Colonization of Mars, the Red Planet: A Feasibility Study on Creating an Atmosphere Using Martian Resources

by

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Abstract

Acting under the assumptions of a restored magnetic field and primary utilization of Martian resources, the current conditions on Mars are described with an emphasis on information necessary to terraform and colonize the planet. Perchlorate, sulfate, and nitrate in the Martian regolith were identified as key sources for atmosphere production. These sources were inventoried using information from the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). These inventories were compared to the mass needed to create an atmosphere on Mars. These resources were found to yield only 2.76% of the mass needed to terraform the planet. The amount of interior atmosphere for habitation facilities that could be generated was also calculated based on the same mass. With nitrogen as the limiting ingredient for atmosphere, the conversion of 100% of the planet's nitrate reserves would result in the creation of 7.01E+14 m^3 of breathable air, over 200 million Superdome sized facilities, with an excess supply of oxygen available from perchlorate and sulfate reserves. The proposed means of conversion was by the use of bioelectrochemical reactors (BERs) in conjunction with highly specialized bacterial populations. These reactors allow for resource efficient reductions to take place, where electrical current is used as the sole electron donor. The reactions would meet weight constraints for travel but were found to be far too slow for effective use. Based on the reaction rate of 50 mg/L per day from pilot scale research, millions of liters of reactor volume would be needed for effective conversions. Research into faster conversion mechanisms and reactor designs are required for colonization of Mars.

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Acknowledgements

This report is a culmination of research into the Martian environment and the processes needed to colonize the planet. Much of the research was supplied by the National Aeronautics and Space Administration and the European Space Agency. Without the grand efforts of these individuals, this report would not have been possible.

I would like to thank my graduate committee: Dr. Trisha Moore, Dr. Donghai Wang, and Dr. Lisa Wilken for allowing me to conduct this type of research. I have greatly appreciated the opportunity to work on research in my desired field. I would also like to thank my editor, Allison Crowther, for her patience though the writing process and excellent spirit, and my parents, Mary and Kevin Wempe, for supporting me throughout my Bachelor's and Master's degrees.

Dedication

To the Opportunity Rover—her efforts on Mars were countless and knowledge sent home priceless. She will be remembered forever and missed dearly.

Chapter 1 - Introduction

1.1 Expansion Explained

From the formation of the UN Population Division in the 1950s until 2015, the world's population grew from approximately 2.6 billion to 5.3 billion (Cassils, 2003). The UN projections based on the current growth rate predict the population reaching 9.7 billion by 2050 and 11.2 billion in 2100 (Cassils, 2003). Though population growth is currently declining, the total population is still increasing, and the maximum sustainable population is speculated to be between 7.7 and 12 billion, averaging at 9.85 billion (Cohen, 1997). More current models conducted by NASA and the UN estimate a peak world population of 9.22 billion that could be reached as early 2041 (Motesharrei et al., 2016). Unless population growth is reduced to replacement level, resulting in a constant total population over time, overpopulation will cause unsustainable levels of scarcity as resource availability declines (Cohen, 1997). Meanwhile, there is already evidence of declining resources; metals such as gold and indium, which are essential to the production of computers, could be depleted within the next 30 years (Dodson et al., 2012). With concerns of over population and resource depletion growing, expanding the human race to new resource pools will be necessary. The asteroid belt that sits between Mars and Jupiter contains several precious metals vital to our current technology (Dodson et al., 2012). In addition, space-related research has historically spurred unprecedented technological progress. The creation of global positioning systems, satellites, and accurate weather prediction systems were all a result of the space race in the 1950's and 60's (Kumar and Moore, 2002). Because of the new challenges and extreme constraints, the research necessary to terraforming or colonizing Mars would likely spawn similar revolutionary technology, particularly in fields such as transportation, environmental remediation, and medicine because of their relevance to the necessary steps. Colonizing Mars would also alleviate overpopulation and provide a much closer launch site for mining missions to the Asteroid Belt, making the prospect of gathering materials from this source much more feasible.

1.2 Objectives and Purpose

The purpose of this paper is to describe the relevant information and processes involved in the colonization of Mars and to determine the feasibility of colonizing Mars using current research and technology. Particular care will be given to descriptions of conditions and processes necessary for creating an atmosphere on Mars using Martian resources to minimize the need for imported materials.

Mars is the 4th planet from the sun and the best planetary candidate in our solar system for colonization. All other planets can be eliminated for reasons such as extreme temperature, toxic atmospheres, and gravity exceeding human tolerance. This leaves Mars and two other lunar bodies as possibilities. In its current state, Mars cannot support life due to its thin atmosphere, freezing temperatures, and lack of liquid surface water and magnetic field. For the purpose of this paper, terraforming means altering the biosphere by artificial and controlled means with the intent of creating an environment that can sustain life similar to Earth. This includes establishing a magnetic field, creating a complete atmosphere as similar to Earth's as possible, and achieving habitable temperatures.

Transporting humans to Mars will require improvement to current technology, including the development of new life support systems for transit and methods to sustain the planet's new occupants (Sridhar et al., 2000). Additionally, the Martian dynamo, must be restored before any meaningful progress can be made in terraforming. The dynamo refers to the magnetic field generated by the core (Brandenburg and Subramanian, 2005). This magnetic field is essential to creating and maintaining habitable conditions. Though these requirements are mentioned as important practical considerations in the overall process, solving these problems is outside the scope of this work, and therefore a functioning dynamo is assumed going forward. An additional assumption of this report is that a feasible means of transportation to Mars exists. With currently available technology and the appropriate time window, traveling from Mars to Earth would take six months (Sridhar et al., 2000).

Even with improvements in existing technologies, transportation is likely to remain as a limiting factor for terraforming, thus importing the materials necessary to create an atmosphere to Mars would make terraforming highly unrealistic. In order to make this type of project feasible, use of resources already found on the planet should be prioritized. This involves the creation of atmosphere from perchlorate, sulfate, and nitrate found in the Martian soil and the production of energy from Martian methane sources, solar power, or nuclear reactions. Outside resources aside from equipment, transport, habitation facilities, and startup resources will not be considered. The creation of a self-sufficient Martian colony is emphasized. The following sections provide additional background material regarding the establishment of Mars as the primary candidate for extraterrestrial colonization, determine the current environmental conditions of Mars, identify the resources available on the Martian planet to aid in the terraforming process, establish efficient methods of conversion of resources, identify the quantities of these resources, and determine if quantities of resources are sufficient for terraforming. If at any point terraforming of the planet is found to be infeasible, focus will switch to supporting colonization of Mars using habitation facilities, defined as artificial pressurized ecosystems where inhabitants will live and work.

1.3 Mars Comparison

There are three main options for colonies in the solar system based on the current exploration efforts of NASA: Mars, the second closest planet to Earth; Titan, one of Saturn's moons; and Europa, one of Jupiter's moons (Raulin, 2005). They will be compared based on distance from Earth, size, and environmental conditions.

Mars is by far the closest of the three to Earth shown in Table 1.1. When two planets or bodies in space are in opposition, they are on opposite sides of another body (Ruggles, 2015). The distance between Mars and Earth is at a minimum during opposition (Ruggles, 2015). Distances during opposition and minimum travel times between colonization candidates and Earth are given in Table 1.1. Even though the window of opportunity to launch mission from Earth opens more often for Europa, the distance to Jupiter's moon is 5-10 times longer before considering the additional time needed to go around the asteroid belt. Based on minimum distance and travel time, Mars is the most feasible body to terraform.

Table 1.1 **Distance and Travel Times to Colonization Candidates During Opposition.** Shown in column two are the minimum distances to each of the colonization candidates. These distances occur when the two bodies are in opposition. The time between opposition events is also displayed in the third column. This time gives an estimate of the maximum time between launches to a colony. The fourth column gives estimated travel times to each of the prospective colonies based on the travel time associated with travel to Mars. (data compiled from Williams, 2005, 2018a, 2018b, 2018c, 2018d)

Planet	Distance from Earth during opposition (10^6 km)	Time period between occurrences of opposition (months)	Travel time from Earth (months)
Mars	55.7	26	6
Europa	588	13	60
Titan	1,276.3	N.A.	132
Jupiter	588.5	13	N.A.
Saturn	1,277.5	N.A.	N.A.

The maximum benefit of terraforming a planet is largely dependent on the amount of usable surface area gained. As shown in Table 1.2, Mars offers nearly as much usable surface area as Earth, much more than Titan or Europa. Sample calculations of surface area available can be found in Appendix A. Using the mean radius of each and the equation for the surface area of a sphere ($4\pi r^2$) the surface area can be estimated. For Earth, the land mass is found by taking the total surface area and multiplying by a factor of .29. This correction is due to 71% of the planet being covered by water ("How much water is there on Earth, from the USGS Water Science School," 2016).

Table 1.2 **Surface Area Comparison of Celestial Bodies.** The surface area of each of the candidates was calculated using the average radius and the equation for the surface area of a sphere. Two values are shown for Earth to represent the total and terrestrial surface area on the planet. The terrestrial values for Earth and the value for Mars are bold and shaded in gray to emphasize their similarity. (Williams, 2005, 2018a, 2018c).

	Mean Radius (km)	Surface Area (km^2)
Earth (Total)	6371	5.10E+8
Earth (Land Mass)	N.A.	**1.48E+8**
Mars	3389	**1.44E+8**
Titan	2575	8.33E+7
Europa	1560	3.06E+7

As one of Jupiter's moons, Europa is exposed to additional radiation from Jupiter's radiation belt. The radiation belt around Jupiter is formed when incoming solar radiation is deflected by Jupiter's magnetic field. This causes the radiation to swirl around Jupiter until it is released near the poles where an aurora occurs, like the Aurora Borealis on Earth. Due to the size of Jupiter, a large amount of radiation is captured (Ringwald, 2000). A dose of 600 rem to humans has a 100% mortality rate within a month due to bone marrow failure if left untreated, including severe radiation sickness for the duration, and doses of over 1000 rem are considered fatal to any human exposed within a maximum of 3 weeks (Mettler and Voelz, 2002). The radiation that bombards Europa is equivalent to 540 rem/day, while the average amount on Earth is .14 rem/day (Ringwald, 2000). This is nearly 3,800 times the average radiation dose on Earth and makes living on the surface of Europa impractical.

Proximity to the asteroid belt is another important factor when discussing the advantages of colonization. When the solar system was formed, Jupiter traveled towards the sun before resuming its current orbit, consuming a large portion of the mass that would have become Mars and preventing the Asteroid Belt from forming a single body as its gravity overwhelmed the gravitational forces pulling these materials together (Walsh et al., 2011). Based on the distance from the Sun, the Asteroid Belt would have formed a planet larger than Earth with proportionally more abundant resources (Walsh et al., 2011). Access to these resources can be used to make metals for structures and plastics and rubbers from hydrogen and carbon supplies (Steve Siceloff, 2013). This makes colonizing planets closer to the asteroid belt much more advantageous.

Mars is much closer than the two moons, 10 and 22 times closer than Europa and Titan respectively, and is right next to the asteroid belt for ease of access to resources. The surface of Europa is unsurvivable due to Jupiter's radiation belt, and though Titan has no foreseeable complications, the distance makes it nearly unreachable with a human crew using current technology. Based on distance, size, and environmental conditions, Mars is the current best choice for terraformation.

