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Humanity and Space

Theoretical Methodologies for the Colonization of Mars

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by

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Abstract

Colonizing Mars is an endeavor that humanity has been looking at for centuries. There have been proposals made on how to colonize Mars, but many fail to be viable or lack funding. This IQP project proposes four theoretical methods that aim to build a sustainable colony on Mars by completely terraforming the planet, tunneling into the Martian depths, sending radiation resistant modules, or restarting Mars' magnetosphere, in addition to discussing the social aspects and implications associated with each colonization strategy.

Executive Summary

Humanity stands to gain much from the colonization of a non-Earth entity. The global incentives for colonizing Mars not only lie in the benefits for human society, but also in the survival of humanity as a whole. Many risk factors could lead to the destruction of society and eventual extinction of the human species. The threat of thermonuclear war is of great concern due to various unstable regions slowly gaining nuclear technology. Ignoring all human caused catastrophes, nature itself poses an insurmountable threat to mankind. A large enough asteroid could result in a mass extinction similar to the one that ended the reign of the dinosaurs. The dangers of the macroscopic world aren't the only ones that pose a threat to all of mankind. Any sufficiently contagious, lethal, and incurable disease could also end human society.

The best way to expand the reach of human society and technological prowess while also ensuring that it isn't prematurely ended would be to colonize another planet, and the easiest planet for humans to colonize at this time is Mars. However, colonizing Mars is not without its drawbacks, as the planet has an atmosphere that is about 1% as dense as that of Earth and is constantly bombarded by radiation due to its patchy, umbrella shaped magnetosphere. Because of this, careful thought needs to be put into deciding what method of colonization is used to accomplish the goal of permanently settling the planet.

Four different strategies were devised to colonize Mars, each with its own set of advantages and disadvantages. The first of these ideas was to fully terraform Mars until the planet resembles Earth. This plan would start by taking Enceladus, one of Saturn's moons, and smashing it into Mars. While this would present colonists with ideal living conditions, the terraforming process itself is prohibitively expensive and time consuming. The next strategy would be to tunnel deep below the Martian surface to create a colony where residents wouldn't

need to fear the natural elements present above. However, the colonists would most likely never return to the surface again due to the dangers present. Should creating an underground colony prove too complex, the next plan would be to create modular, hemispherical pods that could be joined together to create a large surface colony. These pods would be relatively cheap to construct, quick to deploy, and resistant to both radiation and heat transfer. However the colony would rely on an extremely long pipeline to supply its water. The final plan would be to take an asteroid from the area around Mars or in the asteroid belt and use it to give Mars a new moon, therefore restarting its magnetosphere. This would allow the planet to be colonized without the threat of radiation, as well as opening the door for future terraforming. However, the risk of the asteroid failing to properly fall into orbit around Mars is high, and failure could result in a rogue asteroid in the inner solar system.

Each of the four strategies for colonization comes with numerous social aspects and implications, and none are perfect. Colonizing a new planet won't be an easy or simple endeavor, but it is necessary for the economic, technological, social, and even biological future of humanity. A visual representation of the work is displayed on page 109 of this report.

About the Authors

Darien Khea

My motivation for being involved in this year's Humanity and Space IQP stems from my continuous curiosity regarding how far humanity can push the forefront of science and technology. I am most interested in the methodology of voyaging to and colonizing Mars in an economical yet effective manner. In my career, I want to help realize solutions to the many problems that scientists and engineers face when attempting to colonize distant planets. These primarily focus on creating the resources needed for humans to explore, settle, and conduct research beyond Earth. I believe that by moving to Mars, humanity will have the chance to establish a different life that is filled with new communities and experiences.

Ahmed Safat Hossain

My inspiration for this IQP about Humanity and Space surfaces from my childhood curiosity in astronomy and aerospace. However, my motivation behind researching colonization arises from always having believed that society cannot function properly just by learning from history. Space colonization will be a solution for modern, global issues, and Mars is the first step. Humanity needs a new beginning. The colonization of Mars is this new beginning. I want this project to inspire bright intellects to pursue and create the visions of the future. Stephen Hawking once said "Look up at the stars and not down at your feet. Try to make sense of what you see, and wonder about what makes the universe exist. Be curious."

Riley Shoneck

I was motivated to pursue this project out of my own desire to see humanity advance to a stage where the species can be said to be immortal. This can only be said to be true once humans have colonized many different planets. Colonizing Mars is merely the first step to achieving this. Humanity is currently at a point in its development where it has the potential to decimate all life on Earth while lacking the global unity to not, as evident by unstable governments pursuing nuclear power while simultaneously threatening the Western world. A global pandemic or asteroid impact could also eradicate most of humanity. I see the colonization of Mars as the first step to the immortalization of human kind, and hope that one day, the human species will no longer be bound to any single planet, or even a single star.

Introduction

With the passing of Earth Overshoot Day, the need for extraterrestrial colonization grows ever imminent. Because of its relatively close proximity to Earth, and its generally similar characteristics, Mars would make an excellent location for a second home. The purpose of this project is to successfully demonstrate four theoretical methods of colonizing Mars using proven and currently emerging research.

Humanity is constantly developing new technologies. What was once merely a dream of science fiction is becoming science fact. The future of humanity, in the coming century, is very bright. Currently, humanity is on the eve of unlocking the secrets to vast amounts of technologies that will change it for the better. While these technologies will have the power to end humanity, recent history has shown that humans are mostly intelligent enough to know that destroying everything benefits no one.

As it currently stands, Earth is exponentially losing its ability to support the ever-expanding needs of humanity. While the planet may be fine within the near future, it won't be able to support human wants and needs forever. Should humans fail to take the initiative in colonizing other planets, they will be stuck on a dying world without enough resources to support life.

Being a single world species, humans are at incredible risk of being eliminated by a planetary catastrophe. A single virus has the potential to wipe out all of humanity, should it prove infectious and lethal enough. The past and present proves that national and geological borders won't stop the spread of a pandemic, and what little isolation left in the world is sure to vanish as the trends of people to travel internationally continues to rise. Earth has had various mass extinctions in the past from asteroid impacts, and at this point, humanity has no guaranteed way to prevent another massive asteroid from obliterating all complex life on the planet. Nearly all theoretical methods proposed thus far have proven to be ineffective against a massive asteroid, and those that will work won't work that well. Although natural phenomena could easily spell the end of humanity, humans themselves could as well. The looming threat of thermonuclear war, while rarely mentioned, still exists. Should unstable nations acquire nuclear weapons and use them, the world could start down a path to the end of humanity. However, all of these catastrophes could be avoided if human life was not bound to a single planet.

Within this century, humans will leave Earth to colonize extraterrestrial bodies. Talks of leaving the solar system itself may even arise. Extraterrestrial colonization refers to the concept of the human species spreading to locations beyond Earth. It would allow humanity to survive almost any possible catastrophe. Even the complete loss of Earth wouldn't end the human race. Colonizing beyond Earth would allow humanity to exist forever. In the distant future, humans could occupy planets around many different stars, ensuring that even the death of a host star doesn't end humanity. Such a level of colonization would result in the complete immortality of the species. The benefits of colonizing the stars aren't just for humanity's survival. A secondary benefit would be the vast potential for humans to study the universe from different viewpoints. While Earth works well as a research platform, studying distant celestial bodies is a challenge. By having colonies and research stations elsewhere in the universe, humans would be able to get a closer look at various aspects of the universe, leading to a better understanding of it.

The first step in the endeavor to colonize the cosmos is to establish a single colony outside of Earth. Such a colony would have to be on a close by planet, preferably one with some form of water. While the ideal case for this test planet would be to find one that mirrored Earth conditions, no such planet exists. The only two rational choices for planets to colonize are Mercury and Mars. Mercury is a volatile planet with a toxic atmosphere, whereas Mars is a dead planet that had liquid water billions of years ago. Alternatively, if one didn't want to colonize planets, the closest celestial body, the moon, could potentially act as a colony site. However, while it would work to test the concept designs for colonies on dangerous worlds, a moon colony would do nothing to protect humanity in the event that Earth was lost. With these considerations, the best option would be to colonize Mars. The planet is further from the Sun than Earth, but still within the habitable zone. Since it is a hostile planet that lost its magnetic field, Mars also acts as a good example for how humans would colonize more challenging planets and holds the potential to have its magnetosphere and surface conditions restored, albeit slowly.

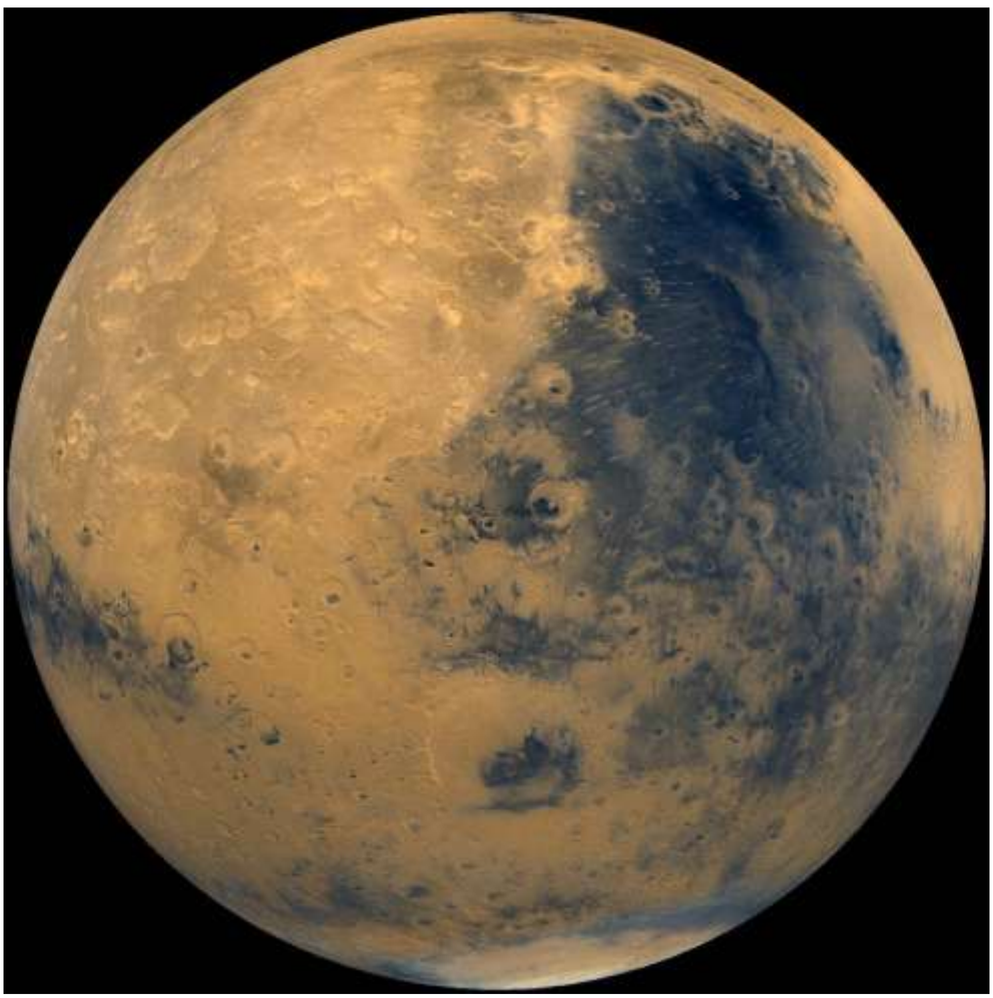

Figure 4.1: Dead planet Mars

Background

Extraterrestrial colonization is the concept of permanent human habitation outside of Earth. Arguments in favor of extraterrestrial colonization include the survival of humanity in the event of a global disaster and the potential to harvest the vast quantities of resources available outside of Earth. As of now, no such colonies exist due to the lack of technological and economic requirements associated with them. An extraterrestrial colony would have to be self-sufficient to be sustainable in the long term. It would have to supply its inhabitants with everything that they needed to survive, and because it is prohibitively expensive to send supplies into space, relying on a supply line from Earth is not a logical solution.

The primary argument for extraterrestrial colonization is to ensure the survival of humanity from any natural or manmade disasters. Stephen Hawking has predicted that if humans don't establish colonies in space within the coming 200 years[1], the prospect of long-term extinction is inevitable. Earth faces a variety of risks that could destroy humanity. If a very large asteroid was to impact Earth, life on the planet might be nearly extinguished. Alternatively, a pandemic virus or thermonuclear war could also wipe out humanity. However, even if none of these comes to pass, the Earth will inevitably become uninhabitable because the Sun will eventually extinguish itself or grow so vast that it consumes Earth. The resources that exist outside of Earth have the potential to support millions of times the current population of Earth. As such, humanity stands to gain much from leaving Earth, while only suffering from temporary economic troubles.

Mars is the closest logically inhabitable planet to Earth and has ice and Carbon already present on it. Because of the presence of these elements, it has been speculated that life could

[1] Malik, Tariq. "Stephen Hawking: Humanity Must Colonize Space to Survive."

have been present on Mars in the past, further fueling the notion that Mars would make a good planet to colonize. However, its current atmosphere is very thin and toxic[2]. It is much colder than Earth and dust storms frequently ravage the surface. At this point, humans cannot survive on Mars without protective gear and specially designed structures. The lack of any real magnetic field also puts any potential Martian colonists at risk of heavy exposure to radiation.

Because the Martian surface is in a state where it is uninhabitable, the terraforming specialists would have to alter the climate on its surface. Should terraforming Mars be determined to be the optimal solution, the climate would have to be changed through artificial means, many of which are prohibitively expensive or technologically unachievable at this time. Low gravity causes many notable effects on humans, primarily muscle degeneration[3]. Long-term Martian colonists may not be able to return to Earth after years of living on the planet. The low gravity also makes it harder for the planet to hold onto its atmosphere. Terraforming the planet would address this problem and attempt to eliminate it by increasing the planet's mass.

Mars lacks a magnetic field and is therefore unable to prevent solar winds from stripping away the planet's already thin atmosphere[4]. Water exists on Earth because the hydrogen atoms in the atmosphere, while very fast due to their small mass, are deflected back toward the planet by the magnetosphere. The ozone layer also helps with this by preventing ultraviolet light from breaking down H_2O into Hydrogen and Oxygen. To become inhabitable, Mars would need a magnetic field similar to that of Earth.

[2] See Table 7.2
[3] Fitts, Robert, Danny Riley, and Jeffery Widrick. "Functional and Structural Adaptations of Skeletal Muscle to Microgravity."
[4] Phillips, Tony. "Solar Wind Rips Up Martian Atmosphere."

Because Mars exists on the outer edge of the habitable zone, it would need a higher concentration of greenhouse gases in order to maintain liquid water, suggesting that the planet could potentially support Earth-like surface conditions. Research suggests that, in the past, Mars had an abundance of liquid water on its surface. However now water only exists as ice on the poles. Samples of the soil taken by the Curiosity rover have shown that the soil contains many of the necessary elements that produce life, such as Nitrogen, Hydrogen, Phosphorus, and Carbon. Additionally, the South Pole of the planet has enough water to coat the entire planet in an ocean of more than 10 meters in depth.

Many terraforming techniques have been suggested in order to enable Mars to support a warm atmosphere without losing it to space. One such technique would be to induce a mass sublimation of the planet's Carbon Dioxide[5]. By causing all of the frozen CO_2 near the South Pole of Mars to sublime, the planet's pressure would rise to levels comparable to the peak of Mount Everest. Additionally, bacteria and algae with the ability to convert CO_2 into Oxygen can hasten this process. The problem with this technique is that it relies on first raising the global temperature of the planet by a few degrees. It also would only lead to a planet where humans can exist without specialized pressure suits. A planet with an entire surface similar to the peak of Earth's tallest mountain is almost as uninhabitable as Mars in its current state.

Another proposed method is to bring vast quantities of ammonia to Mars[6]. Because ammonia is mostly Nitrogen by weight, it could act as a buffer gas, and because of its relatively inert nature, Nitrogen would control the rate of combustion with Oxygen on the planet. However, the problem with this solution, as well as any solutions that involve importing compounds or

[5] Cochrane, Kian. "Kian Cochrane's Terraforming Method."
[6] Cochrane, Kian. "Kian Cochrane's Terraforming Method."

elements in massive quantities from Earth to Mars, is that it is prohibitively expensive. Mars, even at its closest, is millions of kilometers from Earth. Bringing enough of any material between the two worlds would put too much strain on the global economy of Earth.

It has been suggested that orbital mirrors could be used to increase Mars' sunlight exposure[7]. Strategically placed mirrors around the planet would direct sunlight towards the surface, thus directly heating it. Alternatively, the mirrors could be used to cause the frozen CO_2 near the poles to sublime and add to the greenhouse effect. This method, while more economically logical than shipping vast quantities of elements and molecules to Mars, still has problems. Space mirrors would rely on their ability to reflect sunlight. Any dust or debris around Mars could potentially damage or destroy such a mirror. These mirrors would also only be able to heat localized areas. The planet as a whole would still remain relatively similar to its current state.

The two current moons of Mars, Phobos and Deimos, are among the darkest bodies in the solar system. As such, destroying them and spreading the dust across the Martian surface would cause the planets albedo to lower[8]. By doing this, more sunlight would be absorbed by the planet, rather than being reflected.

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[7] Cochrane, Kian. "Kian Cochrane's Terraforming Method."
[8] "The Moons of Mars." *Space Academy*

Figure 5.1: Phobos

Alternatively, dark organisms that could survive the extreme conditions on Mars could be used in place of the two moons. Using extremophile algae or other photosynthesizing life forms would have the added benefit of slowing producing more oxygen. Studies have shown that lichen has the ability to survive Martian conditions[9]; so using this would theoretically work. The problem with this is that the rate of temperature and atmospheric composition change is far too slow and doesn't address the lack of a magnetic field or geological activity. While the

[9] Malaska, Mike. "Earth's Toughest Life Could Survive on Mars."

atmosphere might become habitable eventually, it will still suffer from high levels of solar radiation and winds.

While any of these solutions have the potential to work, they are all prohibitively expensive or complex, and each of them fails to address all of the problems associated with establishing a colony on Mars.

Possible Solutions

Terraforming Mars

There are many ways to approach the issue of colonizing Mars. While each offers varying benefits, none are without drawbacks. These drawbacks can be loosely described as economic, time requirement, social, or technological. Although one idea may shine above the rest as the perfect solution, it won't be without a glaring problem. Terraforming the entire planet to mirror Earth-like conditions would obviously be the best answer for the long term prosperity of life on Mars, however such an endeavor would take millennia to complete. It is possible to colonize Mars in its current form, but the colonists would have to find a way to cope with the radiation that constantly bombards the surface of the planet. An alternative to either of these could be to bring a large planetary body into the Martian gravity well to act as a moon, and thus help to restore the planet's lost magnetic field.

The most ideal long-term solution would be to completely terraform Mars to a point where it resembles Earth. This method is by far the most expensive and time consuming. Terraforming Mars to a completed state would take thousands of years to accomplish and would still hold the chance of not completely matching Earth. To terraform Mars, Enceladus[10] would first be brought to Mars to be crashed into the planet. This would give Mars many of the necessary materials to support life. After this, humans would guide many asteroids into the planet to further heat it up, increase its mass, and restart geological activity in its core. As the process got closer to completion, humans would add life to the planet, eventually rendering the Mars an Earthlike planet. Mars would have to experience many short periods where it holds the potential to support life, which would then be followed by periods of destruction. This flow, although seemingly pointless, would slowly alter the surface conditions of Mars to perfectly

[10] See Table 7.1

refine them to support life. Mars already exists within the habitable zone of the Sun, as proven by evidence that it had liquid water oceans in the distance past. If it were terraformed to a point where it once again had liquid water on its surface, it would be able to support life as we know it, possibly as well as Earth does. Mars merely needs an impact to kick-start the terraforming process.

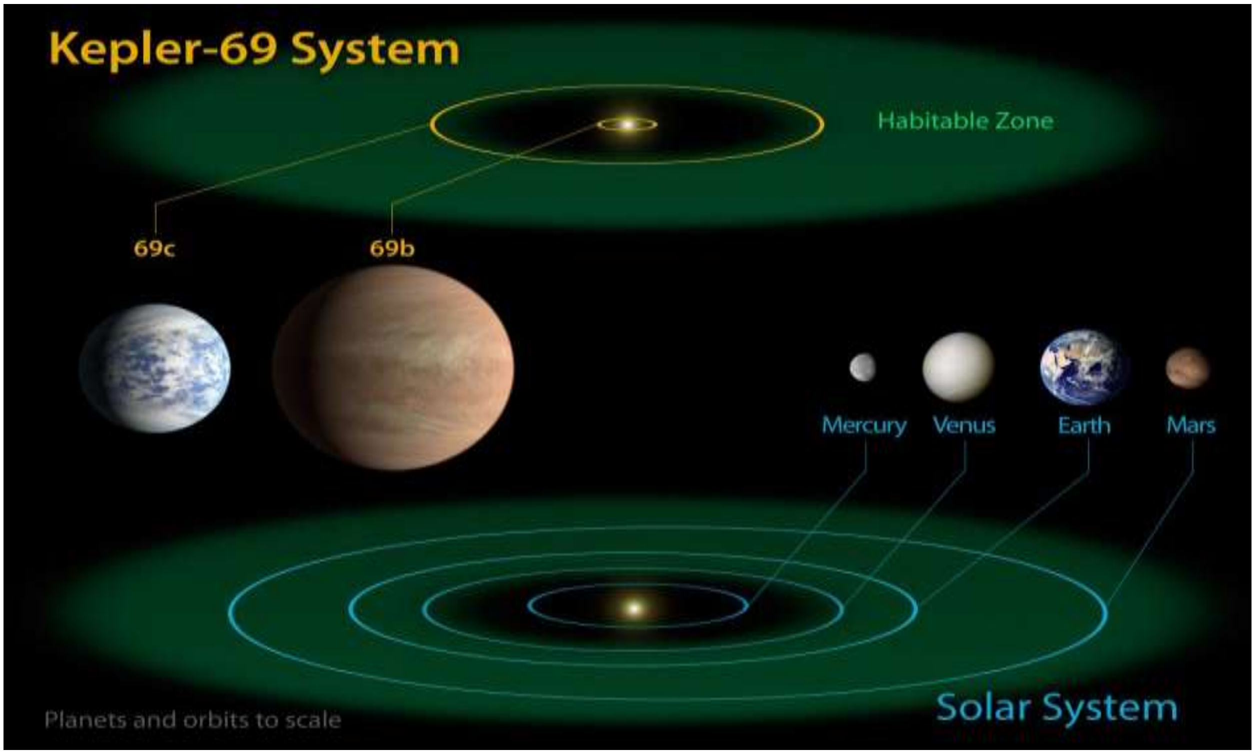

Figure 6.1: Mars in the Goldilocks zone

Underground Colony

Because terraforming a planet from a dead state is infeasible, and Mars has no protective magnetosphere to block radiation, a method to safely colonize the planet in a relatively short timeframe would be to dig subterranean colonies. An underground colony would completely remove conditions on the surface of Mars from the equation. However, it would require large drilling equipment, such as tunnel boring machines, making it much more initially expensive than any potential surface colonies. To start one of these colonies, a tunnel-boring machine would be sent to a crater on Mars and assembled by swarm robots. Both the robots and the TBM would be powered by a small solar array and later a small fusion/fission plant. The goal of the tunnel-boring machine would be to dig a downward-sloped tunnel into the side crater to create an initially straight (and later spiraled) tunnel under the surface. After the TBM has been running for about a year, it will have dug a deep enough tunnel to act as a central pathway for the colony. From there, the swarm robots would dig smaller tunnels and rooms branching off of this central tunnel to loosely resemble an ant colony. The natural ventilation and air quality control that is present within ant nests would be necessary for the long-term sustainability of this type of colony[11]. After various branching tunnels and rooms have been excavated, structural construction materials would need to be sent from Earth to fortify the tunnels and create livable conditions for humans. A thick wall of steel and concrete surrounding a heavy vault-styled doorway designed to resist radiation would seal the entrance where the drill initially entered. While this early version of a subterranean colony would still be powered by the initial energy source that was used to power the robots, it would be completely sealed from the surface. Behind the outer door would be a second, less shielded bulkhead door that would create an airlock room. This is necessary in order to ensure that the interior of the colony can maintain a pressurized environment. When humans first arrive to this subterranean colony, they would bring with them a few months of basic supplies and equipment to start a hydroponics bay. The majority of the colony would only be equipped with basic LED lighting to start off with, while the rooms devoted to hydroponics would have ultraviolet lighting. Early colonists would have to adapt to life without sunlight, but would also not need to worry about surface conditions at all. As the underground colony progressed, the TMB would continue to bore deeper into Mars, allowing for the colony to grow while people inhabit it. Colonists would control the swarm robots to shape

[11] Gill, Victoria. "How Ants Build Nest-ventilating Turrets."

the colony, as they needed it[12]. After a year of colonists living within the colony and operating the tunnel-boring machine, the swarm robots would start excavating a massive central chamber that would eventually house many layered, underground forests. These “forests” would be filled with plants that can most efficiently convert Carbon Dioxide to Oxygen. The chambers would enable the colony to support a greater population and make it more self-sustaining. The final goal of this colony would be to support a population that had a symbiotic relation with swarm robotics. This final form would resemble an ant nest with a large central tunnel surrounded by a network of smaller tunnels and rooms stretching deep into the Martian crust. There would be many forest rooms that make use of the tunnel structure to supply the entire colony with fresh, oxygenated air.

