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System Engineering Analysis of Terraforming Mars with an Emphasis on Resource Importation Technology

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Abstract

This project uses System Engineering principles to delve into the viability of different methods for Terraforming Mars, with a comparison between Paraterraforming, Terraforming and Bioforming. It will then examine one subsystem that will be integral to the terraforming process, which is the space infrastructure necessary to import enough gases to recreate Earth's atmosphere on Mars. It will analyze the viability of Chemical Rockets, Nuclear Rockets, Space Elevators, Skyhooks, Rotovators, Mass Drivers, Launch Loops and Orbital Rings for this subsystem and provide recommendations for an implementation plan.

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1 Executive Summary

Earth needs an insurance policy. There have been five mass extinction events in Earth's history that have driven at least 70% of all species to extinction[23]. Another mass extinction event can occur at any time, whether by a supervolcano, a massive asteroid, a gamma-ray burst or by some devastating act of inhumanity. Imagine the tragedy if humanity became extinct. Imagine the tragedy if all our wondrous civilizations, inventions, religions and philosophies abruptly disappeared. Imagine if you disappeared, along with your family and everyone that you had ever known. This is something that can be avoided if human beings had the ability to flee Earth and survive a previously inescapable extinction event.

Possible Extinction Scenarios

- Supernovae Explosion[22]
- Asteroid
- False Vacuum
- Nuclear Attack
- Disease
- Giant Earthquake
- Artificial Intelligence
- Runaway Greenhouse Effect
- Expansion of the Sun
- Collision with Andromeda Galaxy

With this in mind, it is imperative to examine how we could create an independent, sustainable civilization on a location other than Earth. Though there are a number of other key locations where this can happen, including the Moon, Venus[25], Titan, and Europa, the focus of this project will be on Mars. This is due to its similarity in size to Earth (which rules out examining the Moon), its relatively close proximity to Earth (which rules out examining distant moons such an Titan and Europa, as well as any exoplanet that may be orbiting a distant star), and the fact that its atmosphere isn't an immensely hot, dense soup like Venus. Transportation to Mars as well as long-term civilization construction are two other key problems that must be resolved for humanity to have a true insurance policy, but the focus of this Capstone project will simply be on how to transform the Martian planet into something humans can survive within.

Reasons to Terraform

- Become a multi-planetary species[26]
- An insurance policy in case of devastation to Earth
- Blueprint for future terraforming efforts
- Because it's there (and might be possible)

So is it possible to recreate Earth's atmosphere on Mars? Will humans ever be able to breathe the Martian air and not suffocate? We first need to look at the composition of Earth's atmosphere and compare it to the Martian atmosphere. We need to figure out what type of atmosphere we need to recreate so that humans, as well as a variety of other living organisms, could survive. The creation of a new Martian atmosphere will also require investment into a whole host of different space infrastructure and technologies. The problems and solutions encountered when terraforming Mars will be explored within this paper.

2 Introduction

Mars is currently a lifeless, barren planet that little resembles the fertility and life of Earth. Mars is much colder than Earth since it is on average 227.9 million kilometers away from the sun (with Earth being 150 million kilometers from the sun)[27]. Because of this, Mars has an average surface temperature of less than -62℃ (-80℉)[28]. This is much lower than the lowest temperature at which simple life from Earth can live and grow at -20℃ (-4℉)[29]. Mars also has an atmospheric pressure much lower than that of Earth at 0.6% the amount of Earth's. Its atmosphere is toxic since it is comprised of 96% carbon dioxide and 2% nitrogen[30]. Another nail to the coffin for potential life on Mars is that it gets much more atmospheric-damaging solar wind since it lacks a magnetosphere to protect atmosphere molecules from excitation. This means that any life on Mars would be subject to much more radiation than life on Earth[31].

With all this in mind, Mars is currently the best candidate for terraforming in our Solar System. It is relatively close to Earth and can pass as close as 54.6 million kilometers. This means that a trip to Mars using the low energy Hohmann transfer orbit would only take 9 months[32]. Mars also has a day length of 24 hours and 37 minutes, which is very similar to the length of the Earth day[33]. It also receives a relatively large amount of sunlight at 715 W/m^2, which is close to the solar input of 1367 W/m^2 that Earth receives[34]. Mars has an axial tilt of 25 degrees, which is very close to Earth's axial tilt of 23.5 degrees[35]. Because of this, Mars experiences seasons similar to Earth that correlate to Mars' year length of 687 days[36]. Mars' gravity is not ideal, being 39% of Earth's gravity, but this amount of gravity may be beneficial for plant growth.[37,38] These similarities mean that Mars is a much better candidate for terraforming than planets such as Venus, Jupiter or Mercury.

Mars also has a history of being wet and lush. It has been theorized that when it was first formed 4.2 billion years ago it had an atmosphere and high amounts of water. Since Mars is much smaller than Earth, its internal core gradually hardened, which caused Mars to lose its magnetic field. Without a protective magnetic field, the solar wind was able to strip away most of the Martian atmosphere. The end result is that over the next 500 million years, Mars gradually transformed from a warm, wet planet to a cold, dry planet. Around 3.7 billion years ago, Mars eventually became similar to the barren planet we know of today[40]. Despite this, there is evidence that water still exists on Mars. Water in the form of ice has been found at the poles and underground in the Utopia Planitia region of Mars[41]. There is up to 5 million cubic kilometers of ice on Mars, and if this were to be spread evenly over the entirety of the surface of Mars it would submerge the planet under 35 meters of water[42]. This, unfortunately, pales in comparison to the 1.36 billion cubic kilometers of water found on Earth, but it is a start. We are currently on the hunt for life on Mars, but this has not been found as of yet.

It should also be noted that humans have always had a deep fascination with Mars and its potential for life. In 1877, Giovanni Schiaparelli, an Italian astronomer saw a network of dark areas on mars and called them 'canali'. This was mistranslated on English language maps of Mars as canals, which let Percival Lowell, a prominent American astronomer that founded the Lowell Observatory in Flagstaff, Arizona, to speculate that the Schiaparellian canals were made by an advanced Martian Race. He would then devote much of his life to trying to confirm this theory. Lowell was unfortunately unsuccessful[39]. This fascination with Mars has continued to present day, with over 55 spacecraft missions to Mars (with these missions comprising of Flybys, Orbiters, Landers and Rovers)[43]. There are many famous Martians in fiction, with some of the more famous being Marvin the Martian, the Martian Manhunter, and Mark Watney from the film/novel entitled The Martian.

With Mars so deeply ingrained in the collective consciousness of humanity, it would be an interesting thought experiment to analyze what it would take to convert dry, barren Mars into a lush planet teeming with life similar to Earth. This thought experiment will require several leaps of imagination and a foray into futuristic technologies but will be grounded by solid system engineering principles. It will start by examining the overall terraforming approach and the capabilities of terraforming, para-terraforming, and bio-forming. For the second section of this paper, it will delve into one of the many subsystems that will support the terraforming process, namely the technologies necessary to import large amounts of atmospheric materials from other planetary bodies such as Venus, Jupiter, and Titan to Mars.

This analysis of Terraforming techniques will follow the System Engineering V-model, which is found within the INCOSE handbook and shown in Figure 1.

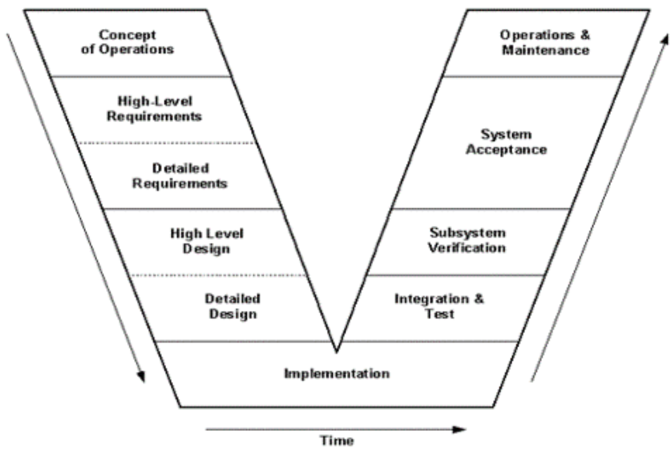

Figure 1: System Engineering V

Since much of the technologies being explored are theoretical, and there is little capability of delving into the right-hand side of the V-Model (such as Integration & Test and Operation & Maintenance), the focus of this project will be on the left hand side of the V-Model, which is the Concept of Operations, High-Level Requirements and High-Level Design, and its proposed implementation. In order to pursue this extremely complex system-of-systems, this paper will explore the unique concepts and technologies associated with the subsystem that will import atmospheric resources.

3 Key Problem

At the Macro Terraforming Level, the key problem to be resolved is shown below. All of the alternatives and goals should be based on the most effective ways of resolving this.

Problem Statement

Allow for humans to develop a long-term independent, sustainable civilization on Mars through terraforming that would allow humankind to survive if any catastrophe may befall humans on Earth

4 Key Stakeholders

Listed below are some of the stakeholders and the benefits and negatives they would receive from the terraforming process. It should be noted that this process would take place far into the future, with there being a high likelihood that there are human inhabitants on planets other than Earth

List of Stakeholders

- Humanity[44]
  - Back up plans in case of a potential extinction event
  - Large-scale project to rally the masses
  - Drives the creation of new technologies
- Government Agencies (UN, NASA, ESA)
  - Concerned with the economic viability of the project
  - Provide financial support from the international community
  - May participate in the terraforming process if it aligns with their goals
    - Terraforming can drive prestige to these agencies
- Humans on Mars
  - Improved living conditions
  - Greater tourism, industry, mining, research
  - The potential destruction of their home
  - Don’t need to live with pressure suits/oxygen masks/underground
  - Potential increase in population
- Asteroid Miners[45]
  - Sell resources and gain Wealth
- Humans on Venus and Titan
  - Sell resources and gain Wealth
- Space Industry
  - Generates wealth and prestige

5 Goals

This is a list of goals that could be used to analyze the viability of different alternatives for terraforming Mars:

List of Goals

1. Allows for useful biological organisms to reproduce and thrive
2. Controllable
3. Long-term
4. Reversible
5. Done within a useful timeframe
6. Results in minimal damage to Mars and any potential native organisms
7. Minimum cost
8. Widespread over most, if not all of Mars
9. Technologically feasible

6 Macro Level Alternatives

This section will delve into the different ways Mars could be terraformed at a macro level. In particular, it will focus on terraforming, para-terraforming, and bio-forming.

6.1 Terraforming

Terraforming consists of making changes across the entirety of the planet Mars. This involves resolving a couple of key problems including atmospheric creation, increasing the temperature and protecting the atmosphere from harmful radiation. Since the changes in this process are planet-wide, it is by far the most widespread, destructive, permanent and costly method. On the flip side of the coin, if it were to be successful, it would be the approach that would best resolve the problem statement and allow for the creation of a permanent, independent human civilization on Mars[44].

The introduction of different resources to Mars has the potential to cause much destruction. If large amounts of water were to be introduced, the low air pressure on Mars would cause high amounts of evaporation and thus torrential amounts of rain. This would cause high levels of erosion on the Martian surface and the potential eradication of pre-existing Martian colonies that may exist under domes or underground. There has to be a solution to mitigate the potential damage caused by the terraforming process if one were to proceed with terraforming Mars.

Terraforming is the most costly approach by far. It is possible to approximate the amount of gases Mars would need if it had the same atmospheric pressure and atmospheric composition of gases as Earth. This can be done by understanding that Earth has 10,000 kg over each square meter of ground in order to create the pressure conditions one feels on the surface of Earth. Since Mars has 39% of the gravity of Earth, Mars would need at least 26,300 kg of air (at Earth temperatures and pressures) over one square meter of ground. We can then extrapolate the overall amount of gas Mars would need by multiplying 26,300 kg by Mars' surface area[46] of 144.8 trillion m^2. This would require Mars to have close to 4 quadrillion metric tons of total air. Earth's atmosphere is 78% nitrogen, 21% oxygen, 1% argon with trace amounts of carbon dioxide and water[47]. If the Martian atmosphere were to simulate this gaseous composition, the amount of gas needed by type is shown in Table 6.1. We can approximate the cost of transporting this amount of gas by using the Space Shuttle program's cost for transporting 1 kilogram of resource into Low Earth Orbit ($50,000)[48]. This may be a good placeholder approximation for the transportation of 1 kilogram of gas from a variety of planet bodies (Jupiter, Venus, Titan) to Mars. The end result of the potential cost for importing enough gases to recreate the Earth's atmospheric composition and pressures on Mars is shown in Table 6.1. The total cost is 1.77 billion times the World's Gross Domestic Product by Per Purchasing Parity[49]. Terraforming is costly.

Type	**Amount (metric ton)**	**Potential Cost**
Total Air	3.79E+15	$1.90E+23
Nitrogen	2.96E+15	$1.48E+23
Oxygen	7.94E+14	$3.97E+22
Argon	3.53E+13	$1.76E+21
H_2O in Atmosphere	1.52E+13	$7.58E+20
Carbon Dioxide	1.55E+12	$7.77E+19

Table 6.1: Air Needed to Simulate Earth on Mars

6.2 Paraterraforming

An alternative to planet-wide terraforming is the smaller process of paraterraforming[50]. This consists of creating dome structures with a breathable atmosphere on the surface of Mars. These domes can be created over naturally occurring craters and canyons such as the Schiaparelli crater (a crater 459 km in diameter)[53], Valles Marineris (a canyon 4000 km long, 7 km deep and 700 km wide)[52] or Pavonis Mons[54]. These dome structures can start out small but can be expanded and connected over time as the process is optimized. Figure 6.2 roughly shows what the para-terraforming process may look like if it were to move forward in a large crater. If para-terraforming were to prove an unmitigated success, one may choose to dome over the entirety of the surface of Mars, a process called Worldforming[51].

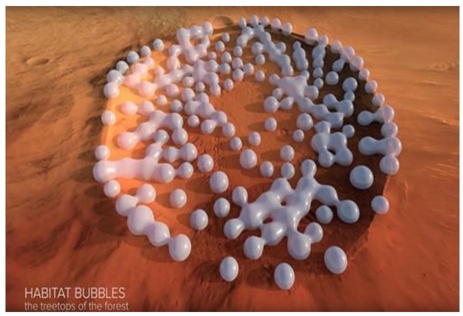

Figure 6.2: Paraterraforming Domes

Paraterraforming is a much smaller and more manageable process for replicating Earth-like conditions on Mars. It would not cause as much destruction to the Martian landscape as full-scale terraforming and would use only a fraction of resources needed by terraforming. Table 6.2 shows how much total gas different types of domes would need to approximate Earth's pressures at Earth temperatures and conditions, as well as what this amount is in relation to terraforming. It would be possible to replicate the conditions of Earth within each dome more closely. This shows that terraforming is technologically more possible, easier and simpler than planet-wide terraforming[55]. If one were to invest in the para-terraforming process, he would see much sooner payback times than terraforming, a process that may take 100 times longer to succeed or see benefits from[56].

Type of Dome	**Volume (cubic meters)**	**% of gas compared to Terraforming**
Pressurized Dome (1 cubic km)	1.00E+09	0.000000085
Pressurized Dome (100 cubic m)	1.00E+02	0.00000000000000852
Pressurized Dome (100 cubic km at lowest pressure humans can survive)	1.00E+11	0.00000093
Pressurized Dome (1000 cubic km)	1.00E+12	0.0000852
Worldhouse (1 km tall dome)	1.44E+17	12.27

Worldhouse (100m tall dome)	1.44E+16	1.23
Worldhouse (10m tall dome)	1.44E+15	0.12

Table 6.2: Resources needed for Paraterraforming

There are still many difficulties that would need to be resolved in order for the paraterraforming process to be a success. We currently do not have the capabilities of creating domes of the size and scale shown in Table 6.2. There is also no good process for maintaining or fixing such a large megastructure. Atmospheric resources may also be lost by absorption into the ground. Oxygen may undergo this process, since it often becomes sequestered to the ground in the form of sand (SiO_2), Limestone ($CaCO_3$) and Iron ore (Fe_2O_3). If there were to be a leak in the dome, this may cause drastic loss of pressure and precious gases, so there would be a need to create a maintenance system to automatically detect leaks and fix those leaks. There would also be a need for protection from the stronger levels of radiation that the Martian surface experiences and from meteor strikes. This may be mitigated by either creating the domes underground or using materials that don't let in UV light, X-rays or Gamma Rays. One could set up a missile defense grid to provide for protection from meteor strikes.

But despite the difficulties the para-terraforming process may experience, it pales in comparison to the vast challenges posed by full-scale terraforming.