1.4 Mars History and the Cessation of the Martian Dynamo

Martian history can be divided into three periods: the Noachian, the Hesperian, and the Amazonian (“The Ages of Mars,” 2015). Since the ability to sample the Martian landscape is limited, scientists must estimate the age of Mars by examining crater patterns (“The Ages of Mars,” 2015). Using this technique, scientists have been able to identify the southern highlands of Mars as the oldest crust, having formed more than 3.8 billion years ago before the formation of the Northern Plains (“The Ages of Mars,” 2015). During the Noachian, Mars had a thick atmosphere with an estimated pressure of .8 bar (Jakosky et al., 2018). Liquid water was also present, and evidence of waterways is still visible today (“The Ages of Mars,” 2015). Some of the largest craters on Mars are due to impacts that occurred during the Noachian period (“The Ages of Mars,” 2015). The largest impact in the history of Mars, encompassing most of the northern hemisphere, is known as the Borealis impact (Chandler et al., 2008). This impact left a crater 8500 kilometers wide, covering nearly 40% of the entire planet (Chandler et al., 2008). Though the Borealis impact did much to shape the current topography of Mars, it is unlikely this impact resulted in the cessation of the Martian dynamo, shown by magnetization patterns in younger impact basins (Roberts et al., 2009). Evidence of other large impacts is seen in the Hellas, Isidis, and Argyre basins (“The Ages of Mars,” 2015). Figure 1.1 gives a visual comparison of the Hellas and Argyre basins to the contiguous United States.

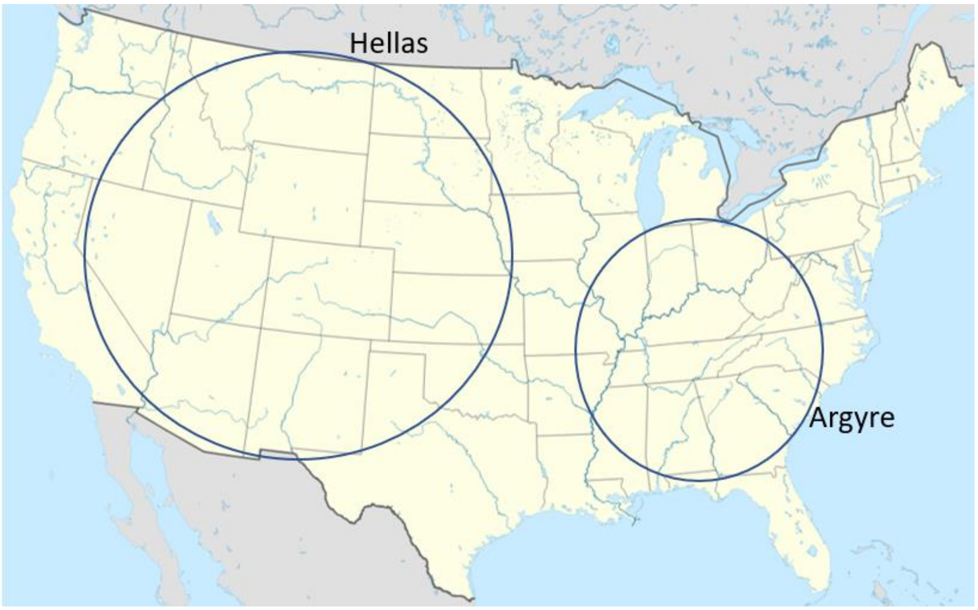

Figure 1.1 **Size of Craters on Mars Compared to the Contiguous United States.** Craters from the two of the largest impacts to every occur in Martian history, Hellas Planitia and Argyre, are displayed to scale against the contiguous United States. The Hellas and Argyre basins have diameters of 2070 km and 1315 km respectively. Adapted from (Meszaros, 1985); map of the United States from (Dedering, 2010).

These basins show enormous collisions that occurred during the Noachian period in the southern highlands of Mars ("The Ages of Mars," 2015). Mars' internal dynamo shut down during the mid-Noachian, resulting in the loss of its magnetic field (Arkani-Hamed and Olson, 2010; Roberts et al., 2009).

Evidence of the ancient Martian magnetic field is shown by crustal magnetization in large portions of Mars and magnetization patterns in older Noachian basins (Roberts et al., 2009). The absence of these magnetization patterns in younger Noachian basins suggests the disruption of the Martian dynamo in the mid-Noachian, roughly 3.9 billion years ago (Roberts et al., 2009). Several scenarios explaining the cessation of the Martian dynamo have been proposed. Some of these include solidification of the core, a premature end to the plate tectonics, and impact heating (Arkani-Hamed and Olson, 2010). The current accepted theory for the loss of the Martian dynamo, impact heating, is explained by Roberts et al. (2009) and Arkani-Hamed and Olson (2010). The theory holds that when enormous impacts such as Utopia, Hellas, and Argyre struck Mars, the massive amount of kinetic energy reduced the heat flow at the core-mantle boundary (CMB) and caused stratification in the core (Arkani-Hamed and Olson, 2010; Roberts et al., 2009). Impacts causing basins with diameters greater than 2,500 kilometers are capable of large-scale reduction of CMB heat flow (Roberts et al., 2009). Core stratification was found to be possible as a result of impacts creating basins larger than 3,000 kilometers in diameter (Arkani-Hamed and Olson, 2010). The global magnetic field is formed by the heat flow at the CMB rotating the fluidized iron core (Roberts et al., 2009). It is estimated that .5 terawatt hours of energy is required to maintain the convection of the core (Roberts et al., 2009). In the event of heat flow reduction, magnetic field reduction can occur in 5,000-20,000 years, with CMB heat flows returning to normal in 13-66 million years (Arkani-Hamed and Olson, 2010; Roberts et al., 2009). Though the CMB heat flow does return, there is no guarantee that the magnetic field will return with it (Roberts et al., 2009). One scenario involves the Martian core operating under subcritical conditions during early formation (Roberts et al., 2009). For convection to occur, the Rayleigh number, which is the product of the Grashof number and the Prandtl number, must be above a critical value (Roberts et al., 2009). The Rayleigh number represents the flow due to convection. The Prandtl number and Grashof number describe the relationship between thermal diffusion and the diffusion of momentum and the relationship between viscosity and buoyancy of a fluid respectively. Temperature within the CMB is the largest driving force for the Rayleigh number being above the critical value needed for internal convection and dynamo functionality, as higher temperatures will reduce viscosity and provide higher buoyancy forces to aid in convection. With the core operating under subcritical temperatures, there would need to be an existing magnetic field for convection to occur (Roberts et al., 2009). In the absence of a magnetic field, the forces caused by the rotation of the planet, known as the Coriolis force, and the shear created by the viscous iron core are equivalent, preventing convection (Roberts et al., 2009). In the presence of a magnetic field, the Coriolis force is partially deflected by the Lorentz force generated by the existing magnetic field (Roberts et al., 2009). This allows for the shear of the fluid to drive motion, and convection is maintained (Roberts et al., 2009). Under this existing magnetic field, it would have been possible for Mars to maintain a magnetic field without meeting the necessary core temperature for convection (Roberts et al., 2009). In this state, the Martian dynamo would be very vulnerable to heat changes in the CMB (Roberts et al., 2009). In a subcritical state, temperature fluctuations as small as 1% can disrupt core convection (Roberts et al., 2009). Once the dynamo is lost, core temperatures must reach 25% above the required temperature for convection to restore the magnetic field (Roberts et al., 2009). Using this model, any of the large impacts should have been enough to disrupt the dynamo, but the dynamo was not lost until after the Utopia impact in the mid-Noachian (Roberts et al., 2009). This suggests that the core originated in a supercritical regime but cooled with each impact until dynamo function was lost (Roberts et al., 2009).

Though Mars appears to be dead, it maintains basic geological function, as observed using the NASA infrared telescope facility located at the University of Hawaii (Steigerwald, 2009). Using spectrometry, the process of splitting light into its base components and observing where the components were absorbed, researchers discovered plumes of Methane escaping from the surface (Steigerwald, 2009). The amount of methane available on mars is disputed; some sources indicate concentrations near 60 ppb, while others reason this is not possible (Zahnle et al., 2011). However, presence of methane on Mars has been confirmed through the comparison of data from the Curiosity rover and European Space Agency (ESA) satellite, Mars Express, during a recorded methane emission from the Martian soil (Giuranna et al., 2019). The overlapping reports from Curiosity and the Mars express satellite confirm a concentration of 15 ppb methane for the event (Zahnle et al., 2011). Methane is produced mainly by biological or geological means (Steigerwald, 2009). Methane produced through geological means requires a heat source and a source of liquid water, both of which are necessary to sustain life (Steigerwald, 2009). This indicates that either life exists below the surface, or geological function is still maintained by Mars, though both are still possible (Steigerwald, 2009).

1.5 Martian Environment

As previously stated, Mars has no magnetic field. The magnetic field protects the planet from solar radiation, and without it, solar winds would remove any atmosphere that was added (Barabash et al., 2007). Figure 1.2 below shows models of the current erosion of the Martian atmosphere by solar winds (Brain et al., 2015). The colored lines indicate relative paths of charged ions being removed from the Martian atmosphere (Brain et al., 2015). For the purpose of this paper, it is assumed that the planet has a functioning dynamo or some form of magnetic shielding.

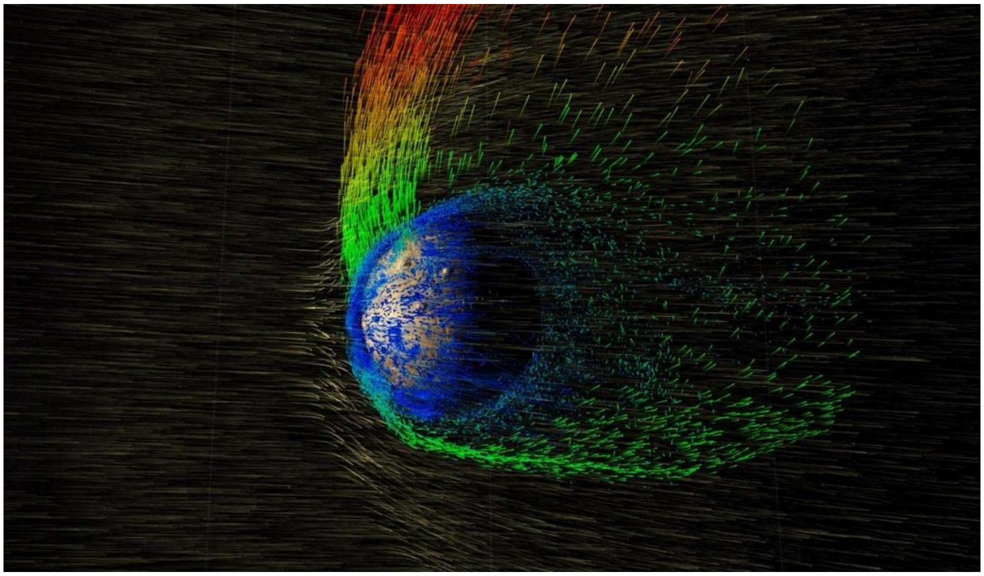

Figure 1.2 **Model of Atmospheric Erosion on Mars by NASA MAVEN Spacecraft.** The MAVEN satellite that orbits Mars monitors the atmospheric boundary layer and space. From the collected data in this region of the Martian atmosphere erosion rates and models can be produced. This model shows the individual ions being removed from the Martian atmosphere. (Garner, 2015)

In September of 2014, NASA's Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft began orbiting Mars (Jakosky, 2015). Using the MAVEN spacecraft instrument suite, data was collected regarding aspects of the Martian atmosphere boundary such as temperature, atmosphere thickness, and weather patterns (Jakosky, 2015). According to data taken by the MAVEN instruments, the current erosion of hydrogen and oxygen by solar winds results in an atmospheric loss of 2-3 kg/s (Jakosky et al., 2018). Based on that value, NASA scientists have extrapolated the thickness of the original Martian atmosphere that contained water long ago and determined that minimum atmospheric pressure of .8 bar of CO_2 (80,000 Pa), compared to the pressure on Earth of 101,325 Pa, was required for current conditions to exist (Jakosky et al., 2018). Thus the Martian atmosphere has been eroding down to current pressure levels of 600 Pa over the last 3.9 billion years.

