which to retain urea while discarding all other pollutants. Therefore, we choose to have the additional Urine Reclamation Systems. After passing through the URS, water automatically passes through the WRS for final treatment. We also see on the system map the Solid Waste Processing Plant. The SWPP accepts human fecal matter from the habitat and allows this refuse to flow downward to the processing area located beneath the primary body of the quarry habitats. The SWPP is capable of extracting a few resources from fecal matter. This system captures water from fecal matter, methane gas radiated off fecal matter, and energy when we burn the feces. We allow respective resources to flow to proper containment devices. For example, we pump the water found in feces to the Water Reclamation System for sterilization and then pass it on to Water Storage. Not only are there many different types of systems, we recognize the presence of many of each system. Even the SWPP’s, which are present as only one per quarry, will eventually have forty models sitting around the colony. Due to the large number of cylinders and living spaces, we determine it is necessary to have individual air filtration and scrubbing equipment. Because these systems produce resources able to be used by colonists, see the table below for production rate

7.5.3 Deployment / Fabrication

The Due to the complexity of ECLSS, four out of five of the systems will be fabricated on Earth. These systems are the Solid Waste Processing System, the Urine Treatment System, the Air Scrubbing System, and the Air Filtration System. Also constructed on Earth are spare parts that are required for upkeep and maintenance of each system within ECLSS

The Water Reclamation System, however, is fabricated on Mars from steel and iron, provided by the metal refinery. It is possible to make the reclamation system on Earth and bring them to Mars, but this will cost mass, volume, and ultimately money. It is more responsible and much easier to manufacture the tanks on mars. To construct the Water Reclamation System, two spherical shells made from steel are welded together. Three holes are drilled into the shell and a pipe is connected to each of these holes. These pipes are for a raw sewage inlet, a pollutant output, and a clean water output. The top of the sphere is cut off and replaced with a steel end cap allowing for maintenance access. Two more holes are drilled through these end caps in which iron bars are run through which serve as the anode and cathode. Lastly a UV light bulb is installed in the very bottom of the tank. UV light bulbs, necessary for the disinfection process in the Water Reclamation System are made on Earth and are packed alongside the spare parts for the other systems.

Once the Solid Waste Processing System, Urine Treatment System, Air Scrubbing System, and Air Filtration Systems are constructed on Earth, they are loaded freely in the cargo bay of an ITS-C. The UV light bulbs and spare parts are packed into 2m x 2m x 2m shipping containers and also placed onboard the ITS-C. The ECLSS is then sent to Mars.

Upon arrival, each system (followed by the spare parts) is individually unloaded from the ITS-C via cargo crane onto a rover. The rovers transport the ECLSS parts to the location of the quarry city in need, where they are unloaded. Prior to the construction of habitat cylinders, an excavator digs a hole in the center of the quarry, below the ground level of the habitat cylinders, where most components of the ECLSS will be located. The rest of the ECLSS deployment is performed by humans. Inside the hole, the colonists assemble the Solid Waste Processing System, Urine Treatment System, and Water Reclamation System, connecting piping from the habitat and farm cylinders, and connecting wiring for power. The Air Filtration System and Air Scrubbing

System are installed by colonists in each individual cylinder as they are constructed. This will result in excess air systems until they are required. Before operation of the Air Filtration System and Air Scrubbing System, the colonists will attach air ducts for air flow and wiring for power. All excess air systems, spare parts, and UV light bulbs will remain in storage until needed.

7.5.4 Operation and Servicing

The operation and servicing of the Urine Reclamation System (URS) will be not so complicated. We have chosen a system that will be state of the art. This means that the servicing of the unit should not come too frequently, but there will likely be issues along the duration of a 100 year journey. As will be discussed later, there will be a set of spare parts, potentially, if colonists need to make repairs to ECLSS, which includes the URS. The URS and the Solid Waste Processing Plants will be located together at the bottom of the quarries so that the waste only has to travel down with fecal matter to get to the destination plant.

7.5.5 Retirement, disposal, and replacement

These systems will need to be maintained fairly regularly, as will be shown later with risk analysis. As the time comes for retirement of the URS, these systems will need to be replaced from Earth. Unfortunately, they are too complex colonists to make URS systems on Mars and must have specialized components. The URS and Solid Waste Processing Plants, which are buried underneath the cylinders within the quarries, will need to be accessible to maintenance crews. Because of the modular, rack design of the URS, swapping one unit for another will not be a large enough task to cause significant problems for maintenance crews [1].

7.5.6 System Cost

For the sake of ECLSS cost discussions, we break the cost into segments: development and production. Never in the past have such large amounts of life support systems been constructed, making long term, multi-system production costs difficult to model. In our case, economies of scale will be applied to production costs and any estimate currently developed will be an overshoot of actual production costs. Using estimates from *Space Mission Engineering: the New SMAD*, an approximate one time development cost for ECLSS falls around $12.5 billion. After the one-time development cost, we determine a recurring production cost. These costs are based upon the 25,000 person quarry city ECLSS. The recurring production cost is roughly one quarter of the development cost, ending up at $4.2 billion for each quarry city.

Table 7.5.6.1 ECLSS Costs Over Mission

Cost Type	Cost (Billions of dollars)
Construction Cost per Quary	12.5
Replacement Parts Cost Per Quarry	4.2
Total ECLSS Cost Over Mission	176.3

7.5.7 Risk Analysis

Failure of the Environmental Control and Life Support System, as with many components of this mission, could be catastrophic to successfully colonizing Mars. In order to determine how best to mitigate risk, we first quantify that risk and determine what forms failure could take. We find that the levels of failure can range drastically from a loss in productivity rates for non-life-critical resources to Loss of Crew (LoC). During the progression through risk analysis, we choose to hone in on failures that lead to Loss of Crew. Thus, the most critical failures take place within the Air Processing Unit—specifically with the Carbon Dioxide Removal Assemblies (CDRAs)

and the oxygen production units—and with both the Water Reclamation System and Urine Reclamation System concurrently. These failures are presented below in Fig. .

Component	Description of Failure	Effects of Failure on the System	Risk Mitigation	Potential Hazard Level
Air Filtration	Air selector on CDRA valve failure	Carbon dioxide buildup	Bring spare parts	Critical
Air Filtration	Carbon dioxide filter failure	Carbon dioxide buildup	Bring spare parts	Critical
Air Filtration	Oxygen production failure	Lack of oxygen provided to crew	Bring spare parts	Critical
WRS	UV light of Water Reclamation System (WRS) burns out	WRS becomes inoperable	Bring spare parts	Critical
WRS	Anode and cathode of WRS burn out	WRS becomes inoperable	Bring spare parts	Critical
URS	Faulty centrifuge in the Urine Reclamation System (URS)	URS becomes inoperable; less water reclaimed; no nitrogen provided to farms	Bring spare parts; Complete urine purification with WRS and bring nitrogen for farms	Critical
URS	Faulty check valves within the URS	URS becomes inoperable; less water reclaimed; no nitrogen provided to farms	Bring spare parts; Complete urine purification with WRS and bring nitrogen for farms	Critical
ECLSS	No spare parts for above listed failures	Above system fails; loss of crew (LoC)	Have redundant ECLSS components	Critical

Fig. 7.5.7.1 Failure Mode, Effects, and Critical Analysis for ECLSS, Describing Critical Failures

Our chosen ECLSS design, through the above listed critical failure modes, is expected to have a reliability rate of 98.30%. Conversely, ECLSS has a probability of failure of 1.70% and a Mean Time to Failure of 89 days.

7.5.8 Risk Mitigation Strategies

With a Mean Time to Failure of 89 days in the context of a long duration mission such as Project Destiny, colonists' lives will be at stake. A critical failure within 89 days with no methods by which to repair the broken ECLSS component will result in Loss of Crew, an unacceptable result. Therefore, risk mitigation strategies are developed. We acknowledge the need for defining what proper risk mitigation looks like for ECLSS. To this regard, we must provide a way to address inevitable failures within ECLSS and prevent failures from becoming critical—such as Loss of Crew—before more repair parts or backup systems can be provided. Therefore, for risk mitigation, we choose to supply spare parts for individual components within ECLSS that are expected to be the most common failure points. Examples of such failure points are outlined in the Appendix. With this risk mitigation strategy, the Mean Time to Failure—here being the time until failure becomes critical—increases from 89 days to 638 days. This new Mean Time to Failure encompasses only a single spare part for each component. However, providing one set of spare parts allows colonists to repair the component and have a seven-fold increase in time to prepare for a second, critical failure. We are capable of quantifying this risk mitigation in terms of expense by showing that a full set of spare parts is equivalent to approximately 34% of the system mass [1]. This is still better than providing a full set of redundant ECLSS components, which is equivalent to another 100% of the system mass added to the original launch mass. All of this information is displayed in the table below.

Table 7.5.8.1: Risk Assessment for ECLSS

Reliability	Probability of Failure	Mean Time to Failure (no spare parts)	Mean Time to Failure (one set of spare parts)	Added Mass of Spare Parts
98.30%	1.70%	89 days	638 days	627 Mg

7.6 References

[1] Garcia, M., ed., "Facts and Figures," NASA Available: https://www.nasa.gov/feature/facts-and-figures [Retrieved 23 January 2017].

[2] "The Greensboro," Modular Buildings and Mobile Offices Available: http://www.roseoffices.com/floorplan-images/the-greensbor

7.7 Rovers and Accessibility

7.7.1 Recreation Rovers

7.7.1.1 *System Description*

The General Purpose Recreation Rover (GPRR) provides the colonists with their weekly recreation time. Each vehicle can hold 4 passengers and is designed to operate during all daylight hours, providing an average of seventeen forty-minute excursions per day. They are also equipped with two robotic arms to support limited science and construction objectives.

7.7.1.2 *CAD / System Totals*

Fig. 7.7.1.1The General Purpose Recreation Rover provides colonists with recreation time outside the habitat. (Credit: J. Kang).

Table 7.7.1.2.1: GPRR Mass, Power, Volume

	Per vehicle
Mass	1.83 Mg
Nominal Power	205 kW
Volume	2.2 m^3

Table 7.7.1.2.2: GPRR Capability Metrics

GPRR- Capabilities	
Average Velocity:	20 km/hr
Maximum Velocity:	40 km/hr
Passenger Capacity:	4 colonists
Trips per sol:	17 trips
Average trip duration:	40 min
Lifetime:	692 sols

7.7.1.3 *Deployment / Fabrication*

Like our other surface vehicles, the recreation rovers are shipped from Earth and deployed via the integrated ITS crane (See Section 6.5).

7.7.1.4 *Operation*

The rovers are intended to be operated manually, as the entire purpose is to provide colonists with an outlet for entertainment. The manipulator arms allow colonists to collect samples as well as conduct small-scale construction work (pipe placement, repairs, etc.).

The mean time to failure of this vehicles is 692 sols. This is because these vehicle failure rates are scaled from failures rates of Earth automobiles, and the GPRR sees very heavy use. This is why the GPRR is the biggest launch cost driver of the surface vehicles.

7.7.1.5 *System Cost*

Table 7.7.1.5.1: GPRR Cost Estimation

Component	Cost	Margin
Base (Tesla Model 3)	$35,000	
Manipulator Arms	$15,000	
ECLSS	$100,000	
Space Hardening Factor	2.5X	
Total	$375,000	50%

7.7.1.6 *Risk Analysis & Mitigation*

Table 7.7.1.6.1: GPRR Risk Analysis & Risk Mitigation

Risk being mitigated	**Probability of failure/MTTF**	**Cost of mitigation strategy in $/MPV**	**Improved**
GPRR reaches end of operational life	MTTF: 692 days (266,00 km)	*S*end replacement GPRR. Cost: $375,000 + 1.1 Mg/7.5 m^3 on ITS per vehicle	N/A
Crash into terrain/rover/rover port	5%	*E*nforce driving rules, Reduce vehicle speed near rover ports, $0	2%
Air leak from vehicle (pressure loss)	5%	*M*aintenance and life support systems - Oxygen masks/ 8 people $2200	4%
Vehicle stranded during mission	7%	*U*se MCPT to rescue crew Cost in oxygen and power based on distance	4%
Manipulator arm failure	10%	*R*egular maintenance, spare part cost range from $100 - $3000 (replacement $15,000)	5%

7.7.2 Recreation Ports

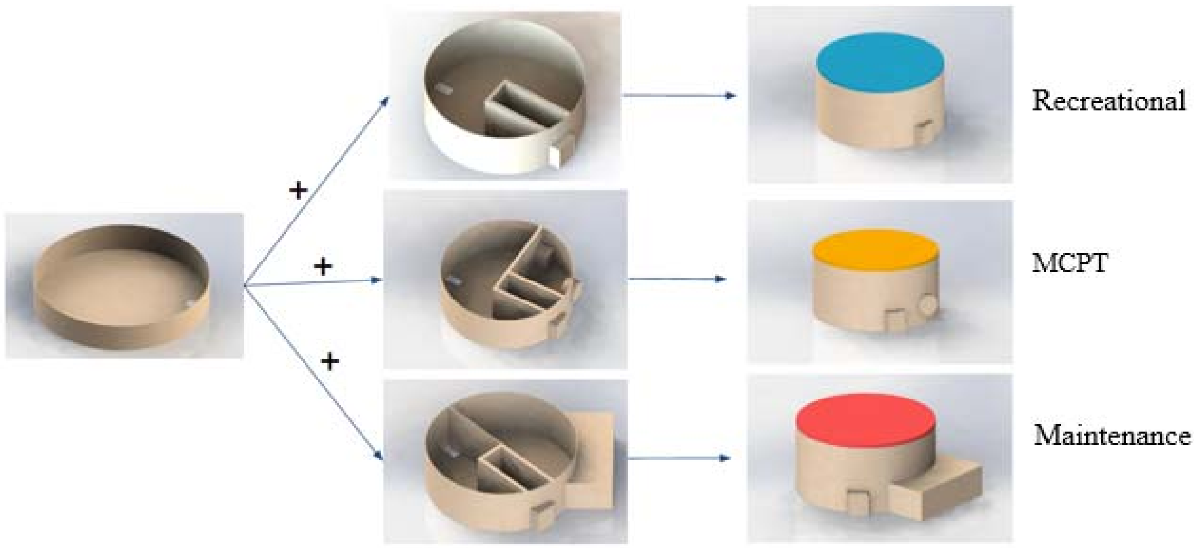

Fig. 7.7.2.1 The combination of the three types of rover port. (Credit: J. Kang)

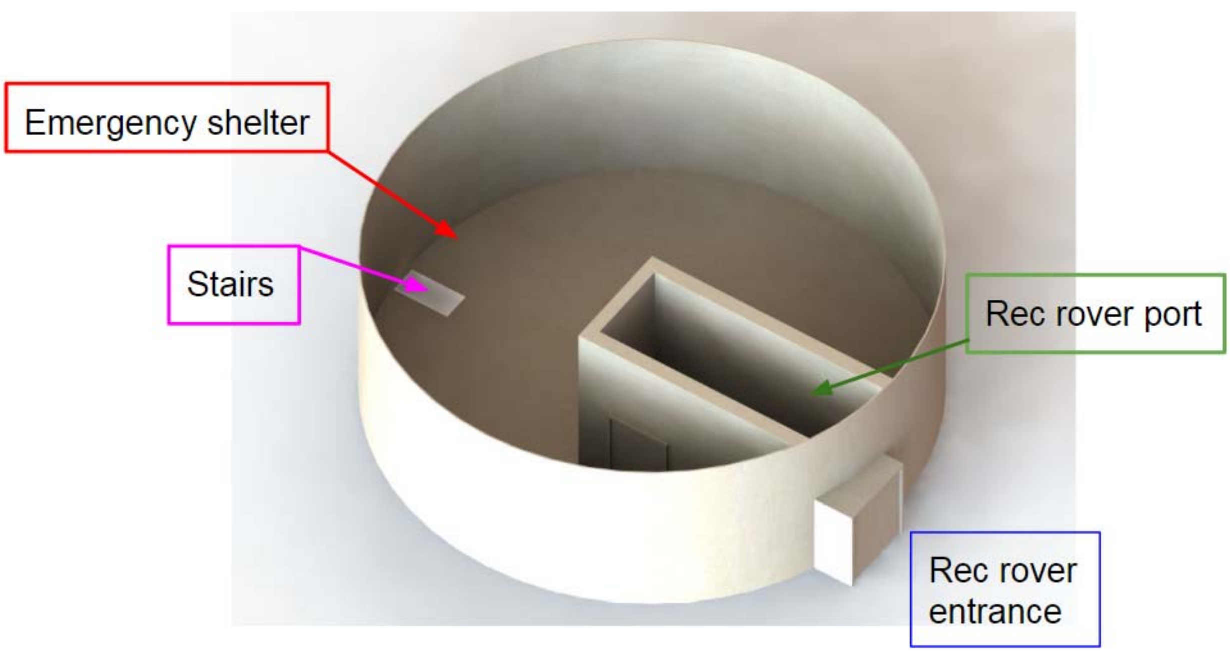

Fig. 7.7.2.2 The internal layout of the recreational only rover port. (Credit: J. Kang)

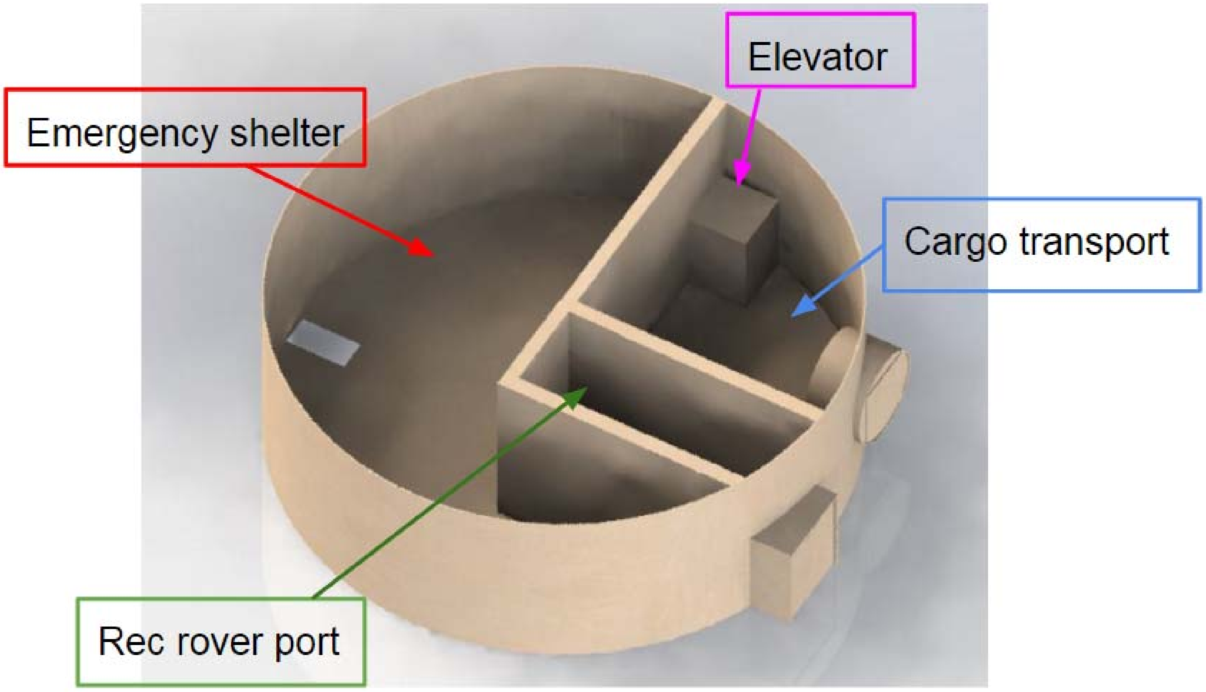

Fig. 7.7.2.3 The internal layout of type MCPT port. (Credit: J. Kang)

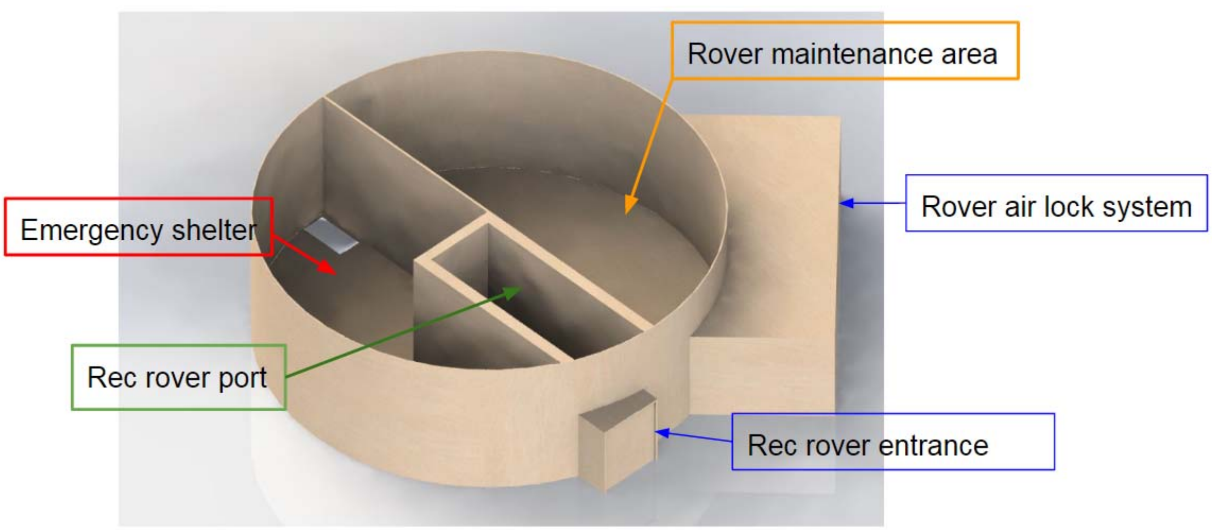

Fig. 7.7.2.4 The internal layout of the maintenance port. (Credit: J. Kang)

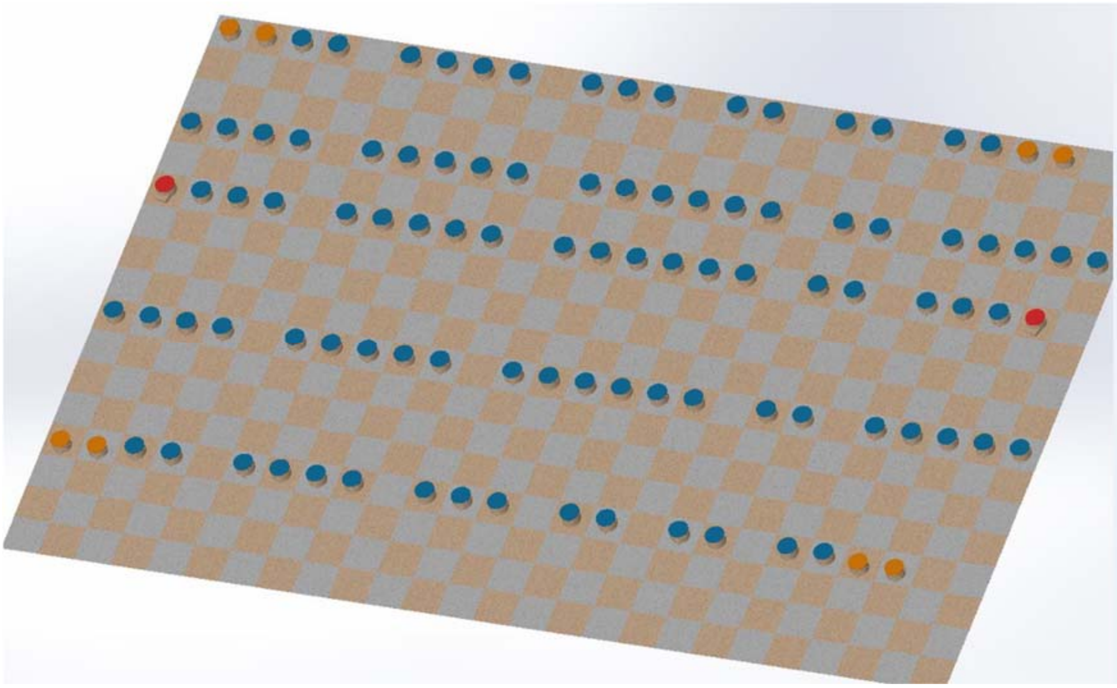

Fig. 7.7.2.5 Isentropic view of the quarry with the rec rover / emergency shelter and the habitat module. (Credit: J. Kang)

Table 7.7.2.1 Amount of Rover Port Types per Quarry

Type	Amount per quarry
Recreational	99
MCPT (Cargo transport)	8
Maintenance	2

Table 7.7.2.2 Total Area of Rover Port Space per Quarry

Recreational rover port, [m^2]	Cargo transport, [m^2]	Rover maintenance area, [m^2]	Stairs, [m^2]	Emergency shelter, [m^2]
3924	590.4	273.6	436	50148

7.7.2.1 *Deployment / Fabrication*

To make the rover ports, we choose to make them out of the same cylindrical structure of the habitat modules. After all the habitat modules are completed for 25,000 person quarry, we fill up any remaining space with Martian regolith and build the rover ports on top of the habitat modules using the same 3D printers that the habitat modules are built from. We place the rover ports on top of each of the emergency-capable habitats whose locations are shown in Fig. . Since there are 109 emergency capable habitats, we have 109 rover ports per quarry.