6.3 Bioforming

The third and final alternative we will examine is bio-forming. This is the process of changing the genetic makeup of Earth animals and planets so that they could survive on Mars[58]. Like para-terraforming, this process could have much more immediate payback for potential investors. Life forms created through the bio-forming process may help supplement terraforming and para-terraforming by sucking up nutrients from the ground to help create an atmosphere. It may be possible to grow the structures and domes needed for paraterraforming through bioforming. Bioforming would require great leaps in our knowledge of genetic engineering, but we currently have four potential methods of altering DNA, which are listed below:

Types of Genetic Engineering

- CRISPR[58]
  - Clustered regularly interspaced short palindromic repeats
  - Spacers are between the repeats
    - Identifiers for DNA
    - Can lay in new segments
  - Allows one to take out and add any DNA
  - Good tool for modifying DNA
- Retroviruses[60]
  - Use viruses to transcribe RNA into the host's DNA
  - Works best with a single cell, hard to alter trillions of cells
- DNA Printing
  - Makes strands of DNA from scratch, straight off a computer model[61]
  - Good for one segment or gene
  - Make anything our minds can imagine

    - Do not need existing gene
- Universal Assemblers
    - Use nanomachines/nanotechnology[62]
    - Tell machines how to build a copy of itself or how to find DNA and cut it up and assemble it how you want

There would need to be a massive overhaul to the structure and DNA of any Earth organism to allow it to survive the conditions on Mars. It would need to survive very low temperatures and pressures as well as high radiation levels. Organisms may also use machines and computers to help survive these rough conditions, which would allow us to supplement bioformed creations with cyborg capabilities[63]. There is much uncertainty about whether this is possible, but one is sure to encounter many ethical issues. Altering DNA can be dangerous, as it allows one to essentially be playing God and it can lead down an uncertain path. If one were to ignore these issues, bioforming can be a very beneficial process that could support Mars colonization, the para-terraforming process, and the terraforming process.

7 Macro Level Trade Study

In order to analyze the capabilities of the three alternative approaches to resolving the Macro-Level problem statement, a trade study was conducted. This was where terraforming, para-terraforming, and bio-forming were reviewed against the nine goals listed in Section 5. A score was assigned on a scale of 1 to 10, with 1 meaning that it would least adhere to the specific goal and 10 meaning it would best adhere to the goal. This trade study was conducted using research found in Isaac Arthur's publications. All three may be used in the final solution, but this trade study can be used to determine the order/viability of each solution in different circumstances.

	Terraforming	**Paraterraforming**	**Bioforming**
Beneficial for organisms	8	5	1
Controllable	1	10	4
Long-term	10	3	6
Reversible	2	9	4
Useful Timeframe	1	10	3
Minimal Damage	1	10	1
Minimal Cost	1	10	4
Widespread	10	2	5
Technologically Feasible	1	5	5
Total	**35**	**64**	**33**

Table 7: Macro Level Trade Study

8 Findings for Overall Terraforming Process

The findings from the trade study are listed below. These were then used to create the Concept of Operations, Requirements and High-Level Design.

Macro Level Conclusions

- Paraterraforming is the best fit based on the Trade Study and the current goals
- Terraforming may be the best solution for the problem statement of creating a long-term, sustainable civilization
- All three alternatives have numerous merits and risks
- Risks would be minimized overall if we used a combination of all three alternatives

8.1 Concept of Operations

Figure 8.1 shows the overall Concept of Operations for terraforming Mars. It starts with the arrival of humans on Mars and progresses to colonizing Mars. The Martian colony will be supplemented through organisms created by the bioforming process. Once it is determined to be economically feasible, paraterraforming will then proceed, with the creation of progressively larger and larger domes. Bioforming will then be used to supplement this process by either creating the materials for the domes or organisms that can survive within the different domes or just outside the domes. If it becomes viable, the paraterraforming process can then progress into full-planet terraforming, with bioforming used to create organisms that can help control and stabilize the planet as it progresses through different atmospheric conditions.

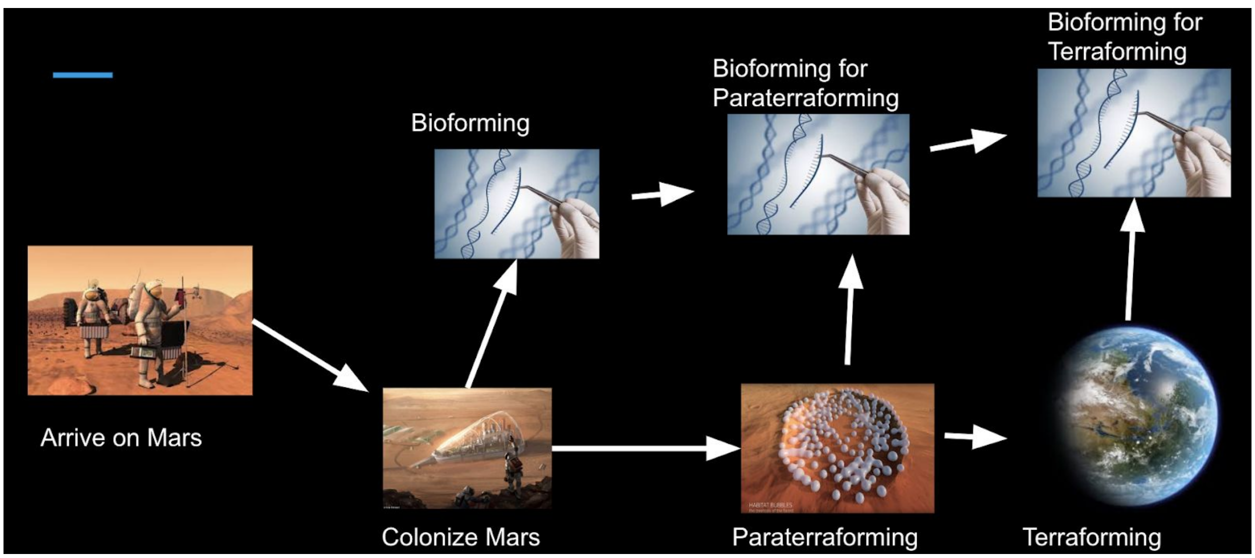

Figure 8.1: Macro-Level Concept of Operations

8.2 High-Level Requirements

Table 8.2 shows a small subset of the high-level requirements necessary to approximate the success of a planet-wide terraforming process. Each requirement corresponds to its correlating numbered goal listed in Section 5.

	Requirement	**Verification Method**

1	**The system shall allow for biological organisms to grow and thrive to support an independent Martian Colony**	Demonstration testing to prove the system is able to provide 90% of the necessary crops for a growing Martian Colony
2	**The system shall be controllable by terraforming efforts**	Demonstration testing of atmospheric pressure conditions and other subsystems to show optimal changes can be made
3	**The system shall last at least 10,000 years after terraforming efforts are completed**	Computer projections of the terraforming process to help determine its long-term viability
4	**The system shall be able to be reversed by ten years in case the efforts causes undesirable circumstances**	Demonstration testing and computer projections of the system to show the reversal of effects is possible.
5	**The system shall be fully terraformed within a thousand years**	Demonstration testing and computer projections
6	**The system shall not cause the annihilation of Martian colonies or para-terraforming efforts or any native Martian life**	Demonstration testing and computer projections of how destructive the Martian terraforming efforts would be to different parts of Mars.
7	**The system shall not cost more than an economically infeasible amount**	Computational projection of long-term economic costs and benefits of the system
8	**The system shall result in at least 50% of the Martian surface in a terraformed state**	Demonstration testing and computational analysis of the spread of the terraforming process
9	**The system shall depend on technologically-feasible technologies**	Computational analysis of the viability of different technologies in their necessary environments.

Table 8.2: Macro High-Level Requirements

8.3 Requirements Decomposition

We will use the systems engineering process to flow down the Macro High-Level Requirements from Table 8.2 to Detailed Requirements at the Macro level and subsequently to subsystem functional and performance requirements that can be imposed on subsystem design. Figure 8.3 provides a graphical description of the requirement decomposition process from macro high-level requirements to detailed system and subsystem requirements. The traceability of goals to requirements to systems and subsystems can be found in the Appendix.

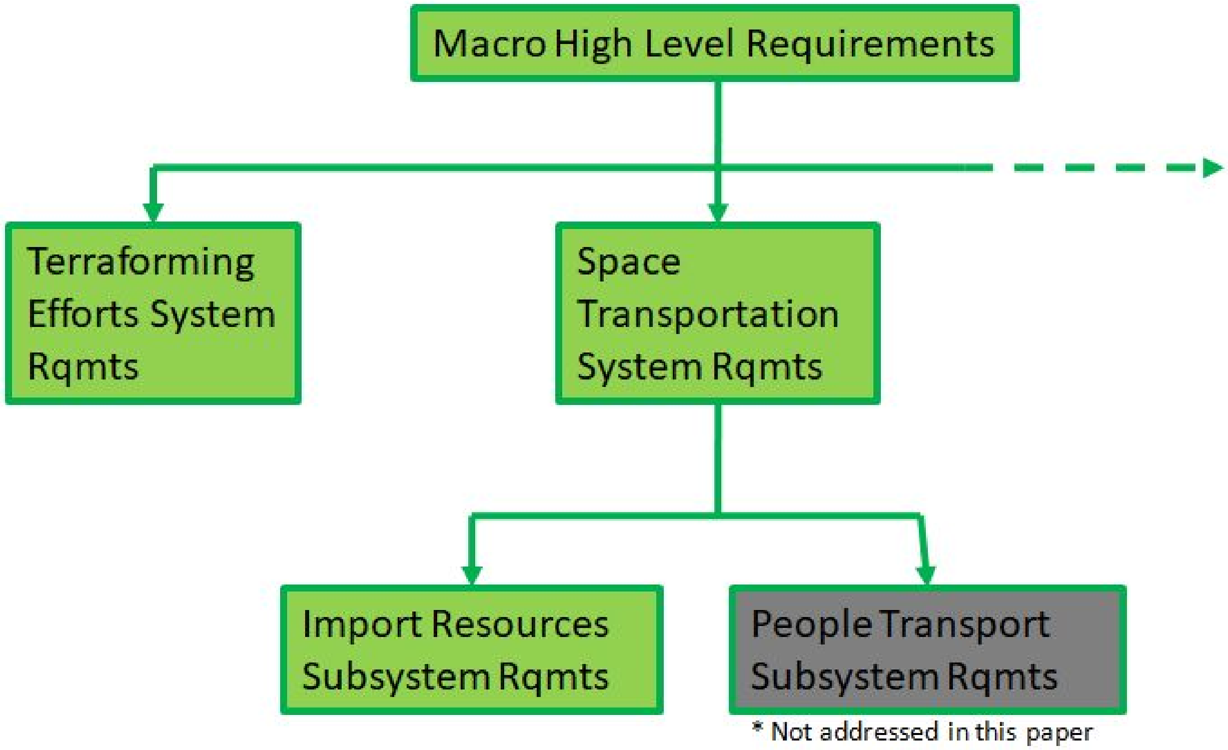

Figure 8.3 Requirement Decomposition Process

8.4 Macro High-Level Design

The following are the steps required for terraforming Mars given the findings found in Section 8

Functional High-Level Design

1. Deploy multiple missions to Mars
2. Instate long-term colonization of Mars
    a. Use bio-forming to help support the colony (develop crops)
3. Setup small domes on Mars
    a. Optimize methods for controlling temperatures/pressures
    b. Optimize methods for building/repairing domes
    c. Develop Bioforming for organisms within domes and outside on Mars
4. Develop larger domes and connect domes using tunnels
    a. May progress to World forming
5. Start the terraforming process
    a. Develop a long-term radiation protection mechanism
    b. Increase the temperature of Mars
    c. Import nitrogen, oxygen, water, and hydrogen to Mars from Venus, Titan, Jupiter and Asteroids
    d. Create a defense grid to shoot down meteors
    e. Ensure minimal destruction to para-terraforming process/Martian colonies throughout the terraforming process
    f. Continuously use computer modeling and weather sensors to analyze progress and

determine best steps to optimize the process
g. Use Bioforming to speed up and control the terraforming process

This leads to a functional allocation of needs and requirements to individual systems and subsystems. Based upon the aggregation of similar functions into separate systems, an overall macro-level, system-of-systems configuration is shown in Figure 8.3. This System View (SV-1) depicts the major systems and their interfaces.

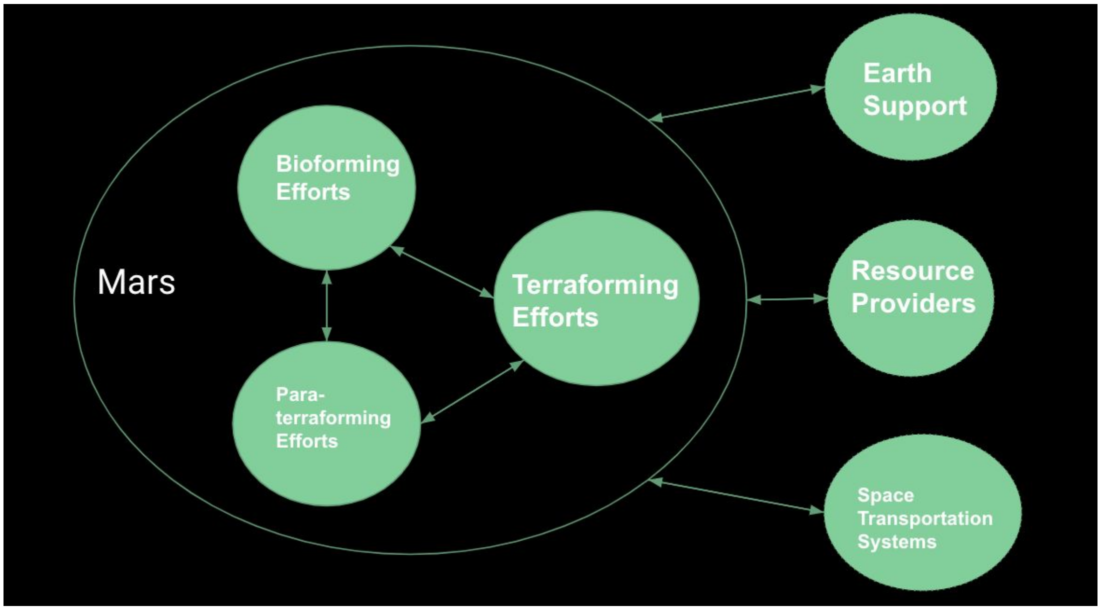

Figure 8.4: Macro Level System View (SV1 - Systems and their Interfaces)

9 Terraforming Efforts System - Detailed Requirements

Now that the system has been examined at a System Level, the project will then drill into the various subsystems that will support the main system.

It is not just enough to understand how would one terraform Mars in terms of a macro level. In this next section, we will examine some of the integral requirements that would need to be resolved in order to proceed with the terraforming process. The following is a list of some of the requirements one would encounter.

Detailed Requirements for Terraforming Mars

1. Increase the temperature on Mars to levels in which organisms can survive and thrive[64]
2. Reduce the cost of movement of materials to Mars to cost-effective levels
3. Increase the air pressure on Mars to human survivable conditions
4. Increase the atmospheric carbon dioxide levels on Mars to replicate Earth
5. Increase the atmospheric oxygen levels on Mars to replicate Earth
6. Increase the amount of water on Mars to replicate Earth conditions
7. Increase the Nitrogen levels on Mars to replicate Earth conditions
8. Shield Mars from atmospheric-damaging solar events and solar radiation as well as galactic cosmic rays to reduce radiation levels to those similar to Earth

9. Overcome or increase the effects of Mars' lower gravity
10. Remove perchlorates from the Martian soil to survivable conditions for Earth plants/animals[67]
11. Bioengineer plants and animals to survive the Martian atmosphere
12. Protect Mars from damaging comets and meteors that may interfere with terraforming efforts
13. Introduce methods of recycling elements such as carbon, oxygen, and nitrogen trapped deep under the Martian crust back to the atmosphere at a rate similar to Earth's
14. Overcome the lower amounts of sunlight Mars receives
15. Overcome the intense dust storms that blacken the Martian skies
16. Overcome the sheer length of time this may take
17. Overcome the sheer amount of energy a project like this may need

One of the more important problems listed is the need to raise the temperature of Mars. The list of relevant temperatures is listed below in Table 9.