The atmosphere on Mars is 169 times thinner than that of Earth (Sebastián et al., 2010). As a result, temperatures on Mars are more extreme than on Earth. The average temperature on Mars is -63 ℃ (-81 ℉), as opposed to 14 ℃ (57 ℉) on Earth (Sebastián et al., 2010). Due to the tilt in the Martian axis, like on Earth, Mars has four seasons: Summer, Fall, Winter, and Spring. Unlike on Earth, the seasons on Mars are not the same length; Spring and Summer last about 6 months each, while Fall and Winter last nearly 5 months each ("Mars Mobile," n.d.). The temperature fluctuations on Mars are drastic. In winter near the poles, the temperature can reach as low as -125 ℃ (-195 ℉) (Sebastián et al., 2010). Day and night fluctuations can be just as severe with summer equator temperatures reaching 20 ℃ (70 ℉) in the day and -73 ℃ (-100 ℉) at night (Sebastián et al., 2010). These harsh temperatures pose a problem for any life on the surface, and further reinforce the need for an atmosphere to support colonization efforts.

The gravity on Mars is only 37.5% of that on Earth (Valles et al., 2005). The acceleration due to gravity on Earth is estimated to be 9.81 m/s^2, while the acceleration due to gravity on Mars is 3.711 m/s^2. As a result, structural materials would be more durable with less force pressing down on them, and equipment would weigh significantly less, allowing for more complex handheld systems. This would also reduce the weight of the colonists to nearly a third of their original weight, potentially reducing muscle mass, bone density, and circulation over time, similar to the muscle atrophy observed in the astronauts returning from the International Space Station, ISS (Holick, 2000). Just six months in space results in significant muscle loss (Holick, 2000). However, this muscle mass is regained after resuming normal activity in Earth's gravity. The travel time of six months is generally used when planning missions to Mars (Sridhar et al., 2000). Based on this travel time, the colonists would experience equal muscle atrophy, but with lower gravity conditions on Mars, full restoration of muscle mass is unlikely (Holick, 2000).

Terraformation and colonization efforts will require plants to convert carbon dioxide into oxygen and as a continuous food source. These plants will need a plentiful growing medium on Mars to survive. Sending soil in shuttles is not feasible due to the weight constraints of the rocket, so Martian soil must be used. The mechanical properties of Martian soil are important for the ability of plants to grow and thrive, but also for the structural stability of buildings and other structures. The angle of internal friction, cohesion, and porosity are especially important properties (Perko et al, 2006). The angle of internal friction and cohesion are measures of the ability of the soil particles to cling to each other. Each individual soil particle under pressure applies a frictional force to any particles in contact. This creates a cementation effect, making the soil more solid. Porosity is a measure of the amount of free space in the soil when not under compaction. This affects the looseness of the soil and the ability for it to hold water. The higher the porosity of a soil, the easier it is for water to flow directly through it. Table 1.3 shows measurements taken on Martian soil simulants made by NASA in the Jet Propulsion Laboratory (Perko et al, 2006).

Table 1.3 **Martian Soil Simulant Properties.** Properties of the Martian soil have been well studied for the purpose of testing and calibrating the rovers Opportunity and Curiosity. The values shown in the table are the most important parameters for understanding the stability of Martian soil. (Adapted from Perko et al, 2006).

	Uncompacted		Compacted
Sample	Porosity (%)	Angle of Friction (°)	Cohesion (N/cm^2)
JSC-1	0.53	40.8	.061

Sample JSC-1 is a Martian soil simulant made to test the structural properties for future Mars landings and rover maneuverability (Perko et al, 2006). The angle of internal friction, cohesion, and porosity of Earth silt are shown in Table 1.4.

Table 1.4 **Characteristics of Common Earth Silt Soil.** A large portion of planting soil on Earth can be considered silt. The values are for direct comparison with Martian soil. These values were identified by Bowling Green State University, for the geology program. (Onasch, n.d.)

Earth soils	Angle of Internal Friction (uncompacted) (average) (°)	Cohesion (compacted) (average) (N/cm^2)	Porosity (uncompacted) (average) (%)
Silt	34	7.5	45

Comparing the characteristics of the Earth silt with those of the JSC-1 Martian soil simulant can reveal differences in building and planting needs. The difference in cohesion and friction angles reveals that Martian soil is less structurally stable than most Earth soil. The angle of internal friction of the Martian soil simulant is approximately 6 degrees higher than Earth soil. This indicates a higher tendency to move under pressure. The cohesion of the Martian soil simulant is nearly 20 times smaller than that of Earth silt, indicating that the soil particles are much less likely to stay together. The average porosity of Earth soil is 8% less than the average of the Martian simulant, when also considering the sandy nature of the Martian regolith, this indicates a lower water retention in Martian soil. When watering plants on Earth, there is a maximum amount of water that should be added to soil for growing purposes based on the saturation point of the soil and the evapotranspiration rate of the plant-soil system (Huffman et al., 2013). Evapotranspiration represents the net water loss in a system after gravitational drainage and represents the cumulative amount of water lost from evaporation to the atmosphere and transpiration by the plant. Based on the properties of the soil and Mars' inability to retain water vapor in its atmosphere, growing operations would likely need to occur indoors with systems in place to catch and recycle the water draining from the bottom of the soil systems.

Wamelink et al (2014) studied the feasibility of growing crops on Mars experimentally by planting tomato, cress, and wheat in Martian and Lunar soil simulants on Earth. Their growth was observed over 50 days at constant conditions of 21∓3.02°C and relative humidity of 65.0∓15.5%. The Martian soil simulant JSC-1, shown in Table 1.3, and the Lunar soil simulant JSC1-1A were prepared by the NASA Jet Propulsion Laboratory for this experiment, and coarse river rhine from a depth of 10m was used as the control (Wamelink et al., 2014). At this depth, nutrients concentrations are lower, and there is no organic material (Wamelink et al., 2014). The mineral composition of Martian soil was determined based on data from Mars Pathfinder (Wamelink et al., 2014). Table 1.5 shows various minerals found on Earth and compares them to the quantities found on Mars and the Moon. The mineral composition of the Martian soil is comparable to the Earth soil control except that it has a high concentration of perchlorate salts (ClO_4^-) that seem to have been ignored in this experiment. The major differences in the mineral composition are in the lack of usable nitrogen in the form of nitrate (NO_3^-) and the large quantities of potassium in the soil (Wamelink et al., 2014).

Table 1.5 Comparison of Nutrient Content in Mars, Lunar, and Earth Soil. Given is a list of the nutrient composition of Earth, Lunar, and Martian soil with averages. Major nutrients like nitrogen and carbon and listed toward the right and micronutrients like aluminum and potassium are listed to the left. (Adapted from Wamelink et al., 2014).

Method		ICP-AES extraction in 0.01 M $CaCl_2$				SFA extraction in 0.01 M $CaCl_2$	pH at 20±1 °C	LCEO-CHN	
Element		Al	Fe	K	Cr	(NO^3+NO_2)		C	N
Unit		mg/kg	mg/kg	mg/kg	µg/kg	mg/kg		g/kg	g/kg
Detection limit		0.5	3.0	3.0	5.0	0.5		3.0	0.3
Averages	Earth	0.0	0.0	4.7	2.0	4.2	8.3	3.2	0
	Mars	0	0	138.0	0	2.1	7.3	30.1	2.5

Plants grown in the Martian soil simulant produced the most biomass compared to those in the other two soils (Wamelink et al., 2014). The plants in all three soils were able to germinate and produce flowers or seeds (Wamelink et al., 2014). Many of the plants grown in the Lunar simulant soil died, likely due to high pH and free aluminum values (Wamelink et al., 2014). These results suggest that using Martian soil as the growth medium for plants is mechanically possible, assuming the Martian soil simulant matches real Martian soil closely enough (Wamelink et al., 2014).

The mass spectrometer and gas chromatograph in the Curiosity rover's instrument suite identified usable nitrogen in the soil in the form of nitrate (NO_3^-) (Stern et al., 2015). Most nitrogen on Earth is found in the form of nitrogen gas (N_2), but this form of nitrogen is so stable that the nitrogen atoms are unusable by most living organisms (Stern et al., 2015). This nitrogen must be fixed or converted to a less stable form to be usable, generally nitrate (NO_3^-) or ammonia (NH_3). The concentration of the nitrate in the soil was approximated as up to 1,100 parts per million (ppm) (Stern et al., 2015). This yields roughly .11% nitrate composition in the soil. These values are similar to the estimated planetary averages, based on volcanic activity on Mars, of 3,040-6,080ppm (Smith et al., 2014). The nitrate levels in unfertilized soil on Earth range from 5 to 10 ppm with the ideal value being higher than 30 ppm for a vegetable garden (Sullivan et al., 2019). The concentration of nitrates sequestered in Martian soil could provide more than adequate nitrogen concentrations for growing crops.

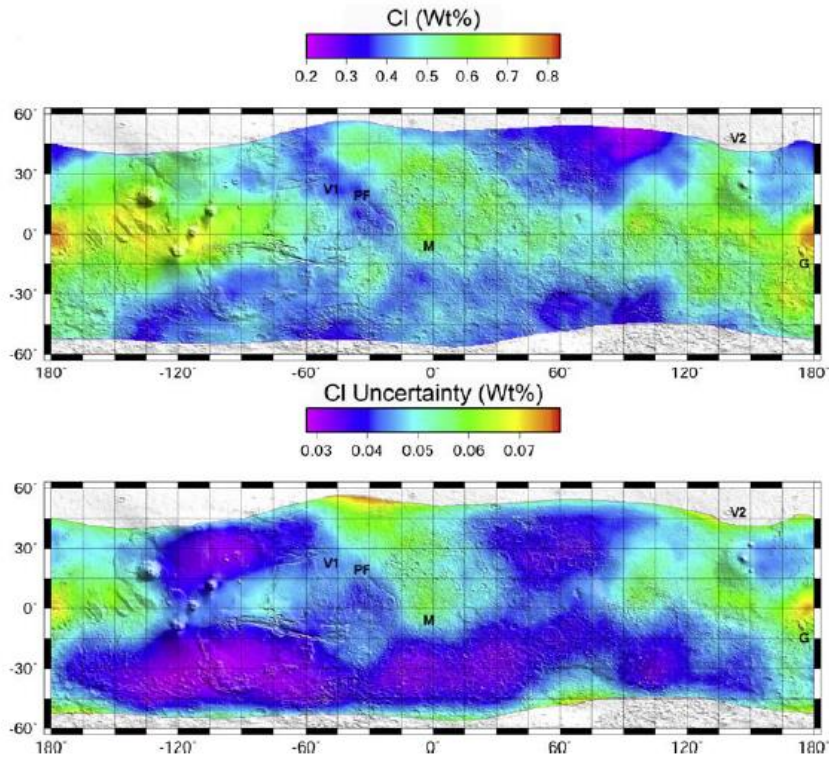

Figure 1.3 **Weight Percent of Chlorine Found in the Equatorial Soil of Mars.** Using the Mars Odyssey Gamma Ray Spectrometer (GRS) mid-latitude perchlorate concentrations were identified in the top meter of Martian regolith. These scans show the largest amount of perchlorate sequestration in equatorial soil. (reproduced with permission from Keller et al., 2007)