To accommodate multiple rovers and uses, we build three distinct rover port designs as shown in Fig. . The three types are: recreational, MCPT, and maintenance. The first level of each type of rover port is distinct. However, the top level of each rover port is an emergency shelter. These shelters are identical across all rover ports. The number of each rover port type constructed for each quarry is shown in

.

First, we construct the first level of the rover ports. We construct at least one airlock for each rover port. These airlocks are fabricated from steel made on Mars. For the recreational rover port we place one airlock that is large enough for the recreational rover to park inside of. For the MCPT port, we choose to place a docking port for the MCPT, which will allow passengers and cargo to move through the port without exposing them to Martian dust. Lastly, we place an airlock large enough to accommodate every rover type we bring to Mars.

After the first level of each rover port is completed we print the emergency shelter on top. We connect the two levels using stairs. Additionally, we also place stairs between the first level of the rover ports and the emergency capable habitat underneath. This provides an access point from the habitat to the surface of Mars.

The recreational rover port has an airlock (8 m × 3.5 m) that will fit two recreational rovers. The reason to have this air lock is for the passenger to go in the recreational rover easily. The wall for the recreational rover port airlock is 0.5 meters thick. This thickness is chosen so the structure can withstand the large stresses at the corners.

The Mars Cargo and Passenger Transport Port has a pathway of 2 meters wide for the colonists to walk and 3meter wide space for the cargo. There is an elevator to lower the cargo

down. The total space of cargo transport is 63.61 m^2 which is quarter of the whole level of the rover port.

The rover maintenance area is 126 m^2 which is the half of the rover port. This area can change due to the size of the rover been maintenance. The Maintenance rover port has additional space to accommodate the largest rover that is brought to the colon.

7.7.2.2 *Operation*

In the case of an emergency in the habitat cylinders, colonists exit the habitat and enter the emergency shelter on the top level of each rover ports and wait until the issue is resolved. If the habitat needs to be completely evacuated, colonists wait in the emergency shelter until rovers arrive to move them to a safe habitat.

For the recreational rover port, colonists use this port to transfer into the recreational rover. The colonists cycle the airlock after entering and securing the recreational rover's hatch. After the airlock is cycled the colonists are able to drive on the surface of Mars. When the colonists finish their drive, they park the recreational rover inside the recreational rover port airlock. They then wait for the airlock to cycle. Once the airlock pressure and oxygen levels match that of the habitat, the colonists open the door of the recreational rover and enter into the habitat through the rover port. Maintenance on the recreational rover is performed when they are in the airlock for the recreational rover port.

For the MCPT rover port, colonists dock the MCPT with the rover port using the docking ring. Cargo and passengers can then freely move between the rover port and the docked MCPT. Cargo is stored in the rover port until it is ready to be unpacked and used in the habitat below.

The maintenance rover port is used to maintain all surface vehicles except for the recreational rovers. When a rover needs maintenance, the colonists drive the rover to the maintenance port and open the airlock. They then move the rover into the maintenance airlock and cycle it. When the air pressure and gas levels of the maintenance airlock reach the same levels as the habitat, the colonists enter the airlock to perform maintenance on the rover.

7.7.2.3 *System Cost*

Since the rover port will be built primarily out of Martian materials, the cost of the ports is just that of the additional usage of the 3D printers and steel production. These costs have already been factored into those respective systems.

7.7.2.4 *Risk Analysis*

This risk analysis focuses on issues specific to the rover ports. Failure of systems that are used on multiple cylinder types, such as ECLSS, are featured in their respective sections. For the risk analysis on the rover port, the main fault is failure of the airlocks which cause loss of pressure. The possible failure modes are shown in the following fault tree in.

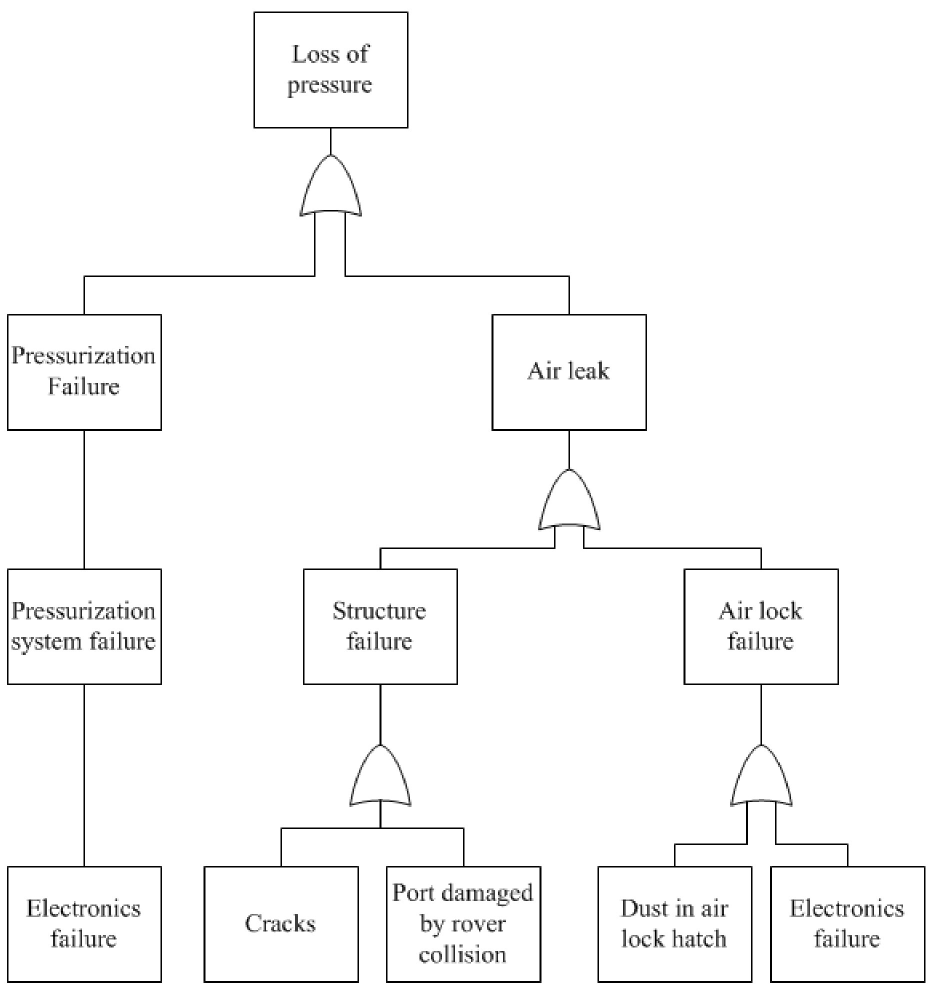

Fig. 7.7.2.4.1 Fault tree for Rover Ports. (Credit: K.Nakagoshi)

7.7.2.5 *Risk Mitigation Strategies*

The risk mitigations for each failure mode are shown in Table 7.7.2.5.1. In order to prevent loss of pressure due to cracking in the structure of the rover port, regular inspections can be made, and cracks could be sealed up and repaired when spotted. To avoid the rover port from being damaged by rovers driving near them we impose a 10 km / hr. speed limit. This will increase the time drives have to respond to mistakes, while also reducing the impact velocity of accidental collisions. To stop dust or debris from preventing the airlock to seal properly, the airlock will be cleaned and cleared of all dust before each closing cycle. We reduce the potential of electronics failure by adding an auxiliary electronics system that uses battery power. By taking these actions we reduce the chance of loss of pressure of the system.

Table 7.7.2.5.1 Effects of failure on system and risk mitigation for each failure

Specific Failure	**Effects of failure on system**	**Risk mitigation**
Cracks	Structure failure	Inspection & Repair
Port damaged by rover collision	Structure failure	Speed limit near ports
Dust in air lock hatch	Air lock failure	Cleaning
Electronics failure	System shutdown	Electronics backup

8 Food Production System

8.1 Timeline/System Operations

Project constraints state that no food is grown during the first synodic period. After the first synodic period, 10% of the food consumed by the colonists is produced on Mars. The portion of food grown on Mars increases by 10% every cycle, so that 100% of the food consumed by colonists is produced on Mars by the 11^{th} synodic period.

It is very important to note that no food is grown during the first synodic cycle. This allows the team to begin building our permanent solution immediately and removes the need of a temporary farming structure.

Our permanent solution is a quarry design with 3-D printed basalt structures. Crops grow in a hydroponics system within these structures. We supply light to crops using a fiber-optic solar collecting array. With this system we are able to grow enough food to support the colony and develop a reserve of food which can support the colony for an extra synodic period.

8.2 System Map

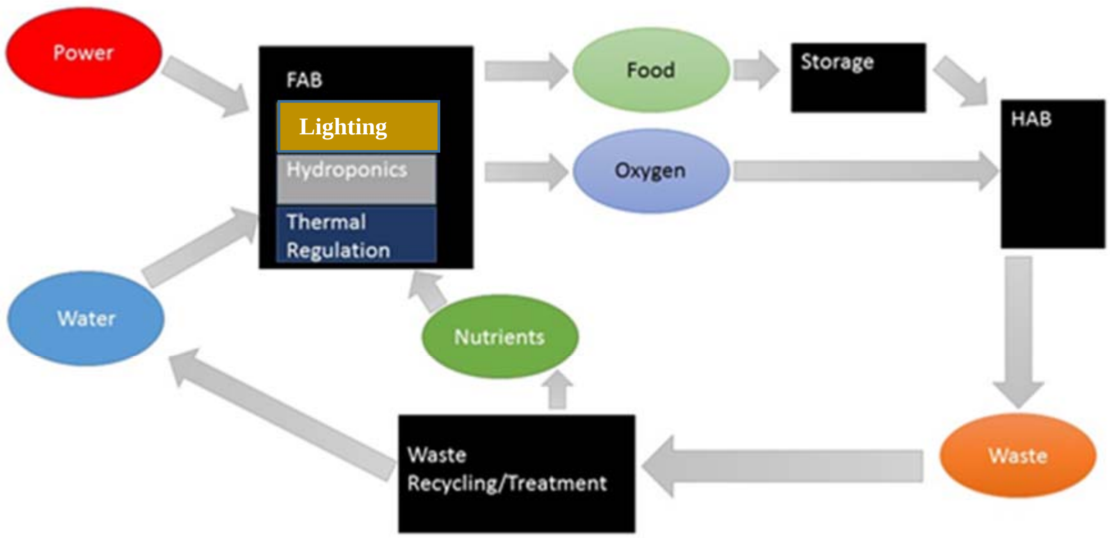

Fig. 8.2.1 System Map for Food Production (Credit: S. Matlock and L. Mozzone)

The Food Production team proposes the solution above (Fig. 8.2.1) to complete the task of providing food for our colony. This basic schematic outlines our system, its inputs, its outputs, and the cycle of progression that makes plant grown possible. To take the steps through the process, the purple arrow will move to illustrate the current system being described.

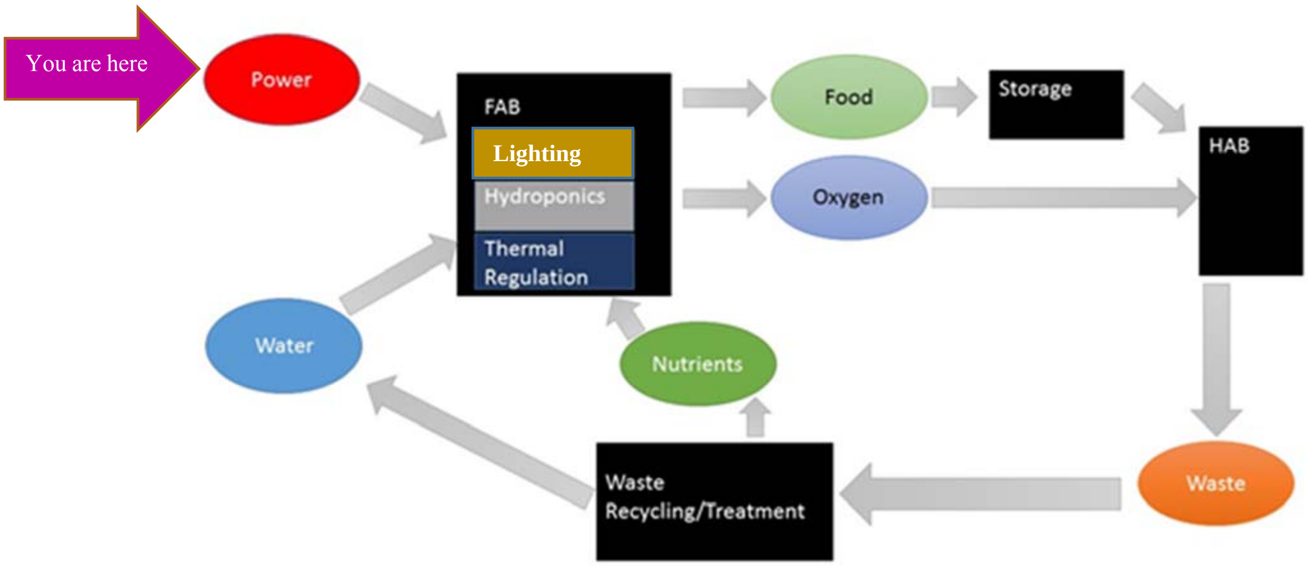

Fig. 8.2.2 System Map, outlining the power supply (Credit: S. Matlock and L. Mozzone)

The first input provided to the farm system is power. This power, supplied by Central Power, enters the Farm Habitat (Fab), and provides electric power to the Oxygen Removal Assembly (ORA) and the vacuum pressurization pumps. These systems are in place to ensure a suitable environment is available to facilitate plant growth. The power source also supplies the Fab with thermal power, allowing the Fabs to be maintained at 20°C, an optimal temperature for growing crops.

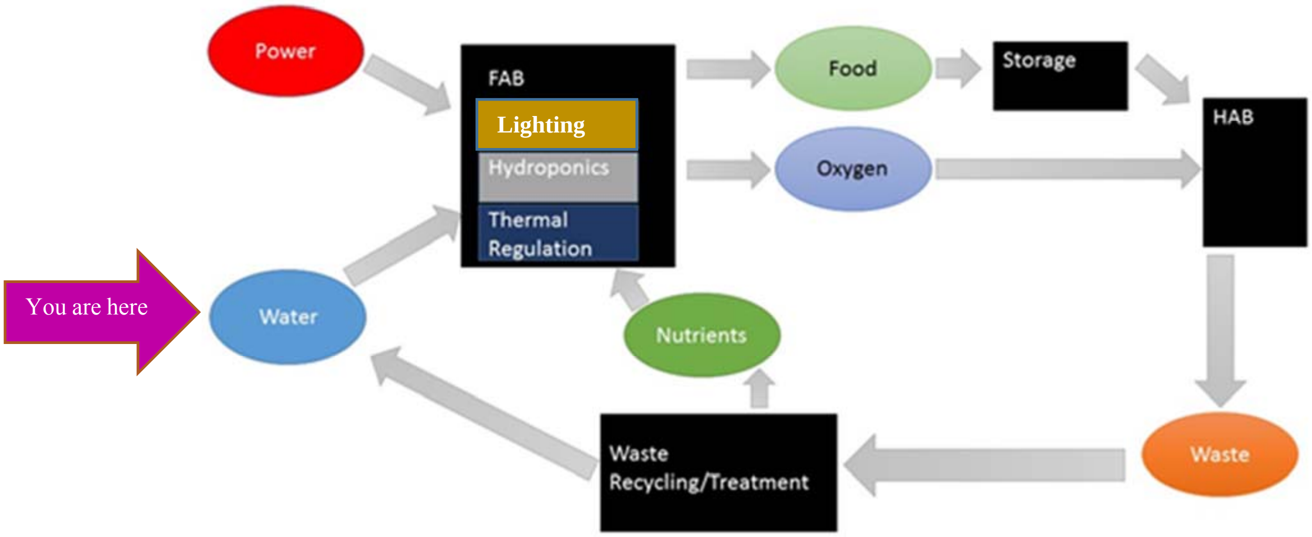

Fig. 8.2.3 System Map, outlining the water supply (Credit: S. Matlock and L. Mozzone)

Water is another input of the Fabs. Water flows inside the hydroponics growing system, providing nutrients to the plants on its way through the cycle. This water moves throughout the hydroponics system, meaning much of the water in the system remains in the hydroponics system, continually circulating. Additional water is occasionally added to account for evaporation into the air and absorption into the crops.

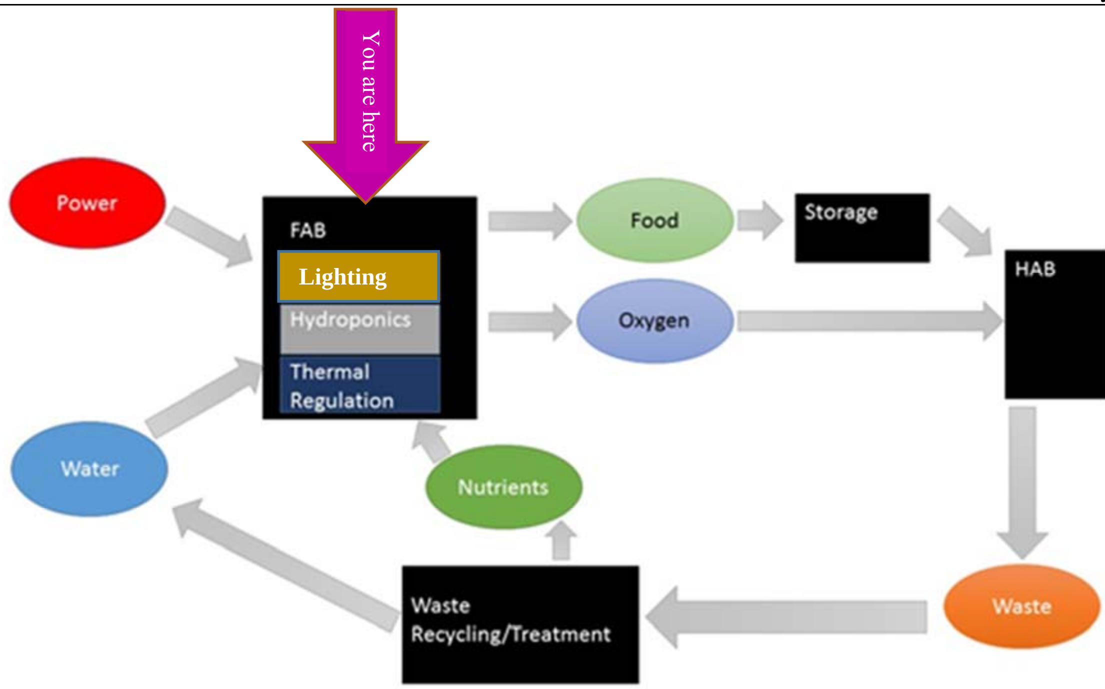

Fig. 8.2.4 System Map, outlining the Fab (Credit: S. Matlock and L. Mozzone)

First, the quarries consist of the 3D printed Fab buildings made of basalt that are printed and then buried. Internally, the Fab contains lights, hydroponics, Oxygen Removal Assembly (ORA), and pressurization pump. These systems are described in detail under Section 8.3. The hydroponics system utilizes the water input to the system to grow the food, while the electric power source provides the needed power for the vacuum pumps and the ORA. The power source also regulates the temperature inside the Fabs using the thermal power the nuclear reactors create. The lights capture the sunlight from the surface using large dishes, and transfer it to our underground Fabs through fiber optic cabling.

The colonists, who work to ensure the crops yield the proper amount of food for the colony, do the planting and harvesting processes. Operating on a rotational harvesting program, the crops are moved from the Fabs to the eating areas to ensure freshness. The excess food is brought to storage, where it remains in case of emergencies, such as loss of farms or bad crop yield. One synodic cycles worth of food is stored for the colony, to ensure that all the colonists can be fed until at least the next ITS launch arrives from Earth (so food can be shipped from Earth in case of emergency).

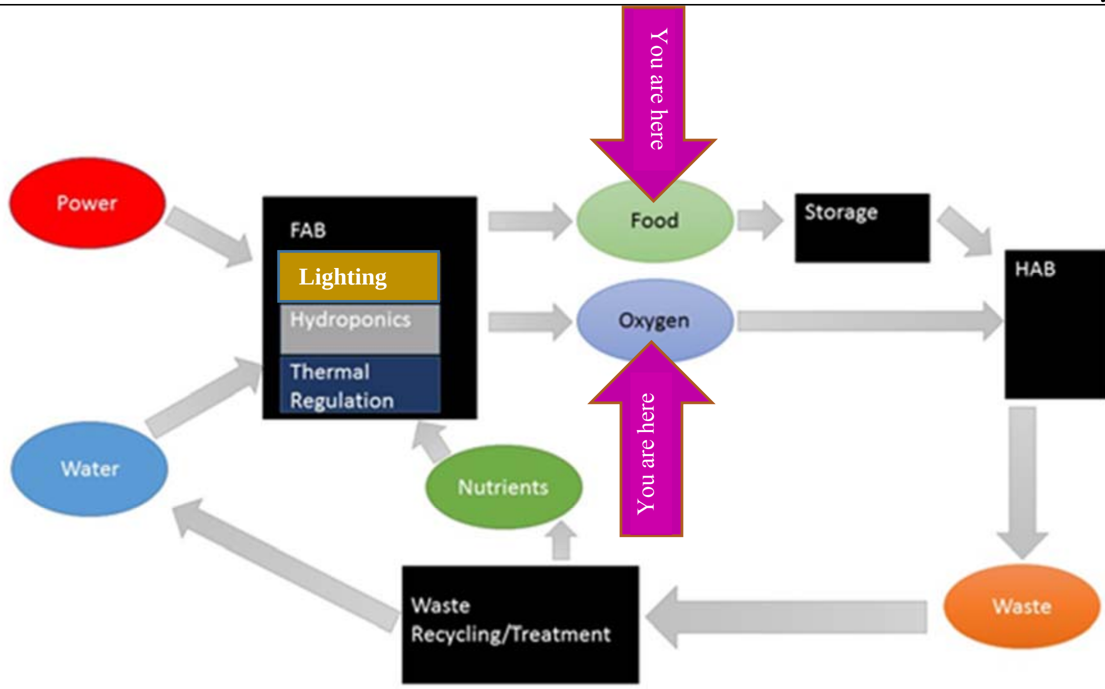

Fig. 8.2.5 System Map, outlining the Food and Oxygen (Credit: S. Matlock and L. Mozzone)

From the FABs, two outputs are produced: food and Oxygen. The crops are harvested from the Fab, and then brought to temporary storage inside the dining areas of the habitats (HABs). Excess food, produced to supply one synodic cycle worth of backup food for our colonists, is moved to storage and remains there in case of a catastrophic loss of food production capabilities. The oxygen produced by our crops will be moved directly to the living HABs, where it provides our colonists breathable air.