Temp (°F)	**Temp(°C)**	**Temp(K)**	**Significance**
-290	-178.89	94.26	Average temperature on Titan[65]
-195	-126.11	147.04	Lowest surface temperature of Mars (near the poles during winter)
-193	-125.00	148.15	Temperature that carbon dioxide sublimes at Martian pressure
-80	-62.22	210.93	Average temperature of Mars
-40	-40.00	233.15	Lowest temperature trees can survive[66]
-4	-20.00	253.15	Lowest temperature at which simple life can live and grow
32	0.00	273.15	Temperature that ice melts at 1 atm (below this temp and pressure water cannot exist in liquid form)
41	5.00	278.15	Temperature of Earth treeline in winter
48	8.89	282.04	Temperature of Earth treeline in summer
58.3	14.61	287.76	Average temperature of Earth
68	20.00	293.15	Highest surface temperature of Mars (in the summer near the equator)
263	128.33	401.48	Temperature of Martian Exosphere
864	462.22	735.37	Average temperature on Venus[70]
2780	1526.67	1799.82	Temperature of Earth's Exosphere

Table 9: Significant Temperatures

The low temperatures on Mars could be resolved in a couple of different ways such as introducing a greenhouse effect by introducing chlorofluorocarbons, hydrocarbons, sulfur compounds, carbon dioxide or sulfur compounds[68]. There are a number of gases that could potentially induce a greenhouse effect at over 10,000 times the capabilities of the same amount of carbon dioxide on Earth[69], and we may be able to discover a similar gas that would work based upon the atmospheric properties of Mars. One could also heat up Mars through nuclear bombardment, using a giant mirror in space to direct light onto the surface of Mars, and by increasing the amount of light absorption on the surface of Mars through the albedo effect[71].

Another large requirement to resolve is the lack of a magnetosphere on Mars[72]. Mars currently has a magnetic field of only 1/10,000 that of Earth at 3.1 nT. This is because Mars lacks a large, liquid core rich

in metals to pair with its high rotation rate. Inhabitants on Mars would experience a much higher level of radiation than on Earth and any atmosphere created on Mars can be easily stripped away by solar wind. This problem can be resolved by using magnetic deflectors at the Martian L1 Lagrange point to deflect the solar wind away. This deflector needs to only be 1-2 Tesla in strength and would save the atmosphere from being stripped away from the vulnerable regions of the North Pole and the Equator[73]. Other methods of creating a protective radiation shield on Mars would be to create a series of planet-encircling superconducting rings[74], to have rings of solar-powered satellites generating magnetic fields or to dump millions of nukes into the center of Mars to respin the planet's core[75].

While each and every requirement listed above could prove disastrous to the terraforming effort if not resolved, the problem that may pose the most engineering difficulties would be the process of reducing the cost of importing enough gases to Mars to recreate Earth atmospheric conditions. Mars simply doesn't have enough gas to approximate the pressures of Earth. If one were to melt all of the frozen carbon dioxides at Mars' poles, it would only double the atmospheric pressure to 1.2% that of Earth's. If one were to also access all of the carbon dioxide trapped in the Martian soil, this would yield an atmospheric pressure only 4% that of Earth's. This would also be a destructive process involving strip mining that would deface much of Mars' surface[16]. There may be enough materials on the surface of Mars and within its atmosphere for small-scale para-terraforming processes, but there are nowhere enough resources for full-scale terraforming.

This lack of resources means that one would need to import gases from other parts of the Solar System. This would necessitate investment in different and new space importation technologies to even approach the 4 quadrillion metric tons of gas necessary to replicate Earth's atmosphere on Mars. A closer look at this subsystem of resource importing technologies will be explored in Section 11.

10 Space Transportation System

The space transportation system consists of 2 major subsystems; one to transport resources such as air, water, minerals, etc which is called the Importing Resources Subsystem and one to transport people and supplies which is called the People Transport Subsystem. Since the Importing Resources Subsystem is the primary priority in Terraforming, this paper will not address the latter subsystem.

11 Importing Resources Subsystem

This section will delve into one of the subsystems necessary for the terraforming process, which are the technologies necessary to power the spacecraft that could import many metric tons of material from faraway planets to Mars. It will examine the necessary atmospheric resources needed to recreate Earth's atmosphere on Mars, where those resources are located, and then use the System Engineering approach to evaluate the different technologies at one's disposal.

11.1 Resources Needed

Some of the more important gases necessary to recreate the Earth's atmosphere on Mars include nitrogen, water, hydrogen, oxygen, and carbon dioxide. Refer to Table 6.1 to determine how much of each resource is necessary to fully terraform Mars.

Here is a quick rundown of each of these resources:

Nitrogen comprises 78% of the atmosphere on Earth and is very important for plants growth. Atmospheric nitrogen is crucial for the nitrogen cycle, where plants fix nitrogen in their roots[76]. Nitrogen is also important in biology for the creation of amino acids and nucleic acids. Nitrogen is vital as a buffer gas in the atmosphere to dampen the ferocity of wildfires on Earth as it provides convection of air to cool flames. One would need 3 quadrillion tons of nitrogen on Mars to replicate Earth's atmosphere. The Martian atmosphere is 2% Nitrogen, which is a drop in the bucket to the amount of nitrogen needed since Mars' atmosphere is 0.6% that of Earth's. Nitrogen can be found on Venus, which has an atmospheric pressure of 92 atm, with 3.5% of its atmosphere comprised of nitrogen. Titan, one of Saturn's moons has an upper atmosphere of almost pure nitrogen.

Another crucial element that needs to be introduced into the Martian atmosphere is water. It is a molecule that is formed from Hydrogen and Oxygen. Water is vital for life and many different biological reactions. Mars has 5 million cubic kilometers of water in the form of ice, but most of it is hypersaline and would be fatal to most life on Earth. Water in the form of ice is very plentiful in comets.

Hydrogen is the most common element in the universe but is rare on rocky planets such as Mars and Earth since it easily escapes from the atmosphere when hit by ionizing rays. A large fraction of Hydrogen atoms may be moving fast enough to achieve escape velocity and thus leave the planet's atmosphere through Jean's Escape Mechanism. The escape velocity of Mars is 5,000 m/s. Jupiter contains a lot of hydrogen since it is a large gravity well. Hydrogen is a necessary element for the creation of water.

Oxygen is much more plentiful on rocky planets than Hydrogen, since it heavier and would not as easily achieve escape velocity. It often becomes sequestered to the ground as sand, limestone and iron ore, but can be extracted from the dirt using energy-intensive procedures[77]. It is important for the creation of water and for many biological processes.

Carbon dioxide currently comprises 96% of the Martian atmosphere. On Earth, plate tectonics and volcanism recycle carbon dioxide into the air from the crust, but this is a process that would need to be manually done on Mars. Researchers think that carbon dioxide pressures similar to Earth's total atmospheric pressure would be enough to raise temperatures to 273 K on Mars, at which ice would be able to melt. Venus is a good source for carbon dioxide.

11.2 Resource Locations

Once one understands the atmospheric resources necessary for the terraforming process, one has to then evaluate the locations that could be a good source for each resource. We will automatically discount Earth since it may kill Earth to harvest so many resources from it. It would be best to import from Venus, Jupiter, Comets and Titan, sources full of resources that are relatively close to Mars.

Resource Locations

- Titan (Saturn's moon)[78]
    - Has an upper atmosphere of almost pure nitrogen
    - Low gravity (14% of Earth's)
    - Thicker atmosphere
    - Escape velocity of 2638 m/s (23.5% earth)
- Venus

    - The atmospheric pressure is 92 times that of Earth
    - Mean surface temperature of 462℃ (863℉)
    - A good source for Nitrogen and Carbon Dioxide
    - There is an average distance of 120,000,000 km between Venus and Mars[17]
    - 0.902 g of Gravity
- Jupiter
    - Good source of Hydrogen (atmosphere comprised of 89% H_2)
    - Has a strong magnetic field and gravity well
        - 2.528 g of Gravity
        - 0.42 mT magnetic field (14 times as strong as Earth)[18]
    - The is an average distance of 550,390,000 km between Jupiter and Mars[17]
- Comets[79]
    - Good source of water in the form of ice
    - Very low gravity

11.3 Subsystem Needs

At the Importing Resources Subsystem Level, the key problem to be resolved is shown below. All of the alternatives and goals should be based on the most effective ways of meeting the mission objective.

Importing Resources Objective

Reduce the cost of the importing materials such as Nitrogen, Oxygen, Water, Hydrogen and Carbon Dioxide from Asteroids, Venus, Titan, Jupiter and Earth for the para-terraforming and terraforming efforts

11.3.1 Subsystem Goals for Importing Resources Subsystem

This is a list of goals that could be used to analyze the viability of different alternatives for importing resources to Mars from faraway planetary bodies for the purpose of creating an atmosphere that would benefit the terraforming process. These goals are subgoals that correlate to Goal #9 found in Section 5 and would relate to the subsystem focused on technologies that can import atmospheric resources.

1. Low cost at scale
2. Low capital costs
3. Low operational costs
4. Works in high gravity environments (Earth, Venus, Jupiter)
5. Works in low gravity environments (Titan, Mars, Moon, Asteroids)
6. Works in high atmosphere environments (Venus, Earth, Jupiter)
7. Works in low atmosphere environments (Mars, Moon, Asteroids)
8. Technological feasible as an Importation System
9. Low destruction if damaged

11.3.2 Detailed Requirements for Importing Resources Subsystem

Table 11.3.2 shows a small subset of the requirements necessary for the Importing Resources Subsystem of the Martian Terraforming efforts to be a success. Each requirement corresponds to its correlating

numbered Goal found in Section 11.3.1. These requirements are detailed requirements that flow from Main Requirement #9 in Section 8.2)

	Requirement	Verification Method
1	**The system shall have enough throughput to transport the amount of materials required to terraform Mars**	Computational projection of long-term cost-effectiveness
2	**The system shall have low enough capital costs to be economically viable**	Computational projection and demonstration testing
3	**The system shall have low enough operational costs to be economically viable**	Computational projection and demonstration testing
4	**The system shall work in high gravity environments such as Earth, Venus, and Jupiter**	Demonstration testing and computational modeling
5	**The system shall work in low gravity environments such as on Titan, Earth's moon, Mars and Asteroids/Comets**	Demonstration testing
6	**The system shall work on environments with high atmospheric pressures**	Computational projection
7	**The system shall work in environments with low atmospheric pressures**	Demonstration testing and computational modeling
8	**The system shall depend on technologically feasible technologies**	Computational modeling and demonstration testing
9	**The system shall cause minimal destruction if it were to be destroyed**	Computational modeling and demonstration testing

Table 11.3.2: Importing Resource System Requirements

11.3.3 Alternatives for the Importing Resources Subsystem

Section 11.3.3.1 through 11.3.3.8 describe the various concepts and technologies that are possible for use in satisfying the Import Resource Subsystem requirements.

11.3.3.1 Chemical Rockets

Most of our current space infrastructure is based on chemical rockets. This is the technology that we know best and it is what is most likely to be invested in moving forward. The problem with chemical rockets is that they are held back since all of its fuel is onboard the ship. This means that every chemical rocket must adhere to the Tsiolkovsky Rocket Equation[80]:

$$\Delta v = v_{exh} ln(\frac{M_0}{M_1})$$

Equation 11.3.3.1.1: Tsiolkovsky Rocket Equation

Δv: Change in Velocity

V_{exh}: Exhaust Velocity
M_0: Takeoff Mass
M_1: Final Mass

This means that in order for a chemical rocket to reach the high speeds needed for space travel found on Table 11.4.1.1, it needs to be using a type of fuel with an extraordinarily high v_{exh} or the majority of the rocket has to be fuel. Currently for every kilogram of ship and cargo one can get into orbit, you would need 20 kilograms of fuel. The relationship between exhaust velocity and specific impulse is shown on Equation 11.4.1.2. Since fuel is so heavy, many chemical rockets use multiple boosters that would be discarded once the fuel in the boosters would be used up after takeoff.

$$\frac{V_{exh}}{g} = I_{sp}$$

Equation 11.3.3.1.2

g= gravity the ship is traveling through

I_{sp}= Specific Impulse (the number that determines the efficiency of a rocket fuel)

This is an extraordinarily expensive method of space transport. The space shuttle program averaged $1.5 billion/launch. Since it had a shuttle payload of 30,000 kg, the cost per kg to get a payload into orbit was about $50,000. This cost can be lowered by reusing boosters or the rocket itself. The Falcon 9 rocket produced by SpaceX is a two-stage rocket with its first stage being recoverable. It has a cost of $60 million/launch, and it costs $5,700 to get a kilogram of payload into Low Earth Orbit with this technology[81]. One could also take advantage of the square-cube law in order to carry more fuel relative to the size of the fuel tank for the ship. This means that if one doubled the size of the fuel tank, the surface area increases by four times and the volume increases by eight times. Therefore, if one could use the same tank thickness, one could cut down on the cost per kilogram of payload for the rocket by creating larger and larger rockets.

Delta-V(m/s)	**Destination (from Earth)**
7900	LEO
13,100	Mars
16,000	Within the Solar System
40,000	Escape the Solar System

Table 11.3.3.1.1: Delta-V Needed for Space Travel

Fuel Type	**Specific Impulse (s)**[82]
LH2/O2	451
RP-1	353
Ethanol	338
Methalox	330
Li/F/H mix	542
Metallic Hydrogen	1700

Nuclear Pulse	6000

Table 11.3.3.1.2: Specific Impulse by Fuel Type

Delta V	I_{sp} (50% fuel)	I_{sp} (90%fuel)	I_{sp} (10% fuel)
1000	14138.4114	4256.085923	93013.97149
2000	28276.8228	8512.171845	186027.943
3000	42415.2342	12768.25777	279041.9145
4000	56553.6456	17024.34369	372055.886
5000	70692.057	21280.42961	465069.8575
6000	84830.4684	25536.51554	558083.829
7000	98968.8798	29792.60146	651097.8005
8000	113107.2912	34048.68738	744111.772
9000	127245.7026	38304.7733	837125.7434
10000	141384.114	42560.85923	930139.7149
11000	155522.5254	46816.94515	1023153.686
12000	169660.9368	51073.03107	1116167.658
13000	183799.3482	55329.11699	1209181.629
14000	197937.7596	59585.20292	1302195.601
15000	212076.171	63841.28884	1395209.572
16000	226214.5824	68097.37476	1488223.544

Table 11.3.3.1.3: I_{sp} of Fuel Needed for Single-Stage Rocket by Delta-V

Despite all of these methods of cutting down on the inefficiencies of chemical rockets (reusability, boosters, larger fuel tanks), chemicals simply do not have enough Specific Impulse (I_{sp}), to be a viable method for importing enough materials to terraform Mars. If one examines Table 11.4.1.3 (a chart derived using the Tsiolkovsky Rocket Equation), it can be determined that with enough speed to reach Mars from Earth (a change in velocity of 13,100 m/s) a rocket without any boosters that started out with 90% of its mass comprised of fuel would need to have a specific impulse of close to 55,000 seconds. This is much more than the specific impulse of most common rocket fuels such as LH_2/O_2 or Methalox, which have a specific impulse between 300-500 seconds. There is a new theoretical fuel called metallic hydrogen that has a specific impulse of 1700 seconds that may be found under Jupiter or Saturn and could be a room temperature superconductor[6]. This number of 1700 seconds still pales in comparison to the specific impulse of 55,000 seconds or better that would be beneficial for the terraforming process.

11.3.3.2 Nuclear Rockets

Another technology to consider that may help with importing vast amounts of resources to Mars is nuclear rockets. This is powered by fission reactions, which are typically a million times greater than the chemical energies of chemical rockets. Fission reactions are typically tricky to use for thrust and are based upon the unstableness of different elements and isotopes and their propensity to decay. For instance, a neutron may collide with Uranium-235 to cause a split into Barium, Krypton and 3 more neutrons that could then collide into more Uranium-235 atoms for a chain reaction.

Americans and Soviets have already experimented with nuclear rockets. Project Rover was an American Project that used nuclear power to heat up liquid hydrogen (LH_2) propellant that was then spewed out the back of the rocket. This was a solid-core nuclear thermal rocket with a specific impulse of 1000 seconds. This project was discontinued because of the major safety concern that if the rocket were to blow up, radioactive materials would be spewed throughout the atmosphere[83]. Table 11.4.2 shows the specific impulse of different types of nuclear rockets.

Fuel Type	Specific Impulse (s)
Solid-core NTR	1000
Open-Cycle Gas-Core NTR	5000
Closed-Cycle Gas-Core NTR	2000
Nuclear Pulse	6000

Table 11.3.3.2: Specific Impulse of Different Nuclear Rockets

Since the propellant of a nuclear rocket is contained on the rocket itself upon launch, nuclear rockets must still adhere to the Tsiolkovsky Rocket Equation (Equation 11.4.1.1). Although the specific impulse of different types of nuclear rockets is significantly greater than that of chemical rockets, it still doesn't approach the 55,000 second number necessary to be beneficial for the terraforming process.

The weight of the fission reactor is also a concern since they need to have a weight to thrust ratio of better than 1:1 in order to lift from the ground. This is less of a concern when rockets are already in space and are in low-gravity environments. It may be difficult to find fissionable materials (Uranium, Plutonium, Polonium) for the Nuclear Rockets at the scale necessary to move an atmosphere's worth of materials from one planet to another.