During the Odyssey, Viking, Phoenix, and Curiosity landings, perchlorate was identified in the Martian soil (Davila et al., 2013). Perchlorate, which is mostly produced commercially as a major ingredient in solid rocket fuel, is toxic to humans and is linked to hypothyroidism (Davila et al., 2013). This is caused by the thyroid gland having a higher affinity for perchlorate than for iodide, the main ingredient in most hormones (Wang and Coates, 2017). Concentrations of perchlorate on Earth range from the minimum detectable limit (MDL) of 4 μg/L to over 3.7 g/L and can be utilized by microbes for growth (Davila et al., 2013). The reduced species chlorate and chlorite are linked to the development of methemoglobinemia, a condition in which hemoglobin is converted to a form that cannot transport oxygen (Wang and Coates, 2017). When chlorate and chlorite come into contact with the heme group of hemoglobin they push the iron atom from its 2+ oxidation state to its 3+ oxidation state. This causes the heme group to have a higher affinity for oxygen preventing it from releasing the oxygen to the body (Wang and Coates, 2017). Based on an experiment conducted by the Mars Odyssey Gamma Ray Spectrometer, shown in Figure 1.3, the average concentration of chlorine in the Martian equatorial soil is 4900 ppm, or mg/L (Keller et al., 2007). Figure 1.3 also shows that some of the highest concentrations of chlorine are found directly along the equator, which is otherwise the optimal location for colonization due to the longer exposure to solar radiation and more temperate climate. This poses problems for using Martian soil as a growth medium for plants that produce food.

Perchlorate and the reduced forms chlorate, chlorite, and hypochlorite are all soluble in water. This allows for plants to absorb them from their environment (He et al., 2013). Environmental perchlorate concentrations of over 500 mg/L severely reduce chlorophyll content, root length, root weight, aboveground weight, and root oxidizing power, and perchlorate accumulation in edible plants could lead to human exposure (He et al., 2013). Plant leaves and vascular tissue tend to sequester more perchlorate than fruiting bodies and seeds do, making fruiting plants such as tomatoes a safer option than leafy plants such as cabbage, spinach, and lettuce (He et al., 2013). For the safety of colonists, the perchlorate would need to be removed from the soil, by solubilizing the perchlorate in water, prior to planting.

Chapter 2 - Process

The methods for this report follow a sequential process of information gathering, analytical processes, and calculations based on data. The process begins with a literature review of the conditions on Mars and synopsis of current research relevant to the terraforming process. From this information, materials available for conversion as part of the terraforming process are identified and efficient means of utilization considered. Further literature review into the utilization processes produced the realistic resources for conversion. Based on the amounts of these resources determined, calculations were conducted to discover if terraforming the planet was viable given the project assumptions. Based on these calculations, focus was redirected toward aiding in the colonization of the planet.

The literature review set forth in Chapter 1 on the conditions of Mars set the baseline for the terraforming feasibility study described herein. This began with analyzing the history of the planet. Mars was not always the barren wasteland that it is perceived as today. There is evidence that suggests the Martian environment contained water, an atmosphere, and a magnetic field (Jakosky et al., 2018). Evidence of large amounts of water on Mars is shown by the vast network of valleys and drainage systems detected by the Mars Global Surveyor (Hynek and Phillips, 2003). The original atmosphere of the planet was predicted to have a lower limit pressure of 0.8 bar, which is approximately 80% of the atmospheric pressure felt on Earth at sea level (Jakosky et al., 2018). The cessation of the Martian dynamo through the impact heating of the Martian core is thought to be the sole cause for the planets current state (Roberts et al., 2009). The ability of Mars to shield its atmosphere from erosion by solar winds is paramount (Jakosky et al., 2018). For this reason, it is assumed that the dynamo is restored, or that an artificial magnetic shield is created before terraforming.

There are many resources available on Mars. These resources are predominantly present in the Martian soil, with the exception of Martian methane reserves. These resources include iron oxide, perchlorate, sulfate, nitrate, and methane. These compounds show promise for conversion into atmospheric oxygen and nitrogen along with energy production. Nitrates in the soil would provide a source of N_2 gas. This is important for building an atmosphere, as nitrogen is highly stable and is non-reactive in human lungs. Without the presence of an inert gas like nitrogen, adequate pressure needed for survival would not be possible. Perchlorate, sulfate, nitrate and iron oxide could be used as oxygen sources. Perchlorate can be biologically reduced into oxygen and chloride by dissimilatory perchlorate-reducing bacteria (DPRB) (Wang and Coates, 2017). Nitrate and sulfate can also be reduced through denitrification and the DMSO pathway respectively (Nilsson et al., 2013). This is also beneficial, as perchlorate and sulfate are toxic to humans and would ideally need to be removed from soil before use for safety concerns. These processes occur biologically and are linked to the growth of many microorganisms. Iron oxides in the soil can be used to produce oxygen and structural material through smelting. The methane detected with a lower limit of 15 ppb could be used as an energy source, while also producing water from the combustion reactions.

For these resources to be used, an efficient means of conversion will be needed. When rockets are being constructed using current technology, the weight of the shuttle and payload versus the amount of fuel needed is determined using the ideal rocket equation (Benson, 2014). The equation dictates that for a shuttle to leave the atmosphere, 90% of the total weight must be fuel (Benson, 2014). After accounting for the weight of the structure of the shuttle and the engines, the final payload weight is only 1% of the total weight of the rocket (Benson, 2014). With such strict weight requirements, everything must be as streamlined as possible. Due to weight restrictions, shuttling a blast furnace to Mars for iron smelting is not feasible. This even limits the processes that can be used to biologically reduce the perchlorate, sulfate, and nitrate, as most reactions of this nature require a chemical electron donor to facilitate the reduction. When considering converting an entire planet worth of resources, a proportional supply of chemical electron donor would be required. The issue of weight led to research into bioelectrochemical reactor (BER) technology.

Normally the reduction of perchlorate, sulfate, and nitrate is facilitated using an electron donor, most commonly acetate (Wu et al., 2008). For the purpose of reducing travel costs to the planet, a method that does not require an additional chemical to carry out the reduction is necessary. Bioelectrochemical reduction is a form of reduction that utilizes the electrons from a cathode directly (Xie et al., 2014). Several species of microorganisms have been identified that are able to utilize electrons directly from the cathode of a BER without the use of an electron shuttle (Su et al., 2012; Xie et al., 2014). One of the primary advantages of the BER, as shown in figure 2.1, is that the water consumed during hydrolysis near the anode is produced near the cathode, allowing for the continuous use of the same very limited water supply for microbial activity (Wang and Coates, 2017). This process reduces perchlorate at a rate of 100 mg/L per day compared to acetate reduction being 664 mg/L per day (Xie et al., 2014). The acetate reduction is much faster, but the mass of acetate required to convert necessary perchlorate and nitrate in the soil is too large for practical transport. Considering the voltage required for the reduction is -0.5 volts, using the BER system would allow the reduction process to take place using solar panels or nuclear reactors equipped to any future Martian facilities.

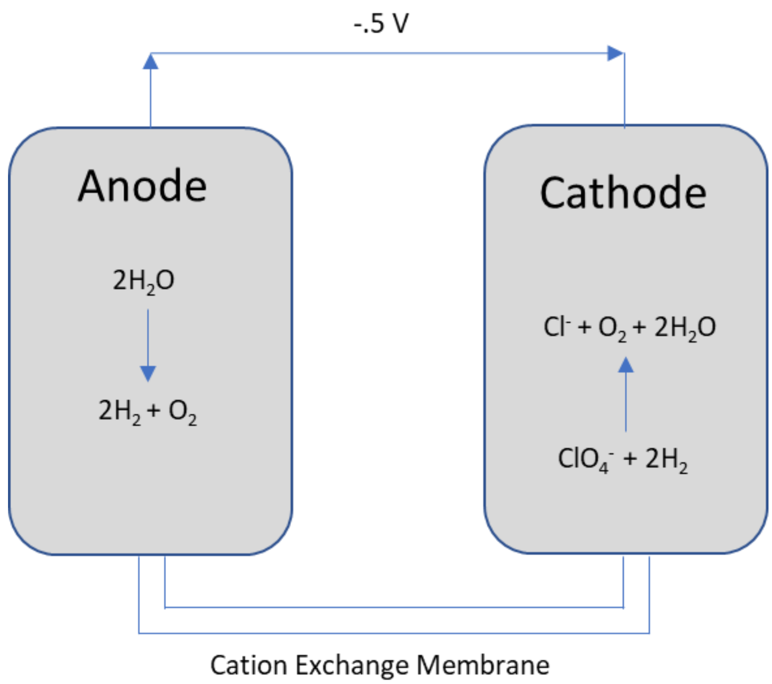

Figure 2.1 Diagram of Reactions Inside of the BER System. In general, the species are reduced in the cathodic chamber using electrical current as the sole electron donor. Some species use hydrogen as the electron donor which is generated through hydrolysis near the anode, as shown above. In the case of nitrate reduction, nitrate will be reduced to ammonia near the cathode then converted from ammonia to nitrogen near the anode.

When both nitrate and perchlorate are present in a BER, the nitrate will have an inhibitory effect on the reduction of perchlorate, depending on the microorganisms used (Xie et al., 2014). Nitrate is preferentially reduced in the BER system over perchlorate, increasing residence times for oxygen generation. Nitrate concentrations as low as 0.07 mM nitrate or 4.3 ppm can have an inhibitory effect on perchlorate reduction using the BER (Xie et al., 2014). To solve the problem of inhibition of perchlorate reduction by nitrate, two strains of bacteria will likely need to be sent to Mars: one strain to reduce the nitrate and the other a DPRB. This could prevent the inhibition of perchlorate reduction and take advantage of the nitrogen production as well. The reaction rate of 50 mg/L per day from the Xie et al. pilot scale experiment was used. These reactions were conducted under the conditions of 30 ±1°C for the temperature of the reactions, inoculation of basal medium as described in Xie et al., and a poised voltage potential of -.5V. Using this method, the breathable atmosphere could be generated from the perchlorate and nitrate in the soil.

Alternatives to BER for converting compounds held in Martian soil to atmospheric components have also been developed. For example, systems for the use of Martian soil for the production of oxygen have already been designed on a small scale for emergency oxygen generation (Davila et al., 2013). The enzymes involved in the reduction of perchlorate are perchlorate reductase and chlorite dismutase (Wang and Coates, 2017). This reduction occurs in a two-step a process: the perchlorate reductase reduces the perchlorate to chlorate and then chlorate to chlorite, and the chlorite dismutase reduces chlorite to chloride ion and oxygen (Wang and Coates, 2017). Using purified reserves of these enzymes, a device has been constructed that can convert the perchlorate in the Martian regolith into oxygen for an astronaut to use (Davila et al., 2013). Adding Water and 100 g of purified enzymes to as little as 6 kg of Martian regolith can generate an entire day worth of oxygen, or 550 liters, in under an hour (Davila et al., 2013). This process could act as a replacement for BER technology.