Modular Martian Colony

Should establishing a massive underground colony prove infeasible for one reason or another, the cheapest and fastest way to colonize Mars would be to create entire, semi-permanent colonies out of a radiation resistant hemispherical modular pods. Early modules would be constructed on Earth and sent to Mars via large-scale rockets. The later modules would be constructed either in orbital factories around Earth or even on the surface of Mars. A module, or pod, would have four airlock connections that could themselves be attached to other pods via bridge sections to create a pressurized network of connecting pods that would act as a full colony. These pods would all serve specific purposes within the colony, ranging from a power station pod to a manufacturing pod. However, the initial pod to be sent would be a nexus pod that contains the bare minimum to support a small population by itself. This nexus pod would have a small energy generator, perhaps one based on solar energy, a small hydroponics farm, and a few cot-style beds. The purpose of this pod would be to act as a starting point for a colony, as well as to gage out what type of pods would be sent and what purpose that specific colony had. Later,

[12] See Relating Future Technologies Section

specialized pods would be sent and connected to the original nexus pod. These 2nd wave pods would include a power station pod, large farm pods, a water-drilling pod, and residential pods. The purpose of the water-drilling pod would be to tap into potential reserves of water frozen beneath the surface of Mars. Residential pods would be large, multi-floored complexes comprised of many individual "apartments" for colonists. The 3rd and final wave pods would be dedicated to initializing mining and manufacturing, as well as improving the quality of life for the colonists. In this way, the modular colony would finally resemble a self-sufficient city. The absolute final goal of this method of colonizing Mars would be to create entirely "interior" cities, similar to simple mall structures. However, these would need to be able to resist all forms of cosmic radiation and wouldn't be established till many years after the completion of the three colonization waves. Creating colonies out of pressurized modular pods is the cheapest and quickest method of colonization, but is very prone to the planet's surface conditions.

Asteroid Moon – Restarting the Martian Magnetosphere

Rather than using highly complex designs to block radiation on a surface colony, an alternative option for colonizing Mars would be to prioritize restarting its core and therefore its magnetosphere, thus causing the planet itself to block radiation. The dynamo effect theory suggests that the molten outer core rotating around the solid inner core to create an electric current generates a planet's magnetosphere[13]. The current, in turn, generates a magnetic field. This new field, when combined with the original field that was present due to the magnetic properties of the core[14], creates a stronger magnetic field along the planet's axis of rotation. The core of Mars is still relatively hot (about 2300 degrees Celsius cooler than Earth's) and therefore exists in a mostly liquid state. It is theorized that Mars has a solid inner core, but this is

[13] "Dynamo Theory." *Encyclopedia Britannica*
[14] "Core." *National Geographic*.

unconfirmed. The composition of the Martian core is primarily composed of an alloy of Iron and Sulfur, unlike the Iron/Nickel alloy core of Earth[15]. However, the fluids of the Martian core are not in a state of constant motion, and thus do not create a dynamo effect. This is because there is no convective cell within the planet to transfer heat and materials between the core and mantle. Even though the Martian day is only forty minutes longer than a day on Earth, it doesn't rotate fast enough to compensate for the lack of a convective cell. In order to alleviate this, a new, relatively massive, moon would need to be placed in orbit around Mars. The gravitational pull of a moon on Mars would pull on the liquid core of the planet, thus initiating the much-needed flow (via tidal friction) that would restart the magnetic field of Mars[16]. Because of its size and location, Ceres would be perfect in this endeavor. This dwarf planet is the largest object in the asteroid belt and is made of rock and ice. The mass of Ceres is about 0.0013 times that of Mars, but because of its position outside the hold of any planet, it would act as the logistically easiest body to turn into a moon for Mars. While Enceladus holds many of the elements necessary to sustain life on a planet, its mass and composition are not enough for it to act as a moon[17]. Transferring the elements of Enceladus to Mars without ensuring that the planet has a proper magnetic field would merely introduce more material to be stripped from the planet by solar winds. The presence of a magnetic field is necessary in order to protect the planet from solar radiation and to maintain an atmosphere. After the magnetic field has been restored, any colony on the planet can be constructed from simple materials that only need to maintain internal pressure. To this end, colonies made of simple, dust storm resistant modules could be created. The goal of these initial colonies would be to prepare sites for and construct larger pressurized, fully interior, cities.

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[15] Coffey, Jerry. "What Is Mars Made Of?"
[16] Laj, Carlo, Hervé Guillou, and Catherine Kissel. "Dynamics of the earth magnetic field in the 10–75 kyr period comprising the Laschamp and Mono Lake excursions: New results from the French Chaîne des Puys in a global perspective."
[17] See Table 7.1

These cities would be made using conventional construction techniques, or if the technology exists, 3D printing on a massive scale. Since the colonists wouldn't have to worry about radiation, the cities could make use of transparent materials so that the colonists would be able to live similar lives to those on Earth. Additionally, the presence of a city infrastructure would allow for the creation of schools, manufacturing plants, and even localized Internet and phone networks. The final aim of a colony build on a Mars with a magnetic field would be to fully recreate Earth-like atmospheric conditions over the entire planet. However this is a goal that exists outside the realm of this colonization strategy and would need to be solved by the later generations of the colonists.

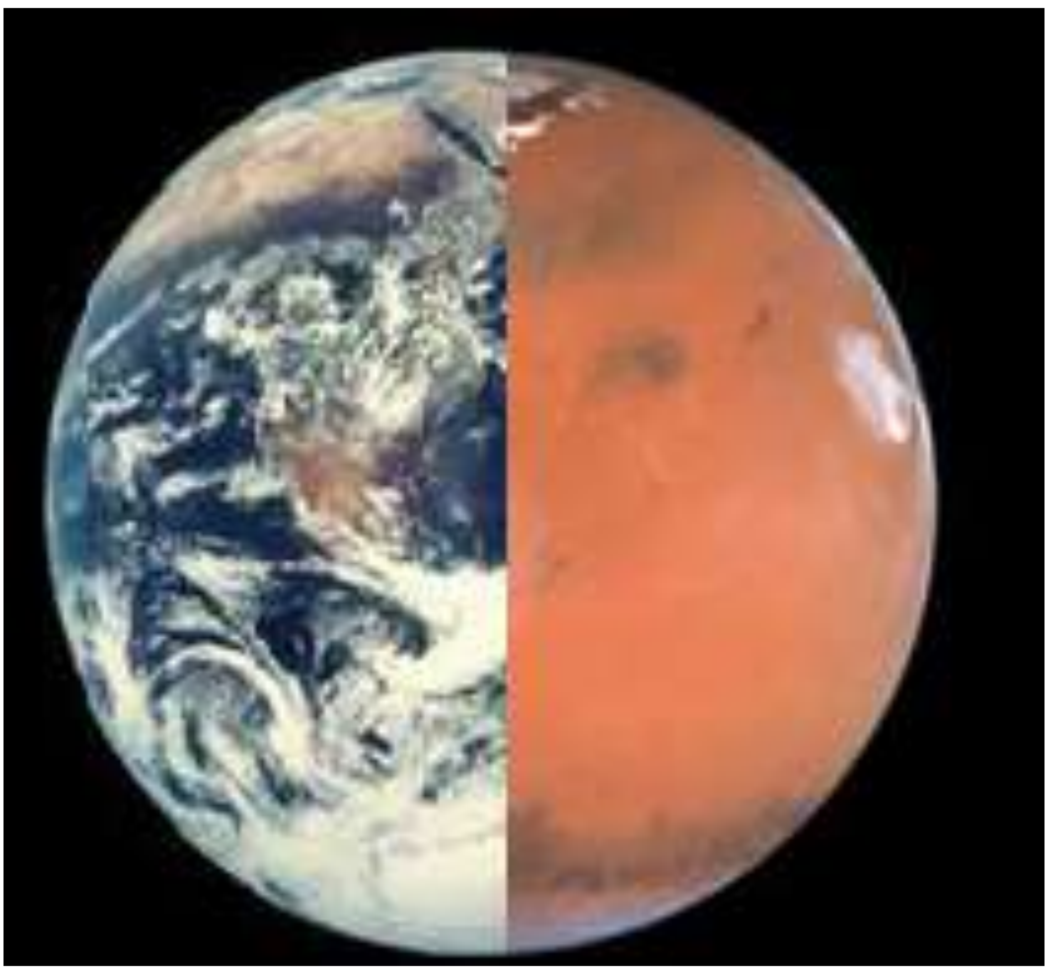


Figure 6.2: Terraformed Mars

Terraforming Mars would result in a planet that most resembled Earth, but would take hundreds, if not thousands, of years to complete. To cope with this, the latter three proposals were designed to act as localized environments for colonists to compensate for the lack of a planetary ecosystem. The first generation of colonists might find these changes in gravity and pressure, as well as living conditions, strange or unnatural, but the second generation and beyond wouldn't be bothered by them. Although not perfectly ideal, any of these options could ensure the survival of humanity in the event that life on Earth was eradicated.

Terraforming Mars

Introduction

The most ideal solution for colonizing Mars would be to fully terraform the planet. More specifically, this solution will focus on the potential of crashing Saturn's ice moon, Enceladus, into Mars. However, to even consider moving such a large body over millions of miles and past the asteroid belt, huge amounts of force and in-depth planning are required. One primary aspect of research regarding this is to figure out how much force is required to break Enceladus away from Saturn's gravity well and to guide it to Mars. The other major aspects are how to accelerate the terraforming process once Enceladus has collided with Mars and how to establish an initial, self-sustaining colony on the planet.

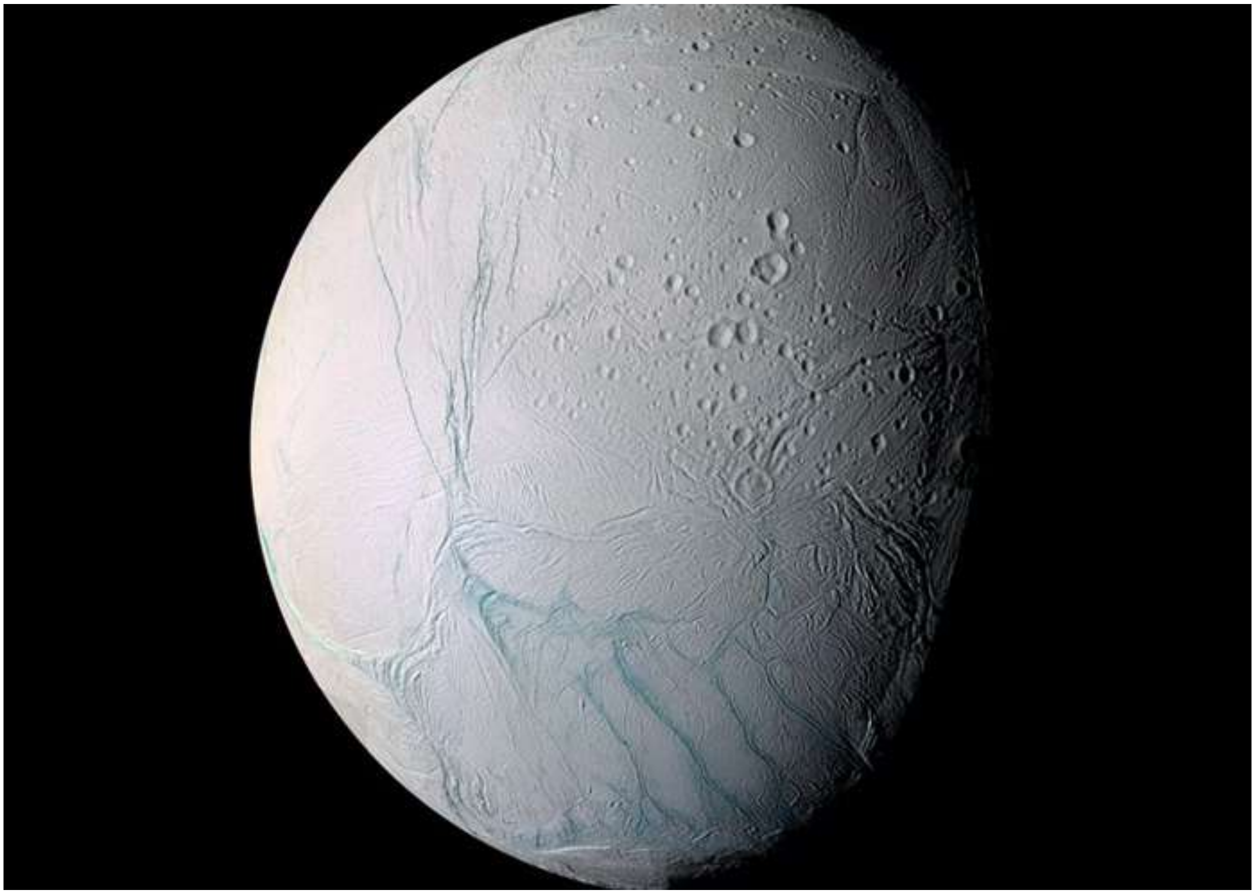


Figure 7.1: Enceladus: Saturn's ice moon

This solution will address how to terraform Mars, as well as how to accelerate this process. The goal of this solution is to terraform Mars by using the theoretical geological forming process of Earth that led to the birth of life, as well as making use of preexisting or developing technologies[18]. Humanity is ready for the prospect of leaving the nest that is Earth, as shown by the general excitement over the Mars One project, but has no truly habitable planet to relocate to. This solution would, in time, provide humanity with one.

Enceladus in brief	
Mean distance from Saturn	238 000 km
Orbital and rotational period	1.37 days
Mean radius	252 km
Bulk density	1.61×10^3 kg/m^3
Interior composition by mass	50–60% silicate, 40–50% water ice
Radiated endogenic power[7]	16 GW
Surface composition	Fine-grained water ice, trace CO_2, possible NH_3, H_2O_2
Plume gas composition by volume*	90% H_2O, 5% CO_2, 0.9% CH_4, 0.8% NH_3, 0.3% H_2CO, 0.3% C_2H_2, many other hydrocarbons, 0.2% H_2S, 0.03% ^{40}Ar
Plume particle composition by mass[16]	99% H_2O, 1% NaCl, 0.3% $NaHCO_3$ or Na_2CO_3, 0.01% KCl
Plume mass-loss rate[13]	200 kg/s
*Determined from mass spectroscopy during the October 2008 flyby.[11] Other flybys give results that differ in detail.	

Table 7.1: Properties of Enceladus

Methodology

Mars, in every sense, is a dead planet. It lacks a magnetic field, volcanic activity, liquid water, and an atmosphere that would support life. Should humans ever hope to sustainably colonize the planet, it must be terraformed. By following the history of Earth, but at an

[18] Windley, Brian. "Geological History of Earth."

accelerated pace, it should be possible to transform Mars into a lush planet within the span of approximately 1000 years.

Orbit Calculation

A conservation of momentum equation is considered between two bodies, Enceladus and Mars, colliding in order to solve for a tangential velocity of the combined masses:

$$M_M\overrightarrow{V_M} + M_E\overrightarrow{U_E} = (M_M + M_E)\overrightarrow{W}$$

The conservation of momentum equation can be broken up into radial and tangential components:

$$M_M V_r + M_E U_r = (M_M + M_E)W_r$$

$$M_M V_t + M_E U_t = (M_M + M_E)W_t$$

Since Mars' orbit is considered circular, it doesn't have a radial velocity component. In this model, Enceladus has an impact angle of 180° on Mars, which would mean that Enceladus doesn't also have a radial velocity component:

$$V_r = 0$$

$$U_r = 0$$

Therefore, the combined masses after the collision don't have a radial velocity component:

$$W_r = 0$$

The conservation of momentum equation in the tangential component remains and can be rearranged to solve for a tangential velocity of the combined masses:

$$W_t = \left(\frac{M_M V_t + M_E U_t}{M_M + M_E}\right)$$

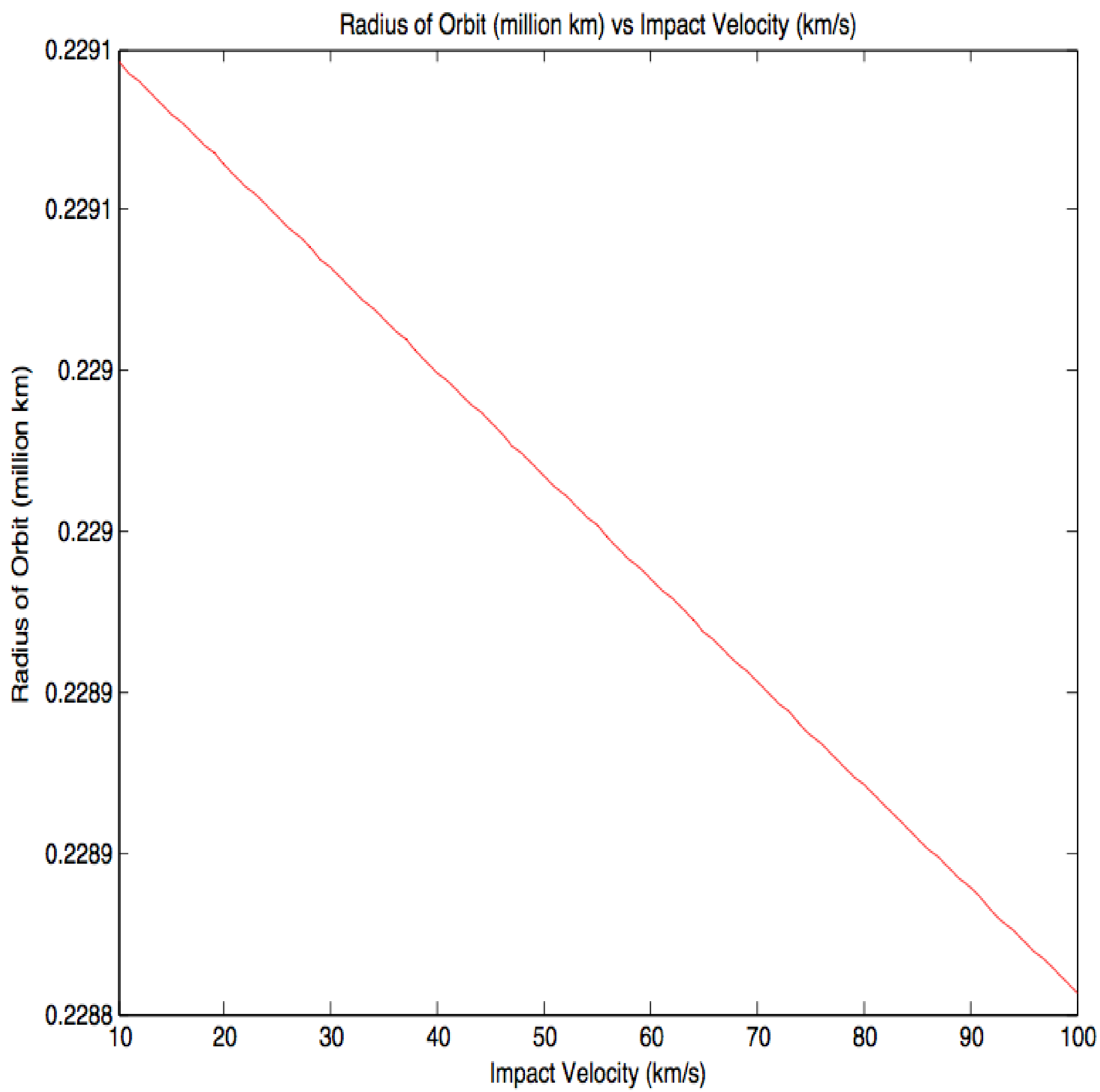
It's important to mention that the tangential velocity of Mars is a fixed value, but the tangential velocity of Enceladus that's chosen to collide with Mars may vary. After the collision, the only forces that are present are the Sun's gravitational pull on the new body and the centrifugal force of the combined masses:

$$\frac{GM_S(M_M + M_E)}{r^2} = \frac{(M_M + M_E)(W_t)^2}{r}$$

By rearranging variables, a new radius of orbit of the new body can be found based on its tangential velocity:

$$r = \frac{GM_S}{(W_t)^2}$$

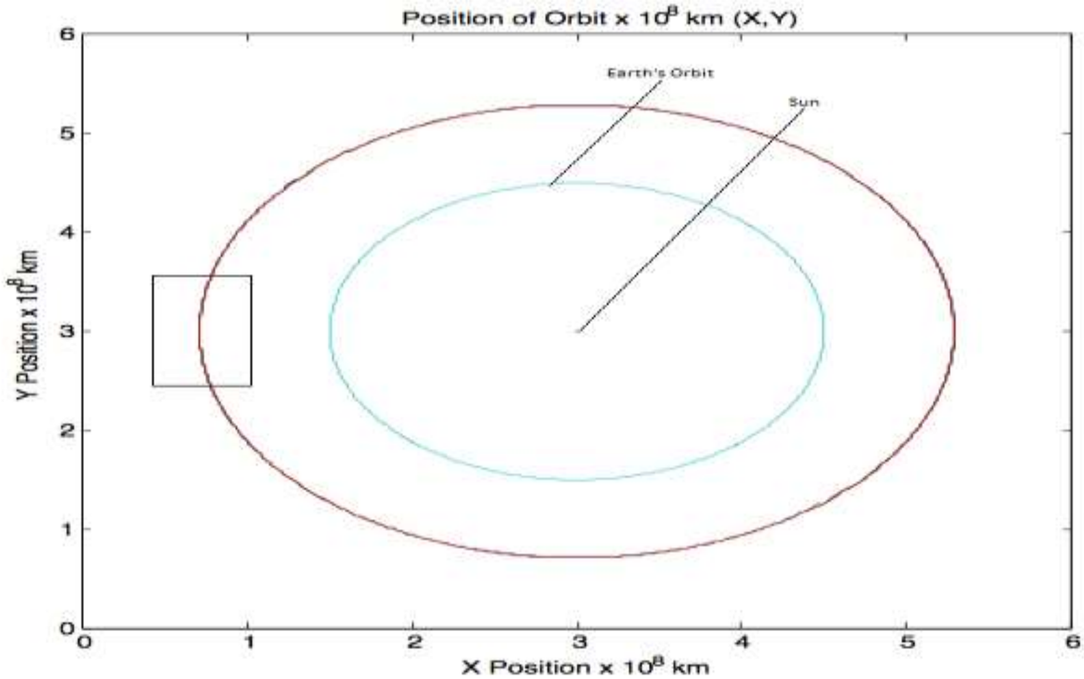
The minimum and maximum impact velocities of Enceladus on Mars were chosen to be 10 km/s and 100 km/s, respectively. As a result, the graph below shows how the range of tangential velocities of the combined masses, influenced by the impact velocities, affects the radius of orbit around the Sun:



Graph 7.1: Anticipated change in Martian orbit

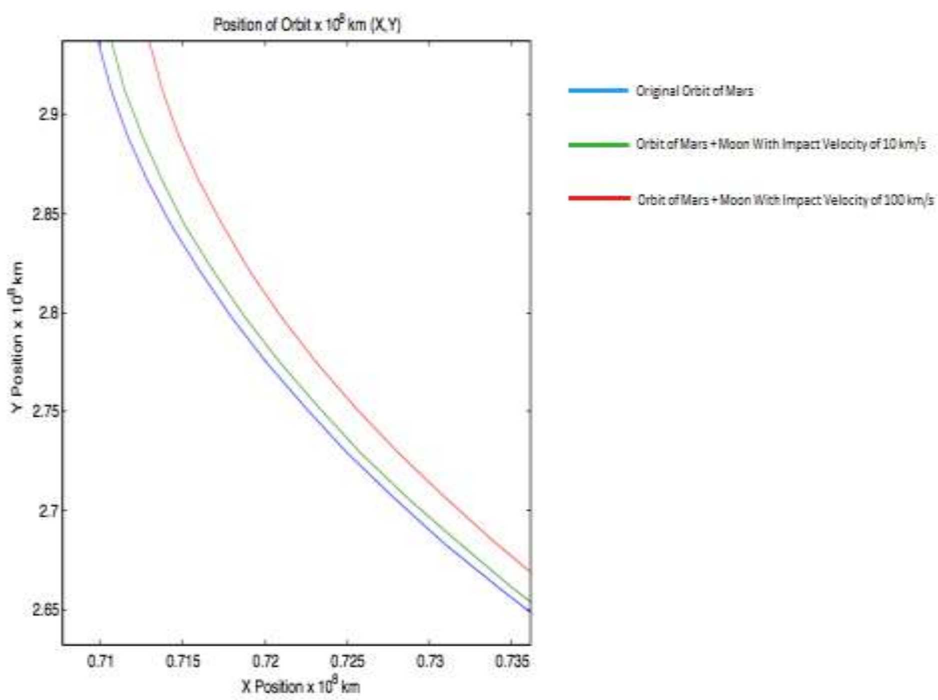
This graph shows that with an impact velocity of 10 km/s, the minimum radius that the orbit of the new mass changes is 83,400 km and with an impact velocity of 100 km/s, the maximum radius that the orbit of the new mass changes is 308,300 km.

From extrapolation, the minimum and maximum radius of orbit of the combined masses are plotted against Mars' original orbit as well as Earth's orbit relative to the position of the Sun:



Graph 7.2: Orbit of Earth compared to the original and new orbits of Mars

The graph below shows a close up of the orbits that are in the box above:



Graph 7.3: Comparison of Martian orbit

0 – Enceladus

- The impact between Enceladus and Mars will initiate the terraforming process with the addition of massive quantities of water and energy.

100 – Convective cell

- The heat and additional rotation speed that resulted from the impact will cause a convective cell to form within the depths of Mars. This will create a magnetic field over Mars, protecting it from radiation.

200 – Asteroid bombardment

- In order to hasten the process of generating a convective cell, humans will bombard the planet with asteroids and comets, thus adding more energy to Mars.

250 – Debris

- Debris from Enceladus, as well as from comets and asteroids, will seed Mars with many of the elements necessary to sustain life, primarily Oxygen, Hydrogen, Carbon and Nitrogen.

400 – Cyanobacteria

- Once the ice caps have melted and Mars is covered in a global ocean, cyanobacteria will be globally introduced by humans to act as Oxygen factories.

450 - Ice age

- CO_2 from volcanic and tectonic activity will mix with atmospheric water, creating acid rain. This acid rain will pull all of the Carbon Dioxide out of the atmosphere and leech it into the ground, resulting in a global temperature drop and finally an ice age.

600 – Thaw

- Humans will use asteroid impacts to melt the thick layers of ice that coat Mars, releasing the Oxygen and greenhouse gases that were trapped below as cyanobacteria continued to flourish deep within the oceans.

750 – Ozone

- Now that the planet has reheated itself to livable levels, scientists will introduce catalyzing technologies to the upper Martian atmosphere to create a blanketing layer of ozone.

850 – Ecosystem

- A self-sustaining ecosystem will be established on Mars and, for the first time, the planet will finally resemble Earth.

900 – Humans

- The first human colony on Mars will be established using the conventional construction methods of the time.

Detailed Description

Early in the forming of the solar system, many small planets formed around the Sun. It is believed that the young Earth collided with a Mars-sized planet called "Theia." This collision not only created the moon that orbits the planet, but also resulted in a massive transfer of energy which inevitably raised the surface temperature of Earth to extreme values. By emulating this process, but with Enceladus, one of Saturn's moons, it is possible that Mars could experience the same levels of energy transfer that Earth received. As it currently stands, Mars has cooled and no longer has any active volcanoes. To geologically resurrect the planet, it is necessary to reheat the core. By making use of deep tunnels near the impact point, lava that results from the impact of Enceladus will flow into the depths, or even to the core, of the planet. The addition of Uranium to the core of Mars will significantly reduce the rate of cooling by releasing heat as it decays.

Figure 7.2: Surface of Mars

The gravitational force between Enceladus and Saturn is approximately $7.22*10^{19}$ Newtons based on their masses and their relative distance. This would mean a force greater than the above value is required in order to bring it out of the orbit. By using a large hollow inverted cone constructed on the surface of Enceladus, a single massive explosion would create the force necessary to achieve separation from Saturn. Based on the gravitational force, it would take an explosion with the force equivalent to 411,568 megatons of TNT; releasing $4.184*10^9$ Joules of energy. This is also the equivalent of 8,078 Tsar Bombs. Thrusters placed in various locations on the surface of Enceladus would act as a "steering" device, allowing the planet to be guided towards Mars and around the asteroid belt.

Long distance space travel would require the use of huge amounts of fuel, especially if the object being moved is on the scale of a dwarf planet. However, due to the cost of fuel, moving such an object using traditional means becomes incredibly expensive. This cost can be reduced with the use of a solar sail[19]. Such a sail is designed to use the energy emitting from the Sun, or any other star, to slowly propel itself forward. While the acceleration experienced by a body attached to a solar sail is incredibly small, there is no fuel cost to operate the sail. Therefore, a solar sail could act as a propulsion source for a massive body, but only if time is not a concern.

The core of Earth consists primarily of Iron, Nickel, and some Uranium, divided up between a solid inner core and a liquid outer core. Iron in the outer core is responsible for the planet's magnetic field, while Uranium slows down the planetary cooling process. A magnetic field is absolutely necessary for supporting an atmosphere. However, the magnetic field that

[19] Eastwood, Jonathan P., et al. "Magnetic field measurements from a solar sail platform with space weather applications."

covers Mars is shaped as various “umbrella” shapes over parts of the surface. The Maven[20] satellite was sent to Mars in order to investigate what caused the changes in the planet’s climate and to ascertain how much CO_2 is being depleted from the remaining atmosphere in order to calculate what the original levels were. It is currently assumed that solar winds stripped Mars of its atmosphere by impacting the planet on the areas that weren’t covered by the protective magnetic field. Without a blanketing magnetosphere, any attempts to make Mars into a livable planet are for naught.

After volcanic activity on Mars has been reactivated by the impact and the planet is once again molten, lava on the surface will cool and sink down as magma from the depths rises. This will result in a convective cell that carries lighter elements and minerals towards the surface. The lightest of these will come together to reform the Martian crust. However, the process will take a prohibitively long time if the convective cell is allowed to form naturally. To accelerate the process, asteroids and comets would be attached to Enceladus along its journey to Mars so that the mass of the moon is increased. Additionally, the remainder of Enceladus after the impact could be kept in a low orbit to maximize its effect on Mars’ core. While this is happening, water vapor and various other gases that were trapped within the planet’s depths will be released by volcanic activity. Along with a continued bombardment of water-laden comets and asteroids, the surface of Mars will become saturated with water.

[20] "Maven." *NASA*

	Mars	Earth
Atmosphere (composition)	Carbon dioxide (95.32%) Nitrogen (2.7%) Argon (1.6%) Oxygen (0.13%) Water vapor (0.03%) Nitric oxide (0.01%)	Nitrogen (77%) Oxygen (21%) Argon (1%) Carbon dioxide (0.038%)
Atmosphere (pressure) **Deepest Canyon**	7.5 millibars (average) ***Valles Marineris*** 7 km (4.35 miles) deep 4,000 km (2,485 miles) wide	1,013 millibars (at sea level) ***Grand Canyon*** 1.8 km (1.1 miles) deep 400 km (248.5 miles) long
Distance from Sun (average)	227,936,637 kilometers (142,633,260 miles)	149,597,891 kilometers (92,955,820 miles)
Equatorial Radius	3,397 kilometers (2,111 miles)	6,378 kilometers (3,963 miles)
Gravity	0.375 that of Earth	2.66 times that of Mars
Largest Volcano	***Olympus Mons*** 26 kilometers (16 miles) high 602 kilometers (374 miles) in diameter	***Mauna Loa (Hawaii)*** 6.3 miles high 121 kilometers (75 miles) in diameter
Length of Day (time required to make a full rotation on its axis)	24 hours, 37 minutes	Just slightly under 24 hours
Length of Year (time required to make a complete orbit of the Sun)	687 Earth days	365 days
Polar Caps **Surface Temperature** (average)	Covered with a mixture of carbon dioxide ice and water ice -81 degrees F (-63 degrees C)	Permanently covered with water ice 57 degrees F (14 degrees C)
Tilt of Axis	25 degrees	23.45 degrees
# of Satellites	2 (Phobos and Deimos)	1 (Moon)

Table 7.2: Comparison of properties of Earth and Mars

Once the collision between Enceladus and Mars is over, the silicate core of Enceladus will be left in low orbit around Mars. While in its low orbit, the gravitational effects of Enceladus will shorten the Martian day by making the planet rotate faster than it previously had. The close proximity of the new moon to Mars will also cause violent atmospheric conditions that will help to redistribute the water across the planet's surface. Because of the close proximity of another large gravitational body, water from the impact between Mars and Enceladus, as well as water from any ice comets, will have extreme tidal activity. Any storm systems that form will also be pushed and pulled across the planet's surface. Shattered pieces of Enceladus will continue to rain down onto Mars, thus furthering the heating and mineral presence on the surface. In addition to the increase in heat and minerals, the pieces of Enceladus will increase the mass of Mars, thereby increasing the gravity and surface area of the planet. The remnants of Enceladus will form a ring around Mars, causing both an extended rain of meteors and the eventual forming of a permanent Martian moon. During this phase of the terraforming process, human-constructed interception satellites could be introduced to quicken the process of pushing the remnants from Enceladus towards Mars. Raining meteors will bring with them small amounts of water and crystalline minerals such as Sodium Chloride. If the human-initiated asteroid bombardment continues into this phase of terraforming, the planet will receive additional minerals, and more importantly, water. As with collecting the remnants of Enceladus, interception satellites could be used to catch and direct asteroids and comets towards Mars. Additional water from these asteroids and comets will accelerate the process of spreading the isolated patches of water on Mars to the entire surface. Additionally, every asteroid that impacts Mars will increase the planet's mass and surface composition. At this point, Mars would look like a violently storming, watery world. Large bodies of water covering a thin crust that hides its volcanic depths would cover its surface.

The human-initiated asteroid bombardment will bring many of the necessary elements for supporting life. As they strike the new oceans of Mars, they will seed the planet with Carbon, Oxygen, and Nitrogen: elements that life, as we know it, cannot survive without. The composition of larger asteroids would be analyzed to ensure that only the most optimal asteroids are chosen for the terraforming process. While asteroids and solar energy heat the surface of the Martian oceans, the depths will be heated by the volcanic activity of the planet itself. Water will seep into cracks in the crust. Once the molten depths have heated it, the water will reemerge into the oceans, carrying minerals and gases with it. Mars would now be coated with a vast, single ocean. The moon, which once ravaged the surface, will have retreated away from the planet, thus loosening its reign on the Martian climate and increasing the length of each day. Because the distance between Mars and its new moon will have increased, its rotation will have slowed. The process that causes the two bodies to separate normally takes millions of years, however because of the relatively small mass and gravitational pull as compared to the original orbit of Enceladus around Saturn, thrusters or comparatively small explosions could accelerate the process of pushing the moon away from Mars.

At this point in the development of Earth, the model being used for this terraforming strategy, early life forms began to develop in the oceans. The elements and minerals from both the asteroids and the ocean floor vents combined to form the earliest microbial life. Because waiting for life to spark isn't within the bounds or time constraints of this enterprise, humans will simply introduce Earth microbes to the Martian oceans. Should the introduction be successful, the shallow areas of the Martian seas will fill up with colossal bacteria colonies, called stromatolites. These structures are created when bacterial colonies trap sedimentary grains within the layers of the colony. Cyanobacteria are the most noted for the construction of stromatolites, and as such, would be the most likely candidate for early introduction. Due to the vastness of the area that needs to be covered in Cyanobacteria, it could take too long to accomplish by simply introducing a patch of the bacteria to a body of water on Mars. Because of this, a breed of Cyanobacteria would have to be created specifically to reproduce much faster. To reduce the time to introduce the bacteria to the planet, dissolvable capsules could be dropped from high altitude using a technique similar to carpet bombing. By doing this, a light layer of fast reproducing Cyanobacteria could be placed over a large portion of the shallow waters that would now coat Mars.

Cyanobacteria, also known as blue-green algae, will act as the primary “factory” of Oxygen during this phase of terraforming Mars. By absorbing solar energy, blue-green algae is able to use photosynthesis to convert CO_2 into Oxygen. Without human intervention, these colonies of bacteria would slowly convert the atmosphere to oxygen, however, by positioning solar mirrors in key locations on and around Mars, it is possible to increase the time that these colonies are exposed to sunlight, thus increasing the rate of oxygen production. Additionally, if the Cyanobacteria can be successfully genetically altered to reproduce faster, its rate of Oxygen production could also potentially increase.

By this point, Mars will be covered by a massive ocean dotted with volcanic islands. The human introduced life will be busy producing the oxygen that is necessary to support life. However, during the predicted 200 years it would take for Mars’ orbit to stabilize again, the convection cell that causes the planet’s volcanic activity will have also restarted the plate tectonics. The motion of these plates will redistribute the volcanic activity of Mars, while also causing new centers of volcanic activity to spawn where the plates move apart. Additionally, the presence of plate tectonics will cause larger landmasses to form where the plates eventually collide with each other. Mountains with no volcanic activity will form at the points where one plate has risen above another. These mountains will play a key role in the future of the planet by creating both a natural water cycle and watersheds: zones where all water flows to a single location.

Rather than just act to heat the planet's surface, the newfound volcanic activity will pump Carbon Dioxide into the atmosphere. The large quantities of this greenhouse gas will inevitably mix with the atmospheric water of Mars to form acid rain. Instead of building up a heat absorbing layer, the acid rain would pour down onto the landmasses of Mars, bringing with it the CO_2 that is needed to warm the atmosphere. In order to accelerate this process, the solar mirrors that were previously proposed to increase the rate of Oxygen production could be repurposed into heating the oceans and therefore increasing the speed of the water cycle. Additionally, strategically placed tunnels could be dug. By detonating large amounts of explosives at the bottom of these tunnels, enough seismic activity could be made in order to theoretically create a volcanic eruption, thus pouring more CO_2 into the atmosphere. In addition to this, Sulfur Dioxide production facilities would be constructed on the surface of Mars to further increase the levels of acid rain. Soon, the temperature of the planet, now devoid of its necessary greenhouse gases, will plummet. The entire planet will freeze over.

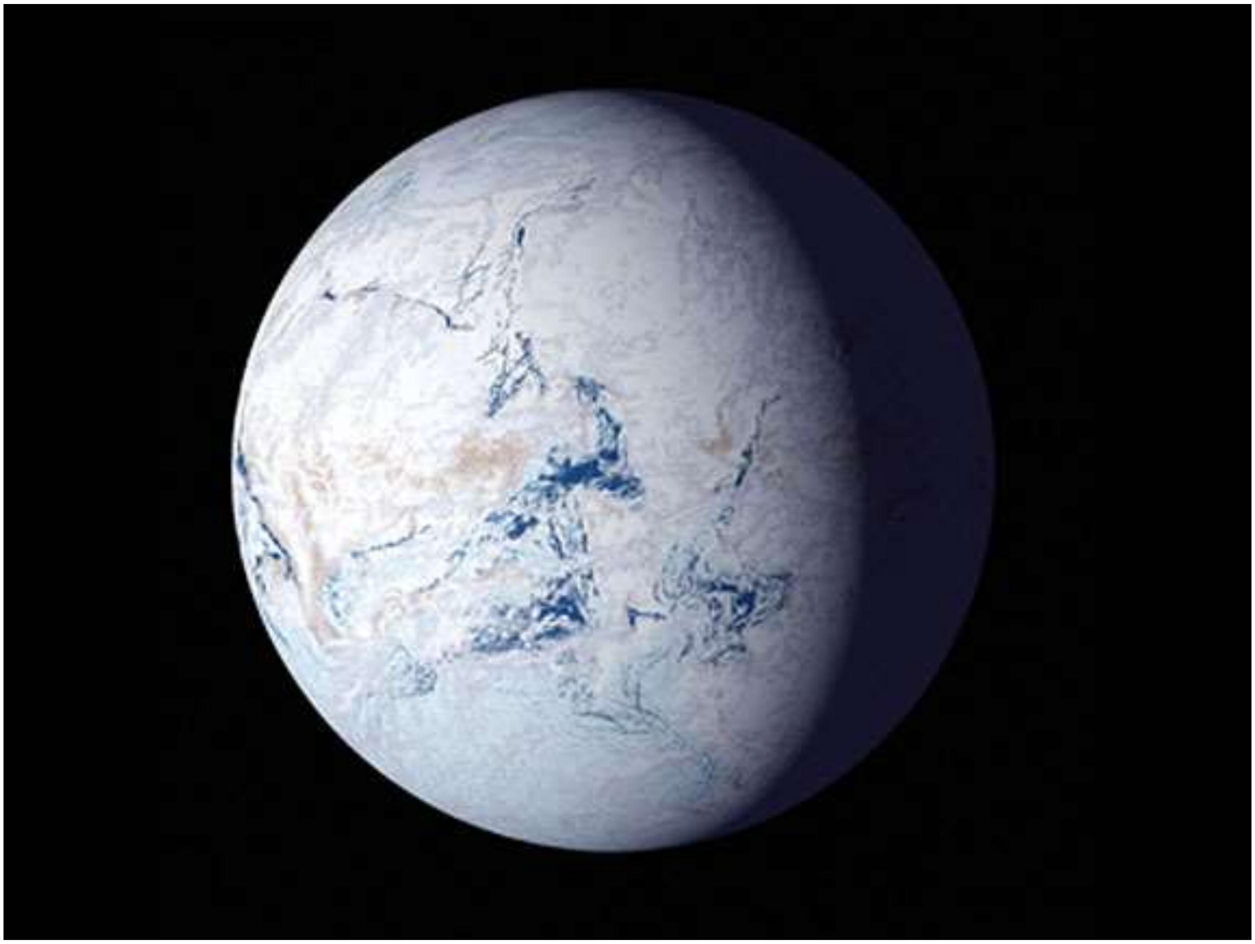


Figure 7.3: Theoretical snowball Mars

The presence of the ice over the entire surface of the planet will reflect more sunlight into space, further solidifying the ice age. However, even when the entire planet is covered in hundreds of feet of solid ice, the volcanic activity will not stop. Eventually the volcanoes will pierce through the ice and once again release Carbon Dioxide into the atmosphere. Now that Mars is frozen, the rocks will be unable to absorb any more greenhouse gases. Because of this, the atmosphere will return to a temperature that can support surface life. However, because this process would take millions of years by itself, human intervention would be a necessity. Drills could be used to tunnel through the ice to release trapped CO_2. Alternatively, more asteroids (albeit smaller than the previously used ones) could be crashed into Mars to melt the ice and add yet more minerals and mass to the planet. As the ice melts, the land beneath it will crack and rupture, allowing more CO_2 to enter the atmosphere. Additionally, Hydrogen Peroxide trapped within the ice will have undergone chemical reactions, producing H_2O and Oxygen.

Prior to the planet freezing, it would have an atmosphere composed of mostly Carbon Dioxide, which inevitably caused it to freeze. By freezing, Mars was transformed into an "incubator" of sorts for water and Oxygen. The ice transformed the chemical composition of the surface, turning poisonous molecules into those that would support life. It also trapped CO_2 underneath the atmosphere, which, when combined with the CO_2 released during the ice age, pushed the atmospheric temperature to higher than it originally was. After the ice has melted, the world will have returned to a state similar to that of before, however, the surface conditions will be more suitable to life than they were previously.

Any life that could have survived the frozen phase of terraforming would have done so within the now highly Oxygenated ocean. In addition to the bacteria that were left on the planet by humans, plant life would then be introduced to the Martian oceans along with a breeding population of small, ocean-dwelling creatures. All of these forms of life would, if left alone for a short period of time, grow exponentially in population. The higher Oxygen levels in the oceans would also support large sea creatures. By introducing such creatures in appropriate numbers, a proper ecosystem could be created for the first time. At this point, the surface of Mars should be both a moderate 30 degrees Celsius and have comparable Oxygen levels to Earth.