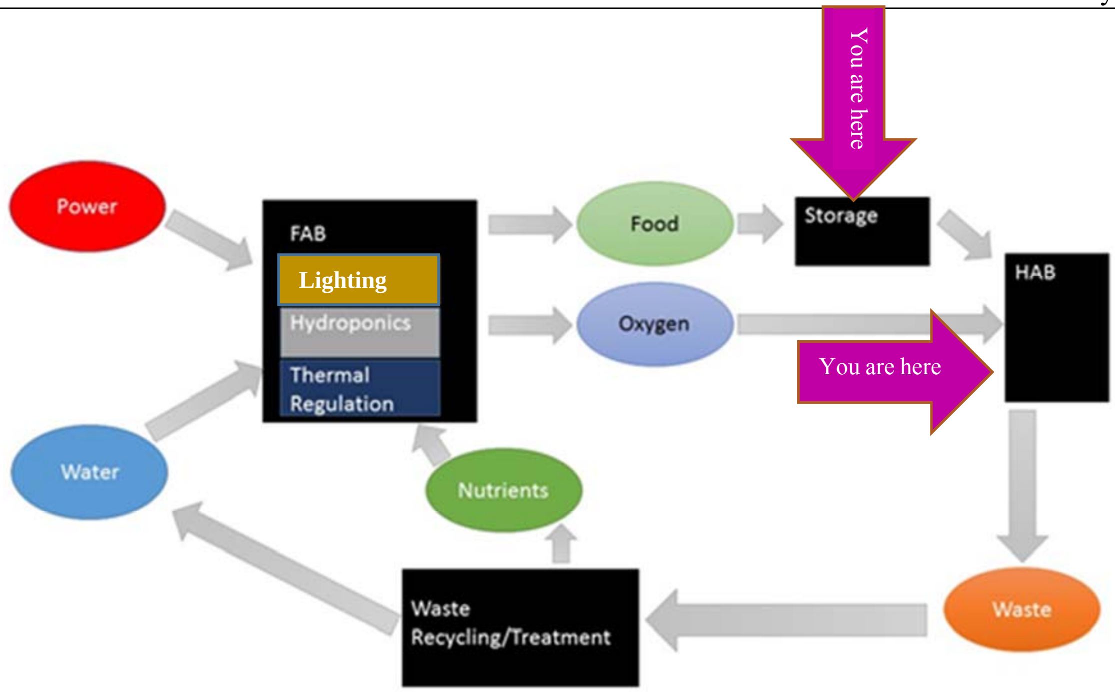

Fig. 8.2.6 System Map, outlining the Storage and HAB (Credit: S. Matlock and L. Mozzone)

The storage facilities provide permanent storage for the food. Structurally they are the same as the Fabs, but there is no internal environment regulators. There is no heating or hydroponics system inside, but instead, it is a large building that is cold enough to store food for what we assumed to be an unlimited amount of time (it is assumed that the food freezes inside the storage facilities, and therefore the food will never spoil). We propose that food is harvested for consumption every 3 days, and the food that is harvested will be brought directly to the dinning habitats, where it will be stored and prepared as needed.

The HABs serve as a blanket term for all the buildings designed by the Martian Habitat Development team. The HABs provide shelter and other facilities necessary to the continued health and happiness of the colonists. As the HABs will be supporting human life, they must be supplied with Oxygen and food, both of which are produced in the Fabs.

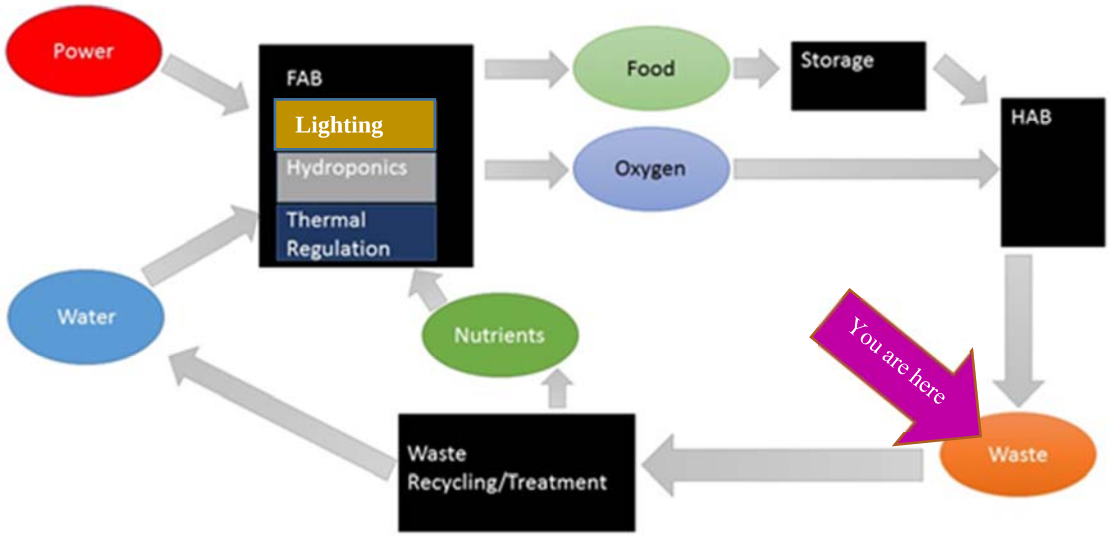

Fig. 8.2.7 System Map, outlining the waste (Credit: S. Matlock and L. Mozzone)

Human waste is an output of the HABs. This waste contains vital nutrients and water that can be recycled and reused in the Fab. Most important of these is urea, which contains nitrogen. Nitrogen is an important element in the facilitation of plant growth, and with a limited supply of Nitrogen in the Martian atmosphere, the Nitrogen must be reclaimed from every avenue possible.

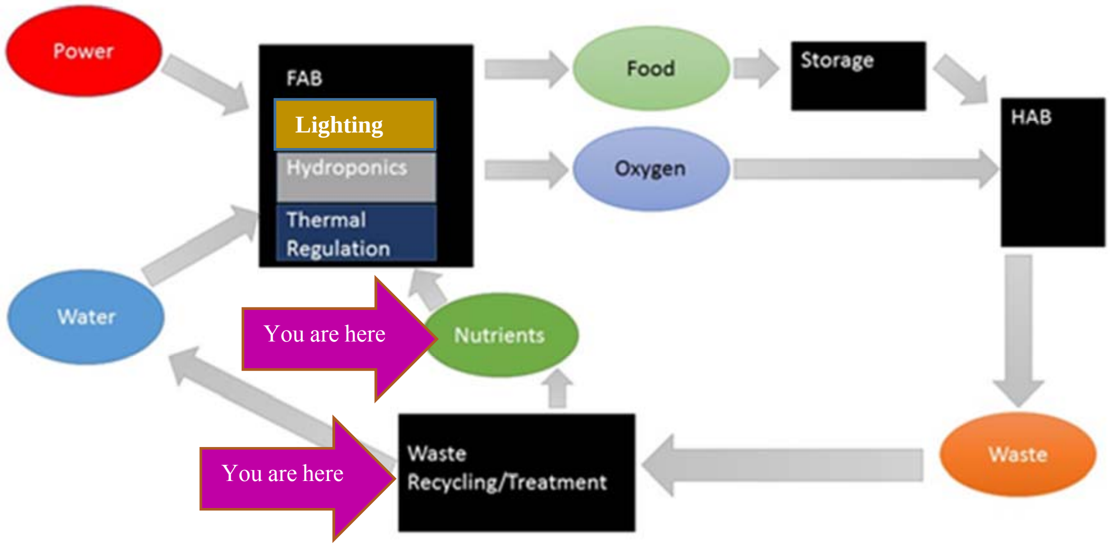

Fig. 8.2.8 System Map, outlining the Waste Recycling/Treatment and Nutrients (Credit: S. Matlock and L. Mozzone)

The waste from the HABs is transferred to a waste recycling and treatment plant. There, the vital nutrients and water are removed from the human waste. These supplies then cycle back into the Fab to be reused to aid in proper plant growth.

8.3 Deployment / Fabrication

8.3.1 Quarry

We propose that our farms be placed in a quarry as part of the permanent solution. A quarry design provides multiple benefits, including radiation protection, thermal insulation, and additional support to withstand pressurization. The quarry design can be seen visualized below in Fig. 8.3.1.1 and Fig. 8.3.1.2.

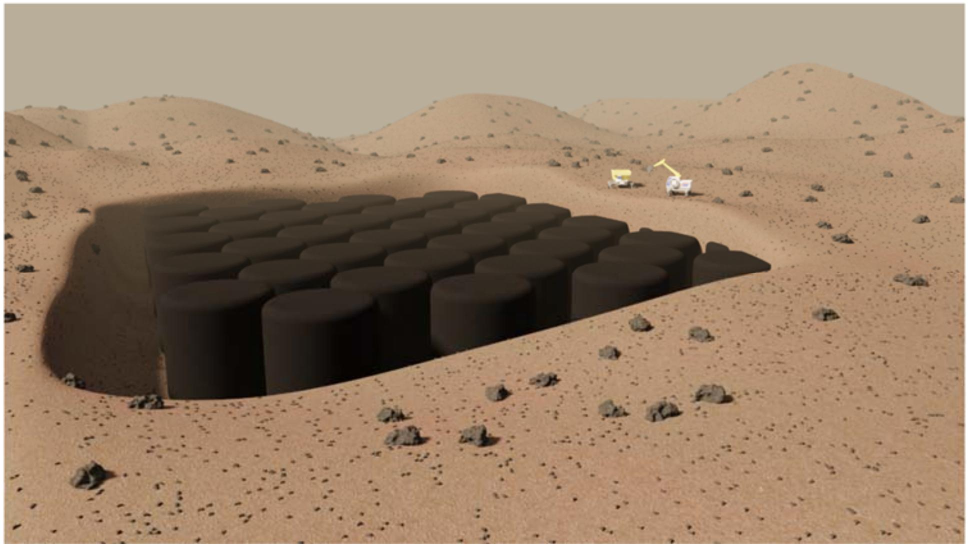

Fig. 8.3.1.1 Depiction of the 1uarry with several habs/fabs exposed, while they are in the process of being buried (Credit: A. Judson)

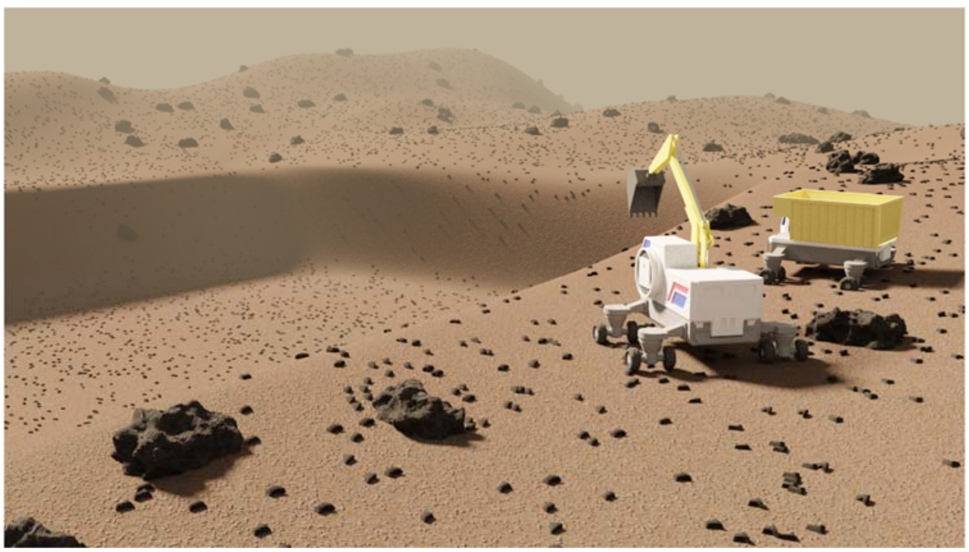

Fig. 8.3.1.2 Depiction of fully excavated quarry (Credit: A. Judson)

The quarry design dictates the hole is 22m deep, to ensure our Fabs are covered with regolith. The Surface Operations team conducts excavation of the quarry, and more in depth details about the excavation is found.

With regards to radiation protection, our structures requires ~1m thick of compacted Martian regolith surrounding them to provide enough protection to keep the colonists and crops below 50mSv/year, which is the upper limit of radiation dosage that a person can withstand without negative implications to their health. This limit was also taken for the farm habitats (Fabs), as we

intend to have colonists working in the Fabs. The radiation values for the Fab can be seen below in Table 8.3.1.1.

Table 8.3.1.1 Radiation Values throughout the Fab structure

Material Type	Thickness (m)	Half Value Layer (m)	Incoming radiation (mSv/day)	Transmitted radiation (mSv/day)	Dosage (Lifetime) (mSv)
Martian Regolith	2	0.25	0.7299	0.00285	104.02
Basalt	0.49	0.03967	0.00285	6.95×10^{-7}	0.25
Steel (top hydroponic stack)	0.005	0.025	6.95×10^{-7}	6.225×10^{-7}	0.23
Steel(bottom hydroponic stack)	0.005	0.025	1.39×10^{-7}	6.95×10^{-8}	0.02

In collaborating with Martian Habitat Development, our design of the quarry intermingles Habitats and Farm Habitats (FABs) near one another, in order to maximize effective movement for the colonists. This design can be thought of as a neighborhood, where the colonists' living, bathing, and working areas are all closely connected. More pertinent to Food Production, this system creates a straightforward method of people retrieving food for themselves and the others in their neighborhood.

8.3.2 3D printing/ structure

Fig. 8.3.2.1 Depiction of a Fab being 3D printed within the quarry (Credit: A. Judson)

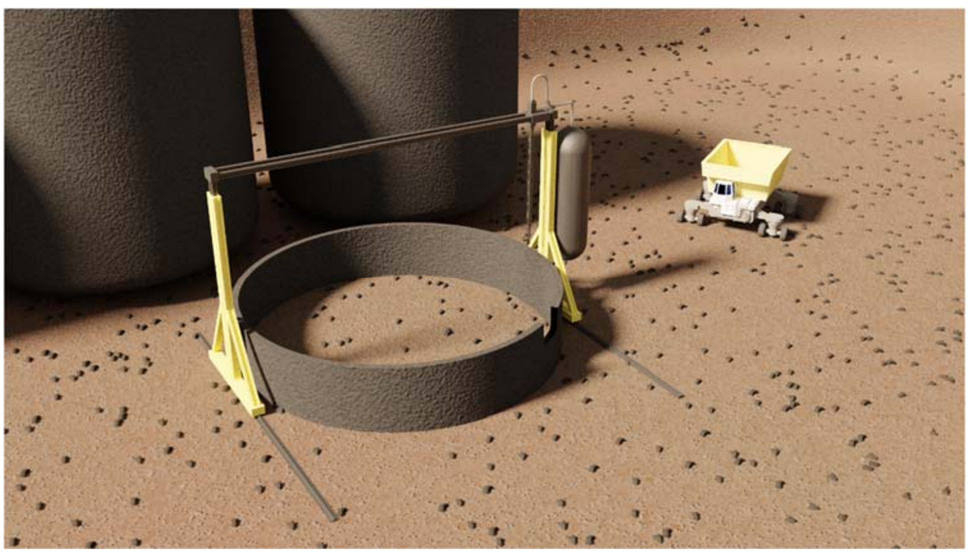

Fig. 8.3.2.2 Top view of the 3D printer constructing a Fab (Credit: A. Judson)

The goal of the permanent model was to create a method of building our structures on Mars for sustainability purposes. It was found with the "100 person model" that bringing the farm structures from Earth created an unsustainable number of ITS launches. To solve this, we propose 3D printing our Fabs with basalt, a material found in abundance in the Martian regolith. A 3D printer designed by the Martian Habitat Development team carries the task of printing our Fabs. The 3D printer design has the capability of constructing a building 18m tall with a diameter of 18m. A cylindrical building design with slightly rounded top and bottom is implemented to best

distribute the internal pressure load of the Fabs. The design and building process are displayed in Fig. 8.3.2.1 and Fig. 8.3.2.2. We constrained the pressure load to 1atm to allow farmers to operate comfortably inside the Fabs without a pressurized suit. Along with the pressure load, the weight of 1m of regolith on top of the structure and the structures own weight were all considered to analyze the structural integrity of the Fab. Implementing a factor of safety of two, the side wall thickness is 0.1093m, while the top and bottom walls are 0.49m thick, and are filleted with a radius of 2.5m. These farm dimensions are displayed in Table 8.3.2.1.

Table 8.3.2.1 Dimensions of the Fab structure

Internal Height (m)	Internal Diameter (m)	Sidewall Thickness (m)	Top, Bottom, and Fillet Wall Thickness (m)	Fillet Radius (m)
18	18	0.1093	0.49	2.5

We need additional farm volume to provide one synodic cycle's worth of excess food for the colony. This way, if we can't produce food on Mars there is time to launch an emergency supply of food from Earth. The excess volume necessary to feed the colonists relies on the population curve. The excess volume necessary to feed the colonists relies on the population curve. As the deliver rate of colonists increases for the first 9 synodic cycles, so must the volume of farm to provide excess food to be stored for these colonists. The volume increase per cycle is shown in Table 8.3.2.2. In total, there is an additional 805,350 m^3 of farm volume to supply 1 synodic cycle's worth of excess food for the colonists. By the end of cycle 9, no more excess farm volume is necessary, as the existing farm volume will then supply the excess food for each cycle of incoming colonists.

Table 8.3.2.2 Farm volume that needs to be added to produce surplus food for each of the first 9 synodic cycles

Cycle Number	Farm Volume To Expand Each Cycle (m^3)
1	21476
2	75166
3	96642
4	96642
5	107380
6	107380
7	107380
8	107380
9	85904

Concerning where this food will be stored, we propose additional Fab structures be built exclusively for the purpose of storing the surplus food. With the average human consuming 2,600 calories per day (assuming the population is 50% male, who consume 3,000 calories per day on average, and 50% female, who consume 2,200 calories per day on average), the number of calories was converted to a mass of food. Considering our food choices (blueberries, carrots, peanuts, squash, and potatoes) and the percent of growing area each of these foods will cover in the Fabs (41% of the Fab growing area will be dedicated to peanuts, while 14% will be dedicated to each of the other foods), the food mass and volume is determined. The total volume of stored food is then transferred into a number of Fabs, in which the stored food will be placed, assuming perfect packing. These values are shown below in Table 8.3.2.3.

Table 8.3.2.3 Excess Food Volume, Mass, and number of structures needed for storage

	Mass of food stored (Mg)	Volume of food stored (m^3)	# of farming structures req.
25,000 person quarry	4.708e4	9.163e4	26
1,000,000 person colony	3.766e6	7.331e6	1715

Though the building process for the storage facilities is the same as the farms, the inside of the storage facilities are not heated or pressurized, as these facilities are meant to store food for lengthy periods of time (assuming no spoiling, the food will have an infinite lifetime within the storage facilities).

Using these structural dimensions and knowing the building material is basalt, a total number of Fabs is calculated, to include the necessary food storage facilities and farming space to provide excess food, as seen in Table 8.3.2.4.

Table 8.3.2.4 Number of Fabs total, including Volume covered by Fabs and Volume and Mass of Basalt needed to Build the Fabs

System	Number of Fabs, including excess and storage	Total Volume of Fabs (m^3)	Total Volume of Basalt (m^3)	Total Mass of Basalt (Mg)
25,000 person colony	256	1,300,700	128,110	371,520
1,000,000 person colony	9432	47,923,000	4,720,000	13,688,000

8.3.3 Farm Habitat Internals

The internal components of the farm consist of four main components: a hydroponic system, lights, an Oxygen Removal Assembly (ORA), and a pressurization pump.

8.3.3.1 *Hydroponics*

First, the hydroponics system is selected as it allows for 5 times more efficient growing than traditional soil farming. In other words, hydroponics farming accomplishes the same job as soil farming using 5 times less growing area (from 95.32 m^2 of growing area to feed 1 person to 19.06 m^2 of growing area to feed 1 person), which in turns means less buildings and supplies needed to grow the same number of crops. The hydroponics system is visualized in Fig. 8.3.3.1.1, Fig. 8.3.3.1.2, and Fig. 8.3.3.1.3. We determined using a circular hydroponics system would increase the growing space with relation to walking room for the workers, as compared to a square hydroponics system.