Select areas of the Martian soil have been analyzed through various NASA and ESA missions. The data collected from the Opportunity, Curiosity, Voyager, MAVEN, and Mars Express missions have yielded a large amount of data on the Martian environment – including estimates of the amounts of perchlorate, sulfate, and nitrate comprising Martian soils – but great speculation is involved in any analysis of Mars. The concentration of perchlorate within the top meter of the Martian soil has been identified (Keller et al., 2007). The Martian soil contains a mean of .49 wt% chlorine (Keller et al., 2007). This information was gathered from the Mars Odyssey Gamma Ray Spectrometer in 2001 during a near-surface pass in the orbit (Keller et al., 2007). Assuming that the majority of the chlorine is in the form of perchlorate, the soil contains

.882 wt% oxygen from perchlorate, which can be converted to its molecular form. Similarly, assuming that nitrogen in the soil is mostly in the form of nitrate, 1.03 wt% of the soil is oxygen in the form of nitrate. The nitrate and sulfate concentrations were predicted using volcanic flux patterns in the planet's past (Smith et al., 2014). The average estimates were 1.35 wt% and .3 wt% in the top 2 meters of soil for sulfate and nitrogen respectively (Smith et al., 2014).

2.1 Calculations

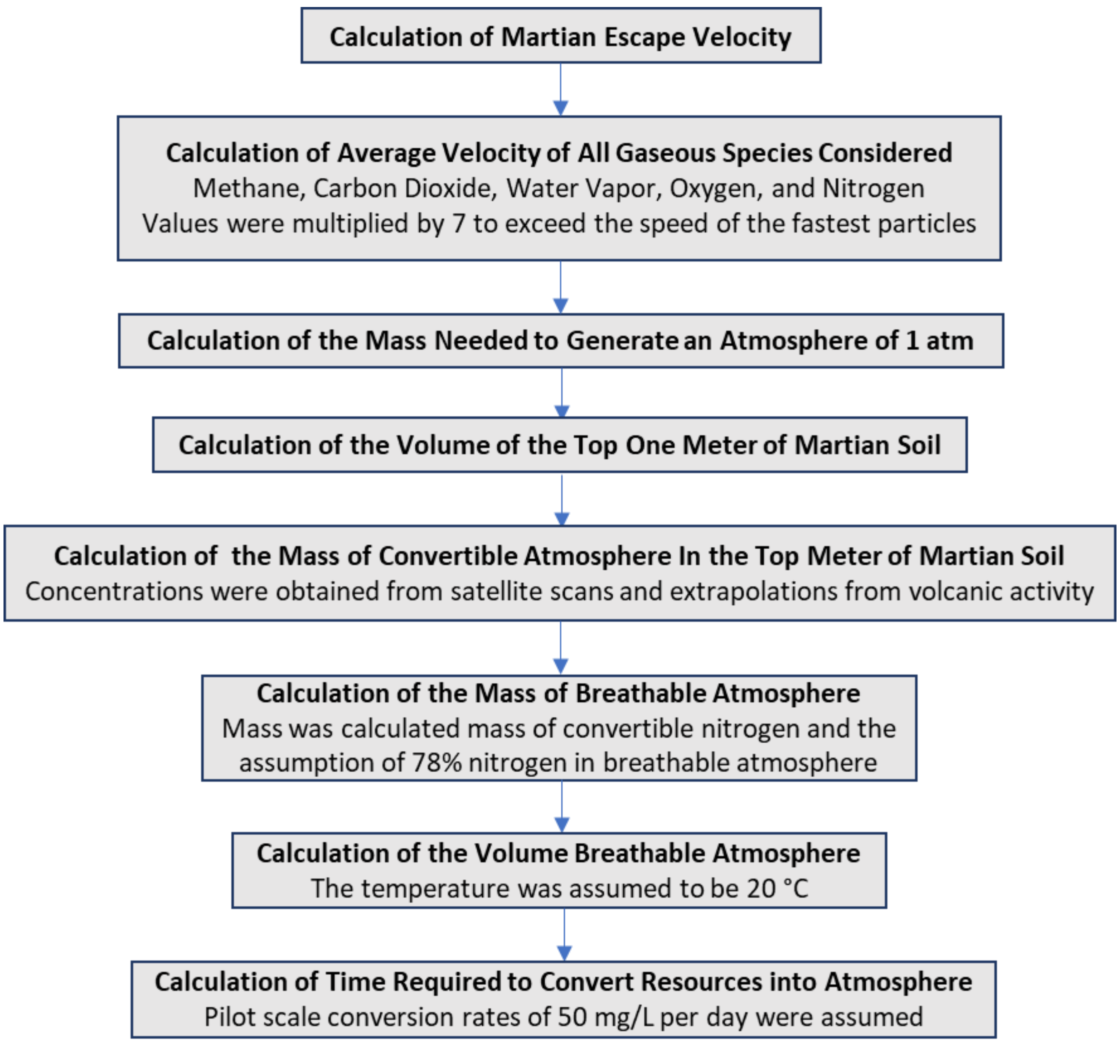

Figure 2.2 Calculation Flow Diagram. Each calculation is listed in the order used with any assumptions displayed below.

Calculations were required to determine whether the Martian gravity is sufficient to maintain the needed atmospheric gases, the amount of atmosphere needed to create near Earth conditions at 1 atm, the amount of atmosphere that can be created from soil reserves, and the time frame for atmosphere production through bioconversion.

Mars is much smaller than Earth. The Martian acceleration due to gravity of 3.71 m/s^2 is used to determine the possible consistency of a future Martian atmosphere (Williams, 2018a).

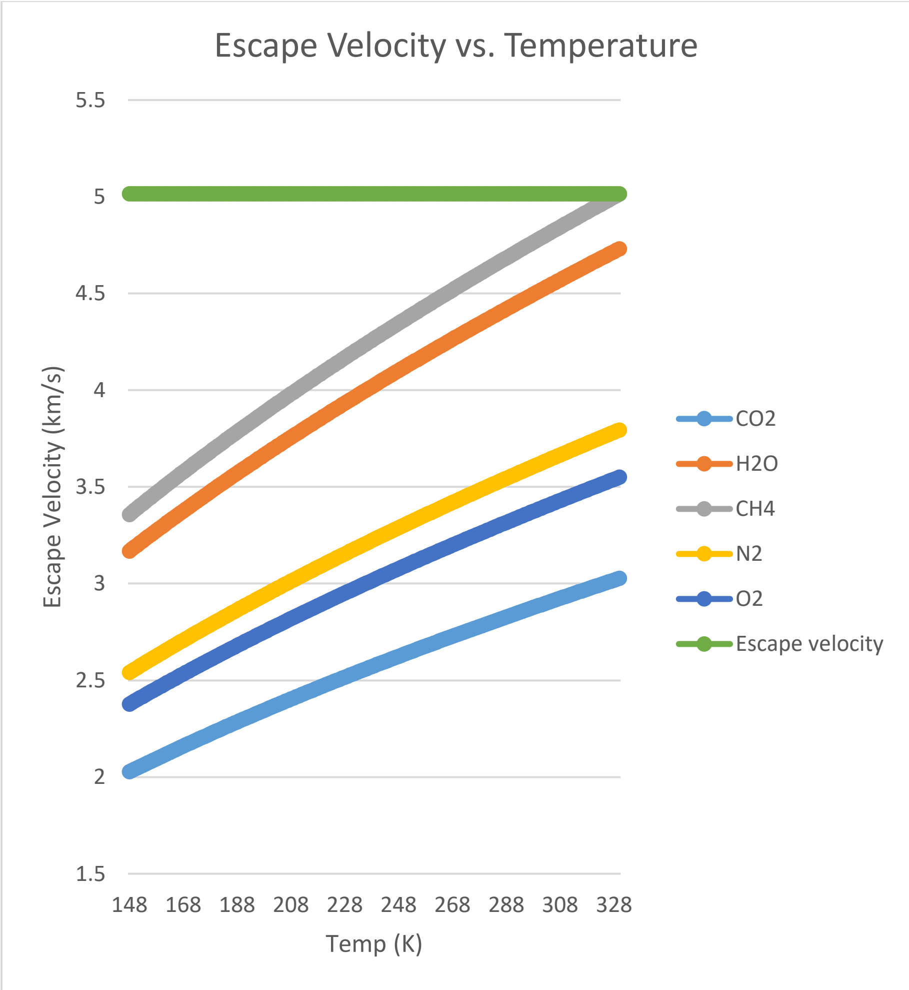

Figure 2.3 Atmospheric Retention Curve. Methane, water vapor, nitrogen, oxygen, and carbon dioxide were identified as key atmospheric gases. At the range of temperatures considered, Mars is currently capable of retaining all of the identified species, even at temperatures well above normal Martian temperatures.

Figure 2.1 shows the results for calculating the escape velocity of Mars in comparison to the fastest particles in each gas mixture. The escape velocity of Mars was calculated using Equation 2.1:

$$\textbf{Equation 2.1} \qquad \boldsymbol{V_{Escape} = \left(\frac{2GM}{R}\right)^{.5}}$$

where G is Newton's universal gravitational constant (6.67 x 10^{-11} N m^2 kg^{-3}), M is the mass of the planet in question [kg], and R is the radius of the planet [m] ("Escape velocity," n.d.). The average velocity of a gas mixture can be calculated using Equation 2.2:

$$\textbf{Equation 2.2} \qquad \boldsymbol{V_{Average} = \left(\frac{3kT}{m}\right)^{.5}}$$

where k is the Boltzmann constant (1.38 x 10^{-16} g cm^2 s^{-2} K^{-1}), T is the temperature [K], and m is the molecular mass of each particle [g] ("Escape velocity," n.d.). Once the average speed of each particle at the specified temperature is calculated, this value is multiplied by seven to account for the fastest moving molecules in the mixture. The value of seven was selected as the multiplication factor because the fastest particles in a mixture of gas particles tend to move four to six times faster than the average speed ("Escape velocity," n.d.).

The amount of atmospheric mass needed to create pressure conditions of 1 atm, (101,325 Pa) (101.325 Bar), can be calculated using Equation 2.3:

$$\textbf{Equation 2.3} \qquad \boldsymbol{M = \frac{PS_a}{G}}$$

where M is the mass required [kg], P is the pressure [Pa], S_a is the surface area of the planet [m^2], and G is the acceleration due to gravity [m/s^2]. The same equation can be used to determine the current amount of mass in the Martian atmosphere. Taking the mass required for an atmospheric pressure of 1 atm and subtracting the current atmospheric mass results in the mass needed for the creation of an atmosphere. The concentrations of the three compounds of interest (perchlorate, sulfate, and nitrate) can then be multiplied by the volume of the top meter of the Martian soil. The volume was found using Equation 2.4:

Equation 2.4 $$V_{Top\ Meter} = \frac{4}{3}\pi R^3 - \frac{4}{3}\pi(R-1)^3$$

where R is the radius of the planet [m]. The average radius of, 3,389 km was used, and the planet was assumed to be spherical. This method was used for each species other than carbon dioxide, the mass of which was obtained from an article published by NASA (Jakosky and Edwards, 2018). The mass of atmosphere that can be converted from soil was calculated using Equation 2.5:

Equation 2.5 $$M = V\rho C$$

where M is the atmospheric mass [kg], V is the volume of the soil used [m^3], ρ is the density of the soil layer [kg/m^3], and C is the weight percent of each compound in the soil [wt%]. Using the density of 1520 kg/m^3, the convertible mass was totaled and compared to the amount needed for a stable atmosphere. The amount of atmosphere able to be created for habitation facilities was also calculated from these numbers.