While the ocean teams with life, the surface would lack any comparable levels of life. Some patches of algae may be present, but nothing complex would survive due to the complete lack of Martian ozone. Solar radiation would constantly bombard Mars' surface, preventing any life from surviving. However, upon making contact with the ultraviolet light emitted by the Sun, Oxygen high in the atmosphere would be transformed into ozone. While this process is naturally very slow, human innovations could be used to catalyze the reaction in order to exponentially hasten the process. One possible solution would be to use many high-atmosphere balloons carrying solar cells with arcing electrical nodes. Such devices would increase the rate of Ozone production in the upper Martian atmosphere[21]. Ozone would blanket the atmosphere and protect the planet from the lethal radiation. Over time, as the ozone layer thickens, it will stop even more of the solar radiation from getting through. Land life cannot exist in the complete absence of an ozone layer. Initially, mosses and robust grasses would be introduced to the now livable surface using a similar carpet bombing technique to the one that was used to coat the oceans in Cyanobacteria. As these initial land plants spread, they will increase the Oxygen levels even more. After some time, the dead plants and animals over the entire planet will form layers of dirt and mud, allowing the surface to support even more varieties of life. The dead ocean creatures will coat the ocean floors, and due to the intense pressure, begin the process of creating fossil fuels such as natural gas and oil.

During Earth's own forming process, the next period it underwent after gaining life was a volcanic mass extinction. Such volcanic activity would burn nearly all life on the planet and cause any that survived the initial eruptions to die from raining carbonic and sulfuric acid. The eruptions cause CO_2 levels to skyrocket and heat the atmosphere. As water evaporated, Oxygen went with it, leaving the remaining water only hospitable to anaerobic algae. On Earth, this cataclysm triggered the release of methane into the atmosphere. Due to its distance from the Sun and still relatively weak atmosphere, Mars would require this step in its own terraforming

[21] "How Is Ozone Formed in the Atmosphere?" *Earth System Research Laboratory*

process. The presence of methane in the atmosphere will cause the temperature to rise to levels higher than prior to the eruption. After some time the intensity of the acid rain would drop and plant life would return. Volcanic activity will continue in places where the Martian tectonic plates collide and separate, but nowhere near as violently as it had previously been.

With the terraforming process nearly completed, it will be possible to start constructing new human settlements. Unlike any form of colonizing Mars that uses the planet in its current state, these settlements would look exactly like Earth towns and cities. Although it is impossible to know what level of space technology that the humans of the future will possess, it can be assumed that, unless some catastrophic event ends humanity, the future space ships will be incredibly fast and reliable, as well as having exuberant levels of transportation capacity. Such ships would easily travel between Earth and Mars.

Social Aspects

The primary concern with terraforming Mars is whether or not it is actually worth the time and resources. Even the fastest estimates would place the time range at over 1000 years. After this time, humans may have already reached a point in their technological development where they are able to casually travel between stars and galaxies. To the humans of that time period, there will be no benefit whatsoever to living on Mars, as they will probably inhabit many planets across the galaxy. In addition to the prohibitively long time estimate, there is also the problem with funding the project. A single country alone could not hope to fund the project over the course of its realization. Many space faring countries would have to work together in order to ensure that the project was well funded. However, even then these countries would have to convince the general populace to fund a project that none of them would ever see. The investment might benefit the humans of the future, but would only have negative global economic impacts for centuries. Humans, by nature, prefer immediate gratification over long term satisfaction. It is this attitude that would render the consented funding of this project next to impossible. Although the act of terraforming Mars could have the effect of saving humanity, many people today have no real sense of urgency or impending doom, and because of this, won't be able to conceive the need to invest in a 1000-year project. Assuming, however, that the project was successfully funded and executed, there is still the issue of the lower gravity that exists on Mars. The humans who travel to and live on the new Mars will experience a loss in muscle and bone mass[22]. This will, in turn, prevent permanent residents of Mars from returning to Earth without physical therapy. In a future where humans will potentially have intergalactic travel capabilities, this drawback far outweighs the benefits of a single planet.

Not all of the social aspects associated with terraforming Mars are negative. Many of the positive aspects come in the form of effects on the human populace itself. By terraforming Mars, the need for human colonists to adjust their standard of living or lifestyle ceases to be a concern. By colonizing a planet that mirrors conditions on Earth, the colonists would have to endure lifestyle changes of a similar caliber to moving overseas. In addition, having a second planet to diffuse humanity onto would solve the growing problem of population density and ratio. Since the countries with space programs also tend to have the higher populations, a natural shift from these nations to Mars would equalize the global population as a side effect of colonization. In addition to the easily noted benefits to population distribution, the shift of population from technologically advanced nations will result in a combination of various global cultures. The end result of this, assuming each nation doesn't have its own colony, will be a single, human culture. However, in a brand new society on a new planet, the socioeconomic positions of the colonists

[22] Fitts, Robert, Danny Riley, and Jeffery Widrick. "Functional and Structural Adaptations of Skeletal Muscle to Microgravity."

will not transfer with them, as Mars will have no preexisting economic system. Because of this, a new, perhaps more ideal, system could be implemented. While capitalism works in a market driven society, the utter lack of any market infrastructure on the newly terraformed Mars won't allow for such a system to function. As the industry of any Martian colony grows, the principles of economies of scale would allow for the potential return of a capitalistic society, however, increased industry profits could potentially be routed into projects that benefit the entire colony, rather than just the hands of the wealthy few. In addition, the early colonies would need a governing body, but as with the economic system, the government systems of Earth are designed to rule over huge populations and tend to favor the wealthy over the general populace. For any early Martian colonies to function properly, the governing body has to place more priority into the equalization of representation and resource distribution.

While terraforming Mars could potentially hold many positive impacts on human society, terraforming the planet itself also holds many benefits. The act of pulling Enceladus from Saturn to Mars poses a huge technological challenge to humanity. As with any major challenge, the resulting technologies not only answer the problem at hand, but also tend to change the lives of all of humanity in the process. Moving Enceladus from Saturn to Mars will show the world that it is possible to make use of the entire solar system for resource collection and scientific study. In order to ensure that the terraforming process proceeded smoothly, there would need to be observation stations orbiting around Mars, furthering the need for all of Earth's spacefaring nations to work together. For the duration of the project, these countries would need to constantly staff various space stations with researchers and planetary experts. In the end, the presence of humans in space and the amount of space stations will grow as the project gains more momentum. Not only will terraforming Mars give humans an understanding of how planets form magnetospheres, it will also act as a source of scientific and economic gains, while depleting the world's nuclear arms in the process. When humans truly gain control of the solar system, the threat of a space-based disaster will be null.

Mankind has always dreamt of finding another world teeming with life. However, while the probability of such a planet existing is incredibly high, the chance of actually finding it is miniscule. Scientists and researchers could search for centuries without ever finding the perfect world, and even then, that world might be completely out of reach. Instead of looking for another habitable planet, why not take matters into humanity's hands and build one.

Underground Colony

Introduction

Completely terraforming the surface of Mars is a massive undertaking that would rely too heavily on investment for a future that nobody alive would ever hope to see. Therefore, colonizing Mars in its current state is a logical alternative solution. However, potential colonists don't need to brave the surface conditions. They can live much safer lives underground. An underground colony solves all of the issues present when colonizing the surface of Mars, including radiation, heating, and atmospheric conditions. Should the colony be constructed far enough under the surface of Mars, any condition on the surface, even an asteroid impact close to the site of the entrance, wouldn't put the colonists at risk. Creating an underground colony is not without its drawbacks, such as the complete lack of any sunlight exposure or the initial cost of establishing it. While the lack of sunlight would have a psychological effect on the pioneering generation, subsequent generations of colonists would not be affected by it. No matter what the cost of constructing and underground colony is, it pales in comparison to the cost associated with terraforming a planet. The biggest challenge in establishing an underground colony is not the cost, but rather the construction itself. Many conditions need to be met in order to ensure that the colony can take shape.

Methodology

Colonizing Mars by tunneling into the planet would entail heavy use of very large tunnel boring machines (TBMs) and swarm robotics. Initially, a crater, cliff face, or preexisting cave would be selected to act as the site for the entrance to the underground colony and as a drop point for a portable power source, the TBM, and maintenance robots. Once assembled by the robots, the TBM would start to drill a corkscrew shaped path under the Martian surface, thus providing a central tunnel for the colony. After the TBM digs roughly one entire circumference, swarm robots would enter the tunnel to dig networks of branches off of the outer sides of the main tunnel, with each branch being offset from the last enough to allow them to overlap without being superimposed. This construction process would rely heavily on advanced sensors and communication between the swarm robots. Such sensors would allow the robots to react to any sudden changes in ground composition. The parallel nature of all aspects of construction would allow the bulk of the underground colony to be made simultaneously, therefore allowing it to support a large population relatively fast.

Each branch would be roughly five city blocks in area and shaped similarly to an isosceles triangle, with a small entrance that fanned out over a large area. The branches would be comprised of network of tunnels and rooms all on the same plane of elevation. This would allow for the subsequent layers to be placed partially underneath and above other layers. Rather than a random assortment of rooms and tunnels, each branch would be designed following patterns noted in large-scale ant colonies in order to utilize natural air flow patterns. This would ensure that the entire colony is always supplied with fresh, oxygenated air. Ideally, one layer of the colony (one section from where the main tunnel starts to where it has circled around to be directly underneath it started) would have 15 branches coming off of it and house 5,000 people. With this estimate, a single branch would only require residential space for about 330 people. Once completed, a single underground colony would be comprised of 10 layers and support a total population of around 50,000 people.

Each stage of the colony's establishment, from early construction to settlement, requires some form of transportation. Both construction equipment and colonists will utilize the same basic rocket launch system, with the only difference being the design of the cargo space. The theoretical maximum payload of NASA's new SLS rocket is 130,000kg.

Within the center of the main corkscrew tunnel would be large rooms entirely devoted to air purification. Depending on the depth traveled by 1 layer of the colony, more than 10 of these air purification chambers would be constructed, allowing for an offset that could potentially produce Oxygen more efficiently than having larger chambers at a 1:1 ratio with the layers. These chambers would be layered above one another and would house a large quantity of vegetation, including fruit bearing plants. Such plants could act as a secondary source of food behind the larger hydroponic sections of the colony. Within these sections, the bulk of the colony's food would be produced using specialized hydroponic fluid and UV lights to compensate for the lack of sunlight[23]. Rather than fully taking the place of one of the branches on any given layer, branches that house hydroponics facilities will be much larger than other branches to allow them to house the same population as anticipated. In addition to simply supplying the colony with food, these hydroponic facilities would also act as major sources of Oxygen. Ideally, both the air purification chambers and the hydroponics facilities would perform their own task as well as part of the task of the other. In this way, neither part will be useless outside of its primary purpose.

The original power source that was sent to fuel the early construction would not be large enough to power the entire colony. Therefore, a much larger, dedicated power source must be installed. Ideally, this power plant would be either fusion or fission nuclear power. The risks involved with such a power plant could be mitigated by placing the plant at the bottom of the colony, hundreds of feet below the lowest living layer and by using a Thorium molten salt reactor rather than a traditional Uranium one. With a dedicated nuclear power facility supplying

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[23] Phutthisathian, A.; Pantasen, N.; Maneerat, N., "Ontology-Based Nutrient Solution Control System for Hydroponics"

power to a relatively small zone, the residents of this proposed underground colony would never need to worry about energy.

Rather than positioning this underground colony on the Martian equator where weather is the warmest, it would be positioned near one of the ice caps. Because of the heavy reliance on vegetation, this colony would need the constant, easy supply of water that the ice caps provide. The extreme surface conditions wouldn’t faze a colony hundreds of feet below solid rock. Pipelines to surface water extraction facilities would act as the sole pathway for water into the colony. They would be constructed of a non-reactive inner pipe (such as PVC) surrounded by a thick steel outer pipe. This design would allow the pipeline to handle the extreme difference in conditions between the colony and the surface. Within the colony itself the water pipelines could be constructed entirely out of PVC[24], with cutoff valves between each of the branches to allow the feed to be shut off in the event of a leak. The exterior pipeline would connect to massive storage tanks in the uppermost layer of the colony. These tanks would have many smaller pipes connected to them, which would supply the entire colony with water.

[24] Cruz, Javier, Bruce Davis, Paul Gramann, and Antoine Rios. "A Study of the Freezing Phenomena in PVC and CPVC Pipe Systems."


Figure 8.1: Sample vault door

Creating an underground colony with air pressure high enough to support human life would require a meticulously crafted entrance. The entrance would have to, at the very least, support the pressure difference without allowing any air to escape. Ideally, the entrance to the underground colony would have a large, multistage locking bulkhead door connecting directly to the outside (similar to a vault door, but airtight). Within this outer door would be an airlock chamber and a second, smaller bulkhead. Beyond that would be an emergency bulkhead and an entrance control room. Such an entrance would prevent any accidental loss of interior atmosphere to the Martian surface, as well as keeping the colony safe in case of an emergency.

Advantages and Disadvantages

Advantages	Disadvantages
Resistance to severe weather: • Incredible structural integrity making them safe from tornadoes, sandstorms, fires, and other natural disasters • A nearly constant interior temperature due to the natural insulating properties	**Microgravity** • The gravity on Mars will remain the same below its surface which would mean that colonists would have to find a solution to deal with a lower gravitational acceleration
Psychological: • Quiet living space • An unobtrusive presence in the surrounding landscape • Interior atmospheric conditions are constantly maintained at an ideal level • Environmental friendliness • Could direct natural light into living spaces with light tubes • Factories and office buildings can benefit from underground facilities for many of the same reasons as underground dwellings such as noise abatement, energy use, and security • Walking distance in branches will provide with health benefits	**Psychological:** • Anxiety • Depression • Insomnia • Homesickness • Isolation • Change in daily routine • Culture
Relatively Cheaper in Cost: • When combined with renewable energy sources, energy cost can be greatly reduced. • Initial building costs are often low, as underground building is largely subtractive rather than additive, and because the natural materials displaced by the construction can be recycled as building materials. • Exposure to the elements.	**Cost:** • The initial and ongoing funding for the project is massive. • TBM • Transportation costs • Raw materials • Maintenance • Construction • Power

Energy: • A significant reduction in utilities and energy costs • Energy Savings	**Hazards:** • A fire can occur at any given point. Some type of system must be created in order to stop any instances of a fire. • In case of an explosion, an underground power facility could be damaging to the colony. A protective structure must be created around the power plant to ensure minimum damage.
Local time: • Relative daytime is dictated by the colonists, not natural light	**Planning:** • It will take an extensive amount of time to initially create structures and livable space
Surface conditions: • The underground colony will be facing almost zero air pollution • The emission of waste from the nuclear facility will be released to above atmosphere to prevent damage to the colony itself, as well as altering the surface atmosphere to a point where it could potentially support an ecosystem • Insect invasion is a non-issue due to their nonexistence • There is no risk of polluting the underground colony • Exterior maintenance is almost nonexistent • Preserving land	**Physiological:** • Motion sickness • Loss of bone and muscle mass • Microgravity can cause the various fluids that make up humans to behave differently. • Low gravity causes a distortion in the shape of the eye, and could therefore result in a loss of vision. • Because of the changes in gravity, and thus blood/fluid flow, humans would experience a change in their sense of taste
Water conditions: • After a certain depth, pipes will no longer hold any risk of freezing	**Flooding:** • A plan must be created in order to stop any flooding situations.
Transportation: • Less time consumption between	**Communication:** • A complex network consisting of wires and localized receivers is

layers, since vertical movements takes people directly from one city place to another • Lowest displacement when in travel between two or more spirals	required for communication throughout an underground colony.

Table 8.1: Advantages and disadvantages of an underground colony

* Weather would no longer be relevant, since it is primarily a phenomenon of the atmosphere. Rain, snow, sleet, fog would not trouble the underground world. Even temperature variations are limited to the open surface and would not exist underground. Whether day or night, summer or winter, subtropical or sub polar, temperatures underground can be set to the ideal value. The damage done by weather to humanity and its structures would be gone.

* The passage of the Sun: the tyranny of day and night coming at different times in different places can be avoided. When underground, where there is no externally produced day, the alternation of work, play and sleep can be adjusted to suit the needs of any particular colony. The whole planet could be on eight-hour shifts, starting and ending on the same stroke everywhere, at least as far as business and community endeavors are concerned.

* Since the colony will be located underground, colonists will have quick access to all metals and other minerals present in the surrounding areas. Mining these elements won't require any additional vertical excavation, merely horizontal mineshafts.

* Lower levels of exposure to sunlight may cause physiological problems. The Sun provides vitamin D which results in the strengthening of bones and maintaining of one's circadian rhythm.

* The colony's transportation system would include two trams within the main corkscrew tunnel and a series of elevators between the various layers. The trams themselves would not travel the

length of the corkscrew, but rather only a single layer. From there, passengers will have to switch to a tram that would travel the length of the next layer. For each layer, both trams would be in either station at the same time. Rather than using the tram system, a colonist could travel between all layers using one of the various elevators.

Social Aspects

Colonizing the depths of Mars comes at the cost of many of the amenities of life that residents of wealthy countries take for granted. While it is the safest method of colonizing the dead husk of Mars, colonists will sacrifice a lot. Living an exclusively underground life will completely eliminate sunlight exposure. Although the negative consequences on the health of the colonists could be mitigated with diet supplements and specialized lighting, sunlight itself cannot be replicated. Colonists would be faced with the reality that they would probably never see the Sun, and by extension, the surface again. To first generation colonists, this sacrifice could have the unintended consequence of inducing severe depression. However, future generations who have never left the colony wouldn't be nearly as affected, and all residents of the underground colony could simulate exterior conditions through the Internet or virtual reality simulations to negate the loss of an exterior world. In addition to the health effects associated with no exposure to sunlight, residents of an underground colony would also have a greater challenge controlling the spread of disease. Due to the enclosed nature of the air purification system, airborne sickness would spread a lot faster than it would on Earth. This could lead to massive outbreaks of otherwise containable sicknesses and therefore a temporary secession of colony activity. Though not as drastic, an underground colony would be the perfect habitat for a number of species of mold. Because of the nature of the water and tunnel systems, colonies of mold could easily grow in great numbers. For the subset of the colony's population with mold allergies, this could cause constant discomfort and unnecessary hardship. Should mold colonies take hold in hard to reach places, they will be next to impossible to remove.

Although colonists would be faced with many physiological challenges, an underground colony would offer many benefits to offset them. By living underground, colonists would have access to many different rock depths. This would ensure that the colony never ran out of raw industrial materials. In the event that the colony was situated on a plot of land rich in iron, it could even repair structural damage without ever venturing to the surface. Since the only costs associated with constructing an underground colony are a tunnel boring machine and excavation robots, the colony itself is comparatively cheap. Because of this, an underground colony offers the greatest defensibility per unit of cost of any colonization solution that doesn't terraform the planet. Due to the synchronous nature of colonization and construction, this planetary colonization technique could be used to colonize any number of planets in the far future, without regard to the location of the planet in relation to its star. Although the colonists will no longer have access to sunlight, living on the surface itself wouldn't result in the same exposure to sunlight that Earth experiences. Due to its increased distance from the sun, the levels of sunlight that colonists would be exposed to on the surface are nothing compared to what the colonists would want. The same can be said about the view offered by the surface beyond the colony. While there would be vast open spaces, the utter lack of life on the surface of Mars negates any of the happiness that could be derived from having an outside view. Lastly, should constructing an underground colony prove to be successful on Mars, there is nothing that would prevent similar structures from being constructed on Earth. Underground colonization could be the solution to both colonizing beyond Earth, as well as saving the global environment by allowing urban areas to expand downward, rather than outward.

Modular Martian Colony

Introduction

The quickest way of producing a colony on Mars is to implement modular colony units. By doing such, the colony is allowed to function while it is still being constructed (or being prefabricated) on Earth. To successfully accomplish such a colony, many new and emerging technologies will be implemented, with the final goal of having a fully functioning, self-sustaining colony within 100 years. The first step in the establishment of a modular colony would be to design and construct a module to act as the central structure of the colony. This first module would be the sole structure of the first phase of colonization. Due to the technological and time requirements associated with building this module, the first phase would begin 20 years after the decision to implement this colonization plan was made. The second phase would include a myriad of new modules where each serves a specific purpose. Again, due to the time, monetary, and technological requirements, an additional 20 years would separate phases 1 and 2. The third, and final, phase of establishing a colony would increase the scale of the colony by 1,000%. To accommodate this drastic growth, the designers on Earth and the colonists on Mars would have 50 years to prepare for it.

Breakdown of Modular Colony Phases

	First Wave (Nexus Pod)	Second Wave	Third Wave
Population	40	400	5000
Capacity	45	500	6000
Number of pods	1	20	50
Types of pods	Nexus Pod (Test colony) with four connections	• Farming (4) • Power Station (3) • Water Drills (3) • Medical Supplies (1) • Residential Pods (8) • Manufacturing (1)	• Residential Pods (10) • Industrial/Manufacturing Pods (8) • Tertiary Sector Pods (5) • Medical Supplies (4) • Server/COM Pods (2) • Farming (13) • Power Station (5) • R&D Pod (3)
Construction site	Earth	Earth/Mars	Earth/Space/Mars
Location	Temperate Zone under magnetic umbrella	Temperate Zone with Water Pipelines to the Ice near poles	Temperate Zone with Underground Water, Heat and natural resource Drills
Residential Pod Structure (Exterior)	Hemi-spherical Structure Diameter: 40 meters Opaque	Hemi-spherical Structure Diameter: 60 meters Opaque/Transparent	Hemi-spherical Structure Diameter: 100 meters Transparent
Number of Floors	5 stories	8 stories	14 stories
Residential Pod Structure (Interior)	Quartered floors Freight elevator Residential Research laboratory Hydroponics Storage Recreational	Residential Pod: Elevators Apartment units (400 ft^2) Storage Recreation level	Residential Pod: Elevators Apartment units (500 ft^2) Storage Recreation level
Radiation layer	Reflective Aluminum Boron Nitrate Polyethylene Thin Metal Meshes	Reflective Aluminum Boron Nitrate Polyethylene Thin Metal Meshes Electromagnetic Shielding	Electromagnetic Shielding Fully Transparent "future technology"
Thermal Layer	Vacuum Layer to prevent heat loss through convection Insulation to prevent heat loss through conduction High emissivity layer to offset radiation loss	Vacuum Layer to prevent heat loss through convection Insulation to prevent heat loss through conduction High emissivity layer to offset radiation loss	Vacuum Layer to prevent heat loss through convection Insulation to prevent heat loss through conduction High emissivity layer to offset radiation loss

Geographical Mobility of Pods	Immobile –Landing must be within a specific range	Mobile-Tank like base structure	Mobile-Tank like base/Propulsion system/Thrusters/Hover Platform
Power/Energy stations	Plutonium radioactive decay Solar Panels Wind Turbine	Carbon nanotube batteries (electrochemical) Thorium Molten Salt Reactor (TMSR)	Fusion reactors More TMSR
Water drilling equipment	Few simple underground water drilling resources Water storage and purification methods for water supply inside pod Start of construction of Pipeline (map)	Pressurized Water Pipelines from polar ice caps to pods. Water Storage and purification methods in pods	Pressurized Water Pipelines from polar ice caps to pods. Water Storage and purification methods in pods Underground reservoir
Safety Mechanisms	Thick Steel Structure Airlocks Emergency bulkheads	Missile Array (against threat) Thick Steel Structure Airlocks Emergency bulkheads	Missile Array (against threat) Thick Steel Structure Airlocks Emergency bulkheads
Type of research conducted by the pods	Determine necessities STEM research	Study low gravity effects on humans More research on our solar system Colonizing other bodies in space Better energy sources	STEM research Harvesting energy from outer space (supernovas/planets) Colonizing other bodies in space
Gravity concerns	Adjust to lower gravity	Adaptation and evolution to adjust to new gravity	Artificial Gravity/ Super Conductor Induced Gravity/ Mass change on Mars
Transportation Methods	Inside Single Pod	Tunnel based walkways	Underground Subway System
Air recycling	TiO_2 Electrolysis from fuel cell Nitride Semiconductors	TiO_2 Electrolysis from fuel cell Nitride Semiconductors High efficiency photosynthesis	TiO_2 Electrolysis from fuel cell Nitride Semiconductors High efficiency photosynthesis

Table 9.1: Breakdown of colonization phase

* The population to capacity ratio was calculated based on the concept of “minimum viable population” which states that about 5,000 genetically diverse members of a population are needed to ensure that the effects of inbreeding aren’t present for at least 1,000 years[25].