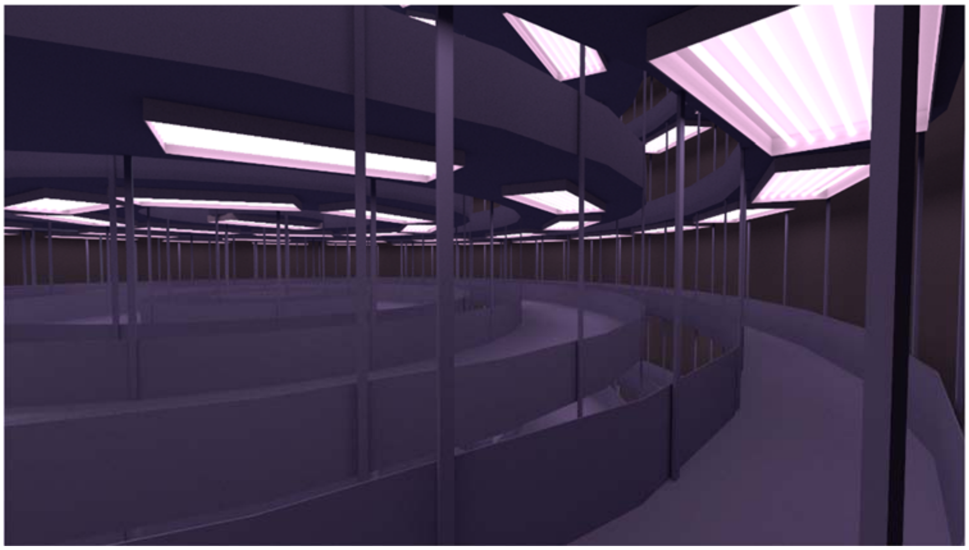

Fig. 8.3.3.1.1 Internal view of the hydroponics system with lighting and stacks included

(Credit: A. Judson)

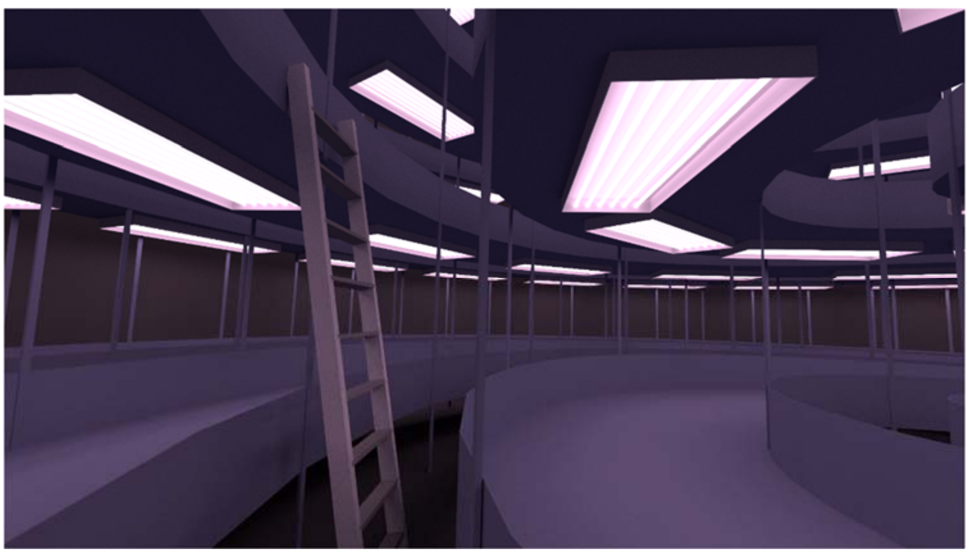

Fig. 8.3.3.1.2 Internal view of hydroponics system with ladder to depict how stacks are accessed

(Credit: A. Judson)

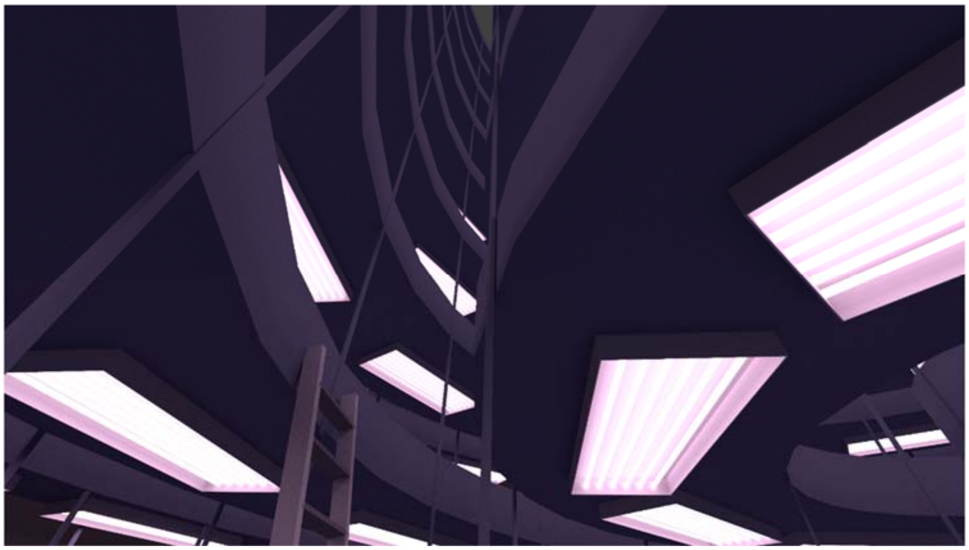

Fig. 8.3.3.1.3 Internal view of hydroponics to depict the shelf stacking system (Credit: A. Judson)

A growing volume of 24.78 m^3 per person was calculated, taking into account height of crops, depth of roots, and percentage of growing area that each crop occupies. This volume was adjusted based on the dimensions of the hydroponics system (seen in Table 8.3.3.1.1Table 8.3.3.1.1 Dimensions of Hydroponics System)Table 8.3.3.1.1 Dimensions of Hydroponics System to account for walking room in the FABs. Taking walking room into consideration, the actual volume needed to feed 1 person is 33.0443 m^3.

To fulfill the growing volume requirements, the hydroponics system is built on Mars, using steel extracted by Mars Resource Management from the Martian regolith. Using steel from Mars means no cost for transporting the hydroponics system from Earth. The mass and volume of steel needed to build the hydroponics system are shown in Table.8.3.3.1.2.

Table 8.3.3.1.1 Dimensions of Hydroponics System

Wall Thickness [m]	Support Beam Dimensions [m]	Wall Height [m]	Mass of steel for one Fab [Mg]	Volume of steel for one Fab [m^3]
0.005	0.05x0.02x2	0.5	39.3	4.884

Table.8.3.3.1.2 Mass, Power, and Volume of the Steel Hydroponics System (built using steel on Mars)

	Mass (Mg)	**Power (MW)**	**Volume (m^3)**
1 Fab	39.3	0	4.884
25,000 person colony	9039	0	1123
1,000,000 person colony	361560	0	44933

Finally, to optimize space and reduce the number of FABs needed to be built, we recommend stacking the hydroponics system. It is assumed that the average crop will take 2m of growing space vertically. With the FABs internal structure being 18m, this allows for 9 stacks of hydroponics shelving with crops.

8.3.3.2 *Lights*

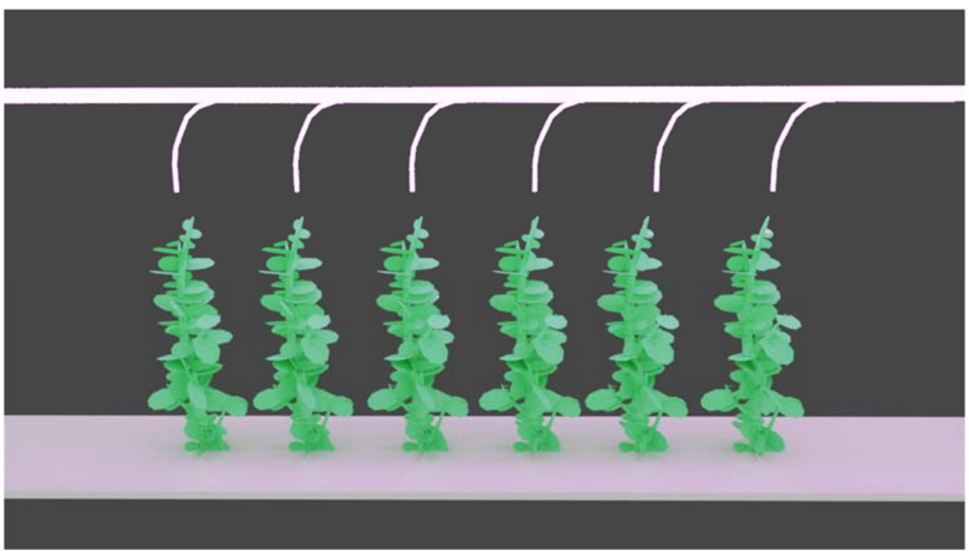

Fig. 8.3.3.2.1 Image of fiber optic cabling providing light to the crops (Credit: A. Judson)

The next component necessary for the success of the farms are lights. A lighting source provides vital light to facilitate plant grown. The lighting method selected incorporates the collection of sunlight using large plates on the Martian surface, and distributing the light using fiber optic cables, as seen in Fig. 8.3.3.2.1. The lighting system is broken down into two main components: the sunlight collection plates and the fiber optic cabling. We propose building the sunlight collection plate with the steel available from Mars Resource Management. The fiber optic

cabling however is brought from Earth, as the infrastructure to make glass cabling is determined to be unrealistic on Mars. The resulting amount of steel needed for the steel plates and the mass, power, volume, and number of launches needed to transport the fiber optic cables are available in Table 8.3.3.2.1 and Table 8.3.3.2.2.

Table 8.3.3.2.1 Mass and Volume of Steel needed to Build Reflective Dishes for Light Collection on Mars

System	Mass Of Steel Needed To Build Reflective Dish (Mg)	Volume Of Steel Needed To Build Reflective Dish (m^3)	Number of Reflective Dishes needed
25,000 Person Colony	3072	388.86	1536
1,000,000 Person Colony	122880	15554.43	61440

Table 8.3.3.2.2 Mass, Power, and Volume for the Fiber Optic Cabling, as well as number of ITS shipments needed

System	Mass Of The Grow Lights (Mg)	Power That The Lights Require (MW)	Volume Of The Grow Lights (m^3)	Length of Fiber Optic Cabling Required (Km)	Number of 2x2x2 Containers To Ship Fiber Optics	Length of Fiber Optic Cabling That An ITS Can Transport (Km)	Number of ITSs Needed To Ship Lights
25,000 Person Colony	3.109	0 (Solar)	2.667	14.1320	1222	1.480	10
1,000,000 Person Colony	124.36	0 (Solar)	106.66	565.2790	48852	1.480	382

8.3.3.3 *Vacuum Pumps*

Fig. 8.3.3.3.1 Depiction of the vacuum pumps used to pressurize the FABs (Credit: A. Judson)

The fourth component necessary for the farm habitats are the vacuum pumps, shown in Fig. 8.3.3.3.1. These pumps have two functions: maintain 1 atm of pressure within the FABs and retain the proper amount of CO_2 in the FABs to facilitate plant growth. The final design implements a Rotary Vane Dry Vacuum Pump to complete this task. This pumps benefits from the ability to pull air from low atmospheric pressures; more specifically, the pump can pull from pressures as low as 2 Pascals, which is a lower pressure than the atmospheric pressure of Mars. One pump is needed per FAB, and the mass, power, volume and number launches to transport the pumps can be seen below in Table 8.3.3.3.1.

Table 8.3.3.3.1 Mass, Power, and Volume for the Vacuum Pumps, as well as number of ITS shipments needed

System	Mass Of Pumps (Mg)	Power That The Pumps Require (Kw)	Volume Of The Pumps (m^3)	Number of Pumps Required	# Of 3x2x2 Containers To Ship Pumps	Number of ITS launches
25,000 Person Colony	72.825	1418.17	2299.75	380	380	0.24275
1,000,000 Person Colony	2913.02	56727.17	91990	15332	15332	9.71

8.3.3.4 *ORA*

Next, an Oxygen removal assembly (ORA) is necessary for the farm. The capabilities of this system allows the Oxygen produced by the plants to be recycled and used for breathing air for our colonists. The mass, power, volume and launches for this system are shown below in Table 8.3.3.4.1.

Table 8.3.3.4.1 Mass, Power, and Volume for the Oxygen Removal Assembly, as well as number of ITS shipments needed

System	Mass Of The ORA (Mg)	Power That The ORA Requires (kW)	Volume Of The ORA (M^3)	Number of ORAs Required	# Of 2x2x2 Containers To Ship The ORA	Number of ITS launches
25,000 Person Colony	83.387	1029.587	41.399	1302	6	1
1,000,000 Person Colony	3335.5014	41183.49	1655.9466	52080	207	19

8.4 Operation

8.4.1 Nitrogen Needs

In order to achieve self-sufficiency for resources, the colony must avoid relying on Earth resources. The goal is to either produce resources on Mars, and/or recycle the resources available, both with the purpose of maintaining resources needed for the farm. For Food Production, the most constraining of these resources is Nitrogen. With a limited amount of Nitrogen present in the Martian atmosphere (only 2.7% of the Martian atmosphere is Nitrogen) and essentially no Nitrogen available in the Martian regolith, there is a need to manage the use of this resource. This is because Nitrogen is necessary for the production of proteins and amino acids within out crops, and without Nitrogen, our crops would not survive.

To collect Nitrogen, we propose reclaiming the nitrogen from the colonists using the Environmental Control and Life Support System (ECLSS), via urine. In conjunction with Martian Habitat Development, we conclude that 93% of the Nitrogen can be reclaimed using the ECLSS.

Though this is a step towards self-sustainability, we propose that Nitrogen must still be brought from Earth, as seen in Table 8.4.1.1. The Nitrogen is brought in the form of Anhydrous Ammonia fertilizer.

Table 8.4.1.1 Nitrogen Needs for the Food Production Team to Facilitate Plant Growth

Values in terms of 25,000 Person Quarry	Mass/Synodic Cycle (Mg/Cycle)
Total Amount of Nitrogen Needed	164.539
Amount of Nitrogen being Reclaimed	134.433
Amount of Nitrogen Needed to be brought to replace the lost Nitrogen	29.419
Total amount of fertilizer (Anhydrous Ammonia) Needed to be Brought to replace the lost Nitrogen	35.877

8.4.2 Crop Choices

We propose five foods to be grown on Mars: squash, blueberries, carrots, potatoes, and peanuts. These selections provide many of the nutrients necessary to sustain human life, as well as high caloric output per square meter of growing area. Though not high in calories, blueberries added nutritional variety, while peanuts provided a source of high protein and a method of Nitrogen fixation.

8.4.3 Area needed

The area is based on the nutrients required per day to sustain a human being. The final calculation indicated that, analyzing the percentages of our five crops to optimize farm area, a growing area of 95.32 m^2 is needed to sustain one person. This is based on peanuts occupying 41.2% of the farm, and squash, blueberries, carrots, and potatoes all occupying 14.7% of the farm each. This growing area represents the growing area for traditional, soil growing tactics. Implementing hydroponics, five times the amount of food can grow in the same area. This means, using hydroponics, our growing area is only 19.06m^2.

8.5 System Cost

The system costs for the Food Production team are shown in Table 8.5.1. The cost of each product necessary to operate the Fabs is available. In order to reduce costs, many of the systems for the Fabs are produced on Mars. This not only reduces the unit cost to $0, but also results in no ITS shipments. The systems brought from Earth are the Oxygen Removal Assembly and the fiber optic cables, while the Fab structure, hydroponics systems, and light refection dish are produced on Mars.

Table 8.5.1 Cost Analysis of the Food Production Systems

Product	Cost/unit	# of Units for Final Colony	Total Cost	Number of ITS launches
Hydroponics System	$0 (built on Mars)	82,000	$0	0 (built on Mars)
Oxygen Removal Assembly	$2,055,472	52,080	$107,048,981,760	12
Fiber Optic Cables	$1430 per Km	560 km	$800,800	382
Steel Reflection Dish	$0 (built on Mars)	61,440	$0	0 (built on Mars)
Farm Habitat (Fab)	$0 (built on Mars)	10,240	$0	0 (built on Mars)
Vacuum Pumps	$10,000	15,200	$152,000,000	10
Anhydrous Ammonia Fertilizer	$600/Mg	31,284 Mg	$18,770,846	105
TOTAL			**$107,201,782,560**	**509**

8.6 Risk Analysis

Food Production is a vital system for the survival of the colony, and it must therefore risk to the food source must be analyzed. The fault tree in Fig. 8.6.1 demonstrates the components of our system, and what impact their failure would have on the rest of our system. If many of the systems fail, especially for a prolonged period of time, it could mean the loss of food, and depending on the extent of the food shortage, the failure could result in the loss of life. Because of this, Food

Production has taken steps to identify potential risks, and then propose strategies on how to mitigate these risks. A closer look at the failure modes of the system can be found in the appendix.depending on the extent of the food shortage, the failure could result in the loss of life. Because of this, Food Production has taken steps to identify potential risks, and then propose strategies on how to mitigate these risks. A closer look at the failure modes of the system can be found in the appendix.

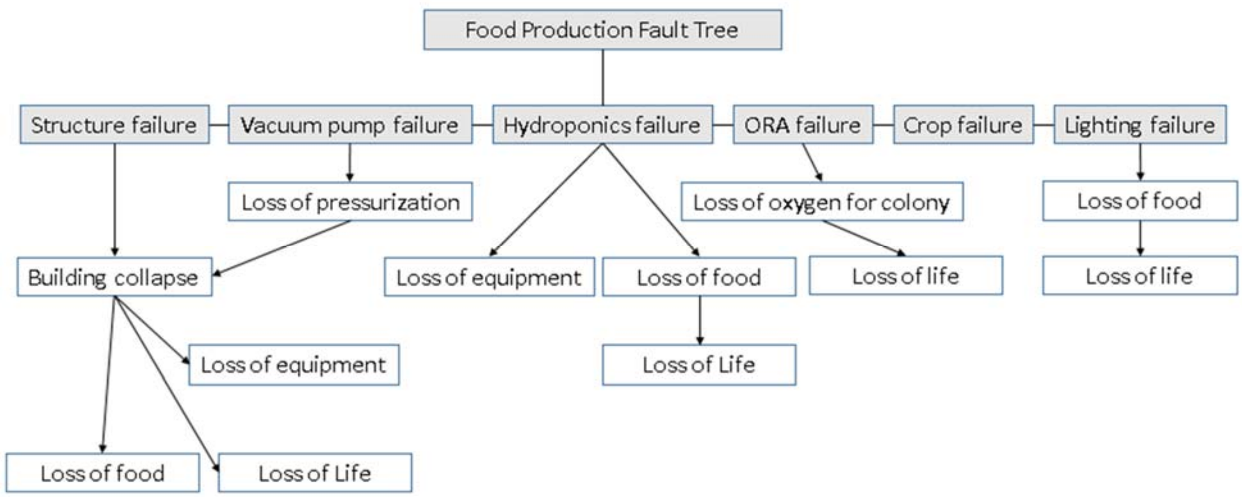

Fig. 8.6.1 Food Production Fault Tree for Risk Analysis (Credit: L. Mozzone)

Risk Mitigation Strategies Table 8.6.1 illustrates the risks associated with the Food Production systems, and how to mitigate the risks. Many of the risks associated with our system involve structural failure, specifically for the hydroponics, the fiber optic cables, the Oxygen Removal Assembly, the vacuum pumps, and the Farm Habitat. These systems rusting/deteriorating/breaking are all possibilities, but a typical resolution to these concerns are structural redundancy and routine maintenance. One unique problem though is plant disease, as this is a prominent concern on Earth, and should not be taken lightly on Mars either.

Table 8.6.1 Risk Mitigation Strategies for Potential Risks Associated with Food Production Systems

Risk	Mitigation strategy	Cost
Pathogen in Hydroponics System	Close monitoring of plants Fungicides, Antibody Engineering	21 Mg/cycle for 1,000,000 person colony
Rust Damage to Hydroponics	Galvanize Steel	Galvanize steel with Zinc which is present on Mars
Internal Structure Failure	Structural redundancy is inherent to the design of the internal structure	Free, design itself protects against this type of failure
Fire	Install a fire suppression system within the Fabs	Bring fire suppression from earth to install within HABs and Fabs
Extreme Temperatures	Insulate Fiber optic sleeves to combat extreme heat and cold	Bring insulated wire sleeves for entire amount of fiber optics
Human Error	Have experienced members work on fiber optic cables along with farmers in the Fab	Replacement cable if system breaks
Dug Up Cable	Have experienced workers handle fiber optics. In addition, have cables marked that are buried underground.	Replacement cable if the system breaks
Fan/Pipe failures In The ORA (Minor Failure)	Maintain and check the system every 100 days	Replacement parts (fans, pipes, valves, actuators)
Desiccant/Absorbent Bed Failure (complete system failure)	Maintain and check the system every 100 days	Replacement parts (desiccant bed, absorbent bed)

Liquid Contamination in pump pipes	During maintenance, do not spray	Man hours spent cleaning pumps
Oil contamination in pump lines	Maintenance checks on pad seals	Man hours spent checking pads often
Carbon contamination in pump lines	Clean pipes before replacing pumps	Man hours spent cleaning pipes whenever a pump is replaced

9 Colony Electric Power and Heating System

9.1 System overview

9.1.1 Power generation

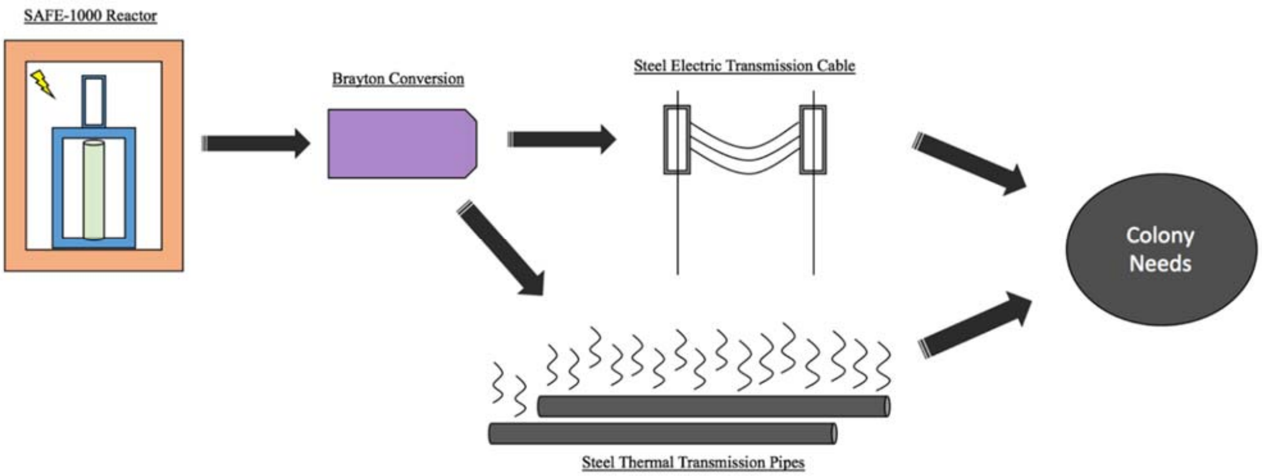

Fig. 9.1.1.1 This map shows the main components of the colony power system. SAFE-1000 reactors generate thermal power, which is converted to electric power for colony use. (Credit: M. Young)

Nuclear fission power plants generate power on the Martian surface to support our colony. We choose the Safe Affordable Fission Engine (SAFE) reactor and a Brayton power conversion system for the nuclear power plants. The reactor generates 1,000 kW thermal power (kWt) and we call it the SAFE-1000 reactor. The Brayton power conversion system is made up of three 100 kW electric power (kWe) assemblies and is coupled to the reactor. Each power plant consists of one SAFE-1000 reactor coupled with one Brayton power conversion system.

The SAFE-1000 is a heat pipe power system (HPS) reactor based on the SAFE-400 space fission reactor designed by engineers at Los Alamos National Laboratories [9.1]. Uranium nitride (UN) fuels the reactor. The SAFE-1000 has 127 heat pipes with sodium (Na) as the working fluid. Three fuel pins surround each heat pipe and transfer heat to the sodium. The heat pipes extend above the reactor's core and couple with the power conversion system. The SAFE-1000 is shown in Fig. 9.1.1.2. The Brayton power conversion system consists of three 100 kWe assemblies. Each assembly has a turboalternator, recuperator and gas cooler [9.2]. We choose a "stacked" layout for the conversion system, which places all three assemblies side-by-side in the same orientation. The

"stacked" layout allows the system to be placed closer to the SAFE-1000 reactor and for a reduction length of piping. One power conversion assembly is seen in Fig. 9.1.1.3.