Nitrate is the limiting ingredient for atmosphere creation. This is due to perchlorate, sulfate, and nitrate being able to produce oxygen while only nitrate can be used to generate nitrogen. Dividing the available mass of nitrogen by .78 yields the maximum mass of breathable atmosphere that can be generated, assuming the nitrogen concentration must be the same as that on Earth for the atmosphere to be breathable. Using the ideal gas law, Equation 2.6:

Equation 2.6 $$V = \frac{MRT}{mP}$$

where V is the volume created [m^3], M is the mass of the gas [g], R is the ideal gas constant [J/molK], T is the temperature [K], m is the molar mass of air [g/mol], and P is the pressure [Pa], the volume of breathable atmosphere was calculated . The value of 28.97 g/mol was used for the molar mass of air, a temperature of 20 ℃, 293.15 K, for T, and Pressure of 101,325 Pa for pressure. This calculation result yields the volume of convertible atmosphere for habitation facilities.

Lastly, the length of time required to convert the compounds into atmosphere was calculated. Using the assumptions of steady-state conditions and constant conversion rate based on pilot scale tests, the conversion time was determined to be 50 mg/L per day of operation. Using this conversion rate, the amount of time to convert the nitrate to atmosphere can be found for differing total reactor volumes.

Chapter 3 - Results

The Escape velocity required for each of the proposed gases, e.g. methane, carbon dioxide, nitrogen, oxygen, and water vapor, was calculated at a range of temperatures from 148 K to 330 K (Figure 2.3). The results show a temperature threshold for methane near 330 K, well above observed temperatures on Mars, meaning that Mars is capable of maintaining an atmosphere composed of these compounds, assuming the magnetic field is restored and atmospheric erosion ceases.

The amount of atmosphere that can be generated was calculated by multiplying the concentrations of each species (perchlorate, sulfate, and nitrate) by the volume and density of the soil. Using an average radius of 3,389 km and the equation for volume of a sphere, the volume of the top meter of the soil was found. Using this data, the mass of the species available for conversion was compared to the mass of the atmosphere needed to maintain 1 atm, 101,325 Pa. The mass required to create an atmospheric surface pressure of 1 atm is 3.94E+18 kg. The amount that can be generated by each of the three species is shown below in Table 3.1.

Table 3.1 Soil Elements Available for Mobilization into Atmosphere. The top panel of the table describes the amount of mass currently in the Martian atmosphere and the amount needed to form an atmospheric pressure of 1 atm. Breath able atmosphere mass is defined as having 78% mass of nitrogen. Calculations of the mass of each of the compounds identified based on the volume of top meter of the planet are presented in the lower panel.

	Radius (m)	Surface Area (m^2)	Pressure (Pa)	Atmospheric Mass (kg)
Needed	3.39E+6	1.44E+14	101325	3.94E+18
Current	3.39E+6	1.44E+14	600	2.33E+16
	Volume of Soil (m3)	Atmospheric Mass (kg)	Breathable Mass (kg)	
Current Atmospheric Mass		2.33E+16		
Perchlorate Mobilization	1.44E+14	1.93E+15		
Sulfate Mobilization	1.44E+14	2.96E+15		
Carbon Dioxide Mobilization		7.76E+16		
Nitrate Mobilization (nitrogen)	1.44E+14	6.58E+14		
Nitrate Mobilization (oxygen)	1.44E+14	2.26E+15		
	TOTALS:	1.09E+17	8.44E+14	
	PERCENT TOTALS:	2.76%	0.02%	

Table 3.1 displays the amount of overall atmosphere and breathable atmosphere that can be created from all sources. The difference between these two numbers is the breathable atmosphere contains 78% nitrogen gas while the other is an indiscriminate mixture. Both of these totals are far less than the amount needed to terraform the planet. The total gas mixture is 2.8% of the needed mass and the breathable gas mixture is less than 1%. Under ideal gas conditions (20°C and 1 atm), the mass of the breathable mixture would occupy a volume 7.01E+14 m^3. This volume is the equivalent of over 200 million Superdome sized facilities.

The final calculation yielded the time required for conversion of the breathable mass in the soil. This was done using the conversion rate of 50 mg per liter of reactor per day (Xie et al., 2014). Using this value and the calculated mass of breathable atmosphere, the time required can be calculated for differing total reactor volumes. Table 3.2 shows the time required to mobilize 1

Superdome, or 3,500,000 m^3, of the nitrate in the Martian soil into atmospheric nitrogen and oxygen.

Table 3.2 Reaction Times to Generate 1 Superdome of Volume Using a BER. These conversion times are for the conversion of 3,500,000 m^3 of breathable atmosphere. This requires a mass of 4.22E+12 mg to be converted into atmosphere. Using the conversion rate of 50 mg/L per day, the time for the required mass conversion using each volume was calculated.

Total volume of reactors (L)	Time (days)	Time (years)
1E+2	8.43E+08	2.31E+06
1E+3	8.43E+07	2.31E+05
1E+4	8.43E+06	2.31E+04
1E+5	8.43E+05	2,308.07
1E+6	84,302.26	230.81
1E+7	8,430.23	23.08
1E+8	843.02	2.31
1E+9	84.30	0.23
1E+10	8.43	0.02

Based on the rates of reaction shown above, the conversion of perchlorate and nitrate would require a total reactor volume of 100,000,000 liters for the reaction to proceed in a reasonable amount of time.

Chapter 4 - Discussion

The current technology is insufficient to terraform the planet. To make Mars into a second Earth would require an enormous amount of resource addition: 36 times the amount currently on the planet, with the largest addition being nitrogen gas. The Atmospheric Retention Curve shown in Figure 2.1 displays the potential for Mars to possess an atmosphere in the future. This atmosphere could partially be created using resources on Mars, but the concentrations of perchlorate, sulfate, and nitrate in the soil cannot support the creation of a fully functional atmosphere. Pools of resources from earth or the asteroid belt would need to be brought to Mars for the terraforming process to be possible.

The concentrations available could be used to create atmospheres for habitation facilities. These facilities would house the inhabitants for the duration of their time on Mars. Any outside operations would require the use of a space suit and oxygen supply. Living spaces, food production, water treatment, and research areas would all be incorporated into the artificial habitat. The total amount of volume able to be created, though not enough to terraform the planet, would produce a tremendous amount of atmospheric volume: over 200 million Superdomes worth of space. This would be sufficient to sustain a large population on Mars if the appropriate facilities were to be built.

Though the resources are available for conversion, rates of reaction in the BERs are too low for time frames to be realistic. The volume of oxygen used by an average adult human being is 550 L/d, or 662 g (Davila et al., 2013). Based on the reaction rates for the BER, it would take over 100 days in a 100 L reactor to produce this volume. The reaction rates would have to be increased by a factor of thousands to become a realistic conversion method.

Chapter 5 - Conclusion

To terraform or even colonize the planet Mars will require the development of many new technologies, and further research is required. The resources on the planet are insufficient for terraforming but would exceed the needs for colonizing the planet with habitation facilities. The perchlorate, sulfate, and nitrate found in the soil could be converted into breathable air with excess reserves of oxygen. The conversion process proposed using BER technology is highly resource efficient, but the conversion times are abysmal. This poses a large problem for the colonization of Mars, as creating even a meager amount of atmosphere would take years using this method.

Future research into faster conversion rates for the BER technology could yield a promising future for Mars. Processes using purified enzymes of perchlorate reductase, chlorite dismutase, nitrate reductase, nitrite reductase could provide the reaction rates needed to make colonization a reality. Further research into reaction rates using different high-efficiency methods of reduction and innovative reactor designs will be needed to make the colonization of Mars realistic. Designs of these processes, reactors, and the habitations facilities themselves will be the future goals of biological systems engineering in the field of Mars colonization.

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Appendix A - Sample Calculations

1.) Calculation of Surface Area of Mars:

$$S_a = 4\pi r^2$$

r=Radius of Mars=3890 km
$4\pi 3890km^2 = 1.44E + 8\ km^2$

2.) Calculation of Martian Escape Velocity:

$$V_{Escape} = \left(\frac{2GM}{R}\right)^{.5}$$

G=Newton's gravitational constant=6.67E-11 N m^2 kg^{-2}
M=Mass of Mars=6.39E+23 kg
R=Radius of Mars=3389000 m

$$\left(\frac{2\left(6.67E-11\frac{N\,m^2}{kg^2}\right)(6.39E+23kg)}{(3.39E+6m)}\right)^{.5} = 5015\frac{m}{s}$$

$$5015\frac{m}{s} \times \frac{1km}{1000m} = 5.015\frac{km}{s}$$

3.) Calculation for Average Velocity of a Gas Mixture:

$$V_{Average} = \left(\frac{3kT}{m}\right)^{.5}$$

k=Boltzmann constant=1.38E-16 g cm^2 s^{-2} K^{-1}
T=Temperature=328 K
m=Molecular Mass of Methane=2.66E-23 g

$$\left(\frac{3\left(1.38E-16\frac{g\ cm^2}{s^2\ K}\right)328K}{(2.66E-23g)}\right)^{.5} = 7.14E+4\frac{cm}{s}$$

$$7.14E+4\frac{cm}{s} \times \frac{1km}{100000cm} = .714\frac{km}{s}$$

4.) Calculation for Atmospheric Mass:

$$M = \frac{PS_a}{G}$$

P=pressure=101325 Pa
S_a=surface area of Mars=1.44E+11 m^2
g=acceleration of gravity on Mars=3.71 m s^{-2}

$$\frac{101325Pa(1.44E+11m^2)}{3.71\frac{m}{s^2}}$$ = 3.94E+18 kg

5.) Calculation for Volume of the Top Meter of Martian Soil:

$$V_{Top\ Meter} = \frac{4}{3}\pi R^3 - \frac{4}{3}\pi(R-1)^3$$

R=radius of Mars=3389000 m

$$\left[\frac{4}{3}\pi(3.39E+6m)^3 - \frac{4}{3}\pi\big((3.39E+6m)-1\big)^3\right] = 1.44E+11\ m^3$$

6.) Calculation of Convertible Mass of Nitrate to Nitrogen Gas:

$$M = V\rho C$$

V= volume of top one meter of Martian soil=1.44E+11 m^3
ρ=density of Martian soil=1520 kg m^{-3}
C=weight percent of nitrogen=.003

$$(1.44E+11m^3)\times 1520\frac{kg}{m^3}\times .003 = 6.58E+14kgN_2$$

7.) Calculation for Volume Breathable Atmosphere for Habitation Facilities:

$$V = \frac{MRT}{mP}$$

M=Mass of gas converted=8.44E+17 g
R=ideal gas constant=8.3144598 J mol^{-1} K^{-1}
T=temperature=293.15 K
m=molar mass of air=28.97 g mol^{-1}
P=pressure=101325 Pa

$$\frac{(8.44E+17g)\times 8.3144598\frac{J}{mol\,K}\times 293.15K}{28.97\frac{g}{mol}\times 101325Pa} = 7.01E + 14m^3$$

8.) Calculation for Time Required to Convert One Superdome of Breathable Atmosphere in the BER System:

$$T = \frac{M}{VZ}$$

M=4.52E+12 mg
V=total volume of reactors=1E+8 L
Z=reaction rate=50 mg L^{-1} day^{-1}

$\frac{(4.52E+12mg)}{(1E+8L)\times 50\frac{mg}{L\,day}}$ (4.52E+12)/((1E+8)50)=904.75 days