* The population rise was calculated based on the viability of sending colonists from Earth, anticipated pregnancies within the colony before it has been established for long enough to maintain itself, as well as maximum ability to produce food and water.

*The population per pod was based on one person’ being sustained by one acre of land indefinitely. The food consumption of the population is anticipated to be below the critical level because the colony is expected to achieve higher levels of farming efficiency from genetically engineered plants and stored food from Earth[26].

*The locations of pod assembly during the later waves will include not only Earth, but also in space and on Mars itself because the scale of the larger pods prohibits them from being launched into Earth’s orbit in their entirety and they would cost too much to do so.

*The pipeline will be manufactured on Earth and sent to Mars where it will be assembled by a swarm of construction robots. It will be over 1,300 km long and made using two layers: an inner PVC layer surrounded by a steel layer to maintain structure under pressure and protect the pipeline from dust storms. This will ensure that the pipeline doesn’t rust and remains durable. Such a pipeline is reasonably viable when compared to the largest pipeline built on Earth[27].

[25] Traill, Lochran. "Minimum Viable Population Size."
[26] Bradford, Jason. "One Acre Feeds a Person."
[27] "Druzhba Pipeline." *Pipelines International*

*The later phases of the colony will have an underground subway system for commuting around the then much larger colony. This subway network will be pressurized and deep enough in the ground to completely block radiation.

*The early phases of the colony will not have the power or technological level to support an artificial gravity system and thus the early colonists will be given simple weighted clothing to offset the effects of low gravity until their bodies adjust to it.

*The pods will have the ability to switch between mobile and immobile modes via deployable tank treads so that the pods can land anywhere and drive to the colony, as well as being used to optimize the location of each pod in the colony.

*The exterior layers of the modular pods will be radiation resistant using a composite of multiple materials in order to block all forms of radiation without the weight of solid lead.

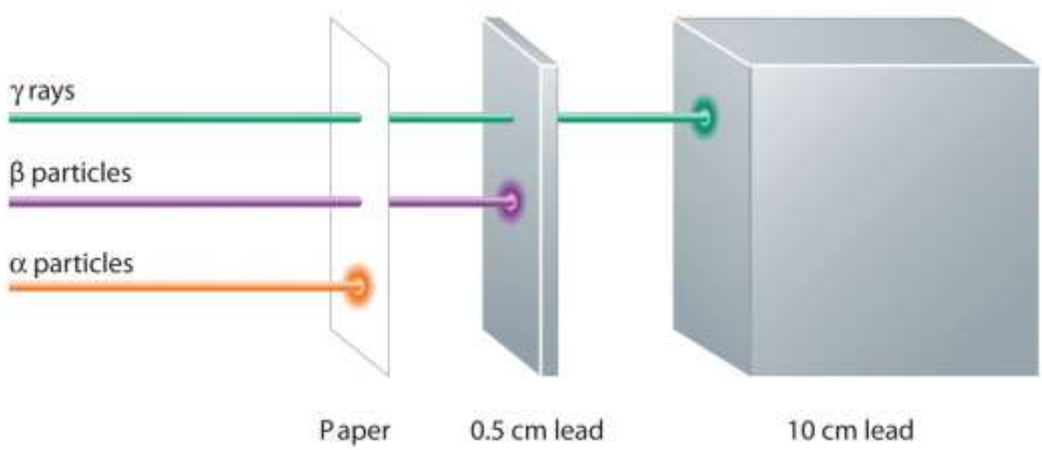

Figure 9.1: Radiation resistance requirements

Comprehensive Description

There will be three phases of constructing a modular colony. The first stage will be the construction and establishment of a singular structure on the Martian surface that will fully support itself. The inhabitants of this initial module (nexus pod) will live entirely within it and therefore the pod itself must be able to produce all of the necessary amenities for supporting a small population of humans. Transportation for the first phase of colonization will use a multi stage rocket system that starts with an SLS rocket for breaking out of Earth's atmosphere, then switches to electric propulsion for traveling to Mars before finally using a decelerating rocket as it enters the atmosphere[28].

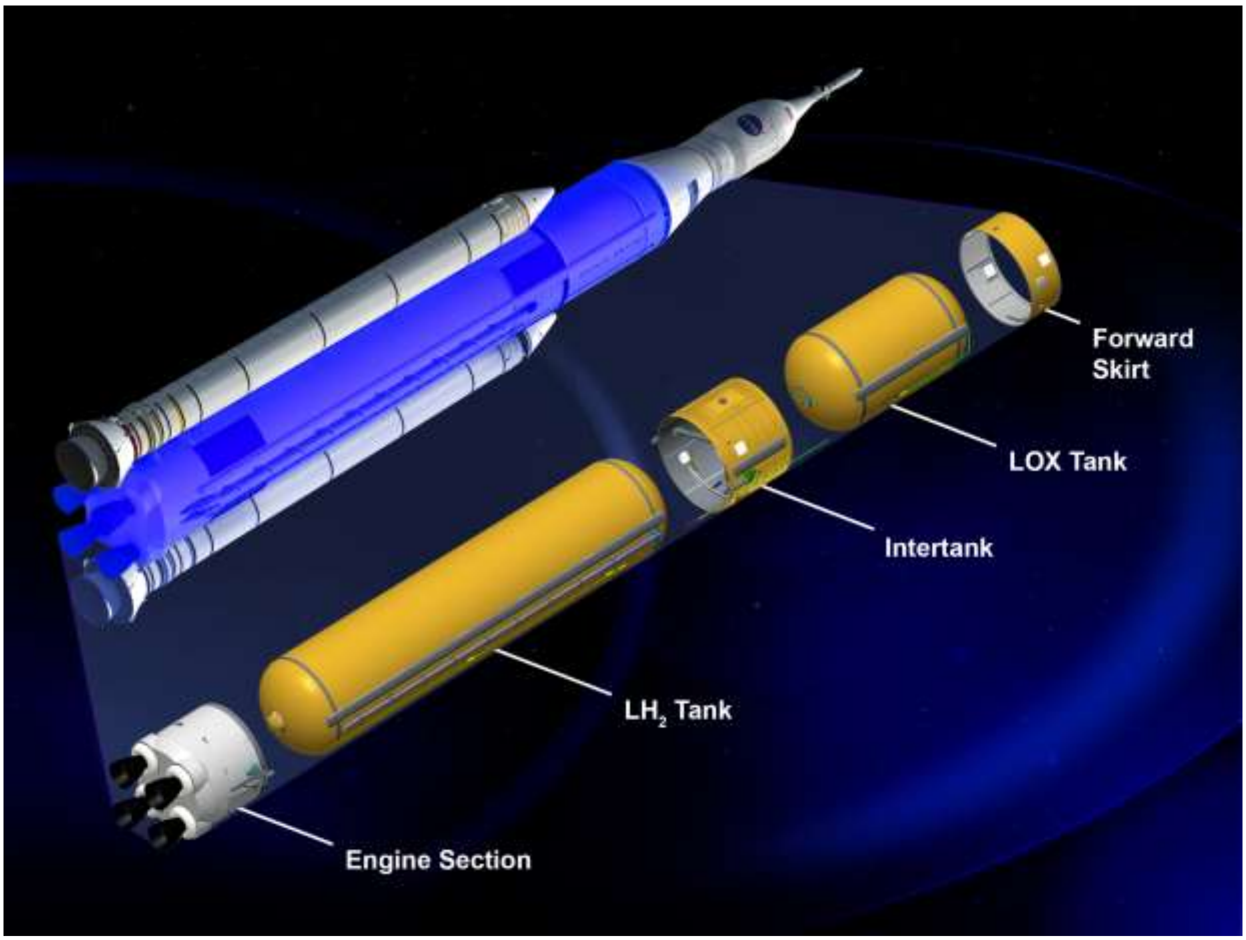

Figure 9.2: Components of an SLS rocket

The goal of the first phase will be to establish a colony zone and figure out the locations for other pods, as well as oversee a fleet of swarm construction robots that will build a pipeline of over

[28] "Space Launch System." *NASA*

1,300 km in length to supply water from the southern ice cap to the colony. The second phase will be roughly 20 years after the establishment of the nexus pod. This phase will be marked by sending waves of second-generation pods to the colony. Second generation pods will be equipped with deployable tank treads to ensure that they can be relocated from the landing zone. These pod types will each have a specific purpose, ranging from hydroponics[29] and water purification to power generation and manufacturing. Once the water purification pods have been properly connected to the colony, water from the pipeline, and possibly from underground reservoirs, will be channeled into the colony, enabling farming on a larger scale. The third and final phase of setting up the colony will start roughly 50 years after the second phase. At this point, the colony would virtually support itself. The third wave pods would include residential pods that were larger than those from the second wave, as well as being equipped with improvements to the quality of life of the colonists. Third phase manufacturing pods would include the machinery and robotics, or possible 3D printing technology, necessary to create both large and small scale materials and electronics. Colonists would finally have access to the same consumable objects that the people of Earth do. Additionally, colonists of the third phase and beyond would be able to produce their own pods and structures using materials extracted from Mars. Depending on the social structure of the colony, a local economy could also be initiated. Aside from changes in material objects present on the colony, there would be over 5,000 genetically diverse people sent from Earth by the third phase. This would ensure that the colony never suffers from the genetic disorders associated with inbreeding. Upon the completion of the third phase, the colony would no longer require contact with Earth to survive.

[29] Phutthisathian, A.; Pantasen, N.; Maneerat, N., "Ontology-Based Nutrient Solution Control System for Hydroponics"

A stable power source would be necessary to ensure that the colony can survive. Without power to maintain the systems on the colony, the colonists would eventually succumb to one of the many dangers of the Martian environment. Initially, the nexus pod would be equipped with a small generator that runs on decaying plutonium. A plutonium rod would be shipped to Mars alongside the colonists so that when they arrive to the previously sent nexus pod, they can simply place it within the generator and activate the pod. Solar panels and small, deployable wind turbines would be used as well to ensure that a fallback would be in place in case any of the power sources failed. In the later phases, Thorium molten salt reactors (TMSRs)[30] could be used to produce power. TMSRs are virtually meltdown proof due to not relying on highly pressurized water. Besides using Thorium, which is much more common than Uranium, TMSRs can run on nuclear waste, allowing them to leave far less, and far less toxic, waste behind. Additionally, carbon nanotube batteries can be used to store energy in a much more space efficient way than current Lithium-ion batteries. Within the third phase and beyond, fusion reactors can be used to generate massive levels of clean energy. Communications between Earth and Mars would utilize a deployable communications tower on one of the pods. This tower would send messages to a relay satellite in a fixed positional orbit over the colony, which would then send the messages to Earth.

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[30] Dodson, A.M.; McCann, R.A., "Investigation of Thermal Feedback Design for Improved Load-Following Capability of Thorium Molten Salt Reactors"

Figure 9.3: Communication satellites

All of the colonial modules must be layered in such a way that minimizes heat loss. To this end, the pods would be designed with three primary thermal layers. The innermost layer would be fiberglass insulation. This would potentially reduce conductive heat transfer to near-negligible levels. The next layer would be an empty space between the two structural shells on the pod that maintains a vacuum to eliminate, or vastly reduce, convective heat transfer. Lastly, the outermost layer of the colony would be covered in a high-emissivity coating to offset as much radioactive heat transfer as possible. Because the surface pressure of Mars is only 0.6% of Earth's, the outer shell that encases the vacuum layer can be made of a radiation shielding material, rather than a structural material[31]. Radiation shielding itself would be the other primary aspect of the walls of the pod.

Because Mars cannot maintain its own magnetosphere, lethal levels of radiation from the Sun constantly bombard the planet's surface. In order to counteract this, the colony modules would have to have many layers of radiation shielding. Traditionally, a thick layer of lead would

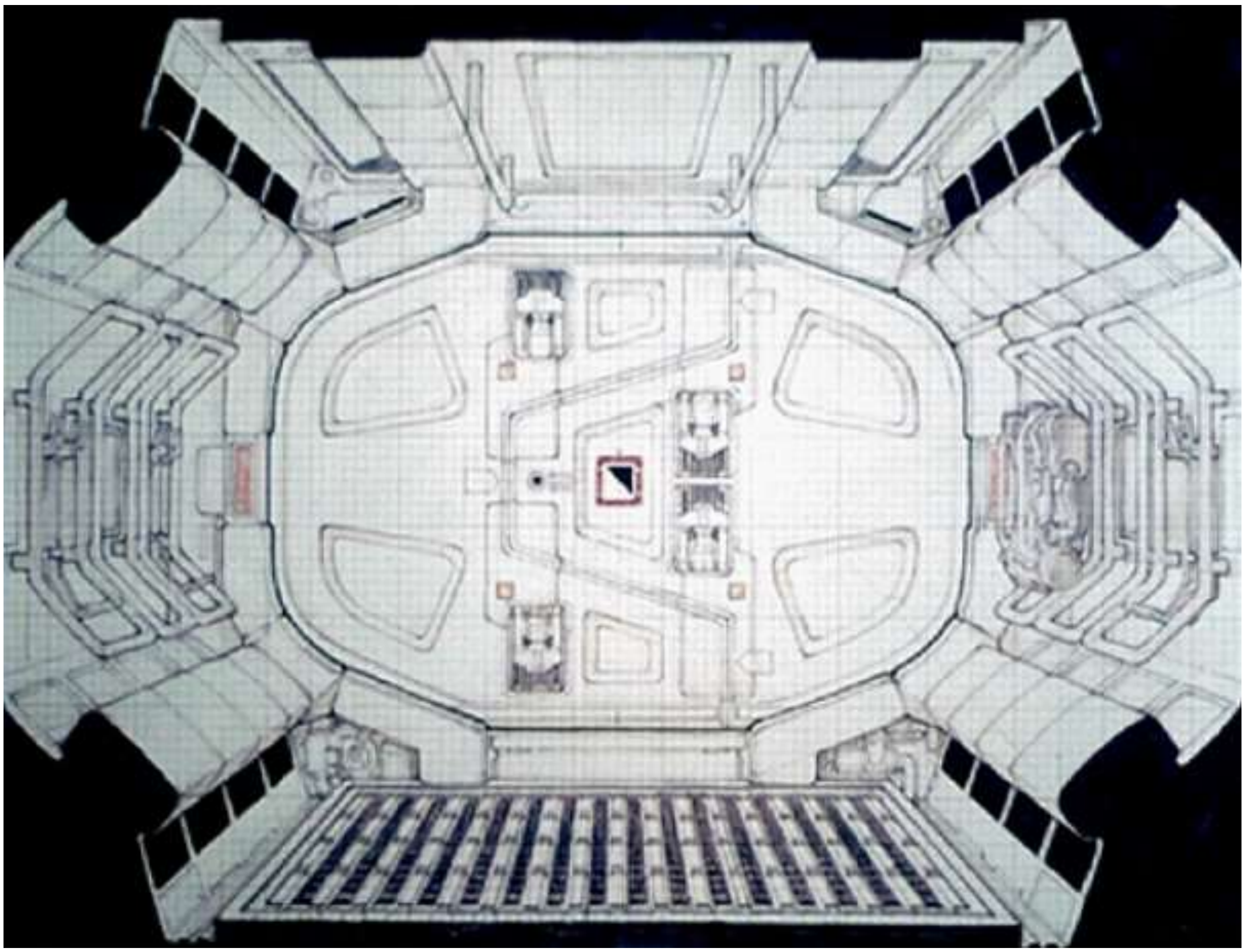

Figure 9.4: Sample airlock chamber

be used. While this would work, the thickness of the layer and the scale of the later-phase pods make it prohibitively expensive to use, especially if only negligible levels of lead are found on Mars near the site of the colony. To answer this, the outer shell of the vacuum thermal layer

[31] Bertelsen, Craig, Eric Burgett, Eric Grulk, Courtney Harrison, Nolan Hertel, and Sean Weaver. "Polyethylene/boron Nitride Composites for Space Radiation Shielding."

would be made out of reflective aluminum: the material used on space station modules. It has been shown that polyethylene and Boron nitrate have radiation shielding properties[32]. Additionally, various thin layers of meshes designed to reflect different wavelengths of radiation would be put over this first layer using a design similar to the mesh grid on the doors of microwaves. Once the power modules have been sent from Earth or created onsite from sent components, active electromagnetic radiation shielding could be implemented. Because of the energy necessary to run this active shielding, it would be necessary to wait for the activation of the colony's TMSRs.

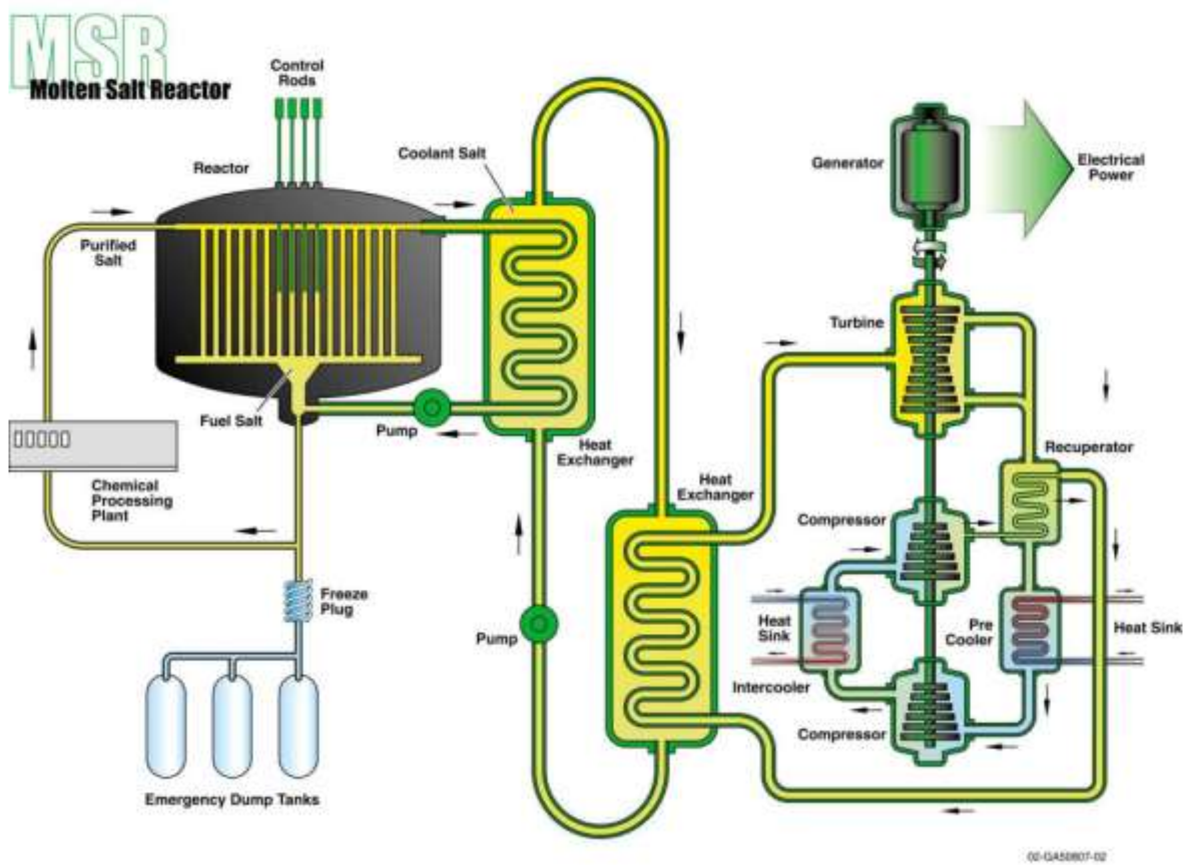

Figure 9.5: Molten salt reactor diagram

[32] Bertelsen, Craig, Eric Burgett, Eric Grulk, Courtney Harrison, Nolan Hertel, and Sean Weaver. "Polyethylene/boron Nitride Composites for Space Radiation Shielding."

The colony modules would all maintain internal air pressure similar to that of sea level on Earth. This would simply require pressurization technology similar to what exists in commercial planes, as well as in the International Space Station. In order to ensure that pressure is maintained, all entrances to all of the modules would be airlock chambers. Once multiple pods have been aligned, walkway sections with shielding similar to the pods themselves would be attached between the aligned doors and pressurized. After a network of pods and paths has been assembled, only pods on the outermost perimeter of the colony would have to maintain sealed airlocks. As a redundancy precaution, all airlock sections would have an emergency bulkhead designed to seal upon detection of pressure drops. The Oxygen levels in the air would be kept stable by using multiple methods. Titanium Dioxide in dye-synthesized solar cells is an emerging form of artificial photosynthesis[33] that could be implemented in a modular colony. The overabundance of Carbon Dioxide on Mars, as well as within the colony itself, would provide the perfect conditions for Oxygen production. In its current form, the Titanium Dioxide doesn't last long enough to be beneficial, however research suggests that a microcrystalline TiO_2 film created from sol gel and deposited onto an aluminum substrate could increase its lifespan. In addition to this, electrolysis could be used to split water molecules into Hydrogen and Oxygen. This conversion is accomplished by running a current through rods in the water. In the third phase or beyond, advances in artificial photosynthesis would allow for faster and more efficient conversion between Carbon Dioxide and Oxygen.

Because Mars lacks a proper magnetosphere, it has a very thin atmosphere and is thus exposed to both solar radiation and asteroid impact. A colony made of pressurized metal shells would be very susceptible to damage should it be struck by anything with large amounts of

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[33] Ayan; Ankit; Aditya; Akhilesh; Nikhil, "Microcrystalline based TiO2 thin film in dye-synthesized solar cell for efficient artificial photosynthesis"

momentum. To prevent catastrophic failure from asteroid impact, the colony would be protected by an automated missile array. This array would detect incoming asteroids and other space debris and shoot them down before they became threats to the colony. In order to ensure that the proper number of missiles was given to a single colony, data on the likelihood of an asteroid impact on the colony's location would be used to determine average impacts per month. This would then be multiplied by 26 months (the minimal time between trips) to get how many asteroids were likely to hit the colony between cycles of shipments. The resulting minimum number of impacts would then be multiplied by the number of missiles needed to shoot down an average asteroid (based on local asteroid crater sizes). If the end result were less than one asteroid per 26 months, the value for one asteroid would be used. After calculating the number of missiles required to destroy the predicted amount of asteroids, the result would be doubled in order to compensate for any unanticipated futures. The missile array itself would have its own deployable shell to prevent damage from the dust storms that ravage the surface of Mars from time to time.