Fig. 9.1.1.2 The SAFE-1000 reactor is shown here. Heatpipes extend above the core and transfer heat to the power conversion system. (Credit: K. Jantze)

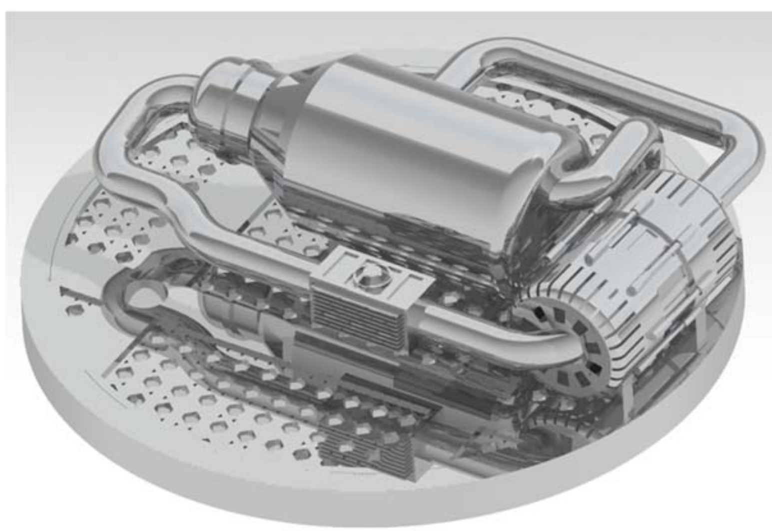

Fig. 9.1.1.3 One Brayton power conversion unit (100 kWe) is shown here. Each power plant has three power conversion units.(Credit: K. Jantze)

Because of the problem of nuclear radiation, we place our nuclear power plants no closer than 100 m from the colony's quarry cities. At this distance, power transmission and distribution

to user loads is a problem that must be addressed. From each Brayton power conversion unit, we transmit and distribute electric power to the habitats, farm habitats (fabs) and other colony loads. We also take advantage of excess thermal power from the plants, which we transmit to thermal loads from habitats, fabs, water pipes, and the water tower.

9.1.2 Electric power transmission

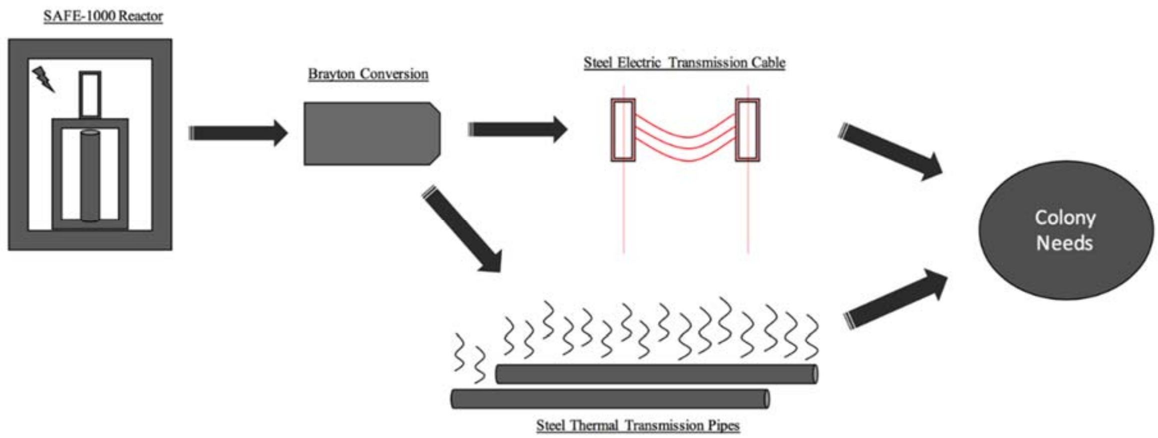

Fig 9.1.2.1 This map shows the main components of the colony power system. We transmit electric power via steel cables to the quarry cities. (Credit: M. Young)

We transmit electric power generated by the nuclear power plants to colony power loads via steel cables. We desire high-voltage transmission to minimize energy loss to electrical resistance. In a study on nuclear power systems for space applications, Lee Mason of NASA Glenn Research Center reports that 5,000 volts alternating current (Vac) is a technology advancement that is projected to occur between 2020 and 2030 [9.3]. We choose the transmission voltage to be 5,000 Vac.

Our choice for transmission cable material is steel. The transmission cables run along the Martian surface, as opposed to underground, to reduce excavation and simplify maintenance. Aluminum and copper are the most common electrical conductors on Earth and these materials were also considered. Both aluminum and copper transmission cables require ITS cargo deliveries from Earth, while we are capable of producing steel cables on Mars. The disadvantage of steel cables is greater power losses in transmission compared to aluminum and copper because of a higher electrical resistivity. Despite greater losses, the number of ITS deliveries required to transport aluminum or copper from Earth make steel transmission cables our obvious choice.

After long-distance transmission, voltage is stepped down to be compatible with user power loads throughout the colony. We step voltage down to 120 Vac as this is used in multiple NASA Mars surface power generation concepts [9.4-9.7]. We employ a buck transformer to provide 120 Vac for colony power loads. We have a map of the electric power transmission system in Fig. 9.1.2.2. The map illustrates the flow of power from generation in the SAFE-1000 reactors to distribution at various colony power loads.

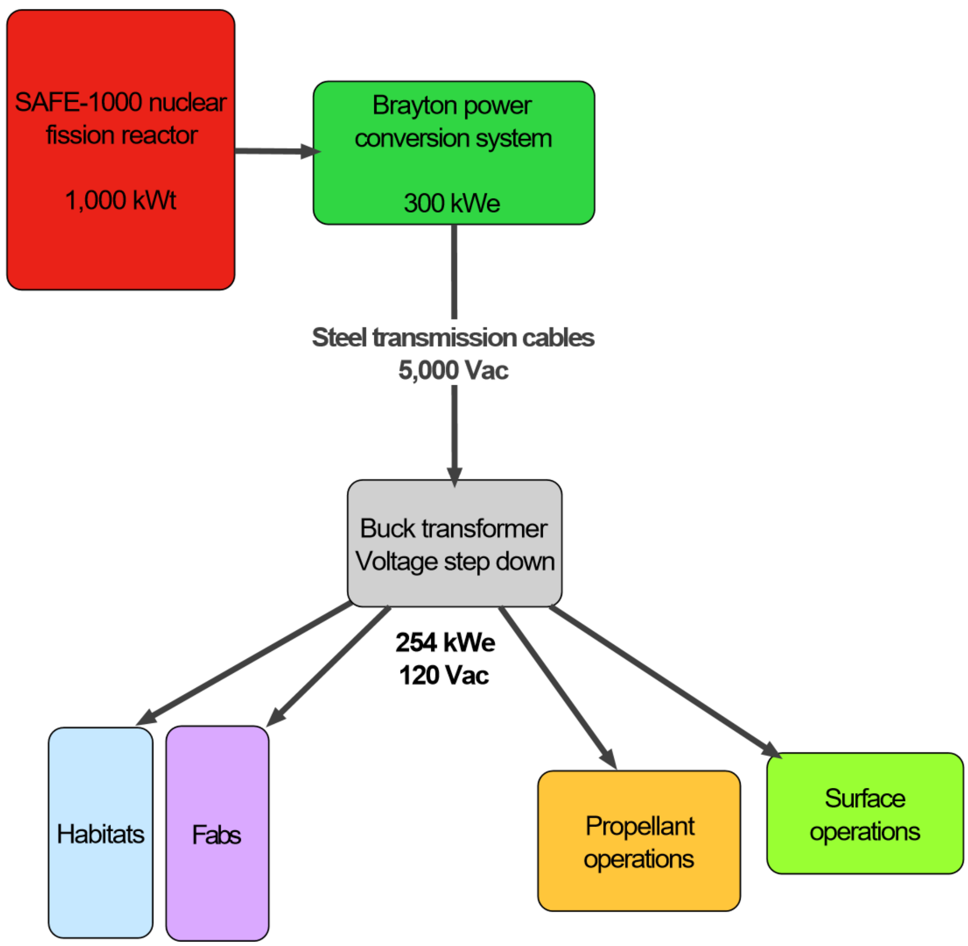

Fig. 9.1.2.2 This electric power transmission system map shows the flow of power from generation at the nuclear power plants to distribution to colony power loads. Credit: R. Clay

9.1.3 Thermal power transmission

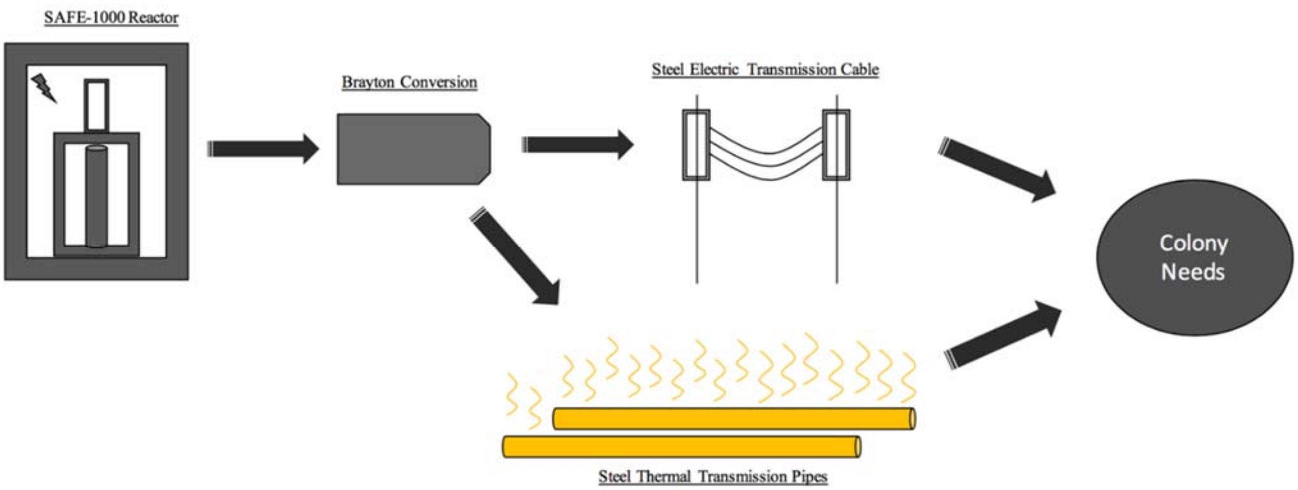

Fig. 9.1.3.1 This map shows the main components of the colony power system. Excess thermal power from the plants is transmitted to colony loads. (Credit: M. Young)

As stated above, each power plant gives off excess heat that the colony can take advantage of to heat the habitats, food habitats, water piping, and water tower. To transfer this thermal power, we employ a system using resources available on Mars reducing ITS deliveries of materials and the cost of the mission. The system design uses steel piping to transfer water vapor around the colony to satisfy all heating requirements.

After all heating requirements are satisfied, the excess heat is then dissipated to the Martian atmosphere through a farm of radiator panels located throughout the power plant's location. It can be noted that radiators above ground are able to dissipate more heat per unit area than radiators underground due to the importance of radiative heat transfer and temperature difference of the Martian atmosphere and the working fluid. A system map is shown in Fig. 9.1.3.2. This shows the interactions of the system with other teams and systems. Trade studies, models and results can be found in the Colony Electric Power and Heating System section of the appendix.

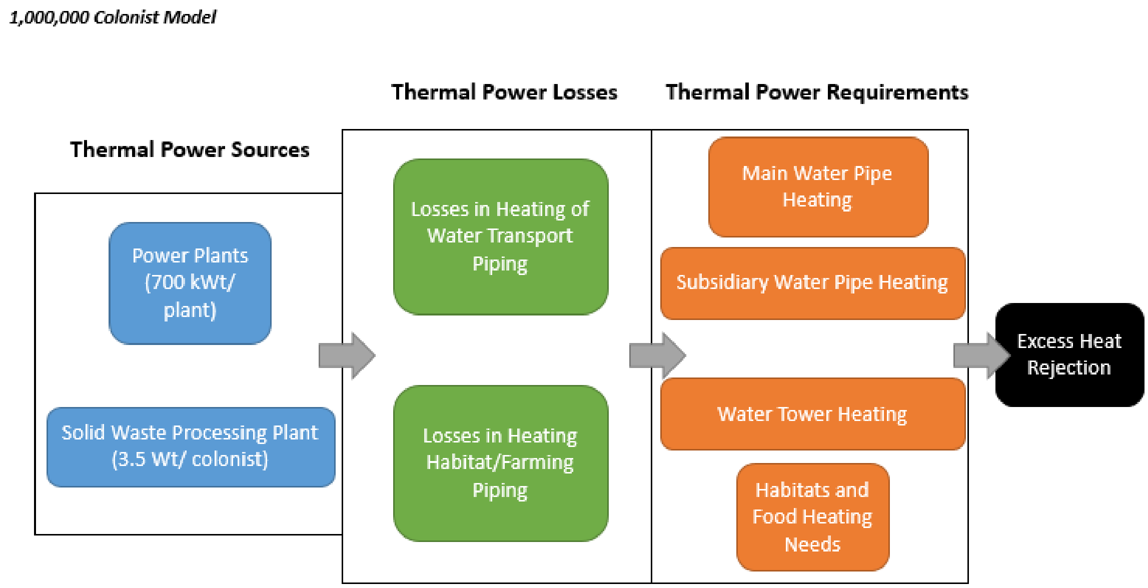

Fig. 9.1.3.2 This figure shows the flow of thermal energy throughout the colony to both satisfy the heating needs and achieve a net zero thermal power production. (Credit: N. Gross)

9.1.4 System totals

The required number of power plants along with mass and volume totals are given in Table 9.1.4.1. Power requirements from habitats and FABs for all forty quarry cities were used to calculate the total number of active power plants required. The number of active plants is how many will be deployed and operational at cycle 46. Each power plant has a lifetime of sixty years, so we deliver replacements starting midway through the mission. The number of replacement plants required for the entire mission is only about one third of the total number of active power plants.

Table 9.1.4.1 Quarry city power plant mass and volume totals

Category	Quantity	Mass [Mg]	Volume [m^3]
Active power plants for all quarry cities	18,076	58,103	116,066
Replacement power plants for all quarry cities	5,733	18,428	36,812

9.2 Deployment

We deliver all nuclear fission power plant components to the surface of Mars from Earth. The SAFE-1000 reactor and Brayton power conversion system can be transported separately and assembled at the deployment site on Mars. SAFE-1000 reactors are packaged in small standard shipping containers (1m x 1m x 1m). With a height of 1 m and an outer diameter of 0.48 m, we pack four reactors inside each shipping container. Fig. 9.2.1 below shows the configuration of SAFE-1000 reactors within a shipping container. We achieve a 72.4% packing efficiency applying this method. It should be noted that it is possible to ship reactors in the large standard container (2m x 2m x 2m). Our efficiency is again 72.4% but stacking two layers of reactors is required in this case. Shipping in the large standard container increases the risk of damage and therefore is not the preferred method. The Brayton power conversion system is transported in a special shipping container (3m x 2m x 2m). Only one unit fits inside this container and the packing efficiency for the Brayton conversion system is 52%. We transport all nuclear power plant components via ITS cargo ship.

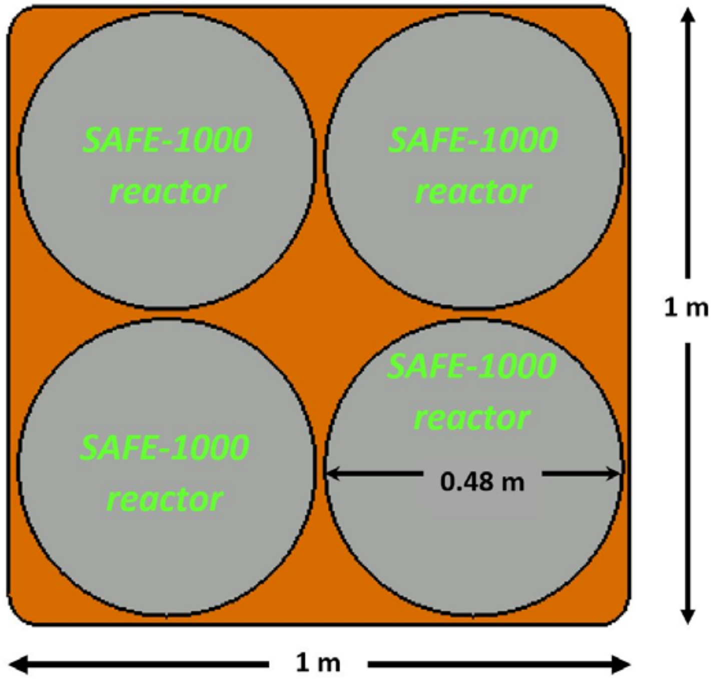

Fig. 9.2.1 This image shows four SAFE-1000 reactors packed in a small standard shipping container for transport to Mars. The packing efficiency with this configuration is 72.4%. Credit: R. Clay

Once landed on the surface of Mars we transport the SAFE-1000 reactors and Brayton power conversion systems to their deployment sites via rover. The SAFE-1000 reactors are deployed in an excavated hole just large enough so that the entire reactor fits inside. Each reactor hole is a circular cylinder with a volume of 0.2 m^3. The reason we deploy the reactors below the surface is for radiation shielding. It was reported in a 2008 joint NASA-Department of Energy study on fission power concepts for Mars that line of sight shielding to a habitat is provided by regolith [9.4]. Power plants will be located no closer than 100 m from the quarries. Radiation dose is reduced to less than 0.137 millisieverts per day at this distance. This dose is acceptable for our colonists and with several other items in and around the quarry cities acting as shielding, radiation from the nuclear fission power plants is not a concern. Our ability to use Martian regolith as radiation shielding for the power plants results in huge cost savings in the form of fewer cargo deliveries from Earth. Shielding delivered from Earth can be the heaviest component in a power plant, weighing in at 40% of the total power plant mass [9.4]. We take advantage of the available Martian resources to avoid this additional cost to the mission.

Crew assistance is necessary for final deployment and coupling of the SAFE-1000 reactor and power conversion systems. The Brayton power conversion system is positioned above the reactor and just above the Martian surface. Once power plant deployment is complete, the crew's job is finished. Nuclear engineers at The University of Tennessee have done extensive work in developing algorithms and strategies for autonomous control of space reactors, and we are confident this can be achieved with a high level of reliability and safety for our mission [9.8]. A full, deployed power plant is shown below in Fig. 9.2.2.

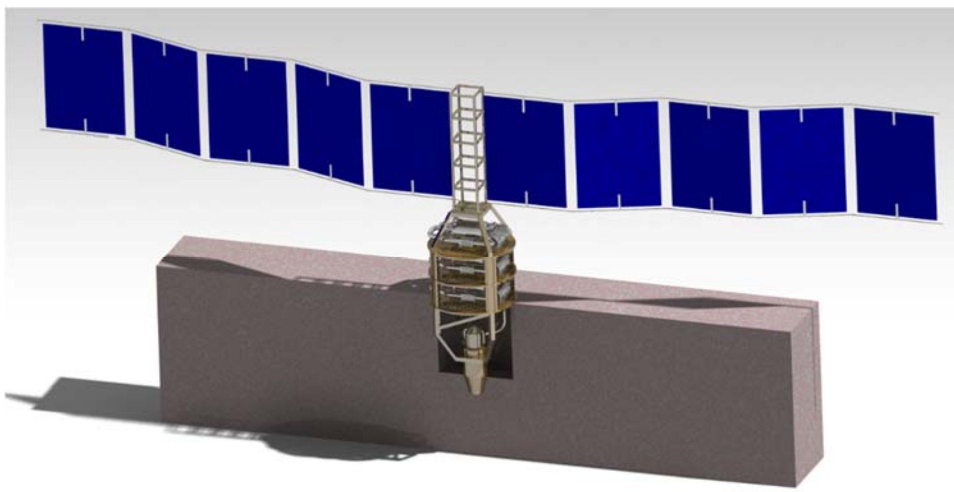

Fig. 9.2.2 A full power plant is shown with radiators for excess heat rejection. The SAFE-1000 reactor is deployed beneath the surface for radiation shielding. (Credit: K. Jantze)

9.3 System Cost

Table 9.3.1 breaks down the cost of colony power system components. For our power plants, we use the construction cost for a NuScale nuclear power plant to model the cost [9.9]. The NuScale plant comes in at $5,078 per kW electric power output and we scale this cost to the output of our power plant. The uranium nitride (UN) needed for refueling adds a cost to system's total. Sixty years is the assumed lifetime of a power plant and we require five refuels over this lifetime. The World Nuclear Association (WNA) reports that in 2015 the cost of 1 kg of uranium dioxide (UO_2) reactor fuel was $1,880 [9.10]. Though we fuel the SAFE-1000 with UN, the WNA data gives us the best cost estimate available. With a known mass of fuel and five refuels required over the lifetime of each power plant, we have a cost per plant of $1.332 million for refueling.

Table 9.3.1 Cost of power plant components

Component	Cost
SAFE-1000 reactor & Brayton power conversion	$1,523,000
Uranium nitride (UN) for refueling	$1,332,000
Steel cable for electric power transmission	$0
Steel pipes for thermal power transmission	$0
Total	$2,855,000 / plant

Because our colony is capable of producing steel on Mars, there is no cost associated with electric power transmission cables or thermal power transmission pipes. Note that our total cost of $2.855 million is for a single power plant over its full lifetime. With 18,076 plants active to support forty quarry cities and 5,733 replacement plants needed over the course of the mission, we can find the total mission cost of all power plants. This cost is broken down in Table 9.3.2. Coming in at just under $68 billion for the mission, our power plants add a significant cost but it should be noted that nuclear power is an economic form of power generation that is competitive with coal- and gas-fired power generation [9.10].

Table 9.3.2 Cost of quarry city power plants for the entire mission

Category	Quantity	Cost
Active power plants	18,076	$51,600,000,000
Replacement power plants	5,733	$16,370,000,000
Mission total	23,809	$67,970,000,000

9.4 Risk Analysis

Table 9.4.1 FMECA table for the colony power generation system

Description of failure	Effects of failure on the system	Probability of failure	Mean time to failure
SAFE-1000 reactor meltdown	Radioactive material released; Power loss	~0.75%	60 years
Brayton conversion system failure	Reduction in electric power available	~0.41%	60 years
Power transmission cable failure	Reduction in electric power available	~0%	100 years
Steel thermal piping puncture / failure	Reduction in heat available	~4.46%	50 years
Improper heat distribution	Overheating or freezing	~4.46%	50 years

Reliance on sophisticated nuclear power plants for the power of the entire colony cannot be considered without analyzing the risks that are involved. A power plant in our system has four main parts: a SAFE-1000 reactor with internal nuclear fuel pins, a Brayton power conversion system, and electric and thermal power transmission mechanisms. Each of these main components carries its own probability of failure, each of which is described in detail below as well as compiled in Table 9.4.1 above. We do not anticipate a complete failure of the system as a whole, but independent systems do have a chance of failure in their anticipated lifetimes. The probability of each failure is based on data acquired from comparable systems on Earth and adjusted to reflect the distinct conditions on Mars.

The component of the power plant with the largest chance of failure is the steel thermal piping. Should there be a puncture or failure of the thermal piping system, the immediate effect would be a loss of thermal power and heat to the subsequent systems, which can range from habitats to propellant production infrastructure. This lack of heat could prove to be catastrophic on

the frigid Martian surface. There is a 4.46% chance of failure per each 161 km of steel piping each year, although the thermal piping will last for an average of 50 years [9.11]. Steel for these pipes is being produced on Mars; there would be no cost for repairs, although an increase in steel production would be necessary.

If the system were to overheat or distribute the heat unevenly, there is a similar risk in the steel piping melting and subsequent systems either freezing or overheating as a result. These pipes will last 50 years and have a 4.46% chance of failure for each 161 km in heat distribution [9.11]. In the event of an overheated pipe, replacement steel pipes and a more constant measuring and maintenance of each pipe would need to be implemented. Beyond the steel itself deforming, the systems that are receiving the thermal energy via these pipes would be in danger.