Appendix B - Excel Spreadsheet Data

Table B 1 Atmospheric Mass Excel Data

	Radius (m)	Surface Area (m^2)	Pressure (Pa)	Atmospheric Mass (kg)
Needed	3.39E+6	1.44E+14	101325	3.94E+18
Current	3.39E+6	1.44E+14	600	2.33E+16
	Volume of Soil (m3)	Atmospheric Mass (kg)	Breathable Mass (kg)	
Current Atmospheric Mass		2.33E+16		
Perchlorate Mobilization	1.44E+14	1.93E+15		
Sulfate Mobilization	1.44E+14	2.96E+15		
Carbon Dioxide Mobilization		7.76E+16		
Nitrate Mobilization (nitrogen)	1.44E+14	6.58E+14		
Nitrate Mobilization (oxygen)	1.44E+14	2.26E+15		
	TOTALS:	1.09E+17	8.44E+14	
	PERCENT TOTALS:	2.76%	0.02%	

Table B 2 Breathable Atmospheric Volume Calculations

Pressure (Pa)	Molar Mass of Air (g/mol)	Mass (g)	Temp (K)	Ideal Gas Constant (J/mol*K)	Volume (m^3)	Olympic Swimming Pools	Superdomes
101325	28.97	8.44E+17	293.15	8.3144598	7.01E+14	2.80E+11	2.0E+08
101325	28.97	4.22E+9	293.15	8.3144598	3500000		
101325	28.97	2.77E+5	293.15	8.3144598	230		
101325	28.97	662.37	293.15	8.3144598	0.55		

Table B 3 Calculations for BER Reaction Times

	Concentration (mg/L)	Volume of Reactor (L)	Mass (mg)	Time (days)	Rate of Reaction (mg/L) per day
	1.00E+02	1	100	2	50
100% mobilization	Mass (mg)	Total volume of reactors (L)	Time (days)	Time (years)	
	8.44E+20	100	1.69E+17	4.62E+14	
	8.44E+20	1000	1.69E+16	4.62E+13	

	8.44E+20	1.00E+04	1.69E+15	4.62E+12	
	8.44E+20	1.00E+05	1.69E+14	4.62E+11	
	8.44E+20	1.00E+06	1.69E+13	4.62E+10	
	8.44E+20	1.00E+07	1.69E+12	4.62E+09	
	8.44E+20	1.00E+08	1.69E+11	4.62E+08	
	8.44E+20	1.00E+09	1.69E+10	4.62E+07	
	8.44E+20	1.00E+10	1.69E+09	4.62E+06	
50% mobilization	Mass (mg)	Total volume of reactors (L)	Time (days)	Time (years)	
	4.22E+20	100	8.44E+16	2.31E+14	
	4.22E+20	1000	8.44E+15	2.31E+13	
	4.22E+20	1.00E+04	8.44E+14	2.31E+12	
	4.22E+20	1.00E+05	8.44E+13	2.31E+11	
	4.22E+20	1.00E+06	8.44E+12	2.31E+10	
	4.22E+20	1.00E+07	8.44E+11	2.31E+09	
	4.22E+20	1.00E+08	8.44E+10	2.31E+08	
	4.22E+20	1.00E+09	8.44E+09	2.31E+07	
	4.22E+20	1.00E+10	8.44E+08	2.31E+06	
10% mobilization	Mass (mg)	Total volume of reactors (L)	Time (days)	Time (years)	
	8.44E+19	100	1.69E+16	4.62E+13	
	8.44E+19	1000	1.69E+15	4.62E+12	
	8.44E+19	1.00E+04	1.69E+14	4.62E+11	
	8.44E+19	1.00E+05	1.69E+13	4.62E+10	
	8.44E+19	1.00E+06	1.69E+12	4.62E+09	
	8.44E+19	1.00E+07	1.69E+11	4.62E+08	
	8.44E+19	1.00E+08	1.69E+10	4.62E+07	
	8.44E+19	1.00E+09	1.69E+09	4.62E+06	
	8.44E+19	1.00E+10	1.69E+08	4.62E+05	
1% mobilization	Mass (mg)	Total volume of reactors (L)	Time (days)	Time (years)	
	8.44E+18	100	1.69E+15	4.62E+12	
	8.44E+18	1000	1.69E+14	4.62E+11	
	8.44E+18	1.00E+04	1.69E+13	4.62E+10	
	8.44E+18	1.00E+05	1.69E+12	4.62E+09	
	8.44E+18	1.00E+06	1.69E+11	4.62E+08	
	8.44E+18	1.00E+07	1.69E+10	4.62E+07	
	8.44E+18	1.00E+08	1.69E+09	4.62E+06	
	8.44E+18	1.00E+09	1.69E+08	4.62E+05	

	8.44E+18	1.00E+10	1.69E+07	4.62E+04	
1 Superdome	Mass (mg)	Total volume of reactors (L)	Time (days)	Time (years)	
	4.52E+12	100	904748569	2477067	
	4.52E+12	1000	90474857	247707	
	4.52E+12	1.00E+04	9047486	24771	
	4.52E+12	1.00E+05	904749	2477	
	4.52E+12	1.00E+06	90475	248	
	4.52E+12	1.00E+07	9047	25	
	4.52E+12	1.00E+08	905	2.48	
	4.52E+12	1.00E+09	90		
	4.52E+12	1.00E+10	9		
1 HAB from Martian	Mass (mg)	Total volume of reactors (L)	Time (days)	Time (years)	
	2.97E+08	100	59455	162.8	
	2.97E+08	1000	5945	16.3	
	2.97E+08	1.00E+04	595	1.6	
	2.97E+08	1.00E+05	59		
	2.97E+08	1.00E+06	6		
	2.97E+08	1.00E+07	0.6		
	2.97E+08	1.00E+08	0.06		
	2.97E+08	1.00E+09	0.0		
	2.97E+08	1.00E+10	0.0		

Table B 4 Escape Velocity Calculations

Mass (Kg)	Radius (m)	Escape Velocity (m/s)	Escape Velocity (km/s)	Average Molecular Speed (km/s)	Molecular Mass (g)	Temp	Gas	Hydrogen	1.67E-24
6.39E+23	3.39E+6	5015	5.015	0.40	7.31E-23	289	CO_2	Carbon	1.99E-23
				0.63	2.99E-23	289	H_2O	Oxygen	2.66E-23
				0.67	2.66E-23	289	CH_4	Nitrogen	2.33E-23
				0.51	4.65E-23	289	N_2		
				0.47	5.31E-23	289	O_2		
				1.89	3.35E-24	289			

Table B 5 Atmospheric Retention Curve Data

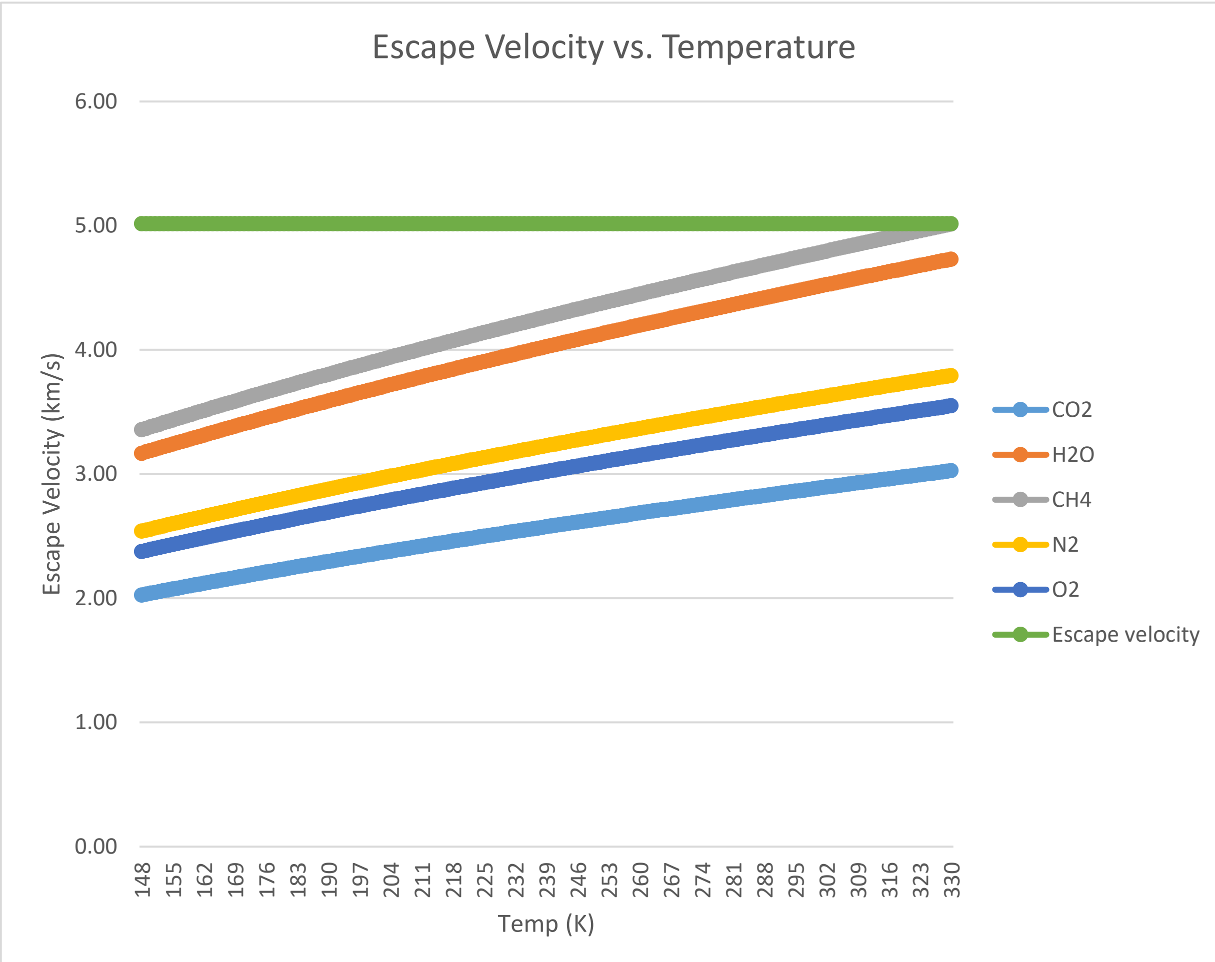
Hydrogen	1.67E-24	Compounds	Molecular mass (g)		7.31E-23	2.99E-23	2.66E-23	4.65E-23	5.31E-23	
Carbon	1.99E-23	Carbon Dioxide	7.31E-23	Temp (K)	CO_2	H_2O	CH_4	N_2	O_2	
Oxygen	2.66E-23	Water Vapor	2.99E-23	148	2.03	3.17	3.36	2.54	2.38	5.015
Nitrogen	2.33E-23	Methane	2.66E-23	149	2.03	3.18	3.37	2.55	2.39	5.015
		Nitrogen (N_2)	4.65E-23	150	2.04	3.19	3.38	2.56	2.39	5.015
		Oxygen (O_2)	5.31E-23	151	2.05	3.20	3.39	2.57	2.40	5.015
		Hydrogen (H_2)	3.35E-24	152	2.05	3.21	3.40	2.57	2.41	5.015
				153	2.06	3.22	3.41	2.58	2.42	5.015
				154	2.07	3.23	3.42	2.59	2.42	5.015
				155	2.07	3.24	3.44	2.60	2.43	5.015
				156	2.08	3.25	3.45	2.61	2.44	5.015
				157	2.09	3.26	3.46	2.62	2.45	5.015
				158	2.09	3.27	3.47	2.62	2.46	5.015
				159	2.10	3.28	3.48	2.63	2.46	5.015
				160	2.11	3.29	3.49	2.64	2.47	5.015
				161	2.11	3.30	3.50	2.65	2.48	5.015
				162	2.12	3.31	3.51	2.66	2.49	5.015
				163	2.13	3.32	3.52	2.67	2.49	5.015
				164	2.13	3.33	3.53	2.67	2.50	5.015
				165	2.14	3.35	3.54	2.68	2.51	5.015
				166	2.15	3.36	3.56	2.69	2.52	5.015
				167	2.15	3.37	3.57	2.70	2.53	5.015
				168	2.16	3.38	3.58	2.71	2.53	5.015
				169	2.17	3.39	3.59	2.71	2.54	5.015
				170	2.17	3.40	3.60	2.72	2.55	5.015
				171	2.18	3.41	3.61	2.73	2.56	5.015
				172	2.19	3.42	3.62	2.74	2.56	5.015
				173	2.19	3.43	3.63	2.75	2.57	5.015
				174	2.20	3.44	3.64	2.75	2.58	5.015
				175	2.20	3.44	3.65	2.76	2.58	5.015
				176	2.21	3.45	3.66	2.77	2.59	5.015
				177	2.22	3.46	3.67	2.78	2.60	5.015
				178	2.22	3.47	3.68	2.79	2.61	5.015
				179	2.23	3.48	3.69	2.79	2.61	5.015
				180	2.24	3.49	3.70	2.80	2.62	5.015
				181	2.24	3.50	3.71	2.81	2.63	5.015
				182	2.25	3.51	3.72	2.82	2.64	5.015
				183	2.25	3.52	3.73	2.82	2.64	5.015