Nuclear rockets may be most beneficial when used for asteroid mining since they could be attached to asteroids or comets to move the entirety of it to a different orbital path. Radiation and disposal concerns are minimal on asteroids in comparison to inhabited areas of Earth and there are no gravity wells to fight. Very little of the mass of nuclear rockets would be fission fuel, so the fuel would be relatively easy to ship to asteroid miners.

Overall, nuclear rockets are cheaper than chemical rockets and an order of magnitude more powerful than chemical rockets. They are not nearly powerful enough to be the primary means of transportation of resources from large planetary bodies and deep gravity wells, but they may be useful with asteroid mining, where there are little gravity and even less safety or regulatory concerns.

11.3.3.3 Space Elevators

Space Elevators are a theoretical concept that was first developed by Konstantin Tsiolkovsky in 1895.[4] It involves building an elevator stretching from the surface of Earth to Geostationary Orbit (36,000 kilometers away). Since one's orbital speed declines with the inverse square root as one travels away from Earth's surface, an object at the end of a Geostationary Orbit-high tether would be moving at the same velocity as an orbiting object at the same height. Since the center of mass of a space elevator needs to be 36,000 kilometers from Earth's surface, an equal amount of mass needs to beyond the geostationary point. This could entail building a space elevator up to 53,000 kilometers long, where the speed of an object at

the end of the space elevator is moving 2 km/s faster than an orbiting object. This would allow an object to gain 2 km/s of speed for interplanetary travel.

While an interesting theory, space elevators are not a practical concept. This is since there is no material strong enough to handle the stresses a space elevators will undergo. One would need a material with a breaking length of over 36,000 kilometers. The closest substance found is carbon nanotubes (shown in Table 11.4.3) and its breaking length of 5000 kilometers pales in comparison. One way to increase the tensile strength of a material is through tapering and to have the part carrying more weight (the top of the space elevator) thicker than the part that is carrying less weight (the bottom of the space elevator). P.K. Aravind has shown that any material with a high enough taper ratio could be used to build a space elevator. Carbon nanotubes would need a taper ratio of 1.6 (where the top would be 26% wider than at the bottom). Kevlar would need a taper ratio of 250,000,000.

Material	Breaking Length (km)
Carbon Nanotube	5000
Zylon	384
Kevlar	256

Table 11.3.3.3: Breaking Length of Different Materials

We currently aren't able to create large enough amounts of carbon nanotubes, so the viability of space elevators remain elusive. The construction process of a space elevator would also be difficult, since one would need to figure out a method of joining tether sections together while maintaining a strong tensile strength. The terminus of the space elevator would also need to be built above the Equator, but one could have multiple space elevators linking up to the same terminus (with some of the space elevators originating from below the equator and some of the space elevators originating above the equator to allow the terminus to be placed above the equator).

There may be concerns with the space elevator breaking or from someone falling off the space elevator. There is also a high cost to the construction of the space elevator, with costs ranging between $6-120 billion. The main benefit of a space elevator is that it would severely reduce the cost of moving a kilogram of material into space from over $50,000 to around $100.

Although space elevators would be beneficial in allowing a high throughput of materials to reach outer space from a planetary body with a large gravity well, it is impractical for use on Earth since there simply is no material with a high enough tensile strength to stretch over 36,000 km. Space elevators are an interesting concept, but shouldn't necessarily be pursued for the purposes of creating space infrastructure on the scale that would allow Mars to be terraformed.

11.3.3.4 Skyhooks

Another method for importing resources into orbit and beyond from large planetary bodies are skyhooks. This is a concept that is similar to a space elevator, except it is not tethered to Earth and is not 36,000 km in length. Instead, a skyhook is orbiting Earth and can be any length from a couple hundred kilometers long to a couple thousand kilometers long. The concept of a space hook is that it has two ends, with one end orbiting Earth closer than the other. The closer end would typically move with a higher orbital

velocity than the far end, but if they were connected, this would cause the closer end to move slower (at slower than orbital velocities) and the far end to move faster (at faster than orbital velocities).

For example, if the end closer to the Earth's surface were 100 km away from earth it would naturally orbit at a speed of 7800 m/s. If the far end of the skyhook were 4000 km away from Earth it would naturally orbit a speed of 6100 m/s. If both ends were connected, the entire system could potentially orbit at a speed of 6800 m/s. This means that a spacecraft wanting to achieve orbital velocities could simply move at lower than orbital velocity to attach to the bottom of the skyhook and then travel up the skyhook to the top and exit at higher than orbital velocities.

The skyhook transfers its momentum to each spacecraft that may tether to it, so it needs a method of restoring its momentum after every lift. This could be done using chemical rockets or nuclear rockets. Another method to consider is electrodynamic tethering which could occur if the tether was comprised of a conductive substance with a large electrical potential between the top and bottom of the tether. This moving electric charge traveling through the Earth's magnetic field could use the Lorentz force to push on the tether, allowing it to restore its momentum.

The smaller size of the skyhook means that one doesn't have to invent new substances with a previously unheard of tensile strength. Instead, we could build skyhooks at a size that our current day materials and the usage of tapering would allow. One major difficulty would be how a spacecraft could attach to the bottom of the skyhook successfully without major risk of failure. This difficulty would need to be resolved if skyhooks were to be implemented.

Skyhooks are a potentially viable concept that could be used in conjunction with a number of different technologies, including chemical/nuclear rockets and mass drivers and orbital rings. It is a technology that has been conceptually explored by large aerospace companies, with Boeing's HASTOL project an architectural study of the viability of skyhooks. In the HASTOL prototype a hypersonic airplane would attach its payload to the bottom of the skyhook[5]. It is a promising technology since it is not beholden to the Tsiolkovsky Rocket Equation, and may be a stepping stone to more advanced technologies such as the rotovator.

11.3.3.5 Rotovators

A rotovator is basically a rotating skyhook[84]. It is where a skyhook is spun backwards, where its tip drops to the bottom of its spin. If one were to have a skyhook that with a close end at 100 km from Earth and a far end at 4000 km from Earth and to have it spin backwards three times every time it orbited Earth, the tether tip at the bottom of its spin would move at the speed of a normal car. The tip at the top of its rotating spin would be moving at 11,000 m/s, which is close to the 13,100 m/s necessary to reach Mars. The high levels of acceleration makes rotovators impractical for human transport, but this is a technology that could be used for flinging cargo such as atmospheric gases inside a can from planet to planet.

A rotovator cannot spin too fast, since centrifugal forces may rip it apart, but it works great in places with little atmosphere and weak gravity (Mars or Earth's moon). It is impractical on gas giants. It may also be very vulnerable to space debris. It would not be practical to clutter an atmosphere with too many rotovators as they may be difficult to avoid for space navigation.

A rotovator may cost in the millions of dollars to manufacture and in the hundreds of millions of dollars to launch, but would more than pay for itself within a couple of launches. It would be an important tool for transporting resources to Mars for terraforming efforts, but wouldn't necessarily be practical for use on the main gas importation locations of Venus, Jupiter and Titan.

11.3.3.6 Mass Drivers

One can think of a mass driver as a giant cannon.[87] It involves accelerating either people or resources down a long barrel at high speeds. The tunnel may be airtight, but this is not necessary as it may entail a high expense. One would not be beholden to the Tsiolkovsky Rocket Equation (Equation 11.3.3.1.1) as one could use electromagnetics on a track running along the length of the tunnel to provide an even and constant acceleration. Cargo would be able to handle even higher levels of acceleration than people. The final velocity of a spacecraft at the end of the tunnel is shown below in Equation 11.3.3.6.

$$v = \sqrt{2ad}$$

Equation 11.3.3.6
v=final velocity
a=constant acceleration
d=length of track

Table 11.3.3.6 shows different track length depending on differing accelerations and a final velocity of either Earth's orbital velocity (7800 m/s) or the velocity necessary to transfer from the surface of Earth to the surface of Mars (13,100 m/s)

Final Velocity (m/s)	**Acceleration (g)**	**Length of Track (km)**
7800	1	3104
7800	2	1552
7800	4	776
7800	10	310
7800	20	155
13100	1	8756
13100	2	4378
13100	4	2189
13100	10	876
13100	20	438

Table 11.3.3.6: Mass Driver Track Lengths

One would want the exit end of the mass driver to be high up so that it would encounter lower air density. If the exit end were placed 50 km up, the density of air would be 0.1% that of sea level. If it were placed 100 km up, the air density would be 0.0001% that of sea level. A mass driver would need lots of power and the entirety of the structure would be very heavy.

A mass driver would be easier to build in places with lower gravity and lower atmosphere. In places with no atmosphere such as the Moon and Mars it wouldn't be necessary to lift the gun above the atmosphere and it could simply be a train track. In places with an atmosphere such as Titan or Venus, it could be perfect for shipping massive amounts of gases in metal airtight containers for Martian terraforming purposes. A mass driver could be placed on floating balloons when in the thick Venusian atmosphere. If mass drivers could be kept aloft in the upper atmosphere of gas giants, it could also be used on Jupiter for shipping hydrogen to Mars.

Mass drivers may be susceptible to terrorist attack, so there were would need to be contingency plans in case damage were to occur.

A mass driver can be considered an elevated version of the hyperloop, which is estimated to cost $6 billion. Any mass driver would cost more than this amount. StarTram has proposed a number of different mass driver concepts with Generation 1 costing $19 billion, containing unmanned pods travelling at 30 g's down a 130 km long tunnel and exiting at the top of a mountain peak. StarTram's Generation 2 design is estimated to cost $67 billion and is built to handle passengers and would comprise of a 1000 km long tunnel providing 3 g's of acceleration and exiting at 22 km of altitude. StarTram's Generation 1 and Generation 2 designs are estimated to cost about $100 to move a kilogram of resource into space (a higher potential cost than the space elevator).

StarTram also has a Generation 1.5 design that is used in conjunction with a skyhook and could thus have a lower exit speed. This design has a 270 km long track length and it is designed for a hypersonic plane to exit from the top of a mountain and link up with a skyhook[86]

Mass drivers may provide the bulk of atmospheric air transport from Venus and Titan to the Martian terraforming efforts due to its ability to bypass the Tsiolkovsky Rocket Equation and its capabilities for bulk transport of materials from areas of high and low atmospheric pressure levels as well as low gravity levels.

11.3.3.7 Launch Loop

Launch Loops (also known as Lofstrom Loops) were a concept proposed by Keith Lofstrom in 2001.[8] He proposed creating a 2000 km long runway suspended 80 km in the air. This would allow a vehicle to accelerate at 3g in order to reach orbital velocity. This runway would use active support in order to hold it aloft. A hollow cylinder called a rotor would have an stream of ions running back and forth down an ion cylinder. Magnetics would push the stream of ions from the sides of the cylinder to allow for frictionless movement. Any launch vehicle travelling down the launch loop would obtain its momentum from the rotor and would thus have an external source of power as well as something to push off of, so it wouldn't have to adhere to the Tsiolkovsky Rocket equation.

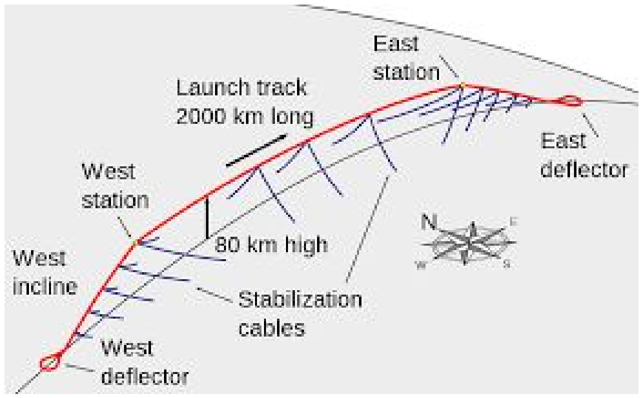

Figure 11.4.7: The Launch Loop[9]

The use of active support to raise the loop would not be particularly necessary on the Moon or on Mars since there would be no need to lift the loop above an atmosphere. It would find usefulness in places with high levels of atmosphere and gravity (Venus, Earth and Jupiter). Lower portions of the launch loop on Venus or a gas giant could be lifted by normal air, whereas the higher part could be lifted by active support.

Lofstrom calculated that the construction costs of a launch loop would be $2 billion and that it would cost only $3 to get a kilogram of material into space (a rate that surpasses that of the space elevator). There are a couple of safety concerns addressed by Lofton such as the explosive capacity of the rotor if it were to be damaged since it is carrying a lot of energy and the destructive power of the track if it were to fall on things. These concerns are addressed in Section 12.2 of the Risk section.

The launch loop is a technology that could provide the bulk of the transport of atmospheric materials along with the mass driver. It would be slightly useful in places with large gravity wells such as Jupiter or Saturn. It can also be used in conjunction with other orbital launch systems such as skyhooks and orbital rings.

11.3.3.8 Orbital Rings

The final type of potential space transportation infrastructure this paper will examine is the orbital ring. This is simply a hoop of copper encircling a planet that is traveling at orbital speeds. The entirety of the hoop is on the same orbital path, so anything on the hoop wouldn't move compared to something else on a different part of the hoop. The hoop would float since the centrifugal force of its orbital velocity would cancel out gravity. One could then place a stationary outer shell around the fast moving hoop of copper. This outer shell would be repelled from the inner hoop by electromagnetism. The entire system could counter the extra weight of the outer shell by having the inner copper hoop spin at faster than orbital speeds. This extra centrifugal force would cancel out the extra weight and allow the system to stay in place[87].

With this system, one could build up speed by accelerating a spacecraft along the ring. One can place an orbital ring at any distance from the planet, with orbital rings further away from Earth encountering less centrifugal force due to the higher turning radius as well as less gravitational force due to being further away from the planetary body's gravity. If a spacecraft were to travel around an orbital ring placed in Earth's geostationary orbit at 1g of constant acceleration, it could reach a change of velocity of 20,000

m/s, which is significantly more than the change in velocity necessary to travel from the surface of Earth to the surface of Mars. If one were to travel on that same orbital ring at 4g of acceleration, it could reach a change in velocity of 40,000 m/s, which is the escape velocity from the solar system.

One could build as many rings as necessary at any distance from the planetary body it is encircling. One could also scale up the size of a ring to be a kilometer or more wide. One could reach an orbital ring using the other space launch technologies mentioned in this paper, or one could drop a cable down to Earth that a craft could grab onto and then use to pull itself up to the ring.

The orbital ring could potentially be the best space infrastructure technology for providing cheap, bulk transport of people and goods between planets. It could provide the cheapest cost per kilogram launched, but may have highest construction costs. The orbital ring would be made out of copper and may weigh more than 100 megatonnes, if it is a meter or more thick and massed a couple of tons per meter of length. An orbital ring may cost just as much as a space elevator to construct (if not an order of magnitude more), but would rely on known technologies and materials. It could lower the cost of throughput of material to space to levels below that of the space elevator or the launch loop.

The orbital ring is the space launch technology the Mars terraforming efforts would eventually build up to. It should be constructed wherever there is mass transport of materials. It would initially be constructed on Earth and on Mars (for shipping and receiving materials and people), but could also be constructed around Venus, Titan, Jupiter and other sources of atmospheric material to outclass the services provided by chemical rockets, nuclear rockets, space elevators, skyhooks, rotovators, mass drivers and launch loops.

11.3.4 Importing Resources Trade Study

The eight different methods of transporting resources through space to support the Martian terraforming efforts were analyzed through a trade study. They were reviewed against the nine goals listed in Section 11.3.1. A score was assigned on a scale of 1 to 10, with 1 meaning it least adhered to a goal and 10 meaning it best adhered to a goal. This trade study was conducted using research found in Isaac Arthur's publications. Most of the technologies may be used in the final solution, but this trade study can be used to determine the best locations/environments each solution can be used for.

	Chemical Rockets	**Nuclear Rockets**	**Space Elevator**	**Skyhook**	**Rotovator**	**Mass Driver**	**Launch Loop**	**Orbital Ring**
Cost/kg	1	2	9	3	6	9	6	10
Capital Cost	10	7	2	4	6	4	5	1
Operating Cost	10	5	1	4	6	3	3	1
High Gravity	1	3	2	3	3	8	9	10
Low Gravity	2	9	5	8	7	8	9	10
High Atmosphere	1	3	5	4	3	8	7	10
Low Atmosphere	2	8	5	8	7	8	7	10
Technological Feas.	10	8	2	9	3	7	6	1
Destruction Impact	10	9	2	7	9	5	8	1
Total	**47**	**54**	**33**	**50**	**50**	**60**	**60**	**54**

Table 11.3.4: Importing Resources Trade Study

11.3.5 Findings

The findings from the trade study are listed below. This was then used to derive the Concept of Operations, Requirements and Design for the Importing Resources subsystem.