A failure or meltdown of the SAFE-1000 reactor would have the largest impact on the colony although with a failure percentage of 0.75% every 60 years, it is not likely [9.12]. If the SAFE-1000 reactor were to severely malfunction, there would be a 300 kW loss of electric power and a 700 kW loss of thermal power to the subsequent system. Additionally, there is a risk of radioactive material flowing into the Martian regolith. This would make the replacement, transportation, and disposal of the reactor much more dangerous. The only cost of this failure would be the reactor hardware sent from Earth, and the loss of nuclear material.

A failure of the Brayton engine has an even smaller risk of 0.41% each 60 years, and would result in a decrease of electric power that can be transported to and used by the colony [9.13]. Although there would be a loss of hardware, the connected systems will not be effected.

The last mode of failure in the central power system would be a break in the steel transmission cables that bring electric power to the colony. Because there is no oxygen or nitrogen in the Martian atmosphere or regolith, the steel cables have little to no chance of eroding, and the risk probability is zero. These steel transmission cables will last 100 years assuming proper manufacturing.

The Mission Fault tree shown in Fig. 9.4.1 clearly illustrates the effects of each component failure. Each system failure will be isolated and be able to be repaired without compromising the performance or hardware of the other components.

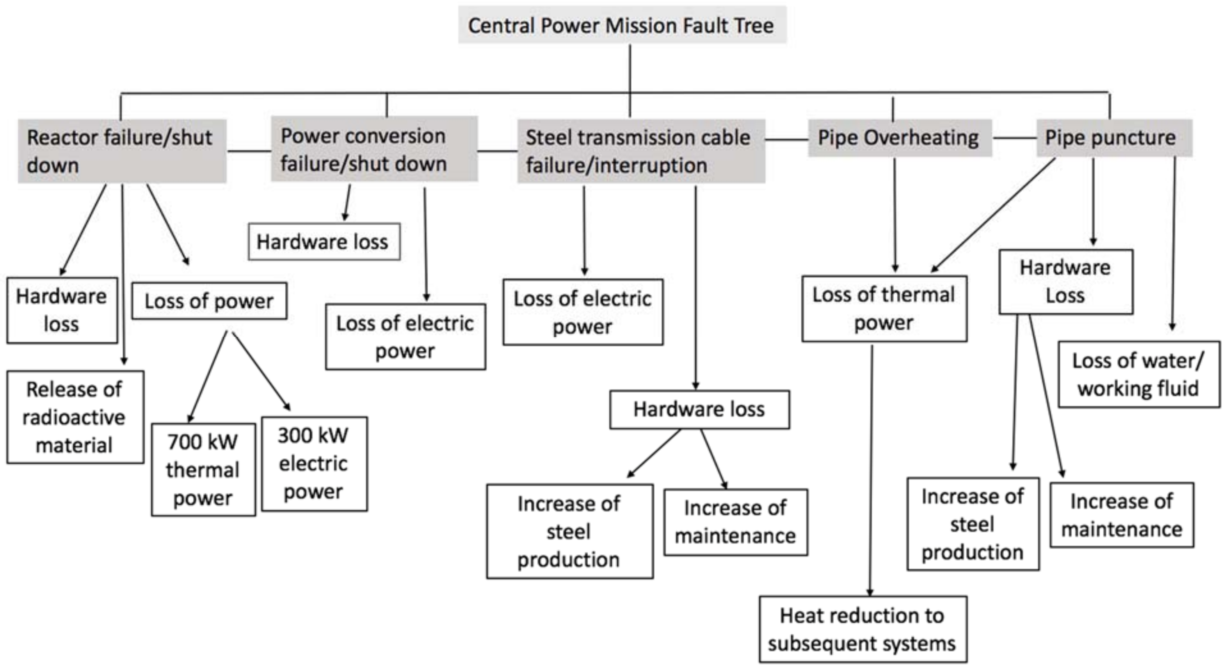

Fig. 9.4.1 This complete mission fault tree for the colony power system shows the effects of a full system failure on each component connected directly to one complete power plant. (Credit: M. Young)

The most common reoccurring problems are a loss of hardware, which is present in all possible faults besides the steel piping, as that is the only component of the power system design that can be produced, and therefore reproduced, on the surface of Mars. Any failure in the steel structures, however, will necessitate a scale up of maintenance and steel production in order to keep up the repairs on the pipes and mitigate fewer future structure failures.

9.5 Risk Mitigation Strategies

A SAFE-1000 failure is highly disruptive to our colony because of the dangers of nuclear radiation and the fact that these reactors generate all power for the colony. In terms of crew survival, a failure in which radioactive material is released is most critical. Table 9.5.1 lists mitigation strategies for a radioactive material release event as well as a simple loss of power event.

Table 9.5.1 Risk mitigation strategies

Risk	Mitigation strategy	Cost
Nuclear reactor meltdown	Deliver crew-rated shielding from Earth for each power plant	1.29 Mg per power plant 39.7% increase in required deliveries
Nuclear reactor meltdown	Completely bury power plants below the Martian surface	Additional 6.42 m^3 regolith excavated per power plant
Nuclear reactor meltdown	Store nuclear fuel away from power plants	--
Power plant downtime	Include 10% margin for extra power plants	Additional 0.32 Mg delivered per power plant

Our first mitigation strategy is to deliver crew-rated shielding from Earth for each reactor to better contain a meltdown. As stated previously, crew-rated shielding from Earth can add up to just under half the total mass of a space power plant in addition to adding considerable volume to the payload. We see that the associated cost is an additional 1.29 Mg that must be delivered via ITS cargo ships. This additional mass results in about a 39.7% increase in the number of deliveries required, which adds a substantial cost to the mission. Our next strategy is to completely bury power plants below the surface as opposed to having only the reactor below the surface. This strategy is not as effective as the former in containing a meltdown but we see that the associated cost includes no additional mass or ITS deliveries.

Our third mitigation strategy is to store fuel pins for refueling in a location entirely separate from the power plants. By doing this, we ensure that a power plant meltdown does not cause further damage or a release of radioactive material. We implement this strategy at no cost. The uranium nitride used for fueling a SAFE-1000 reactor is nonradioactive before use and there are no environmental concerns to warrant a building or structure for storage. Finally, any power plant downtime reduces the power available for colony operations. At peak power loads, we risk critical system not being powered if there is downtime for any reason. To mitigate this risk, we include a 10% margin on the number of power plants delivered to ensure backup power is available.

9.6 References

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10 Exploration and Scientific Capabilities

10.1 Scientific Rovers

10.1.1 System Totals

The Science rover is specifically designed to carry out scientific based objectives that will benefit the people living on Mars. These objectives revolve around determining geologic information of the areas surrounding the colony. The information gathered by the rovers will help in determining what we can learn from ancient Mars, such as if life did exist in the past and what the general conditions were at the time. Other geologic information will help colonists in the present time, such as resource locations for elements and minerals. The objectives are listed out in detail in section 10.1.3 of this system.

Table 10.1.1.1 Mass, Volume, Power of Instruments on Rover

Instrument	Mass (Mg)	Volume (m^3)	Power (kW)
Panoramic Imaging Camera	6.02×10^{-4}	9.33×10^{-2}	2.00×10^{-3}
Microscopic Imager	2.90×10^{-4}	1.99×10^{-4}	5.00×10^{-3}
Thermal Emission Spectrometer	2.40×10^{-3}	5.94×10^{-3}	5.60×10^{-3}
Mossbauer Spectrometer	4.00×10^{-4}	7.00×10^{-4}	2.00×10^{-3}
Alpha Particle X-ray Spectrometer	3.70×10^{-4}	3.51×10^{-4}	1.12×10^{-3}
Millimeter Scale Spectroscopy Vaporization Laser	5.78×10^{-3}	1.40×10^{-2}	1.12×10^{-3}
Geological Sample Extraction Apparatus & Sample Container	4.00×10^{-4}	1.67×10^{-3}	2.00×10^{-3}
Chassis	7.70×10^{-2}	7.50×10^{-1}	N/A
Solar Panel	3.40×10^{-4}	4.40×10^{-6}	N/A

Table 10.1.1.2 Total Mass, Volume, Power per Science Rover

Total	Mass (Mg)	Volume (m^3)	Power (kW)
Value	8.76×10^{-2}	8.66×10^{-1}	1.88×10^{-2}

10.1.2 Operation

One of the instruments on board the chassis for the rover, is the Panoramic Camera. This instrument is designed to take images of the areas that the rover traverses to store as data to be reviewed on its return. The design for the camera was inspired by Athena. The camera can take images in full 360 degrees azimuth and -90 to +90 degrees in elevation. It uses CCD technology and have an active imaging area of 1024 x 1024 pixels. The camera system also works with a calibration target. This helps the camera stabilize calibration of the camera while the rovers are out on their missions.

The next instrument on the Science Rover is the Thermal Emission Spectrometer. This instrument operates with infrared spectroscopy to determine mineralogy of rocks and soils by detecting patterns of thermal radiation from the targets. As stated by NASA, all warm objects emit heat, but the patterns in which they emit the heat is different, (NASA source). The Science Rover examines the spectral data, wavelengths of recorded thermal radiation, and determines minerals present in the rocks in soil as well as their abundances in the target locations. With this information, the colonists can determine where to find the minerals needed for the colony such as clays and even carbonates. While that is the main purpose of the Thermal Emission Spectrometer, it also possesses the ability to record data on temperature, water vapor and dust in the Martian atmosphere.

Another instrument on board the chassis is the Mossbauer Spectrometer. This instrument is designed to detect iron in the soil. The technology in the spectrometer allows it to detect a specific isotope of iron, ^{57}Fe. This is done by an emission and recapture of gamma rays onto the target nucleus. Gamma rays will be sent into the soil the rover collects and it will be able to read back the absorption data recovered from the target. The energy is obtained from Eq. 10.1.

$$E_{\text{recoil}} = \frac{1}{2} E_{\text{gamma}}^2 M_{\text{iron}} \mathrm{c}^2 \tag{10.1}$$

The c variable is the speed of light, measured at $3 * 10^8$ meters/second, M_{Iron} is the mass of iron, measured at $9.42 * 10^{-26}$ kilograms, and E_{Gamma} is the gamma ray energy which is measured at $2.26 * 10^{-15}$ joules. The resulting recoil energy measured is about $1.87 * 10^{-3}$ electron-volts. If the rover detects this recoil energy from the area it observes, it will record the data for the colonists to evaluate back at the science habitats. If the rover happens to find a spot for concentrated iron, the colonists will know where to send vehicles to collect it.

The next instrument on the Science Rover is the Alpha Particle X-Ray Spectrometer. The main components to this instrument are the sensor head and calibration target inside. The instrument will be able to identify elemental compositions of Martian soil. This is done by using alpha particles and X-rays, such as the name suggests. When the Science Rover is using this instrument, alpha particles are emitted unto the target soil. Once these alpha particles hit the target soil, they are bounced back into the detector inside the Alpha Particle X-Ray Spectrometer. The alpha particles also excite the target during this process which releases X-rays that are read from the detector as well. The energy distribution from this emission and recoil of particles is analyzed to determine elemental composition. This is critical to the mission, as the Science Rover can use the Alpha Particle X-Ray Spectrometer to determine important resources around the colony or in destinations farther away, (e.g. Mawrth Vallis), such as locations of water which is vital for the colony to survive. Combined with the Mossbauer Spectrometer, the Science Rover can gather important elemental information regarding composition farther away, to which other vehicles can travel and collect for the people on Mars. Knowing locations that have an abundance of important resources will sustain the colony.

10.1.3 Mission Objectives in Detail

The science rover is designed for science based objectives. The first objective of these is to probe areas on Mars for ancient life. This is an important objective as it is assumed in the past Mars once lied in the habitable area of the Sun, which is where the conditions are right for a planet within a certain distance of the Sun to contain vital elements for life such as water and temperature conditions. If this assumption is correct, there may be signs on Mars that could indicate what life may have existed in ancient Mars.

The second objective follows along with the first objective, in that the rover will be designed to study the geology of mission based areas that could provide information of how the landscapes and conditions were for Mars in the past. Using the properties of geology, such as the Principle of Horizontality, and extracting samples that can be studied at the colony in the science habitats, it could be possible to find out information such as how old are certain rocks and features of Mars that would lead to understanding conditions of ancient Mars.

The last objective is to study locations for abundances of elements and mineral resources. The science rover has instruments aboard the chassis to gather information about resource abundance over the plains of Mars. Some systems and mechanisms will need to be built on the Martian surface. It is important to know where general resources are located so they can be used for the colony. This ranges from elements such as iron to be used for construction or hydrated minerals that can be used to sustain the population.

10.1.4 System Cost

Determining the cost of the rover was done by making a comparison to the rovers Opportunity and Spirit that were sent to Mars. This comparison was made due to having similar instruments on board these rovers. Opportunity and Spirit each cost around $400 million. The Science Rover does not have quite the same number of instruments on board, so the cost is estimated to be a little bit lower, around $350 million. Over the course of the mission, 21 rovers will be sent on ITS launches to Mars, making the total cost for the Science Rovers to be around $7.4 billion.

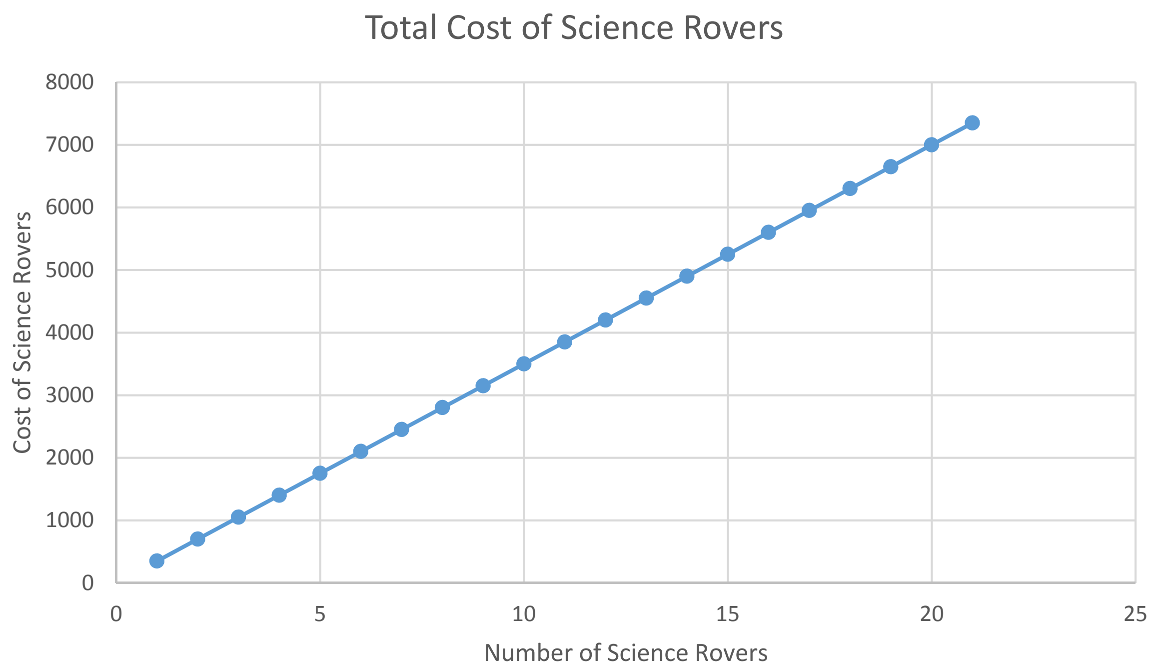

Fig 10.1.4.1

Plot of number of science rovers versus cost. Credit: Jesse Guzman

Fig. 10.1.4.1 is a visual representation of the total cost of rovers over the course of the mission. The x-axis displays the number of Science Rovers while the y-axis displays the gradual increase of cost of the Science Rovers. By the end of the mission, the total cost increases from $350 million to $7.4 billion with a total of 21 Science Rovers.

10.1.5 Risk Analysis

Risks of the rover mainly appear to be wheel damage from crossing treacherous terrain, physical damage overall to the rover from falling, dust coverage of the instruments, (mainly the solar panel), and solar damage from solar flares. Physical damage has the largest risk factor compared to the other risks. According to reports, over treacherous terrain, such as rocks or pointy landscapes, it could only take about a distance of 8 kilometers to do enough damage to the wheels for it to be a major problem for the rover. If the wheels are damaged enough, the rover will need to be retrieved or else it will be stranded and result in a loss of a rover. Another case of physical

damage is from the rover falling over or falling a large distance resulting in breaking of equipment. The costs for this vary as it depends on what instrument is broken. The range is generally anywhere from \$1000's to \$100,000's. In the event that the Panoramic camera is broken, that could result in the rover being stranded. If that is case and it is not retrieved, it will result in a loss of a rover. The probability of overall physical damage is 10-15%.

Solar damage as stated previously, is mainly from solar flares. The average periodicity of a solar flare to occur is once every 153 days. Starting from the time that the first rover is deployed, over the course of the mission, it is estimated that an average of 224 solar flares will occur. This risk is not that high, because the solar flares need to be of high magnitudes to do substantial damage to the rover. While the pattern is irregular, it is more common for the solar flare to be of lower magnitudes. In the event that a solar flare of large magnitude occurs, it will cause the rover to have glitches and not function properly. This will result in either fully replacing the rover, which is another cost of \$350 million, or performing maintenance on the instruments that are affected if they can be salvaged. The probability of failure for this risk is 5%.

Dust coverage is another risk the rovers will face. The damage is like that of solar flares, where if not cleaned out properly or too much dust gets clogged in the rover, the instruments will not function properly. The solar panel is an instrument that puts the risk at a higher danger if it gets covered in too much dust. The solar panel provides power for the rover, so if the solar panel is completely covered, the rover will power down and become stranded if not retrieved. This will result in a loss of a rover. It will be another \$350 million to replace the rover, or if the solar panel is too damaged, it will cost about \$10,000 to replace if the rover is retrieved.

Table 10.1.5.1 FMECA Analysis of the Science Rover

Description of Failure	Effects of Failure on the System	Risk Mitigation	Probability of Failure	Mean Time to Failure
Wheel Failure	Rover can get stuck, resulting in a loss of a rover if left unattended	Perform regular maintenance and plan routes to cross smoother terrain for minimal wheel damage	Medium	2-5 Years
Solar Panel Failure	Rover would lose power, which if left stranded could result in loss of a rover.	Perform regular maintenance upon mission return and make sure no dust is left on it and that it is running at full power	Low	25 Years
Science Instruments Failure	Severity is not high, but would result in the rover being pointless on the mission if the instruments are malfunctioning.	Perform regular maintenance and fine tune the rover upon mission return and make sure all instruments are working at max potential.	Medium	20 Years
Rover tipping over/falling from high elevation	Depending on how high the elevation is, could pose a serious risk for the rover. Too high of a fall would result in loss of a rover.	Similar to wheel failure, try to plan rover routes to not go over too much dangerous terrain to avoid falling risks.	Medium	1-15 Years

Description of Failure	Effects of Failure on the System	Risk Mitigation	Probability of Failure Relative to Deployment	Mean Time to Failure
Wheel Failure	Rover can get stuck, resulting in a loss of a rover if left unattended	Perform regular maintenance and plan routes to cross smoother terrain for minimal wheel damage	Medium	2-5 Years
Solar Panel Failure	Rover would lose power, which if left stranded could result in loss of a rover.	Perform regular maintenance upon mission return and make sure no dust is left on it and that it is running at full power	Low	25 Years
Science Instruments Failure	Severity is not high, but would result in the rover being pointless on the mission if the instruments are malfunctioning.	Perform regular maintenance and fine tune the rover upon mission return and make sure all instruments are working at max potential.	Medium	20 Years
Rover tipping over/falling from high elevation	Depending on how high the elevation is, could pose a serious risk for the rover. Too high of a fall would result in loss of a rover.	Similar to wheel failure, try to plan rover routes to not go over too much dangerous terrain to avoid falling risks.	Medium	1-15 Years

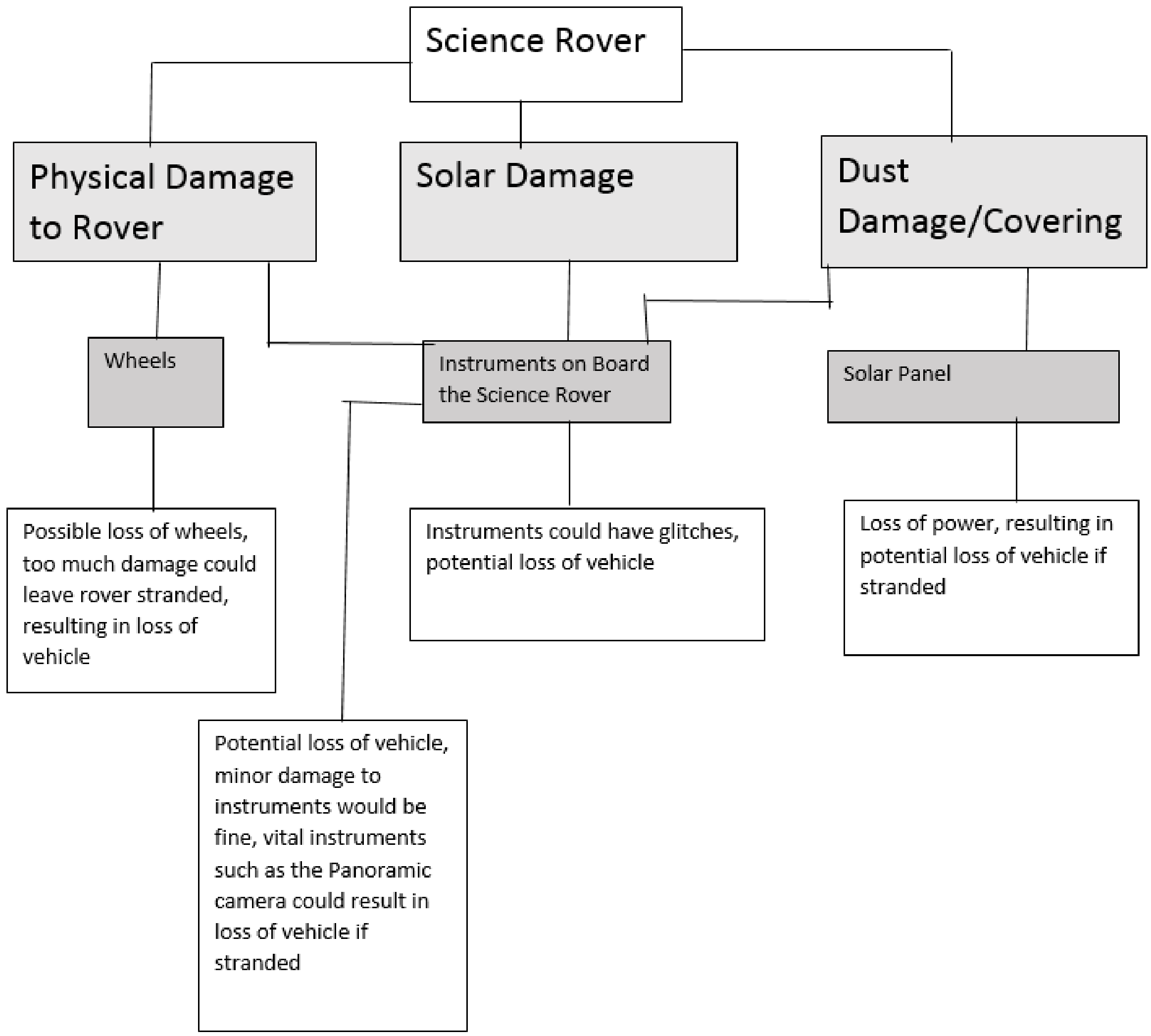

Fig 10.1.5.1

Fault tree risk analysis of the Science Rovers. (Credit: J. Guzman)

Fig. 10.1.5.1 provides a visual representation of the risks the Science Rovers are expected to face over the course of the mission. Each risk stems down to a component of the Science Rovers and then to a description of the damage to come from the risks. Each risk can result in different outcomes of damage, but worst case scenarios result in loss of Science Rovers.