Figure 9.6: Longest oil pipeline on Earth as comparison

The longevity and ability to support a growing population of the colony is directly related to its ability to generate food and water. The colonists would initially get the bulk of their food from massive shipments from Earth. In addition to this, hydroponics would be implemented to bolster the initial food levels in the colony. Hydroponics would later act as the primary source of food. Upon the initiation of the third phase, if radiation shielded glass was already developed, it could be possible to create large traditional farms on the surface of Mars.

Crops sustained via hydroponics are fed through a specially created liquid. It has been found that the pH and electrical conductivity of the nutrient solution have an impact and the production of the crop[34]. Primarily a pipeline from one of the ice caps, whether for drinking or growing crops, would supply water. The water within the pipe would be pressurized to a point where it wouldn't freeze as it traveled to the colony. Once it got to the colony's water module, it would be stored in tanks and distributed throughout the colony. Other sources of water would be recycled waste liquid and underground water reserves[35], should they exist near the colony.

Each of the phases would have the additional goal of researching various aspects related to extraterrestrial colonization. The first wave researchers would determine the necessary requirements for living in a Martian colony as well as STEM research that can benefit from being closer to the asteroid belt. The second wave would study the effects of low gravity[36] on humans, research more into our solar system, and determine how to colonize other celestial bodies. The third wave and beyond would continue STEM research, but in a much more advance setting. In addition, researchers would study methods of procuring energy from celestial bodies, such as black holes or supernovas. By this point, technologies that exist as only a vision today would exist or be in development.

Social Aspects

Creating modular pods to colonize the surface of Mars may be one of the quickest implementable colonization techniques, but it is not without its faults. With current technology, it isn't possible to maintain long term living conditions. Cosmic radiation would pierce through the module's shell and damage colonists. While various technologies exist that could block the

[34] Phutthisathian, A.; Pantasen, N.; Maneerat, N., "Ontology-Based Nutrient Solution Control System for Hydroponics"
[35] "Closing the Loop: Recycling Water and Air in Space." *NASA*
[36] Fitts, Robert, Danny Riley, and Jeffery Widrick. "Functional and Structural Adaptations of Skeletal Muscle to Microgravity."

radiation, a lightweight composite of them has yet to be developed. Even with the creation and implementation of such a composite, early colonists would still be at risk of asteroid impacts for the duration of the early phases. The later phases would have defense systems, but any early colonist would be taking a major risk. As with creating an underground colony, denizens of a pod colony would have to live out the remainder of their lives in a compact, completely interior setting. Due to the dangers of radiation and lack of plans for ever terraforming the planet, colonists would be essentially trapped within the colony's walls. Later phases would include windows and transparent walls, but these would only serve to give colonists a view of a dead planet. Early colonists would have to completely alter their lives to adapt to these new conditions. Once the colony started to grow and the first pure Martian generation reached school age, a system of education would have to be established to teach them the skills necessary to succeed their parents and run the colony. These skills could differ drastically from those on Earth due to the drastically different conditions. Specifically, the colonial education system would probably favor STEM fields over more traditional, liberal arts fields. Communications and the transport of goods between Earth and Mars would require a great deal of planning, precision, and money. Such a task would require experienced specialists on both ends to properly coordinate.

The economic costs to fund the mission are not without their benefits. Constructing the early colony pods and gathering raw materials for the later ones would cause a surge in the manufacturing and construction industries. Associated companies would hire more people, causing colonization to become an integral part of the global economy. As manufacturing and construction for colonization becomes more commonplace, more companies, both government funded and private, would seek to become part of the industry. From there, employment opportunities in related fields would grow exponentially. Due to the heavy reliance of this colonization technique on swarm robotics for construction and maintenance, the robotics industry would receive more funding and therefore produce more results. Anything created for one purpose has a tendency to be used in ways that were completely unintended. Such would be the case with swarm robotics developed for colonization. They would presumably find alternate purposes on Earth doing a variety of tasks for both companies and individuals. In the later stages of this colonization technique, when the construction of the modules is done in space and on the surface of Mars itself, manufacturing, at least for colony related objects, would cease to have an impact on Earth's atmosphere[37]. More commonplace manufacturing requirements could also make use of an orbital factory since shipping to any place on Earth can be more direct should the factory pass over the customer's country. Once one of the primary sources of pollution on Earth has been moved to a position in orbit around the planet, global climate change, and the associated natural disasters, would slowly start to return to previous levels, or at the very least, stop getting worse.

Mars would be a clean slate for government, culture, and economy. The planet does not have any preexisting traditions or laws in place. Because of this, the colony would be free to create systems that would be more ideal than those on Earth. The colonies can be organized in such a way that the governing system is one that does not have any inherent loopholes for those in power or any preference for some of the populace over the rest.

[37] "The Impact of Climate Change on Natural Disasters." *NASA Earth Observatory*

Asteroid Moon – Restarting the Martian Magnetosphere

Introduction

The dynamo effect theory states that the pull of a large orbiting satellite around a planet causes activity in the planet's core, therefore creating a dynamo. This theory gives an explanation as to how celestial bodies, such as the Earth, are able to maintain a magnetic field. Motion of the liquid outer core around a solid inner core and across a preexisting weak magnetic field generates electrical current, which in turn generates a stronger magnetic field. The pull of the orbiting satellite on the planet's conductive, liquid core causes it to generate a convective cell. These effects result in the planet generating a magnetosphere. This is theorized to be the reason why Earth has a magnetosphere. By using a large asteroid as an orbiting satellite around Mars, it should be possible to replicate the conditions that cause Earth to have a magnetosphere. Since the largest feasibly movable objects in the solar system are located in the asteroid belt, the most logical choice for a new Martian moon would be a massive asteroid. However, the orbital speeds of bodies in the asteroid belt are far too slow to safely put it in Mars' orbit. To safely introduce an asteroid as a moon to Mars, it must first be brought into the orbital path of Mars in such a way that a Hohmann transfer will allow Mars to pull it into orbit. However, if the asteroid is placed on the wrong side of Mars when it passes by, it will end up in an orbit against the rotation of Mars, thus slowing its rotation. To ensure that this won't happen, it must be positioned on the "sunny side" of Mars. More specifically, it must be positioned between the Sun and Mars on the plane of Mars' orbit.

The factors that will contribute to this plan are mass, distance, and orbital velocity. Increasing mass or orbital velocity, or decreasing distance will cause the effects of an orbiting body on Mars to increase. Because the mass of an asteroid can be considered constant, the only variables that can be changed are orbital velocity and distance[38]. However, changing one of these will directly change the other. Increasing the distance between the asteroid and Mars will decrease the orbital velocity because the escape velocity of an orbiting body reduces with distance. Since any position within the desired range satisfies the additional velocity requirement, distance becomes the primary variable in determining the effects that an asteroid will have on Mars. Once in orbit, the proposed asteroid will cause tidal friction within the liquid core of Mars. This friction will, in turn, heat the core and therefore the planet itself. Tidal friction itself is correlated with a planet's rotational speed. This means that the asteroid will affect the tidal friction both directly and indirectly. Ideally, the tidal friction generated by the presence of the asteroid will potentially increase the core temperature of Mars to levels comparable to Earth. This would restart some form of geological activity, which would later help to restore some of Mars' atmospheric conditions to livable levels. The revival of geological activity will signal that a convective cell between the core and the mantle of Mars has been established and the planet once again has a flow of elements outward from its depths. Reviving the geological activity of Mars will only be a side effect of the primary goal of putting a large asteroid into orbit around Mars: restarting the planet's magnetosphere.

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[38] McElhinny, M. W., and Phillip L. McFadden, eds. *The magnetic field of the earth: paleomagnetism, the core, and the deep mantle*

Figure 10.1: MMS Magnetosphere studying satellite

The magnetosphere will block solar winds and cosmic radiation, allowing Mars to be colonized without this risk. Any colonies on Mars would only need to be able to maintain their internal temperatures and pressures. However, none of this will be possible unless a massive asteroid can be brought to Mars at the correct position and speed. To accomplish this, the asteroid must be put into a decaying orbit: a Hohmann transfer orbit[39]. To do this, thrusters must be attached to the asteroid at some angle greater than 90 degrees off the tangent of its orbit. Such a position would cause it to decay into an orbital path in line with that of Mars. Table 3.1 shows a list of viable asteroids to act as new moons for Mars.

[39] "Chapter 4. Interplanetary Trajectories." *NASA Jet Propulsion Laboratory*

Name	Type	Mass (x 10^18 kg)	Diameter (km)	Orbital Velocity (km/s)	Eccentricity
1 Ceres	G	946	952	17.882	0.076
4 Vesta	V	259.076	529	19.34	0.089
2 Pallas	B	201	544	17.65	0.231
10 Hygiea	C	86.7	444	16.76	0.115
31 Euphrosyne	C	58.1	(unknown)	16.57	0.222
704 Interamnia	F	38.8	350	16.92	0.154
511 Davida	C	37.7	320	16.59	0.188
532 Herculina	S	33	225	17.65	0.176
15 Eunomia	S	31.8	268	18.16	0.187
3 Juno	S	28.6	233	17.93	0.255

Table 10.1: Data on viable asteroids for a new Martian moon.

Ideal Asteroid

Ceres is the largest celestial body in the asteroid belt. It is the smallest known dwarf planet with a diameter of 950km. The dwarf planet is composed of a rocky inner core surrounded by a thick layer of ice. While Ceres holds the classification of "dwarf planet," it is only about 0.0013 times the size of Mars and can therefore be used as a new Martian moon. Utilizing a concept similar to that of bringing Enceladus to Mars, Ceres could also be relocated. The major difference is that Ceres isn't bound by a gas giant's gravitational field, and therefore it is much easier to initiate the journey from its current orbit to Mars. In its current state, Mars has a core that is 2,300K cooler than that of Earth's. The lack of heat in the Martian core resulted in the planet's lack of a magnetosphere. Because of Mars' lack of a magnetosphere, radiation constantly bombards the planet's surface, preventing it from supporting any life forms, as well as causing all of the liquid water on the surface and most of the Martian atmosphere to be stripped from the planet by solar winds[40]. The introduction of Ceres as a moon addresses the problems with the Martian core. The minimum distance that Ceres can be safely positioned above Mars is at a distance of 4,581 km between the cores, and the maximum desired distance between the cores is 13,880 km. These values were determined using a ratio of Newton's law of universal

[40] Phillips, Tony. "Solar Wind Rips Up Martian Atmosphere."

gravitation. The gravitational force between Earth and the moon was determined at its current distance and the theoretical distance between the Earth and the moon at the time of the moon's forming. While the maximum desired distance was calculated using this ratio of gravitational force at the moon's current distance from Earth, the minimum safe distance was determined by taking the distance from the cores of Mars and Ceres and adding 2,000 km (the maximum value of low orbit above Earth). The distance between Mars and Ceres using the theoretical original moon distance resulted in a distance that would cause the two bodies to be superimposed on one another. Any distance lower than the maximum desired distance will result in Ceres having a greater effect on Mars that the moon currently has on Earth. In addition to causing a dynamo effect, the purpose of Ceres as a moon would be to increase the rotational speed of Mars to further increase the core activity and strength of the resulting magnetosphere. To accomplish this, Ceres would have be places closer than the distance of aero synchronous orbit[41] around Mars. This point is where Ceres' orbital speed would be such that it matched the planet's rotational speed and therefore showed the same face toward the planet at all times. Fortunately, this point is at 17,000km, so any point within the determined range would accomplish this goal.

[41] Thomsen, M. F., et al. "The magnetospheric lobe at geosynchronous orbit."

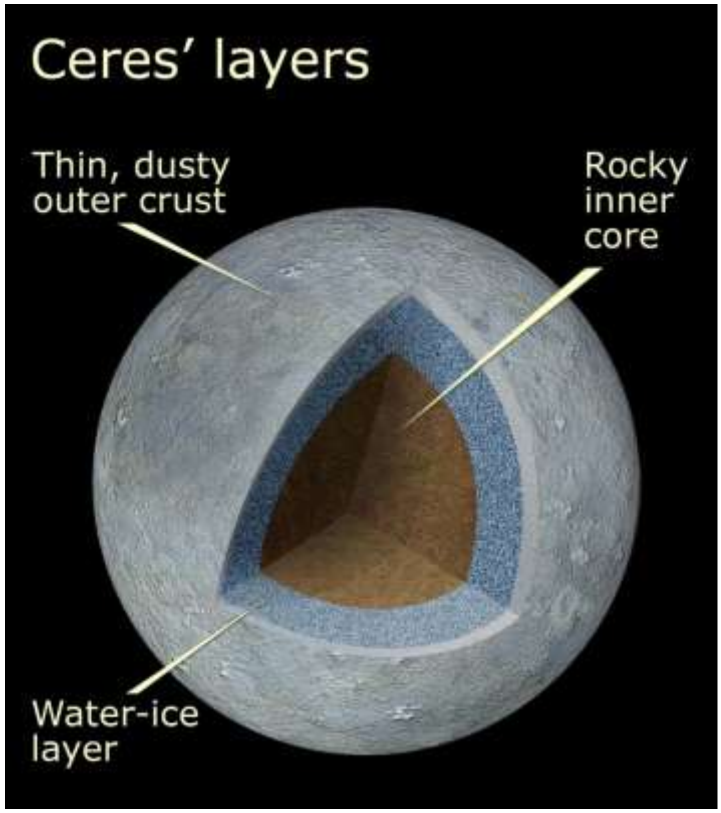

Figure 10.2: Layers of Ceres

Methodology

The dynamo theory describes the method through which a rotating, flowing, and electrically conducting fluid is pulled on by an orbiting natural satellite with such force that it creates a dynamo and is thus able to produce and sustain a magnetic field. In general, there are three variables that have a major impact on the dynamo effect: mass, the distance between the celestial bodies, and the orbital velocity of the natural satellite.

There are three requisites for a dynamo to operate:

- Electrically conductive fluid medium
- Kinetic energy provided by planetary rotation
- Internal energy source to drive convective motions within the fluid

Variables of the Dynamo Theory

Mass:

$$M_{Ceres} = 895.8 \times 10^{18}\ kg$$

The mass of Ceres is considered one of the major components in the dynamo effect for this model because its magnitude determines how strong the gravitational force is for rotating the fluid in Mars' core. The mass of Ceres will affect the kinetic energy provided by planetary rotation.

Distance:

The distance between Mars and Ceres determines the gravitational force, which in turn affects the tidal force in the core. This results in the core increasing its internal energy to drive convection motion within the liquid portion core.

The minimum and maximum distance between Ceres and Mars is based on a working system of the gravitational force between Earth and its moon. Based on the dynamo theory, the entire historical range of distance between Earth and the moon is enough to form a magnetosphere[42]. Using a ratio comparing Ceres and Mars to the moon and Earth, it is possible to establish a distance range for achieving levels of gravitational force similar to what exists between Earth and the moon. The initial distance between Earth and its moon was 40,000 km. In its current state, Earth is 384,400 km away from its moon.

$$G_F = \frac{GM_1M_2}{r^2}$$

[42] Laj, Carlo, Hervé Guillou, and Catherine Kissel. "Dynamics of the earth magnetic field in the 10–75 kyr period comprising the Laschamp and Mono Lake excursions: New results from the French Chaîne des Puys in a global perspective."

G = Gravitational constant

M_1 = Mass of Ceres

M_2 = Mass of Mars

r = Distance between masses

$$G_{F-Earth-Moon} = G_{F-Mars-Ceres}$$

$$\frac{GM_{Earth}M_{Moon}}{r^2_{Earth-Moon}} = \frac{GM_{Mars}M_{Ceres}}{r^2_{Mars-Ceres}}$$

Minimum distance between Mars and Ceres:

$$r_{Mars-Ceres} = \sqrt{\frac{(M_{Mars}M_{Ceres})(r^2_{Earth-Moon})}{M_{Earth}M_{Moon}}}$$

$$= \sqrt{\frac{(639 \times 10^{21}\ kg)(895.8 \times 10^{18}\ kg)(40 \times 10^{6}\ m)^2}{(5.972 \times 10^{24}\ kg)(7.347 \times 10^{22}\ kg)}}$$

$$Minimum: r_{Mars-Ceres} = 1{,}400\ km$$

Maximum distance between Mars and Ceres:

$$r_{Mars-Ceres} = \sqrt{\frac{(639 \times 10^{21}\ kg)(895.8 \times 10^{18}\ kg)(384.4 \times 10^{6}\ m)^2}{(5.972 \times 10^{24}\ kg)(7.347 \times 10^{22}\ kg)}}$$

$$Maximum: r_{Mars-Ceres} = 13{,}880\ km$$

In order for Ceres to have an effect on Mars' rotational velocity, it has to be within the aero synchronous orbit: 17,000 km.

Velocity:

The velocity of Ceres around Mars (within the aero synchronous orbit) will cause Mars to spin faster due to gravitational forces. This increase in velocity for Mars will create more tidal friction, which will in turn cause the fluid in its core to rotate quicker and thus, heat up.

The current velocity of Mars and Ceres:

$$V_{i-Mars} = 24.07\ \frac{km}{s}, V_{i-Ceres} = 17.882\ \frac{km}{s}$$

The escape velocity is defined as the velocity that an orbiting body must have to remain in orbit without decaying or escaping from the planet's gravity well. It is defined as:

$$V_e = \sqrt{\frac{2GM}{r}}$$

G = Gravitational constant

M = Mass of Mars

r = Distance between masses

At r=1,400km:

$$V_e = \sqrt{\frac{2\left(6.67 \times 10^{-11}\,\frac{m^3}{kg - s^2}\right)(639 \times 10^{21}\ kg)}{(1400\ km)}}$$

$$V_e = 7.8\ \frac{km}{s}$$

At r=13,880km:

$$V_e = \sqrt{\frac{2\left(6.67 \times 10^{-11}\,\frac{m^3}{kg - s^2}\right)(639 \times 10^{21}\ kg)}{13880\ km}}$$

$$V_e = 2.478\ \frac{km}{s}$$

The velocity of Ceres will stabilize itself at this point once it has been locked into an orbital path around Mars.

Relevant Formulas

Tidal Acceleration:

The tidal acceleration is an effect of the tidal forces between a natural satellite and a primary planet.

$$a_{tidal} = GM\left(\frac{1}{(r_L - R)^2} - \frac{1}{r_L^2}\right)$$

G = Gravitational constant

M = Mass of Ceres

R = Radius of Mars

r_L = Distance between masses

Tidal Force:

$$F_{tidal} = Ma_{tidal}$$

M = Mass of Ceres

a = Tidal acceleration

Tidal Heating:

Tidal heating is the result of the dissipation of orbital and rotational energy as heat through tidal friction processes.

$$q = \frac{63\rho n^5 r^4 e^2}{38\mu Q}$$

$$\rho = Density\ of\ satellite$$

n = Velocity of satellite

r = Radius of satellite

e = Eccentricity

Q = Dimensionless dissipation factor

$$\mu = Shear\ modulus$$

Magnetosphere:

The constant convection of liquid iron in the core of a planet induces and maintains a magnetic field around the planet.

$$\frac{\partial B}{\partial t} = \hbar \nabla^2 B + \nabla \times (u \times B)$$

u = Velocity

B = Magnetic Field

$$\eta = \frac{1}{\sigma\mu} = Magnetic\ diffusivity$$

$$\sigma = Electrical\ conductivity$$

$$\mu = Permiability$$

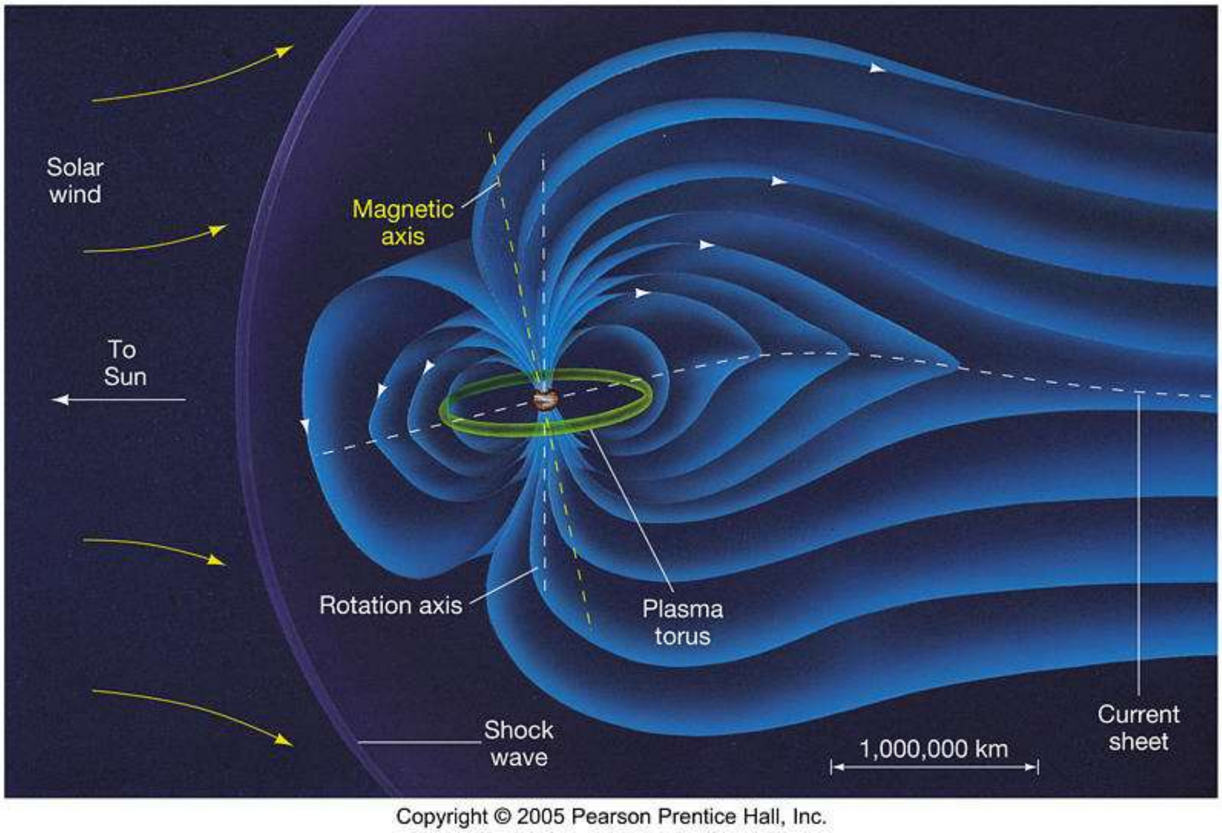

Figure 10.3: Magnetosphere of Earth as an example

Wave 1: The initiation of Wave 1 is marked by the nexus pod landing on Mars. The colonists would oversee an army of construction robots that would build a pipeline from the water-rich southern ice cap to the site of the colony. Robotic extraction units would break up the solid Carbon Dioxide on the poles in order to thicken the atmosphere and coat the cold planet in greenhouse gases. Everything in Wave 1 would be equipped with radiation shielding.

Post Wave 1: As Wave 1 draws to a close, the pipeline between the colony and the southern ice cap will be completed. Autonomous robotics will allow the early colonists to safely oversee the construction from the safety of the nexus pod.

Pre Wave 2: Before Wave 2 can start, the greenhouse gas emission over the surface of Mars must be accelerated. This will increase the atmospheric density to levels closer to those on Earth and global temperature to levels that can more easily support life.