List of Findings

- Currently chemical rockets are the best technology to pursue, but skyhooks are the next technology to invest in
- Skyhooks/Rotovators should be combined with other technologies
- Set up nuclear rockets to help retrieve resources on no atmosphere/no gravity environments
- Mass Drivers are best to be set up on high atmosphere/high gravity environments
- Launch Loops are best to be set up on the low atmosphere/low gravity environments as well as on gas giants such as Jupiter
- Space Elevator option should be ignored
- Orbital rings are the furthest from being technologically feasible, but would be the most helpful technology (good end goal)

11.3.6 Importing Resources Subsystem Design

Steps for the Importing Resources Design

1. Demonstrate effectiveness of different technologies on Earth
2. Set up skyhooks/rotovators on Earth, Moon and Mars
3. Set up nuclear rockets to help retrieve resources found on comets and asteroids
4. Set up Mass drivers on Venus and Titan
    a. Mass drivers on Venus will be floating using buoyant gases
    b. Metal pods full of megatonnes of gases will be shot towards Mars
    c. Mass Driver technology will be supplemented with skyhooks
5. Set up Launch loops on the Moon and on Jupiter
    a. Launch loops on Jupiter will be supported through the means of active support and buoyant materials.
6. Set up Orbital Rings on Earth and on Mars for sending and receiving materials
7. Send atmospheric resources to Mars from Venus, Titan, Jupiter and asteroids/comets

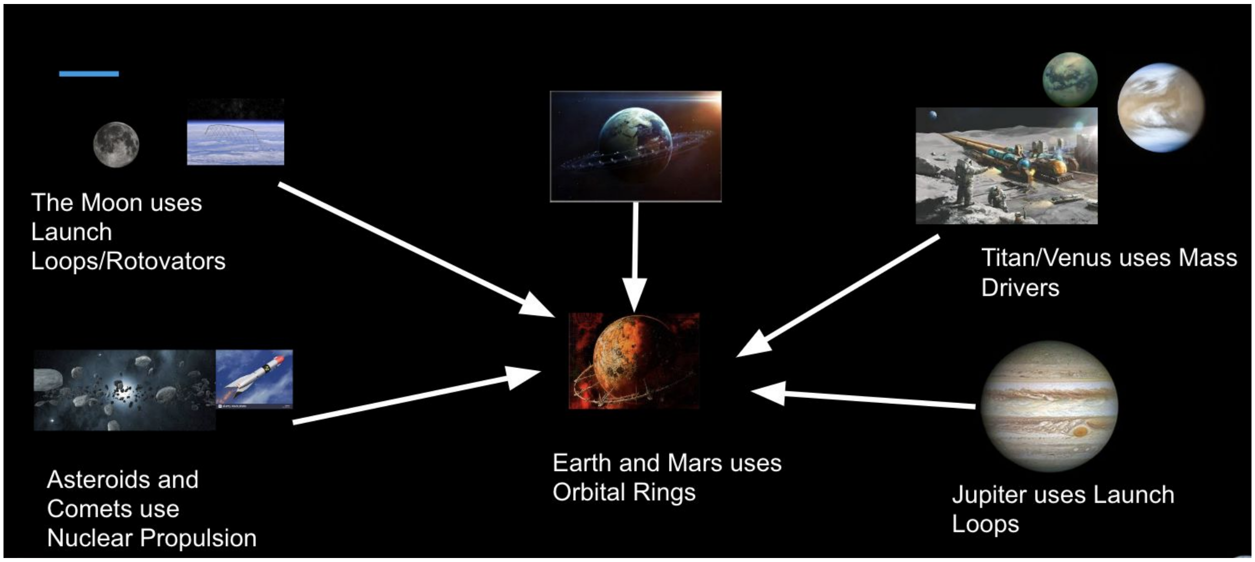

Figure 11.3.6: Importing Resources concept

Figure 11.3.6 shows a possible concept for using the different alternatives for importing resources that will support the overall Martian terraforming project. This is under the assumption that seven of the eight space transport technologies are viable for the project (the lone exception being the Space Elevator, since it necessitates special materials for construction). This subproject will use a variety of different transport mechanisms depending on the conditions of the planetary body it is located. Low gravity and low atmosphere places such as the Moon and Mars would use launch loops. Places with atmospheres and medium gravity would use Mass Drivers. There aren't many technologies that would work well on gas giants such as Jupiter, but the initial attempt of transporting hydrogen from Jupiter could be supplemented by launch loops. Asteroids and Comets could direct their resources towards Mars with the help of Nuclear Rockets. Places with the highest amount of space throughput would have Orbital Rings (with this space infrastructure being initially built on Earth, next Mars and then finally around any planetary body where an orbital ring makes economic sense.

12 Risks

This section will delve into the risks encountered by the Terraforming Mars project (Section 12.1) as well as its subsystem for importing resources (Section 12.2)

12.1 Macro Level Risks

Four risks that may influence the terraforming process are listed below in Table 12.1. They were also evaluated on a scale of 1-5 on Probability and Impact, with 1 being very low and 5 being very high. The Total score for each risk was found by multiplying Probability times Impact. Theses risks were then plotted on a Risk Matrix (Figure 12.1.1). This Risk Matrix shows that most of the risks have high probability and impact and there need to be some steps towards risk mitigation.

Risk Description	Probability	Impact	Total
A: May be too Costly to Proceed	5	5	25
B: Native Martians may not want to completely terraform	4	5	20
C: Technology may be infeasible	3	4	12
D: Terraforming may destroy Mars	4	4	16

Table 12.1: Macro-Level Risks

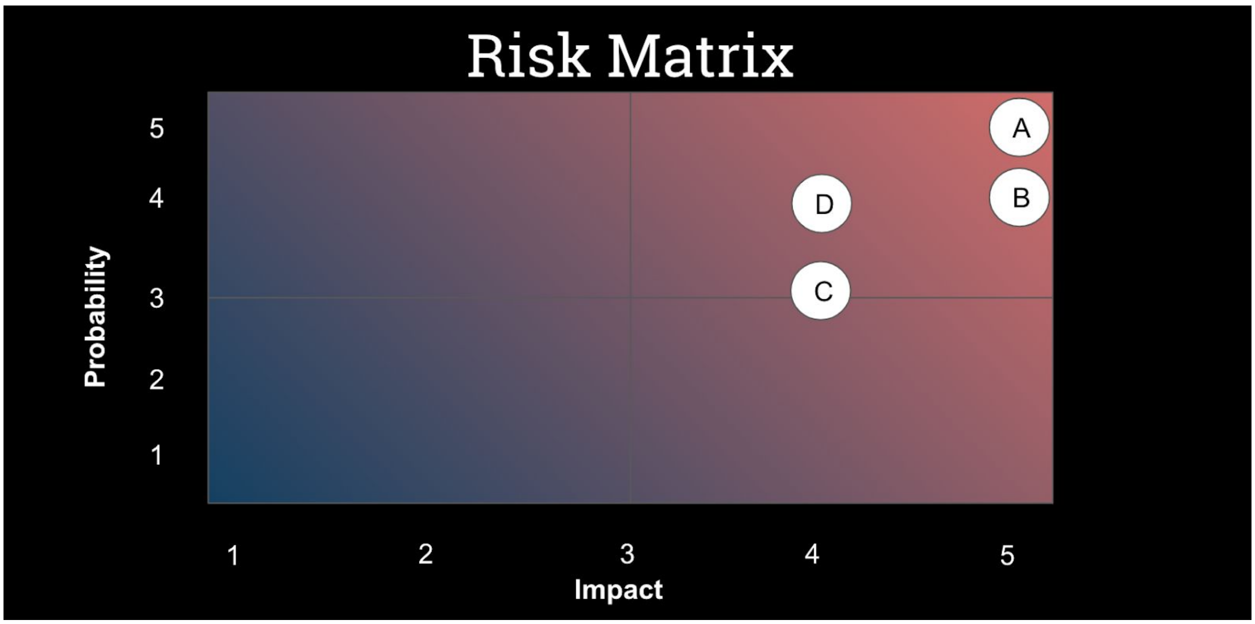

Figure 12.1.1 Risk Matrix Before

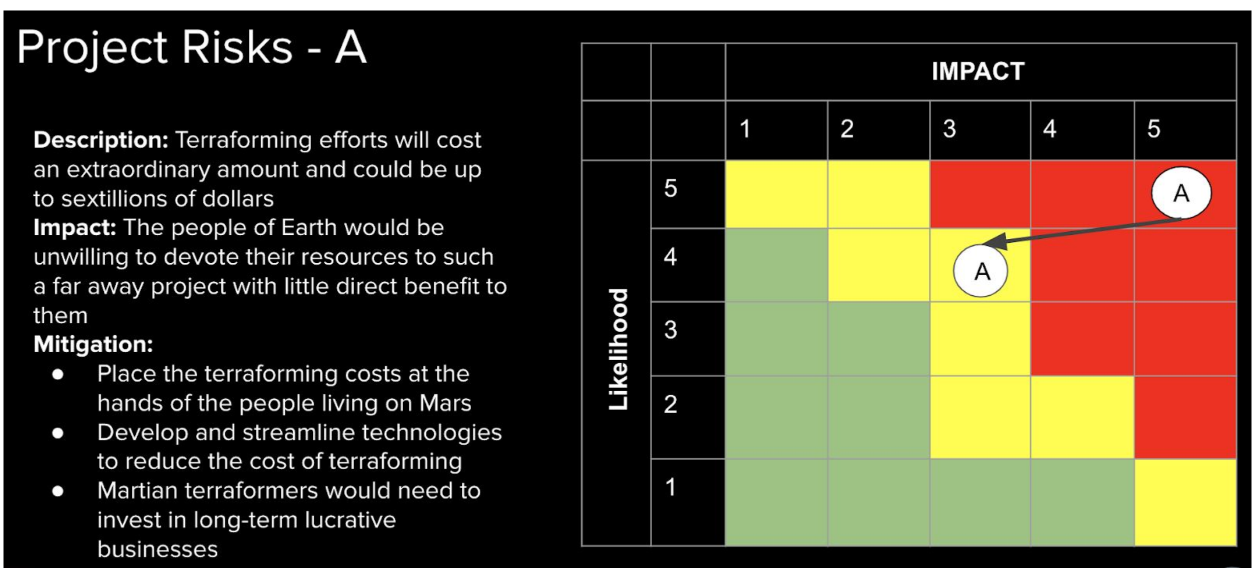

Figure 12.1.2: Project Risk A (High Costs)

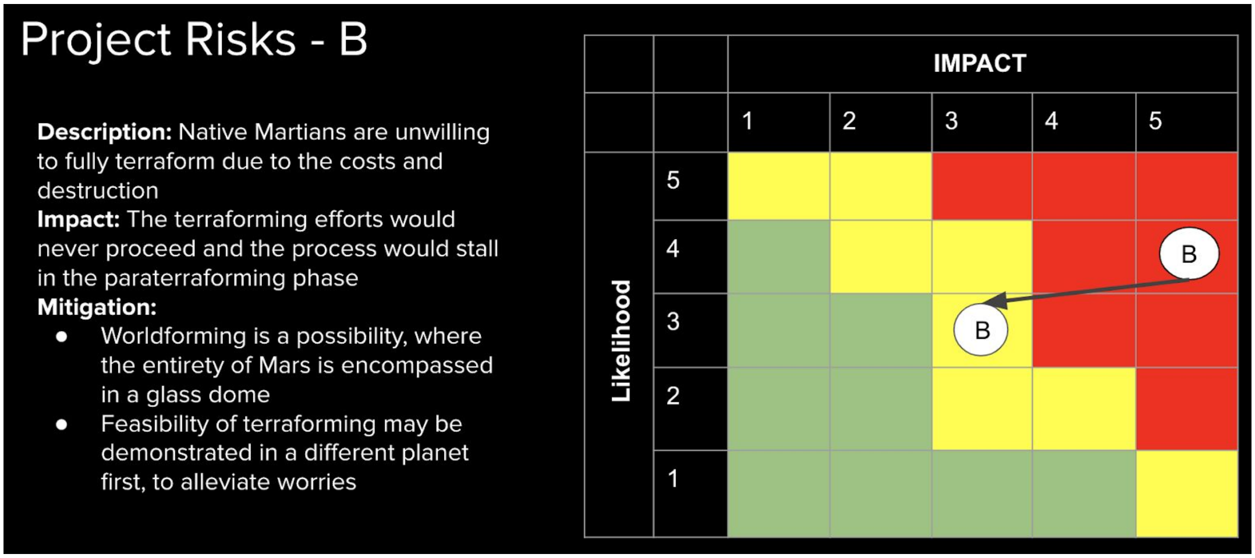

Figure 12.1.3: Project Risk B (Native Martian Doubt)

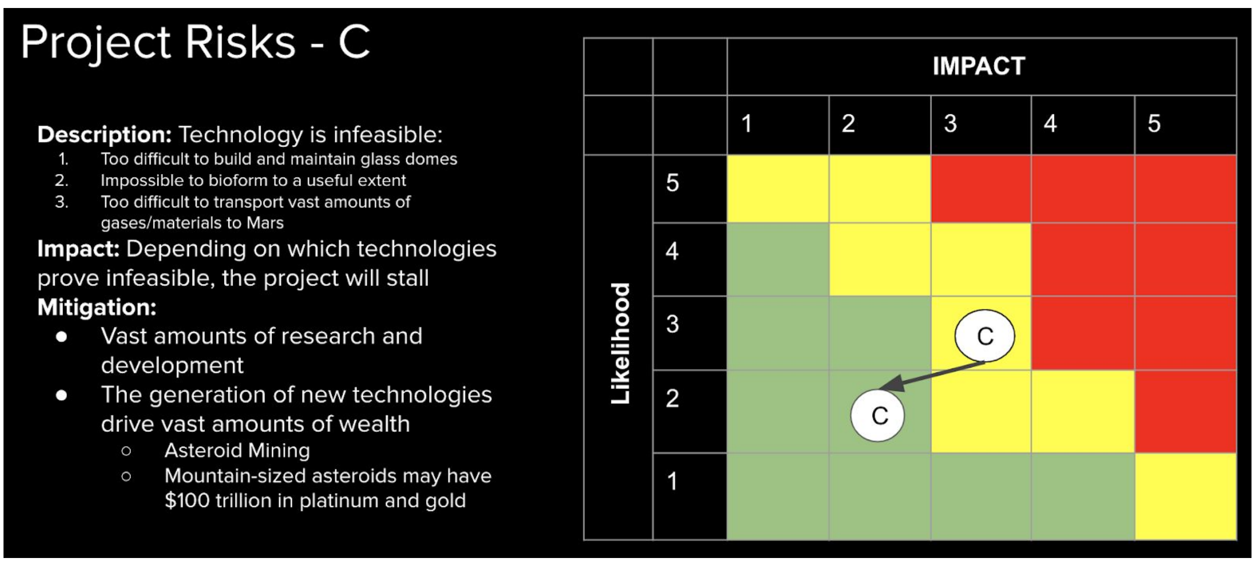

Figure 12.1.4: Project Risk C (Infeasible Technology)

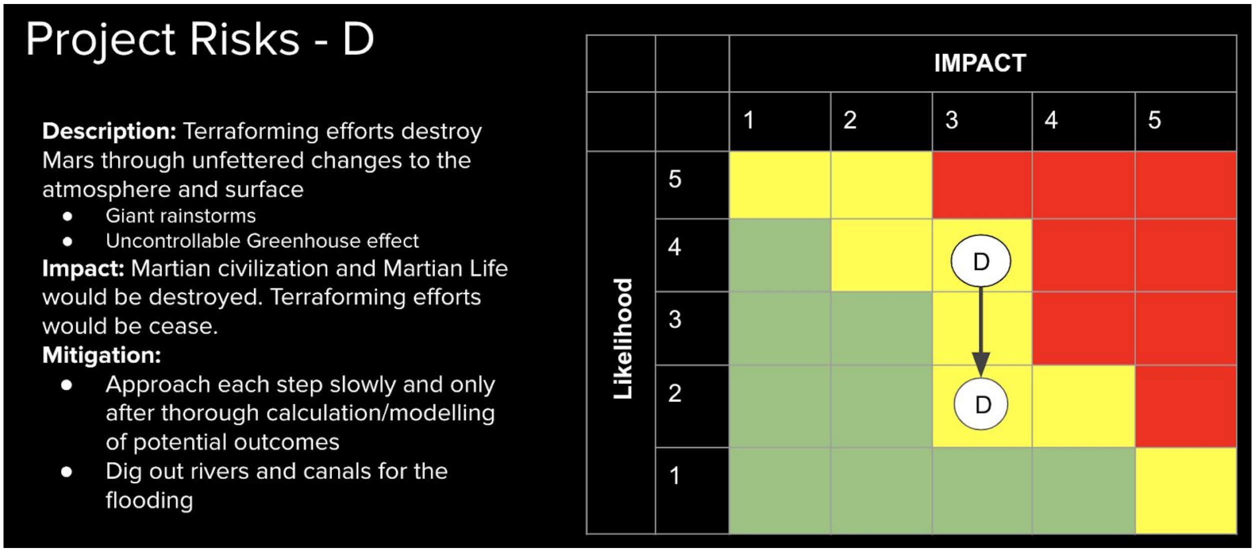

Figure 12.1.5: Project Risk D (Destruction of Mars)