10.1.6 Risk Mitigation Strategies

As stated previously, physical damage from the rover is a big risk. A solution to reduce the probability of failure for wheel damage and prevent falling from high elevations is to plan paths for the rover that are mainly over smoother area. A route has been drawn out using the software JMARS. The data recorded from the path is displayed on the elevation graph in Fig. 10.1.6.1. The elevation on this particular path is relatively even. This path from the colony to the mouth of Mawrth Vallis is the safest path for the rover to travel. This will minimize risks of the rovers' wheels getting too damaged from pointy and dangerous terrain. This should reduce the probability of failure from 10-15% down to 5%.

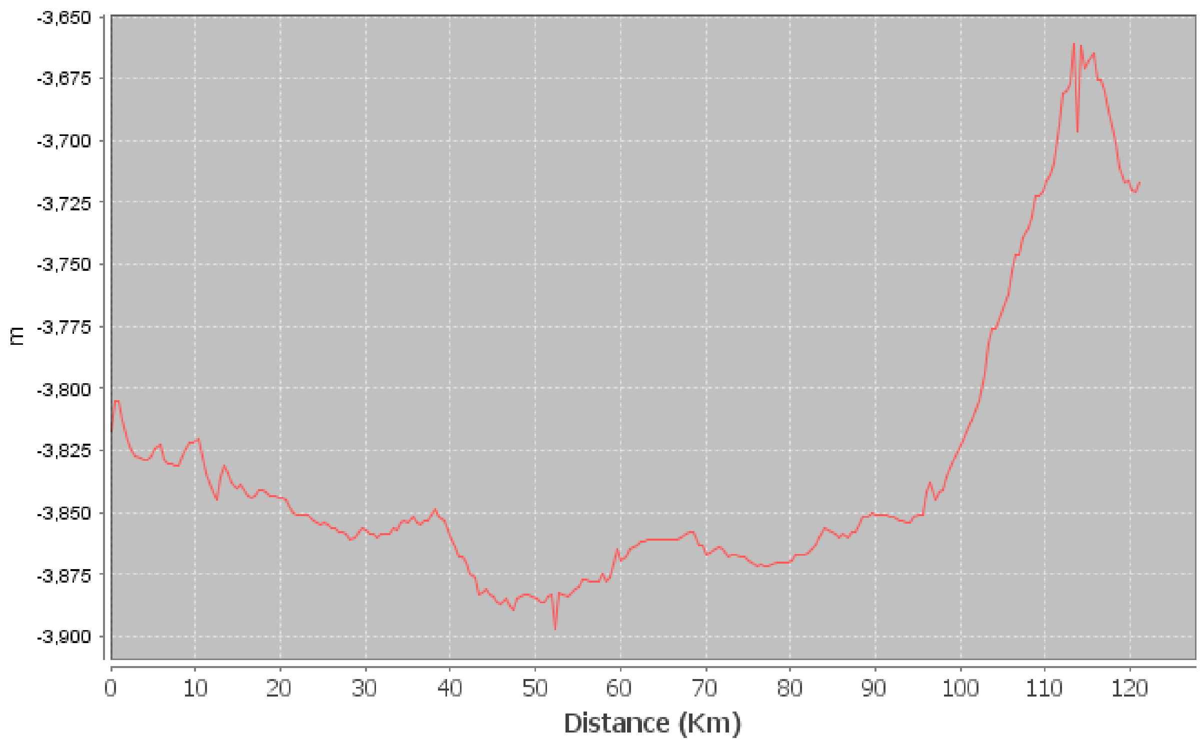

Fig 10.1.6.1 Elevation map profile of path to Mawrth Vallis. Credit: JMARS, Jesse Guzman

Fig. 10.1.6.1 is an elevation map profile of the planned path to Mawrth Vallis. The x-axis displays distance in kilometers and the y-axis displays elevation in meters. The range of elevations here are roughly even until the mouth of Mawrth Vallis. The path there stretches from 0 km to about 100km on the elevation map profile. The lowest elevation point here is around -3,900 m and the highest elevation point is around -3,800 m. With a depth difference of about 100 meters, it

should not be treacherous so that the rover can safely travel from the colony to Mawrth Vallis safely and minimalize damage done and costs of fixing or replacing the rovers.

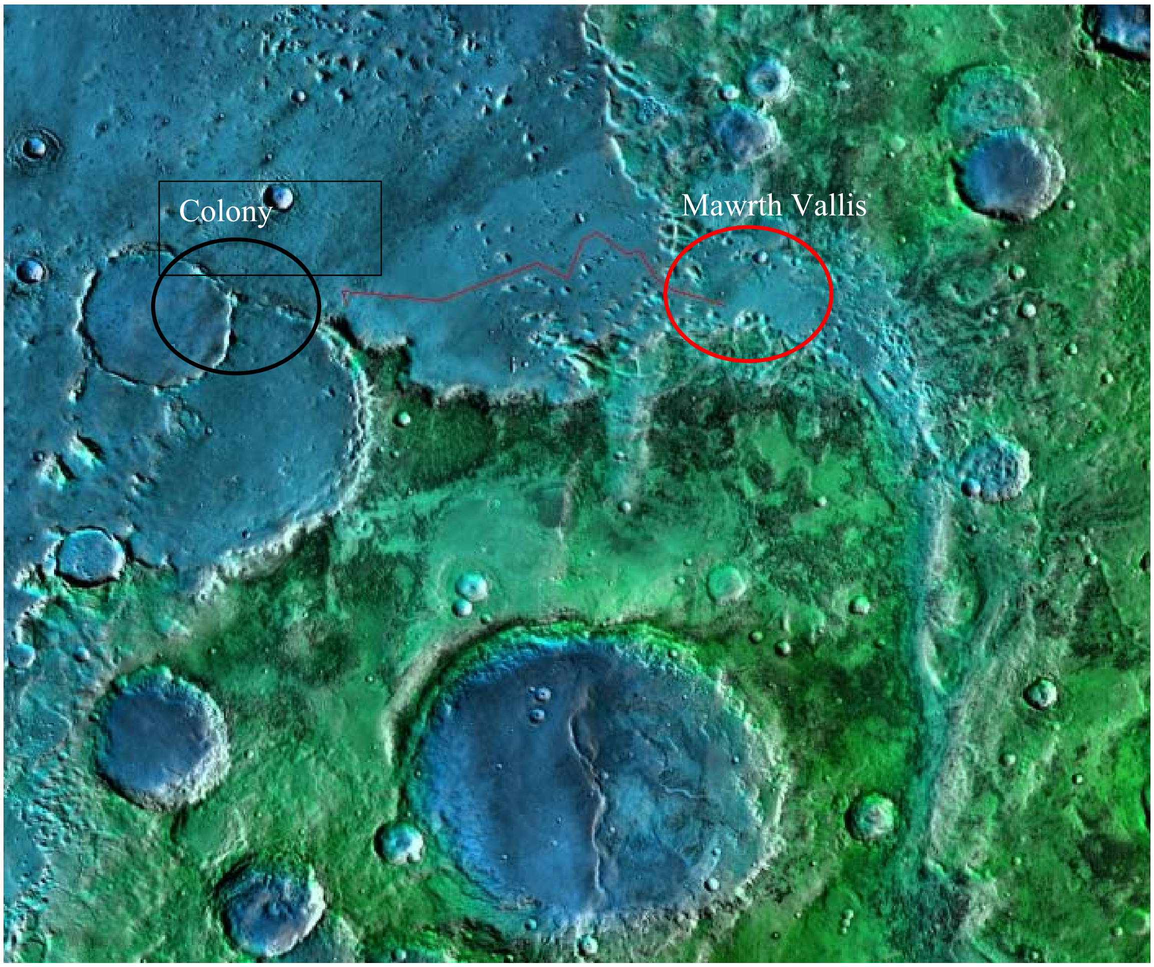

Fig. 10.1.6.2 THEMIS image of the rover path from the colony to the mouth of Mawrth Vallis. (Credit: JMARS, J. Guzman)

Fig 14 is an elevation map generated by JMARS. The area in the black circle is where the colony is located and the red circle indicates the mouth of Mawrth Vallis. The red path drawn out on the map is the planned science rover path to get from the colony to Mawrth Vallis and back safely. While Mawrth Vallis is full of uneven elevations and pose risks to the rover, we can minimalize risks to the rovers on that way there and back and reduce potential costs of damaged or broken rovers.

A solution for the solar flare damage to the rovers would be to perform consistent maintenance and tune up all instruments upon return from every mission. For minor damage, this solution will work and not be costly outside of maintenance costs. This solution will also help reduce corrosion from affecting the instruments after each mission. The probability of failure will be reduced from 5% to 3%.

A solution for the dust coverage damage is like the mitigation strategy as the solar flare damage. The rover should be cleaned out upon return from every mission. This will prevent dust from clogging up ports on the rover and reduce gradual damage from dust building up. This strategy costs $0 as nothing would be repaired. The probability of failure will reduce from 10% to 5%.

Table 10.1.6.1 Risk Mitigation of the Science Rover

Risks	Probability of Failure/MTTF	Cost of Mitigation Strategy in $/MPV	Improved
Physical Damage from Falling / Terrain	10-15%	Plan routes for rover to cross smoother terrain, $0, a rough estimate would be dependent on the instrument damaged, ~($1000's-$100,000's)	5%
Solar Damage (Flares)	5%	Fine tune system, diagnose instruments to prevent continual damage, if instruments get damaged, a rough estimate would be dependent on the instrument damaged, ~($1000's-$100,000's)	3%
Dust Coverage	10%	Clean the rover upon return from every mission, $0	5%
Wheel Damage	10%	Replace wheels if there are too many holes, ~$400/wheel	5%

10.2 Scientific Structures

10.2.1 CAD / System Totals

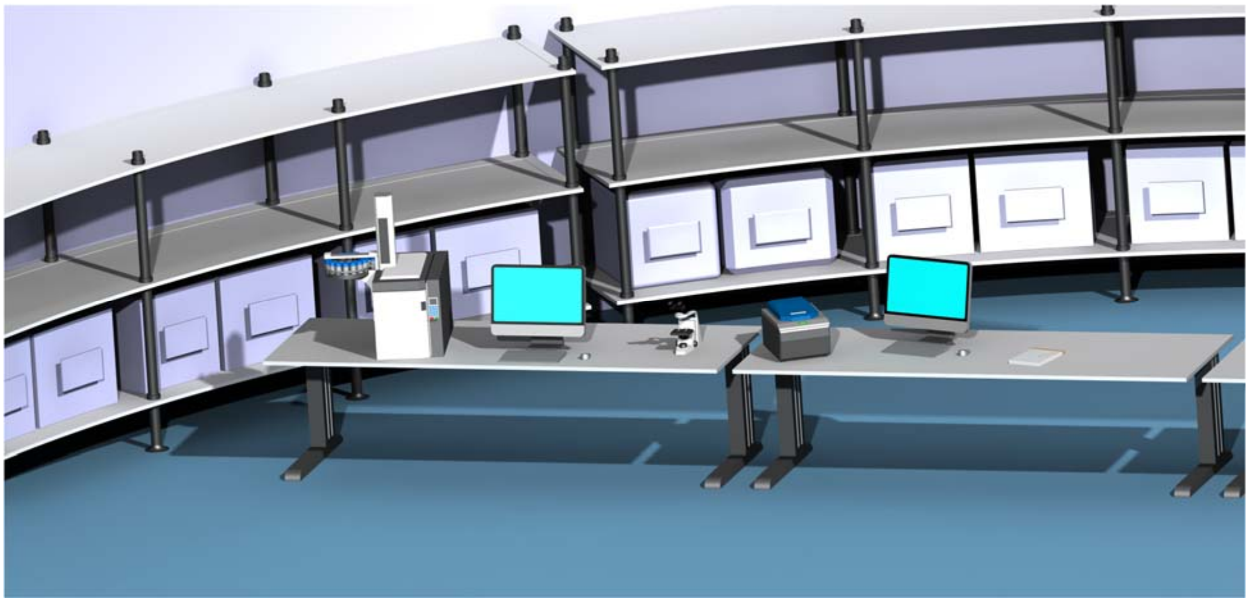

Fig. 8.3.3.4.1 The interior of the Science facilites are shown for the one million person colony.

(Credit: B. Muth)

Table 10.2.1.1 list of internal components for the Science Structures (one million person model).

Component	Number of Units (n)	Mass (Mg)	Volume (m^3)	Power (W)
Lightweight desk (foldable)	50,000	867.5	6550	n.a.
Shelves (lightweight metal)	50,000	295.0	600	n.a.
Portable (mini) Mass Spectrometer	20,000	14.8	15.4	5e4
X-Ray Spectrometer	20,000	1.8	1.7	2.5e4
Gas Chromatograph	20,000	109.5	180	2.5e4
Scanning Electron Microscope	20,000	33.1	290	2e6
Computer	50,000	56.8	575	1.3e6
TOTALS		**1378.5**	**8212.1**	**3.4e6**

10.2.2 Deployment / Fabrication

The deployment of the Science habitats is the similar to the rest of the structures being built. It is started as a cylinder which is 3D printed with basalt. Again, like the other colony structures, it has six floors with a diameter of 18 m. For more information on how exactly the habitats are constructed, see 3D printing and Structure Fabrication in Section 7.3. However, the internal structure varies from the other habitats. It has a walkway going around the perimeter of a large, open room. We choose this layout because it keeps any traffic from interfering with the work going on in the habitat, and it allows researchers to interact with each other easily and have all scientific instruments readily available to them.

10.2.3 Operation

For our 100 person colony, we decide that there are about five colonists working full time who perform scientific work on Mars. As we scale up, we expect the growth rate to be linear. If 5% of people are researchers full time in the science structures, then we will have 50,000 scientists out of one million people by the end of the mission. Therefore, the equipment needed also scales linearly. To provide an adequate environment for scientific research, a list of necessary equipment, as well as their total mass, volume, and power required is created and is shown in Table 10.2.4.1.

The scientific instruments where chosen based on what is currently aboard Martian rovers such as Curiosity and Opportunity, the International Space Station, as well as what can be found in a typical geology laboratory here on Earth [10-1]. A mass spectrometer measures the relative masses of all the atoms and ions in a sample, allowing us to determine the composition of a certain rock or soil [10-2]. An x-ray spectrometer also determines the chemical components of a sample, but does so by exciting it with x-rays which produces a spectrum [10-3]. A gas chromatograph vaporizes a sample, which separates and analyzes its chemical compounds [10-4]. A scanning electron microscope can produce highly detailed images of a rock or soil samples which helps scientists understand their microscopic characteristics [10-5].

A greater variety of instruments would certainly be desired, but at a base level, those listed will be sufficient to perform desired experiments on rock samples. From our 100 person model,

the number of units of each component is based around five people, each getting their own computer, desk, and shelving unit for samples. This is scaled linearly for one million people, as mentioned earlier. Initially, two of each instrument is provided in case of failure, but once the population is constant the ratio is one instrument per 5 people.

The masses, volumes, and power requirements were taken from current and future products, and are the smallest and lightest weight possible. For example, a foldable, compact metal desk and shelving units were found on Amazon [10-6, 10-7]. This would serve the needs of science teams to store samples and equipment. The computers, which will be used to analyze data, create maps, and write up scientific reports, are based off the Dell-XPS 18 touch screen [10-8]. This was chosen because it has a large screen, is lightweight, is portable, and can be folded down, which makes shipping easier and saves volume on the ITS. The numbers for the scientific instruments are based off of smaller, handheld versions that are currently or will be in production, which should be suitable for the first several synodic periods. They also require less power to charge. Once our colony grows to a sufficient size, larger and more powerful versions of the instruments will be sent.

10.2.4 System Cost

Scientific instruments, especially powerful or sensitive ones, can be expensive. A list of the approximated costs for all science equipment, for our 50,000 scientists over 100 years is shown. Table 10.2.4.1. This is based on the equipment previously listed in Table 10.2.4.1. While it is unlikely we will need 10,000 of each instrument, and likely new ones will be added as the population grows, this is a good approximation.

Table 10.2.4.1 A list of proposed science instruments and the costs associated with each item.

Component	Cost ($)
Lightweight desk (foldable)	5,500,000
Shelves (lightweight metal)	1,875,000
Portable (mini) Mass Spectrometer	75,000,000
X-Ray Spectrometer	300,000,000
Gas Chromatograph	248,000,000
Scanning Electron Microscope	2,400,000
Computer	39,000,000
TOTAL	**671, 775,000**

Above is a table listing all of the proposed scientific instruments that we would like to include in our colonists. This includes all equipment found inside the science habitats, as well as larger instruments like telescopes, weather stations, seismometers, and orbiters. It should be noted that not all of these costs may have to be covered by our colonists or SpaceX. Government funded organizations, such as the National Aeronautics and Space Administration (NASA) or the European Space Agency (ESA). These entities are interested in doing research on Mars, and can subsidize some of the costs. This will significantly decrease the costs associated with the science habitats, and it is likely to make the cost negligible when compared to our other systems.

10.3 References

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11 Feasibility Conclusions

11.1 Logistical Feasibility of Mission

We designed our colony with redundancy and safety factors applied to ensure successful operations even in the event of internal failures. However, if the launch system falls behind schedule or has a failure, the colony cannot mitigate this and the mission will fail. As such, the logistical feasibility of the mission overall relies heavily on the logistical feasibility of the launch system performing at the scales required for our mission requirements.

Launch system logistics feasibility is broken down into 3 main categories: manufacturing and launch window saturation.

11.1.1 Manufacturing

One limiting constraint is the number of that are produced in one year. There is currently no data regarding the assembly time of the ITS. As a cap for feasibility, we estimated that SpaceX is not likely to produce more than 3 ITS in a given year. This number was determined by comparing at the number of M1D engines and Falcon 9 cores produced. In 2015, 4 M1D engines were being produced per year, which would result in the engines of 23 Falcon 9s. However, the actual number of Falcon 9 cores produced was 8. In this way, we divide the number of vehicles by engine count produced divided by 3 to get the full vehicles. Applying this logic to the Raptor engines and ITS, we can estimate that for 208 engines (assuming raptor engines take as long as M1D engines), there can be 1.65 ITS produced per year. If we are generous and multiply this by 2, this means at a cap, SpaceX can produce 3 ITS per year at full production with current technology. In table 11.1.1.1, we determined the number of vehicles SpaceX needs to produce per year to stay ahead of the number needed to satisfy the mission timeline.

Table 11.1.1.1Minimum production rates per year for each transportation model

	ITS-D1	ITS-D2	ITS-T
Maximum Fleet Size (including ITS-C)	772	887	534 (ITS-T) 76 (Cyclers)
Min Production Per year [ITS / Year] (including ITS-C)	37	38	25 ITS / Year 3 Cyclers /Year
Maximum Fleet Size (Excluding ITS-C)	772	434	104 (ITS-T) 76 (Cyclers)
Min Production Per year [ITS/Year] (Excluding ITS-C)	37	20	7 ITS / year 3 cyclers /Year

While it is outside the scope of this project to validate what manufacturing rates are possible in the future, we can make quite a few conclusions regarding the data shown in Table 11.1.1.1

- **None of the models meets the feasibility limit.**
- Cargo Vehicles place the greatest strain on manufacturing rates with a minimum of 37 ITS per year.
- ITS-D1 had the highest manufacturing demands independent of the cargo launches
- ITS-D2 had lower manufacturing demands than the ITS-D1
- ITS-T / Cycler had the lowest manufacturing rate, but still exceeds the feasibility limit

11.1.2 Launch Window

The launch rate per day has a very direct impact on the launch infrastructure on earth. It was determined that an absolute launch rate limit of ITS vehicle 6 launches per day could be accomplished. This was determined from how long each of the operations to successfully launch an ITS will take. Table 10.1.2.1 contains the worst-case launch rates per day of each model.

Table 11.1.2.1 Maximum Launches per day for all three models

	ITS-D1	ITS-D2	ITS-T
Maximum Launches / day (with cargo)	5	5	4
Maximum Launches / day (without cargo)	5	3	2

As was the case with manufacturing, the cargo launches dilute the savings each system provides. What we can determine from Table 10.1.2.1 is that the ITS-D1 launch rate cannot be reduced without reducing the number of passengers since the cargo bays are attached. Neglecting cargo, the ITS-T once again had the best maximum launch rate compared to the other two options.

Overall, the ITS-T offers the best logistical feasibility out of any of the 3 options, but the impact will be minor compared to the number of cargo launches necessary to build and maintain our colony mode

11.2 Cost Feasibility of Mission

One of the essential elements in a feasibility study is the cost analysis. In order to determine whether it is realistic to send a million people to Mars in 100 years, we have to understand how much this mission would cost. Elon Musk stated in his proposal that a ticket to Mars would only cost a customer $200,000. A key metric of this feasibility study will be to analyze how much of the mission will be covered by this ticket price, and how much will need to be subsidized by government or private industry.

11.2.1.1 *Launch and Fabrication Cost Analysis*

In his presentation, Musk provided the approximate cost estimates for fabrication of the Interplanetary Transportation System (ITS) shown below in Table 11.1.2.1.

Table 11.1.2.1 ITS Cost Estimations provided by SpaceX

Variable	Booster	Tanker	Ship
Fabrication Cost	$230 M	$130 M	$200 M
Launches per Lifetime	1000	100	12
Launches per Mars Trip	6	5	1

One of the key features that makes this mission plausible is the reusability of the ITS. With the ability to withstand multiple launches, the immense fabrication cost is minimized across multiple trips to Mars and back to Earth. Based on the fabrication cost estimates and Musk's propellant cost of $168 per Mg of methane fuel, we calculated the total prices per Mars trip shown in Table 11.1.2.2 below.

Table 11.1.2.2 Calculated Cost per Mars Trip (Including Only Launch Elements)

Variable	Booster	Tanker	Ship	Total
Maximum Fabrication Cost (1 Mars Trip)	$38.33 M	$26 M	$200 M	$264.33 M
Minimum Fabrication Cost (Full Lifetime Trip)	$1.38 M	$6.5 M	$16.67 M	$24.55 M
Cost of Fuel per Mars Trip	$6.75 M	$2.10 M	$0.33 M	$9.50 M
Cost of Maintenance per Mars Trip	$1.00 M	$2.00 M	$10.0 M	$13.0 M
Total Cost per Mars Trip as Calculated by Project Destiny	$9.13 M	$10.6 M	$27.0 M	$47.05 M
Total Cost per Mars Trip as Calculated by SpaceX	$11.0 M	$8.00 M	$43.0 M	$62.0 M

Note the discrepancy in the total cost per Mars trip between the provided SpaceX amount and the calculated amount. Musk estimated that the total cost per one Mars Trip based on launch costs would be $62.0 million while our calculations using his cost estimates wielded $47.05 million per trip to Mars, which is significantly less. This could be due to additional costs like amortization etc. not disclosed by SpaceX in the original presentation.

Throughout this feasibility study three different modes of transportation to Mars were analyzed. One with Elon Musk's integrated cargo and crew transportation ITS design, another with a separate cargo and crew ITS design, and the last one a cycler concept. Throughout each transportation concept, the cost of the colony infrastructure stayed around the relatively same price in comparison with the transportation. Therefore, let us compare the costs of the transportation system as a critical factor in the overall feasibility of the mission in Table 11.1.2.3.