Wave 2: Wave 2 will be initiated by the next generation of pods landing or being constructed on Mars. These pods will resemble the 3rd generation pods that would be used if no moon was added to Mars. However, because the addition of Ceres will have restarted the Martian magnetosphere, there will be no need for a radiation layer. Additionally, the release of Carbon Dioxide from the poles will have caused changes in the Martian climate to better resemble Earth.

Post Wave 2: The addition of many pods during Wave 2 will facilitate large-scale farming. Since atmospheric pressure on Mars will finally be close to the minimal levels on Earth, farms can make use of the Martian soil, rather than just hydroponics. Because Mars, at this point, will have an atmosphere made almost entirely of Carbon Dioxide, extra Oxygen from the colony’s various Oxygen generation facilities will be released into the Martian atmosphere.

Pre Wave 3: Prior to the start of Wave 3, large colony ships would be constructed in preparation for moving huge amounts of people to the colonies on Mars. While these are being constructed, the Martian colonists will make use of genetically modified crops to increase harvest yields, as well as 3d modelling to create daily necessities. At this point, it should be possible for the colonists to build new structures onsite, finally solidifying the Martian colonies as sustainable settlements.

Wave 3: Wave 3 will be marked by the colonists leaving the safety of the first few pods in favor of structures built onsite. At this stage, farming will be entirely autonomous, allowing the colonists to focus on other aspects of life. The magnetosphere will be fully established, and thus protect Mars from radiation. Additionally, the atmospheric conditions will be such that the global temperature is no longer a serious concern.

Post Wave 3: As Wave 3 draws to a close, the Martian colonies will finally be able to fully support themselves with no additional help from Earth.

Social Aspects

When considering the idea of using complex planetary physics to propel a dwarf planet from the asteroid belt to Mars, the risks cannot be ignored. Primarily, there is a very high risk that somewhere along the way, a mistake in calculations or unexpected alteration in the path of Ceres could cause the dwarf planet to collide with Mars or miss it completely. The immediate effects of such an occurrence would be the failure of the project and the loss of billions of investor dollars. Those who held hope for the project's success would lose everything they put into it. Should Ceres miss Mars, there is a good chance that it will travel into the inner solar system and perhaps, in the worst possible case, collide with Earth itself. While the chances of such an eventuality occurring are incredibly slim and require many consecutive failures to happen, the possibility still exists. Alternatively, should Ceres crash into Mars, it will destabilize the surface of the planet and convert it to a state where terraforming becomes the only valid option of colonization. A final form of failure would be Mars' gravity not catching Ceres. This would leave Ceres to travel around the Sun at a similar distance as Mars. Although nothing devastating would happen, it would still be a major setback at the very least. In its worst possible outcome, sending a dwarf planet towards the inner solar system could end life on an entire planet, but in its best outcome, it could help spread life to a second one.

Assuming that Ceres was successfully situated as a Martian moon, there are many benefits that humanity will be able to reap. Should Mars' magnetosphere be successfully recreated, the dynamo theory will be confirmed and humanity will gain a greater understanding of how magnetospheres are created. The project will allow future Martians to terraform the planet while they inhabit it, as well as showing that any rocky planet in the general habitable range of a star can be colonized and terraformed if given enough time. Since Mars will have a magnetosphere, it will be able to resist solar winds and thus retain what is left of its atmosphere, and in the future, support a denser one. Once the technologies required to move dwarf planets are mastered, the threat of asteroids and comets to Earth will become trivial. If humans can control the motion of the largest object in the asteroid belt, they can control any asteroid. The cost associated with bringing Ceres into orbit around Mars should be relatively smaller than that of bringing Enceladus to Mars due to Mars' proximity to the asteroid belt. Any future colonies will also benefit from this close proximity to the asteroid belt by harvesting resources from asteroids rather than depending solely on Earth. As with simple colony modules, employment in relating construction and manufacturing fields will grow with the scale of colonization. The robotics developed to maintain and manage the wellbeing of the colonies can be used on Earth to simplify the lives of individuals. Although turning Ceres into a new moon for Mars costs far more than simply colonizing the planet as is, the impact of the cost is mitigated by the potential that this colonization strategy has for future terraforming. Humanity doesn't need to wait 1,000 years to settle a second planet, nor does it need to accept the loss in standard of living and risks associated with colonizing a dead planet. This strategy allows for humans to settle now and terraform whenever they so desire.

Relating Future Technologies

Graphene/Carbon Nanotubes

Graphene and Carbon nanotubes are mesh layered or cylindrical nanostructures made up of carbon molecules. The amount of potential that these nanostructures hold for changing human technology is insurmountable. Carbon nanotubes[43] have many appreciable properties such as having a high thermal and electrical conductivity, being lightweight, and having a high tensile strength. Some of the applications that carbon nanotubes can be used for would be to improve the energy storage of batteries, prolong the flight time of electric propulsion systems, and increase the efficiency in electronics. Carbon nanotubes would help the mission to Mars by providing immense amounts of electricity for starting colonies, reducing the price of manned missions by making propulsion systems cheaper, and reducing the weight of pod structures while keeping it reinforced[44].

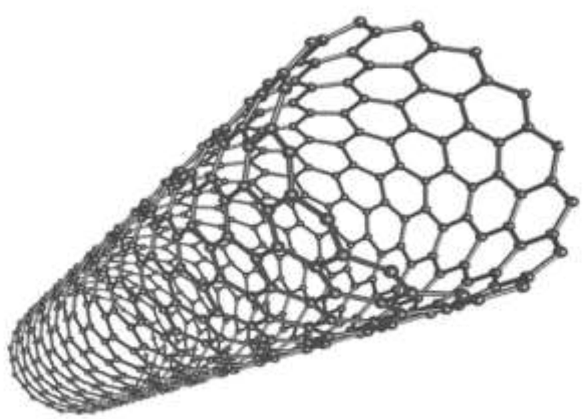

Figure 11.1: Carbon nanotube

[43] Hyer, Andrew. "Microchips and Nanotubes: Using Carbon Nanotubes in Electronics."
[44] Berber, Savas, Young-Kyun Kwon, and David Tomanek. "Unusually High Thermal Conductivity of Carbon Nanotubes."

Shielding Against Radiation

NASA has done an extensive amounts of research and development on creating better materials for shielding their astronauts from cosmic radiation[45]. Liquid hydrogen, polyethylene, and other lightweight polymers are materials that have been proposed to block radiation. The benefit of these materials is that they can be implemented in large structures such as spacecrafts and pods while all being cheap to purchase. Since these materials are affordable, it may be possible to layer them in order to achieve the optimal solution for shielding against cosmic radiation. Colonists would be able to live on the surface on Mars for longer periods of time[46].

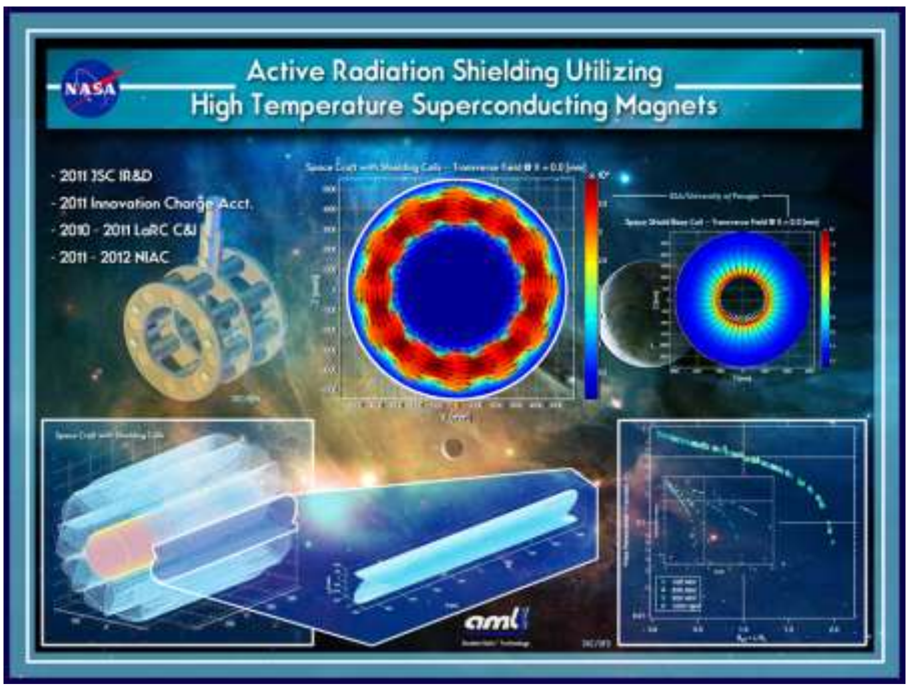

Figure 11.2: Radiation shielding

[45] Chappel, Lori, Francis Cucinotta, and Myung-Hee Kim. "Evaluating Shielding Approaches to Reduce Space Radiation Cancer Risks."
[46] Morring, Frank. "Superconducting Magnets Could Block Space Radiation."

Swarm Robotics

Swarm robotics is a topic based on the interaction of robots in a collective environment. The idea is that robots are interdependent and work only on their task without communicating. They can be used in any number of applications, from construction and maintenance to everyday tasks. This method provides an optimal distribution of the swarm. Swarm robotics can be used for starting colonies on Mars by completing a variety of tasks such as helping with tunnel construction or pod maintenance, and fixing anything that needs repair. Autonomy in swarm robotics is important in order to achieve a well-organized, independent team of robots. As the technology for swarm robotics improves, they're ability to perform executive tasks as planned will improve[47].

Figure 11.3: Swarm robots

[47] "The Kilobot Project." *Self-organizing Systems Research Group*. Harvard University.

Brain-computer interface technology

Researchers at the University of Minnesota have proposed and tested a “noninvasive motor imagery-based brain-computer interface”. This type of technology will allow direct interaction between a brain and a computer. In order to utilize this technology, researchers wanted human subjects to control the flight of a drone with their brain. The results of this experiment show the potential for further development of using a brain-computer interface[48] in a variety of applications. Some applications, that could be used in the future mission of colonizing Mars, would include brain controlled flight systems, having control over swarm robotics without autonomy, and using a brain to control a wide variety of currently existing electronic devices. Some direct use of this in our solutions would be to observe changes in the surface conditions above an underground colony or determine any exterior damages to a modular pod. Maintenance robots could allow humans to fix damaged external devices.

Figure 11.4: Brain/computer interface technology

[48] Cassady, Kaitlin, Alexander Doud, Bin He, Karl LaFleur, Eitan Rogin, and Kaleb Shades. "Quadcopter Control in Three-dimensional Space Using a Noninvasive Motor Imagery-based Brain–computer Interface."

Exoskeletons

Exoskeleton suits consist of actuators attached to vital parts of the Human body for movement (i.e. arms, hips, legs, and feet). This equipment allows humans to exert large forces or support large loads without putting any stress on their bodies. This technology is currently being implemented in the military and in rehabilitation. This technology could also be useful for colonists on Mars. All of the currently proposed method will change the gravitational force on the planet, but not to a value that humans on Earth are used to. Studies have shown the humans in lower gravity have the tendency to lose bone and muscle mass. In order to deal with the health effects of lower gravity, colonists on Mars can use exoskeleton suits[49].

Figure 11.5: Exoskeleton

[49] Aubin, Patrick, Michael Baumann, Kenneth Holt, Ernesto Martinez-Villalpando, Brendan Quinlivan, Leia Stirling, Conor Walsh, Michael Wehner, and Robert Wood. "A Lightweight Soft Exosuit for Gait Assistance."

Holograms

Holographic technology would allow humans to view images in 3D. Companies have been researching and developing this technology for a wide variety of uses from advertising to rendering 3D images[50] of human bodies. There currently exists working models of holograms, but the technology is still being researched and developed for further improvements. Colonists on Mars would be able to use this technology to analyze the human body in 3D to further study the effects on humans in a lower gravity environment.

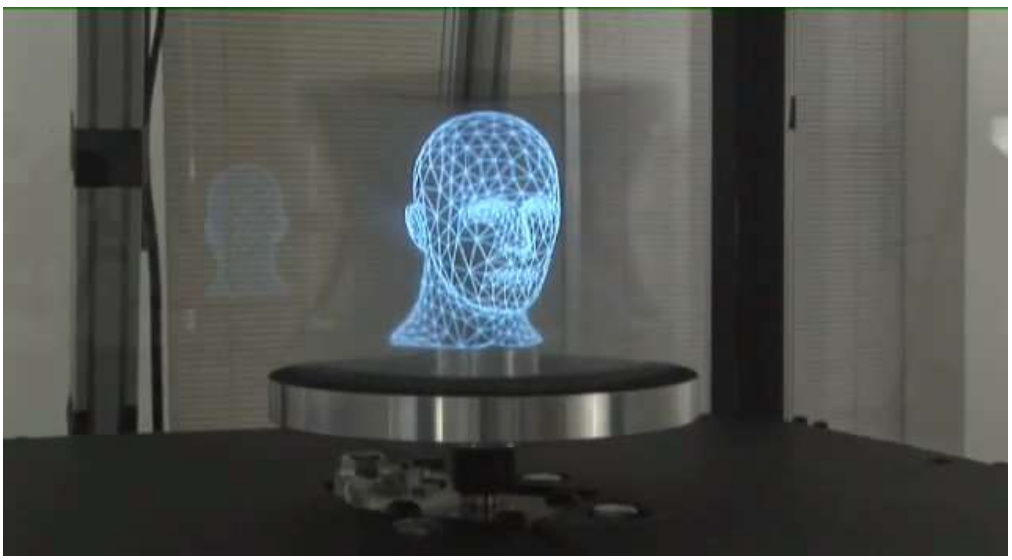

Figure 11.6: Holographic image concept

Supercomputers\Quantum Computers

Quantum computers are able to perform more intricate operations in data calculation. The technology of quantum computing is still being researched due to its complexity. However, if the technology was made available, it could offer solutions to difficult problems that exist today.

[50] Elmorshidy, Ahmed. "Holographic Projection Technology: The World Is Changing."

Some of the solutions that quantum computers could provide include finding distant earth-like planets, improving autonomy in robotics, and detecting the early stages of deadly diseases[51].

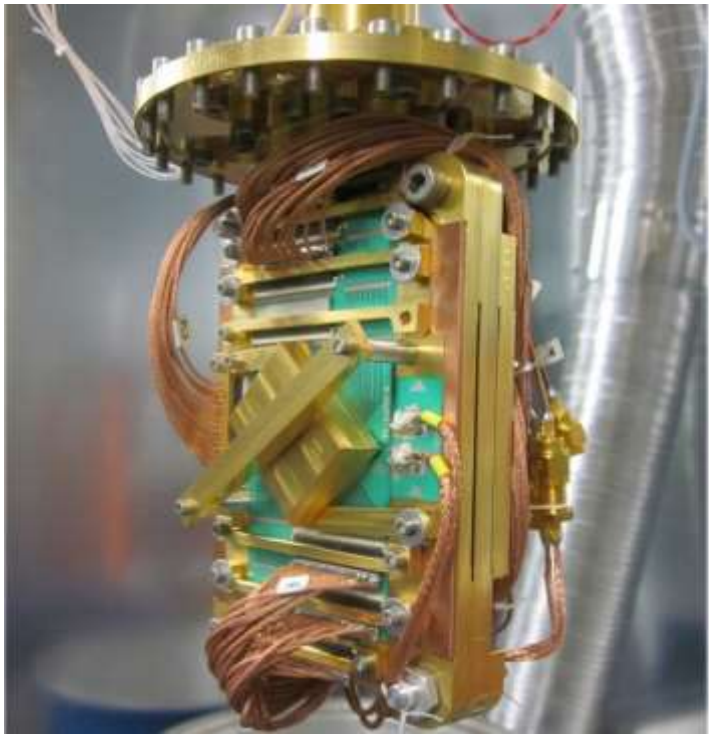

Figure 11.7: Quantum computer

Artificial Intelligence (AI)

Artificial intelligence (AI) is the idea of machines acquiring intelligence. AI[52] research is increasing as companies start to focus on the technology. AI holds a large potential to improve other developing technologies. Since machines would be able to learn and think for themselves, they could prove useful for colonists on Mars. AI would improve the intelligence of robots by introducing them to pattern recognition. Overtime, these robots would be able to understand and speak languages, as well as interact with the environment around them. Smart robots would be

[51] Devitt, Simon, William Munro, and Kae Nemoto. "High Performance Quantum Computing."
[52] Kumar, Sandeep, and Medha Sharma. "Convergence of Artificial Intelligence, Emotional Intelligence, Neural Network and Evolutionary Computing."

able to do tasks that humans would endanger themselves by doing. AI research is just now allowing scientists to devise programs that are able to modify their own code in a form of self optimization.

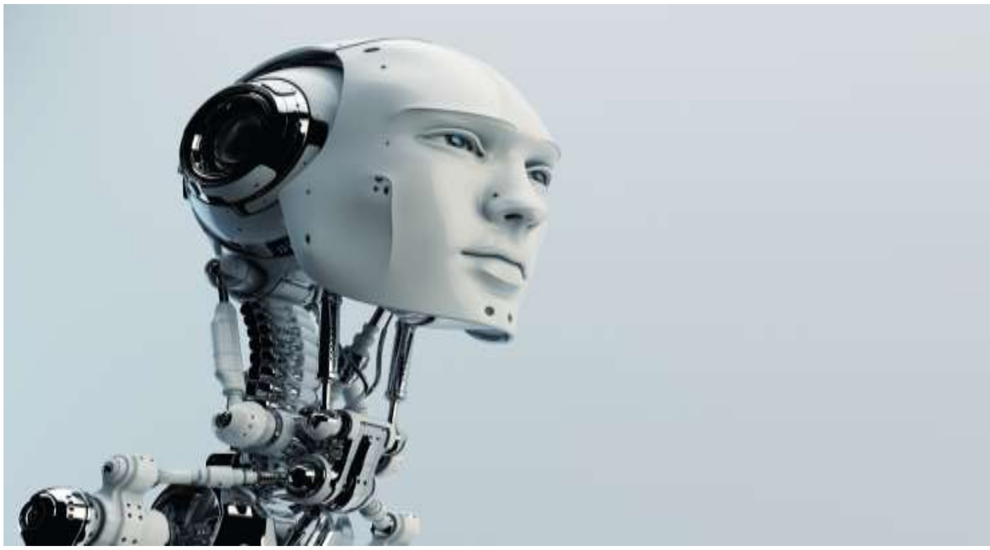

Figure 11.8: Artificial Intelligence

3D Printing (All Materials)

Additive manufacturing, which is colloquially known as 3D printing, is being used in a variety of applications. 3D printing utilizes heat to melt materials and add them layer by layer in a vertical motion, as it uses its other two axes to determine the design on each layer. This technique of manufacturing objects has cut down the required man-hours for production. Different types of material such as plastics and metals can be used for a variety of tasks. Some examples of 3D printed objects that have been successful and are currently in production and use include cars and rockets parts, tools, musical instruments, weaponry and human body parts. It is also being used for construction purposes on a large scale. Colonists on Mars would be able to use this technology to create any number of useful components ranging from temporary repairs to simple tableware[53].

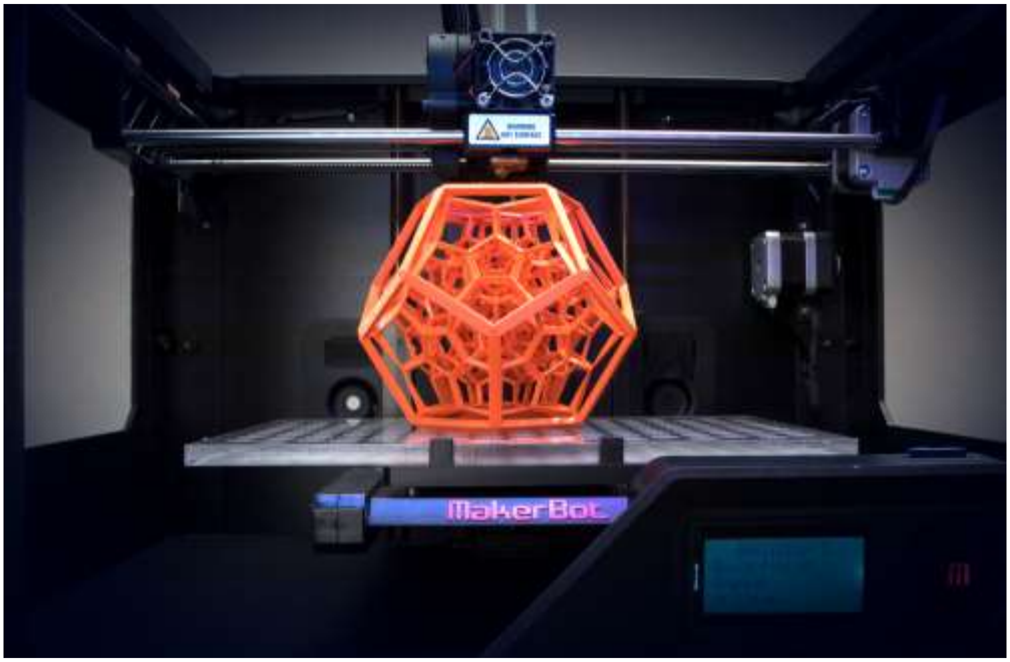

Figure 11.9: 3D printed prism

Fusion Reactors

Nuclear fusion occurs by having two atomic nuclei collide in order to create one new atomic nucleus. Nuclear fusion[54] has the potential to create large amounts of energy while using small amounts of mass. With this reaction, rockets can attain higher thrust and efficiency. These rocket engines would reduce the flight time between any objects in space. With the use of nuclear rocket engines, transportation to Mars would become more cost efficient. The large amounts of energy produced by fusion would take away all energy shortages. Colonizing planets and powering the colonies would not have to have energy as a concern. The depth of research

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[53] Kading, Benjamin, and Jeremy Straub. "Utilizing In-situ Resources and 3D Printing Structures for a Manned Mars Mission."
[54] Cohen, Samuel, Russ Feder, Kevin Griffin, Gary Pajer, Michael Paluszek, Yosef Razin, James Slonaker, and Matthew Walsh. "Direct Fusion Drive for a Human Mars Orbital Mission."

done thus far in the topic is mere speculation and theory, but in the near future, Lockheed Martin plans to build a prototype fusion reactor.