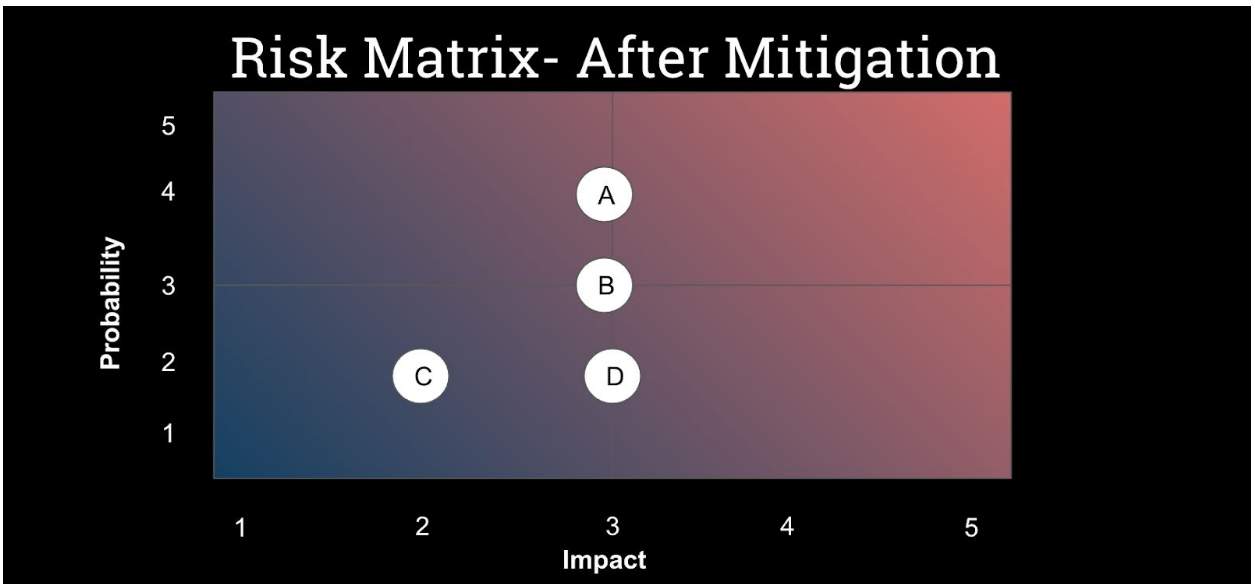

Figure 12.1.6: Risk Matrix After Mitigation

12.2 Importing Resources Subsystem Risks

Three risks that may influence the Importing Resources Subsystem are listed below in Table 12.2. They were also evaluated on a scale of 1-5 on Probability and Impact, with 1 being very low and 5 being very. The Total score is for each risk was found by multiplying Probability times Impact. Theses risks were then plotted on a Risk Matrix (Figure 12.2.1). This Risk Matrix shows that most of the risks have high probability and impact and there need to be some steps towards risk mitigation.

Risk Description	Probability	Impact	Total
A: Cost may be too high	5	5	25
B: May have damage cost by destruction	4	4	16
C: Throughput may be too low	4	5	20

Table 12.2 Importing Resources Risks

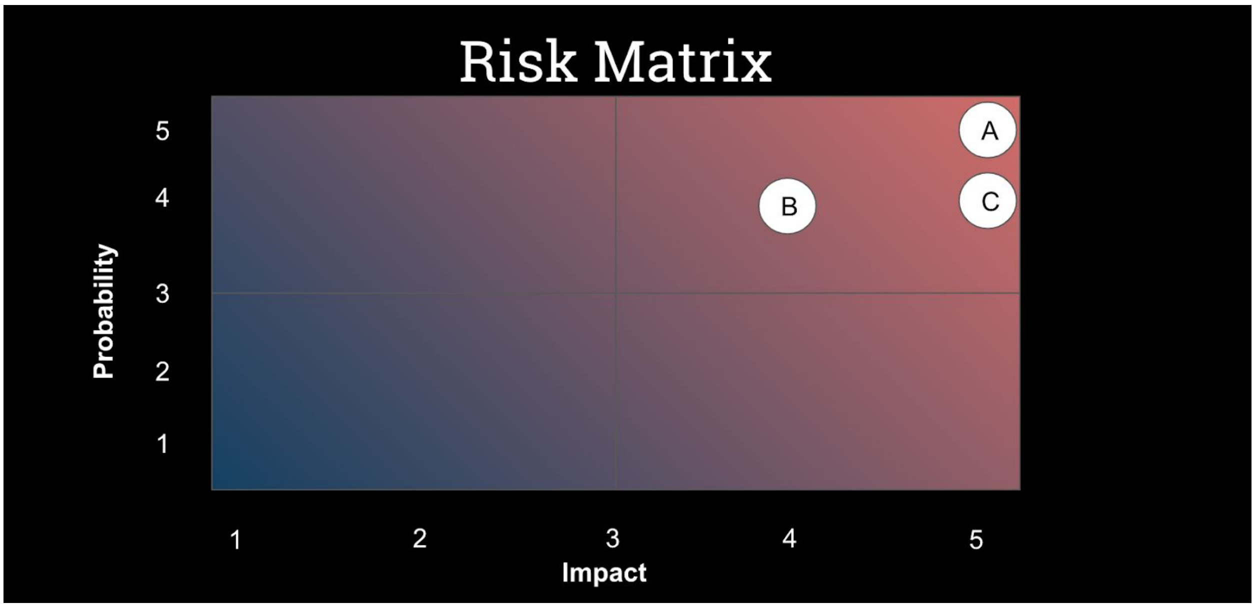

Figure 12.2.1: Importing Resources Subsystem Risk Matrix Before

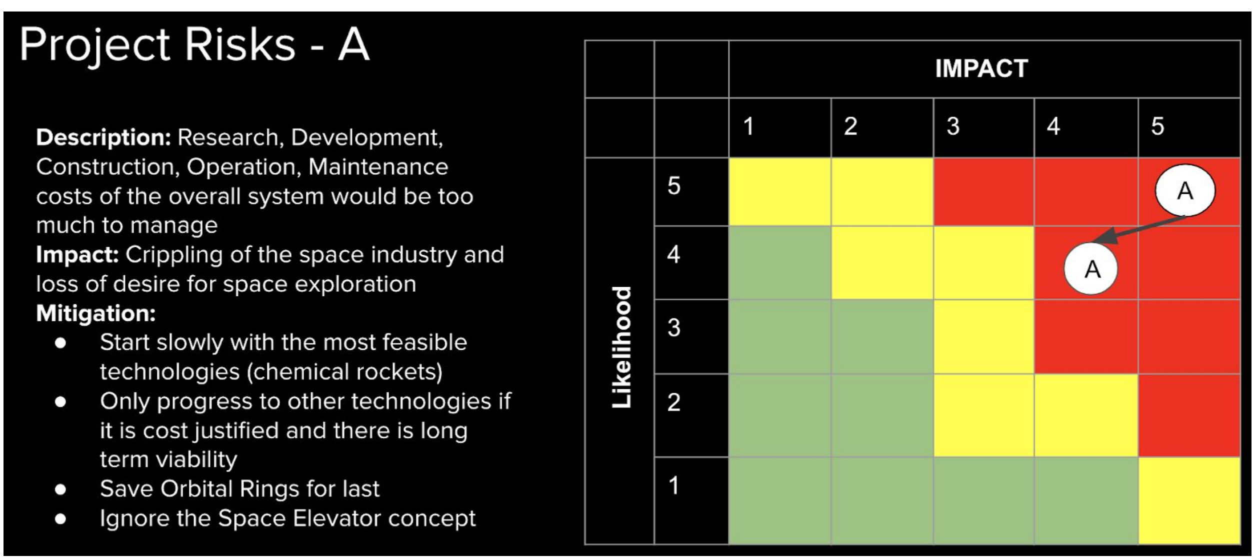

Figure 12.2.2: Importing Resources Substem Project Risk A (High Cost)

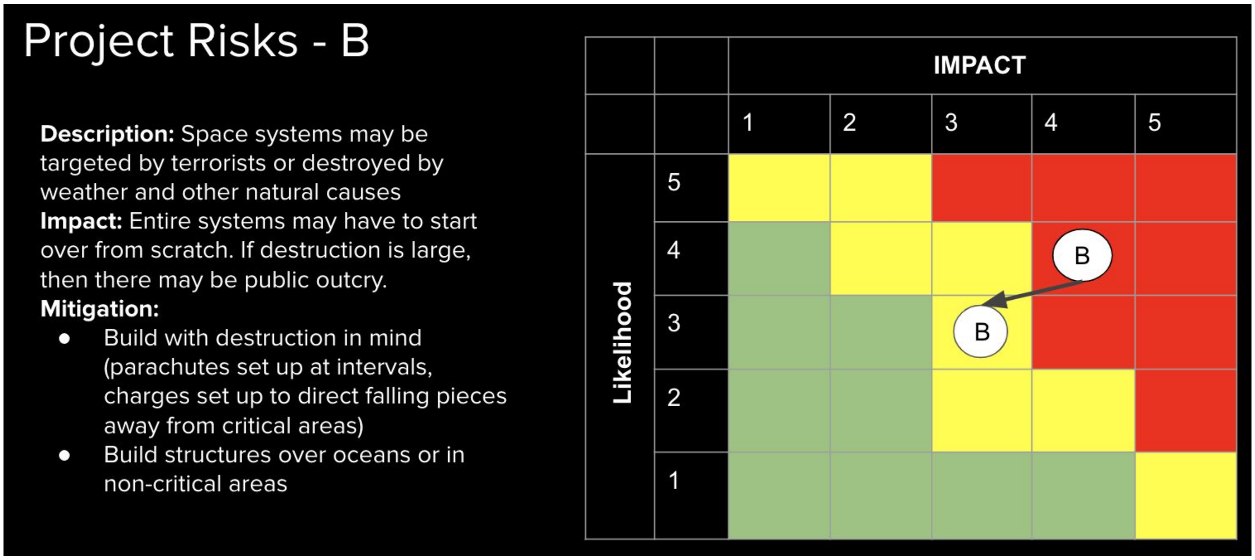

Figure 12.2.3: Importing Resources Subsystem Project Risk B (Destruction Damage)

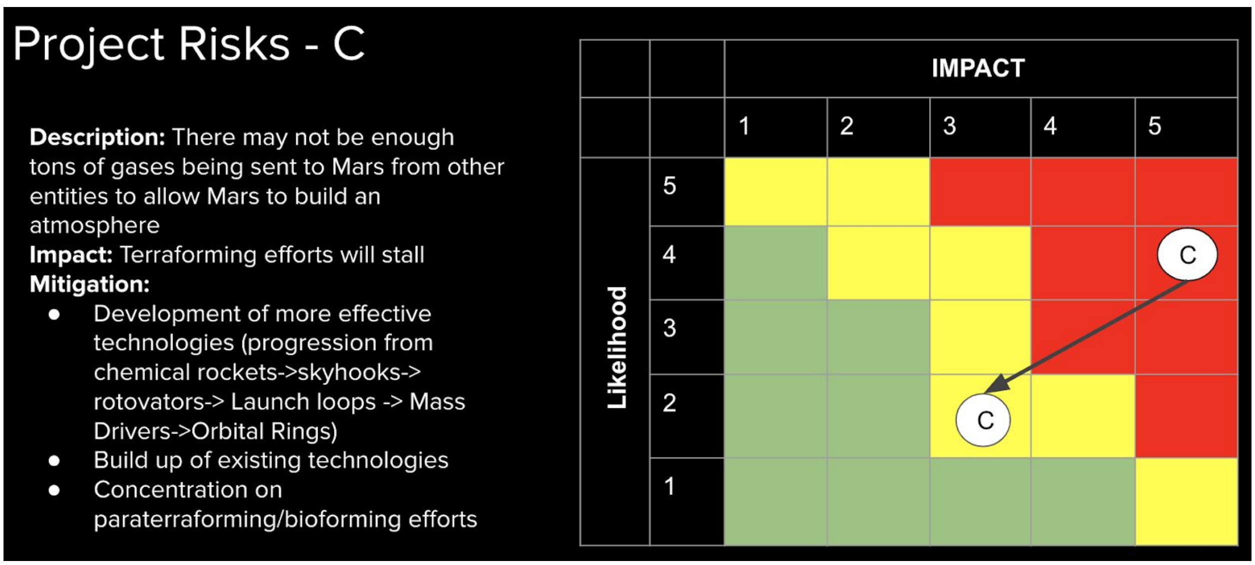

Figure 12.2.4: Importing Resources Subsystem Project Risk C (Low Throughput)

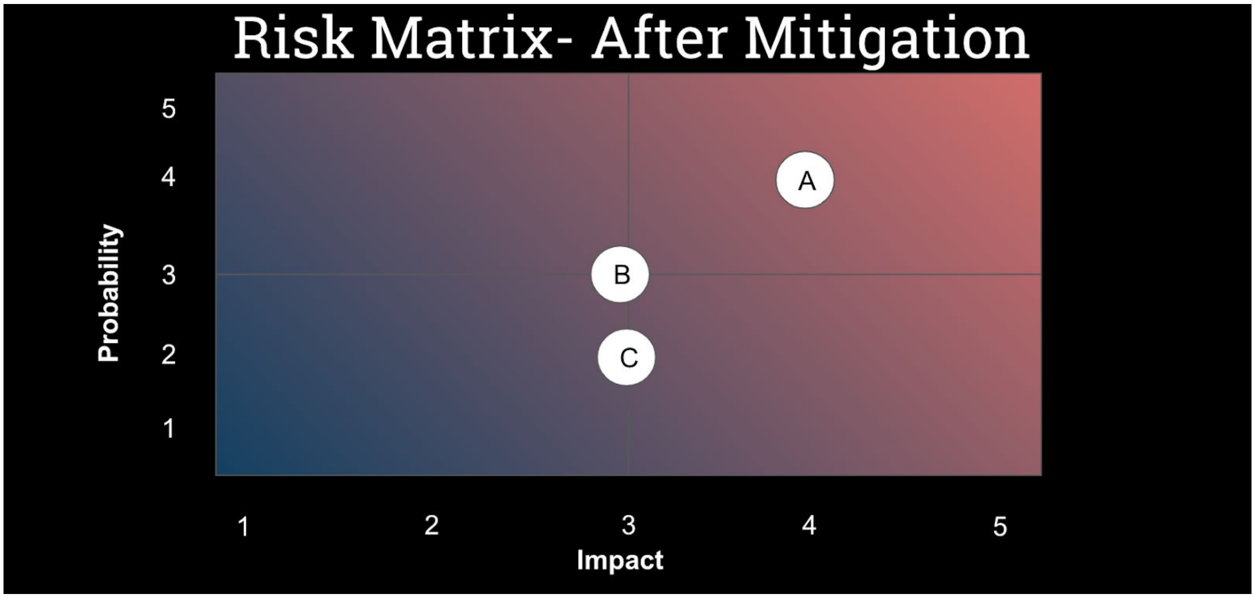

Figure 12.2.5: Importing Resources Subsystem Risk Matrix After Mitigation

13 Lean Strategies

This section will examine a number of lean strategies that could be employed at the Terraforming Project level and at the Importing Resources subsystem level.

There are many different methods the Macro Level Terraforming Project could use to be more lean. The planning process should be thorough and should rely on experts from a variety of different fields. All of the different major problems (increasing temperature, increasing atmosphere, protection from radiation) should have teams that work closely in concert with each other since the success of the entire project relies on the success of resolving every problem and not just one. Each team should also take immediate action on improvement suggestions in an effort to have more accurate results and reporting for the terraforming process.

In order for the importing resources subsection of this Terraforming Project to be more lean it could employ a pulling methodology, where resources are only sent to Mars if the Martian Terraformers actively request the resource. This would prevent a buildup of inventory and allow Terraformers to react to any problems or inconsistencies with resources more quickly. Terraformers would be able to more accurately process the inventory of resources being shipped to Mars with Just-in-Time deliveries from a reduced supply base. The terraforming process could also have delayered management and consistent analysis of the efficiencies of the project by all members of the team, to constantly evaluate the success of the project and how to make it more cost effective and less wasteful.

These are all methods of making a project leaner, more reactive to problems and more cost effective that have been developed by Daniel Jones and James Womack in their lean thinking books.[88]

14 Ethical Considerations

It is important to explore terraforming projects from a couple of different ethical angles. The two issues addressed in the section would be concerning the failure of a terraforming project and the possibility of life on Mars.

If we jumped full force into terraforming Mars, and it ended up in abject failure, this may sour any chances for further large scale space infrastructure megaprojects. Nations may instead turn inward and away from space exploration, being more concerned with their welfare on Earth. There may not be any progress in space infrastructure technologies, and the human species may not invest in new/exotic technologies in general, leaving mankind stuck on Earth and at a low enough Kardashev level where extinction may be possible.