Table 11.1.2.3 Launch Cost Comparison of Three Mission Concepts

Transportation System	Number of Crew ITS Launches	Number of Supplemental Cargo ITS Launches	Launch and Construction Cost over 100 years (Millions)
ITS-D1	31340	327	1,489,932.5
ITS-D2	17619	10,250	1,311,236.45
ITS-T/Cycler	3980	10,250	4,991,062.62

Please note that the cost over 100 years for the ITS-T/Cycler concept includes the cost of the construction of the cycler over the 100 years, making it significantly higher than the direct flights. While the cycler may drastically decrease the complexity of the launch logistics, the construction factor of the Cycler concept drastically increases the overall cost over 100 years.

These cost estimates only cover the launch elements of our mission to Mars. The colonists' costs of living are included in the following sections.

11.2.1.2 *Colony Infrastructure Cost Analysis*

While Elon Musk only reported the estimated launch costs, many more costs that need to be considered when sending a million people to another planet. Although many of the technologies included in our design are still in development, we made cost estimations for each critical life system needed for the colonists over 100 years. While the costs may seem astronomical for certain systems, especially human life support systems, these technologies are expensive for current space technologies but will most likely decrease with time and mass production. These cost breakdowns are included in Table 11.1.2.4.

Table 11.1.2.4 Colony Infrastructure Cost Analysis

Variable	Cost (Millions)
Interplanetary Communication (Launches Included)	$228,000
Food Processing	$179,563
Martian Surface Resources	$16,302
Martian Habitats	$177,000
Steel Production	$1,227
Central Power	$109,444
Total Cost	**$711,586**

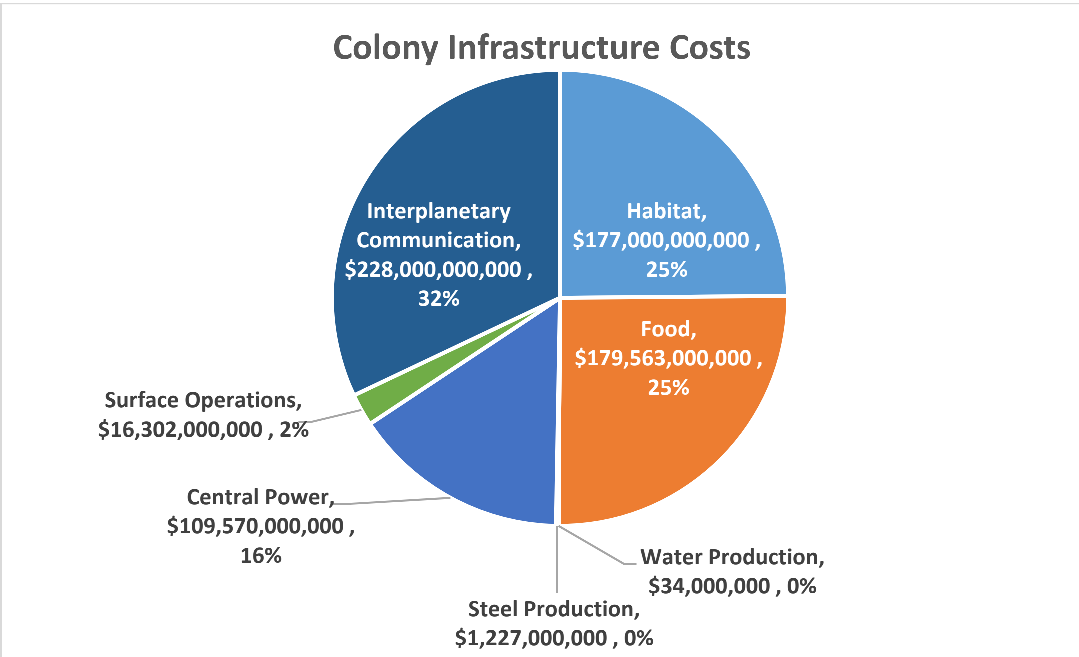

Fig. 11.2.1.2.1 Breakdown of colony infrastructure costs. (Credit: B. Francis)

The colony infrastructure cost is broken down in the figure above. Note that Interplanetary Communication takes up the largest portion of the colony infrastructure cost due to the fact that this cost includes the satellites' launch and construction costs. These launch costs are included due to the fact that they launch on a separate vehicle, not an ITS. A large part of the driving cost factors are the environmental control and life support systems aboard each vehicle and habitat. The only proven human-rated space environmental system in use today is aboard the International Space Station. This system routinely serves six human beings 365 days of the year. The scaling of a million-person colony ECLSS system is on a completely different scale than current space technology. An ECLSS system that will sustain a million people will require a lot more research and development. Over a hundred years, with mass production, these prices could lower significantly thereby decreasing the overall mission cost.

If the mission were to be completely privatized, the cost per ticket would come out to around $5.7 million per person. .If the ticket price is the proposed $200,000 then the total ticket income will be 200 billion dollars, which does not even begin to cover the $5.7 million dollars. However, as a historic mission on Mars, we would expect that the United States government and maybe other foundations or countries would want to subsidize certain portions of the mission.

If we were to break down the cost of the ticket to launch costs and colony infrastructure, and compare the three different transportation concepts we would see that because of the additional construction costs, most of the ticket price in the cycler concept is dedicated towards launch costs.

The results to the ticket breakdown comparison are included in FigFig. 11.2.1.2.2, Fig. 11.2.1.2.3. and Fig. 11.2.1.2.4.

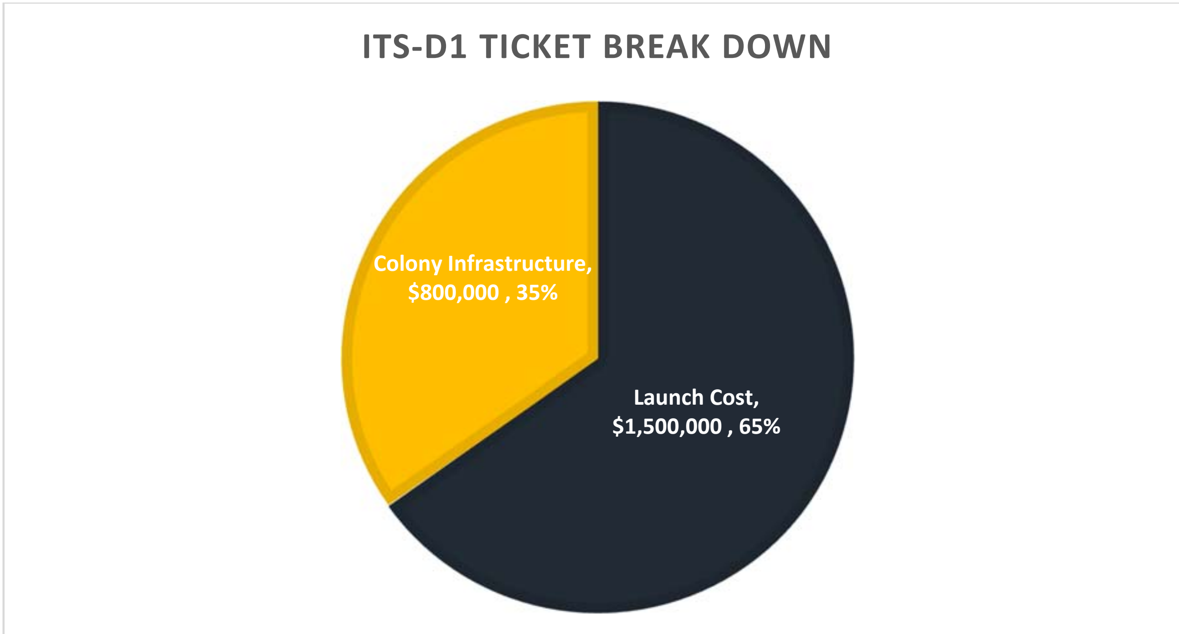

Fig. 11.2.1.2.2 The breakdown of the ITS-D1 mission architecture ticket (Credit B Francis).

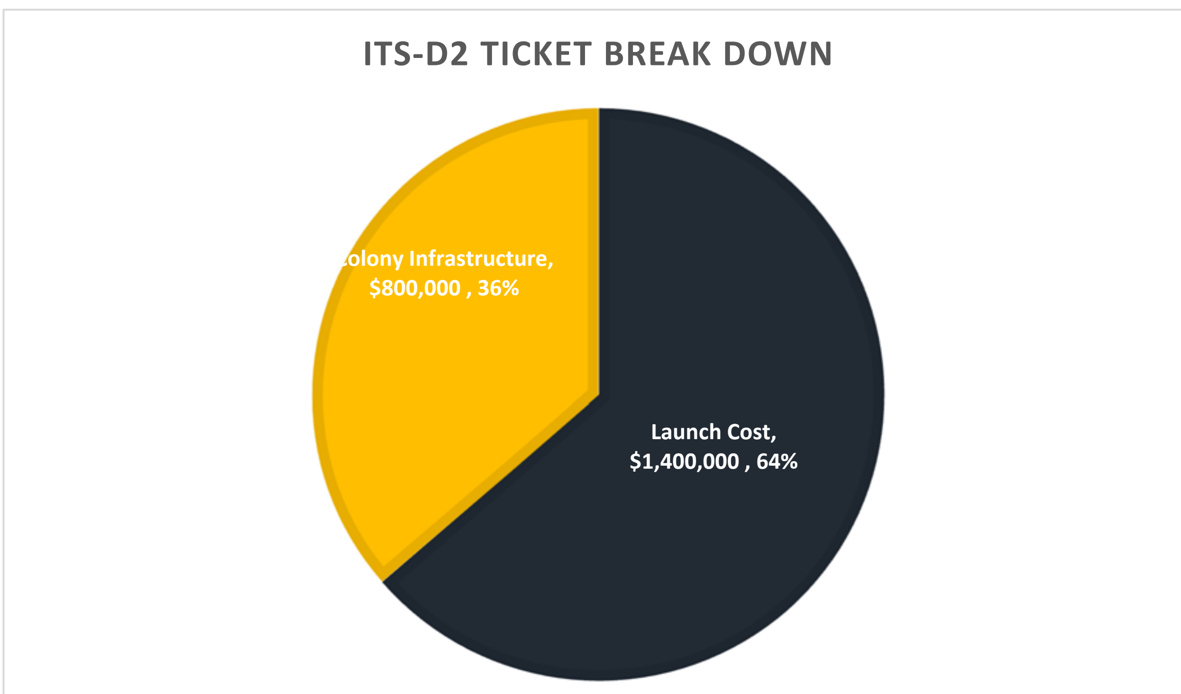

Fig. 11.2.1.2.3 The breakdown of the ITS-D2 mission architecture ticket (Credit: B. Francis)

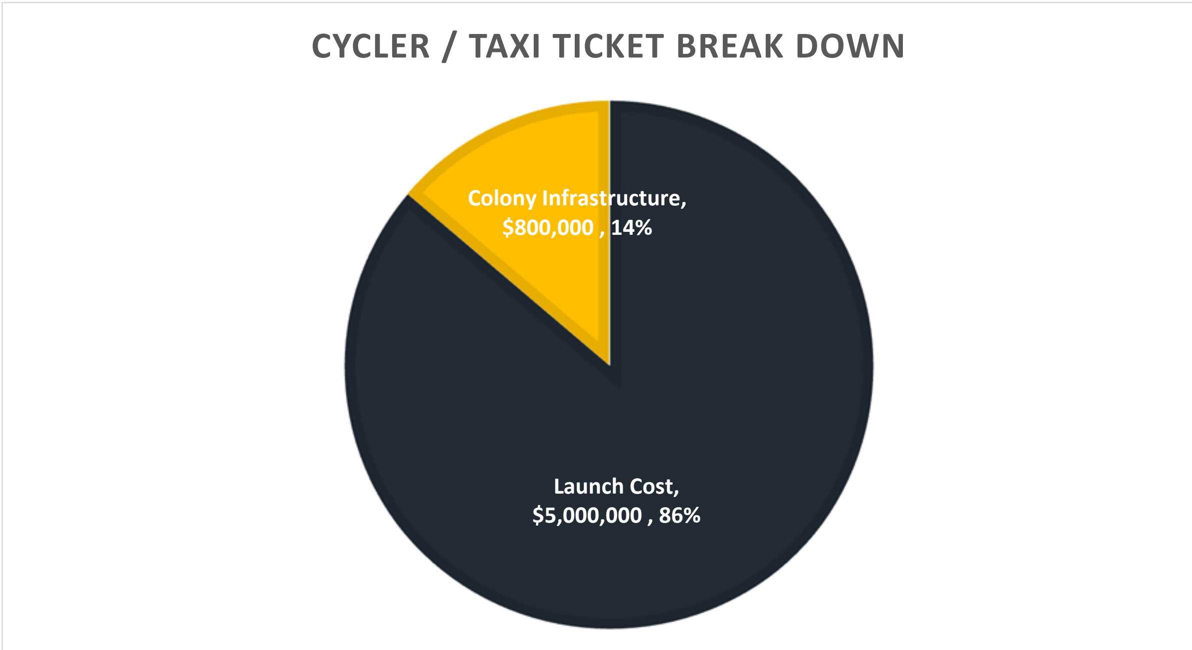

Fig. 11.2.1.2.4 The breakdown of the Cycler mission architecture ticket. (Credit: B. Francis)

11.3 Risk and Safety Feasibility assessment

Another critical factor within determining the feasibility of a mission to Mars is to analyze the relative risk of mission factors. While there are endless amounts of risks possible on a mission of this scale, it's possible risks that are mission critical to human life. Percent success will be given for each of the critical aspects of the mission. The goal is to establish a 90% success rate.

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Table 11.1.2.11 Mission Critical Risks Ranked

Rank	Risk Title	Response	Probability of Success
1	Loss of ITS cargo vehicle	M	94%
2	Cycler construction/structure failure	M	95%
3	Habitat emergency	A	98.5%
4	Colony construction behind schedule	W	98.8%
5	Water extraction malfunction	W	99%
6	Interplanetary communication goes offline	M	99.2%
7	FAB failure /Loss of food storage	M	99.5%
Total			**84.9%**

Despite having high probability of success rates for most systems, SpaceX's overall launch success rate of 94% does hurt the overalls success of the mission. While SpaceX is still a relatively new rocket launch company, they have time to improve this average over the 100-year period. If the 94% launch success rate were to increase to 98% over time, the probability of success would jump to 93% overall, achieving our goal. Notice that the loss of an ITS-T or ITS-D1/ITS-D2 is not included as a major factor, despite the risk of potential loss of life. This factor was not included in the list of mission critical risks because if a crewed ITS were to be lost, it would only affect the crew onboard the ITS. The impact of the loss of 325 lives to the overall colony is less critical than the ITS carrying cargo. If human lives are lost, all that is lost with them is labor and expertise, while by losing an ITS-C could put the whole mission behind on schedule, risking the lives of far many more colonists than the 325 lives aboard ITS-T. Having a large-scale mission of a million

people slightly changes the traditional space community view of the critical importance of human life. This mission mentality may introduce a new greater-good concept view for the colony, which is new to the traditional NASA, “save Mark Watney,” concept. The different response strategies in the table above include M for mitigate, W for watch, and A for accept. All the risks with M have the possibility to mitigate with improved research, practice, and costs. However, for critical systems in the habitat, there will always be certain risks of ECLSS failures as there is here on Earth. The best option for humans is to be prepared and have emergency evacuation procedures in place. Other risks like delaying the mission schedule can be watched and updated as needed throughout the mission.

Impact	5					
	4	[7]		[2]		
	3	[6]	[3] [4][5]	[1]		
	2					
	1					
		1	2	3	4	5
		Probability				

Fig. 11.2.1.2.1 NASA risk matrix compares mission critical risks.

When comparing the mission critical risks, it is helpful to see them both qualitatively and quantitatively. One way to see the risks qualitatively is to use a NASA Risk Matrix [1]. This matrix allows customers to see how the probability compare with the impact of a mission critical failure.

When comparing transportation concepts, the launch risks will all be the same, as they are all launched with the same ITS launch configuration. However, the ITS Cycler concepts inherently carries more risk than the direct mission logistics. Between the construction and the hyperbolic rendezvous, the cycler reduces the overall human transportation success probability from 94% to 89.3%.

Throughout the mission, we also need to track all the outcomes based on the mission critical risks. We devised an overall risk management fault tree in order to track outcomes of the mission and failure work-around. This fault tree is shown in the figure below.

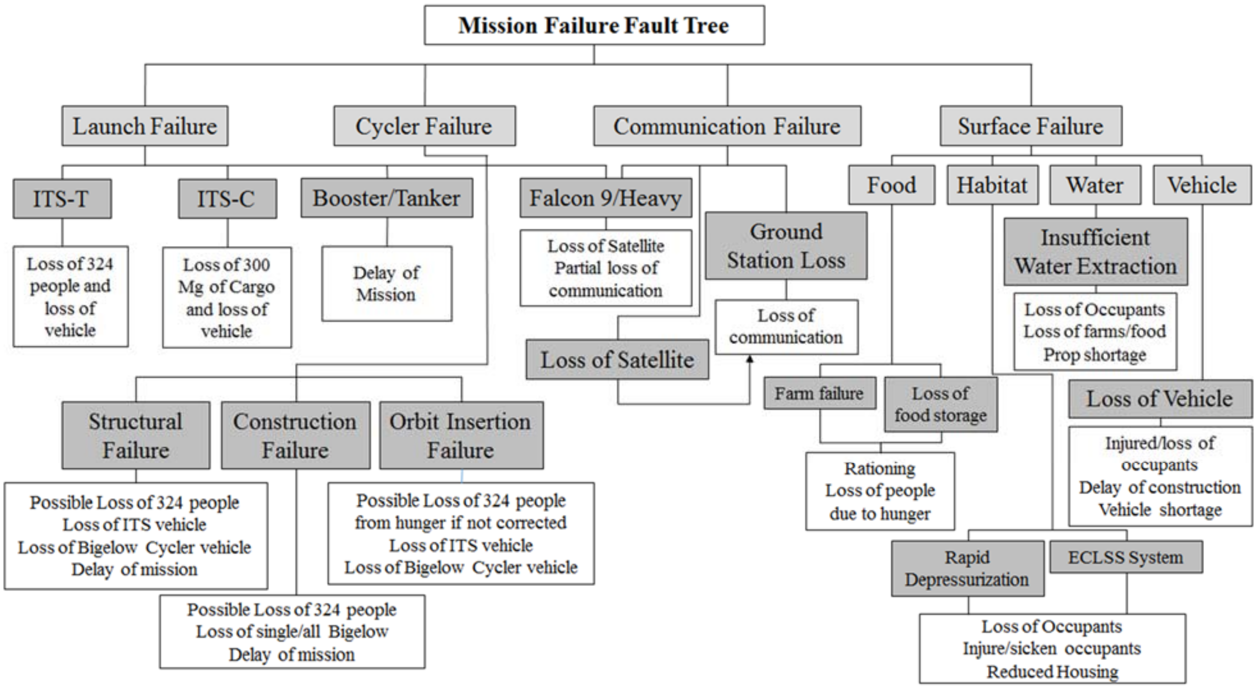

Fig. 11.2.1.2.2 The high-level mission fault tree shows overall failure consequences.

12 Conclusions and Recommendations

12.1 Primary Conclusions

- The model presented by SpaceX or ITS-D1 as we refer to in this report, proved to have the highest demand on manufacturing, and logistical challenges when delivering the same amount of cargo and people. This model was also the second most expensive system behind the cycler /taxi model. This model also had the largest steady state fleet for the same delivery rates of colonists due to its smaller livable volume.
- The Cycler/Taxi model had the lowest logistical and manufacturing demand by having the lowest launch rate per day and lowest production of ITS necessary per year. The Cycler / Taxi model always had the lowest fleet requirements compared to the other models for any given cycle with the same cargo and passenger delivery rate. However, our estimates for the cost for the individual cycler vehicles made the cycler / taxi model the most expensive option.
- Separating the Cargo and crew into different launch vehicles resulted in a lower cost per colonist and lower total number of launch vehicles for the same amount of cargo and passengers. We demonstrate this by the comparison between the ITS-D1 and the ITS-D2.
- Cargo launches make up a majority of the launches and these must be direct flights. The best way to reduce launch costs, launches per day, and reduce the manufacturing rate is to reduce the number of cargo launches.
- ECLSS was the most expensive, most massive and most volume heavy component in every system in the colony.
- If Elon Musk want's the ticket cost to be below $200,000 per person, there will need to millions of dollars in subsidized cost per colonists to account for the infrastructure of the colony.
- We knew very little about what lay beneath 1 meter of Mars surface for most of the planet. This restricted our designs due to the inability to determine more resources and products we could develop on Mars surface.
- Our colony model cannot produce Nitrogen and nuclear material on Mars in our colony model and this prevented our colony from being resource independent of earth.

Feasibility Conclusion

If there are no major design changes to the architecture presented by Elon Musk, our team concludes that it is **not feasible** to establish a **1 million colony** on Mars within **100 years** using any of the models we have presented. Specifically, it is not possible to **manufacture** the necessary vehicles fast enough for any of the models we investigated. We base this conclusion on our design requirements, assumptions and constraints for how we established our colony on the surface. However, we want to make it clear that the Interplanetary Transport System offers a wide variety of opportunities and capabilities for building a colony on Mars that are not available with other launch architectures. The primary issue is the amount of people we need to deliver within our mission timeline. We can confidently say that it is possible to establish a colony of thousands or even hundreds of thousands within 100 years, but 1 million colonists in particular strains our manufacturing capability beyond feasible limits using current technology.

12.2 Recommendations

We based our overarching conclusion with the context of our design assumption that technology, lifetimes, and architecture do not change over time. Because of this, we can point to specific advancements in technology that need to occur. We have the following recommendations as to how to make the 1 million colonists within 100 years more feasible using an interplanetary transport architecture.

- To be cost effective, the ITS needs to have as many people on board it during a launch as possible. From our estimates on cost, there need to be at least 236 people on board the vehicle (at $200,000 a ticket) to break even. This is possible without dramatically scaling up the vehicle by implementing the cycler / taxi model. Long term the Cycler / taxi model is the most cost effective system at delivering colonists contingent upon Cycler lifetime and cost per individual cycler.
- Developing more In-Situ resource utilization methods is essential towards bringing the costs down by reducing the number of cargo launches from earth. Specifically, manufacturing on Mars needs to be studied in much greater depth before we will be able to have a fully self-sufficient colony. Specifically, we need concentration and quality data of ores and raw resources below Mars surface. Most of our manufacturability assumptions are based resources visible on Mars surface as seen from orbiting satellites. This was very limiting in our design process.
- High capacity, high cost efficiency ECLSS models need to be developed. We do not currently have ECLSS capable of sustaining 20, let alone hundreds of people. Our ECLSS models were based on simple scaling approximations of existing systems and this led to ECLSS being the most expensive and mass intensive system. Though we expect ECLSS to remain one of the largest systems for the colony, the specific values we calculated for cost, mass and volume are probably high estimates because we could not apply economies of scale with any specific confidence.
- The ITS-D1 and D2 can establish a large colony on Mars surface in a cost effective manner, but the rate of colonial development depends on the number of vehicles in service. If SpaceX does not wish to use a cycler model, either the timeline needs to be

increased, or arrival rate decreased. This will minimize the propellant production requirements for resupply for the colony as well as the launch logistics back on earth. The reduced passenger capacity in the ITS-D1 had the greatest impact on this model's cost feasibility.