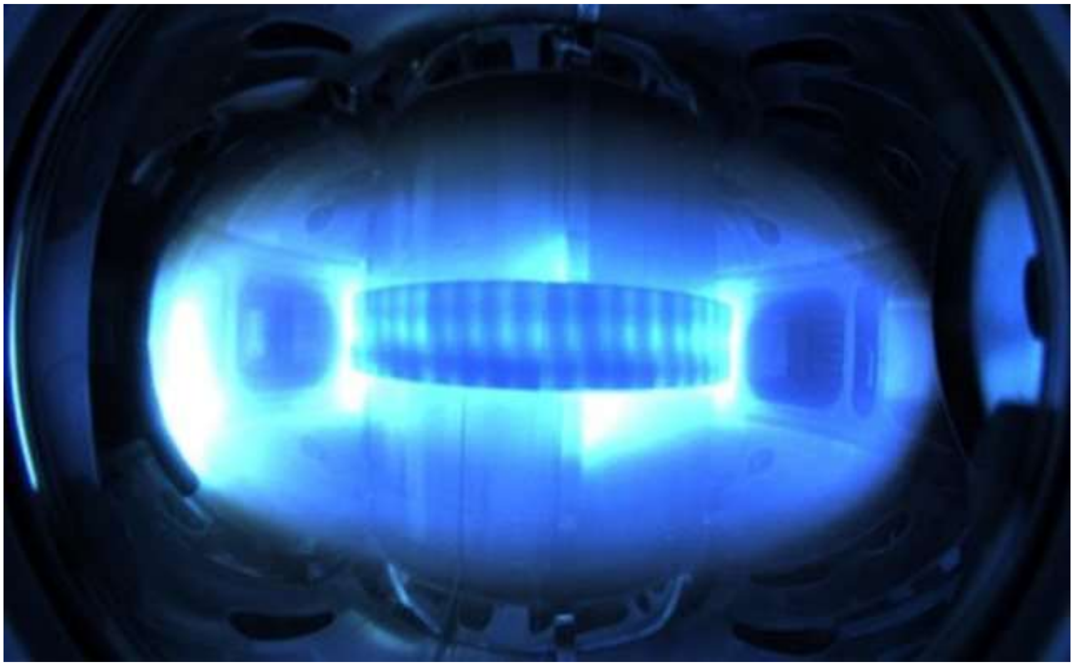

Figure 11.10: Concept fusion reactor

Social Implications

The people of Earth will be the ones who have to shoulder the cost of colonization, rather than the colonies themselves. However, they will only agree to this if global priority shifts to colonization. Any of the four colonization strategies, if successful, could kick start this shift in values. Should colonizing Mars be done in a cooperative, peaceful manner, the colonies will become an international investment in the future and further stabilize global politics on Earth. Since successfully colonizing another planet, especially one that can't support life itself, is such a monumental and technologically complex task, no country could hope to accomplish it perfectly by itself. Thus, the need for cooperation between space faring nations is further solidified. Such participants will most likely include the United States, Russia, the European Union, and China, with many smaller nations supporting them.

People will only be convinced to colonize Mars once the need to colonize outweighs the estimated expenditure. With NASA[55] and SpaceX developing reusable rockets, the theoretical cost of creating a colony on Mars can be predicted to decrease. Should the rocket prove successful, the technology will greatly impact the cost of sending cargo into outer space. At the same time, global enthusiasm for colonizing the planet is growing, as seen by projects like Mars One. In addition to a lowering the cost to ship cargo to space, a monetary incentive could be created by the international community in order to hasten the colonization of Mars. This would have the effect of convincing both governments and the private sector to contribute.

The greatest challenge will be to convince the public to become involved in, or otherwise support, the development of colonization technology. To overcome this, many strategies need to be developed and implemented. The first question the public might raise is why it is necessary to

[55] Williamson, Ray A. "Developing the Space Shuttle1."

sacrifice so much of their standard of living in order to colonize a dead planet. An answer to such would be to appeal not to their greed, but rather to their sense of adventure. Like the colonists who set out to the new world, the ones who travel to Mars[56] will be those seeking adventure and freedom. Another problem is the political nature of the endeavor. Since many countries will be contributing to the colonies, they will need some way of disregarding their differences in order for the mission to succeed. Earth’s political problems will directly impact the stability of the colonies, especially since the colonists will live in close quarters with one another. The colonies will need a centralized governing system in order to function once they become large enough to sustain themselves. Although they could initially follow a system with an equalized distribution of resources, after the colonies grow to populations in the thousands, a command structure will need to be implemented to ensure that the colony stays stable.

Currently, a collection of space treaties[57] exists that dictates what is, and isn’t, acceptable for a country to do outside of the bounds of Earth. These treaties were implemented to prevent any single country from claiming huge volumes of space beyond Earth or putting weapons in orbit. Because a Martian colony would presumably have a single greatest contributor, and thus a bias in ownership, it breaks these treaties. As such, the space treaties themselves need to be rewritten, or at least amended.

People who leave Earth to establish colonies on Mars will leave behind much of their old lives. However, the home they establish for themselves may, or may not, be ideal. It could take the form of a simple city, an independent country, or even an entirely separate planet. The end goal, of course, is for Mars to be independent, but initially, it will be fully dependent on Earth.

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[56] Alpert, Mark, and George Musser. "How to Go to Mars."
[57] "United Nations Treaties and Principles On Outer Space, Related General Assembly Resolutions and Other Documents." *United Nations OFFICE FOR OUTER SPACE AFFAIRS*

The earliest step will be to create test colonies or other samples to determine how populations will react to living on Mars. From there, the test colonies can grow and start taking in colonists. These colonists will go to Mars for a variety of reasons. Some may go to seek out new business or life opportunities. These people would be ones who are dissatisfied with major aspects of life on Earth. They would be the ones who rejected the levels of their government's invasion of their privacy or ones who felt that they had no future on Earth. Others could be simply afraid of some global apocalyptic event. Colonists won't just be from Earth, some will be born and live their entire lives on the red planet.

Similar to the colonization of the Americas, the colonization of Mars will rely on a flow of economic resources. Should space travel become cheap due to innovations in the field, Mars could export large amounts of metals and other minable minerals, and depending on the solution, farmed crops. While this could eventually make the colonization profitable, the upfront cost to establish the colony is massive, and even then, colonies will have to prioritize their own needs before those of Earth. However, the colonies could create a trade agreement to trade raw minerals for fertilizers needed for their farms. To reduce the cost of transportation on the Martian side, the colonists could make use of the reduced gravity to construct a space elevator which would, in turn, enable the colony to bypass the most expensive part of transportation.

Eventually, any colony or network of colonies established on Mars is going to grow to the point where they desire to break free from dependence on Earth. At this point, the governments of Earth will be faced with the choice to allow them independence or fight a suppressive war with another planet. Ideally, a trade agreement of sorts would be implemented to keep the newly formed Martian state as a quasi-vassal for an extended length of time. This would be the most realist way for Earth to maintain a position of superiority over Mars and its inhabitants.

Once fully established, the new colonies of Mars can make use of a government system created from scratch. Equal rights and a relatively fair distribution of wealth could be achieved and, depending on the specifics of the governing system, these points could be maintained for a long time. The early colonies will be able to function under a communistic system, but as the populations grow to larger than a few hundred, order will break down unless a centralized controlling body is established. Once the colony has grown large and independent, it will have developed its own unique cultures and societal structures. Traveling to space could positively alter the colonists' sense of nationalism. It has been shown that astronauts who gaze upon Earth from orbit gain a new appreciation for the beauty and unity of the planet as a whole. People who decide to colonize will be from many diverse backgrounds, but seeing the scale of Earth and lack of clear cut borders could have the effect of dissolving nationalistic tensions. Space travel and seeing Earth from the colony ships should have the effect of unifying the colonists, regardless of their background.

Studies have shown that when groups of people are kept in confined spaces[58] for extended periods of time, group cohesion breaks down. To mitigate this, centralized supporting command structures are needed. These command structures have the effect of ensuring that the group functions as a unified body. The longer these groups of people are kept in close quarters with one another, the greater the risk of the group collapsing. One way to prevent this is to ensure that all colonists have access to recreational activities and aren't constantly working on research or colonial maintenance.

[58] Palinkas, Lawrence. "Psychosocial Issues in Long-Term Space Flight: Overview."

Changes in personality have been observed in people returning from space travel. Such changes include anxiety and depression. Neurotic conditions have also been known to occur, one of which being asthenisation[59]. This condition is related to neurasthenia and causes a variety of symptoms such as irritability and sleep problems. However, the existence of the condition is contested in the West due to its Earth counterpart not being recognized as a condition itself, as it is in China and Russia.

When choosing early colonists, only those who are willing to completely leave behind their entire lives on Earth forever will be able to be selected. The early colonists will most likely undergo extreme training and simulated isolation to ensure that they can handle the colony's conditions, both mentally and physically. The effects that the lowered gravity of Mars will have on human colonists is unknown, and since supplies from Earth can only be sent to Mars roughly every two years and take six months to arrive, colonists will have to deal with any emergencies that arise by themselves. One way of mitigating the isolation felt by early colonists (i.e. when the colony is still very small) would be to enact a series of morale boosting measures such as having video, or more realistically, text-based contact with friends and family. Another would be to allow family members to send personalized gifts to colonists during resupply missions. Due to the sheer distance between Mars and Earth, there will be a notable delay in communications, thus any meaningful amounts of personal contact will take hours, or be full of jarring breaks in conversational flow.

Should the colonies of Mars be granted status as an independent body, potential colonists will be more likely to emigrate to Mars. Without any connections or affiliations with Earth, they will have much more freedom to live their lives as they please than they would on Earth. The

[59] "Perspectives on Asthenia in Astronauts and Cosmonauts: Review of the International Research Literature." *Behavioral Health & Performance Research Element Space Medicine Division*

colonies themselves would be able to make decisions that better answer the problems that the colonists face than a governing body on Earth could. However, an independent colony could decide that it no longer needs to follow the objectives its establishment was meant to achieve. In some cases, a colony might try to break off from Earth based control before it can support itself and thus doom its colonists or enter a parasitic relationship with other colonies. Such an eventuality would require colonies to be able to interact and coexist, perhaps as a nation-state under a single ruling body. However, the process of determining this body could be less than peaceful.

The process for determining who is acceptable for colonization relies on many factors. Early colonists will most likely have to come from an age group between the ages of 20 and 35 to ensure that they are healthy enough for the journey and colony conditions. In addition, these colonists should express a desire to procreate, as they will be responsible for initiating a new population. Married couples would be preferred in this case due to the higher likelihood that they will be able to coexist. This could have the added effect of reducing the psychological effects felt by colonists. Since colonists will come from a diverse national and ethnic background, all colonists must be willing to live together in close quarters with people from cultures that are opposite to their own, and would probably have to go through an extensive cultural education process. The ideal end result of this mixture would be a new Martian culture created from the blending of all of Earth’s cultures. Colonists from some religions will be faced with the problem of never being able to follow certain location based traditions. An example of this being the Muslim pilgrimage to Mecca, as well as praying in the direction of the city. When on another planet, hundreds of millions of miles from their holy city, proper prayer and pilgrimage will be next to impossible. Solutions to such conflicts with tradition must be solved or colonization will have a huge barrier preventing people of certain backgrounds from immigrating to the colonies.

Some of the colonization strategies will come with problems and benefits that others don't. All of the strategies that aren't terraforming could result in conflict over time due to the constricted nature of the associated sacrifices in quality of life. Eventually, this could potentially result in some form of aggressive conflict. One benefit that the non-terraforming colonization techniques do have is that prior to having windows to the outside, time will be at their disposal. The colony could decide that they would prefer days to be longer than 24 hours. By altering the light levels in the colony that would help simulate day and night, this can easily be achieved. While jarring at first, altering the length of the day could have a lot of positive effects, such as increasing the amount of time allocated for sleeping. This would have the effect of ensuring that the colonists would be less likely to suffer from the effects of sleep deprivation. It would also give colonists more time to explore new forms of recreation allowed by reduced gravity. Because the human body's potential for growth wouldn't be diminished by the lowered gravity, various sports could be a lot more extreme than those on Earth, especially if the colonial athletes work to be on par with their Earth counterparts. As the effects of the altered gravity are discovered and documented, humans will become better equipped to deal with altered gravity for any future colonization efforts. Humans could spread life through the universe, rather than just looking for it.

Extraterrestrial colonization will have more effects than just spreading life. It will inspire generations of children to pursue careers related to the new field. As with all major changing points in human history, this colonization will bring with it a myriad of new technologies and fields of research. The value of spreading humanity beyond the borders of Earth is not just in its ability to save humanity from a disaster, but also in the access to new supplies of metals and minerals that it offers. Colonizing Mars will fundamentally change the course of human history and forever alter the way humans view the great expanses of the universe. Reaching out into the depths of space will no longer be an unreachable dream: the humans of the future will make sure of it.

Why not the Moon

The moon is the closest large body to Earth and would seemingly make a decent location for extraterrestrial colonization. It can be said that the Moon would be more convenient due to its proximity to Earth. However, this convenience is far outweighed by the negatives. Earth's moon has a mere 17% of the gravity of its host planet. This level, less than a 5th of Earths, would have a huge effect on the heath of the colonists. A colony on the Moon would never reach a state of sustainable independence from Earth because, due to the close proximity, ties with the planet would never be fully severed. The colony would rely on Earth for supplies indefinitely, and should something catastrophic happen to Earth, this supply line, and therefore the colony itself, would fail.

Earth's moon is not massive enough to ever maintain its own atmosphere. Because of this, the prospects of ever terraforming the natural satellite to an Earth-like state are negligible. In addition to this, because the Moon has no atmosphere, the dust that settles on the surface hasn't been weathered, resulting in the entire surface being coated in an extremely abrasive dust-like layer. Any attempt to farm on the surface of the Moon would be affected by this abrasive dust. Even simply acquiring water poses a significant challenge. The complete absence of water on the surface of the Moon means that any potential colony would have to tunnel deep into the depths of the Moon for water. Even then, there exists the chance that the colony could fail to find any significant source.

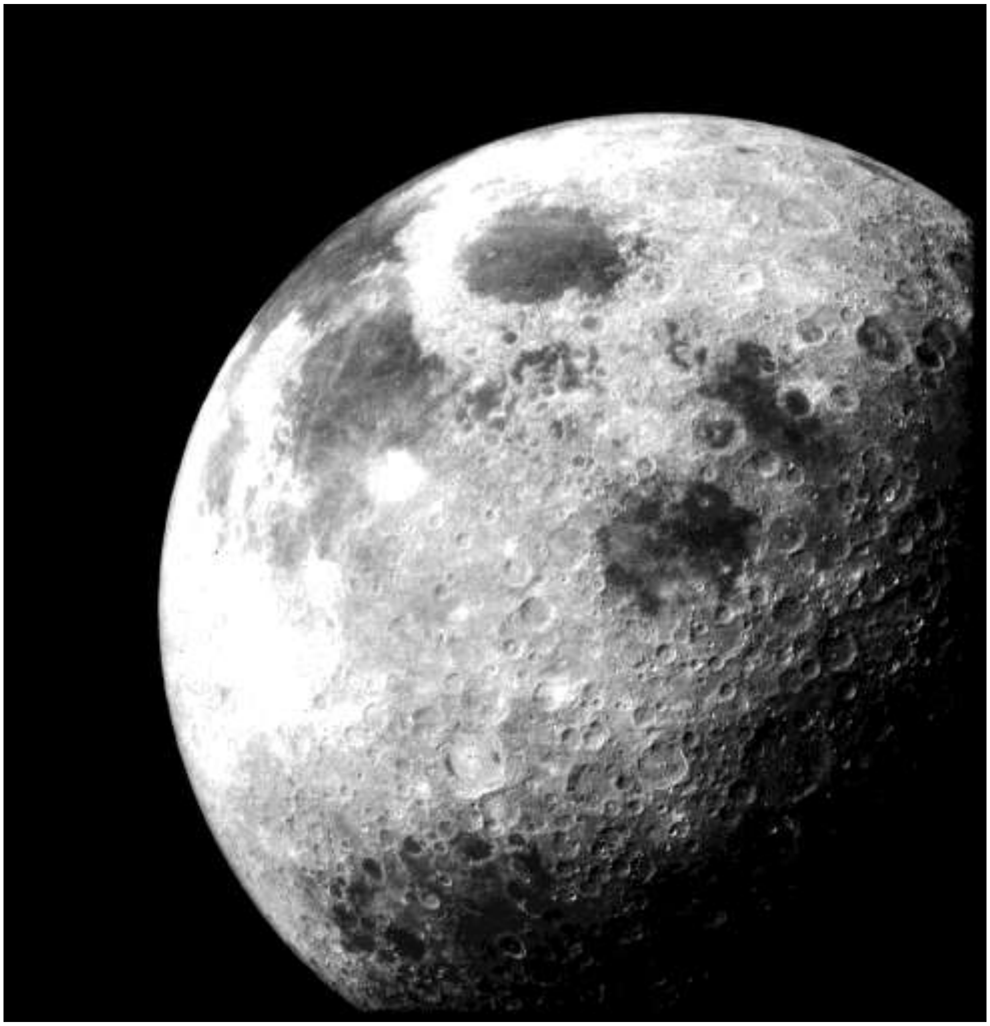


Figure 11.1: The Moon

Colonies established on the surface of the Moon would be at a constant risk of failure from almost every facet of colonization. With no atmosphere to cause asteroids to burn up, any surface colonies are at a high risk of being damaged or destroyed by even small asteroids. These colonies will also be limited in the number of backup power sources available. While a Martian colony could potentially harvest wind energy in the event that other options fail, a moon colony could not. A moon colony could also never hope to harvest hydroelectric power, whereas a Martian colony could, depending on the colonization strategy. The elements of nature are not the only risks that a lunar colony would face. Because colonizing the Moon is within the budget of the more powerful space faring nations, one country could create a colony by itself. With the current treaties in place, this act defies the international laws regarding what can and cannot exist outside of Earth. Alternatively, a single country making a colony could prompt other powerful nations to create their own. While a colonization arms race or sorts may seem beneficial at first, it could lead to fighting over land rights or the Moon’s limited resources.

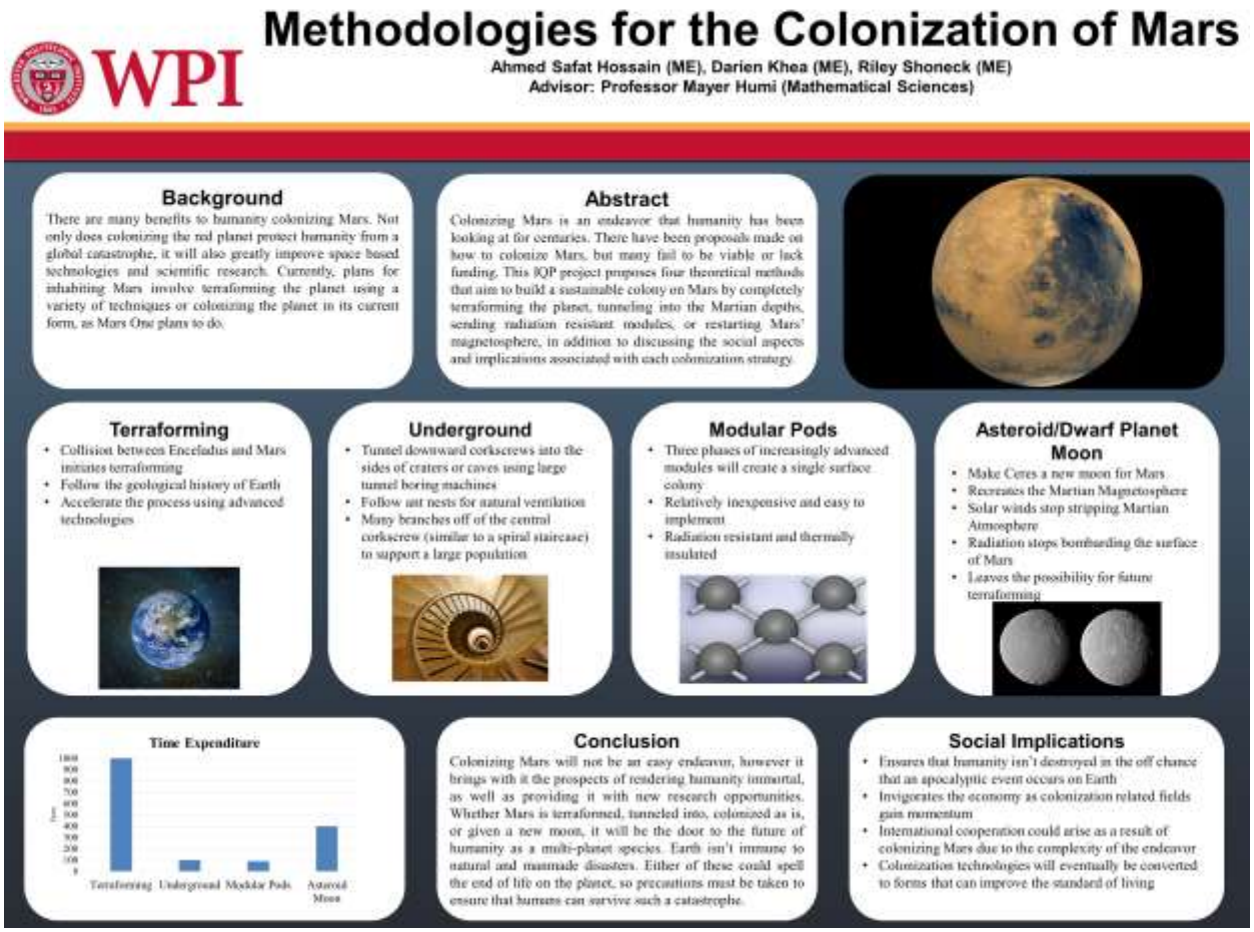
Recommendations for Future Projects

There are many ways that future ventures, IQPs and beyond, can improve on this project. One such way would be to further analyze the scientific research that would go into one or more of the individual colonization strategies. Alternatively, a project group could focus primarily on the social or economic effects resulting from the colonization process and resultant colony. Further defining the specific details of any of the strategies, such as breaking down the timelines and approaching the specific aspects of a single stage of any solution, could prove to be a project in it of itself. Other ways to further improve on the presented project would be to look into the technological advances that could prove to be cost effective and reliable for colonization or to follow up on any of the proposed colonization techniques as new technologies become available. A possible project to take an alternative approach would be to explore the colonization of Mercury, as the planet is rich in H_3. Lastly, a project that focuses on the history of Earth and technology could be done to present alongside this one, as this project itself shows that history plays an equally important role in determining the future of colonization and terraforming.

Conclusion

Colonizing Mars will not be an easy endeavor, however it brings with it the prospects of rendering humanity immortal, as well as providing it with new research opportunities. Whether Mars is terraformed, tunneled into, colonized as is, or given a new moon, it will be the door to the future of humanity as a multi-planet species. Earth isn't immune to natural and manmade disasters. Either of these could spell the end of life on the planet, so precautions must be taken to ensure that humans can survive such a catastrophe. While terraforming Mars would take 1000 or more years to do, it would ensure that humans had a second Earth to settle on. Alternatively, living below the surface of Mars would protect colonists from all of the hazards present on the planet, at the cost of natural sunlight. Living in a modular radiation-resistant pod colony would be the quickest colonization strategy and would give colonists a lot of choice regarding the location, but would be under constant risk of radiation leaks, heat and pressure loss, and even an asteroid impact. Giving Mars a new moon by placing Ceres in orbit around it would recreate the Martian magnetosphere, thus allowing for the eventual terraforming of the planet while also letting humans settle it as is. However, the risk of failure is high and the consequences of failure could be devastating. While any of these solutions could result in a stable colony, no one solution can be unanimously claimed to be the best. Since everything from a virus to a thermonuclear war has the potential to wipe out life on Earth, it is imperative that an extraterrestrial colony be established as soon as possible. It's impossible to know when a global catastrophe will happen. While it could be hundreds of years, it could just as easily be tomorrow. Humanity needs a backup plan. It needs a second home, and Mars will be this home. The Chinese philosopher Lao Tzu once said, "A journey of a thousand miles begins with a single step."

Visual Representation of Work



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