What if we found life on Mars? This would open up a whole can of worms. Many nations and organizations may consider it unethical to tamper with the Martian ecosystem and differing forms of life. It would be argued by purists that it is our duty to ensure that life on Mars stayed undisturbed, and that any disturbance by Earth species could lead to the destruction of Martian life or even Earth life. Other people may consider life on Mars to contain a treasure trove of valuable information that would allow us to understand how life evolved in different areas of the universe. If life on Mars had strong similarities to life on Earth (carbon-based, uses DNA/RNA for replication), then we can assume that life originated in one place and then spread to other places with the help of asteroids and comets. If life on Mars had no logical similarities to Earth life, this would open up new avenues for understanding biology, genetics, engineering and medicine. Examination of Martian life may prove to be the key to unlocking new realms of science. It may spring force such a strong interest in Mars that colonization of Mars may become inevitable despite concerns from purists.[26]

15 Overall Conclusions

- Paraterraforming should begin before terraforming is considered.
- The current focus should be on improving space infrastructure
  - Start research and development on new technologies beyond chemical rockets
  - Skyhooks would be the next logical step beyond rockets
  - Orbital Rings would be the best technology to pursue for high throughput space activities, but all of the different technologies have their merits.

This is a project that may take place far into the future, and it currently only exists in the minds of avid dreamers like myself. Each aspect examined in this report has some grounding in reality, and the next step for this project is to convince the international community of the need and develop an implementation plan derived from our technological capacity. This would help push dreams into reality.

15.1 Proposed Implementation Plan

According to different references[11], developing, a means for importing resources as discussed above can take up 1000 years. In addition, other references suggest that initial paraterraforming of single site may take 5-100 years[11, 51, 56]. The following Chart 15.1 shows a proposed implementation timeline for the entire Terraforming process.

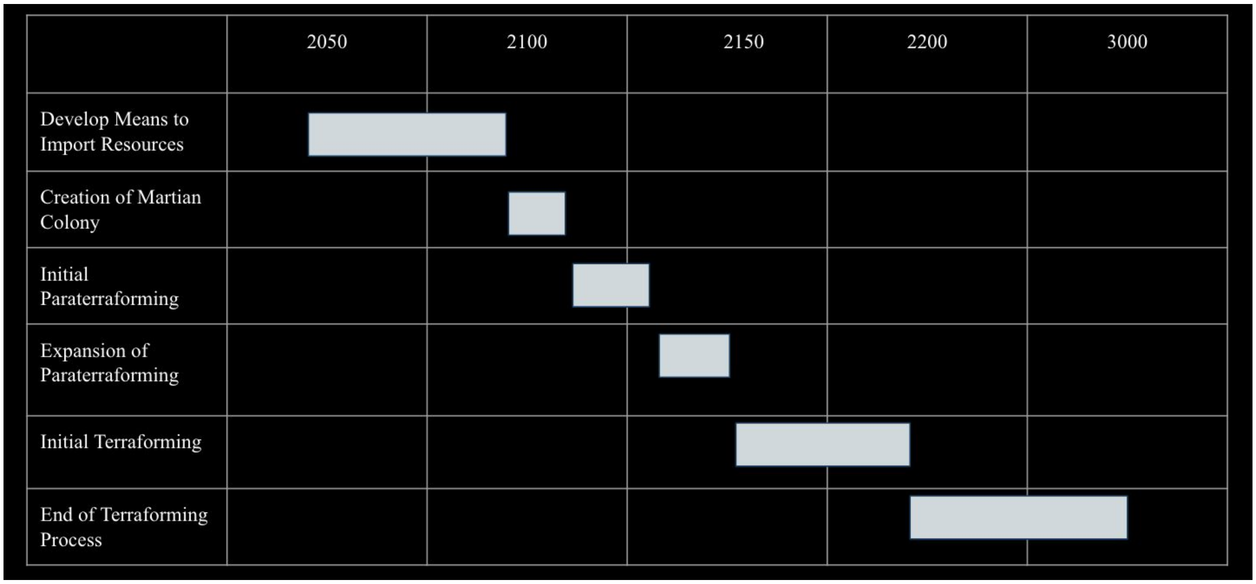

Chart 15.1: Proposed Plan for Terraforming

16 Acknowledgements

- Dr Charles Tang, my Advisor
- Professor Claire Leon and Professor Umesh Ketkar, teachers who sparked my interest in Mars and space
- Joanna Fregoso and Omar Aldawalibi, BFR Group Team Members who encouraged me to dream big
- Isaac Arthur, the greatest source of futurism one could ask for

17 Appendix

17.1 Requirements Flowdown to System Implementation

The following table shows the relationships between the Requirements and Goals from a Macro Level and Detailed Level and their corresponding system implementations/design.

Goals	**Macro Level Requirements**	**Detailed Level Requirements**	**High Level System Design**	**Detail Subsystem/Subsystem Design**
1.1 Allows for useful biological organisms to reproduce and thrive	1.1.1 The system shall allow for biological organisms to grow and thrive to support an independent Martian Colony	1.1.1.1 Atmosphere shall simulate Earth's pressure levels	1.1.1.1.1 Paraterraforming System	
			1.1.1.1.2 Terraforming System	
			1.1.1.1.3 Bioforming System	
			1.1.1.1.4 Space Transportation System	1.1.1.1.4.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.1.1.1.4.2 Mass drivers used to transport Nitrogen and Carbon Dioxide from Venus
				1.1.1.1.4.3 Orbital Rings used to transport resources from Earth
				1.1.1.1.4.3 Mass drivers used to transport Nitrogen from Titan
				1.1.1.1.4.4 Launch Loops used to transport Hydrogen from Jupiter
		1.1.1.2 Increase the temperature on Mars to levels organisms can survive and thrive in	1.1.1.2.1 Paraterraforming System	
			1.1.1.2.2 Terraforming System	
			1.1.1.2.3 Bioforming System	
			1.1.1.2.4 Space Transportation System	1.1.1.2.4.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.1.1.2.4.2 Mass drivers used to transport

				Nitrogen and Carbon Dioxide from Venus
				1.1.1.2.4.3 Orbital Rings used to transport resources from Earth
				1.1.1.2.4.3 Mass drivers used to transport Nitrogen from Titan
				1.1.1.2.4.4 Launch Loops used to transport Hydrogen from Jupiter
		1.1.1.3 Increase the atmospheric carbon dioxide levels on Mars to replicate Earth	1.1.1.3.1 Paraterraforming System	
			1.1.1.3.2 Terraforming System	
			1.1.1.3.3 Space Transportation System	1.1.1.3.3.1 Mass drivers used to transport Nitrogen from Venus
				1.1.1.3.3.2 Orbital Rings used to transport resources from Earth
				1.1.1.3.3.3 Mass drivers used to transport Nitrogen from Titan
		1.1.1.4 Increase the atmospheric oxygen levels on Mars to replicate Earth	1.1.1.4.1 Paraterraforming System	
			1.1.1.4.2 Terraforming System	
			1.1.1.4.3 Space Transportation System	1.1.1.4.3.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.1.1.4.3.2 Orbital Rings used to transport resources from Earth
		1.1.1.5 Increase the amount of water on Mars to replicate Earth conditions	1.1.1.5.1 Paraterraforming System	
			1.1.1.5.2 Terraforming System	
			1.1.1.5.3 Space Transportation System	1.1.1.5.3.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.1.1.5.3.2 Orbital Rings used to transport resources from Earth

				1.1.1.5.3.3 Launch Loops used to transport Hydrogen from Jupiter
		1.1.1.6 Increase the Nitrogen levels on Mars to replicate Earth conditions	1.1.1.6.1 Paraterraforming System	
			1.1.1.6.2 Terraforming System	
			1.1.1.5.3 Space Transportation System	1.1.1.5.3.1 Mass drivers used to transport Nitrogen from Venus
				1.1.1.5.3.2 Mass drivers used to transport Nitrogen from Titan
		1.1.1.7 Shield Mars from atmospheric-damaging solar events and solar radiation as well as galactic cosmic rays to reduce radiation levels to those similar to Earth	1.1.1.7.1 Paraterraforming System	
			1.1.1.7.2 Terraforming System	
		1.1.1.8 Overcome or increase the effects of Mars' lower gravity	1.1.1.8.1 Paraterraforming System	
			1.1.1.8.2 Terraforming System	
		1.1.1.9 Remove perchlorates from the Martian soil to conditions Earth plants/animals can survive	1.1.1.9.1 Paraterraforming System	
			1.1.1.9.2 Terraforming System	
		1.1.1.10 Genetically-engineer plants and animals to survive the Martian atmosphere	1.1.1.10.3 Bioforming System	
		1.1.1.11 Protect Mars from damaging comets and meteors that may interfere with terraforming efforts	1.1.1.11.1 Paraterraforming System	
			1.1.1.11.2 Terraforming System	
		1.1.1.12 Introduce methods of recycling elements such as carbon, oxygen, and nitrogen trapped deep under the Martian crust back to the atmosphere at a rate similar to Earth's	1.1.1.12.1 Paraterraforming System	

			1.1.1.12.2 Terraforming System	
		1.1.1.13 Overcome the lower amounts of sunlight Mars receives	1.1.1.13.1 Paraterraforming System	
			1.1.1.13.2 Terraforming System	
		1.1.1.14 Overcome the intense dust storms that blacken the Martian skies	1.1.1.14.1 Paraterraforming System	
			1.1.1.14.2 Terraforming System	
1.2 Controllable	1.2.1 The system shall be controllable by terraforming efforts		1.2.1.1.1 Paraterraforming System	
			1.2.1.1.2 Terraforming System	
			1.2.1.1.3 Bioforming System	
1.3 Long-term	1.3.1 The system shall last at least 10,000 years after terraforming efforts are completed	1.3.1.1 Overcome the sheer length of time this may take	1.3.1.1.1 Paraterraforming System	
			1.3.1.1.2 Terraforming System	
			1.3.1.1.3 Bioforming System	
1.4 Reversible	1.4.1 The system shall be able to be reversed by ten years in case the efforts causes undesirable circumstances		1.4.1.1.1 Paraterraforming System	
			1.4.1.1.2 Terraforming System	
			1.4.1.1.3 Bioforming System	
1.5 Done within a useful timeframe	1.5.1 The system shall be fully terraformed within a thousand years		1.5.1.1.1 Paraterraforming System	
			1.5.1.1.2 Terraforming System	
			1.5.1.1.3 Bioforming System	
1.6 Results in minimal damage to Mars and any potential native organisms	1.6.1 The system shall not cause the annihilation of Martian colonies or paraterraforming efforts or any native Martian life		1.6.1.1.1 Paraterraforming System	

			1.6.1.1.2 Terraforming System	
			1.6.1.1.3 Bioforming System	
1.7 Minimum cost	1.7.1 The system shall not cost more than an economically infeasible amount	1.7.1.1 Overcome the sheer amount of energy a project like this may need	1.7.1.1.1 Paraterraforming System	
			1.7.1.1.2 Terraforming System	
			1.7.1.1.3 Bioforming System	
1.8 Widespread over most, if not all of Mars	1.8.1 The system shall result in at least 50% of the Martian surface in a terraformed state		1.8.1.1.1 Paraterraforming System	
			1.8.1.1.2 Terraforming System	
			1.8.1.1.3 Bioforming System	
1.9 Technologically feasible	1.9.1 The system shall depend on technologically-feasible technologies		1.9.1.1.1 Paraterraforming System	
			1.9.1.1.2 Terraforming System	
			1.9.1.1.3 Bioforming System	
			1.9.1.1.4 Space Transportation System	1.9.1.1.4.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.9.1.1.4.2 Mass drivers used to transport Nitrogen and Carbon Dioxide from Venus
				1.9.1.1.4.3 Orbital Rings used to transport resources from Earth
				1.9.1.1.4.4 Mass drivers used to transport Nitrogen from Titan
				1.9.1.1.4.3 Orbital Rings used to transport resources from Earth
				1.9.1.1.4.6 Orbital Rings used to receive materials at Mars
				1.9.1.1.4.7 Launch Loops and Rotovators set up to resource

				transportation from Earth's moon
1.9.1 Resource Transportation System is Low cost at scale		1.9.1.1 The system shall be cost effective for transporting large amounts of materials	1.9.1.1.1 Space Transportation System	1.9.1.1.1.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.9.1.1.1.2 Mass drivers used to transport Nitrogen and Carbon Dioxide from Venus
				1.9.1.1.1.3 Orbital Rings used to transport resources from Earth
				1.9.1.1.1.4 Mass drivers used to transport Nitrogen from Titan
				1.9.1.1.1.5 Launch Loops used to transport Hydrogen from Jupiter
				1.9.1.1.1.6 Orbital Rings used to receive materials at Mars
				1.9.1.1.1.7 Launch Loops and Rotovators set up to resource transportation from Earth's moon
1.9.2 Resource Transportation System has low capital costs		1.9.2.1 The system shall be have low enough capital costs to be economically viable	1.9.2.1.1 Space Transportation System	1.9.2.1.1.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.9.2.1.1.2 Mass drivers used to transport Nitrogen and Carbon Dioxide from Venus
				1.9.2.1.1.3 Orbital Rings used to transport resources from Earth
				1.9.2.1.1.4 Mass drivers used to transport Nitrogen from Titan
				1.9.2.1.1.5 Launch Loops used to transport Hydrogen from Jupiter
				1.9.2.1.1.6 Orbital Rings used to receive materials at Mars
				1.9.2.1.1.7 Launch Loops and Rotovators set up to resource transportation from Earth's moon

1.9.3 Resource Transportation System has low operational costs		1.9.3.1 The system shall have low enough operational costs to be economically viable	1.9.3.1.1 Space Transportation System	1.9.3.1.1.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.9.3.1.1.2 Mass drivers used to transport Nitrogen and Carbon Dioxide from Venus
				1.9.3.1.1.3 Orbital Rings used to transport resources from Earth
				1.9.3.1.1.4 Mass drivers used to transport Nitrogen from Titan
				1.9.3.1.1.3 Orbital Rings used to transport resources from Earth
				1.9.3.1.1.6 Orbital Rings used to receive materials at Mars
				1.9.3.1.1.7 Launch Loops and Rotovators set up to resource transportation from Earth's moon
1.9.4 Resource Transportation System works in high gravity environments (Earth, Venus, Jupiter)		1.9.4.1 The system shall work in high gravity environments such as Earth, Venus and Jupiter	1.9.4.1.1 Space Transportation System	1.9.4.1.1.1 Mass drivers used to transport Nitrogen and Carbon Dioxide from Venus
				1.9.4.1.1.2 Orbital Rings used to transport resources from Earth
				1.9.4.1.1.3 Launch Loops used to transport Hydrogen from Jupiter
1.9.5 Resource Transportation System works in low gravity environments (Titan, Mars, Moon, Asteroids)		1.9.5.1The system shall work in low gravity environments such as on Titan, Earth’s moon, Mars and Asteroids/Comets	1.9.5.1.1 Space Transportation System	1.9.5.1.1.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.9.5.1.1.2 Orbital Rings used to receive materials at Mars
				1.9.5.1.1.3 Mass drivers used to transport Nitrogen from Titan
				1.9.5.1.1.4 Launch Loops and Rotovators set up to resource transportation from Earth's moon

1.9.6 Resource Transportation System works in high atmosphere environments (Venus, Earth, Jupiter)		1.9.6.1 The system shall work on environments with high atmospheric pressures	1.9.6.1.1 Space Transportation System	1.9.6.1.1.1 Mass drivers used to transport Nitrogen and Carbon Dioxide from Venus
				1.9.6.1.1.2 Orbital Rings used to transport resources from Earth
				1.9.6.1.1.3 Launch Loops used to transport Hydrogen from Jupiter
1.9.7 Resource Transportation System works in low atmosphere environments (Mars, Moon, Asteroids)		1.9.7.1 The system shall work in environments with low atmospheric pressures	1.9.7.1.1 Space Transportation System	1.9.7.1.1.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.9.7.1.1.2 Orbital Rings used to receive materials at Mars
				1.9.7.1.1.3 Launch Loops and Rotovators set up to resource transportation from Earth's moon
1.9.8 Resource Transportation System is technologically feasible as an Importation System		1.9.8.1 The system shall depend on technologically feasible technologies	1.9.8.1.1 Space Transportation System	1.9.8.1.1.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.9.8.1.1.2 Mass drivers used to transport Nitrogen and Carbon Dioxide from Venus
				1.9.8.1.1.3 Orbital Rings used to transport resources from Earth
				1.9.8.1.1.4 Mass drivers used to transport Nitrogen from Titan
				1.9.8.1.1.3 Orbital Rings used to transport resources from Earth
				1.9.8.1.1.6 Orbital Rings used to receive materials at Mars
				1.9.8.1.1.7 Launch Loops and Rotovators set up to resource transportation from Earth's moon