				184	2.26	3.53	3.74	2.83	2.65	5.015
				185	2.27	3.54	3.75	2.84	2.66	5.015
				186	2.27	3.55	3.76	2.85	2.66	5.015
				187	2.28	3.56	3.77	2.86	2.67	5.015
				188	2.28	3.57	3.78	2.86	2.68	5.015
				189	2.29	3.58	3.79	2.87	2.69	5.015
				190	2.30	3.59	3.80	2.88	2.69	5.015
				191	2.30	3.60	3.81	2.89	2.70	5.015
				192	2.31	3.61	3.82	2.89	2.71	5.015
				193	2.31	3.62	3.83	2.90	2.71	5.015
				194	2.32	3.63	3.84	2.91	2.72	5.015
				195	2.33	3.64	3.85	2.92	2.73	5.015
				196	2.33	3.65	3.86	2.92	2.74	5.015
				197	2.34	3.66	3.87	2.93	2.74	5.015
				198	2.34	3.66	3.88	2.94	2.75	5.015
				199	2.35	3.67	3.89	2.95	2.76	5.015
				200	2.36	3.68	3.90	2.95	2.76	5.015
				201	2.36	3.69	3.91	2.96	2.77	5.015
				202	2.37	3.70	3.92	2.97	2.78	5.015
				203	2.37	3.71	3.93	2.98	2.78	5.015
				204	2.38	3.72	3.94	2.98	2.79	5.015
				205	2.39	3.73	3.95	2.99	2.80	5.015
				206	2.39	3.74	3.96	3.00	2.80	5.015
				207	2.40	3.75	3.97	3.00	2.81	5.015
				208	2.40	3.76	3.98	3.01	2.82	5.015
				209	2.41	3.76	3.99	3.02	2.82	5.015
				210	2.41	3.77	4.00	3.03	2.83	5.015
				211	2.42	3.78	4.01	3.03	2.84	5.015
				212	2.43	3.79	4.02	3.04	2.84	5.015
				213	2.43	3.80	4.03	3.05	2.85	5.015
				214	2.44	3.81	4.04	3.05	2.86	5.015
				215	2.44	3.82	4.05	3.06	2.87	5.015
				216	2.45	3.83	4.06	3.07	2.87	5.015
				217	2.45	3.84	4.07	3.08	2.88	5.015
				218	2.46	3.84	4.07	3.08	2.88	5.015
				219	2.47	3.85	4.08	3.09	2.89	5.015
				220	2.47	3.86	4.09	3.10	2.90	5.015
				221	2.48	3.87	4.10	3.10	2.90	5.015
				222	2.48	3.88	4.11	3.11	2.91	5.015
				223	2.49	3.89	4.12	3.12	2.92	5.015
				224	2.49	3.90	4.13	3.13	2.92	5.015

				225	2.50	3.91	4.14	3.13	2.93	5.015
				226	2.50	3.91	4.15	3.14	2.94	5.015
				227	2.51	3.92	4.16	3.15	2.94	5.015
				228	2.52	3.93	4.17	3.15	2.95	5.015
				229	2.52	3.94	4.18	3.16	2.96	5.015
				230	2.53	3.95	4.19	3.17	2.96	5.015
				231	2.53	3.96	4.19	3.17	2.97	5.015
				232	2.54	3.97	4.20	3.18	2.98	5.015
				233	2.54	3.97	4.21	3.19	2.98	5.015
				234	2.55	3.98	4.22	3.19	2.99	5.015
				235	2.55	3.99	4.23	3.20	3.00	5.015
				236	2.56	4.00	4.24	3.21	3.00	5.015
				237	2.56	4.01	4.25	3.21	3.01	5.015
				238	2.57	4.02	4.26	3.22	3.01	5.015
				239	2.58	4.03	4.27	3.23	3.02	5.015
				240	2.58	4.03	4.28	3.24	3.03	5.015
				241	2.59	4.04	4.28	3.24	3.03	5.015
				242	2.59	4.05	4.29	3.25	3.04	5.015
				243	2.60	4.06	4.30	3.26	3.05	5.015
				244	2.60	4.07	4.31	3.26	3.05	5.015
				245	2.61	4.08	4.32	3.27	3.06	5.015
				246	2.61	4.08	4.33	3.28	3.06	5.015
				247	2.62	4.09	4.34	3.28	3.07	5.015
				248	2.62	4.10	4.35	3.29	3.08	5.015
				249	2.63	4.11	4.35	3.30	3.08	5.015
				250	2.63	4.12	4.36	3.30	3.09	5.015
				251	2.64	4.13	4.37	3.31	3.10	5.015
				252	2.64	4.13	4.38	3.32	3.10	5.015
				253	2.65	4.14	4.39	3.32	3.11	5.015
				254	2.66	4.15	4.40	3.33	3.11	5.015
				255	2.66	4.16	4.41	3.33	3.12	5.015
				256	2.67	4.17	4.42	3.34	3.13	5.015
				257	2.67	4.17	4.42	3.35	3.13	5.015
				258	2.68	4.18	4.43	3.35	3.14	5.015
				259	2.68	4.19	4.44	3.36	3.14	5.015
				260	2.69	4.20	4.45	3.37	3.15	5.015
				261	2.69	4.21	4.46	3.37	3.16	5.015
				262	2.70	4.22	4.47	3.38	3.16	5.015
				263	2.70	4.22	4.48	3.39	3.17	5.015
				264	2.71	4.23	4.48	3.39	3.17	5.015
				265	2.71	4.24	4.49	3.40	3.18	5.015

				266	2.72	4.25	4.50	3.41	3.19	5.015
				267	2.72	4.26	4.51	3.41	3.19	5.015
				268	2.73	4.26	4.52	3.42	3.20	5.015
				269	2.73	4.27	4.53	3.43	3.20	5.015
				270	2.74	4.28	4.53	3.43	3.21	5.015
				271	2.74	4.29	4.54	3.44	3.22	5.015
				272	2.75	4.29	4.55	3.44	3.22	5.015
				273	2.75	4.30	4.56	3.45	3.23	5.015
				274	2.76	4.31	4.57	3.46	3.23	5.015
				275	2.76	4.32	4.58	3.46	3.24	5.015
				276	2.77	4.33	4.58	3.47	3.25	5.015
				277	2.77	4.33	4.59	3.48	3.25	5.015
				278	2.78	4.34	4.60	3.48	3.26	5.015
				279	2.78	4.35	4.61	3.49	3.26	5.015
				280	2.79	4.36	4.62	3.49	3.27	5.015
				281	2.79	4.37	4.63	3.50	3.28	5.015
				282	2.80	4.37	4.63	3.51	3.28	5.015
				283	2.80	4.38	4.64	3.51	3.29	5.015
				284	2.81	4.39	4.65	3.52	3.29	5.015
				285	2.81	4.40	4.66	3.53	3.30	5.015
				286	2.82	4.40	4.67	3.53	3.30	5.015
				287	2.82	4.41	4.67	3.54	3.31	5.015
				288	2.83	4.42	4.68	3.54	3.32	5.015
				289	2.83	4.43	4.69	3.55	3.32	5.015
				290	2.84	4.43	4.70	3.56	3.33	5.015
				291	2.84	4.44	4.71	3.56	3.33	5.015
				292	2.85	4.45	4.72	3.57	3.34	5.015
				293	2.85	4.46	4.72	3.57	3.34	5.015
				294	2.86	4.47	4.73	3.58	3.35	5.015
				295	2.86	4.47	4.74	3.59	3.36	5.015
				296	2.87	4.48	4.75	3.59	3.36	5.015
				297	2.87	4.49	4.76	3.60	3.37	5.015
				298	2.88	4.50	4.76	3.60	3.37	5.015
				299	2.88	4.50	4.77	3.61	3.38	5.015
				300	2.89	4.51	4.78	3.62	3.38	5.015
				301	2.89	4.52	4.79	3.62	3.39	5.015
				302	2.90	4.53	4.80	3.63	3.40	5.015
				303	2.90	4.53	4.80	3.64	3.40	5.015
				304	2.90	4.54	4.81	3.64	3.41	5.015
				305	2.91	4.55	4.82	3.65	3.41	5.015
				306	2.91	4.56	4.83	3.65	3.42	5.015

				307	2.92	4.56	4.84	3.66	3.42	5.015
				308	2.92	4.57	4.84	3.66	3.43	5.015
				309	2.93	4.58	4.85	3.67	3.43	5.015
				310	2.93	4.58	4.86	3.68	3.44	5.015
				311	2.94	4.59	4.87	3.68	3.45	5.015
				312	2.94	4.60	4.87	3.69	3.45	5.015
				313	2.95	4.61	4.88	3.69	3.46	5.015
				314	2.95	4.61	4.89	3.70	3.46	5.015
				315	2.96	4.62	4.90	3.71	3.47	5.015
				316	2.96	4.63	4.91	3.71	3.47	5.015
				317	2.97	4.64	4.91	3.72	3.48	5.015
				318	2.97	4.64	4.92	3.72	3.48	5.015
				319	2.98	4.65	4.93	3.73	3.49	5.015
				320	2.98	4.66	4.94	3.74	3.50	5.015
				321	2.99	4.67	4.94	3.74	3.50	5.015
				322	2.99	4.67	4.95	3.75	3.51	5.015
				323	2.99	4.68	4.96	3.75	3.51	5.015
				324	3.00	4.69	4.97	3.76	3.52	5.015
				325	3.00	4.69	4.97	3.76	3.52	5.015
				326	3.01	4.70	4.98	3.77	3.53	5.015
				327	3.01	4.71	4.99	3.78	3.53	5.015
				328	3.02	4.72	5.00	3.78	3.54	5.015
				329	3.02	4.72	5.01	3.79	3.54	5.015
				330	3.03	4.73	5.01	3.79	3.55	5.015


Escape Velocity vs. Temperature
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Escape Velocity (km/s)
148
155
162
169
176
183
190
197
204
211
218
225
232
239
246
253
260
267
274
281
288
295
302
309
316
323
330
Temp (K)
CO2
H2O
CH4
N2
O2
Escape velocity