1.9.9 Resource Transportation System has low enough destructive capacity if destroyed		1.9.9.1 The system shall cause minimal destruction if it were to be destroyed	1.9.9.1.1 Space Transportation System	1.9.9.1.1.1 Nuclear Rockets used to retrieve resources found on water and asteroids
				1.9.9.1.1.2 Mass drivers used to transport Nitrogen and Carbon Dioxide from Venus
				1.9.9.1.1.3 Orbital Rings used to transport resources from Earth
				1.9.9.1.1.4 Mass drivers used to transport Nitrogen from Titan
				1.9.9.1.1.3 Orbital Rings used to transport resources from Earth
				1.9.9.1.1.6 Orbital Rings used to receive materials at Mars
				1.9.9.1.1.7 Launch Loops and Rotovators set up to resource transportation from Earth's moon

Table 17.1: Table of Requirements Flowdown to System Implementation

18 References

List of References

1. *Incose Systems Engineering Handbook v3.2*. Incose.
2. "International Mars Research Station." *5. Time | International Mars Research Station*, marsbase.org/.
3. "THE PAUL BIRCH WEB ARCHIVE." *Orions Arm - Encyclopedia Galactica*, orionsarm.com/fm_store/Paul Birchs Page.htm.
4. Aravind, P. K. "The Physics of the Space Elevator." *American Journal of Physics*, vol. 75, no. 2, 2007, pp. 125–130., doi:10.1119/1.2404957.
5. Grant, John, et al. "Hypersonic Airplane Space Tether Orbital Launch - HASTOL - A Two-Stage Commercial Launch System." *Space 2000 Conference and Exposition*, 2000, doi:10.2514/6.2000-5353.
6. Silvera, Isaac F, and John W Cole. "Metallic Hydrogen: The Most Powerful Rocket Fuel Yet to Exist." *Journal of Physics: Conference Series*, vol. 215, Jan. 2010, p. 012194., doi:10.1088/1742-6596/215/1/012194.
7. "ATOMIC ROCKETSHIPS OF THE SPACE PATROL." *Atom*, www.projectrho.com/public_html/rocket/index.php.
8. "The Launch Loop - A Low Cost Earth-to-High-Orbit Launch System." *21st Joint Propulsion Conference*, Aug. 1985, doi:10.2514/6.1985-1368.
9. "UpwardBound." *UpwardBound - Launch Loop*, launchloop.com/UpwardBound.
10. Arthur, Isaac. "Home - IsaacArthur.net - Science and Futurism Videos." *Home - IsaacArthur.net - Science and Futurism Videos*, www.isaacarthur.net/.
11. Arthur, Isaac. *Home - IsaacArthur.net - Science and Futurism Videos*, www.isaacarthur.net/video/?playlist=PLIIOUpOge0LuGoV8698AWjDcMYeB9OvEf&category=.
12. "r/IsaacArthur." *Reddit*, www.reddit.com/r/IsaacArthur/.
13. *Sophocles Antigone: Antigone's Age (The Classics Pages)*, www.users.globalnet.co.uk/~mfogg/zubrin.htm.
14. KAKU, MICHIO. *FUTURE OF HUMANITY: Terraforming Mars, Interstellar Travel, Immortality, and Our... Destiny Beyond*. PENGUIN BOOKS, 2019.
15. Verzuh, Eric. *The Fast Forward MBA in Project Management*. Wiley, 2016.
16. Williams, Matt. "Uh Oh, Mars Doesn't Have Enough Carbon Dioxide to Be Terraformed." *Universe Today*, Universe Today, 31 July 2018, www.universetoday.com/139725/uh-oh-mars-doesnt-have-enough-carbon-dioxide-to-be-terraformed/.
17. "Distances Between the Planets of the Solar System • The Planets." *The Planets*, theplanets.org/distances-between-planets/.
18. Brian Dunbar. "NASA - Jupiter." *Razor Tie Artery Foundation Announce New Joint Venture Recordings | Razor & Tie*, Rovi Corporation, web.archive.org/web/20050105155019/http://www.nasa.gov/worldbook/jupiter_worldbook.html.
19. Kaufman, Marc. *Mars up Close: inside the Curiosity Mission*. National Geographic, 2014.
20. STUART, COLIN. *HOW TO LIVE IN SPACE*. ANDRE DEUTSCH, 2018.
21. Dunlop, Storm. *Philips Guide to Weather Forecasting*. Philips, 2013.
22. Leslie, John. *The Science and Ethics of Human Extinction*. Routledge, 1996.
23. Richter, Viviane. "The Big Five Mass Extinctions." *Cosmos*, 6 July 2015, cosmosmagazine.com/palaeontology/big-five-extinctions.
24. Cain, Fraser. "Zubrin on Terraforming Mars." *Universe Today*, Universe Today, 24 Mar. 2012, www.universetoday.com/9730/zubrin-on-terraforming-mars/.
25. Contributor, Quora. "Which Planet Would Be Easier to Terraform: Venus or Mars?" *Slate Magazine*, Slate, 12 Sept. 2013, slate.com/human-interest/2013/09/outer-space-can-we-make-mars-or-venus-habitable.html.
26. Staff, SPACE.com. "Terraforming Mars: Experts Debate How, Why and Whether." *Space.com*, Space.com, 8 Mar. 2016, www.space.com/190-terraforming-mars-experts-debate.html.
27. Sharp, Tim. "How Far Away Is Mars? | Distance to Mars." *Space.com*, Space.com, 15 Dec. 2017, www.space.com/16875-how-far-away-is-mars.html.

28. Sharp, Tim. “What Is the Temperature of Mars?” *Space.com*, Space.com, 30 Nov. 2017, www.space.com/16907-what-is-the-temperature-of-mars.html.
29. “Lowest Temperature for Life Discovered.” *Phys.org - News and Articles on Science and Technology*, Phys.org, phys.org/news/2013-08-lowest-temperature-life.html.
30. Freudenrich, Ph.D. Craig, and Nicholas Gerbis. “How Mars Works.” *HowStuffWorks Science*, HowStuffWorks, 6 Nov. 2000, science.howstuffworks.com/mars.htm.
31. Weigel, Brandon. “Giving Mars a Magnetosphere – Our Space – Medium.” *Medium.com*, Medium, 28 Feb. 2018, medium.com/our-space/an-artificial-martian-magnetosphere-fd3803ea600c.
32. Redd, Nola Taylor. “How Long Does It Take to Get to Mars?” *Space.com*, Space.com, 14 Nov. 2017, www.space.com/24701-how-long-does-it-take-to-get-to-mars.html.
33. “Mars Facts.” *NASA*, NASA, mars.nasa.gov/allaboutmars/facts/#?c=inspace&s=distance.
34. Ma, Lan. “The Greenhouse Effect.” *The Greenhouse Effect*, www.ocf.berkeley.edu/~lan/globalwarming/greenhouse.pdf.
35. Cain, Fraser. “Mars Tilt.” *Universe Today*, Universe Today, 25 Dec. 2015, www.universetoday.com/14894/mars-tilt/.
36. Williams, Matt. “The Orbit of Mars. How Long Is a Year on Mars?” *Universe Today*, Universe Today, 17 Apr. 2017, www.universetoday.com/14718/how-long-is-a-year-on-mars/.
37. Williams, Matt. “How Strong Is the Gravity on Mars?” *Universe Today*, Universe Today, 16 Dec. 2016, www.universetoday.com/14859/gravity-on-mars/.
38. “Plants Grow Fine Without Gravity.” *National Geographic*, National Geographic Society, 7 Dec. 2012, news.nationalgeographic.com/news/2012/121207-plants-grow-space-station-science/.
39. Geggel, Laura. “How Our View of Mars Has Changed from Lush Oasis to Arid Desert.” *Scientific American*, 1 Oct. 2015, www.scientificamerican.com/article/how-our-view-of-mars-has-changed-from-lush-oasis-to-arid-desert/.
40. Lewis, Tanya. “NASA Video Shows Ancient Mars as Lush, Water World.” *Space.com*, Space.com, 14 Nov. 2013, www.space.com/23595-ancient-mars-oceans-nasa-video.html.
41. Anderson, Gina. “NASA Confirms Evidence That Liquid Water Flows on Today's Mars.” *NASA*, NASA, 28 Sept. 2015, www.nasa.gov/press-release/nasa-confirms-evidence-that-liquid-water-flows-on-today-s-mars.
42. Christensen, P. R. “Water at the Poles and in Permafrost Regions of Mars.” *Elements*, vol. 2, no. 3, Jan. 2006, pp. 151–155., doi:10.2113/gselements.2.3.151.
43. “Missions to Mars.” *The Planetary Society Blog*, www.planetary.org/explore/space-topics/space-missions/missions-to-mars.html.
44. Williams, Matt. “The Definitive Guide To Terraforming.” *Universe Today*, Universe Today, 15 May 2017, www.universetoday.com/127311/guide-to-terraforming/.
45. Hughes, Amanda Jane. “Mining Asteroids Could Unlock Untold Wealth – Here's How to Get Started.” *The Conversation*, The Conversation, 19 Sept. 2018, theconversation.com/mining-asteroids-could-unlock-untold-wealth-heres-how-to-get-started-95675.
46. Sharp, Tim. “How Big Is Mars? | Size of Planet Mars.” *Space.com*, Space.com, 29 Mar. 2013, www.space.com/16871-how-big-is-mars.html.
47. Cain, Fraser. “Composition of the Earth's Atmosphere.” *Universe Today*, Universe Today, 25 Dec. 2015, www.universetoday.com/26656/composition-of-the-earths-atmosphere/.
48. *Space Shuttle Era Facts Facts - NASA*. www.nasa.gov/pdf/566250main_2011.07.05 SHUTTLE ERA FACTS.pdf.
49. “List of Countries by Projected GDP.” *Comparing India vs China by GDP - StatisticsTimes.com*, statisticstimes.com/economy/countries-by-projected-gdp.php.
50. “Paraterraforming.” *Terraforming Wiki*, terraforming.wikia.com/wiki/Paraterraforming.
51. “Global Paraterraforming.” *Terraforming Wiki*, terraforming.wikia.com/wiki/Global_paraterraforming.
52. *NASA*, NASA, mars.jpl.nasa.gov/gallery/atlas/valles-marineris.html.
53. Esa. “Wind and Water Have Shaped Schiaparelli on Mars.” *European Space Agency*, www.esa.int/Our_Activities/Space_Science/Mars_Express/Wind_and_water_have_shaped_Schiaparelli_on_Mars.
54. “Pavonis Mons.” *NASA*, NASA, www.jpl.nasa.gov/spaceimages/details.php?id=PIA03790.
55. Contributor, Quora. “Can We Terraform a Portion of Mars by Enclosing It in a Dome?” *Slate Magazine*,

Slate, 26 Oct. 2015, slate.com/human-interest/2015/10/can-we-terraform-a-portion-of-mars-by-enclosing-it-in-a-dome.html.
56. Wang, Brian. "Beyond Dome City Colonies to Shell Worlds or Paraterraforming as a Shortcut to Making Planets Habitable." *NextBigFuture.com*, NextBigFuture.com, 7 Apr. 2017, www.nextbigfuture.com/2016/12/beyond-dome-city-colonies-to-shell.html.
57. "Forget Mars. Here's Where We Should Build Our First Off-World Colonies." *D-Brief*, 8 Sept. 2014, blogs.discovermagazine.com/crux/2014/09/08/where-build-off-world-colonies/#.XAxE5pNKiBs.
58. "Bioforming." *Terraforming Wiki*, terraforming.wikia.com/wiki/Bioforming.
59. "Questions and Answers about CRISPR." *Broad Institute*, 4 Aug. 2018, www.broadinstitute.org/what-broad/areas-focus/project-spotlight/questions-and-answers-about-crispr.
60. *Nature News*, Nature Publishing Group, www.nature.com/scitable/content/replication-of-retroviruses-14465196.
61. Stein, Rob. "DNA 'Printing' A Big Boon To Research, But Some Raise Concerns." *NPR*, NPR, 7 May 2015, www.npr.org/sections/health-shots/2015/05/07/404460240/dna-printing-a-big-boon-to-research-but-some-raise-concerns.
62. *ACS Publications*, pubs.acs.org/cen/coverstory/8148/8148counterpoint.html.
63. Kimel, David Vincent. "Mission to Mars: The Hopes of Success Are Dependent on Cyborg Humans." *Futurism*, Futurism, 10 Mar. 2017, futurism.com/mission-to-mars-the-hopes-of-success-are-dependent-on-cyborg-humans.
64. "Trouble With Terraforming Mars." *Science 2.0*, 27 Aug. 2014, www.science20.com/robert_inventor/trouble_with_terraforming_mars-126407.
65. Tate, Karl. "How Humans Could Live on Saturn's Moon Titan (Infographic)." *Space.com*, Space.com, 10 Mar. 2015, www.space.com/28788-living-on-titan-saturn-explained-infographic.html.
66. Körner, Christian, and Jens Paulsen. "A World-Wide Study of High Altitude Treeline Temperatures." *Journal of Biogeography*, vol. 31, no. 5, 2004, pp. 713–732., doi:10.1111/j.1365-2699.2003.01043.x.
67. David, Leonard. "Toxic Mars: Astronauts Must Deal with Perchlorate on the Red Planet." *Space.com*, Space.com, 13 June 2013, www.space.com/21554-mars-toxic-perchlorate-chemicals.html.
68. "How Terraforming Mars Will Work." *HowStuffWorks Science*, HowStuffWorks, 6 Nov. 2000, science.howstuffworks.com/terraforming2.htm.
69. "Global Warming Potentials." *UNFCCC*, unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials.
70. Redd, Nola Taylor. "How Hot Is Venus?" *Space.com*, Space.com, 14 Feb. 2018, www.space.com/18526-venus-temperature.html.
71. Fenton, Lori K., et al. "Global Warming and Climate Forcing by Recent Albedo Changes on Mars." *Nature*, vol. 446, no. 7136, 2007, pp. 646–649., doi:10.1038/nature05718.
72. Berger, Eric. "How Mars Lost Its Atmosphere and Became a Cold, Dry World." *Ars Technica*, Ars Technica, 5 Nov. 2015, arstechnica.com/science/2015/11/how-mars-lost-its-atmosphere-and-became-a-cold-dry-world/.
73. "NASA Proposes a Magnetic Shield to Protect Mars' Atmosphere." *Phys.org - News and Articles on Science and Technology*, Phys.org, phys.org/news/2017-03-nasa-magnetic-shield-mars-atmosphere.html.
74. *Feasibility of Artificial Geomagnetic Field Generation by ...*www.nifs.ac.jp/report/NIFS-886.pdf.
75. "Is There a Way to Provide a Magnetic Field for Mars?" *Ask An Astronomer*, askanastronomer.org/planets/2015/11/20/can-we-create-a-magnetic-field-for-mars/.
76. *Nature News*, Nature Publishing Group, www.nature.com/scitable/knowledge/library/the-nitrogen-cycle-processes-players-and-human-15644632.
77. Sara Sayed, The Daily Beast Video. "How to Make Oxygen From Mars's Soil." *The Daily Beast*, The Daily Beast Company, 28 Sept. 2015, www.thedailybeast.com/how-to-make-oxygen-from-marss-soil.
78. "Titan Moon Facts." *Space Facts*, Space Facts, 6 Dec. 2017, space-facts.com/titan/.
79. Choi, Charles Q. "Comets: Facts About The 'Dirty Snowballs' of Space." *Space.com*, Space.com, 24 Oct. 2017, www.space.com/53-comets-formation-discovery-and-exploration.html.
80. Rgargente. "The Tsiolkovsky Rocket Equation." *Space, Science and Software*, 5 Sept. 2013, spacesciencesoftware.wordpress.com/2013/08/30/the-tsiolkovsky-rocket-equation/.

81. Spacexcmsadmin. “Capabilities & Services.” *SpaceX*, SpaceX, 28 Nov. 2012, www.spacex.com/about/capabilities.
82. *NASA*, NASA, history.nasa.gov/conghand/propelnt.htm.
83. “NUCLEAR ROCKETS: To Mars and Beyond.” *LANL Newsroom*, 1 Sept. 2009, www.lanl.gov/science/NSS/issue1_2011/story4full.shtml.
84. Moravec, Hans P. *Orbital Bridges*. Carnegie-Mellon University, 1986.
85. “Magnetic Launch System.” *The Space Monitor*, spacemonitor.blogspot.com/2007/03/magnetic-launch-system.html.
86. *Startram*, www.startram.com/home.
87. Davis, Eric W. “Advanced Propulsion Study.” Jan. 2004, doi:10.21236/ada426465.
88. Womack, James P., and Daniel T. Jones. *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. Free Press, 2010.